Active Aeroelastic Control Aspects of an Aircraft Wing by Using Synthetic Jet Actuators: Modeling, Simulations, Experiments

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ABSTRACT

This paper discusses modeling, simulations and experimental aspects of active aeroelastic control on aircraft wings by using Synthetic Jet Actuators (SJAs). SJAs, a particular class of zero-net mass-flux actuators, have shown very promising results in numerous aeronautical applications, such as boundary layer control and delay of flow separation. A less recognized effect resulting from the SJAs is a momentum exchange that occurs with the flow, leading to a rearrangement of the streamlines around the airfoil modifying the aerodynamic loads. Discussions pertinent to the use of SJAs for flow and aeroelastic control and how these devices can be exploited for flutter suppression and for aerodynamic performances improvement are presented and conclusions are outlined.

Keywords: Synthetic jet actuators, aerodynamic modeling, active control, flutter

1. INTRODUCTION

Recent research has proven that the aerodynamic characteristics of a lifting surface can be modified by means of Zero-Net Mass-Flux (ZNMF) fluidic actuators that periodically force fluid through an orifice in and out of a cavity located inside the lifting surface. Figure 1 shows a schematic of such actuators. ZNMF do not require input mass to produce a non-zero momentum output. Among them, the commonly called Synthetic Jet Actuators (SJAs), have already found important applications in boundary layer control; they have the ability to manipulate the airflow at low and high angle-of-attack making them very attractive for a number of aeronautical applications.

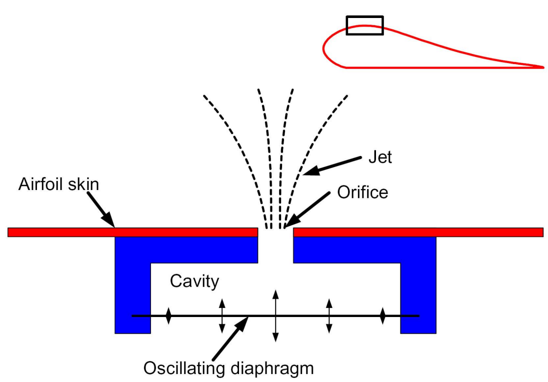

Figure 1: SJA schematics. The two basic components of and SJA are the cavity and the oscillating diaphragm.

SJAs have been employed in boundary layer stability, in delaying the flow transition from laminar to turbulent, and in flow separation. Furthermore, other important advantages include delay aerodynamic stalling, drag reduction, lift enhancements, mixing augmentations and flow-induced noise suppression [1]. The unsteady forcing can be tailored to affect certain global instabilities of separated flow and lead to the reduction in the size of the region of separation and improved performance of the wing. The flow field is changed globally by manipulating the flow field at localized points across the wing. This may be achieved by actuators that energize the boundary layer with steady or pulsed momentum

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through the wing surface. It has been shown that controlled actuation changes the velocity, pressure, and vorticity field around the wing to achieve specific desired performance. Recent results have also shown that SJAs can allow lifting surfaces to carry loads without flow separation at much higher angles-of-attack compared to conventional wings without actuation. The improved performance is credited to SJAs capability of reattaching the flow back onto the airfoil's leading edge in a stall condition. It has been observed that oscillatory blowing takes advantage of inherent local instabilities in the near-wall shear layer that causes the selective amplification of the input oscillation frequency. These amplified disturbances convect downstream along the airfoil as coherent large structures that serve to mix the boundary layer flow and delay separation. As indicated in [2], the efficiency of the mixing provides substantial increases in lift, while concurrently reducing drag even when one assumes that the entire momentum added is recovered as thrust.

Recent works by Seifert et al [3], Wygnanski [4], and Hites et al [5] have also shown that low amplitude, oscillatory blowing can delay separation and enhance lift over a wide range of Reynolds numbers including those corresponding to aircraft takeoff and landing. Computations and experiments have provided new insight and interesting conclusions have been drawn. In particular, it seems that the most effective location for unsteady forcing is near the point of separation, while the optimum reduced frequency for the oscillations is about $f^+ = f\,c/U$ 1, and that the amplitude of the oscillations required for effective separation control is about two orders of magnitude lower than that for steady blowing. In addition, when the actuation is applied to an airfoil that is not separated, the effects produced by the jet are not detrimental to lift or drag. Greenblatt et al. [6] have shown that the net result of excitation in incompressible flows is essentially insensitive to whether an airfoil is stationary or oscillating in pitch. This is primarily due to the large disparity between the time-scales characterizing the airfoil pitch oscillations and those characterizing the excitation-generated large coherent structures, it can therefore be speculated that periodic excitation is also effective in controlling dynamic stall under compressible conditions, even at low perturbation amplitudes.

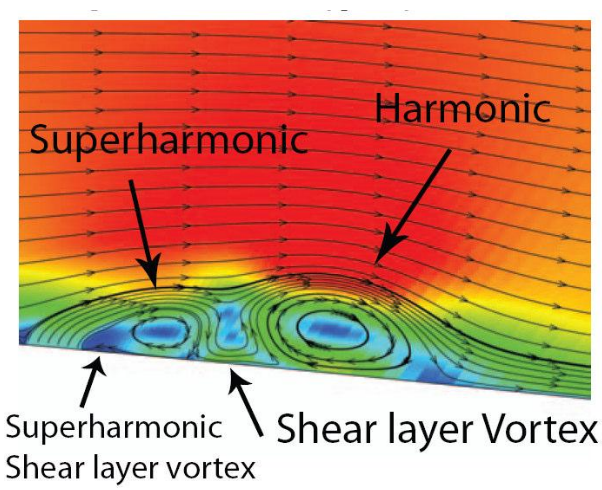
The phenomena called "dynamic virtual shaping", where the momentum exchange created by the SJAs leads to a rearrangement of the streamlines around the airfoil. enable a "virtual" modification of the airfoils shape, that directly alter the aerodynamic forces and moments acting on the lifting surface. The joint research carried out at Delft University of Technology and Clarkson University is mainly interested in the virtual shaping phenomena and in particular, the possible applications of the SJAs for active aeroelastic and aerodynamic control. The team research intends to contribute to the development of lifting surfaces with unsteady aerodynamics accounting for SJAs by means of CFD computations, analytical modeling in the form of Reduced Order Models (ROMs), and experiments. Once validated, the goal is to employ such reduced order models to predict unsteady aerodynamic loading and adopt them for developing modern load alleviation and active aeroelastic control technologies for next generation of aircrafts. In conjunction to the modeling aspects, the team is developing physical actuators that will be installed in a test apparatus to experimentally validate the analytical and computational models.

The rest of this paper is organized as follows. The SJA-airfoil aerodynamic modeling is presented in the next section. It will provide some details about the modeling and simulations via CFD followed by a short overview of the reduced order model based on the Theodorsen's model. A few computational results and comparison with reduced order models is presented in section 3 while the use of SJAs for load alleviation and active flutter control is discussed in section 4. A description of the aeroelastic apparatus that will host the SJAs is presented in Section 5 along with some preliminary non linear aeroelastic experimental results.

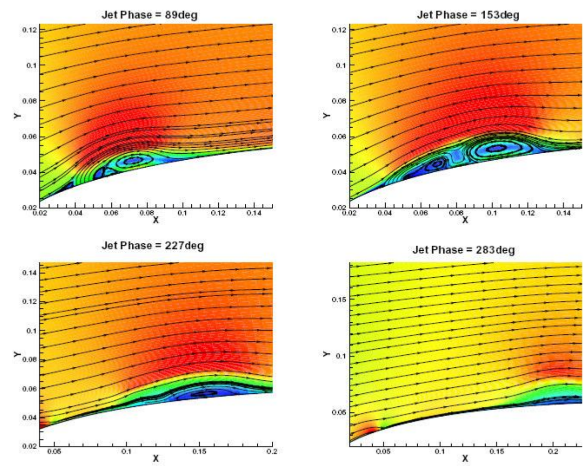
2. SJA AERODYNAMIC MODELING

2.1 Detailed Analysis vs. Reducer-Order Modeling

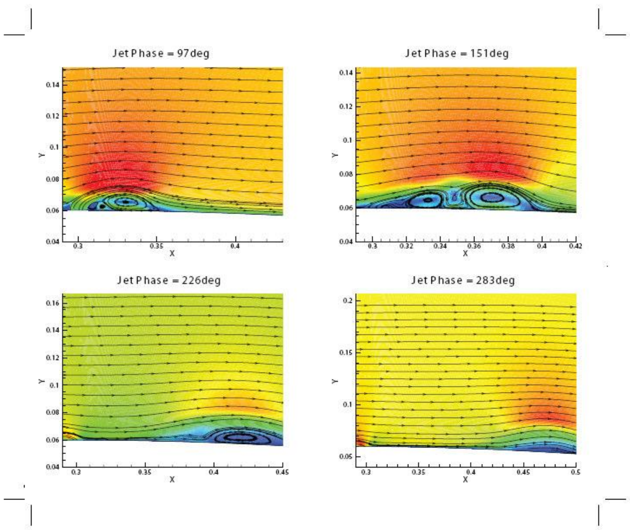
In the typical SJA configurations, jets are formed entirely from the working fluid of the flow system in which they are deployed and thus can transfer linear momentum to the flow system without net mass injection across the flow boundary [7]. The interaction of synthetic jets with an external cross flow over the surface of the wing can displace the local streamlines and induce a virtual change in the shape of the surface and thereby effecting flow changes on length scales that are one to two orders of magnitude larger than the characteristic scale of the jets [8]. The flow structure of a lifting surface with a SJA is quite complicate and so far the characterization of such structure, at all scales, has been done primarily by means of CFD computations, see Figure 2. Attempts for SJA optimization have been carried out with high order Navier Stokes equations using time-consuming and computationally expensive techniques.



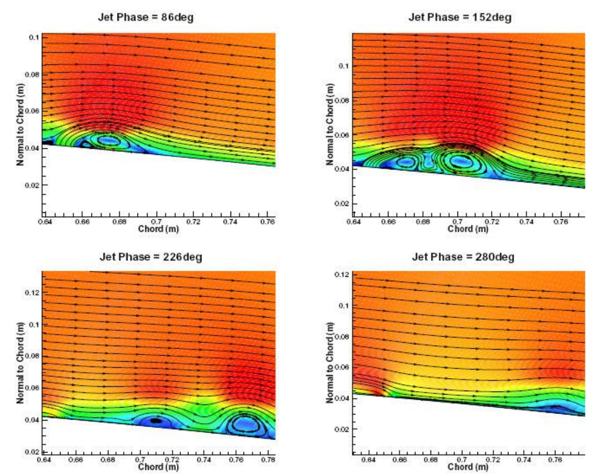
(a) Description of vortical structures



(b) $x_0 = 5\%c$ $F^+ = 1.5$



(c) $x_0 = 30\%c$ and $F^+ = 1.5$



(d) $x_0 = 65\%c$ and $F^+ = 1.5$

Figure 2: Description of the vortical structure; x_0 indicates the location of the SJA along the chord

However, it is difficult to obtain in reasonable time optimal results using optimization schemes based on numerical solutions of NS equations. Furthermore, for application to real-time feedback control, it is crucial to have a computationally efficient and reasonably accurate prediction of the synthetic jet aerodynamic contributions [1,9,10]. When the interest is limited to the determination of global aerodynamic properties, that is, unsteady lift and aerodynamic moment, it is possible to characterize the flow around the lifting surface with SJAs through reduced order models (ROMs). To help guide this and future designs, a ROM based on the Theodorsen's model to predict unsteady aerodynamic loads has been proposed in [9,11]. Herein, analytical and computational simulations have been carried out showing how the ROMs can predict the aerodynamic loading. Via the pertinent use of reduced order model and computational means a detailed investigation of the effects of unsteady excitation frequency, amplitude, and excitation location can be carried out. A number of parameters, such as jet location and frequency of actuation have been considered to estimate the region in which ROMs are valid. In addition, the ongoing research aims also to extend the validity of such ROMs as to account for thickness effects as well as to empirically correct the aerodynamic loads for positions of the jet toward the leading and trailing edges where the ROM could potentially break down. Such corrections to the model will be researched as to extend the validity of the model to a larger domain. Optimal excitation frequency will be searched within the capabilities of a physical actuator. Excitation frequencies may span a wide spectrum depending of flow regimes. Excitation amplitude may exhibit a threshold value and an optimal value.

2.2 SJAs CFD Modeling

The jet is modeled as a velocity inlet and its direction is normal to the boundary of the airfoil. This method of modeling the jet as a velocity inlet has been used successfully and validated by many investigations [12-14]. The nondimensional momentum coefficient, C_μ, is expressed in terms of free stream velocity, v, magnitude of the jet's velocity, $\bar{V}_j$, dimensional frequency of the jet, f_j , and diameter of the jet exit, h_j, as $C_\mu = 2\bar{V}_j^2 h_j / v^2$. The momentum coefficient is kept constant at a value of $C_\mu = 0.002$. The frequency is defined in terms of the reduced frequency, $F^+ = f_j c / v$, where c is the chord of the airfoil. The velocity of the jet, V_j, as a function of time is expressed as periodic function as $V_j = \bar{V}_j \sin\left(2\pi f_j t\right)$. The strategy of applying the jet boundary condition as a velocity inlet yields several advantages over modeling the cavity, the orifice, and the oscillating membrane. The primary advantage is the ability to simulate any frequency and jet exit velocity, which is otherwise limited to the geometry of the jet cavity in the simulation of the deforming membrane. However, the difficultly in applying this boundary condition lies in defining the turbulence parameters on the jet boundary. A conservative assumption suggests that modeling the jet exit as a channel is a good approximation of the turbulence in the flow [11]. More details about this approach are provided in [6].

A numerical solution to the incompressible Reynolds-Averaged Navier-Stokes equations coupled with Menter's Shear Stress Transport k-ω turbulence model are solved by using FLUENT® [16]. FLUENT® is a robust multi-dimensional finite volume formulation capable of providing quantitative solutions with reasonable accuracy. The k-ω SST turbulence model is chosen because it provides satisfactory accuracy in predicting separated flows and it is suitable for systems that exhibit local adverse pressure gradients. The equations are discretized in time using a second order time implicit unsteady formulation. The equations are discretized in space using a second order up-winding scheme. A SIMPLEC pressure-velocity algorithm is utilized to solve segregated equations for maximum time stepping efficiency. The SIMPLEC algorithm uses a relationship between velocity and pressure corrections to enforce mass conservation and to obtain a high order of accuracy pressure field [16].

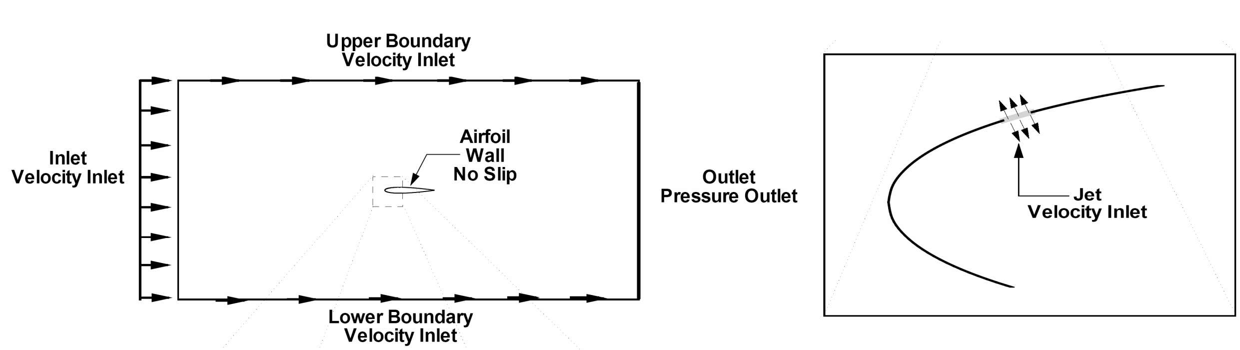


Figure 2a: Computational domain with generic synthetic jet location [11].

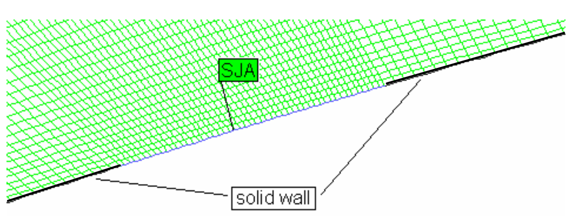


Figure 2b: Closer view of the elements near the SJA on a NACA-0015 airfoil.

The computational domain (Figure 2a) is composed of four outer boundaries; the inlet, the upper and lower boundaries and the outlet. The inlet, upper and lower boundaries are modeled as velocity inlets, at which the magnitude and direction of the velocity is specified. A pressure outlet boundary condition is applied to the right hand side of the meshed domain. The airfoils are modeled as a wall where the no-slip condition is imposed. Full boundary layer resolution is necessary to capture the turbulence in the flow near the boundary and accurately capture the velocity and pressure field. The transitional flow method of the k-ω SST model is utilized to carry out calculations inside the turbulent boundary layer. The velocity inlet boundary condition utilizes a relationship between the reference pressure and the flow velocity to calculate the pressure field. The turbulence parameters are specified at the velocity inlets with low turbulence intensities, such that the jet dominantly introduces the turbulence in the domain. The pressure outlet condition enforces the gradient of velocity at the outlet to be zero. Figure 2b shows a close detail of the computational domain around near the jet. The mesh was refined until very minimal changes in the lift, moment and drag, where reported.

2.3 SJAs Reduced Order Modeling for Aeroelastic Analysis

A detailed ROM model has been presented in [9,11]. The interested reader is referred to the previously cited paper where the model was discussed at length. The 2-D wing section is modeled using linear and torsional springs. The expression of the unsteady aerodynamic loads due to plunging and pitching oscillations have been obtained following Theodorsen's model [9]. The contribution of the SJA to the aerodynamic force and moment has been obtained by extending the development by Theodorsen to include the effect of a discrete source at the SJA location on the surface of the airfoil. The aerodynamic lift and moment contributions of the jet due to the source of volume flow rate , given in the Laplace domain are:

$$L_\sigma = \rho \upsilon C(s) \cot\frac{\theta_0}{2} + \rho b s \sin\theta_0 \tag{1}$$

$$M_\sigma = \frac{1}{2} b\rho \left(v\left(C\left(s\right)-1\right)\cot\left[\frac{\theta_0}{2}\right] + 4\sin\left[\theta_0\right]\right) - \frac{1}{2} b^2 \rho \sin[2\theta_0] s \tag{2}$$

where s is the Laplace variable, C(s) is Theodorsen's function, θ_0 is the location of the jet in circular coordinate ($\theta_0 = 0$ correspond to the trailing edge, while $\theta_0 = \pi$ identifies the leading edge), b is the airfoil semi-chord, ρ and υ are the flow density and velocity, respectively. The moment is calculated around the mid-chord of the airfoil ($\theta_0 = \frac{\pi}{2}$). In straightforward manner, the moment due to the jet around any arbitrary point on the airfoil can be calculated using the lift expression. These load coefficients combined with the unsteady loads due to the airfoil motion in the plunging and pitching degrees-of-freedom can be used to build the aeroelastic governing equation accounting for SJ actuation. These are:

$$(ms^2 + k_h)h + S_\alpha \alpha = L_h h + L_\alpha \alpha + L_\sigma \sigma \tag{3}$$

$$(I_\alpha s^2 + k_\alpha)\alpha + S_\alpha h = M_h h + M_\alpha \alpha + M_\sigma \sigma \tag{4}$$

Herein $m, I_\alpha, k_\alpha, k_h$, and S_α are the mass, inertia and stiffness parameters, while $L_i\left(i = \alpha, h, \sigma\right)$ and $M_i\left(i = \alpha, h, \sigma\right)$ are the lift and aerodynamic moment parameters.

3. COMPUTATIONAL RESULTS AND COMPARISON WITH ROM'S

Computational results of oscillatory SJA embedded in an airfoil in a cross flow have been also presented in [9,11]. In Figure 3 the effect of jet size on the lift coefficient has been highlighted. A NACA-15 airfoil with a chord length of 1m was used in all three cases, and simulations have been conducted for jet sizes of 0.1%, 0.075% and 0.05% of the chord length. It clearly appears that, while holding the jet velocity constant, the magnitude of the lift coefficient increases with the increase of the orifice size. Additional studies are also planned to evaluate the effect of the SJA size on the flow pattern.

The lift response from the CFD results and the analytical ROM based on the Theodorsen model are displayed in Figure 4. These results are generated using a jet location of x^0 = 50%c and a reduced frequency of F+ = 1.0. It is demonstrated that the CFD results indeed shows higher order harmonics as well as a static offset in the lift response. The static offset means that the lift oscillation has non-zero mean value [11]. This is also evident from Figure 3. It is observed that, for this case, the response amplitudes match reasonably well, inferring that both the CFD and the reduced order model compare favorably for the investigated ranges of jet locations and reduced frequencies. It is interesting to observe that the amplitude of the lift coefficient varies linearly with increasing reduced frequency for high frequencies, see Figure 5. This trend is in accordance with Eq. 1, however, at lower frequencies, the trend is no longer linear due to the effect of the Theodorsen's function. This phenomenon is clearly indicated in the frequency response plot in Figure 5. The crosses indicate the CFD results for the corresponding color and thus jet location.

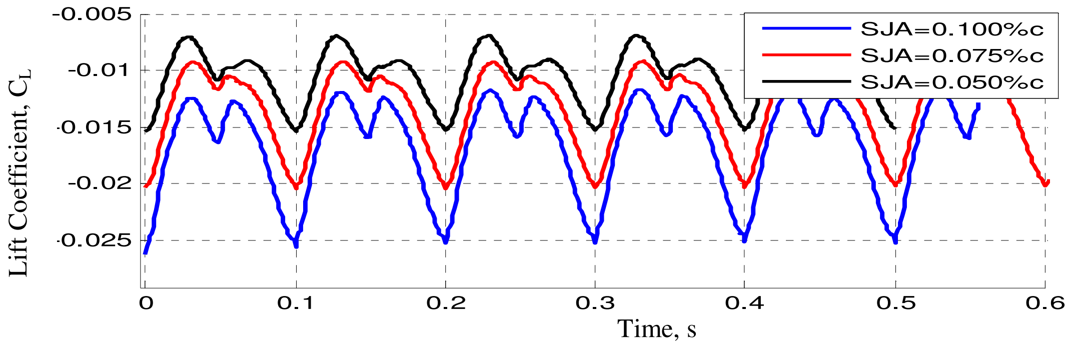


Figure 3: Effect of the size of the SJA on the lift coefficient. SJA located at 5%c and F+=0.5.

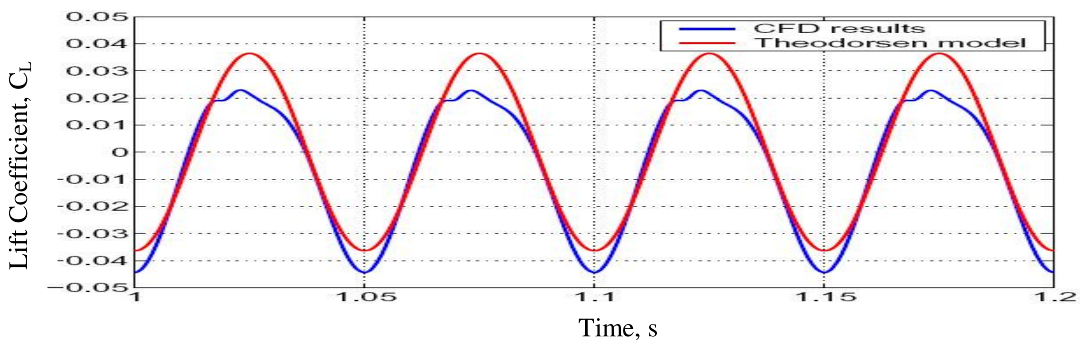


Figure 4. Lift history for CFD and analytical solutions

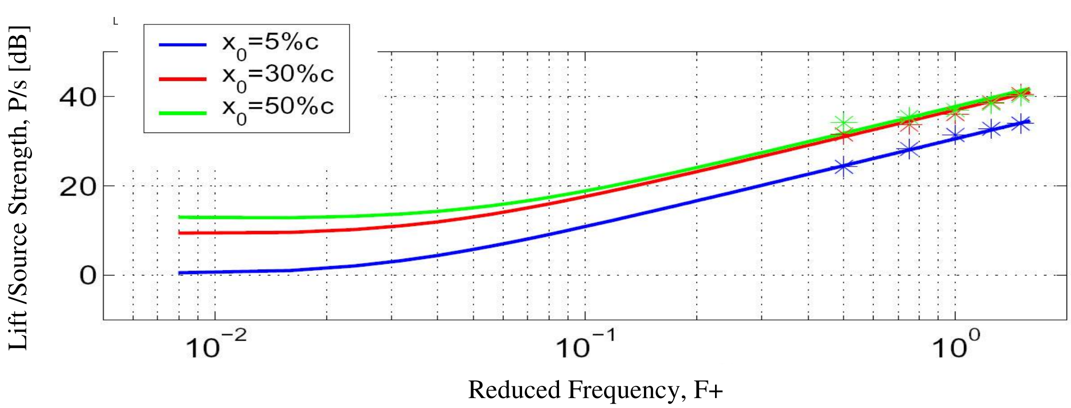


Figure 5. Bode diagram for various jet locations on the airfoil

4. ACTIVE CONTROL BY A SINGLE AND MULTIPLE ACTUATORS

4.1 Aeroelastic Control

Preliminary results have shown that SJAs can be used to effectively extend the flight envelope of an aircraft wing by increasing its flutter speed [9]. The single SJA controller design utilizes simple output feedback control to achieve aeroelastic stability of a pitching-plunging airfoil. As indicated in [9] the only measured output of the controller is the pitch angle α; a relation between α and the jet strength can be found by eliminating h from Eqs. 3 and 4. The control variables are the force and velocity of the fluid exiting the cavity of the SJA through the orifice to the surface of the airfoil and into the boundary layer. SJAs displacement and frequency is directly related to the voltage; therefore the input voltage can be varied in order to achieve the desired SJA output force and velocity. Clearly SJAs based on piezoelectric membrane or on voice coils technologies will require different applied input voltages to get the required output force designated by the control law. The control plant inherently contains the transfer function that is created between the fluid structure interactions with the dynamics of the oscillating membrane. Breuker et al [9] have shown the minimal required feedback control gain is obtained for a frequency ratio $r = \omega_d / \omega_f$ smaller then 1. In Figure 6a the root locus plot for r = 0.7 shows how the poles of the aeroelastic system move for a varying feedback control gain. A frequency ratio of r = 0.77 was selected to check the stability of the system at an airspeed 15% larger than the original flutter speed. It indeed appears that the controller actually can stabilize the system in the unstable region (see Figure 6b) when subjected to a small disturbance. The design of an aeroelastic system with multiple SJA adds to the complexity of the control law due to the need for each individual jet to have its own control law. Moreover since multiple jets are used, a coupled problem exist between jet location and controller design. Numerical calculations also revealed the control plants effectiveness is maximized when the eigenfrequency of the jet is near the flutter frequency [9]. It was also shown that SJAs are not an effective means of load alleviations; this is because the SJAs need to be designed for a certain frequency. Therefore when turbulence occurs it acts across the frequency spectrum rendering the control obsolete. Figures 7 and 8 depict the control plants for the single and multiple jet actuators, respectively.

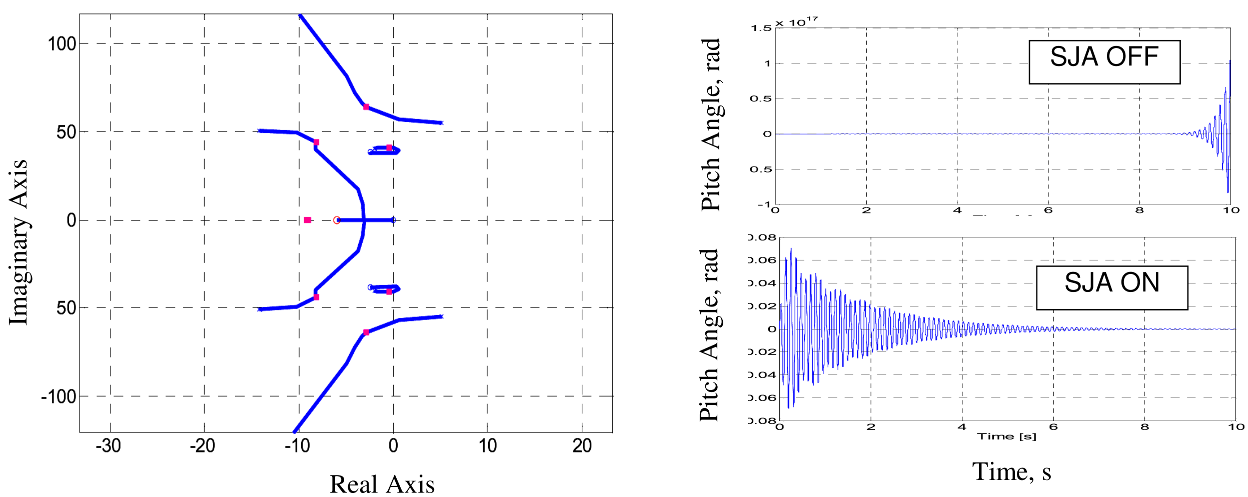


Figure 6: a) Root locus plot for single SJA with given frequency ratio (r = 0.7); b) open/closed loop aeroelastic response for r =0.77.

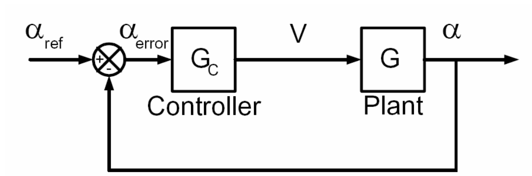


Figure 7: Single SJA controller design

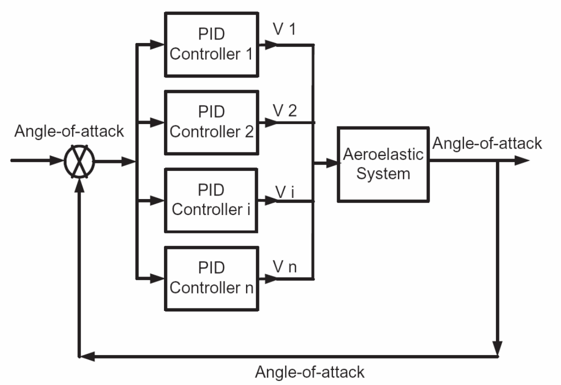


Figure 8: Multiple SJA controller design

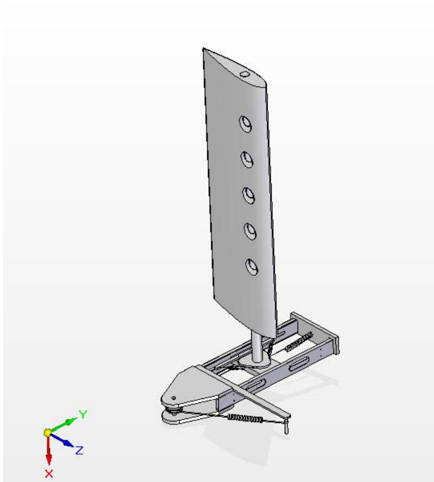
5. NON LINEAR AEROELASTIC EXPERIMENTS

5.1 Aeroelastic Apparatus

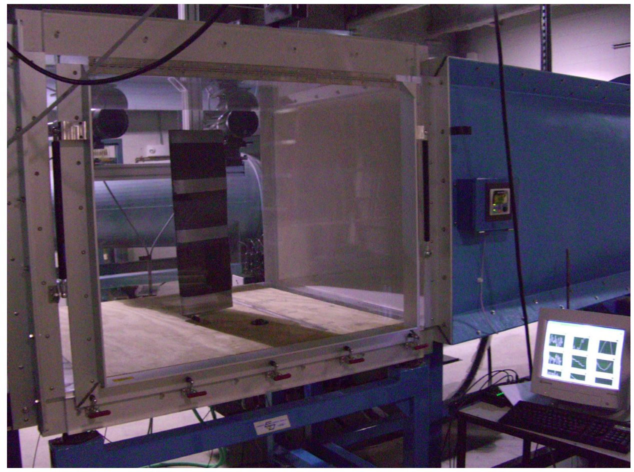
SJAs are going to be installed in a wing section that will be used for static and dynamic tests. An apparatus hosting a NACA 0018 wing section is capable of non-linear plunging and pitching oscillations. Two similar test apparatus designed at NASA Langley and Texas A&M University has helped researches in their aeroelasticity and aeroservoelasticity studies. The ability to demonstrate suppression of aeroelastic instabilities such as LCO and flutter through SJAs necessitated the following apparatus design. Figure 8a), schematically depicts the complete assembly of the 2-DOF test apparatus designed and built at Clarkson University, which has been based on the previously mentioned tests apparatus. The main advantage of this design is the ability to have independent natural frequencies for the motion in the pitching and plunging degrees of freedoms. To accomplish this decoupling of motion a bearing carriage system was utilized. The circular bearing, which allows for pitch motion via a shaft to the elastic axis of the airfoil, is pressed into a carriage that is directly attached to the slider bearing allowing for motion in the plunge direction. To further illustrate the non-linear spring cam retention system shown in Figure 8a) the complete assembly is comprised of a non linear cam mounted to the rotational axis to restrict pitch movement and a linear cam mounted in line with the slider cart to restrict plunge displacement. The composite wing is considered perfectly stiff, therefore the elasticity of the system in contained completely in the spring cam system. The springs connected to the cams are interchangeable allowing for a parametric stiffness test to be conducted. Initial static and dynamic tests will help characterizing the spring stiffnesses. This will allow for the study of the LCO at low wind tunnel velocities. Once sufficient tests have been conducted and the characterization of the aeroelastic model has been completed, the next phase of testing will be carried out using active flow control and post flutter suppression. Preliminary results have shown that this apparatus can achieve LCO for different spring constants and the corresponding dynamic pressures.

5.2 Preliminary Experimental Results

The NACA 0018 wing section shown in Figures 9a,b) has a span of .75 m, and was installed in a $1.2 \times .91 \times 1.2$ m^3 low speed wind tunnel. All other parameters and dimensions that portray the experimental setup can be found in O'Donnell et al [17]. Two sets of experiments have been conducted. To characterize the aeroelastic system, a parametric study of plunge/pitch spring stiffnesses and corresponding LCO free stream velocities was investigated first. Secondly, a static test on a NACA 0018 wing section, at various angles-of-attack, was carried out to quantify the effects of the installed actuation hardware. The information gathered from the two experiments aided in creating an accurate analytical model. This model can be used to vary many different control parameters and efficiently optimize a proper control plant. The control knowledge gained through simulations will be translated to the physical aeroelastic system. Figure 10 depicts the LCO displacement time-histories and phase-space diagram responses respectively for the uncontrolled aeroelastic experiment, at a free stream velocity of 5 m/s. The ultimate goal is to actively monitor and suppress aeroelastic vibrations by means of SJAs. These SJAs are under development at both institutions involved in this project. Delft University of Technology is developing SJAs based on piezo benders while Clarkson University is using solenoids and voice coils to achieve the same purpose. The selected technologies will be able to cover a large frequency spectrum of actuation. However, this research is still on-going and results will be presented elsewhere.



a)



b)

Figure 9: a) Complete assembly of 2-DOF aeroelastic test apparatus; b) Apparatus mounted in Clarkson University wind tunnel facility.

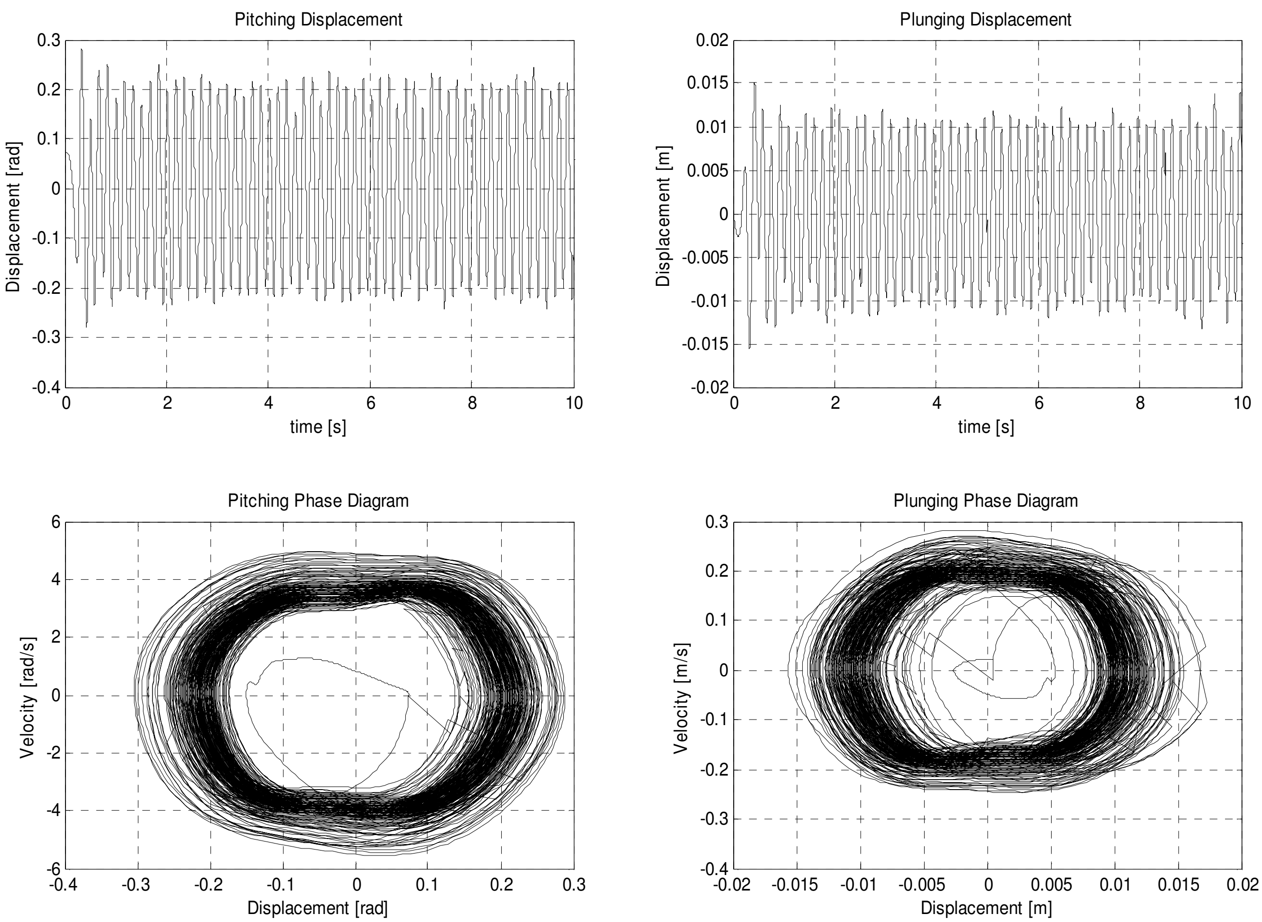


Figure 10: Uncontrolled LCO plunging and pitching time-histories at the free stream velocity of 5 m/s.

6. CONCLUDING REMARKS

In this paper an overview of the work being conducted on aeroelastic active flow control devices is outlined. Selected aspects of the research have been discusses: numerical methods in terms of computational fluid dynamics simulations as well as reduced order methods have been presented along with some initial experimental investigations. Open and closed loop analyses have been conducted taking advantage of the reduced order models that have been developed. SJAs have been implemented into the analytical and numerical simulations to investigate various control capabilities. Comparisons with numerical simulations have shown that the ROM can properly predict the aerodynamic loads to be used for the active control of aircraft wing. Future research work is directed toward the development of active control laws to be used in the suppression of aeroelastic instabilities.

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