## **Piezoelectric Composite Actuators**

Modelling of the Static and Dynamic Behaviour

## **Piezoelectric Composite Actuators**

Modelling of the Static and Dynamic Behaviour

Proefschrift

ter verkrijging van de graad van doctor aan de Technische Universiteit Delft, op gezag van de Rector Magnificus prof. ir. K.C.A.M. Luyben, voorzitter van het College voor Promoties, in het openbaar te verdedigen op donderdag 10 oktober 2013 om 10.00 uur

 $\operatorname{door}$ 

### Peerawan WIWATTANANON

Master of Science in Mechanical and Aerospace Engineering Syracuse University, USA geboren te Nakhonratchasima, Thailand Dit proefschrift is goedgekeurd door de promotor: Prof.dr.ir. R. Benedictus

Copromotor Dr.ir. H.E.N. Bersee

Samenstelling promotiecommissie:

Rector Magnificus, voorzitter
Prof.dr.ir. R. Benedictus, Technische Universiteit Delft, promotor
Dr.ir. H.E.N. Bersee, Technische Universiteit Delft, copromotor
Prof.dr. W.A. Groen, Technische Universiteit Delft
Prof.dr. D. Damjanovic, École polytechnique fédérale de Lausanne, Zwitserland
Prof.dr.ir. R. Akkerman, Universiteit Twente
Dr. S. Aimmanee, King Mongkut's University of Technology Thonburi, Thailand
Dr.ir. O.K. Bergsma, Technische Universiteit Delft
Prof.dr.ir. R. Marissen, Technische Universiteit Delft, reservelid

This research was carried out as part of the "Smart Fixed Wing Aircraft" project under the Clean Sky Joint Technology Initiative program.

ISBN 97890-6562-332-4

Copyright©2013 by Peerawan Wiwattananon

All rights reserved. No part of the material protected by this copyright notice may be reproduced or utilised in any form or by any means, electronic or mechanical, including photocopying, recording or by any information storage and retrieval system, without the prior written permission of the author.

Cover design: Methisa Ward, Nicolene van der Zwan and Peerawan Wiwattananon

Printed by Delft Academic Press (VSSD), Delft, The Netherlands

To my family

# Summary

Smart actuators, made of smart materials, are becoming more attractive in many applications because smart materials are not subjected to wear and does not require lubrication during service. Piezoelectric materials are one of the groups of attractive smart materials that are being investigated for many applications today. Piezoelectric materials show fast responses, high efficiency/accuracy and operate on a large bandwidth. Composite materials are of interest because of their design flexibility and because they are lighter than other materials commonly used in aircraft and other applications. For the research reported here, a piezoelectric material was embedded in a composite material to form a piezoelectric composite actuator.

This research was conducted to expand our knowledge of piezoelectric composite material actuators, and originats from the need to control air flow separation over an airfoil in an aircraft. There is a need to build a profound body of knowledge about such actuators before they can be implemented in an airfoil, and to understand which parameters influence the behaviour of piezoelectric composite material actuators under static and dynamic operating conditions. The actuators were manufactured and tested experimentally under static and dynamic conditions, the experimental results were then compared to data obtained using finite element models of the actuator. The models were incorporated using the piezoelectric material properties that had been determined experimentally. The results showed that a piezoelectric material's response to an input stimulant, e.g. electric voltage and frequency, influences an actuator's behaviour.

**Static condition:** a full static condition was created by applying separate DC electric potentials to the actuators. The actuators showed two distinct behaviours when they were subjected to separate DC input electric potentials. The first behaviour, nonlinear displacements, resulted from a nonlinear response in a piezo-electric material due to a high magnitude electric potential. The second behaviour, an asymmetrical permanent displacement offset, corresponded to two DC electric polarities due to the presence of irreversible domain wall orientations in the piezo-

electric material. This permanent displacement offset was shown to be the most dominant parameter influencing the actuation performance. The second parameter dominating actuation performance was the nonlinear actuation response, the last parameter influencing actuation performance was the piezoelectric material's linear response to the input electric potential.

**Dynamic condition:** two perspectives were taken into consideration, one, macroscopic and two, microscopic. The macroscopic perspective was used to explain the actuator's behaviour from the actuator's scale, i.e. the application perspective, while the microscopic perspective was used to explain how did the piezoelectric material properties varied under dynamic conditions. Using the macroscopic perspective, it was determined that the actuator's actuation displacement is depended on the bending capability of the actuator and a larger bending coefficient, defined in this work, is to be preferred one. The actuators' resonance frequencies showed a direct relationship with a "reduced bending stiffness", i.e. the total bending stiffness was reduced when bending-extension coupling of the actuator existed. At the microscopic perspective, the piezoelectric material softened in response to increasing input voltage. This softening phenomenon of the piezoelectric material led to a reduction in actuator's resonance frequency in relation to increasing input voltage.

## Samenvatting

Slimme actuatoren, gemaakt van slimme materialen, worden steeds aantrekkelijker voor veel toepassingsgebieden, dit omdat slimme materialen niet blootgesteld worden aan wrijving en tijdens gebruik niet gesmeerd hoeven te worden. Piëzo-elektrische materialen vormen een groep uit de vele aantrekkelijke slimme materialen die vandaag de dag worden onderzocht voor vele toepassingen. Piëzo-elektrische materialen vertonen een snelle respons, hoge efficiëntie en nauwkeurigheid en werken in een grote bandbreedte. Composietmaterialen zijn interessant door hun vormvrijheid tijdens ontwerp en omdat ze resulteren in lichtere ontwerpen dan andere materialen die gebruikt worden in vliegtuigen en andere toepassingen. Voor het hier gerapporteerde onderzoek werd een piëzo-elektrisch materiaal ingebed in een gelaagd composiet om zo een piëzo-elektrische actuator te vormen.

Dit onderzoek werd uitgevoerd om de kennis van piëzo-elektrische composiet actuatoren te vergroten en het is ontstaan uit de noodzaak de luchtstroomloslating over een vleugelprofiel te kunnen controleren. Een grondige kennis over dergelijke actuatoren moet opgebouwd worden voordat deze actuatoren in een vleugelprofiel toegepast kunnen worden. Kennis over welke parameters het gedrag van piëzoelektrische composiet actuatoren onder statische en dynamische omstandigheden beïnvloeden is hiervoor nodig. De actuatoren zijn vervaardigd en getest onder statische en dynamische omstandigheden en de experimentele resultaten werden vergeleken met die verkregen via eindige elementen modellen. In de modellen werden piëzo-elektrische materiaaleigenschappen die experimenteel bepaald werden verwerkt. De resultaten toonden aan dat de reactie van een piëzo-elektrisch materiaal op een ingang stimulans, bijv. de elektrische spanning en frequentie, het gedrag van de actuator beïnvloedt.

Statische toestand: een volledige statische toestand werd verkregen door het sequentieel aanbrengen van gelijkspanningspotentialen op de actuatoren. De actuatoren toonden twee verschillende gedragingen als deze werden onderworpen aan gelijkspanningspotentialen. De eerste respons was een niet lineair gedrag veroorzaakt door het niet lineair piëzo-elektrisch materiaalgedrag als gevolg van een grote elektrische potentiaal. De tweede respons was een asymmetrische permanente verplaatsing behorend bij twee tegengestelde gelijkspanningspotentialen ten gevolge van onomkeerbare "domain wall orientations" in het piëzo-elektrisch materiaal. Deze permanente verplaatsing bleek de meest dominante parameter die de actuator prestaties beïnvloed. De tweede parameter die de prestaties domineert was de niet lineaire actuator respons, terwijl de standaard lineaire piëzo-elektrische materiaalreactie op kleine elektrische potentialen de prestaties het minst beïnvloedt.

Dynamische toestand: twee perspectieven werden in aanmerking genomen. i) macroscopische en ii) microscopische. Het macroscopische perspectief werd gebruikt om het gedrag van de actuator vanuit het toepassingsperspectief uit te leggen, terwijl het microscopische perspectief werd gebruikt om uit te leggen hoe de piëzo-elektrische eigenschappen van het materiaal varieerden onder dynamische omstandigheden. Vanuit het macroscopische perspectief werd vastgesteld dat de actuator verplaatsing afhankelijk is van de buigstijfheid van de actuator en dat een grotere buigstijfheid de voorkeur verdient. De resonantiefrequenties van de actuator vertoonden een directe relatie met "verminderde buigstijfheid", dat wil zeggen de totale buigstijfheid was verlaagd als de actuator een buig-extensie koppeling had. Vanuit microscopisch oogpunt verslapt het piëzo-elektrische materiaal in reactie op toenemende ingangsspanning. Dit verslappende effect van het piëzo-elektrische materiaal leidt tot een vermindering van de actuator resonantiefrequentie bij toenemende ingangsspanning.

# Contents

Sı	ımma	ary		i
Sa	amen	vatting	2° 5	iii
1	Intr	oducti	ion	1
	1.1	Flow S	Separation of the Conventional Fixed-Wing Aircrafts	1
	1.2	Air Fl	ow Separation Control Methods	3
	1.3	Adapt	vive Structures	4
		1.3.1	Adaptive Airfoils	4
		1.3.2	Boundary Layer Control	6
	1.4	Resear	rch Objectives	9
		1.4.1	Thesis Outline	10
	Refe	erences		12
<b>2</b>	$\mathbf{Lite}$	erature	e Review	15
	2.1	Smart		15
		2.1.1	Piezoelectric Materials	15
		2.1.2	Shape Memory Alloy (SMA)	25
		2.1.3	Electrostrictives Materials	26
		2.1.4	Magnetrostrictive Materials	26
		2.1.5	Comparisons of Smart Materials	27
		2.1.6	Conclusions	27
	2.2	Nonlir	nearity in Piezoelectric Materials	28
		2.2.1	Introduction to Nonlinearity in Piezoelectric Materials	28
		2.2.2	Frequency Dependent	30
		2.2.3	Stress Dependent	31
	2.3	Smart	Actuators	33
		2.3.1	Piezoelectric Actuators	33
		2.3.2	Comparisons of Smart Actuators	44
		2.3.3	Conclusions	47
	Refe	rences		48

3	Ma	nufact	uring of Piezoelectric Composite Materials Actuators	53
	3.1	Intro	luction	53
	3.2	Manu	facturing Concepts	55
	3.3	Actua	tor Manufacturing and Quality Check Results	57
	3.4	Actua	tor Configurations and Dimensions	61
	3.5	Concl	usions	64
	Refe	erences		65
4	Det	ermin	ation of Piezoelectric Material Properties	67
	4.1	Static	Operating Condition	68
		4.1.1	Nonlinear $d_{31}$ Determination via Three Approaches	68
		4.1.2	Experimental Results	71
		4.1.3	Comparison of the Three Approaches	77
		4.1.4	Conclusions	78
	4.2	Dyna	mic Operating Condition	79
		4.2.1	Dielectric Permittivity: A Function of Input Voltage and	
			Frequency	79
		4.2.2	Piezoelectric Coefficient: A Function of Input Voltage and	
			Frequency	81
		4.2.3	Mechanical Compliance: A Function of Input Voltage and	
			Frequency	84
		4.2.4	Conclusions	85
	4.3	Concl	usions $\ldots$	86
	Refe	erences		87
F	Fin	to Flo	ment Medel of Astustone, Under Statis Condition	01
9	<b>F</b> III 5 1		ion of the Finite Floment Models of THUNDERs / IPCAs	91
	5.1 5.2	Statio	Model of Actuators	92
	0.2	5 9 1	Model of Actuators	95
		5.2.1	Actuation Model	90
		5.0.2	Actuation Model	100
	52	0.2.0 Static	Experimental Setup	100
	0.0 5 4	Concl		102
	J.4 Dof	Conci	usions	103
	nere	erences		104
6	Sta	tic Be	haviour of Piezoelectric Composites Actuators	107
	6.1	Introc	luction	107
	6.2	Static	Experimental Results	108
	6.3	Actua	tion Displacements vs Actuation Predictions using Standard	
		Nonli	near Piezoelectric Coefficients	114
		6.3.1	Experimental Results vs Static Models	114

	6.4	Actua	tion Displacements vs Actuation Predictions with Nonlinear	
		Piezoe	electric Coefficients: Discharged with un-Tuned Strain State $% \mathcal{A}$ .	118
		6.4.1	Experimental Results vs Static Models	119
	6.5	Actua	tion Displacements vs Actuation Predictions with Nonlinear	
		Piezoe	electric Coefficients: Non-Discharged with un-Tuned Strain	
		State		128
		6.5.1	Experimental Results vs Static Models	128
	6.6	Under	standing the Static Behaviour	136
		6.6.1	Predicted Actuation Displacements	136
		6.6.2	Discussions and Conclusions	139
	6.7	Discus	ssions and Conclusions	140
	Refe	erences		142
7	Fini	to Flo	mont Models of Actuators: Under Dynamic Condition	1/2
1	7 1	Dynar	nic Finite Element Model	1/13
	1.1	7 1 1	Dynamic Model	144
		7.1.1 7.1.2	Actuator Configuration	147 $147$
	7.2	Dvnar	nic Experimental Setup	148
	Refe	rences		150
	10010	renees		100
8	Dyr	namic 1	Behaviour of Piezoelectric Composites Actuators	151
	8.1	Introd	uction	151
	8.2	Dynar	nic Experimental Results	152
	8.3	Dynar	nic Experimental Results vs Dynamic Models	154
	8.4	Under	standing the Dynamic Behaviour of Actuators	159
		8.4.1	Understanding the Dynamic Performance: Macroscopic Per-	
			spective	159
		8.4.2	Understanding the Piezoelectric Materials under the Dy-	
			namic Condition: Microscopic Perspective	166
	8.5	Conclu	usions	172
	Refe	erences		174
9	Con	clusio	ns and Recommendations	177
	9.1	Backg	round	177
	9.2	Conclu	usions on Piezoelectric Material Properties	178
		9.2.1	Piezoelectric Material Testing under Static Conditions	179
		9.2.2	Piezoelectric Material Testing Dynamic Conditions	180
	9.3	Conclu	usions on Actuators' Static Behaviour	181
	9.4	Conclu	usions on Actuators' Dynamic Behaviour	183
		9.4.1	The Macroscopic Perspective	183
		9.4.2	The Microscopic Perspective	184

	9.5	Recommendations	185
		9.5.1 Determination of the piezoelectric material properties	185
		9.5.2 Improving an actuator's actuation performance	186
		9.5.3 Applications Oriented	186
	Refe	erences	188
Aj	ppen	ndices	189
A	The	ermal Analogy of NASTRAN/PATRAN	191
	Refe	erences	193
в	Fun	ndamentals of Nonlinear Finite Element Analysis	195
	Refe	erences	200
Li	sts o	of Symbols	201
A	Accronym		205

# List of Figures

1.1	Air flow separation on an airfoil induced by an adverse pressure	
	gradient. (a) pressure distribution. (b) flow field (Adapted from [3])	2
1.2	Air flow separation over the airfoil [4]	2
1.3	Vortex Generator. (a) vortex generator installed on a wing span [7].	
	(b) common vortex generator [8].	4
1.4	Sketch showing an adaptive trailing edge of an airfoil. Sensors detect	
	changing in the pressure distribution over the airfoil. The pressure	
	values are sent to the controller where the command in the form of	
	a signal is sent to the actuators to morph the trailing edge	5
1.5	Spoke configurations for the belt-rip [10]	5
1.6	Finger Concept [11].	6
1.7	Schematic representation of three mechanical actuator concepts. (a)	
	springboard/flipperon without a cavity. (b) springboard/flipperon	
	with a cavity. (c) double-clamped type (bulb) [15]	7
1.8	Schematic of the flow of this thesis	11
2.1	PZT crystal structures [2]	16
2.2	Poling process: (a) prior to polarization polar domains are oriented	
	randomly; (b) during polarization, a very large DC electric field is	
	applied at below the Curie temperature to reorient all the domains;	
	(c) after the DC field is removed, permanent polarization is achieved	
	and the poling process is completed. The piezoelectric materials are	
	ready for applications.	17
2.3	Typical hysteresis loop for a ferroelectric material [3]	17
2.4	Strain during poling and the typical hysteresis loop as observed for	
	piezoelectric ceramic actuators [3]	18
2.5	Strain during poling and the typical hysteresis loop as observed for	
	piezoelectric ceramic actuators $[3]$	19
2.6	Schematic representation of the polycrystalline structure of the ce-	
	ramic [4]	20
2.7	Direct piezoelectric effect in a rectangular shaped component $[3]$ .	20
2.8	Inverse piezoelectric effect in a rectangular shaped component $[3]$ .	21

2.9	A piezoelectric material sheet with the application of the electric flied along the 3-axis [6]	23
2 10	Stacked Piezoelectric [7]	$\frac{20}{24}$
2.10 9.11	Piezoelectric fiber actuator or Active fiber composite (left [7] right [8])	21
2.11	Schematic of shape memory effect in stratching [6]	24 26
2.12 2.12	Electric field dependent of dielectric coefficients. The two inserts	20
2.10	are the P-E relations at low and high electric fields respectively [10]	29
2.14	Illustration of reversible and irreversible domain wall displacements of piezoelectric meteriale [11]	20
0.15	(a) dielectric experiment $c'$ (c. as a function of electric field amplitude	30
2.10	(a) detecting constant $\epsilon_{33}/\epsilon_0$ as a function of electric field amplitude at solected frequencies. (b) the same data plotted as a function of	
	frequency for selected field amplitudes. Solid lines are a guide for	
	the eve. [14]	30
2.16	Stress dependent of piezoelectric coefficient $d_{33}$ and charge density [15]	31
2.17	Illustration of applied lateral stress perpendicular to the poling di-	-
-	rection, direction 3, from Krueger [16]'s.	32
2.18	Illustration of the application of the lateral compressive stress per-	
	pendicularly to the poling direction, shown are solid arrows (left).	
	The poling direction is the out-of-plane direction. The dashed rect-	
	angular represents the original shape of the piezoelectric material	
	when the compressive stress is applied (right)	32
2.19	$d_{31}$ and $d_{32}$ vs lateral stress, $T_1$ . Comparison of all ceramics tested [16]	33
2.20	Arrangement of CAP and DAP Twist-Active Lamina [17]	34
2.21	Layer sequence of a unimorph $[4]$	34
2.22	Behavior of a bimorph subjected by an electrical voltage (top)	
	parallel, (bottom) series $[4] \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots$	34
2.23	Configuration of THUNDER [25]	35
2.24	RAINBOW dome shape $[28]$	37
2.25	Various stages of domain alignment and reorientation in a Rainbow	
	actuator, depicting conditions: (A) as processed and electroded, (B)	~ ~
	first application of voltage and (C) complete application of voltage [31]	38
2.26	LIPCA system with carbon/epoxy and glass/epoxy layers at the	10
a a <b>-</b>	top and bottom layers, respectively [38]	40
2.27	Moment arm of the LIPCA system	41
2.28	Multiple actuated shapes of LIPCA-C2, $Lx/H = 200$ . (a) no electric	40
0.00	field, (b) -2 MV/m and (c) and +2 MV/m [24] $\ldots$	43
2.29	Comparison of emerging and traditional actuators in terms of force	
	ievel. SIMA is the snape memory alloy. MS is the magnetrostric-	15
		40

2.30	Comparison of emerging and traditional actuators in terms of force density level [50]	45
2.31	Comparison of emerging and traditional actuators in terms of stroke level [50]	46
2.32	Comparison of emerging and traditional actuators in terms of bandwidth [50]	46
3.1	Vacuum bagging system for the autoclave manufacturing concept $% {\displaystyle \sum} {$	55
3.2	An actuator is tapped at the 4 corners to prevent the relative move- ment between plies and to prevent the actuator to misplace during transportation. The actuator is sandwiched between the two Kap- ton film	56
3.3	Hot Press System	57
3.4	Cured actautor	58
3.5	A cut-through of [G/PZT/G/C] manufactured by a hot-press and seen through a microscope	58
3.6	A cut-through of $[G/PZT/G/G/C]$ manufactured by an auto- clave and seen through a microscope	59
3.7	Microscopic picture of a cracked PZT when cured at 4 bars of pressure.	59
3.8	Schematic movement of resin to the edge of the PZT (left), inserting a glass layer frame around the PZT (right)	60
3.9	Microscopic pictures of an actuator with voids (left) and without voids (right).	60
3.10	A curing Cycle.	60
3.11	Preparation concept of the actuator with copper foils. The left end is where the 5-mm tab is and the right end (opposite to the copper foils) is where the 3-mm tab is.	61
3.12	Schematic of the actuator, showing the 4 layers of glass fabric at the tabs	61
3.13	Schematic of the actautor layups. The two stacks of glass layers are located at the two ends. A stacked top layers(shown as the black layers) are lightly placed on top of the PZT layer (shown as the light grey block in the middle of the actuator). The copper foils are shown as the yellowish pieces at the left end	63

4.1	Schematic of the applications of positive electric field through the arrows. (a) application of the electric field for a particular time step then it is discharged to a zero electric field before the application of the electric field opposing to the current polarity to fine-tune the strain back to the zero strain state, (b) application of the electric field for a particular time step then it is discharged to a zero electric field before the application of the next higher field level. (c) application of the electric field without discharging.	69
4.2	The two strain gages were attached in the middle of the piezoceramic patch perpendicularly to each other.	70
4.3	Five experiments of $\epsilon_{xx}$ and $\epsilon_{yy}$ under the negative electric field, $\epsilon_{xx}$ and $\epsilon_{yy}$ correspond to (a) and (b), respectively, and under the posi- tive electric field, $\epsilon_{xx}$ and $\epsilon_{yy}$ correspond to (e) and (f), respectively. The PZT is discharged but strain state were un-tuned back to zero. (c) shows averaged values of the last 4 experiments of $\epsilon_{xx}$ and $\epsilon_{yy}$ , (a) and (b), respectively, under the negative electric field. (d) shows averaged of $\epsilon_{xx}$ and $\epsilon_{yy}$ from the last 4 experiments obtained from (c). (g) shows averaged values of the last 4 experiments of $\epsilon_{xx}$ and $\epsilon_{yy}$ , (e) and (f), respectively, under the positive electric field. (h) shows averaged of $\epsilon_{xx}$ and $\epsilon_{yy}$ from the last 4 experiments obtained from (g). 'Ex1' refers to experiment 1 and similarly for experiments 2 to 5	72
4.4	(a) illustrates randomly oriented domain and domain walls in the bulk piezoelectric material before being poled. The arrows represent the direction of the domain inside the piezoelectric material, (b) il- lustrates the bulk piezoelectric material is being poled with domains and domain walls oriented along with the poling direction, denoted 'P', (c) poled bulk piezoelectric material resulting in 180° domain walls orientation, same direction as the poling direction. Note that some domains are slightly reoriented back to their original orienta- tion but still in favour of the poling direction. The poled piezoelectric is now ready for applications. During a small magnitude input elec- tric field, the domain walls rotate with respect to the electric field and are able to orient back to their original state; (d) illustrates a 90° domain wall orientations when the bulk piezoelectric material	

block represents the original size of the piezoelectric material before a large magnitude electric field was applied. Adapted from [6] . . . 73

experiences a large magnitude electric field opposing the poling direction resulting in permanent strain offset, denoted ' $\epsilon$ '. The dashed

4.5	Averaged of $\epsilon_{xx}$ and $\epsilon_{yy}$ from the last 4 experiments. (a) under the negative electric field. (b) under the positive electric field. The PZT was not discharged and strain state were un-tuned back to zero. Note that the representation of (a) and (b) in this figure is similar as the case in Figure 4.3(d) and Figure 4.3(h). The representation of all 5 experiments similar to the case of Figure 4.3(a, b c, e, f and g) are omitted in this figure
4.6	Averaged of $\epsilon_{xx}$ and $\epsilon_{yy}$ from the last 4 experiments. (a) under the negative electric field. (b) under the positive electric field. The PZT was discharged and strain state was tuned back to zero. Note that the representation of (a) and (b) in this figure is similar as the case in Figure 4.3(d) and Figure 4.3(h). The representation of all 5 experiments similar to the case of Figure 4.3(a, b c, e, f and g) are omitted in this figure
4.7	$\epsilon_{33}$ at various input voltages and frequencies $\ldots \ldots \ldots \ldots \ldots 80$
4.8	Displacement sensing mechanism of adjacent fiber-optic elements 82
4.9	$d_{33}$ at various input voltages and frequencies, Vpp is the peak-to- peak value of the AC input voltage with a sinusoidal signal 83
5.1	A simply-supported boundary condition of an actuator. The flat beam represents a flat actuator before manufacturing. The curved shape represents the actuator after manufacturing, u is the displace- ment along the x-axis, v is the displacement along the y-axis 94
5.2	The model dimension of the LIPCA $\rm [G/PZT/G/C]$ used in this study (a) and the actuator actual dimension of $\rm [G/PZT/G/C]$ (b) 101
5.3	Experimental Setup
5.4	The actuation displacements were measured at the free end tip of the actuator
6.1	Schematic of the applications of a positive electric field through the arrows. (a) application of the electric field for a particular time step then the actuator is discharged to a zero electric field before the application of the next higher field level to the actuator. This is denoted "discharging" condition; (b) application of the electric field without discharging before the application of the next higher field level to the actuator. 109

6.2	Static actuation displacement of $[G/PZT/G/C]$ when the actua- tor was not discharged prior to the application of the next higher voltage under a positive (a) and a negative (b) voltages. Static ac- tuation displacements when the actuator was discharged prior to the application of the next higher voltage under a positive (c) and a negative (d) voltages, 'Ex1' refers to experiment 1 and similarly for experiments 2 to 5
6.3	Static actuation displacement of $[G/PZT/G/G/C]$ when the actu- ator was not discharged prior to the application of the next higher voltage under a positive (a) and a negative (b) voltages. Static ac- tuation displacements when the actuator was discharged prior to the application of the next higher voltage under a positive (c) and a negative (d) voltages, $Ex =$ experiment, numbered 1 to 5 111
6.4	Static actuation displacement of $[G/PZT/G/C/G/C]$ when the actuator was not discharged prior to the application of the next higher voltage under a positive (a) and a negative (b) voltages. Static actuation displacements when the actuator was discharged prior to the application of the next higher voltage under a positive (c) and a negative (d) voltages, $Ex =$ experiment, numbered 1 to 5 112
6.5	Combined experimental results of all actuators under both positive and negative voltages when the actuators were not discharged prior to the application of the next higher voltage. A '+' sign in front of each layup represents a positive voltage apply to the actuator. A '-' sign in front of each layup represents a negative voltage apply to the actuator
6.6	Combined experimental results for all tested actuators under both positive and negative voltages when the actuators were discharged prior to the application of the next higher voltage. A '+' sign in front of a layup represents a positive voltage apply to the actuator. A '-' sign represents a negative voltage apply to the actuator 114
6.7	Experimental results of [G/PZT/G/C] under discharging and non- discharging conditions compared to the model with linear piezoelec- tric and nonlinear piezoelectric coefficients. Ex Discharged refers to the experimental results with a discharging condition. Ex NoDis- charged refers to the experimental results without discharging the actuator. Model Linear refers to a model incorporates with a linear piezoelectric coefficient. Model Nonlinear refers to a model incor- porated using a nonlinear piezoelectric coefficient obtained from a standard method

6.8	Experimental results of $[G/PZT/G/G/C]$ under discharging and non-discharging conditions compared to the model with linear piezo- electric and nonlinear piezoelectric coefficients. Ex Discharged refers to the experimental results with a discharging condition. Ex NoDis- charged refers to the experimental results without discharging the actuator. Model Linear refers to a model incorporates with a linear piezoelectric coefficient. Model Nonlinear refers to a model incor- porated using a nonlinear piezoelectric coefficient obtained from a standard method.	116
6.9	Experimental results of [G/PZT/G/C/G/C] under discharging and non-discharging conditions compared to the model with linear piezo- electric and nonlinear piezoelectric coefficients. Ex Discharged refers to the experimental results with a discharging condition. Ex NoDis- charged refers to the experimental results without discharging the actuator. Model Linear refers to a model incorporates with a linear piezoelectric coefficient. Model Nonlinear refers to a model incor- porated using a nonlinear piezoelectric coefficient obtained from a standard method	117
6.10	Experimental results of [G/PZT/G/C] under discharging and non- discharging conditions compared to the model with linear piezoelec- tric and nonlinear piezoelectric coefficients. Left: the actuator was actuated under a positive voltage. Right: the actuator was actuated under a negative voltage	119
6.11	Experimental results of [G/PZT/G/G/C] under discharging and non-discharging conditions compared to the model with linear piezo- electric and nonlinear piezoelectric coefficients. Left: the actuator was actuated under a positive voltage. Right: the actuator was actuated under a negative voltage	120
6.12	Experimental results of $[G/PZT/G/C/G/C]$ under discharging and non-discharging conditions compared to the model with linear piezo- electric and nonlinear piezoelectric coefficients. Left: the actuator was actuated under a positive voltage. Right: the actuator was actuated under a negative voltage	120

6.13	Changes of internal stress at the mid-length throughout thicknesses of $[G/PZT/G/C]$ between zero voltage and 200V from the finite element analysis. '+0V' refers to the stress condition at 0V with initial strain presented obtained under a positive electric field. '- 0V' refers to the stress condition at 0V with reduced initial strain presented obtained under a negative field. Note that there are two 0Vs because the nonlinear piezoelectric coefficients are determined independently between positive and negative fields	3
6.14	Effects of the applied compression and tension stresses affect to the domains inside a bulk piezoelectric layer compared to a stress free state [8]. The arrows pointing toward horizontally represent 90° domain walls; while the arrows pointing toward vertically represent non-90° domain walls. See chapter 2 for further explanation 123	3
6.15	Predicted actuation displacements with corrected initial strains vs experimental results under a discharging condition under the posi- tive polarity	5
6.16	Changes of stress through the piezoelectric layer thickness between $+0V$ with an existence of a permanent displacement offset and at a pure 0V. The pure 0V refers to the stress state at a zero voltage after manufacturing, i.e. zero initial permanent displacement. The $+0V$ refers to the stress state at a zero voltage of the 2nd experiment onward, leaving a permanent initial displacement inside an actuator. 123	5
6.17	Predicted actuation displacements with corrected strain	7
6.18	Combined experimental results for all tested actuators under both positive and negative voltages when the actuators were discharged prior to the application of the next higher voltage, A '+' sign in front of a layup represents a positive voltage apply to the actuator, A '-' sign represents a negative voltage apply to the actuator 12'	7
6.19	Experimental results of [G/PZT/G/C] under a discharging condi- tion compared to the model with linear piezoelectric and nonlinear piezoelectric coefficients. Left: the actuator was actuated under a positive voltage. Right: the actuator was actuated under a negative voltage	9
6.20	Experimental results of [G/PZT/G/G/C] under a discharging con- dition compared to the model with linear piezoelectric and nonlinear piezoelectric coefficients. Left: the actuator was actuated under a positive voltage. Right: the actuator was actuated under a negative voltage	0

6.21	Experimental results of [G/PZT/G/C/G/C] under a discharging condition compared to the model with linear piezoelectric and non- linear piezoelectric coefficients. Left: the actuator was actuated under a positive voltage. Right: the actuator was actuated under a negative voltage
6.22	Internal stress throughout the piezoelectric thickness at 0V or after the manufacturing process
6.23	Predicted actuation displacements with nonlinear piezoelectric co- efficient obtained from a standard approach, a '+' sign in front of each layup represents a positive voltage apply to the actuator a '-' sign in front of each layup represents a negative voltage apply to the actuator
6.24	Combined experimental results of all actuators under both positive and negative voltages when the actuators were not discharged prior to the application of the next higher voltage, a '+' sign in front of each layup represents a positive voltage apply to the actuator, a '-' sign in front of each layup represents a negative voltage apply to the actuator
6.25	Combined experimental results for all tested actuators under both positive and negative voltages when the actuators were discharged prior to the application of the next higher voltage, a '+' sign in front of a layup represents a positive voltage apply to the actuator, a '-' sign represents a negative voltage apply to the actuator 137
6.26	Predicted actuation displacements with nonlinear piezoelectric coef- ficients obtained under a discharging condition and the strain state was un- tuned to zero. A '+' sign in front of each layup represents a positive voltage apply to the actuator. A '-' sign in front of each layup represents a negative voltage apply to the actuator 138
6.27	Predicted actuation displacements with nonlinear piezoelectric co- efficients obtained under a non-discharging condition and the strain state was un-tuned to zero. A '+' sign in front of each layup repre- sents a positive voltage apply to the actuator. A '-' sign in front of each layup represents a negative voltage apply to the actuator 139
6.28	Experimental results of all actuators under both positive and neg- ative voltages without the permanent strain offsets, a '+' sign in front of each layup represents a positive voltage apply to the actu- ator, a '-' sign in front of each layup represents a negative voltage apply to the actuator

7.1	Actuator dimension. (a) represents the actual actuator dimension and as it is in the model. The actual actuator's width is 26 mm. The actuator's width is reduced in half. (b) a side-view of the model
	of an actuator
7.2	Symmetry plane and prescribed displacement. The x, y and z-axes represent the length, width and thickness direction of the actuator. The symmetry plane passes through the actuator's width along the length of the actuator
7.3	Boundary conditions of an actuator, (a) during manufacturing the actuator is simply-supported, (b) during actuation the actuator is in a cantilever beam condition
8.1	Dynamic experimental results of the peak-to-peak displacements of the [G/PZT/G/C], [G/PZT/G/G/C] and [G/PZT/G/C/G/C]. The voltages shown in the plots represent sinusoidal amplitudes of the input electric voltage
8.2	Experimental results vs predictions from COMSOL models of [G/PZT/G/C], (a) Experimental results, (b) Predicted peak-to-peak displacements from with varied piezoelectric material properties, (c) Experimen- tal results and predictions of peak-to-peak actuation displacements taken at the resonance frequencies, (d) Experimental results and predictions of resonance frequencies. The dotted lines in (c) and (d) represent linear curve fitting of the experimental results and of the COMSOL model, x in (c) and (d) represents the input voltage amplitudes
8.3	Experimental results vs predictions from COMSOL models of [G/PZT/G/G/C], (a) Experimental results, (b) Predicted peak-to-peak displacements from COMSOL model with varied piezoelectric material properties, (c) Experimental results and predictions of peak-to-peak actuation displacements taken at the resonance frequencies, (d) Experimental results and predictions of resonance frequencies. The dotted lines in (c) and (d) represent linear curve fitting of the experimental results and of the COMSOL model, x in (c) and (d) represents the input voltage amplitudes

8.4	Experimental results vs predictions from COMSOL models of [G/PZT, (a) Experimental results, (b) Predicted peak-to-peak displacements from COMSOL model with varied piezoelectric material properties, (c) Experimental results and predictions of peak-to-peak actuation displacements taken at the resonance frequencies, (d) Experimental results and predictions of resonance frequencies. The dotted lines in (c) and (d) represent linear curve fitting of the experimental results and of the COMSOL model x in (c) and (d) represents the input	/G/C/G/C],
	voltage amplitudes	157
85	Dynamic amplification factor of a system	158
8.6	Peak-to-peak actuation displacements at the resonance frequencies	100
0.0	Top: the experimental results Bottom: COMSOL model predictions	160
87	Schematic of an actuator with a neutral plane and force events on	100
0.1	the actuator via extension/contraction of the piezoelectric layer	
	The x-axis is along the lengthwise of the actuator	160
8.8	Bending coefficient from an equation 8.7 of each actuator through-	100
0.0	out the input voltage. The markers show values of bending coef-	
	ficient obtained from an equation 8.7. The lines represent curve	
	fitting of the bending coefficient values.	162
8.9	Resonance frequencies between experiments vs COMSOL models.	
	Top: the experimental results. Bottom: COMSOL models predic-	
	tions. There is no experimental resonance frequency determined at	
	0V	164
8.10	Reduced bending stiffness of each actuator from the denominator	
	of Equation 8.7 throughout the input voltage	165
8.11	Changing of a mechanical compliance or as elastic modulus, top,	
	and elastic modulus, bottom, of each layup at various input voltage	
	amplitudes	166
8.12	Location of the neutral axis, $y_o$ relatives to the top surface of the	
	piezoelectric layer, $h = 0.337$ mm, of a layup $[G/PZT/G/C]$	167
8.13	Stress distribution throughout the piezoelectric layer thickness after	
~	manufacturing at $10V$ , $40V$ and $70V$	169
8.14	Changing of the piezoelectric coefficient, $d_{31}$ , of each layup at vari-	1 80
	ous input voltage amplitudes	170
B.1	Large displacement, large strain of a body in a fixed Cartesian con-	
	figuration [1]. $\ldots$ $\ldots$ $\ldots$ $\ldots$ $\ldots$ $\ldots$	196
B.2	Orientation of a particle from time 0 to time t. The vector $d_{\pi}^{0}$ and	
	$d_x^t$ represent the orientation and length of a particle at times $\overset{x}{0}$ and	
	$\tilde{t.}[1]^{-} \dots \dots$	199

# List of Tables

2.1	Comparisons of smart materials. m refers to martensite and a refers to austenite phases [9] 27
3.1	Piezoelectric material properties obtained from the piezoelectric ma- terial manufacturer
3.2	Material properties obtained from the manufacturers used in the models
4.1	Nonlinear piezoelectric coefficient, $d_{31nonli}$ , and initial strain in the piezoceramic from three approaches. 'E' represents the electric field. Note that: throughout all the three cases, the piezoelectric coefficient showed a negative sign. This is because a piezoceramic contracts in the in-plane direction when a positive electric field is applied along the piezoelectric material's thickness direction while it expands in the in-plane direction under negative polarity. It has no mathematical meaning
4.2	Initial dielectric permittivity $\epsilon_{33}$ and their slopes at various input voltages and frequencies $\ldots \ldots \ldots$
5.1	Material properties obtained from the manufacturers used in the models
6.1	Nonlinear $d_{31nonli}$ coefficients under positive and negative fields with initial strain offset in the PZT as assigned in the model, 'E' is the electric field. The nonlinear piezoelectric coefficient was obtained when the piezoelectric was under a discharging condition and the strain state was tuned back to the zero state to diminish the per- manent strain. These coefficients were identical as shown in table 4.1 in section 4.2.2. The coefficients of the linear terms are -2.88 and -4.08 and for the non-linear terms -3.18 and 3.13

6.2	Nonlinear $d_{31nonli}$ coefficients under positive and negative fields with initial strain offset in the PZT as assigned in the model, E is the electric field. The nonlinear piezoelectric coefficient was obtained
	when the piezoelectric material was under a discharging condition and the strain state was un-tuned back to the zero state. These coefficients are identical as shown in Table 4.1 in section 4.2.2. The
	column Permanent Strain Offset Assigned in the Model indicates that the strain under the negative voltage is reduced by 50% from the original value, while the strain under the positive voltage re- mains the same
6.3	Corrected initial strains inside a piezoelectric material to fit with displacement offsets of each actuator layup. The 'Pos' and 'Neg' represent a positive and negative polarities, respectively. The '-' sign represents a percentage reduction. The '+' sign represents an increase in percentage
6.4	Nonlinear $d_{31nonli}$ coefficients under positive and negative fields. E is the electric field. The nonlinear piezoelectric coefficient was ob- tained when the piezoelectric was under a non-discharging condition and the strain state was un-tuned back to the zero state. These co- efficients are identical as shown in Table 4.1 in section 4.2.2 129
6.5	Corrected initial strains inside a piezoelectric material to fit with displacement offsets of each actuator layup. The 'Pos' and 'Neg' represent a positive and negative polarities, respectively. The '-' sign represents a percentage reduction. The '+' sign represents an increase in percentage
6.6	Percentage error between experimental results under a discharging condition and the predicted actuation displacements at $\pm$ 200V 134
6.7	Percentage error between experimental results under a non-discharging condition and the predicted actuation displacements at $\pm$ 200V 135
8.1	Elastic modulus reduction of each layup at different input voltage amplitudes
8.2	Changing of the neutral axis, $y_o$ , of each layups at different input voltage amplitudes
8.3	Piezoelectric parameters used in COMSOL for $[G/PZT/G/C]$ , $V_{amp}$ is a voltage amplitude, $\beta$ is a constant that relates stress to the $d_{31}$ , $\gamma$ is a constant that relates stress to the piezoelectric's elastic
	compliance

8.4	Piezoelectric parameters used in COMSOL for [G/PZT/G/G/C],
	$V_{amp}$ is a voltage amplitude, $\beta$ is a constant that relates stress to
	the $d_{31}$ , $\gamma$ is a constant that relates stress to the piezoelectric's
	elastic compliance
8.5	Piezoelectric parameters used in COMSOL for $[G/PZT/G/C/G/C]$ ,
	$V_{amp}$ is a voltage amplitude, $\beta$ is a constant that relates stress to the
	$d_{31}$ , $\gamma$ is a constant that relates stress to the piezoelectric's elastic
	compliance

xxiv

# Chapter 1 Introduction

An introduction to the air flow separation problem that conventional fixed-wing aircrafts encounter and a discussion of the state-of-the-art of the ideas proposed to cope with this problem is given in this chapter. The chapter is divided into five sections. Air flow separation for conventional fixed-wing aircraft is discussed in section 1.1. Air flow separation control methods are discussed in section 1.2. The state-of-the-art of the ideas and feasibility studies of approaches that can be used to solve the air flow separation problem at the airfoils are presented in section 1.3. Feasibility studies of approach to control air flow locally using smart actuators concepts are presented in section 1.4. The research objectives and thesis outline are presented in section 1.5.

## 1.1 Flow Separation of the Conventional Fixed-Wing Aircrafts

Conventional fixed-wing aircraft encounter separation of the airflow around the wing, because the flight condition parameters, such as altitude and Mach number, normally vary during a flight [1, 2], and this leads to various sub-optimal conditions for a whole range of operating flight condition.

Air flow separation is a physical phenomenon that occurs where there is a contact between a fluid and an object such as that between air and an airfoil surface. When an object moves through a fluid, a thin layer adjacent to the surface of the object develops which is called a boundary-layer. The influence of a fluid's viscosity is limited to the boundary-layer and the flow outside the boundary layer is considered to be inviscid.

Air flow separation results from the development of an adverse pressure gradient

over the surface of an airfoil in the flow direction. This is illustrated in Figure 1.1. The fluid elements moving along a streamline over the airfoil surface have to work against an increasing pressure, p3, while they already have a small velocity due to friction, which causes them to slow down and move in a reverse direction causing the air flow to detach from the airfoil surface, point  $S_3$ , Figure 1.1(b). An airfoil at a high angle of attack shows this phenomenon. The boundary-layer will separate from the surface and a large wake of separated flow will be created downstream of the airfoil, Figures 1.1(b) and 1.2.



Figure 1.1: Air flow separation on an airfoil induced by an adverse pressure gradient. (a) pressure distribution. (b) flow field (Adapted from [3])



Figure 1.2: Air flow separation over the airfoil [4]

Air flow separation at the trailing edge of a wing reduces the effectiveness of flaps by reducing the maximum achievable lift, while increasing drag can result in detrimental consequences for an aircraft's performance. To compensate for decreases in lift, more input power from the engine is required, resulting in more energy consumption. Delaying air flow separation over an aircraft's flaps is beneficial since a higher achievable lift reduces the minimum speed required during take-off and landing, thus reducing the need for long runways and reducing noise in the airport vicinity [5]. Another benefit of having a higher lift is less energy required. Another advantage of delaying air flow separation is that the same lift can be achieved using fewer high-lift devices, thus reducing the weight, complexity, fuel consumption and costs of an aircraft. The control of air flow separation to operate the aircraft wing in sub-optimal flight conditions optimally is therefore beneficial for aircraft performance.

## **1.2** Air Flow Separation Control Methods

Conventional means of controlling boundary layer separation on aircraft wings can be classified into two categories namely, passive control, which requires no auxiliary power, and active control, which requires auxiliary power.

### **Passive Control**

The most common type of passive control is to use vortex generators mounted on the surface of an aircraft wing. A vortex generator is an aerodynamic surface consisting of a small vane or bump that creates a vortex. The installation of the vortex generators runs along the span of the wing, figure 1.3(a). During flight, vortex generators generate a trip vortex which adds momentum to the boundary layer by drawing energetic, rapidly-moving air from outside the slow moving boundary layer into contact with the aircraft skin. The energized boundary layer is able to overcome the adverse pressure gradient and remains attached to the wing surface, and the air flow separation can be delayed. The main disadvantage of the vortex generator is that they cannot be actively controlled and add parasitic drag when air flow separation control is not needed.

#### Active Control

Boundary-layer separation can also be prevented by using a powered device that eliminates viscosity effects and energizes the boundary layer [6]. Active flow control can be classified into two sub-categories namely structure control and boundary layer control. Structure control methods, known as adaptive or smart structures, control the airfoil surface such that the sup-optimal flight conditions can be optimized during the flight. The state-of-the-art active flow control methods are presented in the following section.



(a) Vortex generators installed on a wing (b) Common vortex generators design

Figure 1.3: Vortex Generator. (a) vortex generator installed on a wing span [7]. (b) common vortex generator [8].

## **1.3** Adaptive Structures

Adaptive structures are structures that can change their shape corresponding to the variation of the surrounding parameters to maintain their optimum operating conditions. Within this thesis, for convenience, the generic name for such structures will be denoted adaptive structures. Adaptive structures can automatically morph their shapes by changing their geometry using internal mechanisms such as actuators and joints. The geometry variations are made in response to external effects, e.g. air pressure. The air pressure distributions over the airfoil are measured by sensors and the values are sent to the controller, which calculates to what extent the actuators must activate the structure, Figure 1.4. The signal is then sent to the actuators to morph the airfoil trailing edge to counteract the strong adverse pressure distribution over the whole airfoil profile. The air flow separation will eventually be delayed.

### **1.3.1** Adaptive Airfoils

The belt-rip concept and finger concept are two examples of adaptive airfoils. The belt-rib concept, where the rib from a classical airfoil is replaced by a belt-rib which is designed as a structronic shape-adaptable system. The idea is to produce distributed structural flexibility instead of using an articulated mechanism [9]. The belt, which is in the outer part of the flap, is reinforced by in-plane stiffeners, spokes, as shown in figure 1.5. The angle the spokes make with the camber are easily changed due to the low stiffness of the belt.



Figure 1.4: Sketch showing an adaptive trailing edge of an airfoil. Sensors detect changing in the pressure distribution over the airfoil. The pressure values are sent to the controller where the command in the form of a signal is sent to the actuators to morph the trailing edge.



Figure 1.5: Spoke configurations for the belt-rip [10].

Monner et al. [2, 11] and Monner [12] proposed using a partially adaptable flap section of the trailing edge which allows both a chordwise and a spanwise differential camber variation and is called a finger concept. The flexible ribs which are made of Carbon Fibre Reinforced Polymer (CFRP) [11] are realized by plate elements integrated by revolute joints, figure 1.6 (right). The motion of each plate element is achievable through kinematic motion of the joint. A linear actuator is mounted on the rear spar. The linear actuator produces horizontal motion to the transmission beam, figure 1.6(left), and in turn initiates vertical motion through a slide block which is connected to the rib element, figure 1.6(left).



Figure 1.6: Finger Concept [11].

### 1.3.2 Boundary Layer Control

Control of air flow separation involves energization of the boundary layer upstream of the separation point, so that the boundary layer can negotiate adverse pressure gradients without separating [13]. The active flow separation control at an airfoil can be optimized locally down to the boundary layer scale and is known as a periodic excitation. The periodic excitation or perturbation of the air flow at the airfoil is a method that is used to prevent a transition to turbulence occurring at the airfoil by either adding or removing the air flow into or out of the airfoil by blowing or suction, respectively. Boundary layer suction involves eliminating the effect of viscosity by removing the decelerating fluid elements close to the wing surface; allowing them to be replaced by high-energy elements from the external flow, and thus preventing flow separation [6]. Blowing refers to adding kinetic energy to the boundary layer by injecting high-energy air, using pumps, into the boundary-layer. Although the blowing and suction methods are quite effective, a considerable amount of energy is needed to drive the pumps. Furthermore, integration of this system into a wing increases the weight and structural complexity of the wing. Due to high energy requirements, their weight and complexity, these active techniques are rarely implemented in standard commercial aircraft.

Apart from using suction and blowing air, a periodic excitation method can be accomplished by triggering the air flow via an actuator periodically to re-energize the air flow by adding the momentum to the air flow without adding mass air flows. As a consequence, the air flow can withstand stronger adverse pressure gradients. This method has been demonstrated to be more efficient for the control of boundary-layer separation than suction or blowing [14]. An example of an actuator for this type of air flow control is called a flipperon or ribbon. Three
possible types of the periodic excitation concept are: a flipperon without and with a cavity in the control surface, figure 1.7(a) and (b), respectively; another one is a double-clamped flipperon type without a cavity, figure 1.7(c).



Figure 1.7: Schematic representation of three mechanical actuator concepts. (a) spring-board/flipperon without a cavity. (b) springboard/flipperon with a cavity. (c) double-clamped type (bulb) [15].

Two examples of feasibility studies of the periodic excitation approach for the adaptive structures concept will now be presented. The first example is the Airfoil THUNDER Testing to Ascertain Characteristic (ATTACH) project [16–18]. The study was done to examine the airfoil shaping effectiveness of THUNDER <sup>1</sup> actuators under aerodynamic loading to investigate their ability to reduce drag over an airfoil. A THUNDER actuator was attached at the upper surface of an airfoil, and it was shown that, while the THUNDER was actuating up to meet the air flow, allowing an increase in camber of the upper surface, the onset of the large adverse pressure gradient was delayed. This allows a longer air flow attachment region, and the air flow separation was therefore delayed.

The second example is a preliminary conceptual idea for adaptive wind turbines using a periodic excitation approach researched by Hulskamp [19]. Note that wind turbine blades exhibit similar profiles to airfoils. The THUNDER actuators were attached to the trailing edge of the wind turbine blades to act as an aerodynamic load control surface to alleviate the aerodynamic load imposed on the blades.

The THUNDERs are made of a piezoelectric material, which belongs to the family of smart materials. Smart materials have been defined by Harvey [20] as "materials that receive, transmit, or process a stimulus and respond by producing a

 $<sup>^1\</sup>mathrm{The}$  THUNDER is a unimorph-type of actuator made out of a piezoelectric material. See Chapter 2.

useful effect that may include a signal that the materials are acting upon it. Some of the stimuli that may act upon these materials are strain, stress, temperature, chemicals (including pH stimuli), electric field, magnetic field, hydrostatic pressure, different types of radiation, and other forms of stimuli [21]." These adaptive materials are increasingly being used in smart actuators development because they are not subjected to wear and do not require lubrication. This leads to lower inspection and maintenance costs during service.

Piezoelectric materials were chosen for further study for the research reported in this thesis because they exhibits a large operating bandwidth and respond very fast to an input electric field; however, their major drawback is the small strains produced by input electric field. The large bandwidth promotes wider operational frequency ranges in the structures. The drawback of the small strains can be overcome by attaching or embedding the piezoelectric materials to inactive materials to amplify the small strain from the piezoelectric materials. The inactive materials used for the research reported here were composite materials, chosen because of their design flexibility and because they are lighter than counterpart materials such as stainless steel.

#### **Piezoelectric Unimorph Actuators**

Piezoelectric unimorph actuators consist of one piezoelectric layer attached to other inactive material layers. Extensive research has been done on the static behaviour of THUNDER [16, 22, 23] and Lightweight Piezoceramics Composite Actuators (LIPCA) [24] but their dynamic behaviour has not been widely investigated due to the more complex behaviour seen in the dynamic setting.

Since the development of such actuators requires a multi-disciplinary background, we have got to achieve an in-depth understanding of the actuators' dynamic behaviour and the effects this behaviour has. Moreover, as discussed above, because the piezoelectric materials produce small strains, to obtain a large strain, a large input electric field is needed to actuate the piezoelectric material. As a consequence of a large input electric field to the piezoelectric materials, the piezoelectric materials show nonlinear output strains. This nonlinearity of the piezoelectric materials increases the difficulties faced by researchers trying to make predictions of the behaviour predictions. Accurate models that can be used to predict an actuators' behaviour still need to be developed.

Given the complexities of the piezoelectric materials used in actuators, there is a need for more research into accurate behaviour prediction and to gain an understanding of the actuators' behaviour particularly in dynamic conditions, before these actuators can be exploited and implemented on adaptive structures.

The research discussed in this thesis deals with the nonlinear properties of piezoelectric materials which were determined experimentally under static and dynamic conditions. These properties were then incorporated into the models that can be used to improve the accuracy of the actuators' behaviour predictions. Since actuation mechanisms originate at the piezoelectric material level an understanding of the actuator's behaviour on this piezoelectric material level is essential. Moreover, such an understanding the actuators' behaviour from the macroscopic view used in this research should provide more practical information on actuator performance for the designers of actuators.

# 1.4 Research Objectives

The above discussion demonstrates how actuators can only be implemented on an airfoil surface to delay the air flow separation once their static and dynamic behaviours are better understood. Moreover, accurate predictions of these behaviours need to be possible before the actuators can be manufactured. The main question of this research is:

# What parameters influence actuators' behaviour under static and dynamic operating conditions?

Several key questions needed to be answered to answer the main question:

Microscopic aspect

1. From the piezoelectric material aspect: How do the piezoelectric properties of the materials used in actuators influence the behaviour of the actuators?

a. How do the piezoelectric material properties change in a large input DC electric field range?

b. How do the piezoelectric material properties change with respect to input AC voltages in a frequency range?

Macroscopic aspect

- 2. Understanding an actuators' behaviour from an actuator perspective.
  - a. What are the parameters that influence the static behaviour of actuators?
  - b. What are the parameters that influence the dynamic behaviour of actuators?
- 3. Development of accurate models to predict actuators' behaviour.
  - a. How accurate are the static models used to predict an actuator's behaviour

when the piezoelectric material properties obtained by determining the piezoelectric material properties under the static operating conditions are incorporated into the static model?

b. How accurate are the dynamic model prediction for an actuator's' behaviour when the piezoelectric material properties obtained by determining the piezoelectric material properties under the dynamic operating conditions are incorporated into the dynamic model?

#### 1.4.1 Thesis Outline

The thesis is divided into 2 main parts: a static part and a dynamic operating conditions part, see also figure 1.8.

**Chapter 2:** here the literature review will be presented with an introduction to piezoelectric materials and their nonlinear behaviour. The chapter continues with an extensive state of the art look at piezoelectric material unimorph types of actuators such as THUNDER, RAINBOW and LIPCA.

**Chapter 3:** a description of how the actuators used in this research were manufactured and how their manufactured quality was checked. Two different composite material manufacturing concepts will be explored.

**Chapter 4:** a description of how the piezoelectric material properties under static and dynamic operating conditions were experimentally determined. *The key questions 1a and 1b are answered in this chapter.* 

**Chapter 5:** a finite element model to predict the actuators' behaviour under the static condition is introduced in this chapter. The model includes piezoelectric material properties obtained under static operating conditions. The experimental setup for the static operating condition is explained.

**Chapter 6:** comparisons between the predictions of the actuators' performance under the static condition, i.e. actuation displacements, and the experimental results are discussed in this chapter. The parameters influencing the actuators' performance under the static condition are discussed. Furthermore, the orders of the parameters influencing the actuator performance will be explored. The key questions 2a and 3a will be answered in this chapter.

**Chapter 7:** a finite element model to predict the actuators' behaviour under the dynamic condition is introduced in this chapter. The model includes nonlinear piezoelectric material properties obtained under dynamic operating conditions. The experimental setup for the dynamic operating condition is explained.

**Chapter 8:** comparisons between the predictions of the actuators performance under the dynamic conditions, i.e. actuation displacements and resonance frequencies are made, and the experimental results are discussed in this chapter. The parameters influencing the actuators' performance under dynamic operating conditions are discussed. *The key questions 2b and 3b will be answered in this chapter.* 

**Chapter 9:** consists of discussions, conclusions and recommendations for the research presented in this thesis.



Figure 1.8: Schematic of the flow of this thesis

# References

- Th. Bein, Hanselka H., and E. Breitbach. Adaptive spoiler to control the transonic shock. *Smart Materials and Structures*, 9(2):141–148, 2000. Cited By (since 1996): 21 Export Date: 1 February 2012 Source: Scopus.
- [2] H.P. Monner, E. Breitbach, Th. Bein, and H. Hanselka. Design aspects of the adaptive wing - the elastic trailing edge and the local spoiler bump. *Aeronautical Journal*, 104(1032):89–95, 2000. cited By (since 1996) 24.
- [3] J. D. Anderson. Fundamentals of Aeradynamics. McGraw-Hill, 1991.
- [4] WIKIPEDIA. Flow separation, Accessed 20/11/2012.
- [5] G. Ruijgrok. *Elements of Airplane Performance*. Delft University Press, The Netherlands, 2nd edition, 2004.
- [6] P. K. Chang. Control of flow separation. Hemisphere Pub. Co., 1st edition, 1976.
- [7] www.greghughes.net. Micro vortex generator, Accessed 20/11/2012.
- [8] www.aerospaceweb.org. Vortex generator design, Accessed 20/11/2012.
- [9] L.F. Campanile and S. Anders. Aerodynamic and aeroelastic amplification in adaptive belt-rib airfoils. Aerospace Science and Technology, 9(1):55–63, 2005. cited By (since 1996) 33.
- [10] L.F. Campanile and D. Sachau. Belt-rib concept: a structronic approach to variable camber. *Journal of Intelligent Material Systems and Structures*, 11(3):215–224, 2000. cited By (since 1996) 39.
- [11] D. Sachau H. P. Monner and E. Breibach. Design aspects of the elastic trailing edge for an adaptive wing. In *RTO AVT Specialists*, 1999.
- [12] H.P. Monner. Realization of an optimized wing camber by using formvariable flap structures. Aerospace Science and Technology, 5(7):445–455, 2001. cited By (since 1996) 43.
- [13] P.R. Viswanath. Some thoughts on separation control strategies. Sadhana -Academy Proceedings in Engineering Sciences, 32(1-2):83–92, 2007. cited By (since 1996) 1.
- [14] David Greenblatt and Israel J. Wygnanski. The control of flow separation by periodic excitation. Progress in Aerospace Sciences, 36(7):487 – 545, 2000.

- [15] L.L.M. Veldhuis and K. Artois. Active separation control by periodic excitation in an adverse pressure gradient. In AIAA Applied Aerodynamics Conference, volume 1, pages 359–379, 2007. cited By (since 1996) 0.
- [16] R.R. Antcliff and A.M.R. McGowan. Active Control Technology at NASA Langley Research Center. National Aeronautics and Space Administration, Defense Technical Information Center, 2001.
- [17] J.L. Pinkerton and R.W. Moses. A Feasibility Study to Control Airfoil Shape Using THUNDER. NASA technical memorandum. NASA, Langley Research Center, 1997.
- [18] Jennifer L. Pinkerton, Anna-Maria R. McGowan, Robert W. Moses, Robert C. Scott, and Jennifer Heeg. Controlled aeroelastic response and airfoil shaping using adaptive materials and integrated systems. In *Proceedings of SPIE The International Society for Optical Engineering*, volume 2717, pages 166–177, 1996. cited By (since 1996) 6.
- [19] A.W. Hulskamp. The smart roter concept on wind turbines: actuators and structures. PhD thesis, Delft University of Technology, 2011.
- [20] James A. Harvey. Smart materials. Mechanical Engineers' Handbook Materials and Mechanical Design. John Wiley and Sons, 3rd edition, 2006.
- [21] J. A. Harvey. Kirk-Othiner Encyclopedia of Chemical Technology. Wiley, New York, 4th edition, 1998.
- [22] K.M. Mossi and R.P. Bishop. Characterization of different types of high performance thunder actuators. *Stainless Steel*, 302:0–1524, 1999.
- [23] K.M. Mossi, G.V. Selby, and R.G. Bryant. Thin-layer composite unimorph ferroelectric driver and sensor properties. *Materials Letters*, 35(1):39–49, 1998.
- [24] KY Kim, KH Park, HC Park, NS Goo, and KJ Yoon. Performance evaluation of lightweight piezo-composite actuators. Sensors and Actuators A: Physical, 120(1):123–129, 2005.

# Chapter 2 Literature Review

As explained in Chapter 1 the aim of the research reported in this thesis was to investigate the parameters that influence actuators' behavior under static and dynamic operating conditions. It was, therefore, essential to have an overview of the smart materials used in actuators especially piezoelectric materials and those used in piezoelectric unimorph actuators. The chapter is divided into four sections; the different types of smart materials ranging from piezoelectric material to shape memory alloy, electrostrictive and magnetrostrictive materials are introduced in section 2.1. Nonlinear behavior of piezoelectric materials is discussed in section 2.2. The state-of-the-art of different types of piezoelectric unimorph actuators are reviewed in section 2.3. Conclusions on the smart materials, especially the piezoelectric materials, and state-of-the-art of piezoelectric material actuators are given in section 2.4.

# 2.1 Smart Materials

## 2.1.1 Piezoelectric Materials

Piezoelectric materials were discovered in the 1880 by Jacques Curie [1]. A material is called a piezoceramic when this material is based on a ceramic. The most widely used piezoceramic is lead-zirconate-titanate (PZT). Piezoelectric materials have become one of the most popular sets of materials, among other smart materials, for use as sensors and actuators due to their unique reversible functionality. When a piezoelectric ceramic is subjected to deformation, an electrical voltage is produced; and vice versa, when it is subjected to electric potential, it will undergo deformation. The former phenomenon is known as a direct effect and the latter is known as a converse effect, and it is these direct and converse effects that define the working functions of a piezoelectric material, i.e. sensor and actuator, respectively.

#### Piezoelectric Materials Structure: from lattice to domain

The coupling between mechanical and electrical responses in a piezoelectric material initiates at a micro-scale in the crystal lattice as a result of a non-zero net dipole moment. Piezoelectric materials such as piezoceramics are poly-crystalline and do not demonstrate such piezoelectric characteristics in nature until they are poled. A non-zero net dipole moment is generated from the poling process of the lattice by first heating the piezoelectric materials to below the Curie temperature while a large DC electric field is applied to the materials until the polar axes align with the electric field, Figure 2.1. This process is called polarization. It can be imagined that the central ion of this crystal lattice structure will then move slightly off-center and align with the electric field. The structure of the lattice then changes from cubic, i.e. ion is at the center, Figure 2.1(left), to tetragonal, i.e. ion is slightly off-centered, Figure 2.1(right).



Figure 2.1: PZT crystal structures [2]

Before a piezoelectric material is poled, the domain walls are randomly oriented, Figure 2.2(a). During polarization, a very large DC electric field is applied to the piezoelectric material to orient the domains, Figure 2.2(b). Once the DC electric field is removed, permanent polarization is achieved and the poling process is completed, Figure 2.2(c). In contrast, when piezoelectric materials are exposed to very high electric field applied in the opposite direction to the poling direction, the piezoelectric material will lose its piezoelectric property, resulting dielectric loses and lower efficiency and eventually permanent deformation will occur. This is called depoling.



Figure 2.2: Poling process: (a) prior to polarization polar domains are oriented randomly; (b) during polarization, a very large DC electric field is applied at below the Curie temperature to reorient all the domains; (c) after the DC field is removed, permanent polarization is achieved and the poling process is completed. The piezoelectric materials are ready for applications.

#### Polarization/Strain vs Electric Field

Polarization of piezoelectric materials can be illustrated in a figure 2.3. For unpoled piezoelectric materials, the polarization is zero due to random orientations of domain walls. When an electric field is applied to the piezoelectric materials, the domain walls will orient themselves with the electric field, resulting in polarization of the piezoelectric material. As the input electric field strength increases, larger amount of domain walls will orient themselves to the electric field resulting in more polarization, shown as the virginal curve in a figure 2.3.



Figure 2.3: Typical hysteresis loop for a ferroelectric material [3]

The polarization increases until it reaches the maximum value, i.e. the saturation polarization,  $P_s$ . After the electric field is removed, not all the aligned domain walls to the poling direction, i.e. the direction of the applied electric field, will stay oriented because of stresses are present. These stresses will cause some parts

of the dipoles to reorient back to their original directions resulting a slightly decreases of polarization. The remaining polarization at the zero electric field is called the remnant polarization,  $P_r$ . When an electric field is applied in the opposite direction, the polarization will be reduced until the electric field is high enough and cause reversal of the polarization. At this point, the piezoelectric material is polarized in the opposite direction and the electric field that causes the opposite polarization is called the coercive field,  $E_c$ . When an electric field is applied in the direction the piezoelectric material was originally poled, the polarization direction will be changed in association with the applied electric field until it complete the polarization loop. This is called a hysteresis loop.

During a polarization process of the piezoelectric material in a figure 2.3, strain in the piezoelectric material develops and can be illustrated as shown in a figure 2.4. When the piezoelectric material is applied by an electric field, the piezoelectric material elongates along the direction of the electric field, while the piezoelectric material contract in the direction perpendicular to the electric field. The strain produced along the direction of the applied electric field accompanying the virginal curve in the figure 2.3 is shown as the virginal curve in the figure 2.4.



Figure 2.4: Strain during poling and the typical hysteresis loop as observed for piezoelectric ceramic actuators [3]

Once polarization reaches its maximum and the opposite electric field is applied to the piezoelectric material, strain along the poling direction reduces until the electric field reaches a zero field. At the zero field state, strain along the poling direction reduces but does not come back to the zero strain and it shown as a permanent strain. This permanent or an irreversible strain is called a poling strain. At this zero field state, if the electric field is applied to the piezoelectric material in the same direction as the poling direction, strain will be produced but it does not follow the same path and is shown as a hysteresis loop. The hysteresis loop is reversible. However, if the electric field is applied in the opposite direction to the poling direction, the piezoelectric material contracts and becomes shorter than the original state until the electric field reaches a certain value, the piezoelectric material will extend, figure 2.5. The electric field that causes the piezoelectric material to extend is called a coercive field. The strain versus electric field is called a butterfly loop, figure 2.5.



Figure 2.5: Strain during poling and the typical hysteresis loop as observed for piezoelectric ceramic actuators [3]

Moving from the lattice scale to the domain scale, poly-crystalline materials are compose of numerous of random microcrystal shapes and all orientations are the same within a "domain". The ferroelectric domain is known as a region that gathers similar polarization lattice is together by having domain walls as a separate region. The ferroelectric domains between the two adjacent walls can be divided into two sub types: 180° domain walls and non-180° domain walls, Figure 2.6. The non-180° domains are also known as 90° domains for the tetragonal crystals because the non-180° domains are a 90° polarization vector apart. Note that the non-180° domains may have other polarization apart angels, e.g. 71°, 109°, 60° or 120° [1], depending on the crystal types.



Figure 2.6: Schematic representation of the polycrystalline structure of the ceramic [4]

The electrical-mechanical coupling scheme of a piezoelectric material is shown in figures 2.7 and 2.8 and can be explained as follows.

**Sensor Scheme:** Figure 2.7(a) shows a piezoelectric material without an external load. If an external load, compressive or tensile, applies to the piezoelectric material, electric charges are produced and appear at the electrode, Figure 2.7(b) and (c). Note that the polarity of the electric charges depend on the loading direction.



Figure 2.7: Direct piezoelectric effect in a rectangular shaped component [3]

Actuator Scheme: Figure 2.8 illustrates an inverse effect. Figure 2.8(a) shows a piezoelectric material without an applied electric field. When an electric field is applied to the piezoelectric material, the piezoelectric material can either shorten or elongated with respect to the direction of the applied electric field. The piezoelectric material is shorten or elongate, depending on the direction of the applied electric field, Figures 2.8(b) and (c).



Figure 2.8: Inverse piezoelectric effect in a rectangular shaped component [3]

#### **Piezoelectric Materials Constitutive Relations**

Piezoelectric response can be explained through constitutive relations based on the assumption that the total strain in the actuator is a summation of the mechanical strain induced by the stress, the thermal strain caused by temperature, and the controllable actuation strain caused by electric voltage [5]. The coupled mechanical and electrical relation is shown in Equation (2.1):

$$\epsilon_k = d_{jk}^c \cdot E_j + S_{km}^{E,T} \cdot \sigma_m + \alpha_k \cdot \Delta T \tag{2.1}$$

where  $\epsilon_k$  is strain,  $E_j$  is the applied electric field,  $\sigma_m$  is stress,  $d_{jk}^c$  is the piezoelectric coefficient,  $S_{km}^{E,T}$  is the elastic compliance and  $\alpha_k$  is thermal coefficient expansion. The piezoelectric coefficients are defined as the ratio of developed free strain to the applied electric field. Free strain is the strain when all external stresses are held constant. Elastic compliance is the ratio of the strain in the k-direction to the applied stress in the m-direction, given that there is no change of stress along the other two directions. These notations are based on Voigt notation. The superscript c refers to converse effects, E and T refer to the quantity measured at a constant electric field and a constant temperature, respectively. The above relationship can be written in a full matrix form as shown in Equation (2.2):

$$\begin{pmatrix} \epsilon_{1} \\ \epsilon_{2} \\ \epsilon_{3} \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{pmatrix} = \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{31} \\ 0 & 0 & d_{33} \\ 0 & d_{15} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \cdot \begin{pmatrix} E_{1} \\ E_{2} \\ E_{3} \end{pmatrix} + \begin{bmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & 0 \\ S_{12} & S_{11} & S_{13} & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{66} \end{bmatrix} \cdot \begin{pmatrix} \sigma_{1} \\ \sigma_{2} \\ \sigma_{3} \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{pmatrix} + \begin{pmatrix} \alpha_{1} \\ \alpha_{2} \\ \alpha_{3} \\ 0 \\ 0 \end{pmatrix} \cdot \Delta T$$

$$(2.2)$$

The actuation strain can be explained through the piezoelectric coefficient matrix, Equation (2.2). The electrical-mechanical couplings can be explained through, for example  $d_{31}$  which characterizes the in-plane strain in 1 and 2 directions with the input electric field is applied in the 3-direction, Figure 2.9, due to applied electric field  $E_3$  in the 3-direction,  $d_{33}$  characterizes the out-of-plane strain in the 3-direction due to applied electric field  $E_3$  in the 3-direction. Likewise,  $d_{15}$  characterizes shear strains in 2-3 and 3-1 planes due to applied electric field  $E_1$  and  $E_2$ respectively.

The coupled mechanical and electrical relations when they function as a sensor through the direct effect is shown in Equation (2.3):

$$D_i = e_{ij}^{\sigma} \cdot E_j + d_{im}^d \cdot \sigma_m + p_i \cdot \Delta T$$
(2.3)

where  $D_i$  is the dielectric displacement,  $E_j$  is the applied electric field,  $\sigma_m$  is stress,  $d_{im}^d$  is the piezoelectric constant,  $e_{ij}^{\sigma}$  is the dielectric permittivity and  $p_i$  is the pyroelectric constant. The superscript d and  $\sigma$  refer to direct effect and the quantity that is measured at constant stress, respectively. The electric charge is generated when the piezoelectric is exposed to a stress field. The above relationship can be written in a full matrix form as in Equation (2.4):

$$\begin{pmatrix} D_{1} \\ D_{2} \\ D_{3} \end{pmatrix} = \begin{bmatrix} e_{11}^{\sigma} & 0 & 0 \\ 0 & e_{22}^{\sigma} & 0 \\ 0 & 0 & e_{33}^{\sigma} \end{bmatrix} \cdot \begin{pmatrix} E_{1} \\ E_{2} \\ E_{3} \end{pmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{25} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{bmatrix} \cdot \begin{pmatrix} \sigma_{1} \\ \sigma_{2} \\ \sigma_{3} \\ \tau_{23} \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{pmatrix} + \begin{pmatrix} p_{1} \\ p_{2} \\ p_{3} \end{pmatrix} \cdot \Delta T$$

$$(2.4)$$

The use of the piezoelectric materials as actuators can be operated both in the in-plane and the out-of-plane modes. The out-of-plane mode makes use of the piezoelectric coefficients  $d_{31}$  and  $d_{32}$ , Figure 2.9. The electric field is applied in the 3-direction, which is a poling direction, and the resulting deformation is also in the 3-direction.



Figure 2.9: A piezoelectric material sheet with the application of the electric flied along the 3-axis [6]

The drawback of this type of piezoelectric actuators is the relative low strain that it can be achieved. To overcome this drawback, the stacked actuators can be produced by stacking many layers of piezoelectric mateiral sheets with electrodes alternatively, Figure 2.10. The electric field is applied equally at each electrode through the actuator thickness resulting in accumulative displacements. This results in the production of a large force and greater displacement can be achieved through the 3-direction, but small displacements are produced in 1 and 2 directions.



Figure 2.10: Stacked Piezoelectric [7]

The use of the in-plane mode has been developed with a form of patch. The piezoelectric actuator patch is made of embedded piezoceramic fibers in the matrix and the electrodes are applied on both the top and bottom faces, Figure 2.11. This is called an active fiber composite (AFC). These AFC patches can either be attached directly to the structure or embedded in the laminate. The piezoelectric actuator patches produce the in-plane deformation and applied electric field are in 3-direction which is along the fibers longitudinal direction.



Figure 2.11: Piezoelectric fiber actuator or Active fiber composite (left [7], right [8])

#### Polyvinylidenefluoride (PVDF)

Piezoelectric PVDF films, which have high coupling coefficients that are lower than those for a piezoceramic, are used in an alternative form of piezoelectric actuators or sensors. PVDFs are very ductile, compared to piezoceramics which are very brittle, and these are mostly used in a sensors to measure induced stress. The piezoelectric coefficients of the PVDF are shown in Equation (2.5)

$$d = \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{32} \\ 0 & 0 & d_{33} \\ 0 & d_{24} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$
(2.5)

Note that  $d_{31} \neq d_{32}$  and  $d_{25} \neq d_{15}$ . This shows that the film is non-isotropic on the surface.

#### 2.1.2 Shape Memory Alloy (SMA)

Shape memory alloy (SMA) is increasingly used as an adaptive material in aerospace applications in some cases replacing piezoceramics. The interesting phenomenon of the SMA is that it can memorize a certain stretched or bent shape and recover to that particular shape at high temperatures. The memorizing phenomenon can be explained through the two temperature phases known as the austenite and martensite phases , Figure 2.12. At room temperature, SMA will be in a martensite phase in its undeformed original shape. At this phase, the crystal structure is twinned resulting in a lower elastic modulus and yield stress. As an applied extensional stress exceeds the yield stress, but still in room temperature, large deformation occurs causing detwining. The original shape of the SMA is recoverable through the application of heat. The progressive recovery of the original shape may be observed during this process until the new higher temperature phase is reached. This new phase is known as the austenite phase where the original shape is completely recovered. The crystal lattice in the austenite phase is cubic resulting in a higher elastic modulus and yield stress.

The SMA can produce a mechanical strain up to 8% at low temperature. Any larger mechanical deformation than 8% will result in permanent or irrecoverable plastic strain. The above phenomenon is called a shape memory effect, Figure 2.12. New shape can be assigned or reassigned using an annealing process with a temperature above 400 - 600°C.



Figure 2.12: Schematic of shape memory effect in stretching [6]

#### 2.1.3 Electrostrictives Materials

The working principle of electrostrictives materials is similar to that of the piezoelectric materials, i.e. induced mechanical strain is produced when the electric field is applied to the materials. In some of them, as the electric field is applied, the randomly oriented electric regions align with the electric field resulting in the rotation of these electric regions. These rotations in turn produce mechanical extension in the same direction as the field direction and contractions perpendicular to it. One example of an electrostrictives material is lead magnesium niobate, PMN.

#### 2.1.4 Magnetrostrictive Materials

Magnetrostrictive materials are similar to electrostrictives materials except that the coupling occurs between mechanical strain and applied magnetic field. As the magnetic field is applied to these materials, the magnetic regions align with the magnetic field resulting in the rotation of these magnetic regions. These rotations in turn produce mechanical extension in the same direction to the field direction and contraction perpendicular to it. Applying a negative magnetic field causes phenomenon opposite to those described above. Magnetrostrictive materials function both-ways: as actuators and sensors. The actuator scheme is described above. The sensor scheme is achieved by the applying mechanical strains. As the mechanical strain is applied to the magnetrostrictive materials, the magnetic regions begin to rotate resulting in changes to the magnetic field produced by the materials. The actuation phase is called the Joule's effect while the sensor phase is called the Villari effect. Magnetrostrictive materials are nonlinear and exhibit hysteresis, they generate low strain and moderate forces over a wide frequency range. Terfenol-D is an example of a magnetosrtictives actuator.

#### 2.1.5 Comparisons of Smart Materials

The SMA exhibits the largest actuation displacement when compared to the rest of the materials discussed above; however, the majority drawback is the bandwidth, i.e. the actuation range is very low, Table 2.1. The major drawback of PZT is its brittleness. A good candidate for a sensor is PVDF that can be embedded in a structure due to its ductility. Terfenol provides a relatively large actuation strain but does not show such a good bandwidth as PZT. The response time of PZT is very fast, SMA's is slow. The accuracy of the PZT is high while that of SMA is low, and lastly, the power required to activate PZT is moderate, while the power required to actuate SMA is high.

Materials	PZT G-1195	PVDF	PMN	$\operatorname{Terfenol}(\mathrm{DZ})$	Nitinol(NiTi)
Actuation mechanism	Piezoceramic	Piezo film	Electrostrictor	Magnetostrictor	$\operatorname{SMA}$
$\epsilon_{max}, \mu \text{strain}$	350	10	500	580	8500
$E, 10^6 kPa$	62	2	117	48	27.5(m);89(a)
Bandwidth	High	High	High	Moderate	Low

Table 2.1: Comparisons of smart materials. m refers to martensite and a refers to austenite phases [9]

As aforementioned, due to the small displacements that the PZT can produce but is greater bandwidth; most applications of PZT are in noise and vibration suppression. In contrast, SMA can handle large mechanical strains compared to PZT, but its bandwidth is rather small, less than 1 Hz while this is 0-20 kHz for PZT. One of the interesting properties of the SMA is that it can increase its modulus of elasticity from 2 to 4 times during phase change.

#### 2.1.6 Conclusions

The SMA has been shown to be a promising smart material for large displacement applications, however, due to its low bandwidth, SMA might not be a good candidate for a vibration suppression application on an aircraft wing. In contrast, PZT is a good candidate for applications that require a high actuation bandwidth, however, its actuation displacement is low. To cope with the small actuation displacement in the PZT, an alternative approach such as using kinematic systems to amplify the low actuation displacement produced from the PZT maybe used. Another alternative is to embed the PZT in a structure designed to amplify the small strain.

# 2.2 Nonlinearity in Piezoelectric Materials

Strains produced in a piezoelectric material are very small; therefore, to obtain a large output strain, a large input electric field must be achieved. A large input electric field usually comes with the penalty of nonlinear behavior between output strain and input electric field; however, this nonlinearity becomes less pronounced for hard piezoelectric materials. The nonlinear behaviour of piezoelectric materials due to different inputs such as electric field, frequency and stress will be presented in this section.

### 2.2.1 Introduction to Nonlinearity in Piezoelectric Materials

The linear relations of direct and converse piezoelectric effects were introduced in equations (2.1) and (2.3). At a low applied mechanical stress or low applied electric field, the linear relationship remains true. At a large mechanical stress or electric field, the direct and converse piezoelectric effects become nonlinear. These stress and electric-dependencies are observed in the piezoelectric coefficient, dielectric permittivity and elastic compliance.

The primary contribution to the piezoelectric nonlinearity and hysteresis is believed to be motion of the ferroelectric and/or ferroelastic domain walls in the piezoelectric materials. Hysteresis is shown in a form of losses as depicted in the two P-E relations, polarization-electric field relation, in Figure 2.13.



Figure 2.13: Electric field dependent of dielectric coefficients. The two inserts are the P-E relations at low and high electric fields, respectively [10]

In ferroelectric materials, the spontaneous polarization and strain can be reoriented by an applied *electric field* through the motion of domain walls or other interfaces that separate regions of crystallographic continuity and uniform spontaneous polarization. In ferroelastic material, the spontaneous polarization and strain can be reoriented by an applied *elastic field* through the motion of domain walls or other interfaces that separate regions of crystallographic continuity and uniform spontaneous strain [11].

The macroscopic electromechanical effects arise from *intrinsic* and *extrinsic* effects. The intrinsic effect is a result of local atomic displacements in a unit cell and is known as the "piezoelectric effect". The piezoelectric effect is the linear electromechanical interaction in the unit cell and it is a reversible process. The extrinsic effect results from elastic deformation caused by domain walls displacement and any motion of domain walls is both reversible and irreversible process.

The reversible process can be illustrated that the domain walls vibrate around an equilibrium position and come back to the original position when the electric field is removed, Figure 2.14. As the field level increased, the domain walls move within the potential energy wells as long as the field is still below the coercive field level. The coercive field level is an electric field level that defines the reversibility of the domain walls motion. Once the electric field strength reaches the coercive field, it causes the domain walls to move across the potential energy barrier to the next equilibrium state after the electric field is removed. This phenomenon causes irreversible domain wall motion and is also known as local domain switching.



Figure 2.14: Illustration of reversible and irreversible domain wall displacements of piezoelectric materials [11]

#### 2.2.2 Frequency Dependent

The piezoelectric properties such as piezoelectric coefficient  $d_{33}$  [12, 13],  $d_{31}$  and  $d_{15}$  [13] and dielectric permittivity  $\epsilon$  [14] are frequency, stress and electric field dependent, Figure 2.15. The higher the frequencies, the more the dielectric and piezoelectric coefficients are suppressed because the response of the domain-wall motion is delayed [10]. The reason is that the extrinsic response takes a finite time to occur much more slowly than an intrinsic response but when the frequency increases, only those non-180° domains that can keep pace with the frequency will contribute to the piezoelectric response.



Figure 2.15: (a) dielectric constant  $\epsilon'_{33}/\epsilon_0$  as a function of electric field amplitude at selected frequencies. (b) the same data plotted as a function of frequency for selected field amplitudes. Solid lines are a guide for the eye. [14]

#### 2.2.3 Stress Dependent

Damjanovic and Demartin [15] has shown that piezoelectric coefficient is stress dependent, Figure 2.16. Stress is applied parallel to the poling direction and the piezoelectric coefficient  $d_{33}$  linearly increases as the applied stress level increases.



Figure 2.16: Stress dependent of piezoelectric coefficient  $d_{33}$  and charge density [15]

Krueger [16] has shown experimentally that when static lateral compressive stress is applied perpendicularly to the poling direction of a soft PZT, i.e. along the two opposite edges denoted as direction 1 while direction 2 is stress free, as shown in Figure 2.17, the piezoelectric coefficient  $d_{31}$  decreases, however,  $d_{32}$  increases as shown in Figure 2.19.

The mechanism of stress that enhances the piezoelectric constant is a result of the reversible domain wall motion. The unaligned domains which are the non-180° domains tend to show larger reversibility than the well aligned ones. Stresses generally promote non-180° domain wall motion, hence promoting the piezoelectric response; while an electric field promotes both non-180° domain and 180° domain wall motion. From Krueger's results [16]; it can be concluded that if a piezoelectric is under compressive stress perpendicular to the poling direction, the piezoelectric coefficient along the compressive stress direction is suppressed, the opposite is promoted under stress-free sides. Figure 2.18(left) illustrates how compressive stress is applied perpendicularly to the poling direction. The dashed rectangular shape illustrates the original shape of the piezoelectric material under compressive stress, while the solid rectangular shape illustrates contraction along the compressed direction, and elongation of the piezoelectric materials along the stress free direction,

2-direction, figure 2.18(right).



Figure 2.17: Illustration of applied lateral stress perpendicular to the poling direction, direction 3, from Krueger [16]'s.



Figure 2.18: Illustration of the application of the lateral compressive stress perpendicularly to the poling direction, shown are solid arrows (left). The poling direction is the out-of-plane direction. The dashed rectangular represents the original shape of the piezoelectric material when the compressive stress is applied (right).



Figure 2.19:  $d_{31}$  and  $d_{32}$  vs lateral stress,  $T_1$ . Comparison of all ceramics tested [16]

# 2.3 Smart Actuators

Unimorph-type piezoelectric actuators are discussed in this section, including their uses, design concepts and performance. The comparison of different types of smart actuators will be presented at the end of this section.

#### 2.3.1 Piezoelectric Actuators

Piezoelectric materials can be attached onto metals or composites. Various attachment configurations could be arranged such as conventionally attached piezoelectric (CAP) [17] or for a higher twist [18], a directionally attached piezoelectric (DAP), Figure 2.20.

Among the PZT-based actuators are piezoelectric stacks, unimorphs, bimorphs, THUNDER (Thin layer composite UNimorph ferroelectric DrivER and sensor), RAINBOW (Reduced And Internally-Biased Oxide Wafer) and LIPCA (Lightweight Piezoceramics Composite Actuators). Unimorphs are comprised of one active piezoelectric material layer and one passive elastic layer, Figure 2.21. Bimorphs consist of two electrically opposed piezoelectric material layers bonded together with one or more passive layers sandwiched in between, Figure 2.22. Unimorphs and bimorphs are known as benders. The benders exhibit bending through extension and contraction of individual piezoelectric material layer with the application of the electric field, Figure 2.22.



Figure 2.20: Arrangement of CAP and DAP Twist-Active Lamina [17]







Figure 2.22: Behavior of a bimorph subjected by an electrical voltage. - (top) parallel, (bottom) series [4]

#### THUNDER

THUNDER was first developed by NASA-Langley [19–21] as a high-force and displacement unimorph-type piezoelectric actuator for drag reduction. THUNDER was considered as a stress-biased actuator meaning that the internal stress was not zero because the internal stresses were developed upon manufacturing due to differences in the coefficient of thermal expansion of different materials, Figure 2.23. As a result, the THUNDER formed a dome shape or a curved shape after manufacturing. It was demonstrated that the performance of a THUNDER has a direct relationship with the manufactured dome height; i.e. the larger the dome height, the greater the actuated displacement [22, 23]; since the internal stress enhanced actuation performance through better interaction between electric field and piezoelectric domain walls [22]. Aimmanee et al. [24] concluded that the actuation displacements are dependent on the initial dome height, and on the aspect ratio.



Figure 2.23: Configuration of THUNDER [25]

Aimmanee et al. [24] predicted the actuator behaviour, manufactured and actuated curvatures, of THUNDER at different aspect ratios taking into account the geometric nonlinearity of the actuator. For a rectangular actuator, the shorter one, Lx/H = 166, Lx is the length, H is the thickness, gave a single manufactured shape; while the longer one, Lx/H > 166, gave multiple shapes through a snapthrough phenomenon. In contrast; for a beam-like actuator (Ly=0.33Lx), there was no snap-through phenomenon. Moreover, a rectangular THUNDER produced larger actuation displacement than circular ones [20].

An actuator's neutral axis location played a role in its performance. Mossi et al. [19] proposed that greater actuation displacement was produced when the neutral axis was at or a bit lower than the piezoelectric material layer towards the bottom face of an actuator. In contrast, Wise [26] and Schwartz et al. [22] demonstrated that the highest displacements were produced when the neutral axis was further away from the bottom face. Ounaise Z. et al. [23] demonstrated that when heat was introduced into THUN-DER during actuation, displacement increased as the temperature increased. The displacement decreased slightly when the temperature reached higher than 150°C. It was explained that at a temperature higher than 150°C, THUNDER was dominated by extrinsic effects; i.e. the stress between the domains changed and relaxed, consequently resulting in a decrease in overall displacement performance. In addition, the performance of a THUNDER decreased with thermal aging duration and heating level.

Pinkerton and Mosses [27] ran a continuous fatigue test on a THUNDER and after 2 weeks of testing, the displacement was noticeably degraded with a capacitance dropped to 33%.

The THUNDER resonance frequency depended on the device geometry and boundary conditions [19] and it decreased as the input electric field increased due to the piezoelectric material softening of the piezoelectric [23].

#### Conclusions

A THUNDER is a stress-biased type actuator with internal thermal stress developed due to differences in the coefficient of thermal expansion from the different materials used in the actuator, resulting in an enhancement of the actuation displacement. The proposed design concepts to achieve greater displacement based on; for example, ratio of piezoelectric material to the metallic layer and the aspect ratios. Furthermore, the dome height produced after manufacturing may promote greater actuation displacements depending upon the actuator aspect ratio.

#### RAINBOW

The RAINBOW actuator was developed by NASA-Langley as a high-force and displacement uimorph-type piezoelectric actuator for drag reduction [21]. RAIN-BOW was produced by chemically reducing one side of a high lead-containing ferroelectric wafer (PLZT) with graphite in an oxidizing atmosphere at an elevated temperature, Figure 2.24. The remaining part contains the original piezoelectric material composition. The reduced layer acted as one electrode and another layer with a silver-based coating was used as another electrode. The dome-like shape of RAINBOW was assumed to be due to the reduction in volume of the reduced layer and also due to the thermal contraction between the reduced and unreduced layer during cooling. Wise S.A. [26] have demonstrated that with the same ceramic-to-total thickness ratio RAINBOW produced larger actuation dis-

placement than THUNDER under no-load conditions. Under loaded conditions, THUNDER showed higher load resistance [26].



Figure 2.24: RAINBOW dome shape [28]

#### Internal Stress Effects to RAINBOW

Similary to THUNDER, internal stress was developed in the RAINBOW as a result of high processing temperature. For ordinary ferroelectric ceramics, the major contribution to the field-induced strains were (1) the piezoelectric effect of individual domains which was known as the intrinsic effect and (2) the domain reorientation which was known as the extrinsic effect. The intrinsic effect, or piezoelectric effect, was described as a response of the domain walls response with respect to low magnitude of applied electric field causing small and linear output strain [29]. It was linear because the domain walls that moved with the electric field were able to orient back to their initial state. The extrinsic effect could be described as a nonlinear response of the non- $180^{\circ}$  domain walls, to a large applied electric field resulting in large magnitudes of nonlinear output strain [30]. The 180° domains, sometimes called the "c-domains", were the poled domains oriented along the poling direction, as defined in [31–33]. The 180° domain walls would be developed when the piezoelectric material was under compression perpendicular to the poling direction [34]. The non-180° domains, sometimes called "a-domains", were those resulting from the piezoelectric material being in tension perpendicular to the poling direction, as defined in [31–33], and where the polarities made some angle to the poling direction [34]. For example, the non-180° domains were those whose polarities were perpendicular to the poling direction, shown as horizontally aligned domains at the top surface in Figure 2.25. Compressive pressure acting opposite to the poling direction on the piezoelectric material suppressed the domain by switching the 180° domains to the non-180° domains, but this stress could not cause depolarization. Moreover, the amounts of reoriented domains had

a direct contribution to the extrinsic piezoelectric effect and produced a larger displacement than that of intrinsic effect. To promote more non-180° domains, the tensile stresses developed in the RAINBOW were the preferred one and they greatly contribute to the actuation displacement [33]. Figure 2.25 illustrates domain reorientation of the RAINBOW during actuation.



Figure 2.25: Various stages of domain alignment and reorientation in a Rainbow actuator, depicting conditions: (A) as processed and electroded, (B) first application of voltage and (C) complete application of voltage [31]

Heartling [31], Li et al. [32] and Schwartz and Moon [33] have demonstrated that internal induced stresses developed during manufacturing of RAINBOW played an important role in actuation displacements by enhancing the out of plane displacement of the RAINBOW. The 180° domain would grow along with the direction of the electric field, as defined in these literatures [31–33], and the non-180° domain also contribute to the amplification of the displacement through the rotation in response to the direction of the electric field.

The manufactured dome height was directly related to internal stress but only up to an optimum stress; once beyond the optimum state the displacement would not be enhanced anymore [35]. It could also be explained that the non-180° domains undergone enhanced relaxations originating from internal friction due to the presence of high internal stress, and eventually became locked [31].

It was demonstrated that piezoelectric nonlinearity increased with increasing internal stress [31], however, there was an optimum stress, beyond this optimum value nonlinearity became smaller [34]. This was caused by the internal stress distribution; which was, greater the dome height, the higher the neutral axis moved upward to the top surface, thus, reducing the tension area. As a result, less associated domain reorientation takes place and there is less chance in the nonlinearity of a piezoelectric material.

#### **Frequency Dependent**

Heartling [31] and Dausch [36] have shown that under higher frequencies, the domains lying in the tensile stress region might not had enough time to switch from non-180° domains to 180° domains. As a result, there was less contribution from the non-180° domains to the overall actuation displacement; thus, the actuation displacement was reduced progressively.

#### Conclusions

RAINBOW is a stress-biased type of actuator with internal thermal stresses developed through the manufacturing process. Most research on RAINBOW has been focused on the domain walls distribution resulting from internal stress throughout the piezoelectric material thickness. The domain walls were largely influenced by the internal stress. Tensile stress was more favorable than compressive stress. This was because the tensile stress promoted more non-180° domain walls movement, therefore, larger displacements were developed. The manufactured dome height directly related to the developed thermal stresses and this enhanced the output displacements but up to an optimum value. When the dome height was greater than this optimum value, the displacement would not be enhanced anymore. The study showed that the output displacements increased with the frequency but up to an optimum value then the displacements were suppressed at a higher frequency, because the domain walls could not keep pace with the high frequency input electric field.

#### LIPCA

The LIPCA [37] system is composed of a piezoelectric material layer embedded between top plies made of a low coefficient of thermal expansion (CTE) materials such as carbon or kevlar layer and lower plies made of a higher CTE base such as glass layers, Figure 2.26. LIPCA was developed by a research group at Konkuk University in Seoul, Korea. Similar to THUNDER and RAINBOW, LIPCA is considered to be a stress-biased actuator. It was developed to replace existing heavy metal layer piezoelectric material-based actuators such as THUNDER. Since LIPCA is a composite-based actuator, it has design flexibility achievable by manipulating the layup orientations and dimensions. LIPCA has become a good candidate to replace THUNDER as its weighs more than 30% less than THUNDER and larger displacements are possible.



Figure 2.26: LIPCA system with carbon/epoxy and glass/epoxy layers at the top and bottom layers, respectively [38]

**Boundary Conditions Study** Yoon K.J. et al. [25, 39] have compared LIPCA with THUNDER. The LIPCA actuation displacement was up to twice as much as that for THUNDER under screw-fixed simply supported boundary condition [39] but the actuation displacement of a LIPCA has turned to be 10% lower than that for THUNDER under simply supported ends conditions [25].

Nguyen et al. [40, 41] demonstrated that when LIPCAs were configured under simply-supported boundary condition, their actuation displacements were improved when a load was simultaneously applied against the actuation direction during actuation. They explained that this was because the compressive load helped align the domain walls to the electric field. Goo et al. [42] have derived a one dimensional relationship between actuator's mechanics properties and the actuation performance under simply-supported boundary condition, but, this relationship did not take thermal stress into account.

Layups Study Kim et al. [38] have compared the actuation performance of LIPCA with different layups and studied the effects on the bending stiffness of the LIPCA. Goo and Yoon [43] and Kim et al. [38] proposed the following LIPCA design philosophies; (1) maximize the moment arm of the piezoelectric material neutral axis to the LIPCA's neutral axis, as shown in Figure 2.27, (2) the neutral axis should be outside of the piezoelectric material layer and also (3) it was essential to locate the piezoelectric material in the compression side of the LIPCA system because the compressive failure strain of the piezoelectric material was larger than the tensile failure strain [38]. This was illustrated in a fatigue test of the LIPCA in which the micro void grew more slowly at the interface of the piezoelectric material and glass when the PZT was fully under compression [44]. Moreover, the compressive stress state in the piezoelectric material was helpful for aligning the dipoles well in the piezoelectric material [45] and the actuation

displacement would be enhanced [25, 43, 46].

The above design philosophies on placing the piezoelectric material in a compressive stress contradicted the previous studies on RAINBOW [29, 32, 33]. The RAINBOW studies showed that locating the piezoelectric material under tensioned helped to enhance the displacements, while the displacements were suppressed when it was under compression.

The actuation displacements could be explained through changes in the actuation curvature ( $\Delta \kappa$ ), which was linearly related to the coefficient of a unimorph actuator ( $C_{ua}$ ), elastic modulus of the piezoelectric plate ( $E_a$ ), piezoelectric coefficients ( $d_{31}$ ) and the applied electric field ( $\Delta V$ ) [25, 38]. The LIPCAs experiments were done under two boundary configurations: simply-supported and both ends were clamped. The coefficient of unimorph was defined as the ratio of a moment arm of the piezoelectric plate to the LIPCA's neutral axis (a) to the LIPCA's total bending stiffness (D) [47]. From the relationship shown below, with the same piezoelectric material properties and applied electric field, it can be seen that  $C_{ua}$ is the governing parameter related to the actuator layup that contributed to the changes of the curvature.



Figure 2.27: Moment arm of the LIPCA system

$$\kappa = C_{ua} \cdot E_a \cdot d_{31} \cdot \Delta V \tag{2.6}$$

$$C_{ua} = \frac{a}{D} \tag{2.7}$$

The coefficient of a unimorph  $(C_{ua})$  has been shown to depend on a boundary condition. Some studies have demonstrated that a larger  $C_{ua}$  did not always produce larger displacements when configured under skew-fixed boundary condition [39], and under a simply-supported condition [43].

**Initial Dome Height Study** Some discrepancies regarding the LIPCA design philosophies could be observed within the Yoon et al. [25, 43] and Woo et al. [48]

research group. Yoon et al. [25, 43] proposed that a greater bending stiffness, shown as greater initial dome height, reduced actuation displacements; while Woo et al. [48] have demonstrated that a greater bending stiffness enhanced the actuation displacements. Woo et al. [48] explained that more elastic energy was stored in the laminate with a greater bending stiffness, and the stored elastic energy enhanced larger displacements. Woo et al.'s results [48] showed that the the  $C_{ua}$  was not the most dominant parameter influencing the actuation displacement as demonstrated by Yoon et al. [25, 43]. The differences between these studies [43, 48] and Woo et al. [48] could come from the different aspect ratios used in the studies. Further Mossi K. et al. [49] have shown that the relationship between initial dome height and actuation displacement could not be used as a performance indicator between THUNDER and LIPCA. The LIPCA with a 65% flatter initial dome height showed a much larger actuation displacement than the THUNDER.

In conclusion, results from Yoon's research group [25, 38, 43, 46, 48], it indicate it is necessary to maximize the moment arm of the piezoelectric material. In addition, it is essential to locate the piezoelectric material in the area of compression. A stiffer actuator will not always lead to smaller actuation displacement if the moment arm from the piezoelectric neutral axis was maximized. Concrete conclusions regarding which parameters, e.g.  $C_{ua}$ , dome height, aspect ratio, are the most dominant for actuation displacements still need to be done.

**Dimensions Study** Using the same layup and material properties, but different sized and shaped actuators; a square shape LIPCA (92 mm x 82 mm) [48] showed less actuation displacements than the rectangular and smaller actuators (100 mm x 24 mm) [38] under the same applied electric field and boundary condition, however, we do not know yet exactly why this happens [48].

Extensive dimension studies by Aimmanee et al. [24] on the manufactured and actuated curvatures on LIPCA-C1 [G/G/PZT/C], LIPCA-C2 [G/PZT/G/C/G] with different aspect ratios. The aspect ratios were short/long actuator which was explained by various sidelength-to-thickness ratios (Lx/H). The actuator sizes such as Ly=0.7Lx and Ly=0.33Lx, where Ly was actuator's width, Lx was actuator's length and H was the actuator thickness. The former size of the actuator is referred to as rectangular and the latter size is referred to as beam-like.

There could be multiple actuated shapes depending on the sidelength-to-thickness ratios. The longer actuator was shown to have more feasibility of having multiple actuated shapes. Figure 2.28 showed multiple actuated shapes of a LIPCA-C2 under no electric field (a), -2 MV/m (b) and +2 MV/m (c) with Lx/H = 200.
Different actuated shapes also depended upon the applied electric field.



Figure 2.28: Multiple actuated shapes of LIPCA-C2, Lx/H = 200. (a) no electric field, (b) -2 MV/m and (c) and +2 MV/m [24]

A rectangular shape LIPCA-C2 actuation response showed asymmetry between positive and negative fields; i.e. a positive field showed 5 times greater response than a negative field, this is even more pronounced with a square shape but the beam-like shape showed a less pronounced effect. In addition to the asymmetry, nonlinearity between actuation displacement and input electric field had been observed [24]. A rectangular LIPCA-C2 posed a snap-through phenomenon at Lx/H = 200 but not Lx/H = 100. The snap-through phenomenon could be explained by the curvature changing sign from positive to negative. Mechanically, this could be done by applying moments along opposite edges of an actuator. The snap-through of this LIPCA-C2 was asymmetric between increasing the electric field and reducing the field [24]. In conclusion, LIPCA-C2 showed highly non-linear effects due to the aspect ratio, sidelength-to-thickness ratio and actuator length, in contrast to C1 of rectangular shape; while both showed influences due to non-linear effects when in a beam-like shape [24].

**Frequency Dependent Study** Mossi K. et al. [49] have compared the dynamic response of THUNDER and LIPCA by actuating these actuators under various voltages and frequencies. The hysteresis curves became less symmetric as the input voltage increased, this was more pronounce for the THUNDER than the

LIPCA. They observed that as the voltage increases, the resonance frequency linearly shifted to a lower value. The shifting of the resonance frequency was due to the piezoelectric material softening with increasing electric voltage [23].

#### Conclusions

Extensive researches into LIPCAs' performance using different boundary conditions and laminate stacking sequences is discussed in this sub-section. The design philosophies of the LIPCAs have been outlined, i.e. to maximize the moment arm of the piezoelectric material layer's neutral axis to the LIPCA's neutral axis. It is necessary to place the piezoelectric material layer in the compression side of the LIPCA to minimize fracture under the tensile load. We still do not have concrete boundaries for which parameter, e.g. aspect ratio, bending stiffness, moment arm and  $C_{ua}$ , is the most influential. In addition to actuator performance, multiple actuated shapes and a snap-through phenomenon during actuation were introduced. From the above discussion, multiple manufactured and actuated shapes and snapthrough phenomenon can be explained as being are to the actuator aspect ratios and shape: rectangular or beam-like.

### 2.3.2 Comparisons of Smart Actuators

Different types of smart actuators will be discussed with respect to different actuation performance below.

#### Force and Force Density

Piezoelectric stacks and SMA show the highest force produced and also highest force density, i.e. force produced per unit actuator density. Inchworm actuators and piezoelectric multimorph give the least force and force density, Figures 2.29 and 2.30.

#### Stroke

Piezoelectric stack actuators give the lowest stroke, actuation displacement, while multimorph actuators produce a relatively higher stroke similar to the SMAs and are considered to function in a moderate stroke range. Inchworm piezoelectric actuators produced the largest stroke amongst the piezoelectric material actuators ranging from a moderate to a high stroke range, as shown in Figure 2.31.



Figure 2.29: Comparison of emerging and traditional actuators in terms of force level. SMA is the shape memory alloy. MS is the magnetrostrictives. [50]



Figure 2.30: Comparison of emerging and traditional actuators in terms of force density level [50]



Figure 2.31: Comparison of emerging and traditional actuators in terms of stroke level [50]

### Bandwidth

Piezoelectric stack and multimorph and Magnetrostrictive actuators produce the largest bandwidth ( $f \ge 10^2$  Hz), while the SMA and pneumatic actuators produce the lowest bandwidth ( $f \le 1$  Hz), Figure 2.32.



Figure 2.32: Comparison of emerging and traditional actuators in terms of bandwidth [50]

### 2.3.3 Conclusions

Various types of actuators based on different smart materials such as piezoelectric, SMA and magnetrostrictive materials were introduced in this chapter. The well known piezoelectric material-based actuators unimorph-type that were discussed were THUNDER, RAINBOW and LIPCA which are considered to be stress-biased actuators. That is, the internal stresses are developed during manufacturing due to differences between the coefficient of thermal expansion of the different materials used to build actuators. The stress developed inside actuators during manufacturing demonstrate a major contribution to different curvatures. The design concepts used to produced greater actuation displacements were discussed. These are, the location of the piezoelectric layer with respect to the whole thickness, the location of the neutral axes of both piezoelectric material and the whole actuator, bending stiffness and moment arm. Another important parameter that governs the actuation displacement and manufactured/actuation shapes is the aspect ratio. All these mentioned parameters are inter-mingled and it is still unclear for which parameter is the most dominant under which circumstances.

The SMA and magnetrostrictive were discussed briefly in this chapter; however, they were not a major focus of this literature review. The performances of different the actuators was compared, piezoelectric stacks and SMA show highest produced force, and also the highest force density, piezoelectric stacks produce the lowest stroke. Piezoelectric stack and magnetrostrictive actuators produce the largest bandwidth while the SMA produce the lowest bandwidth.

## References

- B. Jaffe, W.R. Cook, and H.L. Jaffe. *Piezoelectric ceramics*. Non-metallic solids. Academic Press, 1971.
- SO Moheimani and A.J. Fleming. Piezoelectric transducers for vibration control and damping— NOVA. The University of Newcastle's Digital Repository. Springer, 2006.
- [3] Jan Holterman and Pim Groen. An introduction to piezoelectric materials and applications. Stichting Applied Piezo, Netherlands, 2013.
- [4] RG Ballas. Piezoelectric multilayer beam bending actuators and aspects of sensor integration, 2007.
- [5] J. Sirohi and I. Chopra. Fundamental behavior of piezoceramic sheet actuators. Journal of intelligent material systems and structures, 11(1):47–61, 2000.
- [6] I. Chopra. State-of-the-art of smart structures and integrated systems. Smart materials, structures, and MEMS, pages 2–44, 1998.
- [7] I. Chopra. Review of state of art of smart structures and integrated systems. AIAA journal, 40(11):2145–2187, 2002.
- [8] http://www.matsysinc.com/. Active fiber composites, Accessed: 10/11/2012.
- [9] E.F. Crawley. Intelligent structures for aerospace-a technology overview and assessment. *AIAA journal*, 32(8):1689–1699, 1994.
- [10] S. Li, W. Cao, and LE Cross. The extrinsic nature of nonlinear behavior observed in lead zirconate titanate ferroelectric ceramic. *Journal of applied physics*, 69(10):7219–7224, 1991.
- [11] A. Pramanick, D. Damjanovic, J.E. Daniels, J.C. Nino, and J.L. Jones. Origins of electro-mechanical coupling in polycrystalline ferroelectrics during subcoercive electrical loading. *Journal of the American Ceramic Society*, 94(2):293–309, 2011.
- [12] D. Damjanovic. Logarithmic frequency dependence of the piezoelectric effect due to pinning of ferroelectric-ferroelastic domain walls. *Physical Review B*, 55(2):R649, 1997.

- [13] AJ Masys, W. Ren, G. Yang, and BK Mukherjee. Piezoelectric strain in lead zirconate titante ceramics as a function of electric field, frequency, and dc bias. *Journal of applied physics*, 94:1155, 2003.
- [14] JE Garcia, R. Perez, DA Ochoa, A. Albareda, MH Lente, and JA Eiras. Evaluation of domain wall motion in lead zirconate titanate ceramics by nonlinear response measurements. *Journal of Applied Physics*, 103:054108, 2008.
- [15] D. Damjanovic and M. Demartin. Contribution of the irreversible displacement of domain walls to the piezoelectric effect in barium titanate and lead zirconate titanate ceramics. *Journal of Physics: Condensed Matter*, 9:4943, 1997.
- [16] H.H.A. Krueger. Stress sensitivity of piezoelectric ceramics: part 3. sensitivity to compressive stress perpendicular to the polar axis. The Journal of the Acoustical Society of America, 43:583, 1968.
- [17] R.M. Barrett and F. Brozoski. Adaptive flight control surfaces, wings, rotors, and active aerodynamics. In *Proceedings of SPIE*, volume 2717, page 178, 1996.
- [18] R. Barrett. All-moving active aerodynamic surface research. Smart Materials and Structures, 4:65, 1995.
- [19] K.M. Mossi, G.V. Selby, and R.G. Bryant. Thin-layer composite unimorph ferroelectric driver and sensor properties. *Materials Letters*, 35(1):39–49, 1998.
- [20] K.M. Mossi and R.P. Bishop. Characterization of different types of high performance thunder actuators. *Stainless Steel*, 302:0–1524, 1999.
- [21] R.R. Antcliff and A.M.R. McGowan. Active Control Technology at NASA Langley Research Center. National Aeronautics and Space Administration, Defense Technical Information Center, 2001.
- [22] R.W. Schwartz, P. Laoratanakul, W.D. Nothwang, J.M. Ballato, Y. Moon, and A. Jackson. Understanding mechanics and stress effects in rainbow and thunder stress-biased actuators. In *Proceedings of SPIE*, volume 3992, page 363, 2000.
- [23] Z. Ounaies, Institute for Computer Applications in Science, and Engineering. Low-field and high-field characterization of THUNDER actuators. ICASE, NASA Langley Research Center, 2001.

- [24] S. Aimmanee and MW Hyer. A comparison of the deformations of various piezoceramic actuators. *Journal of intelligent material systems and structures*, 17(2):167–186, 2006.
- [25] K.J. Yoon, K.H. Park, S.K. Lee, N.S. Goo, and H.C. Park. Analytical design model for a piezo-composite unimorph actuator and its verification using lightweight piezo-composite curved actuators. *Smart Materials and Structures*, 13:459, 2004.
- [26] S.A. Wise. Displacement properties of rainbow and thunder piezoelectric actuators. Sensors and Actuators A: Physical, 69(1):33–38, 1998.
- [27] J.L. Pinkerton and R.W. Moses. A Feasibility Study to Control Airfoil Shape Using THUNDER. NASA technical memorandum. NASA, Langley Research Center, 1997.
- [28] G.H. Haertling. Rainbow ceramics- a new type of ultra-high-displacement actuator. American Ceramic Society Bulletin, 73(1):93–96, 1994.
- [29] G. Li, E. Furman, and G.H. Haertling. Stress-enhanced displacements in plzt rainbow actuators. *Journal of the American Ceramic Society*, 80(6):1382– 1388, 1997.
- [30] DA Hall. Review nonlinearity in piezoelectric ceramics. Journal of materials science, 36(19):4575–4601, 2001.
- [31] G.H. Haertling. Stress-induced effects in plzt ceramics. In Applications of Ferroelectrics, 1996. ISAF'96., Proceedings of the Tenth IEEE International Symposium on, volume 1, pages 65–68. IEEE, 1996.
- [32] G. Li, E. Furman, and GH Haertling. Fabrication and proprerties of pszt antiferroelectric rainbow actuators. *Ferroelectrics*, 188(1):223–236, 1996.
- [33] R.W. Schwartz and YW Moon. Domain configuration and switching contributions to the enhanced performance of rainbow actuators. SPIE Smart Structures and Materials, Active materials: Behavior and Mechanics, 4333(408):201, 2001.
- [34] Gene H. Haertling. Stress induced effects in plzt ceramics. In Proceedings of the Tenth IEEE International Symposium on Applications of Ferroelectric, 1997.
- [35] Youngwoo Moon and Gene Heartling. Characterization of nonlinear piezoelectric behavior of rainbow ceramics. NASA-CR-205146, 1997.

- [36] D.E. Dausch. Asymmetric 90 domain switching in rainbow actuators. Ferroelectrics, 210(1):31–45, 1998.
- [37] N.S. Goo, C. Kim, Y.D. Kwon, and K.J. Yoon. Behaviors and performance evaluation of a lightweight piezo-composite curved actuator. *Journal of intelligent material systems and structures*, 12(9):639–646, 2001.
- [38] KY Kim, KH Park, HC Park, NS Goo, and KJ Yoon. Performance evaluation of lightweight piezo-composite actuators. Sensors and Actuators A: Physical, 120(1):123–129, 2005.
- [39] K.J. Yoon, S. Shin, H.C. Park, and N.S. Goo. Design and manufacture of a lightweight piezo-composite curved actuator. *Smart Materials and Structures*, 11:163, 2002.
- [40] Q.V. Nguyen, N.S. Goo, and H.C. Park. Behavior of lightweight piezoceramic composite actuator under compressive load. *Key Engineering Materials*, 326:1403–1406, 2006.
- [41] Q.V. Nguyen, S. Lee, and H.C. Park. Improvement of actuation displacement of lipca implementing bifurcation phenomena. In *Proceedings of SPIE*, volume 6170, page 61701L, 2006.
- [42] N.S. Goo, A. Haris, H.C. Park, and K.J. Yoon. Validation of a laminated beam model of lipca piezoelectric actuators. *Journal of intelligent material* systems and structures, 16(3):189–195, 2005.
- [43] N.S. Goo and K.J. Yoon. Analysis of lipca-c actuators. International Journal of Modern Physics B, 17(8/9; PART 2):1959–1964, 2003.
- [44] C. Kim and K. Yoon. Fatigue behavior degradation due to the interlaminar conditions in lightweight piezoelectric composite actuator (lipca). International Journal of Modern Physics B, 20(27):4365–4370, 2006.
- [45] N.S. Goo, V.P. Phan, and H.C. Park. Actuation displacement performance change of pre-stressed piezoelectric actuators attached to a flat surface. *Smart Materials and Structures*, 18:037003, 2009.
- [46] KJ Yoon, KH Park, HC Park, and D. Perreux. Thermal deformation analysis of curved actuator lipca with a piezoelectric ceramic layer and fiber composite layers. *Composites science and technology*, 63(3-4):501–506, 2003.
- [47] K. Park, Y. Kim, Y.S. Kim, H.C. Park, and K.J. Yoon. Experimental performance evaluation of lightweight piezo-composite curved actuators. In *Proceedings of SPIE*, volume 4699, page 315, 2002.

- [48] S.C. Woo, K.H. Park, and N.S. Goo. Influences of dome height and stored elastic energy on the actuating performance of a plate-type piezoelectric composite actuator. *Sensors and Actuators A: Physical*, 137(1):110–119, 2007.
- [49] K. Mossi, Z. Ounaies, R. Smith, and B. Ball. Prestressed curved actuators: characterization and modeling of their piezoelectric behavior. *Smart Structures and Materials 2003*, 5053:423–435, 2003.
- [50] J.L. Pons. *Emerging actuator technologies: a micromechatronic approach*. John Wiley and Sons Inc, 2005.

# Chapter 3

# Manufacturing of Piezoelectric Composite Materials Actuators

The state-of-the-art of the piezoelectric material actuators was reviewed. In section 2.3, it was demonstrated that the LIghtweight Piezoelectric-composite Curve Actuator (LIPCA) exhibits the most design flexibility compared to other types of actuators. It is because of the existence of the composite materials that allows viable design feasibility. Therefore, in this chapter approaches to manufacture the piezoelectric composites actuators similarly to LIPCAs and the manufactured quality checks so that they can be investigated experimentally throughout this thesis are discussed. The chapter is divided into five sections. An introduction to the chapter is presented in section 3.1. In section 3.2, manufacturing the actuators using an autoclave and a hot press is described. In section 3.3, quality control of the manufactured actuators are discussed. In section 3.4, geometry of the actuators is described. In section 3.5, the chapter ends with the concluding remarks on the manufacturing concepts and the manufactured actuators' quality. Since the piezoceramic, acronym PZT, was used to make all the actuators used in the research reported here, acronym PZT will be used.

## 3.1 Introduction

The two most important processing parameters for polymer curing/consolidation are temperature and pressure. The required curing/consolidation temperatures and pressures are very dependent on the resin type: thermoplastic resins require higher processing pressures than the thermosetting resins.

The piezoelectric domains inside the piezoelectric materials are influenced by the compressive pressure acting parallel but opposite to the poling direction and when the pressure is large enough, the domains can be irreversibly switched causing permanent strains [1]. The onset of compressive pressure that causes permanent strain is as high as several tens of mega-pascal [1] and is, therefore, far greater than the pressure required during processing. However, the composite processing pressure might cause cracks to the undeformable and very brittle piezoelectric materials. From this reason, in order to be able to embed the piezoelectric material in the composite laminate and co-cure the whole composite laminate, the processing parameters, in particular the curing/consolidation pressure, had to be optimized. After manufacturing, each individual actuator was further checked for its quality, in particular voids in the composite materials and cracks in the PZT, by cutting through the actuator thickness and checking through an optical microscope. Voids are a high concern issue as they are an indicator of whether enough pressure has been reached to impregnate the fibers with the resin. Moreover, they are an indicator of whether there is intimate contact between adjacent layers, and all the entrapped air has removed between layers during curing/consolidating. Poorly cured/consolidated actuators will show voids and/or delamination inside the actuator. Stress concentration will develop at the voids and crack can initiate inside the actuator.

The composite manufacturing processes used in this thesis were autoclave and hot press. The actuators used for the experiments were manufactured with a hot press concept for the static operating condition and with an autoclave concept for the dynamic operating condition<sup>1</sup>. This is due to the equipment availability during the time the research was conducted.

The epoxy prepregs were used to make the actuators for this thesis because the processing temperature require is lower than that required for the thermoplastic semi-pregs, which can reach as high as 350°C. There is a high chance for the depolarisation of the PZT at the high processing temperatures required by the thermoplastic semi-pregs while the PZT's Curie temperature used in this research was 350°C. Once the PZT is heated up to a high temperature, depolarisation occurs resulting in the loss of polarity of the PZT and therefore of its piezoelectric effect. The depolarization can start at the temperature magnitude below the Curie temperature. The epoxy prepregs used to make the actuators were glass fabric epoxy prepregs and carbon unidirectional epoxy prepregs.

<sup>&</sup>lt;sup>1</sup>The limitation of the hot press compared to the autoclave in general is that the composite laminates must be flat and have constant thickness; while in the autoclave, the composite laminates can have any shape.

# 3.2 Manufacturing Concepts

Two composite manufacturing concepts, autoclave and hot press, used to manufacture the actuators are presented in this section.

### Autoclave

Autoclaves are pressure vessels that allow simultaneous imposition of pressure by vacuum and heat. The composite laminates are vacuum bagged prior the curing/consolidation process. The vacuum bagging process is aimed at ensuring that the air entrapped between the prepreg layers during the lay-up process is removed. The application of vacuum during curing/consolidation when the resin is less viscous has the benefit of removing the volatiles in the resin. The volatiles may include residual solvents used in prepregs manufacturing and volatiles absorbed by the neat resin prior to prepregs manufacturing. The elimination of the volatiles helps to lower the void content of the final composite laminates [2]. The autoclave manufacturing steps are as follows, and are illustrated in Figure 3.1.



Figure 3.1: Vacuum bagging system for the autoclave manufacturing concept

1) The stainless steel mould and a release film such as a perforated Teflon film or a Kapton film are cleaned by PFQD cleaning solvent to remove dust, dissolves the contaminant and degreasing. The stainless steel mould and a release film are coated with Marbocote release agent to prevent the actuators to stick to the mould surfaces and for ease of demoulding. The stainless steel mould is used because its coefficient of thermal expansion is not as large as aluminum [3] and is closer to the coefficient of thermal expansion of the prepress used to manufacture the actuators in this thesis. This is to prevent large differences in the material expansion/shrinkage between the moulds and the actuators during heating and cooling down. The actuator is placed between the cleaned and coated release films as shown in Figure 3.2.

2) A breather cloth is applied on top of the release film. The breather cloth acts as a distributor for the air and for helping volatiles and gasses to escape, as well as a buffer between bag wrinkles and actuator surfaces [2].

3) The value is placed on top of the breather to allow vacuum to be distributed over the entire part but it must not be located exactly on top of the actuator. The vacuum line is connected to the vacuum pump.

4) A sealant tape is placed around the entire assembly to form an airtight seal with the vacuum bag.



Figure 3.2: An actuator is tapped at the 4 corners to prevent the relative movement between plies and to prevent the actuator to misplace during transportation. The actuator is sandwiched between the two Kapton film

#### Hot Press

In the hot press process, the actuator is placed between two flat stainless steel moulds. The moulds are then placed between the two heated platens and pressure is applied through these two heated platens. The manufacturing procedures are as follows, and as shown in Figure 3.3.



Figure 3.3: Hot Press System

1) The moulds and the release films are identically prepared as described in the autoclave concept.

2) A silicone rubber sheet is placed on top of the release film in order to distribute the pressure over the whole actuator system. Silicon rubber sheet is expandable and deformable and it has the same function of the breather cloth used in the autoclave.

3) Two thermocouples were inserted inside small slots on the edges of the moulds in order to control the temperature at the moulds.

4) The cleaned and coated top mold identical to the bottom one is placed on top of the silicone rubber.

5) The whole system is placed between the platen of the hot press machine and the curing cycle starts.

# 3.3 Actuator Manufacturing and Quality Check Results

A manufactured actuator is shown in Figure 3.4. The actuator formed a curved shape after manufacturing because of different coefficient of thermal expansions from different materials used. The manufacturing quality was checked by cutting the actuators, with a diamond blade, randomly in multiple locations and checking for cracks in the PZT layer, voids and delamination between the interfaces by

the optical microscope. The optical microscope used is Ziess Axiovert 40 MAT Inverted Microscope. Cracks in the PZT layer are the indicator of large pressure during manufacturing. The absence of voids and delamination is an indication of good quality of the actuator: it indicates good contact between the adjacent plies and that all the entrapped air has been removed. Optimization of curing pressure was to prevent cracks in the PZT layer. Modifications of the actuators layup process were needed to resolve the problems of voids and delamination.



Figure 3.4: Cured actautor

The optimum curing pressure for this actuator is 3 bars. Within the 3 bars of pressure, there is no crack at the PZT layer [4]. Figure 3.5 and Figure 3.6 show the cut-through results obtained from the hot press and the autoclave, respectively. The microscope pictures show that there are no voids and no crack within these actuators. Once the curing pressure rises above 3 bars, cracks initiate at the PZT layer, Figure 3.7.



Figure 3.5: A cut-through of  $\left[G/\mathsf{PZT}/G/C\right]$  manufactured by a hot-press and seen through a microscope.



Figure 3.6: A cut-through of [G/PZT/G/G/C] manufactured by an autoclave and seen through a microscope.



Figure 3.7: Microscopic picture of a cracked PZT when cured at 4 bars of pressure.

To eliminate voids, some modifications were introduced during the layup. The assumption was that some of the resin was drawn to fill the gap around the edges of the PZT, thereby creating voids [4]. Gap comes from the thickness of the PZT, Figure 3.8(left). The modification was achieved with stacks of glass fabric prepreg layers were placed around the PZT in order to compensate the gap between the bottom and the top faces of the PZT layer, Figure 3.8(right). It was found that the voids were filled up, shown in Figure 3.9(left)(right), because the resin out-flow has been prevented. Figure 3.9(left) shows an actautor manufactured without stacks of glass fabric prepregs at the edges resulting voids at the interfaces.



Figure 3.8: Schematic movement of resin to the edge of the PZT (left), inserting a glass layer frame around the PZT (right).



Figure 3.9: Microscopic pictures of an actuator with voids (left) and without voids (right).

All the actuator manufacturing processes used throughout this thesis followed the same modification by inserting stacks of glass fabric prepregs layers at the edges. The curing cycle used was 125°C at 3 bars of pressure for both autoclave and hot press and the whole cycle took 3 hours[6], Figure 3.10.



Figure 3.10: A curing Cycle.

# 3.4 Actuator Configurations and Dimensions

Within this thesis, the actuators have the total dimension of 80 mm x 26 mm. The glass fabric prepregs layers and carbon prepregs layers are 80 mm x 26 mm x 70  $\mu$ m and 80 mm x 26 mm x 72  $\mu$ m, respectively, and the PZT layers are 72 mm x 24 mm x 267  $\mu$ m (length x width x thick). The PZT layer is intentionally made smaller than the whole actuator in order to protect it from the direct contact to the surrounding environment, Figure 3.11 and Figure 3.12.



Figure 3.11: Preparation concept of the actuator with copper foils. The left end is where the 5-mm tab is and the right end (opposite to the copper foils) is where the 3-mm tab is.



Figure 3.12: Schematic of the actuator, showing the 4 layers of glass fabric at the tabs.

The copper foils are used as the electric power inlet and are 60  $\mu$ m thick, therefore, they will not cause big thickness difference between the prepress. Moreover, only small part of the copper foils are required to attach to the PZT layer, Figure 3.11, as the PZT layer has already been covered by the electrode. Thus, once the electric potential is applied to the PZT layer through the copper foils, electrons will distribute over the whole PZT area via the electrode.

The 5-mm length tab where the copper foils are attached is a non-PZT part and it is a stacked of glass layers to prevent the resin out-flow, Figure 3.11 and Figure 3.12. The other tab, opposite to the copper foils end, is 3-mm long and serves the resin out-flow purpose at the other end and to protect the PZT from the outside environment. The asymmetric length of the tabs is for the clamping purposes, i.e. the 5-mm tab is clamped end. The tabs are made out of a stack of 4 layers of glass fabric. The total thickness of the 4 layers of glass at the tabs exceed the PZT thickness before curing but the total thickness of these tabs are reduced due to high applied pressure during the curing process; while the PZT thickness remains unchanged. To protect the PZT layer from the surrounding environment, the PZT width is smaller than the top and bottom layers by 1 mm at each side. Stacks of glass fabric prepregs layers are not placed along the actuator length because the allowable width left is too narrow, i.e. 1 mm wide each side. Figure 3.11 shows how the PZT layer is smaller than the whole actuator. Figure 3.12 illustrates schematic of the top and side views of an actuator.

The two tabs are located at the two ends in relative to the PZT layer. The 5-mm tab is inserted between the 2 copper foils for the symmetric purposes along the thickness, Figures 3.12 and 3.13. During the layup, the top layers are stacked together separately from the PZT layer to allow the applicability of the pressure in order to squeeze the air pockets out during the layup. The PZT layer is placed on top of the bottom layer, in this case is the glass fabric prepress layer, Figure 3.13. The stacked top layers are then lightly placed on top of the PZT layer to finish up the layup process, Figure 3.13.



Figure 3.13: Schematic of the actautor layups. The two stacks of glass layers are located at the two ends. A stacked top layers(shown as the black layers) are lightly placed on top of the PZT layer (shown as the light grey block in the middle of the actuator). The copper foils are shown as the yellowish pieces at the left end.

Material properties of a piezoelectric material, 5A4E, given by the manufacture [5] are given in a table 3.1.

Properties	PZT (5A4E)
$E_1$ [GPa]	66
$E_2$ [GPa]	66
$E_3$ [GPa]	52
$G_{12}, G_{13} \; [\text{GPa}]$	-
$\alpha_1, \alpha_2 \ [1 \ge 10^{-6} / \text{K}]$	4, 4
Coercive Field [V/m]	$1.2 \times 10^{6}$
Initial Depolarizing Field $[V/m]$	$5 \times 10^5$
Polarizing Field [V/m]	$\geq 2 \times 10^6$
Density $[kg/m^3]$	7800
Thickness $[\mu m]$	267
Piezoelectric Coefficient, $d_{31}$ , $d_{33}$ [m/V]	$-190 \times 10^{-12}, -390 \times 10^{-12},$
Coupling Coefficient, $k_{31}$ , $k_{33}$	0.35,  0.72
Curie Temperature, [°C]	350
Manufacturer	Piezo System, Inc., USA

Table 3.1: Piezoelectric material properties obtained from the piezoelectric material manufacturer.

Material properties of glass fabric and carbon unidirectional given by the manufacture are given in a table 3.2.

Properties	Glass fabric (GEP-108)	Carbon UD (USN 75B)
$E_1$ [GPa]	21.7	128.32
$E_2$ [GPa]	21.7	4
$G_{12}, G_{13}$ [GPa]	3.99,  3.99	2.5, 2.5
$\alpha_1, \alpha_2 \ [1 \ge 10^{-6} / \text{K}]$	14.2,  14.2	-6.25, 36.27
Poisson Ratio, $\mu_{12}$	0.13	0.3
Density $[kg/m^3]$	1800	1120
Thickness $[\mu m]$	70	72
Glass transition temperature $[^{\circ}C]$	112.72	112.72
Curing Temperature [°C]	125	125
Manufacturer	SK Chemicals	SK Chemicals
	Korea	Korea

Table 3.2: Material properties obtained from the manufacturers used in the models

# 3.5 Conclusions

Two different composite manufacturing concepts have been discussed with the optimization of applied pressure to the actuator in order to produce good manufacturing quality. "good manufacturing quality" means that there are no voids in the actuator and no cracks in the PZT layer. It has been discovered that void elimination in the actuators is achievable by preventing the resin out-flow around the edges of the PZT layer. This is a result from differences of the PZT layer thickness from the top and bottom prepregs layers. To prevent the out-flow issue, introduction of a stacked of glass fabric prepregs layers around the edges to compensate the difference of the PZT thickness has been proved to be a good practice. A applied pressure of 3 bars is enough to allow the resin flow and impregnate between the prepregs layers. Moreover, such processing pressure has proved to produce no voids in the adjacent layers and no crack at the PZT layer.

# References

- H. Cao and A.G. Evans. Nonlinear deformation of ferroelectric ceramics. Journal of the American Ceramic Society, 76(4):890–896, 1993.
- [2] B. Strong. Fundamentals Of Composites Manufacturing: Materials, Methods and Applications. Society of Manufacturing Engineers, USA, 2008.
- [3] S. K. Mazumdar. Composites Manufacturing: Materials, Product, and Process Engineering. CRC Press, USA, 2002.
- [4] P. Wiwattananon, T.J. Ahmed, A.W. Hulskamp, and Bersee H.E.N. Investigation of a thermoplastic alternative for lipca. 20th International Conference on Adaptive Structures and Technologies, 2009.
- [5] Piezo Systems Inc. piezoelectric coefficient (5a4e), Accessed 2/10/2012.

# Chapter 4

# Determination of Piezoelectric Material Properties

Piezoelectric materials are often operated using large input electric fields, this is because only small strains are obtained when there is a small input electric field. As a consequence of this, piezoelectric materials exhibit nonlinear output strains at large electric fields. The piezoelectric material properties for a piezoelectric material obtained from the manufacturer, such as piezoelectric coefficients, are always determined using a small input electric field and are therefore linear. If the operation range required for the piezoelectric material is beyond the small input electric field range, as will be seen later in this chapter, the linear material properties supported by the manufacturer will not adequately describe the piezoelectric material behaviour. It is therefore important to determine the properties of the piezoelectric material beyond the small input electric field range. Given the above, in this chapter we discuss the experimentally determined properties of the piezoceramic used in this research<sup>1</sup>. Knowledge of these properties is essential for understanding how the actuators, discussed in later chapters, perform.

This chapter is divided into three sections. The nonlinear piezoelectric coefficient which is the most significant property for the actuators' static performance analysis is determined in section 4.1. Piezoelectric materials behave differently under dynamic operating conditions, thus, the material properties of piezoelectric materials determined under dynamic operating conditions are discussed in the section 4.2. A set of conclusions on the static and dynamic properties of piezoelectric

<sup>&</sup>lt;sup>1</sup>As mentioned in Chapter 3, the term piezoceramic, is used to denote a subgroup of piezoelectric materials throughout this thesis, therefore, the term "piezoceramic material" will be used to refer to the specific material used for the research reported in this thesis. The term "piezoelectric" will still be used in general discussions regarding piezoelectric materials or piezoelectric material properties.

materials is given in section 4.3.

## 4.1 Static Operating Condition

Under the assumption that the applied electric field is constant over the piezoelectric thickness, in-plane expansion and contraction is produced when an electric field is applied across the thickness of the piezoelectric material. The proportionality constant that relates the input electric field to the output in-plane expansion/contraction is called a piezoelectric coefficient. The piezoelectric coefficient,  $d_{31}$ , is the major contribution to the actuator out-of-plane displacement, therefore, the nonlinear piezoelectric coefficient, denoted  $d_{31nonli}$ , was determined under the static condition.

### 4.1.1 Nonlinear $d_{31}$ Determination via Three Approaches

The nonlinear piezoelectric coefficient was determined using three approaches, one, the standard approach described in [1], plus two novel approaches which are introduced here. The two approaches were developed to replicate a situation closer to that experienced by a piezoceramic material in real applications.

The standard method for determining the nonlinear piezoelectric coefficient consists of eliminating any permanent deformation or remaining strain that may have arisen in the piezoceramic material due to the applied electric field. To achieve such goal, the piezoceramic material was discharged and the strain state was fine-tuned back to the zero strain state by applying the opposite input polarity of electric field before the application of the next higher electric field, Figure 4.1(a). The in-plane strains were measured at the input electric field peaks shown as numbers 1, 2, 3,..., n in Figure 4.1(a). In order to tune the strain state back to the zero strain state, a large magnitude electric field with opposite polarity was applied. For example, if the current positive electric field is applied at the peak number 3, the negative electric field must be applied to diminish the remaining strain that has arisen from the electric field peak number 3. To remove the remaining strain, the electric field must be fine-tuned until the strain state is lowered to  $\pm 0.03 \ \mu$ -strain [1].

In the first non standard approach the strain is allowed to remain inside the piezoceramic, while it is discharged before the application of the next higher electric field, Figure 4.1(b). This approach was introduced with the assumption that it is impossible to measure the remaining strain state of the piezoceramic material during real applications; therefore, diminishing the strain state is omitted in this approach.<sup>2</sup> Similarly to the standard approach, the strains were measured at the input electric field peaks shown as numbers 1, 2, 3,..., and n, and the piezoceramic was discharged before the next higher electric field was applied.

In the second non standard approach a similar assumption is made as that made in the second approach. In this approach, the piezoceramic material was not discharged before the next higher electric field was applied, Figure 4.1(c). The strains were measured at the input electric peaks shown as numbers 1, 2, 3,..., and n, Figure 4.1(c).

Positive and negative DC electric fields were separately applied to the piezoceramic material for all three approaches and the output strains were measured. The nonlinear piezoelectric coefficients were then determined. This allowed us to investigate the piezoceramic response to the two polarities separately.



Figure 4.1: Schematic of the applications of positive electric field through the arrows. (a) application of the electric field for a particular time step then it is discharged to a zero electric field before the application of the electric field opposing to the current polarity to fine-tune the strain back to the zero strain state, (b) application of the electric field for a particular time step then it is discharged to a zero electric field before the application of the next higher field level. (c) application of the electric field without discharging.

<sup>&</sup>lt;sup>2</sup>Note: for the research discussed in this thesis, the piezoceramic material was embedded in the composite laminates; therefore, it was impossible to remove the remaining strain state inside the piezoceramic material because it was constrained to move freely inside the composite laminate.

#### Procedures

To determine the piezoelectric material properties of the piezoceramic used in the research reported here, two strain gages were attached orthogonally in the middle of the 72 mm x 72 mm square piezoceramic material. Placing the strain gages in the middle of the piezoceramic patch was done to avoid non-homogeneous strain response at the edge that might come from cutting, Figure 4.2. Then a strain gage was attached along the horizontal x-direction of the piezoceramic patch. The horizontal strain was denoted  $\epsilon_{xx}$ . Similarly, another strain gage was attached along the vertical y-direction of the piezoceramic patch. The vertical strain was denoted  $\epsilon_{uu}$ . The copper wires of the strain gages were attached at one end to the strain gages and at the other end to the electronic inlet patch. The electronic inlet patch acted as a medium between the strain gage wires and the power inlet. The thin copper wires were attached directly to the strain gages to prevent the formation of local stresses caused by heavy wires being directly connected to the strain gages and the piezoceramic material. The piezoceramic material was freely hung from a fixture so that it would not experience any restriction with respect to free expansion and contraction. Note that the piezoelectric material used here is already poled from the manufacturer.



Figure 4.2: The two strain gages were attached in the middle of the piezoceramic patch perpendicularly to each other.

It was recommended that the electric field should be applied for at least 10 cy-

cles<sup>3</sup> to allow enough time for the piezoceramic material to respond and come to a stable state before any measurements were taken [1], for our experiments, the DC electric field was applied at each peak for 15 seconds before the strains were measured using the strain gages.

To ensure the repeatability of the measurements and the output strains, 4 to 5 experiments were carried out per approach and averaged values were determined. Once the average output in-plane strains were determined, the piezoelectric coefficients,  $d_{31}$ , were obtained from the derivative of the in-plane strain with respect to the input electric field, as shown in Equation 4.1 [2–4]:

$$d_{31} = \frac{\partial \epsilon}{\partial E} \tag{4.1}$$

### 4.1.2 Experimental Results

The nonlinear piezoceramic coefficients obtained using the three approaches will be discussed separately. The order of the presentation does not follow the proposed order from the last sub-section. The results are, instead, arranged to provide a logical explanation of the physical phenomenon.

#### Discharged Piezoceramic: Non-Zero Strain State

The five experiments of the in-plane strain-electric field response between  $\epsilon_{xx}$  and  $\epsilon_{yy}$  were identical as shown in Figure 4.3(a and b) and Figure 4.3(e and f), under a negative and positive input electric field, respectively. The jump of the strain observed between the first and the second experiment is a result of the 90° domain wall orientations. This jump is due to the large magnitude of the electric field which contributes to the permanent strain offset.

 $<sup>^{3}1</sup>$  cycle is a one period of an alternative input electric field.



Figure 4.3: Five experiments of  $\epsilon_{xx}$  and  $\epsilon_{yy}$  under the negative electric field,  $\epsilon_{xx}$  and  $\epsilon_{yy}$  correspond to (a) and (b), respectively, and under the positive electric field,  $\epsilon_{xx}$  and  $\epsilon_{yy}$  correspond to (e) and (f), respectively. The PZT is discharged but strain state were untuned back to zero. (c) shows averaged values of the last 4 experiments of  $\epsilon_{xx}$  and  $\epsilon_{yy}$ , (a) and (b), respectively, under the negative electric field. (d) shows averaged of  $\epsilon_{xx}$  and  $\epsilon_{yy}$  from the last 4 experiments obtained from (c). (g) shows averaged values of the last 4 experiments of  $\epsilon_{xx}$  and  $\epsilon_{yy}$ , (e) and (f), respectively, under the positive electric field. (h) shows averaged of  $\epsilon_{xx}$  and  $\epsilon_{yy}$  from the last 7 experiments obtained from (g). 'Ex1' refers to experiment 1 and similarly for experiments 2 to 5.

The permanent strain of the piezoceramic material can be explained using Figure 4.4. The piezoelectric response can be described by two effects, namely an intrinsic effect and an extrinsic effect, see section 2.2. Before the extrinsic and permanent strain offset are illustrated, we will introduce the simple strain-electric field response known as the intrinsic effect or "piezoelectric effect". This effect is a response of the domains inside the piezoelectric material with respect to a low magnitude applied electric field causing small and linear output strains [5]. The output strain is linear because the domain walls that move with the electric field are able to orient back to their initial state, Figure 4.4(c).



Figure 4.4: (a) illustrates randomly oriented domain and domain walls in the bulk piezoelectric material before being poled. The arrows represent the direction of the domain inside the piezoelectric material, (b) illustrates the bulk piezoelectric material is being poled with domains and domain walls oriented along with the poling direction, denoted 'P', (c) poled bulk piezoelectric material resulting in 180° domain walls orientation, same direction as the poling direction. Note that some domains are slightly reoriented back to their original orientation but still in favour of the poling direction. The poled piezoelectric is now ready for applications. During a small magnitude input electric field, the domain walls rotate with respect to the electric field and are able to orient back to their original state; (d) illustrates a 90° domain wall orientations when the bulk piezoelectric material experiences a large magnitude electric field opposing the poling direction resulting in permanent strain offset, denoted ' $\epsilon$ '. The dashed block represents the original size of the piezoelectric material before a large magnitude electric field was applied. Adapted from [6]

The extrinsic effect can be described as a nonlinear response of the 90° domain walls, sometimes called non-180° domain walls, to the large applied electric field. The extrinsic effect is shown as large magnitudes of nonlinear output strain [7]. It is believed that the origin of the nonlinearity is truly the extrinsic effect, while the nonlinearity that comes from the intrinsic contribution is very small [8]. The piezoelectric material experiences a permanent strain offset when a large magnitude electric field is enough to cause permanent 90° domain wall orientations, Figure 4.4(d). As stated by Li et al. [8] it is important to note that the nonlinearity in the piezoelectric properties could come from both intrinsic and extrinsic effects but the major contribution is derived from the extrinsic effect, while the intrinsic effect could account for a small part to the nonlinearity but the contribution is very small.

The irreversibility of the 90° domain walls is more prone to the applied electric field opposing to the polarization direction, figures 4.3(d) and(h). This is due to it being difficult for the domain walls to reorient back when they have been oriented opposing their polarization direction. Fewer 90° domain wall orientations tend to occur under the positive field compared to the negative field. This results in less pronounced permanent strain offset.

The initial strain offset stabilized from the second experiment onward, Figure 4.3(a, b, e and f). This indicated that the 90° domain walls were permanently orientated the first time the piezoceramic material experienced a high magnitude electric field. To entirely include the permanent 90° domain wall orientations into the piezoelectric coefficient, only the averaged values of the last 4 experiments were taken into consideration. Therefore, Figure 4.3(a and b) becomes Figure 4.3(c). Since  $\epsilon_{xx}$  and  $\epsilon_{yy}$  were identical, Figure 4.3(c), these strains were averaged and yielded Figure 4.3(d). Similarly to the negative case, Figure 4.3(a - f), the positive case also shows the effects of the 90° domain wall orientations except that this phenomenon is less pronounced, Figure 4.3(e - h). The last 4 experiments were taken into account, and the averaged values of  $\epsilon_{xx}$  and  $\epsilon_{yy}$  is shown in Figure 4.3(h). The nonlinear piezoelectric coefficients under positive and negative electric fields, obtained from Equation (4.1), in Figure 4.3(d) and Figure 4.3(h) are tabulated in Table 4.1 in the "Piezoceramic is discharged but strain state were un-tuned to the zero state".

Polarity	$d_{31nonli}[\mathbf{m/V}]$	Permanent Strain Offset	
Piezoceramic is discharged but strain state were un-tuned to the zero state			
Positive	$-18.89 \times 10^{-17} \times (E) -2.65 \times 10^{-10}$	$-2.64 \times 10^{-5}$	
Negative	$-2.69 \times 10^{-16} \times (E) -1.20 \times 10^{-10}$	$2.52 \times 10^{-4}$	
Piezoceramic is not discharged and strain state were un-tuned to the zero state			
Positive	$-15.66 \times 10^{-17} \times (E) -2.58 \times 10^{-10}$	$-3.41 \times 10^{-5}$	
Negative	$-3.13 \times 10^{-16} \times (E) -1.57 \times 10^{-10}$	$2.42 \times 10^{-4}$	
Standard Method			
Positive	$-3.18 \times 10^{-16} \times (E) -2.88 \times 10^{-10}$	$-6.13 \times 10^{-6}$	
Negative	$-3.10 \times 10^{-16} \times (E) -4.08 \times 10^{-10}$	$1.46 \times 10^{-7}$	

Table 4.1: Nonlinear piezoelectric coefficient,  $d_{31nonli}$ , and initial strain in the piezoceramic from three approaches. 'E' represents the electric field. Note that: throughout all the three cases, the piezoelectric coefficient showed a negative sign. This is because a piezoceramic contracts in the in-plane direction when a positive electric field is applied along the piezoelectric material's thickness direction while it expands in the in-plane direction under negative polarity. It has no mathematical meaning.

#### Non-Discharged Piezoceramic: Non-Zero Strain State

Figure 4.5 exhibits trend of the strain-electric field similar to the previous case. The permanent strain offset is shown as a jump of the starting strain. This indicates that the 90° domain wall orientations exist in this case. Similarly to the previous part, the averaged  $\epsilon_{xx}$  and  $\epsilon_{yy}$  from the last 4 experiments under negative and positive fields are separately shown in Figure 4.5(a) and Figure 4.5 (b) respectively. The nonlinear piezoelectric coefficients are presented in the Table 4.1 in the "Piezoceramic is not discharged and strain state were un-tuned to the zero state".



Figure 4.5: Averaged of  $\epsilon_{xx}$  and  $\epsilon_{yy}$  from the last 4 experiments. (a) under the negative electric field. (b) under the positive electric field. The PZT was not discharged and strain state were un-tuned back to zero. Note that the representation of (a) and (b) in this figure is similar as the case in Figure 4.3(d) and Figure 4.3(h). The representation of all 5 experiments similar to the case of Figure 4.3(a, b c, e, f and g) are omitted in this figure.

These trends are similar to the previous case. This indicates that the permanent strain offset remains from both charging conditions as long as the strain state is not adjusted to zero. The permanent strain offset that comes from the 90° domain wall orientations still remains. The strain state can be adjusted back to zero by reorienting the 90° domain walls back to their original state.

When the strain state remains permanently, the nonlinear term under the negative electric field is greater than the one under the positive field, as seen from the first two cases in Table 4.1. These apply to both charging conditions. The greater nonlinear term under the negative electric field is due to the greater irreversible  $90^{\circ}$  domain wall orientations occur under the negative field than under the positive field. The nonlinear term represents the extrinsic effect [8], which can be seen as a result of the  $90^{\circ}$  domain wall orientations effect.

In contrast, the linear term under the negative electric field is smaller than under the positive field, as can be seen from the first two cases in Table 4.1, because the linear term consists of both piezoelectric effect and  $90^{\circ}$  domain wall orientations [9]. This can be explained by the fact that greater amount of the domain walls have already contributed to the  $90^{\circ}$  domain wall orientations, as shown in the larger nonlinear term. Therefore, a reduced contribution from the  $90^{\circ}$  domain wall orientations can contribute to the linear term. The linear term is largely contributed by the piezoelectric effect, which is always smaller than the contribution from the  $90^{\circ}$  domain wall orientations.

#### Discharged Piezoceramic: Zero Strain State (standard method)

The standard method to determine the nonlinear piezoelectric properties is completed by discharging the piezoceramic and diminishing of the 90° domain wall orientations before the application of the next higher electric field. This resulted in a very small permanent strain offset under both negative and positive fields, as shown in Figures 4.6(a) and 4.6(b).

Since the 90° domain wall orientations are diminished under both electric field polarities, the nonlinear terms of the piezoelectric coefficient are comparable under both polarities, as seen in the third case in Table 4.1. In contrast, the linear term of the piezoceramic coefficient under the negative electric field is greater than the one under the positive field. This is due to the fact that the domain walls contributed more to the linear term than the nonlinear term. Initially, majority of these domain walls should contribute to the nonlinear term rather than the linear term, this is a consequence of the strain state which was diminished back to zero. As can be observed from the previous two cases, the nonlinear term in the negative polarity is always larger than the one in the positive polarity because the negative polarity is more prone to the  $90^{\circ}$  domain wall orientations than the positive polarity.



Figure 4.6: Averaged of  $\epsilon_{xx}$  and  $\epsilon_{yy}$  from the last 4 experiments. (a) under the negative electric field. (b) under the positive electric field. The PZT was discharged and strain state was tuned back to zero. Note that the representation of (a) and (b) in this figure is similar as the case in Figure 4.3(d) and Figure 4.3(h). The representation of all 5 experiments similar to the case of Figure 4.3(a, b c, e, f and g) are omitted in this figure.

### 4.1.3 Comparison of the Three Approaches

The piezoelectric coefficient  $(d_{31})$  obtained from the piezoelectric material manufacturer was  $-190 \times 10^{-12}$  [m/V], while the linear terms obtained within this study were all greater than  $-190 \times 10^{-12}$  [m/V]. This was due to the fact that within this study, the linear terms consist of both the piezoelectric effects and 90° domain wall orientations because the applied electric field was large enough to cause extrinsic effects to the piezoceramic. Moreover, the electric field magnitude that the manufacturers often use to determine the piezoelectric coefficient is small and causes only the piezoelectric effect and does not cause the extrinsic effect, or the 90° domain wall orientations. In fact, if one wants to produce a purely piezoelectric effect, a magnitude of electric field as low as 10V/mm has been suggested [8].

It can be observed from Table 4.1 that regardless of the charging or discharging conditions, while the permanent strain state remains, the magnitudes of the linear and nonlinear terms are comparable and of the same order of magnitude. In addition, the permanent strain offsets of both cases are of the same order of magnitude, while the permanent strain offset under the negative electric field is larger than the one under the positive field. These result support the previous discussions: the 90° domain wall orientations largely influence the piezoelectric response when

a large electric field is applied. The reason for the fact that the linear term of the positive polarity is smaller than that for the negative one can be explained by the fact that the negative field influences more to the 90° domain wall orientations than the positive field.

The effect of the 90° domain wall orientations contribute more to the negative polarity than to the positive, which can be observed from the standard case. Tuning the strain inside the piezoelectric material back to its zero state will cause the contribution of the 90° domain wall orientations in the nonlinear terms to be similar under both polarities. The influence of the 90° domain wall orientations contribute more in the linear term under the negative polarity, i.e. a larger linear term for the negative polarity, while the strain offsets from both polarities are very small. This indicates that it is harder to remove the 90° domain wall orientations effects under negative polarity than under a positive one.

It can be observed that the nonlinear terms of the standard approach for both polarities are larger when compared to the other two cases. This can be explained by the fact that the strain state was tuned back to its zero state, causing the domain walls to be forced to come back as close to the initial state as possible. This results in greater chance for the domain walls to respond fully to the electric field and contribute largely to the 90° domain wall orientations which resulted in larger nonlinear terms than when the strain states were not forced to come back to their initial state.

### 4.1.4 Conclusions

The above discussions show that piezoceramic materials exhibit nonlinear output strains depending on the magnitude of the applied electric field. These relationships are represented as nonlinear piezoelectric coefficient  $d_{31nonli}$ . The  $d_{31nonli}$  were determined using three approaches: one followed a standard approach [1] the other two approaches were developed to replicate real applications.

The two non-standard methods exhibit similar behaviour and show obvious asymmetric permanent strain offsets in the piezoelectric material, and these phenomena show in both positive and negative polarities. A slight asymmetric behaviour is shown in the standard method and the degree of the asymmetry is smaller than the two non-standard methods. The permanent strain offset is more pronounced under the negative polarity than the positive one. The permanent strain offsets are developed by large magnitude of applied electric fields regardless of the charging conditions as long as the strain state remains inside the piezoelectric material. To diminish the permanent strain offsets, large magnitude of the electric field oppos-
ing to the currently applied electric field polarity must be applied to reorient the permanent  $90^{\circ}$  domain wall orientations back to their original state.

## 4.2 Dynamic Operating Condition

Two piezoelectric properties, the dielectric permittivity and the piezoelectric coefficient, of the piezoelectric material were experimentally determined under dynamic operating conditions. Elastic compliance, which is the third necessary property for the dynamic behaviour study, was not determined experimentally due to a lack of appropriate equipment being available during the time the research was conducted. Despite a lack of the equipment, an elastic compliance could be determined using the Taylor's series expansion relationship. The experiments were conducted at the Ceramic Laboratory of the École polytechnique fédérale de Lausanne, Switzerland.

#### 4.2.1 Dielectric Permittivity: A Function of Input Voltage and Frequency

The application of an electric field to a piezoelectric material produces interaction between the applied charge and the electric dipoles. The electric dipole rotations cause electric displacement and is measured across the piezoelectric thickness. The proportionality constant between the input electric field and the output electric displacement is called dielectric permittivity, denoted  $\epsilon$ . The dielectric permittivity,  $\epsilon_{33}$ , as a function of input voltages <sup>4</sup> and frequencies of input sinusoidal signal were determined using two pieces of equipment: 1) a HEWLETT PACKARD 4284A Precision LCR meter, and 2) a Sawyer-Tower Ferroelectric Loop Measurement instrument. The LCR meter was used to determine the dielectric permittivity of the piezoelectric material at a lower voltage, and the Sawyer-Tower instrument was used to determine the dielectric permittivity of the piezoelectric material at higher voltage. The dielectric permittivity,  $\epsilon_{33}$ , is the permittivity measured along the piezoelectric material's thickness direction, i.e. denoted the second subscript '3', while the electric field is applied along the piezoelectric material's thickness direction, i.e. denoted the first subscript '3'.

The dielectric permittivity decreased as the input sinusoidal frequency increased, Figure 4.7. The reduction of the  $\epsilon_{33}$  with respect to the input sinusoidal frequency has been observed by many researchers [10–12]. The reduction is due to the fact

<sup>&</sup>lt;sup>4</sup>Note that the unit of the input voltage is Volt in the case of the dynamic conditions and the unit of the electric field is V/m for the static condition. Electric field =  $\frac{V}{t}$ . V is the voltage and t is the piezoceramic thickness.

that the domain walls of the piezoelectric material are not able to respond correspondingly at high input voltage frequencies. This results in a delayed response of the domain wall motions at high frequencies [8, 13, 14]. Generally speaking, only those domain walls that can keep up with the pace of the changing of input voltage frequencies contribute to the output dielectric permittivity. As a result, polarization will be lower at higher input voltage frequencies. As shown in Table 4.2, the rate of change (slope) of the dielectric permittivity with respect to frequency decreases as input voltage frequency increases, Figure 4.7. This reduction is due to the lower response of the domain walls.



Figure 4.7:  $\epsilon_{33}$  at various input voltages and frequencies

Frequency [Hz]	$\epsilon_{init}[\mathbf{F/m}]$	slope
40	$2.05 \times 10^{+3}$	11.06
70	$2.11 \times 10^{+3}$	7.56
120	$2.10\times10^{+3}$	7.76
220	$2.09\times10^{+3}$	7.31
400	$2.08 \times 10^{+3}$	7.13
600	$2.07 \times 10^{+3}$	6.72
700	$2.07 \times 10^{+3}$	6.65
1000	$2.06 \times 10^{+3}$	6.99

Table 4.2: Initial dielectric permittivity  $\epsilon_{33}$  and their slopes at various input voltages and frequencies

In contrast to input voltage frequency, dielectric permittivity increases linearly as the input voltage increases [8]. Within this thesis, the interesting frequency range of the dielectric permittivity is up to 70 Hz to cover up to the first resonance frequency of the actuators. The averaged value of the dielectric permittivity  $\epsilon_{33}$  as a function of input voltages at 40 and 70 Hz is given below:

$$\epsilon_{33} = 2077 + 9.3085 \cdot V \tag{4.2}$$

The domain walls are greatly influenced by the input electric field and by the mechanical stress applied. From this reason, dielectric permittivity will therefore change with respect to the mechanical stress as observed by many researchers [2, 10, 12, 15]. In order to take the effects of mechanical stress into account; the slope of the  $\epsilon_{33}$ , Equation 4.2, therefore, will be varied in addition to the input voltage. The  $\epsilon_{33}$  equation can be written as follows:

$$\epsilon_{33} = 2077 + \alpha \cdot V \tag{4.3}$$

The variable  $\alpha$  is a function of the mechanical stress experienced by the piezoceramic material inside the actuator and V is the input voltage.

#### 4.2.2 Piezoelectric Coefficient: A Function of Input Voltage and Frequency

Out of plane displacement from the piezoelectric material is produced with the application of the electric field across the piezoelectric material's thickness. The piezoelectric coefficient,  $d_{33}$ , was determined as a function of input voltage and frequencies using an optical approach and an MTI-2000 Fotonic Sensor. The fotonic sensor contained one pair of fiber optic level displacement sensors located in a probe. One of the fiber optics was light-transmitting and the other light-receiving. The operating mechanism is based on the the interaction between the field of illumination of the transmitting, or source fibers, and the field of view of the receiving or detector fibers, see Figure 4.8. An increase in the probe-to-target distance, resulting from the out of plane displacement of the piezoelectric material, will result in some reflected light being captured by the receiving fiber, and the out-of-plane displacement of the piezoelectric material.



Figure 4.8: Displacement sensing mechanism of adjacent fiber-optic elements.

Figure 4.9 shows the piezoelectric coefficient  $d_{33}$  as a function of peak-to-peak input voltage <sup>5</sup> and frequencies up to 70 Hz, Figure 4.9(top), and up to 720 Hz, Figure 4.9(bottom). The piezoelectric coefficient  $d_{33}$  has a direct relationship to the input voltage, i.e. the larger the input voltage, the larger the  $d_{33}$ . This is a result of the greater response of the domain wall movements in the piezoelectric material at a higher input voltage [8]. Moreover, the slope and magnitude of the  $d_{33}$  response decreases with increasing of the frequency, Figure 4.9(bottom). The reduction of  $d_{33}$  with respect to the input frequency has also been observed by Perrin et al. [16]. This reduction of  $d_{33}$  with respect to the input frequency was reported to be due to the difficulties the domain wall motions had in keeping pace with the changing input voltage frequency [17]. The scatter of the  $d_{33}$  values and the  $d_{33}$  at a small voltage shown in Figure 4.9(below) are due to noise such as electronic equipments during the experiments.

 $<sup>^5\</sup>mathrm{The}$  peak-to-peak input voltage (Vpp) is the summation of two peaks from the sinusoidal signal.



Figure 4.9:  $d_{33}$  at various input voltages and frequencies, Vpp is the peak-to-peak value of the AC input voltage with a sinusoidal signal.

The  $d_{33}$  shows a linear relationship with the input voltage up to a large input voltage amplitude of 70V, or 140 Vpp, in Figure 4.9. In contrast to the dynamic condition, the piezoelectric coefficient determined using the DC input electric field shows a nonlinear relationship between the piezoelectric coefficient and the input DC electric field up to an identical voltage amplitude of 70V, see section 4.1. This can be explained by the fact that, when an AC sinusoidal signal is applied, some of the domain walls are forced back to their original state along with the alternating field. When a DC field is applied as shown in section 4.1, in contrast, the domain walls are not forced to reorient back to their original state. The permanently oriented domain walls, when the DC field is applied, therefore contribute to a greater nonlinear response when compared to those that are partially reoriented back to the original state under an AC field. This explains why the  $d_{33}$  shows a linear relationship with the input voltage up to a large input voltage amplitude of 70V.

under the application of an AC electric field but it is a nonlinear relationship under the application of a DC electric field.

Within this research, the interesting frequency range is up to 70Hz, therefore, the averaged value of  $d_{33}$  as a function of input voltage (V) in the frequency range from 1 - 70 Hz is:

$$d_{33} = 359.38 + 1.21165 \cdot V \tag{4.4}$$

The  $d_{31}$  value was determined by assuming that it is half of the  $d_{33}$  as given from the manufacturer [18]. The slope of the  $d_{33}$  remains the same because it represents the rate of change of the out of plane displacement as a function of input voltage. From this reason, the rate of change of the in-plane displacement as a function of input voltage, denoted  $d_{31}$ , will be the same. Therefore, it is:

$$d_{31} = -179.69 + 1.21165 \cdot V \tag{4.5}$$

The discussion in section 4.2.1 shows that the domain walls are affected by stresses; similarly, the piezoelectric coefficients depend on the electric field and on the stresses [2, 10, 15, 19–25]. As a result, the  $d_{31}$  in Equation 4.5 may be written as follows:

$$d_{31} = -179.69 + \beta \cdot V \tag{4.6}$$

The variable  $\beta$  varies in a function of the mechanical stress experienced by the piezoelectric material inside the actuator.

#### 4.2.3 Mechanical Compliance: A Function of Input Voltage and Frequency

When a piezoelectric material is under stressed, strain is produced. At a lower range of the stress-strain curve, the linear relationship is called a modulus  $[N/m^2]$ . The reciprocal of the modulus is called a mechanical compliance or an elastic compliance  $[m^2/N]$ . Due to a lack of available equipment, the mechanical compliance values were not determined experimentally for the research reported here. Since knowledge of the mechanical compliance of the piezoceramic used in this research was required for the study reported in Chapters 7 and 8; a Taylor's series expansion and a piezoelectric material resonance frequency equation are used to demonstrate the mathematical relationship of the mechanical compliance as a function of input voltage and mechanical stress. It is known from literatures [26–28] and it will be observed experimentally in the Chapter 8 that the piezoelectric's resonance frequency reduces with increasing voltages. The relationship between the mechanical compliance  $s_{11}^E$  and the resonance frequency response  $f_R$  of a rectangular piezoelectric material is shown in Equation 4.7 [29, 30]. The superscript 'E' of the term  $s_{11}^E$  demonstrates that the compliance value is determined at a constant electric field [1]:

$$f_R \propto \frac{1}{2L\sqrt{\rho \cdot s_{11}^E}} \tag{4.7}$$

As the magnitude of mechanical compliance  $s_{11}^E$  increases, the resonance frequency response  $f_R$  decreases as can be seen from Equation 4.7. The variables L is the length of the piezoelectric material,  $\rho$  is the piezoelectric material density. From a Taylor's series expansion [31]:

$$f(x) = \frac{1}{(1+x)^n} \approx 1 - n \cdot x + \dots$$
 (4.8)

The equation 4.7 can be written as a function of an input voltage and with a proof from a Taylor's series expansion as:

$$f(V)_R = \frac{1}{2L\sqrt{\rho \cdot s_{11}^E}} = \frac{1}{C\sqrt{s_{11}^E}} = \frac{1}{C\sqrt{s_{11}^0 + \gamma \cdot V}} \approx A - B \cdot V \qquad (4.9)$$

The variable C represents the parameter  $2L\sqrt{\rho}$ , A and B are variables. The equation 4.9 proved that in order for the piezoelectric material resonance frequency to reduce as the input voltage increases, the piezoelectric material mechanical compliance must be in a function of an input voltage. Thus, from the above derivation, the piezoelectric material mechanical compliance can be written as:

$$s_{11} = s_{11}^0 + \gamma \cdot V \tag{4.10}$$

where  $s_{11}^0$  is the initial elastic compliance without the influence of input voltage and mechanical stress and  $\gamma$  is a constant that relates how compliance changes with mechanical stress inside the piezoceramic layer. The above derivation implies that the elastic compliance increases at greater input voltage resulting in decreases in the frequency response.

#### 4.2.4 Conclusions

The dielectric permittivity and piezoelectric coefficient of the piezoceramic material used in the research presented here were determined experimentally under dynamic operating condition. It was demonstrated that these two properties show a dependency on input voltage and frequency of a sinusoidal signal. Dielectric permittivity and the piezoelectric coefficient increase with higher input voltages but decrease at higher frequencies. Since the piezoceramic material is exposed to mechanical stresses inside the actuator, coefficients that relate these two properties to the mechanical stress were introduced. Mechanical compliance as a function of input voltage and mechanical stress can be theoretically obtained using the relationships between dielectric permittivity and the piezoelectric coefficient.

### 4.3 Conclusions

The piezoelectric material properties of the piezoceramic material used in our research were determined experimentally under static and dynamic operating conditions. It was observed that, under both operating conditions, the piezoelectric material properties were a function of the input voltage. This phenomenon originated from the domain wall orientations with changes of the input voltage.

Under static conditions, regardless of the charging conditions applied to the piezoelectric material, as long as the strain state remains inside the piezoelectric material, the irreversible domain wall orientations will cause large magnitude of permanent strain offsets in the piezoelectric material. These strain offsets are asymmetric between positive and negative polarities and the magnitude is more pronounced under negative voltage.

Under dynamic conditions, in addition to the input voltage, the domain walls exhibit frequency dependency, i.e. the response decreases as the input sinusoidal voltage frequency increases. This was explained with the fact that the the domain walls are incapable continuing to respond at a high frequency pace. Moreover, mechanical stress dependency factors have been introduced into the piezoelectric properties which relate the output piezoelectric properties such as piezoelectric coefficient, dielectric permittivity and mechanical compliance, to input mechanical stress. These mechanical stress factors will be used in Chapter 8 to investigate to what extend these material properties change according to the internal mechanical stress applied to the piezoeramic material inside the actuator.

## References

- [1] J. Sirohi and I. Chopra. Fundamental behavior of piezoceramic sheet actuators. Journal of intelligent material systems and structures, 11(1):47–61, 2000.
- [2] Helmut H. A. Krueger. Stress sensitivity of piezoelectric ceramics: Part 1. sensitivity to compressive stress parallel to the polar axis. The Journal of the Acoustical Society of America, 42(3):636–645, 1967.
- [3] H. Jaffe and D.A. Berlincourt. Piezoelectric transducer materials. Proceedings of the IEEE, 53(10):1372–86, 1965.
- [4] B. Jaffe, W.R. Cook, and H.L. Jaffe. *Piezoelectric ceramics*. Non-metallic solids. Academic Press, 1971.
- [5] G. Li, E. Furman, and G.H. Haertling. Stress-enhanced displacements in plzt rainbow actuators. *Journal of the American Ceramic Society*, 80(6):1382– 1388, 1997.
- [6] RG Ballas. Piezoelectric multilayer beam bending actuators and aspects of sensor integration, 2007.
- [7] DA Hall. Review nonlinearity in piezoelectric ceramics. Journal of materials science, 36(19):4575-4601, 2001.
- [8] S. Li, W. Cao, and LE Cross. The extrinsic nature of nonlinear behavior observed in lead zirconate titanate ferroelectric ceramic. *Journal of applied physics*, 69(10):7219–7224, 1991.
- [9] A. Pramanick, D. Damjanovic, J.E. Daniels, J.C. Nino, and J.L. Jones. Origins of electro-mechanical coupling in polycrystalline ferroelectrics during subcoercive electrical loading. *Journal of the American Ceramic Society*, 94(2):293–309, 2011.
- [10] P.M. Chaplya and G.P. Carman. Dielectric and piezoelectric response of lead zirconate-lead titanate at high electric and mechanical loads in terms of non-180 domain wall motion. *Journal of Applied Physics*, 90:5278, 2001.
- [11] JE Garcia, R. Perez, DA Ochoa, A. Albareda, MH Lente, and JA Eiras. Evaluation of domain wall motion in lead zirconate titanate ceramics by nonlinear response measurements. *Journal of Applied Physics*, 103:054108, 2008.

- [12] V. D. Kugel and L. E. Cross. Behavior of soft piezoelectric ceramics under high sinusoidal electric fields. *Journal of Applied Physics*, 84(5):2815–2830, 1998.
   Cited By (since 1996): 47 Export Date: 25 October 2012 Source: Scopus.
- [13] D.E. Dausch. Asymmetric 90 domain switching in rainbow actuators. *Ferro-electrics*, 210(1):31–45, 1998.
- [14] G.H. Haertling. Stress-induced effects in plzt ceramics. In Applications of Ferroelectrics, 1996. ISAF'96., Proceedings of the Tenth IEEE International Symposium on, volume 1, pages 65–68. IEEE, 1996.
- [15] H.H.A. Krueger. Stress sensitivity of piezoelectric ceramics: part 3. sensitivity to compressive stress perpendicular to the polar axis. The Journal of the Acoustical Society of America, 43:583, 1968.
- [16] V. Perrin, M. Troccaz, and P. Gonnard. Non linear behavior of the permittivity and of the piezoelectric strain constant under high electric field drive. *Journal of Electroceramics*, 4(1):189–194, 2000. Cited By (since 1996): 14 Export Date: 25 October 2012 Source: Scopus.
- [17] AJ Masys, W. Ren, G. Yang, and BK Mukherjee. Piezoelectric strain in lead zirconate titante ceramics as a function of electric field, frequency, and dc bias. *Journal of applied physics*, 94:1155, 2003.
- [18] Piezo Systems Inc. piezoelectric coefficient (5a4e), Accessed 2/10/2012.
- [19] D. Damjanovic and M. Demartin. The rayleigh law in piezoelectric ceramics. Journal of Physics D: Applied Physics, 29:2057, 1996.
- [20] D. Damjanovic and M. Demartin. Contribution of the irreversible displacement of domain walls to the piezoelectric effect in barium titanate and lead zirconate titanate ceramics. *Journal of Physics: Condensed Matter*, 9:4943, 1997.
- [21] D. Damjanovic. Stress and frequency dependence of the direct piezoelectric effect in ferroelectric ceramics. *Journal of applied physics*, 82:1788, 1997.
- [22] Q. M. Zhang, J. Zhao, K. Uchino, and J. Zheng. Change of the weak-field properties of pb(zrti)o3 piezoceramics with compressive uniaxial stresses and its links to the effect of dopants on the stability of the polarizations in the materials. *Journal of Materials Research*, 12(1):226–234, 1997. Cited By (since 1996): 84 Export Date: 25 October 2012 Source: Scopus.

- [23] G. Yang, S. F. Liu, W. Ren, and B. K. Mukherjee. Uniaxial stress dependence of the piezoelectric properties of lead zirconate titanate ceramics. In *Applications of Ferroelectrics, 2000. ISAF 2000. Proceedings of the 2000 12th IEEE International Symposium on*, volume 1, pages 431–432, 2000.
- [24] S. W. Meeks and R. W. Timme. Effects of one-dimensional stress on piezoelectric ceramics. *Journal of Applied Physics*, 46(10):4334–4338, 1975. Cited By (since 1996): 9 Export Date: 25 October 2012 Source: Scopus.
- [25] F. Xu, S. Trolier-McKinstry, W. Ren, B. Xu, Z. L. Xie, and K. J. Hemker. Domain wall motion and its contribution to the dielectric and piezoelectric properties of lead zirconate titanate films. *Journal of Applied Physics*, 89(2):1336– 1348, 2001. Cited By (since 1996): 208 Export Date: 25 October 2012 Source: Scopus.
- [26] K. Mossi, Z. Ounaies, R. Smith, and B. Ball. Prestressed curved actuators: characterization and modeling of their piezoelectric behavior. *Smart Structures and Materials 2003*, 5053:423–435, 2003.
- [27] S.C. Woo, K.H. Park, and N.S. Goo. Influences of dome height and stored elastic energy on the actuating performance of a plate-type piezoelectric composite actuator. *Sensors and Actuators A: Physical*, 137(1):110–119, 2007.
- [28] Z. Ounaies, Institute for Computer Applications in Science, and Engineering. Low-field and high-field characterization of THUNDER actuators. ICASE, NASA Langley Research Center, 2001.
- [29] The Institute of Electrical and Inc Electronics Engineers. Ieee standard on piezoelectricity, 1988.
- [30] Uchino K. The development of piezoelectric materials and the new perspective. Advanced piezoelectric materials Science and Technology. Woodhead Publishing Limited, UK, 2010.
- [31] http://www.haverford.edu/physics. Taylor series, 22/08/2013.

# Chapter 5

# Finite Element Model of Actuators: Under Static Condition

In Chapter 3 we discussed how the thermal stresses that develop during the manufacturing process remain inside the actuators; and these thermal stresses have been shown to influence the actuators' performance, as discussed in Chapter 2. The notable nonlinear phenomenon in the piezoelectric material that occurs when a large magnitude electric field is applied to the piezoelectric material was discussed in Chapter 4. A finite element static model that can be used to predict an actuator's static performance will be described in this chapter. The thermal stresses and nonlinear phenomenon in the piezoelectric material are included in the model to improve its prediction accuracy. The chapter is divided into four sections. An overview of finite element models developed for THUNDERs and LIPCAs, the two similar types of actuators used in this research, will be discussed in section 5.1. A model to predict the manufactured shape of the actuators is discussed in subsection 5.2.1, followed by a discussion of a model that can be used to predict the actuation displacements in subsection 5.2.2. The thermal stresses discussed in subsection 5.2.1 are transferred as initial stresses for the static model in subsection 5.2.2., and the nonlinear piezoelectric coefficient and the permanent residual strain offset in the piezoelectric material obtained from section 4.1 are introduced into the static model. An experimental setup for static measurements will be explained in section 5.3. A brief conclusion on the finite element model that can be used to determine manufactured shape of the actuators and the static displacement predictions is given in section 5.4.

## 5.1 Overview of the Finite Element Models of THUNDERs/LIPCAs

The advantage of using the finite element method over an analytical approach to determine approximate solutions to partial differential equations is that it allows the geometries and shape of any device or structure to be analyzed. The basis of finite element analysis(FEA) is that any continuous functions can be approximated by discretization over the volume of the geometry of an object. The volume of the object is divided into elements, and at each vertex of an element, known as a node, a number of independent variables which represent the degree of freedom are present.

The finite element method has been used to predict the manufactured shape and the actuation response of stress-biased actuators such as THUNDER [1] and [2, 3]. Stress-biased actuators exhibit considerable curvature once the LIPCA curing process at elevated temperature has taken place as thermal stresses develop inside the actuators. The curvature is a result of the differences in the coefficients of thermal expansion of the different materials used to build the actuators, and these thermal stresses, inherent in the actuator, have been shown to make a contribution to the performance of an actuator [4–8]. When building a stress-biased actuator model the thermal stresses and the piezoelectric effect must be coupled in the model to predict the actuation behaviour of such stress-biased actuators. A number of finite element models have been developed to model stress-biased actuators, such as THUNDERs and LIPCAs, based on ANSYS [1, 2], NASTRAN [1, 9] and ABAQUS [3]. The linear finite element model largely under predicted the actuation response of the THUNDER [1], however, the prediction properties of the models have been improved by applying a NASTRAN nonlinear finite element model [9].

Taleghani and Campbell [9] compared a manufactured dome height obtained using NASTRAN and a non-linear plate solution incorporating von Karman's strain approximation for THUNDER. The dome height comparisons between NASTRAN and the nonlinear plate solution were in the range 3-16%. The comparisons between NASTRAN and measurements of the dome height was in the range 0-26%, while the actuation displacements were in the range 0 - 22%. Taleghani [1] has compared NASTRAN and ANSYS to predict the actuation displacements of THUNDER. The thermal analogy, see Appendix A, was used in the NASTRAN, while in the ANSYS model the piezoelectric finite elements were used directly. The NASTRAN and ANSYS showed comparable percentages for errors of manufactured dome height when compared to the measurements, NASTRAN showed a 1 -

10% error, while ANSYS showed a 2 - 12% deviation from the experimental data. Taleghani [1] has extended these comparisons to the actuation displacements for various actuators' dimensions and input voltage ranges, here NASTRAN gave a 0-53% error range, while ANSYS gave a 6 - 188% error range [1].

Freed and Babuska [10] discuss a limitation of the application of thermal analogy used to calculate the voltage loads in the piezoelectric layer in NASTRAN in their 1997 publication. If multiple layers of piezoelectric materials are attached together; the thermal analogy is restricted to identical piezoelectric coefficients [10].

Spencer [11] discusses the limitations of ABAQUS for predicting the piezoelectric strain in actuation devices, these are: piezoelectric constants depending on the voltage applied, hysteresis effects and the residual strain offset inside the piezoelectric materials after a large magnitude voltage has been applied.

#### Finite Element Model: COMSOL

The COMSOL Multiphysics model provides a number of physics interfaces which consist of predefined partial differential equations, PDEs, and variables for specific areas of physics [12]. The physics interfaces consist of a number of features in domains and on boundaries, edges, and at points with predefined PDEs [12]. Each physics interface forms one or several PDEs and boundary conditions from these settings. In addition to the predefined PDEs, the model allows an equation-based modeling interface, and equation coefficients can be directly defined. The model collects all the equations and boundary conditions formulated by the physics interfaces into one large system of PDEs and boundary conditions and solves the system using a weak formulation.

In the following section, descriptions of the static model of the actuators used in this research will be presented. The model includes two sub-coupled models: one presenting the manufacturing shape predictions, and a second sub-model which is used to predict the actuation displacements under a static input electric voltage.

### 5.2 Static Model of Actuators

The 2D finite element models of actuators reported in this research were developed using finite element software called COMSOL Multiphysics, version 4.2. The snap-through effect, in which a laminate's curvature changes from one sign to the opposite, i.e. positive to negative curvature or vice versa, is a result of the geometric nonlinearity of an actuator, which has been shown to depend on an actuators' geometry, i.e. actuators with an aspect ratio greater than 0.33 are more prone to exhibit the snap-through effect [3]. Warping due to an asymmetric layup of actuators has also been shown to influence the snap-through effect [3].

The actuators' aspect ratio used in this research was 0.32, therefore, the snapthrough effect due to geometric nonlinearity did not play a role [3], this also reduced the warping of the asymmetric layup actuators so that it ceased to be significant. Thus, using a 2D model to model the actuators used in this research was sufficient to capture the static actuation displacements. Had the asymmetric layup actuators used in this research exhibited large warping as a result of a large aspect ratio, a 3D model would have been necessary to capture the displacements at various locations along the actuators' width.

The finite element model is comprised of two sub-models with two coupled physics. The first sub-model is used to compute the manufactured shape of an actuator after is has gone through the manufacturing process using solid mechanics (solid) physics. The second sub-model computes the actuation displacements of the actuator when electric potential is applied to an actuator using piezoelectric device (pzd) physics. The piezoelectric material used in this research was covered with a thin layer of electrode to distribute electric charges over the whole face of the piezoelectric material. It was considered that the thin layer of electrode material was of little consequence to the mechanics of the actuator; therefore, the electrode was omitted from the model [13]. Since an actuators' thickness is very thin compared to its in-plane dimension, the plane stress type could be assumed in the two sub-models. To predict the manufactured shape of an actuator, the boundary condition was simply-supported to allow free deformation of the actuator resulting in a considerable curvature observed as a dome shape, Figure 5.1.



Figure 5.1: A simply-supported boundary condition of an actuator. The flat beam represents a flat actuator before manufacturing. The curved shape represents the actuator after manufacturing, u is the displacement along the x-axis, v is the displacement along the y-axis.

#### 5.2.1 Manufacturing Model

The principle of virtual work was used to solve for the actuator's stress at the deformed geometry. <sup>1</sup> The principle of virtual work states that the internal virtual work must be equal to the external virtual work or the work resulting from the external body forces. When attempting to solve the principle of virtual work one first needs to determine the external forces acting at the body, e.g. body force, surface force and virtual displacement of the body. The virtual strain can be determined, when the virtual displacement of the body is known. The Cauchy stresses, which represent the physical stress of the body at the deformed geometry can be solved in correspondence to the virtual strain.

Since the actuators used in this research exhibited large out-of-plane displacement, the geometric nonlinearity of the actuator was taken into account. In the geometric nonlinearity, the normal stress tensor was replaced with a second Piola-Kirchhoff stress and the normal strain tensor was replaced with a Green-Lagrange strain and the problem was solved using a total Lagrangian formulation [12]. The second Piola-Kirchhoff stress was introduced to transform the stress and deformation state of the material at the deformed configuration, time t or  $t + \Delta t$ , to the material initial or undeformed configuration, time 0. Similarly, the Green-Lagrange strains were defined with reference to the material initial configuration.

The constitutive thermoelastic equation by Duhamel-Hooke's law relates the stress tensor to the strain tensor and temperature can be written as:

$$\sigma = \sigma_0 + C : (\epsilon - \epsilon_0 - \alpha \Delta T) \tag{5.1}$$

where  $\sigma$  is the Cauchy stress at the deformed geometry,  $\sigma_0$  is the initial stress such as stresses from the previous analysis,  $\epsilon$  is the nonlinear strain at the deformed geometry,  $\varepsilon_0$  is the initial strain such as strain from previous analysis,  $\Delta T = T - T_{REF}$ . T is the elevated temperature and  $T_{REF}$  is the reference temperature and it is the room temperature, C is the 4<sup>th</sup> order elasticity tensor, : stands for a double-dot tensor product, or a double contraction,  $\alpha$  is the coefficient of thermal expansion, CTE.

The manufactured shape of an actuator is influenced by thermal effects due to differences in the CTE of different materials. The stresses result from the glass transition temperature, which is the stress-free temperature, at which residual

 $<sup>^1{\</sup>rm The}$  reader can refer to the Appendix B for an outline for the fundamentals of nonlinear finite element analysis.

stress starts to build up in the composite laminate upon cooling. To simulate the true temperature where residual stress starts to build up inside the actuator, the initial temperature, T, used was not the material curing temperature, 125 °C, but rather the glass transition temperature of 112 °C, and the final temperature,  $T_{REF}$ , was room temperature, 25 °C.

The elastic tensor, C, of the whole laminate is given as follows:

$$C = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{12} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{15} & C_{25} & C_{35} & C_{45} & C_{55} & C_{56} \\ C_{16} & C_{26} & C_{36} & C_{46} & C_{56} & C_{66} \end{bmatrix}$$
(5.2)

the Duhamel-Hooke's law can be presented in a form involving the elasticity matrix as the following vectors:

$$\begin{bmatrix} \sigma_{x} \\ \sigma_{y} \\ \sigma_{z} \\ \sigma_{xy} \\ \sigma_{yz} \\ \sigma_{yz} \\ \sigma_{xz} \end{bmatrix} = \begin{bmatrix} \sigma_{x} \\ \sigma_{y} \\ \sigma_{z} \\ \sigma_{xy} \\ \sigma_{yz} \\ \sigma_{xz} \end{bmatrix}_{0} + C \left\{ \begin{bmatrix} \epsilon_{x} \\ \epsilon_{y} \\ \epsilon_{z} \\ 2\epsilon_{xy} \\ 2\epsilon_{yz} \\ 2\epsilon_{yz} \\ 2\epsilon_{yz} \end{bmatrix} - \begin{bmatrix} \epsilon_{x} \\ \epsilon_{y} \\ \epsilon_{z} \\ 2\epsilon_{xy} \\ 2\epsilon_{yz} \\ 2\epsilon_{yz} \\ 2\epsilon_{yz} \end{bmatrix}_{0} - \Delta T \begin{bmatrix} \alpha_{x} \\ \alpha_{y} \\ \alpha_{z} \\ 2\alpha_{xy} \\ 2\alpha_{yz} \\ 2\alpha_{yz} \\ 2\alpha_{xz} \end{bmatrix} \right\}$$

The elastic tensor, C, for isotropic material, such as a piezoelectric layer, is defined as:

$$C = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1-\nu & \nu & \nu & 0 & 0 & 0 \\ \nu & \nu & 0 & 0 & 0 & 0 \\ \nu & \nu & 1-\nu & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1-2\nu}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1-2\nu}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1-2\nu}{2} \end{bmatrix}$$
(5.3)

where E is the Young's modulus and  $\nu$  is the Poisson's ratio.

The elasticity matrix for orthotropic materials, such as glass and carbon layers, has the following form:

$$C = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{31} & C_{32} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix}$$
(5.4)

where the components are as follows:

$$C_{11} = \frac{E_x^2 \left( E_z \nu_{yz}^2 - E_y \right)}{C_{denom}}$$
(5.5)

$$C_{12} = -\frac{E_x E_y \left( E_z \nu_{yz} \nu_{xz} + E_y \nu_{xy} \right)}{C_{denom}}$$
(5.6)

$$C_{13} = -\frac{E_x E_y^2 \left(\nu_{xy} \nu_{yz} + \nu_{xz}\right)}{C_{denom}}$$
(5.7)

$$C_{22} = \frac{E_y^2 (E_z \nu_{xz} - E_x)}{C_{denom}}$$
(5.8)

$$C_{24} = -\frac{E_y E_z \left(E_y \nu_{xy} \nu_{xz} + E_x \nu_{yz}\right)}{C_{denom}}$$

$$(5.9)$$

$$C_{33} = \frac{E_y E_z \left( E_y \nu_{xy}^2 - E_x \right)}{C_{denom}}$$
(5.10)

$$C_{44} = G_{xy} \tag{5.11}$$

$$C_{55} = G_{yz} \tag{5.12}$$

$$C_{66} = G_{xz} \tag{5.13}$$

where:

$$C_{denom} = E_y E_z \nu_{xz}^2 - E_x E_y + 2\nu_{xy} \nu_{yz} \nu_{xz} E_y E_z + E_x E_z \nu_{yz}^2 + E_y^2 \nu_{xy}^2$$
(5.14)

#### 5.2.2 Actuation Model

The second sub-model computes the static actuation displacement using an input DC electric field. The second Piola-Kirchhoff stress and Green-Lagrange strain, see for more details in Appendix B, when inserted into the direct piezoelectric constitutive relation, see Chapter 2, yields:

$${}_{0}^{t}\epsilon_{k} = {}_{0}^{t} d_{jk} \cdot {}^{t}E_{j} + {}_{0}^{t} s_{km} \cdot {}_{0}^{t} S_{m}$$

$$(5.15)$$

 ${}_{0}^{t}\epsilon_{k}$  is the Green-Lagrange strain in a configuration at time t relative to configuration at time t = 0. The configuration at time t refers to the material or actuator at deformed configuration. The configuration at time 0 refers to the actuator at the initial configuration or at the undeformed configuration.  ${}_{0}^{t}S_{m}$  is the second Piola-Kirchhoff stress in configuration at time t relative to configuration at time t = 0. Two configurations, i.e. at time t and at time 0, were used because the actuator underwent a large deformation. When solving a large deformation, the equation must be transformed back to the undeformed configuration because the material properties are known at the undeformed configuration but not at the deformed configuration.

Rearranging the Equation 5.15 yields:

$${}^{t}_{0}s_{km0}{}^{t}S_{m} = -{}^{t}_{0}d_{jk} \cdot {}^{t}E_{j} + {}^{t}_{0}\epsilon_{k}$$
(5.16)

Multiply through by the inverse of the compliance matrix,  ${}^{t}_{0}s^{-1}_{km}$ , yields:

$${}_{0}^{t}S_{m} = -({}_{0}^{t}d_{jk} \cdot {}_{0}^{t}s_{km}^{-1})^{t}E_{j} + {}_{0}^{t}c_{km} \cdot {}_{0}^{t}\epsilon_{k}$$
(5.17)

where  ${}_{0}^{t}e_{ji} = {}_{0}^{t}d_{jk} \cdot {}_{0}^{t}s_{km}^{-1} = {}_{0}^{t}d_{ji} \cdot C_{ij}$ . And  ${}_{0}^{t}e_{ji}$  is the elastic modulus of the piezoelectric material and  $d_{ji}$  is the piezoelectric coefficient:

$${}_{0}^{t}S_{m} = {}_{0}^{t}c_{km} \cdot {}_{0}^{t}\epsilon_{k} - {}_{0}^{t}e_{ij}^{-1} \cdot {}^{t}E_{j}$$
(5.18)

where  ${}^{t}E_{j}$  is the electric field in the actuator's deformed configuration. The electric field in the actuator's deformed orientation can be transformed into the undeformed orientation electric field by  ${}^{0}E_{j} = {}^{t}_{0} \underline{X} \cdot {}^{t}E_{j}$ ; where  ${}^{t}_{0}\underline{X}$  is the gradient of the deformed configuration of a material point, see Appendix B, and  ${}^{0}E_{j}$  is the electric field in the actuator's undeformed configuration.

The nonlinear piezoelectric coefficients as a function of the electric field and a permanent strain offset inside the piezoelectric material are included in the general constitutive equation as follows:

$${}_{0}^{t}\epsilon_{k} = {}_{0}^{t} d_{jk} \cdot {}^{t}E_{j} + {}_{0}^{t} s_{km} ({}_{0}^{t}S_{m} - {}^{0}S_{m}) + {}^{0}\epsilon_{k}$$
(5.19)

The thermal stresses developed from the manufacturing process are included as the initial condition to the second sub-model through the constitutive thermoelastic equation by Duhamel-Hooke's law in Equation 5.1. These thermal stresses and permanent strain offset are denoted  ${}^{0}S_{m}$  and  ${}^{0}\epsilon_{k}$ , respectively in Equation 5.19.

Writing in a full matrix form yields:

$$\begin{pmatrix} t_{0} \epsilon_{1} \\ t_{0} \epsilon_{2} \\ t_{0} \epsilon_{3} \\ t_{0} \gamma_{23} \\ t_{0} \gamma_{31} \\ t_{0} \gamma_{12} \end{pmatrix} = \begin{bmatrix} 0 & 0 & t_{0} d_{31} \\ 0 & 0 & t_{0} d_{31} \\ 0 & 0 & t_{0} d_{33} \\ 0 & t_{0} d_{15} & 0 \\ t_{0} d_{15} & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{pmatrix} t_{E_{1}} \\ t_{E_{2}} \\ t_{E_{3}} \end{pmatrix} + \begin{bmatrix} t_{0} s_{11} & t_{0} s_{12} & t_{0} s_{13} & 0 & 0 & 0 \\ t_{0} s_{13} & t_{0} s_{13} & t_{0} s_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & t_{0} s_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & t_{0} s_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & t_{0} s_{66} \end{bmatrix}$$
$$\begin{pmatrix} t_{0} S_{1} - {}^{0} S_{1} \\ t_{0} S_{2} - {}^{0} S_{2} \\ t_{0} S_{3} \\ t_{0} S_{31} \\ t_{0} S_{12} \end{pmatrix} + \begin{pmatrix} 0 \epsilon_{1} \\ 0 \epsilon_{2} \\ 0 \\ 0 \\ 0 \end{pmatrix}$$
(5.20)

This piezoelectric constitutive equation is solved using the principle of virtual work.

#### 5.2.3 Actuator Configuration

As discussed earlier, the actuator model was composed of two sub-models, one was used to determine the actuator's manufactured shape and a second one was used to simulate the actuator's actuation displacements. To determine the actuator's manufactured shape, a simply-supported boundary condition was used. To simulate the actuator's actuation displacement, the actuator was configured with a cantilever beam configuration. The actual actuator length was 80 mm. The simply-supported boundary condition allowed the whole length of the actuator to deform. The actuator was clamped by 5 mm length at one end to form a cantilever beam configuration, the actuator's length was therefore reduced to 75 mm. To simplified the whole actuator model dimension, the actuator model was simplified by reducing the whole actuator's length from 80 mm to 75 mm for the two sub-models making the actuator's length identical to the cantilever beam configuration, Figure 5.2(a). Thus, the simply-supported boundary condition is applied at the two ends along the actuator length to allow the whole length of the actuator to deform.

Three 2D models of three actuator layups, i.e. [G/PZT/G/C], [G/PZT/G/C/C]and [G/PZT/G/C/G/C], were developed using COMSOL Multiphysics, version 4.2, 'G' refers to a glass fabric layer, 'C' refers to a unidirectional carbon layer and 'PZT' refers to a piezoceramic layer. The sequence [G/PZT/G/C] represents a stacking sequence according to composite laminate convention. An example of a modeled dimensions of a [G/PZT/G/C] for the simulation of the actuator's manufactured shape and the actuator's static actuation displacement can be seen in Figure 5.2.



Figure 5.2: The model dimension of the LIPCA [G/PZT/G/C] used in this study (a) and the actuator actual dimension of [G/PZT/G/C] (b).

The dimensions of the material layers inside the model of the actuator are as follows: the glass layers were 72 mm x 70  $\mu$ m (length x thickness), the carbon layer were 72 mm x 72  $\mu$ m and the PZT dimension were 72 mm x 267  $\mu$ m, Figure 5.2(a). To compensate for the differences between the piezoelectric thickness and the top and bottom glass layers, four layers of glass, 3 mm x 66.75  $\mu$ m each layers, were applied at the right end in the model, making a 3-mm long tab. In the actual actuator the glass layers were 80 mm x 70  $\mu$ m (length x thickness), the carbon layer were 80 mm x 72  $\mu$ m. The left glass tab was 5 mm x 70  $\mu$ m and the right were 3 mm x 70  $\mu$ m as shown in Figure 5.2(b), and in Figures 3.12 and 3.13 of chapter 3. The differences in the tabs lengths, i.e. one side was 5 mm long and another one was 3 mm long, were made for clamping purposes; i.e. the 5 mm length was used as the actuator clamping point. In the actual manufacturing process, 4 layers of glasses were applied at the two taps. Since the glass later's thickness was 70  $\mu$ m thick, a stack of 4 layers exceeded the piezoelectric thickness before curing but the total thickness of these tabs was reduced due to the high pressure applied during the curing process, while the piezoelectric material's thickness remains unchanged. The model and actual dimensions for the other two layups, i.e. [G/PZT/G/G/C]

and [G/PZT/G/C/G/C], were similarly developed. The material properties of carbon unidirectional, glass fabric and piezoelectric material are tabulated in Table 5.1.

Properties	Glass fabric(GEP-108)	Carbon UD (USN 75B)	PZT(5A4E)
$E_1$ [GPa]	21.7	128.32	66
$E_2$ [GPa]	21.7	4	66
$G_{12}, G_{13}$ [GPa]	3.99,  3.99	2.5, 2.5	-
$\alpha_1, \alpha_2 \ [1 \ge 10^{-6} / \text{K}]$	14.2, 14.2	-6.25, 36.27	4, 4
Poisson Ratio, $\mu_{12}$	0.13	0.3	0.3
Density $[kg/m^3]$	1800	1120	7800
Thickness $[\mu m]$	70	72	267
Linear $d_{31}$ [m/V]	-	-	$-190 \times 10^{-12}$
Manufacturer	SK Chemicals	SK Chemicals	Piezo System, Inc.
	Korea	Korea	USA

Table 5.1: Material properties obtained from the manufacturers used in the models

## 5.3 Static Experimental Setup

The experimental setup for the static testing of the actuator is discussed in this section. The actuator was clamped at the 5-mm long edge, and the input DC voltage was applied to the actuator using a Piezo-driver, Figure 5.3.



Figure 5.3: Experimental Setup

In order to ensure the consistency of the excitation, each excitation set was repeated 4-5 times. The actuation displacement at the free end tip was measured using a non-contact laser beam (KEYEGENCE), which was controlled by a laser controller (LK-G Series). The laser controller received the measurement values from the laser beam and the values were sent to the data acquisition system (DAQ). The actuation displacements could be interpreted through the host computer. The actuator was clamped in a cantilever configuration fashion, oriented vertically to prevent the gravitational effect, see Figures 5.3 and 5.4.





## 5.4 Conclusions

The static finite element model of the actuator was discussed in this chapter. In this model a manufacturing model was coupled with a static actuation model to give a model consisting of two sub-models: one was the solid mechanics and one was the piezoelectric devices. The solid mechanics model was used to predict the manufactured shape of the actuator, while the piezoelectric device model was used to predict the static actuation displacements of the actuator when input DC electric potential is given to the actuator.

The thermal stresses calculated from the solid mechanics physic was considered as the initial stresses in the piezoelectric device physics. Moreover, the geometric nonlinearity of the actuator was taken into account in the two sub-models because the actuator exhibited large out-of-plane displacement. Furthermore, the nonlinear piezoelectric coefficient and the permanent strain offset inside the piezoelectric material obtained in section 4.1 were included in the models.

### References

- B. Taleghani. Validation of high displacement piezoelectric actuator finite element models. NASA Technical Memorandum, (210309):1–9, 2000. cited By (since 1996) 0.
- [2] S.-C. Woo and N.S. Goo. Prediction of actuating displacement in a piezoelectric composite actuator with a thin sandwiched pzt plate by a finite element simulation. *Journal of Mechanical Science and Technology*, 21(3):455–464, 2007. cited By (since 1996) 10.
- [3] S. Aimmanee and MW Hyer. A comparison of the deformations of various piezoceramic actuators. *Journal of intelligent material systems and structures*, 17(2):167–186, 2006.
- [4] Z. Ounaies, Institute for Computer Applications in Science, and Engineering. Low-field and high-field characterization of THUNDER actuators. ICASE, NASA Langley Research Center, 2001.
- [5] R.W. Schwartz, P. Laoratanakul, W.D. Nothwang, J.M. Ballato, Y. Moon, and A. Jackson. Understanding mechanics and stress effects in rainbow and thunder stress-biased actuators. In *Proceedings of SPIE*, volume 3992, page 363, 2000.
- [6] G. Li, E. Furman, and GH Haertling. Fabrication and proprerties of pszt antiferroelectric rainbow actuators. *Ferroelectrics*, 188(1):223–236, 1996.
- [7] R.W. Schwartz and YW Moon. Domain configuration and switching contributions to the enhanced performance of rainbow actuators. SPIE Smart Structures and Materials, Active materials: Behavior and Mechanics, 4333(408):201, 2001.
- [8] G.H. Haertling. Stress-induced effects in plzt ceramics. In Applications of Ferroelectrics, 1996. ISAF'96., Proceedings of the Tenth IEEE International Symposium on, volume 1, pages 65–68. IEEE, 1996.
- [9] Barmac K. Taleghani and Joel F. Campbell. Non-linear finite element modeling of thunder piezoelectric actuators, 1999.
- [10] Brian D. Freed and Vit Babuska. Finite element modeling of composite piezoelectric structures with msc/nastran. pages 676–688, 1997.

- [11] C.M. Spencer. Determining limitations in the ability of the abaqus commercial finite element analysis program to accurately predict piezoelectric strain behavior in actuation devices. 2004.
- [12] COMSOL Multiphysics 4.2. Comsol multiphysics, Accessed 5/11/2012.
- [13] Fiona Lowrie, Markys Cain, and Mark Stewart. Finite element modelling of electroceramics. National Physical Laboratory.Great Britain, Centre for Materials Measurement and Technology, 1999. (Great Britain.).

# Chapter 6

# Static Behaviour of Piezoelectric Composites Actuators

A static model to predict actuation displacements under a static operating condition was introduced in Chapter 5. In this chapter, the static model is compared with experimental results under a static operating condition. This chapter is divided into seven sections. The introduction to the chapter is presented in section 6.1. The experimental results of three different actuator layups are discussed in section 6.2. The predicted actuation displacements are compared with the experimental results in section 6.3, where the model incorporates nonlinear piezoelectric coefficients obtained from the standard method discussed in section 4.1. The predicted actuation displacements are compared with the experimental results in sections 6.4 and 6.5. The models in sections 6.4 and 6.5 incorporate two nonlinear piezoelectric coefficients obtained using the two non-standard novel methods discussed in section 4.1. Explanations of which parameters influence the static actuation displacements of different actuator layups are given in section 6.6. Conclusions are drawn on the actuation behaviour shown in the experiments, and the parameters that influence the static actuations are discussed in section 6.7.

### 6.1 Introduction

Quasi-static actuation performance has been investigated extensively using sinusoidal input voltages to study peak-to-peak actuation displacements [1-7]. The term quasi-static actuation refers to a sinusoidal input electric voltage at 1 Hz [5], however, in some applications, fluctuation of actuator sinusoidally might not be interesting. Flow conditions around an aircraft wing change all the time, therefore, the passive flow control requires the vortex generator to be operated under a full static condition at various displacements to control the flow in various conditions. In addition, in certain circumstances, when passive flow control is not needed, parasitic drag may be initiated. This cannot be achieve using a conventional passive flow control method because its displacements are in-adjustable.

In this chapter we investigate the behaviour of actuators under full static actuation conditions with various unipolar DC input voltages. The term unipolar DC input voltage refers to positive and negative polarities that are applied separately. The advantage of investigating many unipolar DC voltages is that the numbers of displacement magnitudes at a full static condition can be studied to control various flow conditions. The unipolar input voltage is interesting because the actuation response can be investigated independently between the positive and negative polarities. The actuators are actuated with two charging conditions: nondischarging and discharging. Two charging conditions were introduced to allow a deeper investigation into the actuators' behaviour to replicate actual actuator applications. The three actuator layups used were [G/PZT/G/C], [G/PZT/G/G/C]and [G/PZT/G/C/G/C]. These three layups were chosen to provide a close look at how much the behaviour will change when the actuator's stiffness gradually increases by increasing one layer of material at a time. It should be noted that the piezoelectric material layer, PZT, must be sandwiched between two layers of glass to prevent an electrical short circuit since the carbon layer acts as a conductor. The baseline layup is [G/PZT/G/C]. A Carbon or a glass layer is added into this baseline layup to increase the bending stiffness of the actuator. The objective was to investigate how actuators respond to unipolar input voltages and to understand the parameters influencing the actuation performance in different layups. In recent literature on piezoelectric composite materials actuators, the focus is on the macroscopic mechanics of the actuator, however the actual actuation starts at a microscopic scale, i.e. at the piezoelectric material level. Therefore, the focus of this chapter is to look into this behaviour by incorporating the nonlinearity of the piezoelectric materials level.

## 6.2 Static Experimental Results

Each experiment started with the actuator in a non-discharging condition, followed by a discharging condition. The experimental orders were (1) a positive voltage non-discharging condition followed by (2) a negative voltage non-discharging condition, followed by (3) a positive voltage discharging condition and finally (4) a negative voltage discharging condition. The discharging and non-discharging conditions are illustrated in Figure 6.1. The unipolar DC input voltage was applied for 15 seconds at each particular voltage before the displacement of the actuator was measured and recorded. The application of a unipolar DC voltage for 15 seconds was done to allow the actuator to reach its stable state. All actuators were not re-polarized after manufacturing because the curing temperature of the composite material was much below the piezoelectric material's Curie temperature. Thus, the piezoelectric material was not depolarized due to a high curing temperature.



Figure 6.1: Schematic of the applications of a positive electric field through the arrows. (a) application of the electric field for a particular time step then the actuator is discharged to a zero electric field before the application of the next higher field level to the actuator. This is denoted "discharging" condition; (b) application of the electric field without discharging before the application of the next higher field level to the actuator. This is denoted "non-discharging" condition.

The nonlinear actuation displacements caused by the applied voltage are shown in Figures 6.2, 6.3 and 6.4. The permanent displacement offset <sup>1</sup> clearly appears in all actuators and charging conditions. The offset exhibit a large influence on the actuators' performance especially under the negative voltage, regardless of discharging or non-discharging condition. The offset is a result of irreversible 90° domain wall orientations resulting from a large magnitude of applied voltage opposing the poling direction, as discussed in section 4.1. The application of the voltage opposing the poling direction makes it difficult for the domain walls to reorient back to their original state.

<sup>&</sup>lt;sup>1</sup>Note that the word "permanent displacement offset" used in this research refers to a shift in an initial displacement between the experiment number 1 and the rest of the experiments.



Figure 6.2: Static actuation displacement of [G/PZT/G/C] when the actuator was not discharged prior to the application of the next higher voltage under a positive (a) and a negative (b) voltages. Static actuation displacements when the actuator was discharged prior to the application of the next higher voltage under a positive (c) and a negative (d) voltages, 'Ex1' refers to experiment 1 and similarly for experiments 2 to 5.

It can be observed that the permanent displacement offset of the [G/PZT/G/C] is minimal under a positive voltage with a non-discharging condition, Figure 6.2(a). The cause of the permanent displacement offset can be explained by the fact that all the actuators were actuated the first time under a positive polarity and a non-discharging condition, resulting in a low amount of 90° domain wall orientations. However, a difference can be seen when comparing [G/PZT/G/C/G/C], figure 6.4(a), to figures 6.2(a) and 6.3(a), showing a larger amount of permanent displacement offset under a positive potential with the non-discharging condition. These different responses arise from larger irreversible 90° domain wall orientations of the layup [G/PZT/G/C/G/C] than the other two layups.



Figure 6.3: Static actuation displacement of [G/PZT/G/G/C] when the actuator was not discharged prior to the application of the next higher voltage under a positive (a) and a negative (b) voltages. Static actuation displacements when the actuator was discharged prior to the application of the next higher voltage under a positive (c) and a negative (d) voltages, Ex = experiment, numbered 1 to 5.

The most common behaviour of all actuators is that the actuation displacements are repeatable from the second experiment onward. This is an indication of the effect of the permanent displacement offset, caused by the irreversible 90° domain wall orientations, which occur only once, with the first experiment. It can be observed that the permanent displacements under the positive discharged condition, figures 6.2(a), 6.3(a) and 6.4(a), and the negative under the two charging conditions, figures 6.2(b,d), 6.3(b,d) and 6.4(b,d), initiated from the second experiment onward. In regards to this phenomena, it can be concluded that regardless of the charging conditions, the actuators exhibit permanent displacement offset after the first experiment and this offset remains permanent in the actuators.



Figure 6.4: Static actuation displacement of [G/PZT/G/C/G/C] when the actuator was not discharged prior to the application of the next higher voltage under a positive (a) and a negative (b) voltages. Static actuation displacements when the actuator was discharged prior to the application of the next higher voltage under a positive (c) and a negative (d) voltages, Ex = experiment, numbered 1 to 5.

To give a clear picture of the actuation response under both charging conditions, figures 6.2(a,b), 6.3(a,b) and 6.4(a,b) were combined into a figure 6.5. Figures 6.2(c,d), 6.3(c,d) and 6.4(c,d) were combined into a figure 6.6. These figures 6.5 and 6.6 show the asymmetry of the actuation response of all actuators when comparing the two polarities under both charging conditions. Even though there are some variations in the permanent displacement offsets under the positive voltage between the discharged and the non-discharged cases; the trends of all layups are similar under both polarities. This is an indication of how, regardless of having the actuators discharged or not discharged prior to the next higher input voltage, the permanent displacement offsets due to the irreversible 90° domain wall orientations still remain. These offsets are due to two effects; one is a restriction of the piezoelectric material from free movement as it was embedded inside a composite laminate and the second effect results from a large input voltage, as discussed in section 4.1. As a consequence of these two effects, the strain state inside the piezoelectric material can not be reduced or diminished to a zero strain even under a discharging condition. In addition, when only discharging the actuator, the irreversible 90° domain walls can not be reoriented back as this requires a greater magnitude of opposite input polarity to reorient the irreversible domain walls, as discussed in section 4.1.

The variation of the permanent displacement offsets under the positive voltage might come from the experimental sequence. Once the actuators had gone through the negative voltage with a non-discharging condition; the domain walls had already been oriented resulting in a permanent displacement offset to the actuator. The actuation response from this point onward depends on the previous effects of the irreversible 90° domain wall orientations. After the actuators have gone through the negative voltage with a non-discharging condition, the actuators were followed by a positive voltage with a discharging condition, while the 90° domain walls were already oriented irreversibly.



Figure 6.5: Combined experimental results of all actuators under both positive and negative voltages when the actuators were not discharged prior to the application of the next higher voltage. A '+' sign in front of each layup represents a positive voltage apply to the actuator. A '-' sign in front of each layup represents a negative voltage apply to the actuator.



Figure 6.6: Combined experimental results for all tested actuators under both positive and negative voltages when the actuators were discharged prior to the application of the next higher voltage. A '+' sign in front of a layup represents a positive voltage apply to the actuator. A '-' sign represents a negative voltage apply to the actuator.

# 6.3 Actuation Displacements vs Actuation Predictions using Standard Nonlinear Piezoelectric Coefficients

The standard approach used to determine the piezoelectric coefficients is achievable if measurement of the strain state of the piezoelectric material surface is feasible. Experimental results of three actuators and the actuation displacements predictions for these actuators are compared in this section. The predictions included the nonlinear piezoelectric coefficients obtained from the standard approach.

#### 6.3.1 Experimental Results vs Static Models

The predicted actuation displacements obtained from determining the two piezoelectric coefficients were compared with the experimental results. The first coefficient is a linear piezoelectric coefficient obtained from the manufacturer, and the second coefficient was a nonlinear piezoelectric coefficient obtained using the standard approach: see section 4.1 Discharged Piezoceramic: Zero Strain State (standard method). It can be seen from section 6.2, that all the actuation displacements are repeatable from the second experiment onward. The actual actuation was re-
quired to be actuated more than once, therefore, the actuation displacements from the second experiment onward were averaged and compared to the experimental results.

The experimental results and the predictions of all three actuators are depicted in figures 6.7 to 6.9.



Figure 6.7: Experimental results of [G/PZT/G/C] under discharging and non-discharging conditions compared to the model with linear piezoelectric and nonlinear piezoelectric coefficients. Ex Discharged refers to the experimental results with a discharging condition. Ex NoDischarged refers to the experimental results without discharging the actuator. Model Linear refers to a model incorporates with a linear piezoelectric coefficient. Model Nonlinear refers to a model incorporated using a nonlinear piezoelectric coefficient obtained from a standard method.

It can be observed that at a low positive voltage value, the models incorporate with the linear piezoelectric coefficient, denoted Model Linear, show comparable agreement with the experimental results under a positive voltage. A large deviation from the experimental results can be observed at a large voltage. Apart from that, a large deviation between the models and the experimental results under a negative voltage, especially at 0V, can be observed. This large deviation is due to the lack of the permanent displacement offset in the linear piezoelectric coefficient.



Figure 6.8: Experimental results of [G/PZT/G/G/C] under discharging and non-discharging conditions compared to the model with linear piezoelectric and nonlinear piezoelectric coefficients. Ex Discharged refers to the experimental results with a discharging condition. Ex NoDischarged refers to the experimental results without discharging the actuator. Model Linear refers to a model incorporates with a linear piezoelectric coefficient. Model Nonlinear refers to a model incorporated using a nonlinear piezoelectric coefficient obtained from a standard method.

When the nonlinear effect in the piezoelectric coefficients is taken into account, the predicted actuation displacements exhibit larger displacement slopes, forcing the predicted displacements to come closer to the experimental results at a higher voltage than found without the nonlinear effect. This nonlinear model is denoted a Model Nonlinear.

The Model Nonlinear does not exhibit a highly nonlinear graph when compared to the nonlinear experimental results. This is because the nonlinear effect in the form of the irreversible domain wall orientations, is diminished by using the standard approach, see chapter 4. Therefore, the standard method is still not capable to predict the nonlinear experimental results especially with a presence of permanent displacement offset. The lack of the permanent displacement offset arise from the fact that the standard method is due to the irreversible 90° domain wall orientations have been diminished. These irreversible domain wall orientations are presented in the nonlinear coefficients,  $d_{31nonli}$ , are shown in table 6.1.

Polarity	$d_{31nonli}[\mathbf{m/V}]$	Permanent Strain Offset
Positive	$-3.18 \times 10^{-16} \times (E) -2.88 \times 10^{-10}$	$-6.13 \times 10^{-6}$
Negative	$-3.13 \times 10^{-16} \times (E) -4.08 \times 10^{-10}$	$1.46 \times 10^{-7}$

Table 6.1: Nonlinear  $d_{31nonli}$  coefficients under positive and negative fields with initial strain offset in the PZT as assigned in the model, 'E' is the electric field. The nonlinear piezoelectric coefficient was obtained when the piezoelectric was under a discharging condition and the strain state was tuned back to the zero state to diminish the permanent strain. These coefficients were identical as shown in table 4.1 in section 4.2.2. The coefficients of the linear terms are -2.88 and -4.08 and for the non-linear terms -3.18 and 3.13.



Figure 6.9: Experimental results of [G/PZT/G/C/G/C] under discharging and nondischarging conditions compared to the model with linear piezoelectric and nonlinear piezoelectric coefficients. Ex Discharged refers to the experimental results with a discharging condition. Ex NoDischarged refers to the experimental results without discharging the actuator. Model Linear refers to a model incorporates with a linear piezoelectric coefficient. Model Nonlinear refers to a model incorporated using a nonlinear piezoelectric coefficient obtained from a standard method.

The effects of the reversible and irreversible domain wall orientations are presented as the slope of the linear term in  $d_{31nonli}$ , see for more information section 4.1. A large slope in the linear term in  $d_{31nonli}$ , see table 6.1, contributes to a large slope in the displacement predictions. Thus, the Model Nonlinear which incorporates with the  $d_{31nonli}$  from the standard method shows less nonlinearity than the  $d_{31nonli}$ obtained using the other two non-standard method. The two non-standard methods will be discussed in the following two sections. The Model Nonlinear of the negative voltage shows a larger slope for the predicted actuation response than for the actuator under the positive voltage. The larger slope is a result of a greater number of 90° domain wall orientations and can be quantified using the coefficients of the linear term shown in table 6.1<sup>2</sup>. A coefficient of the linear term of the negative voltage,  $-4.08 \times 10^{-10}$  [m/V], is almost twice that of the linear term of the positive voltage, which is  $-2.88 \times 10^{-10}$  [m/V]. This indicates that the negative voltage poses more 90° domain wall orientations than the positive one.

Further observation can be made through the very small permanent strain offset inside the piezoelectric material. The small permanent strain offset is amplified during actuation and developed into a significant amount of permanent displacement offset at the macroscopic scale, i.e. actuator level. The amplification depends upon the constraints of the piezoelectric material to move freely inside the composites. This allowable movement varies upon different layups and is discussed further in section 6.6

## 6.4 Actuation Displacements vs Actuation Predictions with Nonlinear Piezoelectric Coefficients: Discharged with un-Tuned Strain State

Measurement of the strain state at a piezoelectric material's surface becomes difficult when the piezoelectric material is embedded inside a composite laminate. In addition, turning the strain state of the piezoelectric material to the zero state is even more difficult because of a constraint imposed by the composite laminate, therefore, a permanent residual strain will always remain inside the piezoelectric material due to the particular actuators used in this study. For this reason, using the nonlinear piezoelectric coefficient obtained using the standard method may not be the best approach because all the permanent residual strains in the piezoelectric material are diminished to zero in the standard method. To replicate the actual circumstances a piezoelectric coefficients obtained using a non-standard method are included in the model to predict the actuation displacements. These coefficients were

<sup>&</sup>lt;sup>2</sup>The term without a multiplication of an electric field (E) is called a linear term while the terms with an electric field is called a nonlinear term. This is due to the fact that the  $d_{31nonli}$  will be multiplied by an electric field (E) to produce an output strain, as explained in chapter 4. Therefore, the term with a multiplication of E will become  $E^2$  and it is nonlinear. Similarly, the term without an E will be multiplied by E to produce an output strain.

obtained from a discharging condition while the strain state was un-tuned back to its zero state, see Discharged Piezoceramic: Non-Zero Strain State in section 4.1. To study the actuators' static behaviour, the experimental results discussed in the section 6.3 were also compared with the predicted actuation displacements.

### 6.4.1 Experimental Results vs Static Models

Due to the fact that the actuators were always operated in multiple cycles, the actuation displacements from the second experiment onward were averaged to maintain permanent displacement offsets inside the piezoelectric material and these averaged actuation displacements were compared to the models. The investigation was focused on both charging conditions taken from the experimental results. The experimental and prediction results for all the three actuators are shown in figures 6.10 to 6.12.



Figure 6.10: Experimental results of [G/PZT/G/C] under discharging and non-discharging conditions compared to the model with linear piezoelectric and nonlinear piezoelectric coefficients. Left: the actuator was actuated under a positive voltage. Right: the actuator was actuated under a negative voltage.

Ex Discharged refers to the experimental results with a discharging condition. Ex NoDischarged refers to the experimental results without discharging the actuator. Model Linear refers to a model incorporates with a linear piezoelectric coefficient obtained from a manufacturer. Model Nonlinear refers to a model incorporates with a nonlinear piezoelectric coefficient and initial strain to fit with the experimental results. The nonlinear piezoelectric coefficient was obtained when the piezoelectric material has been discharged but the initial strain remains inside the piezoelectric material. Model Nonlinear 100%strain refers to a model which incorporates a nonlinear piezoelectric coefficient with 100% initial strain.



Figure 6.11: Experimental results of [G/PZT/G/G/C] under discharging and non-discharging conditions compared to the model with linear piezoelectric and nonlinear piezoelectric coefficients. Left: the actuator was actuated under a positive voltage. Right: the actuator was actuated under a negative voltage.



Figure 6.12: Experimental results of [G/PZT/G/C/G/C] under discharging and nondischarging conditions compared to the model with linear piezoelectric and nonlinear piezoelectric coefficients. Left: the actuator was actuated under a positive voltage. Right: the actuator was actuated under a negative voltage.

The influence of the irreversible  $90^{\circ}$  domain wall orientations on the actuation

response can clearly be observed from the existence of permanent displacement offsets. The Model Linear, which incorporates the linear piezoelectric coefficient, fails to predict the nonlinear phenomenon in all cases. This can be explained by the fact that the piezoelectric manufacturers usually use small magnitude input electric fields to determine the piezoelectric coefficient. These small magnitude electric fields produce linear response to the material. A linear range does not contain a contribution from the 90° domain wall orientations, but only the piezoelectric effects, see also chapter 4. The influence of the irreversible 90° domain wall orientations is more pronounced in the negative field than in the positive one, see section 6.2.

#### **Negative Voltage**

The "Model Nonlinear 100% strain" in the negative voltage incorporates a nonlinear piezoelectric coefficient plus the full magnitude of the permanent residual strain in the piezoelectric material is taken into account. The nonlinear piezoelectric coefficient and magnitudes of permanent residual strain are tabulated in table 6.2. It is observable that with full initial strain, the displacement offsets of all three actuators are much larger than the experimental results. To correct for the displacement offset under the negative field; the permanent strain offset in the piezoelectric material is reduced by 50% from the full permanent strain offset values as shown in Table 6.2. The magnitude 50% reduction was approximately made to match the initial displacement offsets of each actuator to the experimental results. The magnitude of 50% initial strain reduction had to be approximately made because at the time the research was conducted, there was no available equipment to determine the true strain of the piezoelectric material inside a composite laminate. Even though the offsets were not perfectly made in each individual actuator layup the 50% reduction provides a close approximation to the experiments. If the actuators are stiffer than the ones investigated for this research, the initial strain offsets would have been chosen to be lower than 50%. This initial strain reduction is a result of the constraint imposed by the composite laminate to allow free expansion/contraction of the piezoelectric material. While the bulk piezoelectric material without constraint from the composite material, as used in this study, will freely expand and contract the initial strain will not be reduced.

The "Model Nonlinear" in the negative voltage which takes the nonlinear piezoelectric coefficient plus reduced the magnitudes of strain offset into account, can pick up the nonlinear phenomenon in the actuation response very well. The initial displacement offsets of all actuators show close agreement between experiment and predicted results, see figures 6.10(right) to 6.12(right).

Polarity	$d_{31nonli}[\mathbf{m/V}]$	100% Permanent Strain Offset	Permanent Strain Offset Assigned in the Model
Positive	$-18.81 \times 10^{-17} \times (E) -2.65 \times 10^{-10}$	$-2.64 \times 10^{-5}$	$-2.64 \times 10^{-5}$
Negative	$-2.69 \times 10^{-16} \times (E) -1.20 \times 10^{-10}$	$2.53 \times 10^{-4}$	$1.26 \times 10^{-4}$

Table 6.2: Nonlinear  $d_{31nonli}$  coefficients under positive and negative fields with initial strain offset in the PZT as assigned in the model, E is the electric field. The nonlinear piezoelectric coefficient was obtained when the piezoelectric material was under a discharging condition and the strain state was un-tuned back to the zero state. These coefficients are identical as shown in Table 4.1 in section 4.2.2. The column Permanent Strain Offset Assigned in the Model indicates that the strain under the negative voltage is reduced by 50% from the original value, while the strain under the positive voltage remains the same.

#### **Positive Voltage**

A "Model Nonlinear 100%strain" takes a nonlinear piezoelectric coefficient plus a full magnitude of permanent residual strain in the piezoelectric material into account. It can be observed that the predicted initial displacement offsets of all actuator layups is smaller than the experimental results. The discharging condition is of interest because is was completed after the non-discharging condition, therefore, the actuators have already been influenced by a large magnitude of electric voltages resulting in 90° domain wall orientations. The 90° domain wall orientations influences the actual applications and needs to be investigated. The smaller initial displacement under the positive voltage case can be explained by the fact that the permanent strain offset instead of being reduced similarly to the negative potential, is amplified by a tensile stress during actuation under the positive voltage, see figures 6.13 and 6.14. From figure 6.13 it can be seen how the piezoelectric layer experience more tension at +200V than at +0V. From figure 6.14 it can be seen that the  $90^{\circ}$  domain wall orientations are amplified when the piezoelectric layer is under tension. When the tensile stress is large, and the magnitude of the applied voltage is high, the 90° domain walls will orient irreversibly. In this case the initial strain in the piezoelectric layer is amplied under a positive field by a tensile stress at +200V. The tensile stress stretches the domain walls to form  $90^{\circ}$ domain wall orientations, promoting a larger initial permanent strain offset in the piezoelectric layer under a positive potential.



Figure 6.13: Changes of internal stress at the mid-length throughout thicknesses of [G/PZT/G/C] between zero voltage and 200V from the finite element analysis. '+0V' refers to the stress condition at 0V with initial strain presented obtained under a positive electric field. '-0V' refers to the stress condition at 0V with reduced initial strain presented obtained under a negative field. Note that there are two 0Vs because the nonlinear piezoelectric coefficients are determined independently between positive and negative fields.



Figure 6.14: Effects of the applied compression and tension stresses affect to the domains inside a bulk piezoelectric layer compared to a stress free state [8]. The arrows pointing toward horizontally represent  $90^{\circ}$  domain walls; while the arrows pointing toward vertically represent non- $90^{\circ}$  domain walls. See chapter 2 for further explanation.

When the actuator is actuating under a negative potential, the compressive stress, inside the piezoelectric layer forces the oriented domain walls to reorient back towards their initial strain state. This reorientation of the domain walls back to their initial strain state results in a lower permanent displacement offset than 100%, as illustrated in figures 6.13 and 6.14. This is why the "Model Nonlinear" comprises of reduced initial strain inside a piezoelectric material as explained earlier in the negative votlage case. Even though the permanent initial strain offset in the negative voltage has been reduced due to the compressive stress, the amount of irreversible 90° domain wall orientations under a negative voltage still contributes more to the permanent displacement offset than a positive voltage. A larger permanent displacement offset from a negative voltage is due to the larger positive electric field required to reorient the domain walls back towards their original state when they have been oriented by a negative field. While the domain walls will require a smaller magnitude negative field to reorient the domain walls back when they have been oriented by a positive field.

Under the positive potential, the permanent displacement offsets obtained from the "Model Nonlinear 100%strain", figures 6.10(left) to 6.12(left) still does not show a good agreement of the permanent displacement offset between the model and each individual actuator layup. This is due to the smaller magnitudes of initial strain offset inside a bulk piezoelectric material inserted in the models under the positive potential, see table 6.2, rather than the actual permanent displacement offset produced by the actuators. The initial strains inside the piezoelectric material were corrected for an individual layup to match better the experimental results, table 6.3. The table 6.3 is showing how much initial strains have been corrected under positive and negative polarities. This was done only under the positive polarity, figure 6.15.

Layup	Original In	itial Strain	Corrected I	nitial Strain	Percentag	e Difference
	$Pos(\times 10^{-5})$	$Neg(\times 10^{-4})$	$Pos(\times 10^{-5})$	$Neg(\times 10^{-4})$	Pos(%)	Neg(%)
[G/PZT/G/C]	-2.64	2.53	-5.28	1.26	+100	-50
[G/PZT/G/G/C]	-2.64	2.53	-8.00	1.26	+203	-50
[G/PZT/G/C/G/C]	-2.64	2.53	-10.0	1.26	+278	-50

Table 6.3: Corrected initial strains inside a piezoelectric material to fit with displacement offsets of each actuator layup. The 'Pos' and 'Neg' represent a positive and negative polarities, respectively. The '-' sign represents a percentage reduction. The '+' sign represents an increase in percentage.

The discussion of why a larger initial strain must be applied to a piezoelectric material under positive polarity can be made with a look at figure 6.16. Here the piezoelectric layer is under more tension at +0V when compared to the zero initial permanent displacement after manufacturing, pure 0V. It should be noted that +0V consists of the remaining of the displacement offsets from the 2nd experiment onward. As can be seen from figure 6.14, the 90° domain wall orientations

are promoted under tension; this results in larger initial permanent strain in the piezoelectric layer, and explains why a larger initial strain magnitude must be applied to the piezoelectric layer under positive polarity.



Figure 6.15: Predicted actuation displacements with corrected initial strains vs experimental results under a discharging condition under the positive polarity.



Figure 6.16: Changes of stress through the piezoelectric layer thickness between +0V with an existence of a permanent displacement offset and at a pure 0V. The pure 0V refers to the stress state at a zero voltage after manufacturing, i.e. zero initial permanent displacement. The +0V refers to the stress state at a zero voltage of the 2nd experiment onward, leaving a permanent initial displacement inside an actuator.

The predicted actuation displacements with corrected initial strain of all layups, denoted as "Model Nonlinear" from figures 6.10(right), 6.11(right) to 6.12(right) and a lower right figure in figure 6.15 are combined and become a figure 6.17. It can be observed that the actuation displacements obtained from the model with corrected initial strain to match with the experimental results under a discharging condition, figure 6.17, show good agreement with the actual actuation displacement trends under a discharging condition, figure 6.18.



Figure 6.17: Predicted actuation displacements with corrected strain..



Figure 6.18: Combined experimental results for all tested actuators under both positive and negative voltages when the actuators were discharged prior to the application of the next higher voltage, A '+' sign in front of a layup represents a positive voltage apply to the actuator, A '-' sign represents a negative voltage apply to the actuator.

## 6.5 Actuation Displacements vs Actuation Predictions with Nonlinear Piezoelectric Coefficients: Non-Discharged with un-Tuned Strain State

Sometimes, an actuators may not be discharged prior to the next higher electric field and the permanent strain offset inside the piezoelectric material will remain. Thus, to replicate the real situation, a nonlinear piezoelectric coefficient obtained under a non-discharging condition and the strain state remaining inside the piezoelectric material was included in the model, see Non-Discharged Piezoceramic: Non-Zero Strain State in section 4.1. Within this section, a set of experimental results for three actuators identical to sections 6.3 and 6.4 are compared to the models.

## 6.5.1 Experimental Results vs Static Models

## Negative Voltage

A discussed in section 6.4 the Model Nonlinear 100%strain overestimated the initial permanent displacement offset under the negative voltage; therefore, the initial strain inside the piezoelectric material was reduced by approximately 50 - 60% from the original value in a manner similar to that discussed in section 6.4. This is denoted "Model Nonlinear corrected strain" in figures 6.19 to 6.21.

The nonlinear piezoelectric coefficient was obtained when the piezoelectric material had not been discharged but the initial strain remained inside the piezoelectric material, table 6.4. The "Model Nonlinear corrected strain" predicts very good agreement with the actuation displacements. The idea behind the initial strain reduction under the negative voltage, while increasing the initial strain under the positive voltage is similar to that discussed in section 6.4.2. The strains are tabulated in table 6.5. "Ex DIS" refers to the experimental results with a discharging condition. The experiment under a discharging condition is of interest, when compared to the non-discharging condition, because it shows a larger displacement offset. having larger displacement offset should represent the real actuation situation better because it consists of high influence of 90° domain wall orientations. "Model Linear" refers to a model incorporates with a linear piezoelectric coefficient obtained from a manufacturer. The "Model Nonlinear 100%strain" refers to a model incorporating with a nonlinear piezoelectric coefficient with 100% initial strain. The "Model Nonlinear corrected strain" refers to a model incorporated with a nonlinear piezoelectric coefficient and initial strain to match with the experimental results.



Figure 6.19: Experimental results of [G/PZT/G/C] under a discharging condition compared to the model with linear piezoelectric and nonlinear piezoelectric coefficients. Left: the actuator was actuated under a positive voltage. Right: the actuator was actuated under a negative voltage.

Polarity	$d_{31nonli}[\mathbf{m/V}]$	100% Permanent
		Strain Offset
Positive	$-15.64 \times 10^{-17} \times (E) -2.58 \times 10^{-10}$	$-3.41 \times 10^{-5}$
Negative	$-3.13 \times 10^{-16} \times (E) -1.57 \times 10^{-10}$	$2.42 \times 10^{-4}$

Table 6.4: Nonlinear  $d_{31nonli}$  coefficients under positive and negative fields. E is the electric field. The nonlinear piezoelectric coefficient was obtained when the piezoelectric was under a non-discharging condition and the strain state was un-tuned back to the zero state. These coefficients are identical as shown in Table 4.1 in section 4.2.2.



Figure 6.20: Experimental results of [G/PZT/G/G/C] under a discharging condition compared to the model with linear piezoelectric and nonlinear piezoelectric coefficients. Left: the actuator was actuated under a positive voltage. Right: the actuator was actuated under a negative voltage.



Figure 6.21: Experimental results of [G/PZT/G/C/G/C] under a discharging condition compared to the model with linear piezoelectric and nonlinear piezoelectric coefficients. Left: the actuator was actuated under a positive voltage. Right: the actuator was actuated under a negative voltage.

Layup	Original In	itial Strain	Corrected I	nitial Strain	Percentag	ge Difference
	$Pos(\times 10^{-5})$	$Neg(\times 10^{-4})$	$Pos(\times 10^{-5})$	$Neg(\times 10^{-4})$	Pos(%)	Neg(%)
[G/PZT/G/C]	-3.41	2.42	-6	1.2	+76	-50
[G/PZT/G/G/C]	-3.41	2.42	-10.5	0.97	+208	-60
[G/PZT/G/C/G/C]	-3.41	2.42	-11.7	0.97	+243	-60

Table 6.5: Corrected initial strains inside a piezoelectric material to fit with displacement offsets of each actuator layup. The 'Pos' and 'Neg' represent a positive and negative polarities, respectively. The '-' sign represents a percentage reduction. The '+' sign represents an increase in percentage.

#### Positive Voltage

Figures 6.19 to 6.21 illustrate that the "Model Nonlinear 100%strain" show closer agreement to the experimental results when compared to the "Model Linear". The Model Linear shows a different initial displacement offset when compared to the Ex Discharged because the "Model Linear" does not contain irreversible 90° domain wall orientations inside the linear piezoelectric coefficient. The "Model Nonlinear 100%strain" exhibits smaller initial displacement offset from the experimental result. In order to correct for the initial displacement offset from the model, the initial strain offset inside a piezoelectric coefficient must be increased. This is because the piezoelectric layer is imposed by large tensile stress when actuated according to the positive polarity as discussed in section 6.4.2. The new strains are tabulated in table 6.5. After the strain correction, the "Model Nonlinear corrected strain", shows better initial displacement offset alignment to the experimental results.

The actuator layup [G/PZT/G/C] has approximately 76% increment of its initial strain; the actuator layup [G/PZT/G/G/C] has approximately 208% increment of its initial strain and the actuator layup [G/PZT/G/C/G/C] has approximately 243% increment of its initial strain. The trend of increasing in initial strain depends on how much the piezoelectric material experiences tensile stress. With an example of Figure 6.22, the layup [G/PZT/G/C] possess the smallest proportion of tensile stress throughout the piezoelectric material's thickness in relation to compressive stress when compared to the layups [G/PZT/G/G/C] and [G/PZT/G/C/G/C]. The layup [G/PZT/G/C/G/C] exhibits the largest proportion of tensile stress throughout the piezoelectric material's thickness in relation to compressive stress than the other two layups, thus, more  $90^{\circ}$  domain wall orientations are promoted when compared to the other layups. Thus, the layup [G/PZT/G/C/G/C] requires more initial strain to correct with the initial actuation displacement. In contrast, the reduced amount of strain offset under a negative potential, Table 6.5, when the piezoelectric material is under more compression, is approximately similar in all actuator layups, i.e. approximately 50 - 60% in all layups. This could be explained that proportion of the tensile stress throughout the piezoelectric material's thickness of all actuator layups are more than the proportion of the compressive stress. This indicates that the tensile stress has more influence to the domain walls movement than the compressive one, leaving similar magnitudes of reduced initial strain of all the layups. After all the initial strain offsets have been accounted for, the initial displacement offsets obtained from the model nonlinear corrected strain of all the actuator layups show good alignments with the initial displacement offsets obtained from the experimental results.



Figure 6.22: Internal stress throughout the piezoelectric thickness at 0V or after the manufacturing process.

The error percentages of the experimental results from both charging conditions and the predicted actuation displacements at  $\pm 200$ V are shown in tables 6.6 and 6.7. It can be observed that the models including the nonlinear piezoelectric coefficient obtained from the standard approach show a large error at  $\pm 200$ V. The models incorporating nonlinear piezoelectric coefficients from the two non-standard methods have a substantially smaller error. This substantial reduction illustrates the importance of taking into account the nonlinear effects from the voltage dependent effects and the residual strain offset. The residual strain offset effect gives more impact to the overall actuation displacements when compared to the nonlinear effect from the voltage dependent because the residual strain offset shifts the starting actuation displacement of the actuators, while the nonlinear effect from the voltage dependent influence the actuation displacements at large voltage magnitudes. The layup [G/PZT/G/C/G/C] shows an increase in error at -200V when the models and the experimental results are compared, tables 6.6 and 6.7. The increase in error is shown in the models incorporating the two piezoelectric coefficients obtained from the two non-standard methods. The increasing error comes from the initial residual strain in the piezoelectric material that has not been fine-tuned to reduce to achieve a perfect magnitude to fit with the permanent displacement offset at -0V with the experimental results, this effect can also be seen in figures 6.12(right) and 6.21(right). It can be observed that the reduced amount of strain offset in the case of nonlinear piezoelectric coefficients: discharged with untuned strain state is -50%, table 6.3, and for the case of nonlinear piezoelectric coefficients: discharged with un-tuned strain state is -60%, table 6.5. These two amount of reduced strain offsets were approximated to provide a rough idea for how much strian offset should be reduced.

		Standard	d PZT coefficient ap	proach		
Layup	Model at	Experimental	[%]Error	Model at	Experimental	[%]Error
	+200V[mm]	Discharged	Model at $+200V$	-200V [mm]	Discharged	Model at -200V
		+200V [mm]	vs Experimental		-200V [mm]	vs Experimental
			Discharged			Discharged
[G/PZT/G/C]	-0.82	-1.53	46.01	1.35	1.96	31.2
[G/PZT/G/G/C]	-0.78	-1.77	55.56	1.42	1.80	20.6
[G/PZT/G/C/G/C]	-1.06	-1.79	40.05	1.50	1.70	9.8
Nonline	ar PZT coefficient	under a discharg	ging condition but st	rain state was un-	tuned to the zer	o state
Layup	Model with	Experimental	[%]Error	Model with	Experimental	[%]Error
	corrected strain	Discharged	Model at $+200V$	corrected strain	Discharged	Model at -200V
	+200V[mm]	+200V[mm]	vs Experimental	-200V [mm]	-200V [mm]	vs Experimental
			Discharged			Discharged
[G/PZT/G/C]	-1.23	-1.53	-19.22	2.08	1.96	6.1
[G/PZT/G/G/C]	-1.77	-1.77	-0.05	1.89	1.79	5.4
[G/PZT/G/C/G/C]	-1.98	-1.79	10.71	1.89	1.66	13.8
Nonlinear	PZT coefficient ur	nder a non-discha	arging condition and	strain state was u	in-tuned to the z	tero state
Layup	Model with	Experimental	[%]Error	Model with	Experimental	[%]Error
	corrected strain	Discharged	Model at $+200V$	corrected strain	Discharged	Model at -200V
	+200V[mm]	+200 V[mm]	vs Experimental	-200 V [mm]	-200V [mm]	vs Experimental
			Discharged			Discharged
[G/PZT/G/C]	-1.27	-1.53	-16.60	1.96	1.96	0.1
[G/PZT/G/G/C]	-1.55	-1.77	-12.32	1.91	1.79	6.9
[G/PZT/G/C/G/C]	-2.07	-1.79	15.58	1.99	1.66	20.0

ts	
men	
lace	
disp	
tion	
ctua	
ed a	
edict	
e pro	
nd th	
n ar	
ditio	
con	
ging	
schar	
a dis	
nder	
ts ur	
resul	
ntal	
rime	
expe	
een e	
oetw	
ror	
ge er	
entag	
Perce	
.6: F	.VOC
ble 6	± 2(
Ta	at

		Standard	<u> 1 PZT coefficient a</u>	proach		
Layup	Model at	Experimental	[%]Error	Model at	Experimental	[%]Error
	+200 (mm]	Non-Discharged	Model at +200V we Experimental	-200V [mm]	Non-Discharged	Model at -200 vs Exneriment
			Non-Discharged			Non-Discharg
[G/PZT/G/C]	-0.82	-1.15	28.40	1.34	1.96	31.48
[G/PZT/G/G/C]	-0.78	-1.32	40.49	1.42	1.84	23.13
[Ġ/PZT/Ġ/Ċ/Ġ/Ċ]	-1.07	-1.58	32.09	1.49	1.69	11.67
Nonlir	near PZT coefficie	nt under a discharg	ging condition but s	train state was un-	tuned to the zero s	state
Layup	Model with	Experimental	[%]Error	Model with	Experimental	[%]Error
	corrected strain	Discharged	Model at +200V	corrected strain	Discharged	Model at -200
	+200V[mm]	+200V [mm]	vs Experimental	-200V [mm]	$-200V \ [mm]$	vs Experimen
			Non-Discharged			Non-Discharg
[G/PZT/G/C]	-1.23	-1.15	7.12	2.08	1.97	5.70
[G/PZT/G/G/C]	-1.77	-1.31	33.84	1.89	1.85	2.04
[Ġ/PZT/Ġ/Ċ/Ġ/Ċ]	-1.99	-1.58	25.40	1.89	1.70	11.48

ά	
ğ	
g	
:=	
9	
L L	
.9	
ät	
Ē	
H	
ğ	
a B	
Ř	
.≅	
8	
Ĕ	
0	
ē	
구	
—	
2	
al	
2	
<u>ت</u> .	
÷=	
ĕ	
ō	
0	
<b>b</b> 0	
. 20	
F	
Ĩ	
ů.	
-0	
ċ	
<u> </u>	
р	
_	
<u>e</u>	
ĕ	
Б	
S	
<u>1</u>	
Ц	
ŝ	
2	
Ē	
4	
L L	
é	
.≘.	
5	
ă	
X	
Ð	
L	
ê	
¥	
口	
é	
<u> </u>	
7	
ž	
e	
<u>ر</u> ه	
ക്	
, D	
ht	~
ē	$\geq$
2	č
e	5
Δ	_1
	+
∽.	÷
9	đ
Ð	Y
Ā	Ē
	<b>a</b>

## 6.6 Understanding the Static Behaviour

Asymmetry of the actuation displacements can be seen between two polarities and it is a result of the unequal permanent displacement offset. Parameters influencing the asymmetry of the actuation displacement of all actuators are discussed in this section.

## 6.6.1 Predicted Actuation Displacements

The predicted actuation trends for the actuators under positive polarity using a piezoelectric coefficient obtained from a standard method, shown in figure 6.23, do not entirely follow the experimental results, shown in figures 6.24 and 6.25. The displacement at  $\pm 200$ V are clearly smaller than those obtained in the experiments. This is because the nonlinear piezoelectric material coefficient obtained using a standard method did not contain a permanent residual strain offset.



Figure 6.23: Predicted actuation displacements with nonlinear piezoelectric coefficient obtained from a standard approach, a '+' sign in front of each layup represents a positive voltage apply to the actuator a '-' sign in front of each layup represents a negative voltage apply to the actuator.



Figure 6.24: Combined experimental results of all actuators under both positive and negative voltages when the actuators were not discharged prior to the application of the next higher voltage, a '+' sign in front of each layup represents a positive voltage apply to the actuator, a '-' sign in front of each layup represents a negative voltage apply to the actuator.



Figure 6.25: Combined experimental results for all tested actuators under both positive and negative voltages when the actuators were discharged prior to the application of the next higher voltage, a '+' sign in front of a layup represents a positive voltage apply to the actuator, a '-' sign represents a negative voltage apply to the actuator.

A shift in the initial displacement of the actuators can be observed when the permanent displacement offsets are included in the model, see figures 6.26 and 6.27. Two piezoelectric coefficients obtained using two non-standard methods produced identical displacement trends. This indicates that identical actuation trends will be produced as long as the strain state remains permanently inside the piezoelectric material in these actuators regardless of the charging conditions. The trends of the predicted displacements, as shown in figure 6.26, are identical to the experimental results, as shown in figure 6.25, when the actuators have discharged. Similarly, the trends of the predicted displacements, figure 6.27, are identical to the experimental results, shown in figure 6.24, when the actuators have not been discharged.



Figure 6.26: Predicted actuation displacements with nonlinear piezoelectric coefficients obtained under a discharging condition and the strain state was un- tuned to zero. A '+' sign in front of each layup represents a positive voltage apply to the actuator. A '-' sign in front of each layup represents a negative voltage apply to the actuator.



Figure 6.27: Predicted actuation displacements with nonlinear piezoelectric coefficients obtained under a non-discharging condition and the strain state was un-tuned to zero. A '+' sign in front of each layup represents a positive voltage apply to the actuator. A '-' sign in front of each layup represents a negative voltage apply to the actuator.

## 6.6.2 Discussions and Conclusions

The actuation response of an actuator without the influence of the permanent displacement offset can be investigated by subtracting the actuation displacements from its own displacement offset for each polarity. The results are shown in figure 6.28. Within a small electric field range,  $\leq \pm 50$ V as observable within this study, all actuators behave almost indistinguishably; i.e. there is no big influence from different layups of the actuator. Within the range, between  $\pm 50$ V and  $\pm 100$ V, the actuators' performance starts to be distinguishable. Considering the high voltage range,  $\geq \pm 100$ V as observed within this study, each individual layup shows differences in its actuation response. This indicates that without a permanent displacement offset; nonlinear actuation displacement distinguishes the actuation response of the individual layup, see figure 6.28. Nevertheless, the nonlinear range still shows less influence of actuation response from different layups when compared to the large impact of the permanent displacement offset, see figures 6.24 and 6.25.



Figure 6.28: Experimental results of all actuators under both positive and negative voltages without the permanent strain offsets, a '+' sign in front of each layup represents a positive voltage apply to the actuator, a '-' sign in front of each layup represents a negative voltage apply to the actuator.

Thus it can be concluded that, the first parameter that influences an actuator's performance is the permanent displacement offset. The second parameter that influences the performance of the actuator is the piezoelectric nonlinear effect that yields the nonlinear actuation displacement in correspondence to the input voltage. The last parameter is the linear piezoelectric effect that governs the linear electric field range, i.e.  $\leq \pm 50$ V. If the actuators are going to be operated in the linear range or at a very low input voltage, the actuator's layup does not play a role, thus, any layups will produce similar results. If the actuators are operating in the nonlinear range, the actuator's layup play a major role by influencing two effects to the actuators, i.e. permanent displacement offset and the nonlinear response.

## 6.7 Discussions and Conclusions

Finite element models were developed to predict the actuation displacements of piezoelectric composite material actuators. Three different layups actuators were manufactured for this investigation. The predicted actuation displacements were compared with the experimental results obtained under two unipolar DC input voltages, i.e. positive and negative voltages. The application of the unipolar input voltage exhibited asymmetry actuation displacement between the positive and negative polarities. The asymmetry results from the permanent displacement offsets, and is cause by the unequal response of the irreversible 90° domain wall orientations of the piezoelectric materials, which result from a large application of an electric field to an actuator. The actual magnitudes of permanent residual strain offsets at the piezoelectric material are very small, see chapter 4, but they are amplified during actuation and become large out-of-plane displacement offsets.

In this thesis it is demonstrated that neither the nonlinear piezoelectric coefficient obtained using a standard approach nor a linear piezoelectric coefficient obtained from a manufacturer are capable of predicting the actuation displacements when the actuator is actuated with a larger electric voltage accurately. This is due to a lack of a permanent strain offset value inside the piezoelectric material using the standard method and a linear piezoelectric coefficient. The other two novel methods used to determine nonlinear piezoelectric coefficients are capable of picking up the permanent displacement offset. This permanent displacement offset has been proved to be a major cause of actuation asymmetry and has been proved to be the first parameter influencing actuation performance.

Looking at the parameters influencing actuation performance, it can be concluded that the permanent displacement offset dominates the actuation performance. The nonlinear piezoelectric effect in the form of nonlinear actuation displacements corresponding to input electric potential is the second parameter that influence an actuator's performance. Lastly, the linear piezoelectric effect has the smallest influence on the actuator's performance. In practice, operating an actuator in the small voltage range,  $\leq \pm 50$ V as shown in this study, the performance of the actuator does not depend on the actuator's layup. Once one begins operating in the higher voltage range,  $\geq \pm 100$ V shown in this study, the actuator performance is mainly layup dependent.

## References

- N.S. Goo and K.J. Yoon. Analysis of lipca-c actuators. International Journal of Modern Physics B, 17(8/9; PART 2):1959–1964, 2003.
- [2] KY Kim, KH Park, HC Park, NS Goo, and KJ Yoon. Performance evaluation of lightweight piezo-composite actuators. Sensors and Actuators A: Physical, 120(1):123–129, 2005.
- [3] K. Park, Y. Kim, Y.S. Kim, H.C. Park, and K.J. Yoon. Experimental performance evaluation of lightweight piezo-composite curved actuators. In *Proceed*ings of SPIE, volume 4699, page 315, 2002.
- [4] R.W. Schwartz and YW Moon. Domain configuration and switching contributions to the enhanced performance of rainbow actuators. SPIE Smart Structures and Materials, Active materials: Behavior and Mechanics, 4333(408):201, 2001.
- [5] S.C. Woo, K.H. Park, and N.S. Goo. Influences of dome height and stored elastic energy on the actuating performance of a plate-type piezoelectric composite actuator. Sensors and Actuators A: Physical, 137(1):110–119, 2007.
- [6] KJ Yoon, KH Park, HC Park, and D. Perreux. Thermal deformation analysis of curved actuator lipca with a piezoelectric ceramic layer and fiber composite layers. *Composites science and technology*, 63(3-4):501–506, 2003.
- [7] K.J. Yoon, S. Shin, H.C. Park, and N.S. Goo. Design and manufacture of a lightweight piezo-composite curved actuator. *Smart Materials and Structures*, 11:163, 2002.
- [8] G. Li, E. Furman, and G.H. Haertling. Stress-enhanced displacements in plzt rainbow actuators. *Journal of the American Ceramic Society*, 80(6):1382–1388, 1997.

# Chapter 7

# Finite Element Models of Actuators: Under Dynamic Condition

A finite element model to predict the actuators' dynamic performance is presented in this chapter. The predictions of the actuators' dynamic behaviour will be compared with the dynamic experimental results in chapter 8. The chapter is divided into two sections. The model to predict the dynamic actuation displacements and resonance frequencies of the actuators is presented in subsection 7.1.1. The 3D model geometry of the actuator is presented in subsection 7.1.2. The dynamic experimental setup is presented in section 7.2.

## 7.1 Dynamic Finite Element Model

The model that describes the dynamic behaviour of the actuator is comprised of two coupled sub-models, namely a solid mechanics sub-model and a piezoelectric device sub-model. The solid mechanics model predicts the manufactured shapes of the actuator, the piezoelectric device model predicts the dynamic responses such as resonance frequencies and actuation displacements of the actuator. The differences between the piezoelectric device discussed in this chapter and the one discussed in chapter 5 is that the frequency response of the system is taken into account for the dynamic model. Only the piezoelectric device from the frequency study will be discussed in this chapter, the solid mechanics of the model, which are identical to those presented in chapter 5, are not repeated in this chapter, please see chapter 5 for a detailed explanation of the solid's mechanics.

### 7.1.1 Dynamic Model

The piezoelectric device from COMSOL comprises two sub-interfaces: a solid mechanics part made of a piezoelectric material and an electrostatic part made of a piezoelectric material. A brief explanation of the piezoelectric device interface starts with a linear model, where the deformation of the actuator is small and continues until the deformation becomes large and the model becomes nonlinear.

#### Linear Model

The solid mechanics part of a piezoelectric material is described using the *principle* of virtual work, equation 7.1 [1]:

$$-\rho\omega^2 u - \nabla \cdot \sigma = F_V e^{i\phi} \tag{7.1}$$

where  $-\rho\omega^2 u$  represents the inertia of the system,  $\omega$  represents the angular frequency,  $\rho$  is the material density and u is the displacement. The term  $-\nabla \cdot \sigma$  represents the Cauchy stress and the virtual strain of the system,  $\nabla$  is the divergence, the term  $F_V e^{i\phi}$  represents the input force in a harmonic excitation load. Under the static condition, where the angular frequency is zero and there is no damping effect, the term  $-\rho\omega^2 u$  is omitted and the right hand side of equation 7.1 will be a static force, i.e. without the  $e^{i\phi}$  term, as shown in equation 7.2.

$$-\nabla \cdot \sigma = F_V \tag{7.2}$$

The converse piezoelectric constitutive relation with initial stress and strains is:

$$\varepsilon - \varepsilon_o = s_E : (\sigma - \sigma_o) + d^T \cdot E \tag{7.3}$$

where  $\sigma$  and  $\sigma_o$  represent Cauchy stress and initial Cauchy stress, respectively, the  $\epsilon$  and  $\epsilon_o$  represent strain and initial strain, respectively,  $s_E$  is the elastic compliance,  $d^T$  is the piezoelectric coefficients and T represents the transpose of the matrix, E is the input electric field, ":" stands for a double-dot tensor product, or a double contraction. The electrostatic part of a piezoelectric material is described by one of the Maxwell's equations, i.e. Gauss' law, which describes the electrostatic field in the dielectric material:

$$\nabla \cdot \left( D + \frac{J_i}{j\omega} \right) = \rho_V \tag{7.4}$$

where D is the electric charge displacement,  $J_i$  is the current density,  $\rho_V$  is the space-charge density, j represents the complex value of the loss factor, and  $\omega$  represents the angular frequency. The electric field is defined by:

$$E = -\nabla V \tag{7.5}$$

where V is the electric potential.

The electric charge displacement is related with the electric field and the stress by the following equation:

$$D - D_r = e : (\sigma - \sigma_o) + \epsilon_s \cdot E \tag{7.6}$$

where  $D_r$  is the initial electric charge displacement,  $\epsilon_s$  the static permittivity,  $e = ds_E^{-1}$ .

#### Nonlinear Model

As discussed in chapter 5 the actuator exhibited a large actuation displacement, therefore, the linear model ceased to be valid. To model a large actuation displacement, a nonlinear finite element model needs to be introduced into the dynamic model. To achieve the nonlinear model, the Cauchy stress,  $\sigma$ , is replaced with the 2<sup>nd</sup> Piola-Kirchhoff stress tensor, denoted S, and the strain tensor is replaced by the Green-Lagrange strain tensor and use a Total Lagrangian formulation, see also chapter 5 how the stress and strain are represented. The electrostatic part of a piezoelectric material, equation 7.4, is split into two parts: the polarization energy within the solid part and the electric energy of free space occupied by the deformed solid part [1]. The polarization energy within the solid:

$$\nabla_m \cdot \left( P_m + \frac{J_{im}}{j\omega} \right) = \rho_V \tag{7.7}$$

where  $P_m$  is the electric polarization in the material orientation,  $J_{im}$  is the current density at the deformed configuration, the subscript 'm' denotes the material orientation of the deformed configuration<sup>1</sup>.

The electric energy of free space occupied by the deformed solid can be explained in an equation 7.8. The subscript 's' represents a global coordinate of the system.

$$\nabla_s \cdot (\epsilon_0 E) = 0 \tag{7.8}$$

The electric charge displacement relation, equation 7.6, is replaced by an expression that produces electric polarization in the material orientation:

$$P_m - D_r = d : (S - S_o) + \chi_s \cdot E_m$$
(7.9)

where  $E_m$  is the electric field at the deformed configuration, S and  $S_o$  are the  $2^{nd}$  Piola-Kirchhoff stress and initial stress tensors, respectively. The term  $\chi_s$  is the dielectric susceptibility<sup>2</sup>, and defined as:

$$\chi_s = (\epsilon_s - \epsilon_0) I \tag{7.10}$$

The loss factor is the fractional loss of energy per cycle. The given value of the loss factor is in the form of mechanical quality factor  $Q_m$ :

$$\eta_s = \frac{1}{Q_m} \tag{7.11}$$

The mechanical quality factor of a piezoelectric material that was given by the manufacturer was 80. The loss factor appears in the stress-strain relationship as:

$$S - S_0 = (1 + j\eta_s) \ c_E : (\varepsilon - \varepsilon_0) - e^T \cdot E_m$$
(7.12)

<sup>&</sup>lt;sup>1</sup>similar to at time t or t  $+\Delta t$  in Chapter 5. All the variables in the material orientation are transformed back to the initial configuration through the transformation gradient as discussed in chapter 5.

<sup>&</sup>lt;sup>2</sup>The dielectric susceptibility  $\chi$  is a constant to quantify the degree of polarization of a dielectric material in response to an applied electric field. The greater the dielectric susceptibility, the greater the ability of a material to polarize in response to the field.

where  $c_E$  is the elastic of piezoelectric material,  $e = d s_E^{-1}$ , T represents the transpose of the matrix, d is the piezoelectric coefficient, j represents the complex value of the loss factor.

## 7.1.2 Actuator Configuration

The actuator was modeled in 3-dimensions in COMSOL. The actuator model was made in 3-dimensions in the dynamic case, while it was in 2-dimensions in the static case, because the 3D model allows one to investigate if there is a distortion of an actuator along the actuator's width during the dynamic actuation at high frequencies, especially at the resonance. The distortion will show different actuation displacements along the actuator's width. The displacements at the resonance frequencies were investigated at the actuator's tip, point 'A' in a figure 7.1. The dimensions of the actuator used for the model were as given in figure 7.1.



Figure 7.1: Actuator dimension. (a) represents the actual actuator dimension and as it is in the model. The actual actuator's width is 26 mm. The actuator's width is reduced in half. (b) a side-view of the model of an actuator.

A symmetry plane was introduced into the model to reduce the model size to half in order to reduce the simulation time. The symmetry plane was placed along the actuator's length to reduce the width of the actuator to half as shown in figure 7.2, thus, the actuator width in the model is 13 mm, figure 7.1(a), instead of 26 mm. The actuator's boundary conditions during the manufacturing process were simplysupported and, during actuation, a cantilever beam condition, where one end is fixed with no rotation and deflection and the other end is free to deflect, figure 7.3.



Figure 7.2: Symmetry plane and prescribed displacement. The x, y and z-axes represent the length, width and thickness direction of the actuator. The symmetry plane passes through the actuator's width along the length of the actuator.



Figure 7.3: Boundary conditions of an actuator, (a) during manufacturing the actuator is simply-supported, (b) during actuation the actuator is in a cantilever beam condition.

## 7.2 Dynamic Experimental Setup

The experimental setup for the dynamic testing was identical to that reported in chapter 5. The actuators were actuated under the dynamic operating condition at a range of frequencies from 1 Hz - 80 Hz with an increment of 0.5 Hz; and sinusoidal

input signals with amplitudes of 10V, 40V and 70V. To ensure the repeatability of the actuation response, each actuator was actuated 5 times at each input sinusoidal amplitude and the results were averaged. The dynamic experimental results are compared to the models in chapter 8.

# References

[1] COMSOL Multiphysics 4.2. Comsol multiphysics, Accessed 5/11/2012.
# Chapter 8

# Dynamic Behaviour of Piezoelectric Composites Actuators

The static behaviour of piezoelectric composites actuators was discussed in chapter 6. The dynamic behaviour of the actuators will be discussed in this chapter. This chapter is divided into five sections, with the introduction given in section 8.1. The dynamic experimental results for the actuators are presented in section 8.2. A comparison of the dynamic behavior predictions and the dynamic experimental results for all the actuators is discussed in section 8.3. The dynamic behavior predictions were obtained using the models presented in chapter 7 incorporating the piezoelectric material properties discussed in section 8.4. The conclusions of this chapter are presented in section 8.5.

# 8.1 Introduction

The static behavior of stress-bias actuators, such as THUNDER and LIPCA, has been studied on the macroscopic level, see chapter 2, however there is a limited number of studies on the dynamic behaviour of such actuators. Mossi et. al. [1] conducted dynamic experiments to compare THUNDER and LIPCA actuators at a frequency range from 1 Hz - 300 Hz and with various input voltages. The results indicate that a LIPCA actuator exhibits significantly larger displacements than a THUNDER actuator. The authors comment that a LIPCA actuator experiences a higher electric field since the electric leads are directly connected to the PZT layer, whereas in the case of a THUNDER actuator, the applied electric field has to pass through the metal and an adhesive layer. Woo et. al. [2] have performed dynamic testing of square plates of PZT material embedded inside composite laminates with various stacking sequences under simply-supported and cantilever beam configurations. They conclude that the actuation performance of an actuator depends on the moment arm from the PZT mid-plane to the actuator neutral axis, the larger the moment arm, the greater the actuation displacement [2].

Within this chapter, investigations of the dynamic behaviour of three different actuator layups will be discussed. The layups are identical to those used for the static operating condition case as presented in chapter 6. The results of the finite element model discussed in section 7.1 will be compared to the dynamic experimental results of all the actuators. The dynamic experimental conditions 1) a frequency range from 1 Hz to 80 Hz and 2) the input voltage amplitudes were 10. 40 and 70V. The frequency range of up to 80 Hz was chosen to cover the first resonance frequency of all the actuators. The first resonance frequency is interesting because it provides the largest actuation displacement. The input voltage amplitude limitation under an AC electric field, was given by the manufacturer, for the particular piezoelectric material used in this study, and was 90V. Thus, the highest voltage amplitude used in this study was chosen to be 70V to ensure that the piezoelectric material would not over-exposed to a high input electric voltage that might cause depolarization of the piezoelectric material. The objective was to investigate the dynamic behavior of the actuators and understand which parameters influence the dynamic performance of the actuators under dynamic operating condition.

# 8.2 Dynamic Experimental Results

The dynamic experimental results of the peak-to-peak displacements<sup>1</sup> at the resonance frequencies of the three actuators layups are presented in figure 8.1. It can be observed that the resonance frequencies decrease as the input voltage increases. This is because the resonance frequency of the piezoelectric material is inversely proportional to the square-root of the compliance, as explained in chapter 4. This implies that, with increasing input voltage amplitude, the piezoelectric's mechanical compliance increases resulting in a decrease in the resonance frequency. The overall actuation trends showed that the layup [G/PZT/G/C] performed the best, while [G/PZT/G/G/C] and [G/PZT/G/C/G/C] showed relatively similar peak-to-peak displacement magnitudes. The performance and the parameters governing the dynamic performance of the actuators will be discussed in section 8.4. The

<sup>&</sup>lt;sup>1</sup>The peak-to-peak displacements are a summation of the actuation displacements of an actuator at the two peaks voltage amplitude, e.g. at +70V and -70V.

difference in the initial displacement of each layup could be explained from the influence of 90° domain wall orientations explained in chapter 6. From the result in chapter 6, it could be explained that the layup [G/PZT/G/C] exhibited the largest initial displacement offset under the negative polarity compared to the other two layups, therefore, the layup [G/PZT/G/C] exhibited the largest initial displacement of all, figure 8.1. The layup [G/PZT/G/C] showed the second largest initial displacement offset, therefore, it exhibited a smaller initial displacement offset than the layup [G/PZT/G/C] but larger than the layup [G/PZT/G/C/G/C]. Only the displacement offset under the negative polarity was taken into consideration because there was more influence of the 90° domain wall orientations under the negative polarity than the positive one, Chapter 6. It is more difficult for the irreversible 90° domain walls along the negative polarity to reorient back to their initial state than when they have been oriented along the positive polarity.



Figure 8.1: Dynamic experimental results of the peak-to-peak displacements of the [G/PZT/G/C], [G/PZT/G/C] and [G/PZT/G/C/C]. The voltages shown in the plots represent sinusoidal amplitudes of the input electric voltage.

# 8.3 Dynamic Experimental Results vs Dynamic Models

The peak-to-peak actuation displacements predicted by the COMSOL models will be compared here to the dynamic experimental results. Following the discussions of chapter 4, the properties of a piezoelectric material depends on the input voltage, and the internal stress inside a piezoelectric material. The latter varies depending on the individual layup. This means that to get accurate predictions of the actuation displacements and resonance frequencies, it is necessary to vary the piezoelectric material properties of the individual layups at each input voltage and include these in the models.

The elastic compliance was varied to fit the shifted resonance frequencies; while the piezoelectric coefficient,  $d_{31}$ , was varied to fit the actuation displacements <sup>2</sup>. The elastic compliance and piezoelectric coefficient were varied according to the constants  $\beta$  and  $\gamma$ , respectively, as introduced in Chapter 4.

### Actuator Layup [G/PZT/G/C]

It can be observed that the models showed shifting of resonance frequencies and actuation displacements similar to the experimental results depicted in figures 8.2 (a) and (b). The actuation displacements between the models and experiments are shown in figure 8.2(c). It can be observed that the actuation displacements are linearly related to input voltage, and the model shows very close predictions to the experiments. The largest percentage error between the model and the experimental result is 11.8%, found at a 70V amplitude. The rates of change of the displacements with voltage, denoted by x, between predictions and experiments are almost identical.

Differences in the resonance frequencies between the models and experiments are shown in figure 8.2(d). It can be observed that the resonance frequencies decrease linearly with increasing input voltage; and the model shows a good fit to the experiments. Moreover, the rate of change of the resonance frequencies, denoted by x, from the models show close fit to the experiments. At a 70V input amplitude, the resonance frequency prediction calculated a 2% lower value than that found for the experimental measurements. Similar resonance frequencies reductions have

<sup>&</sup>lt;sup>2</sup>The dielectric permittivity  $\epsilon_{33}$  was not varied because the dielectric permittivity shows how much electrical displacement, or electric charge, is produced when a mechanical stress is applied to a piezoelectric material. This dielectric permittivity becomes significant in the sensing mode but does not need to be taken into consideration in the actuator models

been observed by Mossi et al. [1], Woo et al. [2] and Ounaise et al. [3], who state that the reduction of the resonance frequencies with increasing input voltages is a result of the piezoelectric material softening, or reduction of elastic modulus [3].



Figure 8.2: Experimental results vs predictions from COMSOL models of [G/PZT/G/C], (a) Experimental results, (b) Predicted peak-to-peak displacements from with varied piezoelectric material properties, (c) Experimental results and predictions of peak-to-peak actuation displacements taken at the resonance frequencies, (d) Experimental results and predictions of resonance frequencies. The dotted lines in (c) and (d) represent linear curve fitting of the experimental results and of the COMSOL model, x in (c) and (d) represents the input voltage amplitudes.

### Actuator Layup [G/PZT/G/G/C]

Similar trends between the models and experiments are shown in figures 8.3(a) and (b). It can be observed that the model shows a very close fit of the rate of increase of the actuation displacements as a function of voltage when compared to the experiments, figure 8.3(c). The model under-predicts the displacements of the actuator layup [G/PZT/G/G/C] at a 70V amplitude by 14.8%, figure 8.3(c). The rates of decrease of the resonance frequencies as a function of input voltage between the model and the experiments were identical. The models under-predicted the resonance frequency at a 70V amplitude by 0.87%, figure 8.3(d).



Figure 8.3: Experimental results vs predictions from COMSOL models of [G/PZT/G/G/C], (a) Experimental results, (b) Predicted peak-to-peak displacements from COMSOL model with varied piezoelectric material properties, (c) Experimental results and predictions of peak-to-peak actuation displacements taken at the resonance frequencies, (d) Experimental results and predictions of resonance frequencies. The dotted lines in (c) and (d) represent linear curve fitting of the experimental results and of the COMSOL model, x in (c) and (d) represents the input voltage amplitudes.

### Actuator Layup [G/PZT/G/C/G/C]

Decreasing of the resonance frequencies from both the experiments and the predictions are shown in figures 8.4(a) and (b). Peak-to-peak displacements at the resonance frequencies of the model are very close to the experiments and increases linearly with increasing input voltage, figure 8.4(c). The model shows a very good fit of slope of the displacements versus input voltage, when compared to the experimental results. The model over-predicts the displacement at the 70V input amplitude by 8.47%. The resonance frequencies decreases linearly with the input voltage. The slope of the resonance frequency versus input voltage between the models and experiments also shows a good fit, figure 8.4(d). The model underpredicts the resonance frequency at the 70V input amplitude by 0.7%, figure 8.4(d).



Figure 8.4: Experimental results vs predictions from COMSOL models of [G/PZT/G/C/G/C], (a) Experimental results, (b) Predicted peak-to-peak displacements from COMSOL model with varied piezoelectric material properties, (c) Experimental results and predictions of peak-to-peak actuation displacements taken at the resonance frequencies, (d) Experimental results and predictions of resonance frequencies. The dotted lines in (c) and (d) represent linear curve fitting of the experimental results and of the COMSOL model, x in (c) and (d) represents the input voltage amplitudes.

Looking at figures 8.2 to 8.4, the model successfully predicts the resonance frequencies and peak-to-peak actuation displacements of the three actuator layups in a frequency range of 1 - 70Hz with various input voltages. The model predicts a good fit of the slope, of displacements and resonance frequencies, with the experiments. These predictions are useful for actuator designers to predict the displacements and the resonance frequencies of the actuators in a frequency range and at various input voltages. The errors found between the model and the actuation displacement experimental results are in a larger magnitude than the errors between the model and the resonance frequencies. This could be due to the coarse values of piezoelectric coefficients given to the model to fit with the actuation displacements, thus, if finer values of the piezoelectric coefficients can be provided to the model to have a better fit with the experimental data. Another source of error could also come from the mis-alignment of fibres during hand layup, this can lead to changes in an actuator's stiffness and cause actuation displacement during testing. Another mismatch between the model and the experimental result was the initial displacement offset before the actuator reached its resonance frequency. A shift of the initial displacement produced by the actuator before the resonance frequency and the sudden displacement drop to zero after the actuator reaches its resonance frequency can be explained using a dynamic amplification factor (DAF) [4], sometimes known as a dynamic magnification factor, for the system, figure 8.5. The DAF was not included in the model, although, it presents quantitatively of the dynamic response, relative to the static response [4] or it indicates how much the displacement will be magnified compared to the static displacement of the system. The DAF is given by equation 8.1:

$$DAF = \frac{1}{\sqrt{(1-r^2)^2 + (2\cdot\eta\cdot r)^2}}$$
(8.1)

where  $\eta$  is a damping coefficient of the system and 'r' is a frequency ratio between an external applied frequency to the system's natural frequency. The term 'r' is therefore  $\omega/\omega_n$ .



Figure 8.5: Dynamic amplification factor of a system.

It can be observed from equation 8.1 and figure 8.5 that when r = 0, i.e. no external frequency is applied to the system, it is a pure static case, and a DAF is one. At the static region, the actuation displacement depends on an actuator's stiffness. When r approaches one, i.e. the applied frequency is equal to the system's natural frequency, the DAF approaches infinity, resulting in a very large

dynamic displacement. When r is very large, the DAF is less than one, i.e. the dynamic actuation displacement vanishes. This means the dynamic load shows less influence on the system than the static load. In other words, if the external frequency is very high the system does not have enough time to respond to a high input frequency. This results in a less dynamic response from the system, and this explains the sudden drop in the actuation displacements at higher frequencies beyond the resonance frequencies. Therefore, the dynamic amplification factor can be taken into account in the model by including an actuator's damping coefficient and its natural frequency in the model.

# 8.4 Understanding the Dynamic Behaviour of Actuators

The dynamic behavior of the actuators was investigated from two perspectives: one, a macroscopic perspective, the mechanics of the actuator; two, a microscopic perspective, the behaviour of the piezoelectric material. The macroscopic perspective of the actuator provides us with more practical information for the actuator designers; while the piezoelectric material perspective will allow us to understand how the piezoelectric material properties vary inside a composite laminate during dynamic actuation.

## 8.4.1 Understanding the Dynamic Performance: Macroscopic Perspective

The discussions over the actuator dynamic performance are divided into two parts: one, a discussion of peak-to-peak actuation displacements and two, a discussion of resonance frequency.

### Peak-to-Peak Actuation Displacements

The trends of the peak-to-peak actuation displacements at the resonance frequencies versus input voltage amplitudes indicated that the actuator layup [G/PZT/G/C] performed the best while the actuator layup [G/PZT/G/C] and the actuator layup [G/PZT/G/C/G/C] performed in a relatively similar manner, see in figure 8.6. The model successfully predicts trends of the peak-to-peak displacements as can be seen from the slopes of the peak-to-peak displacements of all actuators when compared to the experiments, shown in figure 8.6. The actuation performance of each of the actuators can be explained by using an equation 8.2. Figure 8.7 clarifies the relationship between the bending load,  $M_x$ , and the extensional load,  $N_x$ , of the actuator and the moment arm between the piezoelectric layer mid-plane to the actuator's neutral axis a:

$$M_x = N_x \cdot a \tag{8.2}$$



Figure 8.6: Peak-to-peak actuation displacements at the resonance frequencies. Top: the experimental results. Bottom: COMSOL model predictions.



Figure 8.7: Schematic of an actuator with a neutral plane and force exerts on the actuator via extension/contraction of the piezoelectric layer. The x-axis is along the lengthwise of the actuator.

The extensional load and bending load along the x-axis of the actuator, lengthwise, are given by:

$$N_x = A_{11} \varepsilon_x^0 + B_{11} \kappa_x \tag{8.3}$$

$$M_x = B_{11} \varepsilon_x^0 + D_{11} \kappa_x \tag{8.4}$$

where  $A_{11}$  is the extensional stiffness coefficient that relates the extensional strain,  $\epsilon_x^0$ , to the extensional load,  $N_x$ . The extensional stiffness coefficient is much like the modulus of elasticity.  $B_{11}$  is the coupling stiffness coefficient which relates plate curvature,  $\kappa_x$ , to the extensional load,  $N_x$ , and relates the extensional strain,  $\epsilon_x^0$ , to the bending load,  $M_x$ . And  $D_{11}$  is the bending stiffness coefficient that relates the amount of plate curvature,  $\kappa_x$ , to the bending load,  $M_x$ . The subscript 11 and x represent the longitudinal direction. Re-arranging equation 8.3 yields:

$$\varepsilon_x^0 = \frac{N_x}{A_{11}} - \frac{B_{11}}{A_{11}} \kappa_x \tag{8.5}$$

Substitute equation 8.5 into equation 8.4 yields:

$$M_x = \frac{B_{11}}{A_{11}} N_x + \left( D_{11} - \frac{B_{11}^2}{A_{11}} \right) \kappa_x \tag{8.6}$$

Substituting equation 8.2 into equation 8.6 yields:

$$\kappa_x = \frac{\left(1 - \frac{B_{11}}{A_{11} a}\right)}{\left(D_{11} - \frac{B_{11}^2}{A_{11}}\right)} \cdot M_x \tag{8.7}$$

Equation 8.7 presents a relationship between the bending load of the actuator and the output curvature of the actuator.<sup>3</sup> The coefficient  $\frac{\left(1 - \frac{B_{11}}{A_{11} a}\right)}{\left(D_{11} - \frac{B_{11}^2}{A_{11}}\right)}$  implies

how well the actuators can produce output curvature or, in other words, output actuation displacements when the actuator is subjected to an input bending load. The bending analysis is considered only along the longitudinal axis, lengthwise,

<sup>&</sup>lt;sup>3</sup>The bending load  $M_x$  depends on the material properties and layup.

because these actuators are considered as a beam configuration, thus, it is assumed that there is no influence of the bending along the transverse, actuator's width, direction. Moreover, during the experiments, the author did not see distortion of actuators, i.e. bending along the actuator's width. Thus, to simplify the analysis, the bending coefficient is focused on its influence along the actuator's length.

The performance of the trends of each actuator through the bending coefficient taken from equation 8.7 are shown in figure 8.8. The values at each voltage were calculated using varied elastic modulus of piezoelectric material at each voltage, table 8.1. It can be observed that the actuator layup [G/PZT/G/C] exhibits larger bending coefficient than the other two actuator layups and its peak-to-peak actuation displacements are the best as can be seen from figure 8.6. Likewise, the actuator layup [G/PZT/G/C] and the actuator layup [G/PZT/G/C]/G/C exhibit lower bending coefficient than the actuator layup [G/PZT/G/C]/G/C and they show lower performance than the actuator layup [G/PZT/G/C].



Figure 8.8: Bending coefficient from an equation 8.7 of each actuator throughout the input voltage. The markers show values of bending coefficient obtained from an equation 8.7. The lines represent curve fitting of the bending coefficient values.

% Elastic Modulus Reduction	[G/PZT/G/C/G/C]	0	-8.96	-19.88	-27.23	
	[G/PZT/G/G/C]	0	-10.46	-21.87	-27.85	
	[G/PZT/G/C]	0	0	-3.47	-21.87	
[GPa]	[G/PZT/G/C/G/C]	66	60.09	52.88	48.03	
ZT Elastic Modulus	[G/PZT/G/G/C]	66	59.09	51.57	47.62	
Ч	[G/PZT/G/C]	99	65.99	63.71	51.56	
Voltage	Amplitude [V]	0	10	40	02	

S
ğ
Ĕ.
d
E
ð
g
ta
õ
'n
ď
 -
БП
еĽ
Ű.
σ
at
م
٧,
<u>a</u>
-
ac
Ū.
ę
c
.9
Ţ
٦
ē
S
Ę
ğ
ц
<u> </u>
ï
as
Ш
• •
00
Э́е
af
_

#### **Resonance Frequency**

The resonance frequencies of the individual layups and input voltages were determined by varying the elastic moduli, or elastic compliance, of the piezoelectric material of the individual layups at each input voltage. It can be observed that the models predict the resonance frequencies well when compared to the experimental results, see in figure 8.9. The slopes from the model predictions demonstrate good agreement with the experimental results.



Figure 8.9: Resonance frequencies between experiments vs COMSOL models. Top: the experimental results. Bottom: COMSOL models predictions. There is no experimental resonance frequency determined at 0V.

An explanation of the resonance frequency trends from the different layups can be made using the denominator of equation 8.7, this is known as the reduced bending stiffness (RBS), of an un-symmetric laminate [5]. The RBS demonstrates how much the pure longitudinal bending stiffness of the actuator has been reduced by the effects of extensional stiffness,  $A_{11}$ , and bending-extension coupling,  $B_{11}$ , on the actuator. The RBS of each of the actuators that were calculated using the varied piezoelectric material properties, i.e.  $d_{31}$  and elastic moduli, at each voltage are given in figure 8.10. It can be observed that the larger the RBS, the higher the resonance frequency. That means, the actuator that has less influence of extensional stiffness,  $A_{11}$ , and bending-extension coupling,  $B_{11}$ , will exhibit higher resonance frequency. The RBS term, figure 8.10, can be used to explain the actuation displacement performance of each actuator, i.e. the stiffer the actuator, the smaller the actuation displacements, as shown in figure 8.6.



Figure 8.10: Reduced bending stiffness of each actuator from the denominator of Equation 8.7 throughout the input voltage.

Possessing a small RBS indicates for an actuator that its overall pure bending stiffness is lower than that for an actuator with a larger RBS. This leads to higher deflections and lower vibration frequencies [5–9]. The stiffer actuator, indicated with a larger RBS, exhibits smaller actuation displacements while the resonance frequency is higher. The degree of orthotropy of a composite laminate, which is a stiffness ratio between the longitudinal bending stiffness of the composite laminate, i.e. along the length of the composite laminate, to the transverse bending stiffness of the composite laminate, i.e. along the width direction [10], can be used to investigate the composite laminate's resonance frequencies in a similar manner as the RBS. The composite laminate's longitudinal bending stiffness is reduced when a composite laminate's bending-extension coupling,  $B_{11}$ , exists. With little effect from the composite laminate's transverse stiffness, the composite laminate's longitudinal stiffness dominates the resonance frequency response, i.e. the larger the composite laminate's longitudinal stiffness, the larger the resonance frequency [10–13].

## 8.4.2 Understanding the Piezoelectric Materials under the Dynamic Condition: Microscopic Perspective

The variations of piezoelectric properties, i.e. elastic compliance, elastic modulus and  $d_{31}$ , of each layup at each voltage will be discussed in this section. These variations were made to fit the peak-to-peak actuation displacements and the resonance frequencies between the model and the experiments at various input voltage amplitudes.

#### **Elastic Modulus Reduction**

The increases in the piezoelectric material's compliance or the reduction of elastic modulus for each layup at various input voltage amplitudes are shown in figure 8.11.



Figure 8.11: Changing of a mechanical compliance or as elastic modulus, top, and elastic modulus, bottom, of each layup at various input voltage amplitudes.

It can be seen that the piezoelectric materials get softer, shown as a reduction of the elastic modulus, with increasing input voltage. The piezoelectric material inside the actuator layup [G/PZT/G/C/G/C] and the actuator layup [G/PZT/G/C/G/C] were softened the most; while the actuator layup [G/PZT/G/C] was the least softened. The slope of the reduction of the elastic modulus of the actuator layup [G/PZT/G/C] was the lowest, and the actuator layup [G/PZT/G/C] and the actuator layup [G/PZT/G/C] are almost identical. It is observable that at an input voltage amplitude of 70V, for the actuator layup [G/PZT/G/C] reduces

its stiffness by 21.87%, while the actuator layup [G/PZT/G/G/C] and the actuator layup [G/PZT/G/C/G/C] show comparable stiffness reductions of 27.85% and 27.23%, respectively, table 8.1. The differences between the softening of the piezoelectric material for each layup can be explained through the stress states inside the piezoelectric layer.

Before the stress distribution throughout the piezoelectric layer thickness is discussed, it is necessary to look at how the neutral axis location changes in an actuator due to a variation in elastic modulus. A neutral axis location indicates where the stress in an actuator changes from one type of stress to its opposite, i.e. the stress changes from compression to tension or vice versa. The neutral axis of the composite laminate is calculated from the relationship as follows:

$$y_o = \frac{\sum_{i=1}^{n} \eta_i E_i A_i}{\sum_{i=1}^{n} E_i A_i}$$
(8.8)

where  $E_i$  is the elastic modulus of each layer,  $A_i$  is the thickness of each layer,  $\eta_i$  is the centroid of each layer measured with respect to the bottom face of the actuator and  $y_o$  is the neutral axis of the actuator measured with respect to the bottom face of the actuator, figure 8.12. From the relationship in equation 8.8, it can be predicted that the neutral axis of each layup varies at different input voltages due to changes in the piezoelectric material's elastic modulus. New neutral axes at different input voltage amplitudes obtained from the COMSOL models, are tabulated in Table 8.2.



Figure 8.12: Location of the neutral axis,  $y_o$  relatives to the top surface of the piezoelectric layer, h = 0.337 mm, of a layup [G/PZT/G/C].

	Neutral Axis Locations from COMSOL [mm]						
Voltage	[G/PZT/G/C]	[G/PZT/G/G/C]	[G/PZT/G/C/G/C]				
Amplitude [V]							
manufacturing	0.17	0.16	0.09				
10	0.27	0.31	0.34				
40	0.28	0.33	0.37				
70	0.29	0.32	0.38				

Table 8.2: Changing of the neutral axis,  $y_o$ , of each layups at different input voltage amplitudes.

The location of the top surface of the piezoelectric layer, which is fixed at 0.337 mm, relative to the bottom of the actuator is shown in figure 8.12. From table 8.2 and figure 8.12, it can be seen that the neutral axis of the actuator layup [G/PZT/G/C] is always inside the piezoelectric layer. The neutral axis of the actuator layup [G/PZT/G/C] is almost at the piezoelectric material's top surface, while the neutral axis of the actuator layup [G/PZT/G/C] is always further away from the piezoelectric material's top surface in correspondence to the input voltage.

The stress distribution throughout the piezoelectric layer thickness at different input voltages is shown in figure 8.13. From table 8.2 and figure 8.13, it can be observed that the piezoelectric layer of the actuator layup [G/PZT/G/C] has both compression and tension stresses throughout the piezoelectric layer thickness. The actuator layup [G/PZT/G/G/C] and the actuator layup [G/PZT/G/C/G/C], however, show the most extreme stress condition, i.e. either almost only compression or tension, upon the input voltage polarity along the sinusoidal signal <sup>4</sup>. It is assumed that the displacements of the actuator at each voltage amplitude polarity, i.e. +40V and -40V, are symmetric because the input voltage amplitude is small compared to the input DC voltage, i.e. up to +200V and -200V, experienced by actuators in chapter 6 that led to asymmetry of the actuation displacement under the full static condition. From this symmetry peak-to-peak actuation displacement, it can be assumed that the internal stress distribution throughout the piezoelectric layer thickness is symmetry between both voltage polarities along the sinusoidal signal.

<sup>&</sup>lt;sup>4</sup>The actuator deflects in different direction upon negative and positive voltage peaks along the input sinusoidal signal. This leads to different stress states inside the piezoelectric layer according to different polarities.



Figure 8.13: Stress distribution throughout the piezoelectric layer thickness after manufacturing at 10V, 40V and 70V.

Fett et al. [14] have shown that the elastic moduli of piezoelectric materials change under different stress states. Their experiments show that the elastic modulus increases if the piezoelectric material is under compression perpendicularly to the poling direction while the electric field is applied. As a result, the domain walls are constrained to move according to the electric field. In contrast, if the piezoelectric material is under tension perpendicularly to the poling direction, the elastic modulus is reduced. The elastic modulus variation depends on the magnitude of the applied stresses. Referring back to Figure 8.13, the stress state of the actuator layup [G/PZT/G/C] is a combination of both tension and compression, while the actuator layups [G/PZT/G/G/C] and [G/PZT/G/C/G/C] are under either almost only tension or compression depending upon the bending direction of the actuator with respect to the positive or negative polarity of the sinusoidal signal. This implies that elastic modulus of the actuator layup [G/PZT/G/C] will not change as much as the actuator layups [G/PZT/G/G/C] and [G/PZT/G/C/G/C]. This explains why the elastic module of the actuator layup [G/PZT/G/C] does not reduce as much as in the case of the actuator layups [G/PZT/G/G/C] and [G/PZT/G/C/G/C].

#### Variation of piezoelectric coefficient

It has been demonstrated that piezoelectric material's piezoelectric coefficients vary with input voltages [15, 16]. If the piezoelectric coefficient varies solely due to the input voltage, then the piezoelectric coefficients values of all actuators would be the same for all the layups. Yet the piezoelectric coefficient,  $d_{31}$ , of all the layups varies with input voltage except in the case of the actuator layup [G/PZT/G/C] as can be seen from figure 8.14. It can be observed that the actuator layup [G/PZT/G/C] exhibits constant values of a piezoelectric coefficient throughout the input voltage, while the actuator layups [G/PZT/G/C] and [G/PZT/G/C] showed relatively similar reduction in the  $d_{31}$ . Moreover, the actuator layups [G/PZT/G/C] and [G/PZT/G/C/G/C] show larger piezoelectric coefficient reductions than the actuator layup [G/PZT/G/C].<sup>5</sup>



Figure 8.14: Changing of the piezoelectric coefficient,  $d_{31}$ , of each layup at various input voltage amplitudes.

Yang et al. [17] observed that when the piezoceramic exposed to approximately 20 MPa magnitude of dynamic stress, i.e. sinusoidal input stress, the piezoelectric coefficient,  $d_{31}$ , decreased. Since all the actuator layups presented in this study were initially exposed to very large stresses, several tens MPa, see figure 8.13, upon manufacturing, the  $d_{31}$  could have already been lowered. All the layups were exposed

<sup>&</sup>lt;sup>5</sup>The negative sign of  $d_{31}$  indicates that the piezoelectric materials shrink along the in-plane direction upon an application of the electric field along the out-of-plane direction. The negative sign has no mathematical meaning.

to sinusoidal stresses during actuation, corresponding to the sinusoidal input voltage, figure 8.13, and the stress magnitude increased with increasing input voltage. As a consequence, the  $d_{31}$  was reduced with the increase of the sinusoidal stresses with regard to the larger input voltage amplitudes. It can also be observed that the actuator layup [G/PZT/G/C] has a combination of two stress states, compared to the actuator layups [G/PZT/G/C/G/C] and [G/PZT/G/C/G/C], which were exposed to mostly one type of stress state, figure 8.13. Therefore, the reduction of  $d_{31}$  of the actuator layup [G/PZT/G/C/G/C] is not as great as the actuator layups [G/PZT/G/C/C] and [G/PZT/G/C].

Given the above explanations, it can be seen that the piezoelectric layer was under competition between the input voltage given to the actuator and the application of stress during actuation, which alters the piezoelectric coefficients of the piezoelectric material inside the actuator. It has been shown that such coefficients increased with an increasing input electric field [18–20], however, from Figure 8.14, it can also be concluded that the sinusoidal stress, in relation to larger input voltage amplitudes, dominated the  $d_{31}$  values more than the influence of the input voltage. This resulted in a reduction of  $d_{31}$  instead of an increase.

The comparisons of constants  $\beta$  and  $\gamma$ , introduced in chapter 4, that relate to the influence of the stress inside the piezoelectric material of each individual actuator layup will now be discussed further. The  $\beta$  represents the influence of stress on the piezoelectric coefficient  $d_{31}$  and the  $\gamma$  represents the influence of stress on the elastic compliance. These values were varied to fit the model to the experiments, and are tabulated in tables 8.3 to 8.5. It can be quantified that the actuator layups [G/PZT/G/G/C] and [G/PZT/G/C/G/C] are dominated more by the stress states than the actuator layup [G/PZT/G/C], as is shown through their larger magnitudes of  $\beta$  and  $\gamma$  as compared to those for the actuator layup [G/PZT/G/C].

A note should be made is that magnitudes of the elastic moduli of the piezoelectric material used in the model were calculated from a reciprocal of the piezoelectric mechanical compliance. However, the true values of the elastic moduli of the piezoelectric material is not exactly equal to the reciprocal of the mechanical compliance because these values are in a tensor form. Therefore, inverse of the tensor will produce some small magnitudes add up to the elastic modulus. Moreover, the mechanical compliance and the elastic modulus are complex numbers. However, these small magnitudes will not contribute to substantial deviation from the calculations presented here.

$V_{amp}[V]$	β	$d_{31}$	$\gamma \times 10^{-3}$	Compliance $s_{11}$	Elastic
		$[\mathrm{pm/V}]$	$[m^2/NV]$	$ imes 10^{-11} \ [1/Pa]$	Modulus [GPa]
0	0	-179.69	0	1.51	66
10	8.0	-100	3.64	1.51	65.99
40	2.0	-100	1.05	1.57	63.71
70	1.14	-100	1.13	1.94	51.56

Table 8.3: Piezoelectric parameters used in COMSOL for [G/PZT/G/C],  $V_{amp}$  is a voltage amplitude,  $\beta$  is a constant that relates stress to the  $d_{31}$ ,  $\gamma$  is a constant that relates stress to the piezoelectric's elastic compliance.

$V_{amp}[V]$	β	$d_{31}$	$\gamma, \times 10^{-3}$	Compliance $s_{11}$	Elastic
		$[\mathrm{pm/V}]$	$[m^2/NV]$	$ imes 10^{-11} \ [1/Pa]$	Modulus [GPa]
0	0	-179.96	0	1.51	66
10	10.0	-80	5.41	1.70	59.09
40	3.0	-60	1.97	1.94	51.57
70	1.96	-43	1.35	2.1	47.62

Table 8.4: Piezoelectric parameters used in COMSOL for [G/PZT/G/G/C],  $V_{amp}$  is a voltage amplitude,  $\beta$  is a constant that relates stress to the  $d_{31}$ ,  $\gamma$  is a constant that relates stress to the piezoelectric's elastic compliance.

$V_{amp}[V]$	β	$d_{31}$	$\gamma, \times 10^{-3}$	Compliance $s_{11}$	Elastic
		$[\mathrm{pm/V}]$	$[m^2/NV]$	$\times 10^{-11}$ [1/Pa]	Modulus [GPa]
0	0	-179.96	0	1.51	66
10	10.0	-80	5.13	1.66	60.10
40	3.19	-52	1.85	1.70	52.88
70	2.07	-35	1.33	2.08	48.03

Table 8.5: Piezoelectric parameters used in COMSOL for [G/PZT/G/C/G/C],  $V_{amp}$  is a voltage amplitude,  $\beta$  is a constant that relates stress to the  $d_{31}$ ,  $\gamma$  is a constant that relates stress to the piezoelectric's elastic compliance.

# 8.5 Conclusions

Three actuators were actuated under dynamic conditions using a range of frequencies from 1 - 70Hz and at various input voltage amplitudes of 10, 40 and 70V. The experimental results showed that the resonance frequencies of all the actuators shifted to lower values with increasing input voltage amplitudes. The shifting of

the resonance frequencies was due to the piezoelectric material softening, i.e. the elastic modulus was reduced.

Finite element models were developed to predict the peak-to-peak actuation displacements and resonance frequencies at various input voltage amplitudes. These models take into account changes in the piezoelectric material properties, piezoelectric coefficient and piezoelectric elastic compliance inside the actuators. The models showed reasonable predictions when these were compared to experimental results.

The chapter ended with a discussion of the actuator's performance from two perspectives: the mechanics of the actuator, and changes in the piezoelectric material properties of the actuator. A bending coefficient was introduced to describe the actuation displacement performance. The resonance frequencies could be described through a reduced bending stiffness. It can be concluded that an actuator's performance depends on the mechanics of the actuator through a combination of extensional stiffness, coupling stiffness and bending stiffness. The smaller the bending coefficient, the larger the actuation displacements. The smaller the reduced bending stiffness, the resonance frequencies will be smaller.

Variations in piezoelectric materials used for actuators were explored. It could be concluded that the embedded piezoelectric material inside a composite laminate was both input voltage and stress state dependent. The layup of a laminate exposes an actuator to a combination of compression and tension stresses throughout a piezoelectric material's thickness and these show less tendency towards an elastic modulus reduction than layups exposed to the most extreme types of stress states, i.e. either compression or tension, throughout a piezoelectric material's thickness.

It has been demonstrated in the literatures that under a stress-free condition,  $d_{31}$  will increase in correspondence to increasing input voltage, however, the calculated piezoelectric coefficients  $d_{31}$  of all the layups corresponding to the input voltage are, in contrast to the experimental results from the literatures, under a stress-free condition. The calculated piezoelectric coefficients  $d_{31}$  showed a constant value and some decrease with respect to the input voltage, indicating that there is competition between the input voltage given to the piezoelectric layer thickness. This indicates that the effect of the sinusoidal stress state inside the piezoelectric during actuation, due to the sinusoidal input voltage, dominated the piezoelectric coefficient  $d_{31}$  more than did the input voltage to the actuator.

# References

- K. Mossi, Z. Ounaies, R. Smith, and B. Ball. Prestressed curved actuators: characterization and modeling of their piezoelectric behavior. *Smart Structures and Materials 2003*, 5053:423–435, 2003.
- [2] S.C. Woo, K.H. Park, and N.S. Goo. Influences of dome height and stored elastic energy on the actuating performance of a plate-type piezoelectric composite actuator. *Sensors and Actuators A: Physical*, 137(1):110–119, 2007.
- [3] Z. Ounaies, Institute for Computer Applications in Science, and Engineering. Low-field and high-field characterization of THUNDER actuators. ICASE, NASA Langley Research Center, 2001.
- [4] M.; Quau, L.M.; Kimiaei and M.F. Randolph. Dynamic amplification factors for response analysis of steel catenary risers at touch down areas. In *Twentyfirst (2011) International Offshore and Polar Engineering Conference.*
- [5] R.M. Jones. Mechanics of composite materials. 1999.
- [6] K. Chandrashekhara, K. Krishnamurthy, and S. Roy. Free vibration of composite beams including rotary inertia and shear deformation. *Composite Structures*, 14(4):269–279, 1990.
- [7] R.M. Jones. Buckling and vibration of unsymmetrically laminated crossply rectangular plates. In AIAA, ASME, and SAE, Structures, Structural Dynamics, and Materials Conference, 14 th, Williamsburg, Va, page 1973, 1973.
- [8] E. Reissner. Bending and stretching of certain types of heterogeneous aeolotropic elastic plates. J. Appl. Mech., 28:402–408, 1961.
- [9] CW Bert and TLC Chen. Effect of shear deformation on vibration of antisymmetric angle-ply laminated rectangular plates. *International Journal of Solids and Structures*, 14(6):465–473, 1978.
- [10] A.K. Noor. Free vibrations of multilayered composite plates. AIAA Journal, 11:1038, 1973.
- [11] AA Khdeir and L. Librescu. Analysis of symmetric cross-ply laminated elastic plates using a higher-order theory: Part iibuckling and free vibration. *Composite Structures*, 9(4):259–277, 1988.

- [12] LS Teoh and C.C. Huang. The vibration of beams of fibre reinforced material. Journal of Sound and Vibration, 51(4):467–473, 1977.
- [13] CW Bert. Optimal design of a composite-material plate to maximize its fundamental frequency. *Journal of Sound and Vibration*, 50(2):229–237, 1977.
- [14] T. Fett, S. Muller, D. Munz, and G. Thun. Nonsymmetry in the deformation behaviour of pzt. *Journal of materials science letters*, 17(4):261–265, 1998.
- [15] A. Pramanick, D. Damjanovic, J.C. Nino, and J.L. Jones. Subcoercive cyclic electrical loading of lead zirconate titanate ceramics i: nonlinearities and losses in the converse piezoelectric effect. *Journal of the American Ceramic Society*, 92(10):2291–2299, 2009.
- [16] A. Pramanick, D. Damjanovic, J.E. Daniels, J.C. Nino, and J.L. Jones. Origins of electro-mechanical coupling in polycrystalline ferroelectrics during subcoercive electrical loading. *Journal of the American Ceramic Society*, 94(2):293–309, 2011.
- [17] G. Yang, S.F. Liu, W. Ren, and B.K. Mukherjee. Uniaxial stress dependence of the piezoelectric properties of lead zirconate titanate ceramics. In *Applications of Ferroelectrics, 2000. ISAF 2000. Proceedings of the 2000 12th IEEE International Symposium on*, volume 1, pages 431–434. IEEE, 2000.
- [18] S. Li, W. Cao, and LE Cross. The extrinsic nature of nonlinear behavior observed in lead zirconate titanate ferroelectric ceramic. *Journal of applied physics*, 69(10):7219–7224, 1991.
- [19] D. Damjanovic. Logarithmic frequency dependence of the piezoelectric effect due to pinning of ferroelectric-ferroelastic domain walls. *Physical Review B*, 55(2):R649, 1997.
- [20] AJ Masys, W. Ren, G. Yang, and BK Mukherjee. Piezoelectric strain in lead zirconate titante ceramics as a function of electric field, frequency, and dc bias. *Journal of applied physics*, 94:1155, 2003.

# Chapter 9

# Conclusions and Recommendations

The research discussed in this thesis was focused on understanding which parameters influence the behaviour of a piezoelectric composite materials actuator under static and dynamic operating conditions.

# 9.1 Background

The initial drive for conducting this research was to expand our knowledge of piezoelectric composite material actuators which are being developed to control air flow separation over airfoils. Piezoelectric materials were chosen because of their larger operation bandwidths, fast responses and because they are more efficient in use than other, alternative, smart materials (Chapter 2). Composite materials were chosen because of their design flexibility and because they are lighter than other materials used in this field such as stainless steel. Nevertheless, before an actuator can be implemented in a structure, we need to have a profound understanding of how it will behave, and we need to be able to predict this behaviour.

The actuators were manufactured by embedding a piezoelectric material between composite layers to form a laminate, and the whole laminate was co-cured at an elevated temperature and at a pressure of 3 bars (Chapter 3). The curing pressure of 3 bar was found to be the maximum pressure that the piezoelectric material can withstand without cracks being initiated inside the material.

The actuators' functionality was tested to characterize their performance under static and dynamic operating conditions. Positive and negative unipolar DC electric potentials were applied independently to the actuator to allow a close investigation of the actuators' behaviour when they were operated in a full static condition (Chapter 6). The behaviour of the actuators operating under dynamic conditions, i.e. under a sinusoidal electric field with varying voltage amplitudes of 10 - 70 V, and a frequency range from 1 - 80 Hz was reported in Chapter 8. The maximum voltage amplitude was limited to 70V because this was the maximum voltage the piezoelectric material used for the actuator could withstand before the piezoelectric material lost its polarization causing the actuator to malfunction. The frequency range was operated up to 80 Hz to include the first resonance frequency to obtain the highest actuation displacements as it is more desirable to produce very large actuation displacements.

To save manufacturing time and reduce the cost of producing different actuator designs, it was essential to develop a model that could be used to predict reliable actuation displacements. The finite element models were developed by taking into account the changes in behaviour of the piezoelectric material to improve the models prediction accuracy. The results obtained using these models were then compared to the results obtained experimentally using actuators operating in static and dynamic conditions.

# 9.2 Conclusions on Piezoelectric Material Properties

A soft type of piezoelectric material was chosen for this research because larger output strains are produced in this material than in the hard type piezoelectric material. The use of the soft type makes development of actuators more attractive, however, the drawback of the soft type piezoelectric material is its nonlinear behaviour when large strains are required. The soft piezoelectric material is more prone to exhibiting a nonlinear output response than the hard type. Studies have shown that the properties of piezoelectric material vary in response to the magnitude of various input stimulants such as the magnitudes of the electric field and frequencies of the electrical stimuli that the actuator is subjected to [1-4]. The piezoelectric material properties obtained from the manufacturers are given as constants which are often determined under small input stimulant conditions. If the actuators have been operated under small stimulant conditions, the piezoelectric material properties may be adequate but applications of the materials will be limited by the small range used by the manufacturer. In the situation when the actuators are to be operated beyond the small input stimulants, new piezoelectric material properties need to be determined experimentally, as they are needed to

incorporate into a model.

## 9.2.1 Piezoelectric Material Testing under Static Conditions

The piezoelectric coefficient,  $d_{31}$ , is the most dominant property that influences the actuation displacements of a beam-like actuator as used in this thesis; thus, this coefficient  $d_{31}$ , was determined experimentally to improve the accuracy of the models (Chapter 4). The static operating conditions in this research were designed such that the piezoelectric material's responses to high input electric fields at different charging conditions could be investigated.

The nonlinear output strains and permanent strain offset inside a piezoelectric material result from irreversible domain wall orientations. When these domain walls are oriented by a large magnitude electric field, they tend to stay in this position permanently. Another interesting point is the asymmetry of the nonlinear output strains and the permanent strain offset between the positive and negative input electric fields, which is more pronounced in the negative potential than in the positive potential. The asymmetry of these responses results from the asymmetric domain wall orientations of the two electric potential polarities, and the fact that it is more difficult for the domain walls oriented along the negative potential, i.e. the opposite polarity from the piezoelectric material's poling direction, to reorient back to their initial state than it is for those domain walls that have been oriented along the positive potential, i.e. along the piezoelectric material's poling direction.

This asymmetry phenomenon will not stand out and it is hard to detect when the piezoelectric material is operated using an alternative electric field such as a sinusoidal signal because some of the domain walls are forced to oriented back to the opposite direction along the sinusoidal signal. The larger the magnitudes of the input electric fields are, the harder it is for the permanently oriented domain walls to reoriented back and the piezoelectric material is more prone to exhibiting large permanent strain offsets. When positive and negative input DC electric fields are applied separately to the piezoelectric material an asymmetric permanent displacement offset is shown. These phenomena introduce more complexity when modelling the actuators' behaviour if these asymmetry responses go undetected or the effect is unknown. These small asymmetric nonlinear output strains and the permanent strain offsets in the piezoelectric material influence up to an actuator's scale, i.e. the actuator's performance, as will be discussed in section 9.3. These nonlinear output strains and permanent strain offset effects can be diminished by reorienting the irreversible domain walls in the piezoelectric material back to their initial state. This can be achieved by applying a large electric potential that opposes the currently applied polarity.

Another interesting point is the charging conditions of the piezoelectric material prior to the application of the higher electric field. With a large input electric field, regardless of whether it is a discharging or non-discharging condition, as long as the irreversible domain walls have not been reoriented back to the initial state, the permanent strain offsets will remain. It can be concluded that the domain wall orientation inside the piezoelectric material is a major cause of the nonlinear output strain and permanent strain offset effects inside the piezoelectric material (Chapter 4).

### 9.2.2 Piezoelectric Material Testing Dynamic Conditions

Piezoelectric material properties such as dielectric permittivity, the piezoelectric coefficient and elastic compliance change in response to the input electric voltage and the frequency of the electric voltage. The piezoelectric material's dielectric permittivity and a piezoelectric coefficient were determined experimentally using various voltage amplitudes and a range of frequencies. The piezoelectric material's elastic compliance was not determined experimentally because the equipment required to determine a piezoelectric material's elastic compliance was not available. To circumvent this problem, the value of the piezoelectric material's elastic compliance was derived using its values from its dielectric permittivity and its piezoelectric coefficient.

The experiments showed that the effects of input sinusoidal voltage amplitudes and their frequencies are counterbalanced. Higher electric voltage magnitudes enhance the domain wall motions, and, as a consequence, the magnitudes of the piezoelectric properties increase. At the same time, the domain wall motions are hindered by the higher input frequency, which results in a decrease in the piezoelectric material properties response. Thus, the piezoelectric material properties are enhanced at higher electric voltage amplitudes, while suppressed at higher frequencies. The suppression of the piezoelectric properties come from the domain walls that cannot keep pace with the domain wall orientations at high frequencies. When these two effects are introduced simultaneously, the piezoelectric material properties will be improved as a function of the increasing input electric voltage, while the properties are counterbalanced by the high frequency and which suppresses of the piezoelectric material properties when compared those for a lower frequency with the same electric voltage amplitude (Chapter 4).

# 9.3 Conclusions on Actuators' Static Behaviour

The experimental condition was designed to investigate an actuators' behaviour from two perspectives: one, actuators response to the input DC electric voltage when subjected to separate input positive and negative electric polarities. Two, actuators response to two charging conditions, namely discharging and nondischarging. Separate polarity DC electric voltage was used to investigate these perspectives and provide actuator designers with an understanding of how actuators behave when two opposite directions exist. A DC voltage will produce a full static condition in an actuator for a specific period of time and this is beneficial when various actuation displacements and periods are needed when different air flow separation conditions have to be met.

The experimental results showed that all of the actuators used for the research reported in this thesis behaved similarly and produced similar results to those for the bulk piezoelectric material's responses when tested statically, except that the magnitudes of displacement were much larger than the strains and permanent strain offsets produced by the bulk piezoelectric material (Chapter 6). The actuators exhibited asymmetric nonlinear actuation displacements and permanent displacement when positive and negative polarities were compared. The nonlinear actuation displacements and permanent displacement offsets of all the actuators resulted from the irreversible domain wall orientations inside the piezoelectric material (Chapters 4 and 6).

When the actuators were subjected to two charging conditions, i.e. the actuators were discharged prior to the next higher electric voltage and in another condition they were continuously subjected to higher magnitudes of input voltages without discharging, the experimental results showed that regardless the charging conditions of the actuators, the recorded permanent displacement offsets exist and in a similar fashion to the bulk piezoelectric material. These permanent displacement offsets are an effect of the irreversible domain wall orientations. It can be concluded that the permanent displacement offsets phenomenon will remain permanently if the irreversible domain wall orientations have not been reoriented back to their initial state (Chapters 4 and 6). It is feasible to reorient the irreversible domain walls back to the initial state in the bulk piezoelectric material (Chapter 4), but this is more complex when the piezoelectric material is constrained from expanding and contracting by composite laminates (Chapter 6). Given this behaviour, actuator operators must take into account that there will be a permanent displacement offset produced from the actuators when they have been actuated at a large input voltage. This permanent displacement offset arises in both charging

#### conditions.

Only characterizing actuators experimentally will not provide enough information to actuator designers, they need to have a model that can be used to predict an actuators' behaviour before new actuator designs are manufactured. A finite element model was developed for each actuator layup using the nonlinear piezoelectric properties obtained under the static conditions obtained in Chapter 4. The models gave successful predictions when the model results were compared to the experimental results. They captured the nonlinear actuation displacements at large electric potential and the permanent displacement offsets from both input voltage polarities.

Further conclusions can be made for parameters that influence an actuator's performance. The first, and the most dominant parameter of an actuators functioning, is the permanent displacement offset of the actuator as they promote leap jumps to the overall actuation displacements in both polarities. The second parameter is the nonlinear actuation displacements that results from the nonlinear piezoelectric output strain when the actuator is subjected to a large electric voltage. The last parameter is the linear actuation displacement that results from the linear piezoelectric output strain at low electric voltage amplitudes. It was found that if the permanent displacement offset is omitted, different actuator layups do not influence the actuation response at a small input electric voltage range, i.e.  $\leq \pm 50$ V. A slightly distinguishable performance from different actuator layups can be seen at an input electric potential range between  $\pm 50$ V and  $\pm 100$ V, and  $\pm 50$ V and  $\pm 100$ V. The influence of the actuator layup starts to dominate at a large input electric voltage from  $\geq |100|$  V.

In conclusion, if an actuator is operated under full static conditions at small input electric voltage magnitudes, all the asymmetric actuator layups will be vary similar and no significant difference can be seen. If the actuators are operated at a large input electric voltage magnitude, less stiff actuator layups should be applied. Moreover, it is not necessary to include carbon layers in an actuator layup as long as the layup is asymmetric to allow a bending moment to occur. An asymmetric layup is necessary to create a bending moment during actuation, however, it is not recommend to place a carbon layer directly adjacent to the piezoelectric material because a carbon layer will act as a conductor and this may cause the actuator to be short circuited.

# 9.4 Conclusions on Actuators' Dynamic Behaviour

The dynamic experimental conditions were designed to provide preliminary knowledge regarding different actuators' dynamic behaviour and to understand which parameters influence actuators' dynamic performance. All the actuators were dynamically characterized using various sinusoidal input voltage amplitudes and frequencies. The peak-to-peak displacements of the actuator were measured at the resonance frequencies.

The actuation displacement increased as a function of input electric voltage amplitudes because the domain wall motion increased at large input electric voltage amplitudes. The actuators' resonance frequencies showed an inverse relationship with the input electric voltage amplitudes, this was because the piezoelectric material softened with increasing input voltage, this phenomena is also known as a reduction of the piezoelectric material's elastic modulus. A piezoelectric material's elastic modulus changes linearly with increasing applied electric voltage (Chapters 4 and 8). In the model developed in this work, the changing of piezoelectric material's properties were taken into account, which were, a piezoelectric coefficient,  $d_{31}$ , and the piezoelectric material's elastic modulus. These piezoelectric material properties vary with input electric voltage and the actuator layups. These were used to match the model predictions to the experimental results. The piezoelectric coefficient,  $d_{31}$ , was varied to match the actuation displacement at each input electric voltage. The variation of the piezoelectric material's elastic modulus was necessary to match the shifting of the resonance frequencies at each input electric voltage. The predictions from the models showed good agreement to the experimental results.

The conclusions regarding the actuators' dynamic performance will be made from two perspectives: a macroscopic perspective, i.e. the mechanics of the actuator perspective, and a microscopic perspective, i.e. a piezoelectric material's perspective.

### 9.4.1 The Macroscopic Perspective

At this level, the actuator's actuation displacements is dependent on a bending coefficient, derived in this thesis. The bending coefficient is a combination of an extensional stiffness, a bending-extension coupling stiffness, a bending stiffness and a moment arm of the piezoelectric material. The piezoelectric material's moment arm was measured from the piezoelectric material's mid-plane to the actuator's neutral axis. It was found that the dynamic actuation displacements were a direct function of a bending coefficient, i.e. a larger bending coefficient promotes greater displacements. The actuators' resonance frequency could be described from a 'reduced bending stiffness' of the actuators. The actuator's total bending stiffness was reduced when bending-extension coupling exist. The actuators' resonance frequencies showed a direct relationship with the reduced bending stiffness, when the bending stiffness was largely reduced, the resonance frequencies was decreased.

Practically, to obtain a large actuation displacement, an actuator that has the largest bending-extension coupling coefficient is most desirable. In contrast, to obtain a higher resonance frequency, an actuator that has a small bending-extension coupling coefficient is most desirable. Moreover, actuator designers should avoid designing an actuator that has only one type of stress state throughout the piezo-electric material's thickness to prevent a higher input power requirement due to smaller  $d_{31}$ . Good practise is to design an actuator in which the two types of stress states co-exist.

### 9.4.2 The Microscopic Perspective

At this level, the piezoelectric material becomes softer at large electric voltages, however, the softening also depends on the internal stress state. The actuator with a layup exposed to a combination of compression and tensile stress throughout the piezoelectric material's thickness exhibits a lower modulus reduction. This is because the tensile stresses that are acting perpendicularly to the piezoelectric material's poling direction promote more domain walls mobility (Chapter 6 and section 9.3) resulting in softening of the piezoelectric material's elastic modulus. In contrast, the compression stresses that act perpendicularly to the piezoelectric material's poling direction constrain the domain walls' mobility (Chapter 6 and section 9.3) resulting in a hardening of the piezoelectric material's elastic modulus. When two types of stresses co-exist within the piezoelectric layer, they tend to counterbalance each other causing the softening and hardening of the piezoelectric material to be compensate resulting in a minor reduction of the piezoelectric material's elastic modulus. For these reasons, an actuator with a layup that exposes largely to one type of internal stress throughout the piezoelectric materials' thickness is more prone to a major modulus change.

Another parameter that should be taken into consideration is the piezoelectric coefficient,  $d_{31}$ , which increases as a function of increased input electric voltage amplitudes under a stress-free condition. It was found that there is competition between alternative sinusoidal stresses acting on a piezoelectric material and the input electric voltage amplitudes. The internal stress varies following a sinusoidal

signal input electric voltage by deflecting the actuator upward and downward along the sinusoidal signal. It was found that the coefficient  $d_{31}$  showed an inverse relationship with the input electric voltage amplitude. This indicated that the effect of the sinusoidal stress state inside the piezoelectric material during actuation dominated the piezoelectric coefficient  $d_{31}$  over the input voltage.

Given the above finding at the microscopic scale, it is expected that an actuator with only one type of stress state condition throughout the piezoelectric material's thickness has a low  $d_{31}$  and it will be more prone to a significant piezoelectric material's elastic modulus reduction. Such an actuator shows smaller actuation displacements than an actuator that has a larger  $d_{31}$  and for which the piezoelectric material's elastic modulus is larger. This indicates that the magnitude of the coefficient  $d_{31}$  dominates the actuator's performance over the piezoelectric material's elastic modulus reduction.

## 9.5 Recommendations

The research reported in this thesis was intended to investigate the behaviour of piezoelectric composite material actuators with aerospace applications in mind. However, these actuators can be useful in some others applications such as in wind turbine blades and robotics. Some recommendations can be made to improve the way to investigate the behaviour of piezoelectric composite material actuators. The discussions are divided into three aspects: one, the need for a more precise determination of the piezoelectric material properties, two, suggestions for further investigations into an actuators' actuation performance and three, future applications.

## 9.5.1 Determination of the piezoelectric material properties

Some recommendations can be made to improve how to determine the piezoelectric material properties of an actuator to obtain a set of more precise piezoelectric material properties for the model. The piezoelectric material was under stress inside a composite material after the manufacturing process and during actuation. Therefore, to obtain more precise data on the piezoelectric material properties, the experimental setup should include measuring the stress applied to the piezoelectric material and input electric voltage simultaneously at the piezoelectric material under the static condition. Simultaneous application of applied stress, electric voltage and frequencies to the piezoelectric material can be made during dynamic condition. Moreover, a non-contact 3D digital image camera could be used to investigate the strain field of the piezoelectric patch instead of using strain gages. This 3D digital camera can provide the overall strain fields of the whole piezoelectric patch as well as at the edges.

The piezoelectric material properties such as piezoelectric coefficients are varied with the temperature [5]. If actuators are implemented onto an airfoil or any structure that will experience large temperature variations, it becomes useful to conduct investigations into how the piezoelectric material properties will change as a function of temperature.

### 9.5.2 Improving an actuator's actuation performance

Some suggestions can be made to improve the actuation displacement. More piezoelectric layers could be introduced into the actuators to enhance larger actuation displacements.

A soft piezoelectric material such as the one used for the research reported here exhibits large nonlinear material properties. A single crystal type piezoelectric material could be used to replace the soft type piezoelectric material to reduce the nonlinear effects and larger output strains could be produced from the single crystal piezoelectric material. If the nonlinear effects can be minimized, predictions of the actuator behaviour will be simpler. To ensure a precise calculated thermal stress from the model and calculated internal stress during actuation, research to determine internal stress at the piezoelectric material surface inside composite materials after manufacturing and during actuation could be done and compared to the model. The model to predict an actuator's behaviour under dynamic condition could take into account the air/fluid interaction to the actuator as these interactions will give additional loads on an actuator during actuation. In addition, it is essential to determine the actuators' blocking force as this will provide us with an idea of how much force the actuators can withstand. Lastly, fatigue in actuators should be researched to determine the actuators' life span and understand the actuators' failure mode to improve the actuator long-term performance.

### 9.5.3 Applications Oriented

When the piezoelectric material is applied by an input electric field continuously for an extended period, the piezoelectric material's output strain will keep increas-
ing gradually at a constant input electric field. The increase in output strain at a constant input electric field from the piezoelectric material is called the drift effect. If actuators are required to be operated at a full static condition for a long period of time, it is needed to investigate the control of these actuators and implement measures to prevent the drift effect. An alternative to reduce the input power consumption use to actuate the actuators at a full static condition might be accomplished by discharging the actuator and allowing the actuator to operate at the permanent displacement offsets, see more chapter 6. Nevertheless, the permanent displacement offsets of these actuators will gradually degrade [6]. To maintain a constant permanent displacement offset of these actuators at a full static condition, a small pulse of electric field could be applied from intermittently to control the permanent displacement offsets [6].

In dynamic condition, operating the actuators with a DC bias field, i.e. a DC offset plus an AC field, will improve the actuation displacement [3]. The maximum limitation of the input electric field along the negative field is lower than the positive field, because the domain walls can be permanently oriented along the negative polarity more easily than along the positive polarity. The limitations of the bipolar electric voltage given by the manufacturer was to ensure that there would be no depolarization of the piezoelectric material when the piezoelectric material was subjected to negative field. Given this reason, the piezoelectric material could be operated at a higher positive field than the negative one. Thus, to improve the overall performance, a DC offset along the positive field could be introduced simultaneously with a sinusoidal electric field, while keeping the maximum sinusoidal voltage amplitude along the negative field lower than the limitation.

Lastly, comparisons of actuators with different dimensions could be useful for many applications.

#### References

- S. Li, W. Cao, and LE Cross. The extrinsic nature of nonlinear behavior observed in lead zirconate titanate ferroelectric ceramic. *Journal of applied physics*, 69(10):7219–7224, 1991.
- [2] D. Damjanovic. Logarithmic frequency dependence of the piezoelectric effect due to pinning of ferroelectric-ferroelastic domain walls. *Physical Review B*, 55(2):R649, 1997.
- [3] AJ Masys, W. Ren, G. Yang, and BK Mukherjee. Piezoelectric strain in lead zirconate titante ceramics as a function of electric field, frequency, and dc bias. *Journal of applied physics*, 94:1155, 2003.
- [4] JE Garcia, R. Perez, DA Ochoa, A. Albareda, MH Lente, and JA Eiras. Evaluation of domain wall motion in lead zirconate titanate ceramics by nonlinear response measurements. *Journal of Applied Physics*, 103:054108, 2008.
- [5] QM Zhang, H. Wang, N. Kim, and LE Cross. Direct evaluation of domainwall and intrinsic contributions to the dielectric and piezoelectric response and their temperature dependence on lead zirconate-titanate ceramics. *Journal of applied physics*, 75(1):454–459, 1994.
- [6] T. Ikeda and T. Takahashi. Feasibility study of shape control with zero applied voltage utilizing hysteresis in strain-electric field relationship of piezoelectric ceramics. In SPIE Smart Structures/NDE 2013.

## Appendices

## Appendix A

## Thermal Analogy of NASTRAN/PATRAN

#### Thermal Analogy

The total strain in the piezoelectric material consists of strains from the electric field, applied stress and thermal strain. These strains must be taken into account when modeling the piezoelectric material effect. The NASTRAN/PATRAN model has no piezoelectric material property, therefore, there is no direct way to introduce an input voltage into the model. A thermal analogy was therefore developed to overcome this limitation and allow us to represent voltages at nodes as equivalent temperatures or effective temperature [1, 2]. The thermal analogy will be briefly explained in this appendix. The total strain in the piezoelectric material consists of strains from applied electric field, applied stress and applied temperature and is expressed as:

$$\epsilon_{total} = d_{jk}E_j + s_{km}\sigma_m + \alpha_k\Delta T \tag{A.1}$$

where  $\epsilon_{total}$  is a piezoelectric output strain,  $d_{jk}$  is a piezoelectric coefficient,  $E_j$  is an applied electric field,  $s_{km}$  is an elastic compliance,  $\sigma_m$  is an applied stress to the piezoelectric material and  $\alpha_k$  is a thermal coefficient of a piezoelectric material, and  $\Delta T$  is a difference of the temperatures between the processing temperature during curing and the room temperature. The total strain in the piezoelectric material caused by temperature and the electric field is expressed as follows:

$$\epsilon_{total} = \epsilon_{thermal} + \epsilon_{piezo} \tag{A.2}$$

The thermal strain is expressed as follows:

$$\epsilon_{thermal} = \alpha_{PZT} \Delta T \tag{A.3}$$

where  $\alpha_{PZT}$  is the coefficient of thermal expansion of a piezoelectric material.

Strain resulting from the applied voltage, represented as equivalent temperature, is represented as follows:

$$\epsilon_{piezo} = \frac{d_{31}}{t}V \tag{A.4}$$

where  $d_{31}$  is a piezoelectric coefficient of a piezoelectric material, t is the piezoelectric material's thickness and V is the applied voltage to the piezoelectric material. The total strain in the piezoelectric layer becomes:

$$\epsilon_{total} = \alpha_{PZT} \Delta T + \frac{d_{31}}{t} V \tag{A.5}$$

Rearranging the terms in Equation A.5, it can be written as:

$$\epsilon_{total} = (\Delta T + \frac{d_{31}}{t \cdot \alpha_{PZT}} V) \alpha_{PZT} \tag{A.6}$$

Then the input effective temperature of the piezoelectric layer can be expressed as follows:

$$\Delta T_{eff} = (\Delta T + \frac{d_{31}}{t \cdot \alpha_{PZT}}V) \tag{A.7}$$

by applying the input effective temperature at the piezoelectric material as described in equation A.7, the piezoelectric effect, i.e. the piezoelectric material shows output strain in accordance to the input electric potential, and can be modeled in the NASTRAN/PATRAN software.

### References

- B. Taleghani. Validation of high displacement piezoelectric actuator finite element models. NASA Technical Memorandum, (210309):1–9, 2000. cited By (since 1996) 0.
- [2] Barmac K. Taleghani and Joel F. Campbell. Non-linear finite element modeling of thunder piezoelectric actuators, 1999.

## Appendix B

## Fundamentals of Nonlinear Finite Element Analysis

A fundamental nonlinear finite element analysis in solid mechanics is introduced in this appendix. In solid mechanics physics, a stationary Cartesian coordinate system is defined and it is assumed that the body undergoes large displacements, resulting in large strains due to a nonlinear stress-strain response. A nonlinear finite element analysis method is used to determine the equilibrium positions of the body at a discrete time step. For example, the solution for the static and kinematic variables of the body from time 0 to time t can be solved, then the solution for the next time step  $t+\Delta$  t can be determined. This process is continued reiteratively until the complete solution path of the body is solved, see Figure B.1, where:

 ${}^{t}x_{i}$  is the location of a particle at time t along the Cartesian coordinate i-axis;

 ${}^t\boldsymbol{u}_i$  is the displacement of a particle at time t along the Cartesian coordinate i-axis and

 $u_i$  is the incremental displacement of a particle;



Figure B.1: Large displacement, large strain of a body in a fixed Cartesian configuration [1].

Since the analysis follows each particle from the original configuration, time 0, to the final configuration of the body, the Lagrangian formulation is implemented.<sup>1</sup>

The Lagrangian incremental is expressed base on the *principle of virtual work*:

$$\int_{t+\Delta t_V} {}^{t+\Delta t} \sigma_{ij} \cdot \delta_{t+\Delta t} \epsilon_{ij} \cdot d^{t+\Delta t} V = \int_{t+\Delta t_V} {}^{t+\Delta t} F_i^B \cdot \delta u_i \cdot d^{t+\Delta t} V + \int_{t+\Delta t_S} {}^{t+\Delta t} F_i^P \cdot \delta u_i^P \cdot d^{t+\Delta t} p$$
(B.1)

where  $t + \Delta t \sigma_{ij}$  are the Cartesian components of the Cauchy stress tensor at time  $t + \Delta t$ . The Cauchy stress is defined as a force per unit area at the deformed geometry.

 $\delta_{t+\Delta t}\epsilon_{ij} = \frac{1}{2} \left( \frac{\partial \delta u_i}{\partial^{t+\Delta t} x_j} + \frac{\partial \delta u_j}{\partial^{t+\Delta t} x_i} \right) \text{ is a virtual stress at time t} + \Delta t,$  $\delta u_i \text{ are components of virtual displacement.}$  ${}^{t+\Delta t}F^B_i$  are body forces at time  $t + \Delta t$ .  ${}^{t+\Delta t}F^P_i$  are surface forces at time  $t + \Delta t$ .

 $^{t+\Delta t}V$  and  $^{t+\Delta t}p$  are volume and surface at time t +  $\Delta t$ .

<sup>&</sup>lt;sup>1</sup>Note this contrasts to the Eulerian formulation where the particles are considered to be at a stationary control volume, as if the particles are snapped shot, and the static and kinematic variables are analyzed.

The principle of virtual work states that the internal virtual work, the left-handside of Equation B.1, must be equal to the external virtual work or the work resulting from the external body forces, the right-hand-side of Equation B.1. The approach to solving the principle of virtual work is to know the external forces, e.g. body and surface forces, and virtual displacement of the body. The virtual strain can be determined corresponding to the virtual displacement. The Cauchy stresses can then be solved and these Cauchy stresses represent the physical stress applied to the body at the deformed geometry.

Since the actuators used in this research exhibit large out-of-plane displacement, the geometric nonlinearity of the actuator had been taken into account in the analysis. In the geometric nonlinearity, the normal stress tensor was replaced with a second Piola-Kirchhoff stress, the normal strain tensor was replaced with a Green-Lagrange strain and the problem was solved using a total Lagrangian formulation [2]. Moreover, the principle of virtual work must be rewritten using the second Piola-Kirchhoff stress and Green-Lagrange strain because it is not possible to integrate over an unknown volume and unknown material properties at large deformed configurations at time  $t + \Delta t$ . This is different from linear analysis in which it is assumed that the rotation and displacements are infinitesimally small and the material properties at the undeformed configuration can be used so that the same configuration can be used. Furthermore, it is not possible to add increments in the Cauchy stresses directly due to straining of the material caused by the unknown Cauchy stress at time t as  $\Delta t \sigma_{ij}$ , to obtain Cauchy stress at time t  $+\Delta t$  and become  $t^{t+\Delta t}\sigma_{ij}$  [3]. This is due to the fact that the material is not only strained but it also rotates, therefore, the calculation of Cauchy stress at time t  $+ \Delta t$  must also take into account the rigid body rotation of the material because the Cauchy stress tensor changes when the material is subjected to a rigid body rotation [3].

The second Piola-Kirchhoff stress is introduced to transform stress and deformation state of the material at the deformed configuration, time t or  $t + \Delta t$ , to the material initial configuration, at time 0. Similarly, the Green-Lagrange strains are defined with reference to the material initial configuration.

The second Piola-Kirchhoff stress tensor with a relationship to the Cauchy stresses is expressed as:

$${}_{0}^{t}S_{ij} = \frac{{}_{0}^{0}\rho}{{}_{t}\rho} \cdot {}_{t}^{0}x_{i,m} \cdot {}^{t}\sigma_{mn} \cdot {}_{t}^{0}x_{j,n}$$
(B.2)

Equation B.2 can be interpreted as stresses, S, in configuration at time t which refers to the configuration of the body at time 0.  ${}^{0}_{t}x_{i,m} = \frac{\partial^{0}x_{i}}{\partial^{t}x_{m}}$  is the deformation

gradient tensor,  ${}^{t}\rho$  is the mass density at time t,  ${}^{0}\rho$  is the mass density at time 0.  ${}^{t}_{0}S_{ij}$  is the second Piola-Kirchoff stress tensor in configuration at time t refers to configuration at time 0.  ${}^{t}\sigma_{mn}$  are the Cauchy stresses in configuration at time t.

The Green-Lagrange strain tensor is:

$${}_{0}^{t}\epsilon_{ij} = \frac{1}{2} \left( {}_{0}^{t}u_{i,j} + {}_{0}^{t}u_{j,i} + {}_{0}^{t}u_{k,i0}^{t}u_{k,j} \right)$$
(B.3)

The first two terms on the right hand side of Equation B.3 represent linear strain and the third term represents the nonlinear strain. Note that the strain tensor in Equation B.3 is exact and holds for any amount of strain [3]. The term  ${}_{0}^{t}u_{i,j} = \frac{\partial^{t}u_{i}}{\partial^{0}u_{j}}$ is the differentiate of the virtual displacement.

The internal virtual work at time t can be rewritten using the second Piola-Kirchhoff stress and Green-Lagrange strain tensors at time 0 because the initial material configuration at time 0 is known:

$$\int_{t_V} ({}^t\sigma_{ij} \cdot \delta_t \epsilon_{ij}) d^t V = \int_{0_V} ({}^t_0 S_{ij} \cdot \delta_0^t \epsilon_{ij}) d^0 V$$
(B.4)

The deformation gradient tensor is used to transform the stress and strain at the current material configuration, deformed state, back to the material initial configuration, which is the undeformed state. To visualize the gradient tensor, consider a particle, initially located at the coordinate at time 0 that moves to a new configuration at time t, Figure B.2. During deformation to the current material configuration, this particle follows a path which is described by a deformation gradient tensor as shown in Figure B.2. The orientation and length of a particle at time t is related to the one at time 0 by a gradient tensor as shown in Equation B.5:



Figure B.2: Orientation of a particle from time 0 to time t. The vector  $d_x^0$  and  $d_x^t$  represent the orientation and length of a particle at times 0 and t. [1]

$$d^{t}\underline{x} = {}^{t}_{0} \underline{X} \cdot d^{0}\underline{x} \tag{B.5}$$

 ${}_{0}^{t}\underline{X}$  is the deformation gradient tensor and is defined as:

$${}^{t}_{0}\underline{X} = \frac{\partial^{t}x_{i}}{\partial^{0}x_{j}} \begin{bmatrix} \frac{\partial^{t}x_{1}}{\partial^{0}x_{1}} & \frac{\partial^{t}x_{1}}{\partial^{0}x_{2}} & \frac{\partial^{t}x_{1}}{\partial^{0}x_{3}} \\ \frac{\partial^{t}x_{2}}{\partial^{0}x_{1}} & \frac{\partial^{t}x_{2}}{\partial^{0}x_{2}} & \frac{\partial^{t}x_{2}}{\partial^{0}x_{3}} \\ \frac{\partial^{t}x_{3}}{\partial^{0}x_{1}} & \frac{\partial^{t}x_{3}}{\partial^{0}x_{2}} & \frac{\partial^{t}x_{3}}{\partial^{0}x_{3}} \end{bmatrix}$$
(B.6)

The deformation gradient tensor represents how an infinitesimal line element  ${}^{0}x_{1}$  is mapped to the corresponding deformed current configuration line element  ${}^{t}x_{1}$ . Physically, the deformation gradient describes the stretches and rotations that the material fibers have undergone from time 0 to time t [3].

After the Cauchy stress tensor is replaced with the second Piola-Kirchhoff stress and the normal strain is replaced with Green-Lagrange strain tensor, the problem is then solved using a Total Lagrangian formulation. Using total Lagrangian formulation means that the reference is referred back to the initial configuration at time 0.

#### References

- K. J. Bathe. Finite element procedures for solids and structures-nonlinear analysis, 11/2012 2012.
- [2] Fiona Lowrie, Markys Cain, and Mark Stewart. Finite element modelling of electroceramics. National Physical Laboratory.Great Britain, Centre for Materials Measurement and Technology, 1999. (Great Britain.).
- [3] K. J. Bathe. Finite Element Procedures. Cambridge, MA, 2007.

# Lists of Symbols

#### Chapter 2

$\epsilon_k$	strain
$E_j$	applied electric field
$\sigma_m$	stress
$d^c_{jk}$	piezoelectric coefficient
$\check{S}^{E}_{km}$	elastic compliance
$\alpha_k$	thermal coefficient
$D_i$	dielectric displacement
$E_j$	applied electric field
$\sigma_m$	stress
$d_{im}^d$	piezoelectric constant
$e_{ij}^{\sigma}$	dielectric permittivity
$\alpha_i$	thermal constant
$\Delta \kappa$	changes of the actuation curvature
$C_{ua}$	coefficient of a unimorph actuator
$E_a$	elastic modulus of the piezoelectric plate
D	LIPCA's total bending stiffness
a	moment arm of the piezoelectric plate to the actuator's neutral axis

#### Chapter 4

$\epsilon_{xx}$	horizontal strain
$\epsilon_{yy}$	vertical strain
V	voltage
t	thickness
$\epsilon_{33}$	dielectric permittivity along the out-of-plane direction
$\alpha$	a constant relates stress to the dielectric permittivity
$\epsilon_{init}$	initial dielectric permittivity
$d_{33}^d,  d_{31}^d$	piezoelectric constant
$\beta$	a constant relates stress to the piezoelectric constant
$s_{11}$	elastic compliance or mechanical compliance
$k_{31}$	piezoelectric coupling coefficient
$s_{11}^0$	initial piezoelectric compliance
$\gamma$	a constant that relates stress to the compliance
$f_R$	resonance frequency
L	length of the piezoelectric material

#### Chapter 5

Cauchy stress at the deformed geometry
initial stress from the previous analysis
nonlinear strain at the deformed geometry
initial strain from previous analysis
$4^{th}$ order elasticity tensor
Young's modulus
Poisson's ratio
Green-Lagrange strain
second Piola-Kirchhoff stress
gradient of the deformed configuration of a material
shear modulus

#### Chapter 6

 $d_{31nonli}$  nonlinear piezoelectric electric coefficient

#### Chapter 7

$\omega$	angular frequency
ho	material density
u	displacement
$\nabla$	divergence
$\sigma$	Cauchy stress
$\sigma_o$	initial Cauchy stress
$\epsilon$	strain
$\epsilon_o$	initial strain
$s_E$	elastic compliance
D	electric charge displacement
$J_i$	current density
$ ho_V$	space-charge density
$\omega$	angular frequency
$D_r$	initial electric charge displacement
$\epsilon_s$	static permittivity
$P_m$	electric polarization in the material orientation
$J_{im}$	current density at the deformed configuration
$E_m$	electric field at the deformed configuration
S	$2^{nd}$ Piola-Kirchhoff stress
$S_o$	$2^{nd}$ Piola-Kirchhoff initial stress
$\chi_s$	electric susceptibility
$Q_m$	mechanical quality factor

#### Chapter 8

$M_x$	bending load
$N_x$	extensional load
a	moment arm
$A_{11}$	extensional stiffness coefficient
$B_{11}$	coupling stiffness coefficient
$\kappa_x$	extensional load
$\epsilon_x^0$	extensional strain
$D_{11}$	bending stiffness coefficient
$E_i$	elastic modulus of each material layer
$A_i$	thickness of each material layer
$\eta_i$	centroid of each layer
$y_o$	neutral axis of the actuator

#### Appendix A

$\epsilon_{total}$	piezoelectric output strain
$d_{jk}$	piezoelectric coefficient
$\check{E_j}$	applied electric field
$s_{km}$	elastic compliance
$\sigma_m$	applied stress to the piezoelectric material
$lpha_k$	thermal coefficient of a piezoelectric material
$\Delta T$	difference of the temperatures
$\epsilon_{thermal}$	piezoelectric material thermal strain
$\epsilon_{piezo}$	piezoelectric material electric field strain
$\alpha_{PZT}$	coefficient of thermal expansion of a piezoelectric material

#### Appendix B

$^{t}x_{i}$	location of a particle at time t along the Cartesian coordinate i-axis
$^{t}u_{i}$	displacement of a particle at time t along the Cartesian coordinate i-axis
$u_i$	incremental displacement of a particle
$F^B$	body force
$F^P$	surface force
ρ	mass density
σ	Cauchy stress
S	$2^{nd}$ Piola-Kirchhoff stress
${}^{t}_{0}\underline{X}$	deformation gradient tensor

## Acronym

CFRP	Carbon Fibre Reinforced Polymer
PZT	Lead-Zirconate-Titanate
PVDF	Piezoelectric Films
SMA	Shape Memory Alloy
PMN	Lead magnesium Niobate
CAP	Conventionally Attached Piezoelectric
DAP	Directionally Attached Piezoelectric
THUNDER	Thin Layer Composite Unimorph Ferroelectric Driver and Sensor
LIPCA	Lightweight Piezoceramics Composite Actuators
RAINBOW	Reduced and Internally-Biased OxideWafer
CTE	Coefficient of Thermal Expansion
RBS	Reduced Bending Stiffness

### About the author

Peerawan Wiwattananon was born on December 27th, 1979, in Nakhonratchasima province, Thailand. She developed her curiosity for science at an early age and is still fascinated by how things work. After she finished her high school at Suranari Wittaya school, she continued her education in Mechanical Engineering at the Sirindhorn International Institute of Technology, Thammasart University, Bangkok, Thailand. Here, she received the "The King Bhumibol Adulyadej Scholarship" conferred by the King Bhumibol Adulyadej for achieving the highest academic rank among the first class honour students in Mechanical Engineering. She then won a scholarship from DAAD-Siemens to continue education and do a master's degree at the Technische Universität Hamburg-Harburg, Germany. She did her master's thesis at the Institute of Composite Structures and Adaptive Systems, the German Aerospace Centre, where she started her composite materials research on the repair of composite material. Having decided to continue to work with composite materials, she applied for and received a full scholarship to do a second master's degree at Syracuse University, New York, USA. During her time at Syracuse, she was hired as a research assistant to conduct research into impact damage in sandwich structures. After this, she decided to come back to Europe and was accepted to do a PhD degree at the Design and Production of Composite Structures department, which later on changed to Structural Integrity and Composites department of the Aerospace Engineering Faculty at the Delft University of Technology. Here, making a slight change, her PhD research was in piezoelectric composite material actuators.

### Acknowledgements

The research described in this thesis could not have been completed without the support from many others during the last 4 years. This last 4 years have allowed me to build so much experience which has filled one of the thickest chapters of my life. I truly appreciate the support, encouragements and suggestions that I received from everyone. I would like to express my sincere gratitude to committee members, supervisors, colleagues, technicians, students, friends and family.

First of all, I would like to thank Prof. Rinze Benedictus for supporting my research. I would like to thank Prof. Adriaan Beukers for giving me opportunity to come to TUDelft to carry out my research and do a research here. I would like to thank Harald Bersee for navigating me throughout many years from starting to the end. Harald, thank you for believing in me and giving me freedom to prove the ideas I had. I still remember what you told me in our early meeting "go to the lab, play with the materials, do some mistakes and learn from those mistakes so you will not do those mistakes again". Without your guidance, I wouldn't have come to the end. Otto Bergsma, I would like to thank you for all of your support and guidance. I really enjoyed our meetings and discussions. Prof. Dragan Damjanovic, I would like to thank you for letting me visit your laboratory and perform some experiments that resulted to be a very crucial part of my thesis. Thank you for sharing your experience and expertise with me. I still find that piezoelectric materials are very fascinating, although very complicated. Dr. Sontipee Aimmanee, I would like to thank you for your advices and and for sharing your research experience in Thailand with me. I appreciate the time we discussed over the research; it allowed me to see things from different angle. I would like to thank Prof. Remko Akkerman and Prof. Pim Groen for accepting to be my committee member and to thank them for their valuable comments. I would like to thank the Rector Magnificus Prof. ir. K.C.A.M. Luyben for being part of my committee. Lisette, thank you for organizing so many things for me in the past 4 years. Without you, searching for accommodation, recruiting students and travel arrangements would have been troublesome. Gemma, thank you for making arrangements and helping me to sort out many things in the past years. Marianne, thank you for keeping me to update the Clean Sky project report.

I would like to thank my old time colleagues for their support and inputs: Teun, Tahira, Jordy, Julie, Irene, Carlos, Ab, Shafqat, Didier, Natcha, Paola, Haujie, Lei, Shrikant, Nassira and Maria, for your support and inputs. I enjoyed making long hours of discussions over research, exchanging ideas during our GS ("Gossip Session") with you guys a lot. Those GS meetings provided me so much of inputs to my research and gave me various approaches to tackle different problems. Thank you, Irene, for your support and helped me out over various issues in the past 4 years. Tahira, thank you for guiding me in my research in the first year. It was a good startup year I had. Jordy: our discussions over the research, life and career was fun. Julie, you always wanted to support and guide me over obstacles I had - thank you very much. Carlos, I had never imagined that I would meet someone who I could call "a walking aerospace history book". I still haven't got a chance to watch "the right stuff" yet, but I will do it very soon. Paola, Thank you for your support, friendship and advice. I truly thank you for the delicious Italian food and the "Olive Oil 101" lesson. Now, I can choose a good quality olive oil myself. Huajie, many hours of exchanging experience over the COMSOL program with you was valuable; thank you for helping me to sort out my thesis documents. Lei, thank you for always helping me to fix my bike -it requires an engineer to fix it. Natcha, thank you for the good time we had together and for the delicious Thai food. Shafqat and Shrikant, thank you for your time and advices. Teun and Adrian Lara, thank you very much for your suggestions, discussions, ideas about the smart structures project. I really appreciate the time I spent working with both of you in the HAL 0.07. Teun: thank you for your guidance and help in starting with the research and for your suggestions about how to work with Dutch people. Maria, thank you for always offering your help and always wanting to support me. I really loved playing squash with you. Roger, thank you very much for your advice and for sharing your career path experience with me. Freek and Konstantin, thank you so much for helping me to kill bugs in my LaTeX files. These bugs are everywhere and very hard to kill. Berthil, without your help, the LabView program would have never been finished and ready to be used for my experimental setup. I really appreciate your expertise. Hans, thank you for helping me out to setup the experiments with a whole bunch of wires. Thank you for being so patient to connect so many strain gages and prepare the copper foils for me. Fred and Cees, thank you for your efforts to support me to manufacture the actuators and for helping me to transport the heavy manufacturing metal plates to the autoclave. They are too heavy and I cannot lift them myself. Frank de Pont, thank you for your support on my COMSOL technical problems. I would like to thank all the students that I supervised in this in the past 4 years: Dejan,

Ertan, FX, Ishaq, Juliette, Marco and Xiaofeng. I appreciate your assistance and hard work in this project. I learned a lot from supervising all of you throughout many months.

Thank you for the Thai community for your support. I enjoyed cooking and "learn how to cook" Thai food with all of you. Peiwen: I love the Taiwanese sweets every time you brought them back from Taiwan and thank you for being beside me during my hard times. Methisa and Nico: thank you for helping me realizing my ideas to become a wonderful cover design. Juan Manuel Castillo Sanchez: thank you for helping me with all the moving and your great advice. Miranda: thank you for the time you spent to correct my thesis. Thank you my friends around the world for your encouragement during the hard times.

Thank you: Adrian Fernandez, Alfonso, Beatriz, Bob, Chongxin, Cyril, Daniel, Derek, Ed, Frans, Freddy, Gregory, Gustavo, Hao, Ilhan, Jarret, Johan, John-Alan, Lei Zu, Marcelo, Maro, Mayank, Ping, Wandong and all the technicians in the mechanical lab.

Finally, I would like to express my gratitude to my parents: Dr. Suwat Wiwattananon and Mrs. Pensiri Wiwattananon. Thank you for your unconditioned love and endless support. Thank you for your encouragement, for supporting me to follow my dreams and for giving me the opportunity to see the world. I would like to thank my sister, Koranee Wiwattananon for her help and support.

Lastly, before I end this chapter, I would like to thank all of you once again for assisting me to shape and realize this wonderful chapter.