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Reliability of Tapered Bimorph Piezoelectric Energy Harvesters - an Experimental Study

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***Abstract*—Cantilever piezoelectric energy harvesting from ambient vibrations is a viable solution for powering wireless sensors and low-power electronics. However, the greatest issue preventing these systems from being widely used is their poor reliability. With the aim to maximise their power output, the devices are often operated close the fracture strength, which results in cracks in the brittle piezoceramic layer. Tapered cantilevers are suggested to improve the mechanical reliability. A relative comparison is made between tapered piezoelectric cantilevers and conventional rectangular cantilevers in terms of reliability and power output. Tensional strains causing fractures show a serious reduction of power output and eigenfrequency. Experiments show that tapered cantilevers have a higher power output per unit area.**

Keywords*—*Mechanical reliability, PZT, vibration energy harvester, tapered cantilever

I. Introduction

Vibration energy harvesting provides long term alternatives to replaceable batteries across a number of applications. The most attractive applications are found in environments where battery replacement is expensive, inconvenient and/or prohibited by regulations. Examples of such applications are medical implants such as pacemakers or wireless sensor networks for the internet of things. The working principle of piezoelectric vibration energy harvesting is based on the piezoelectric effect. The piezoelectric ceramic material converts mechanical strain to electrical power that can be used to power small (wireless) devices. The piezoelectric effect results from pressure on ceramic crystals yielding an electric potential. Most vibration energy harvesters are based on a cantilever beam spring structure [1–3].

However, piezoelectric vibration energy harvesters (PVEH's) suffers from low reliability. With the aim to gain maximum energy output, the PVEH's are operated at resonance frequency. Resulting in large deformations causing fractures in the piezoceramic layer where strain is the largest. In practice, high reliability is required for their desired applications. Prior arts suggest three ways to improve the reliability of the PVEH's [4]; use motion limiters to limit the maximum deflection, a pply c ompressive s train at the piezoceramic by the composite and thirdly tapering the piezoelectric cantilevers. The first d esign p rinciple, limiting the maximum deflection, shows experimentally improved shock resistance [5–7]. Strain distribution design principle is suggested by multiple researches to improve the lifetime of the PVEH's [8–10]. However, previous work on the reliability of tapered piezoelectric cantilevers is only theoretically investigated. To the author's knowledge, there exists no experimental data to validate these claims.

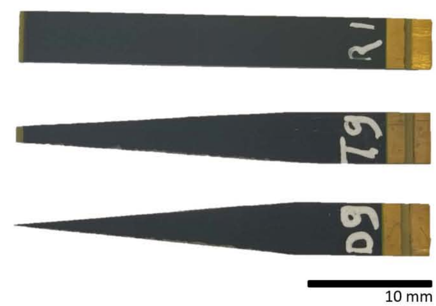

Fig. 1: **Three bimorph piezoelectric cantilevers shaped by abrasive water cooled cutting for reliability and power output experiments.**

The goal of this research is to experimentally validate the effect of tapering on the reliability and power output of piezoelectric cantilevers. This research uses tapered bimorph Lead Zirconate Titanate (PZT) cantilevers for PVEH for improving reliability.

In Section II the experimental method and test setup are explained. The results from the experiments are presented in Sections III. Section IV compares the findings and evaluates the results. The conclusions are drawn in section V.

II. Method

Piezoceramic samples

The samples used for the experiments are bimorph Morgan Advanced Ceramics High-Performance PZT-508. These are chosen for two reasons. First of all, for their high reliability and efficient energy harvesting properties. Secondly, because of the bimorph structure and parallel polarisation. This makes it possible to distinguishes power output between the top and bottom layers of the piezoelectric cantilever. Two different

TABLE I: **Properties and parameters of PZT508 samples.**

	Rectangular	**50% tapered**	**100% tapered**
L	47.0 mm	47.0 mm	47.0 mm
L_0	34.0 mm	34.0 mm	34.0 mm
w	4.0-4.0 mm	4.0-2.0 mm	4.0-0.0 mm
t	0.8 mm	0.8 mm	0.8 mm
m_0	$0.950 \pm 0.005g$	$0.737 \pm 0.021g$	$0.634 \pm 0.015g$
C_{p0}	$28.0 \pm 1.17nF$	$18.8 \pm 0.64nF$	$15.5 \pm 0.83nF$
ω_0	320Hz $\pm 5Hz$	470 $\pm 5Hz$	665$\pm 5Hz$

taperings of the rectangular piezoceramic cantilever are made to find relationships between the degree of tapering, the power output and reliability. The 50% tapered and 100% tapered PZT cantilevers are shaped by water-cooled abrasive diamond cutting (Struers Secotom-10). In total there are 21 samples, 7 for each shape.

The properties and dimensions of the three cantilevers are listed in Table I. Where L, w and t are the length, width and thickness of the cantilever respectively. L_0 is the free length of the cantilever and ω_0 the eigenfrequency. The mass (m_0) and capacitance (C_{p0}) of the free vibrating area of all 21 samples are measured to verify the consistency of the samples. The matched resistance can be found analytically with the measured capacitance, according equation 1.

$$R = \frac{1}{\omega C} \tag{1}$$

In which the internal leakage resistance of the piezocantilever is neglected. Where ω is the eigenfrequency in open loop in rad/s and C the capacitance in nF.

Test setup

A picture of the setup can be found in Figure 2. The input frequency and amplitude of the shaker are generated by a Keysight 33220A function generator. A vibration Exciter type 4809 and amplifier of Brüel and Kjær are used for generating vibrations. The piezoelectric cantilevers are clamped in by an aluminium clamping that is fixed on the shaker. The power output of each piezoelectric layer is measured over a decade resistance box. The deflection of the piezoceramic cantilever is measured by two Keyence LK-H052 and LK-H022 laser distance sensors. The acceleration at the base of the piezoelectric cantilever is measured by PCB accelerometer model Y356A32. The data is acquired by a National Instruments BNC compact DAQ 9215 and processed in Matlab with the Data Acquisition toolbox. The shaker is feedback controlled for constant peak accelerations at the base of the PZT cantilever.

Experimental method

The experimental method can be divided into two parts: power output comparison and quasi-static deformation experiments. For the power output comparison a resistance sweep and frequency sweep are done. The resistance sweep is performed from 100 Ω to 200 $k\Omega$, at the conditions of 1g peak acceleration and at the eigenfrequency of the cantilever.

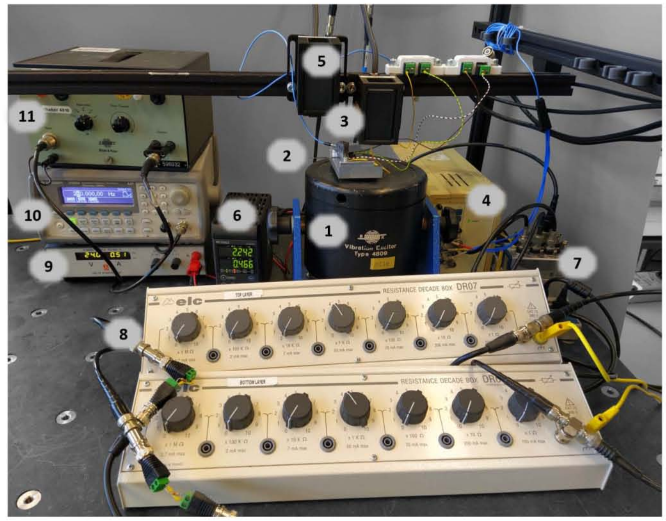

Fig. 2: **Picture of the vibration test setup, with the following hardware present: (1) Shaker, (2) Piezo cantilever, (3) Accelerometer, (4) Accelometer signal conditioner, (5) Laser distance meter, (6) Laser distance controler, (7) DAQ, (8) Resistance box, (9) Function generator, (10) Power supply.**

The matched optimal resistance for each tapered cantilever is used in further experiments. In order to quantify the power output over the frequency spectrum a frequency sweep from 280 Hz to 730 Hz is performed with a resolution of 2 Hz at 1g peak acceleration. The power output of each layer is calculated over the optimal resistance for 1 second. The total average power output for each frequency is the sum of both layers. As an extra verification the deflection is also measured. With this data a reference baseline is set for the intact PZT cantilevers and a comparison of power output can be made.

A quasi-static deformation experiment is performed on the three different PZT cantilevers to identify the static fracture strength. A PI linear stage(M505) with Futek (549178-10lb) force sensor is used for the force deflection test setup. The PZT cantilevers are clamped at the base with the same aluminium clamping being used in other experiments. The piezoceramic cantilevers are deformed by a round tip ($\varnothing 0.5mm$) with a point of application 4mm from the tip. The point of application could not be precisely at the tip, due to the lack of area at the tip of 100% tapered cantilevers and the lateral shift of the point of application during deformation. As an extra verification an audio recording of the fracture is made during the measurement. After the quasi-static deformation experiment a same frequency sweep is performed. In order to evaluate how severely the fractures in the material affect the power output.

III. Results

Power comparison

The measured capacitance (C_{p0}) and mass (m_0) can be found in Table I. With equation 1 the analytical optimal

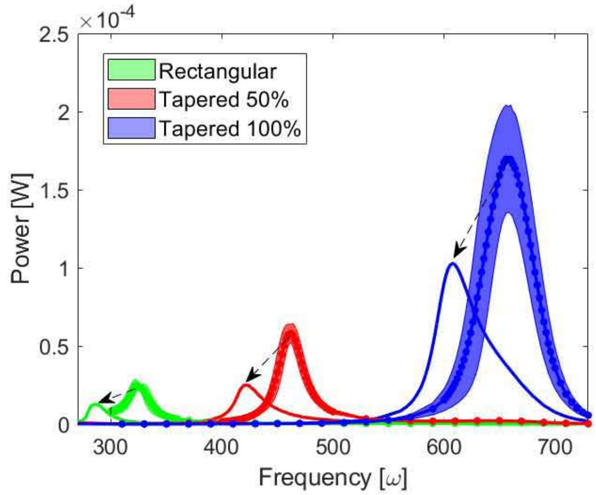

Fig. 3: **Frequency sweep at 1g showing the power output of the three cantilevers (N=7) before and after quasi-static deformation. After quasi-static deformation a drop in eigenfrequency and power output of the three different samples is visible.**

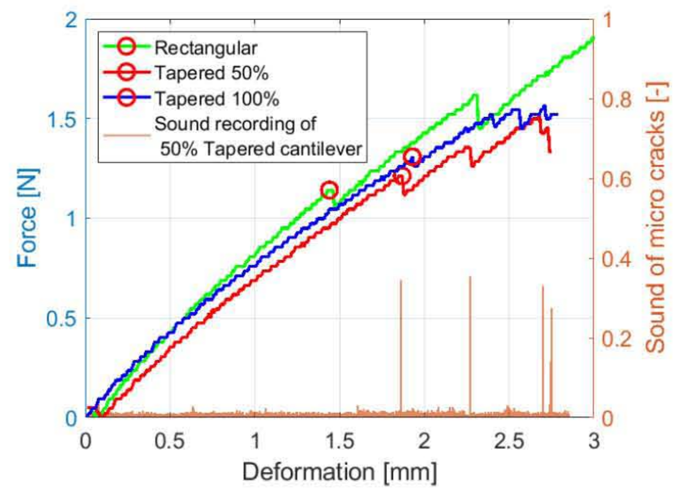

Fig. 4: **Force-deflection curve at static deformations initiating cracks in ceramic material shown by the red circle markers. A audio recording of the cracks in the 50% tapered cantilever is shown by the red audio peaks.**

TABLE II: **Normalised power output**

	Rectangular	**50% tapered**	**100% tapered**
Normalised power	$2 \cdot 10^{-4}W$	$2 \cdot 10^{-4}W$	$2 \cdot 10^{-4}W$

resistance for the rectangular is calculated. The 50% tapered and 100% tapered cantilever are respectively 16.9, 18.4 and 16.6 kΩ. The experimental optimal resistances of the tapered cantilevers are experimentally found at 28, 43 and 21 kΩ for the rectangular, 50% tapered and 100% tapered cantilever respectively.

The power output of the three cantilevers is identified by a frequency sweep. The results of the frequency sweep can be found in Figure 3. The shaded areas represent standard deviation of the measurement. The resulting displacements of the tip and base the deformations are measured. The following deformations at eigenfrequency are found for respectively the rectangular, 50% tapered and 100% tapered cantilevers, 0.018 ± 0.003 mm 0.029 ± 0.001 mm and 0.037 ± 0.04 mm.

Quasi-static deformation

Figure 4 depicts the results of the quasi-static deformation experiment. The first internal crack at a static deformation occurs around 1.4mm. This can be seen in the graph by the discontinuity of the blocking force. Larger strain levels lead to increased cracking. During the experiment the occurrence of the cracks was also audible, indicated by the red spiked line at the bottom of Figure 4.

Figure 3 shows a frequency sweep showing the destructive consequences of internal cracks in the material. The power output drops significantly. Since the experiments are done with a bimorph parallel poled cantilever, the voltage output of the top and bottom layer can be compared. The piezoceramic layer deformed in tension has a voltage output of half the voltage output of the layer deformed in compression. Moreover, the eigenfrequency drops approximately 10%.

IV. Discussion

Power output comparison

It can be seen in Figure 3 that the 100% tapered cantilever generates significantly more power compared to the conventional rectangular cantilevers. To make a fair comparison between the different eigenfrequencies of the cantilevers, the power output of the energy harvester can be normalised by the input frequency ($P \propto \omega$) and input acceleration ($P \propto a$) [11, 12]. With the input power normalisation the tapered cantilevers still generate significantly more power compared to the rectangular PHEV's, see Table II. This can be explained by the fact that tapered cantilevers have more uniform deformation, therefore utilise the full piezoceramic area for power generation. Hence, tapered cantilevers generate more power per unit area. This is in line what literature suggests [8, 10]. Considered the higher eigenfrequency of tapered cantilevers it could be suggested to use stiffness tuning to obtain a static-balanced mechanism, for low frequency applications [13].

Quasi-static deformation

Quasi-static experiments show that fractures in the ceramic material lower the eigenfrequency and power output. The lower power output can be related to the reduction of voltage output at the tensional layer where the fractures are present. The drop of eigenfrequency can be explained by the reduction of stiffness after fracture [14, 15]. The reduction of stiffness can be observed in the force-deflection graph by a reduction of slope after fracture. Important is to realise that in practice, the eigenfrequency does no longer match with the input frequency of the application. This causes a power output reduction of at least 50% for the application. Additionally, the cracks in the piezoceramic material cause a softening effect of the cantilever. The microcracks act as a hinge, with lower stiffness than the surrounding ceramic material. This causes a geometric non-linearity in the PZT cantilever. The effect can be seen in Figure 3, by the non-symmetric parabolic curve around the eigenfrequency.

Future research

Three recommendations are given for future research. First, abrasive cutting of PZT samples is the preferred method for shaping PZT cantilevers over laser cutting or sawing, because of the low shear stresses and minimal temperature effects. Secondly, a sound recording could be used in experiments to identify the event of fractures in PZT bimorph cantilevers. Finally, future research towards long term cyclic loading with a proofmass should be investigated.

V. CONCLUSION

This paper presents experimental results on the degradation of piezoelectric cantilevers for application of energy harvesting. It can be concluded that tapered cantilevers generate more power per unit area. Therefore less deformation is needed to harvest the same power as rectangular cantilevers. Furthermore, the static deformation at which the cantilevers fracture is found. The fractured PZT cantilevers show a significant reduction of eigenfrequency and power output, due to the reduced stiffness caused by the fractures. This dramatically reduces the power output, emphasising the importance of the reliability of the piezoelectric cantilevers for energy harvesting applications.

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