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SUPPRESSION OF SIMULATED SELF-EXCITED OSCILLATION USING SMART MATERIALS ON FLEXIBLE WING STRCUTURE

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Abstract: Suppression of simulated self-excited oscillation due to aeroelastic effects using piezoelectric patches is reported. The focus of the present work is suppressing simulated flutter oscillation using piezoelectric patches bonded to the wing structure. First, a clean wing is exposed to airflow in the wind tunnel where it experienced limited amplitude oscillation. The responses were recorded. This is followed by bonding piezoelectric patches to the identical wing that was tested in the wind tunnel. Two of the patches were used as actuators to simulate self-excited oscillation in a control manner. The selected mode for excitation is 1st bending mode. The other two patches were used as suppressor for active control using negative velocity feedback Single-Input, Single-Output approach. The single input signal for negative feedback is also sensed using piezoelectric patches. The controller manages to suppress the simulated flutter response to a lower oscillation amplitude values. This works demonstrated the used of piezoelectric material as actuator to reproduce the oscillation amplitude during self-excited oscillation and suppress the oscillation at the same time.

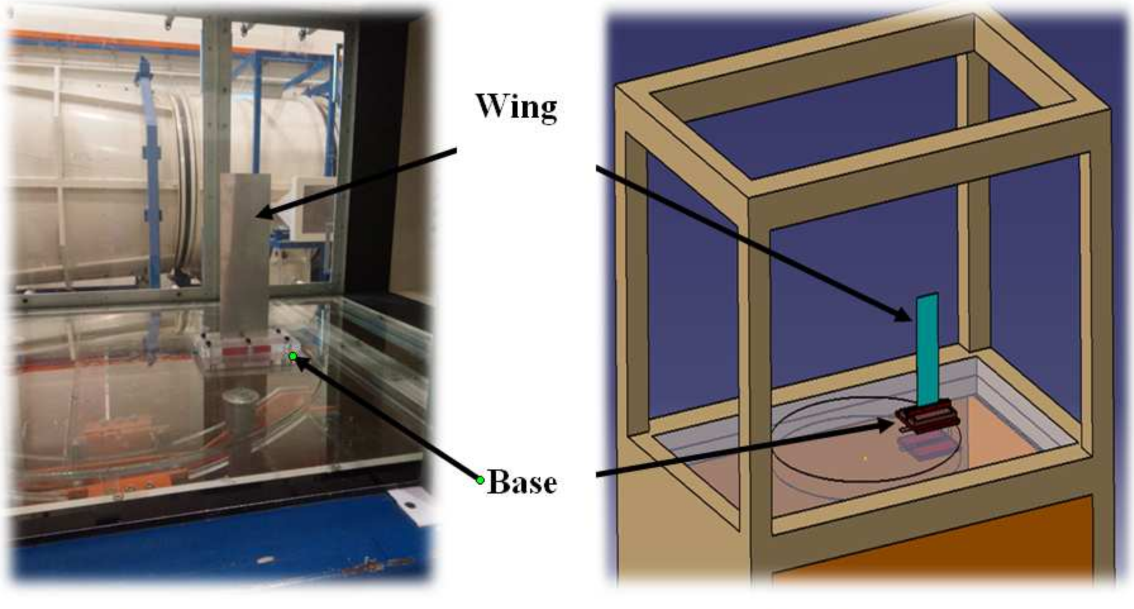
1 INTRODUCTION

Dynamic aeroelastic phenomena have plague aircraft structures for years. The phenomena manifest from the interaction of aerodynamic, inertia and elastic forces of flexible structures. One of the phenomena could lead to catastrophic failures of aircraft structure. There are a few dynamic phenomena that arise from the interaction of these forces such as flutter, stall flutter, buffeting and galloping. The most dangerous among these is flutter. It is a self-excited oscillation resulted from coupling between two vibration modes. The coupling absorbs energy from the airflow and overcome the damping. This leads to exponential growth of the oscillation response amplitude in linear aeroelastic system. The existence of nonlinearity in aeroelastic systems such as aircraft structures could yield different type of oscillation where the amplitude is limited. This type of oscillation is known as Limit Cycle Oscillations or LCOs. The amplitude is limited by the nonlinear forces acting in the system.

LCOs have been proven to manifest when there are strong nonlinear properties exist within the aeroelastic system. The nonlinearity could either originate from structural and/or aerodynamic part of the aeroelastic system [1-2]. Apart from flutter, there are other aeroelastic phenomena such as buffet that yields LCOs. Buffet is caused by unsteady aerodynamic forces induced by separated flow or vortices exciting aircraft structure. The resulting oscillation causes fatigue damage leading to limited capabilities and availability of the aircraft [3].

These aeroelastic phenomena are detrimental to aircraft structures and should be suppressed. Dynamic aeroelastic suppression techniques have been available for quite some time. It can be divided into two categories which are passive and active. At present, passive flutter suppression techniques involve modifying the stiffness of the structures or altering the position of the flexural axes by changing the mass distribution. These solutions result in higher cost and a decrease aircraft performance [4].

Alternatively, there has been an extensive research in the development of active flutter suppression techniques. The method utilizes conventional aerodynamic control surfaces such as spoilers and ailerons to suppress aeroelastic oscillations. These methods have not been widely adopted into operational industrial practiced because of a few reasons. The primary concern is the flutter phenomenon itself. It is catastrophic in nature and should be avoided in the first place. Another reason is based on the notion of dual use of aircraft control surfaces which could lead to safety issues.



(a) Experimental setup (b) CAD design

Figure 1: Clean wing test Setup in the closed circuit wind tunnel

A different option being explored in active flutter suppression technique is by utilizing smart materials in place of aircraft control surfaces and [3, 4 and 5]. There are different type of smart materials available ranging from piezoceramic, SMA wires and shape memory alloy [6]. Among these smart materials, piezoelectric is the best option available. It has advantages in terms of lightweight, can be operated at wide frequency bandwidth, can be bonded and embedded within composite structures.

Piezoceramic are materials which are characterized by their ability to generate electric voltage when experiencing mechanical strain. Reversing the process by applying electric voltage will cause the piezoelectric material to undergo strain. These effects are coined piezoelectric effects [6]. By bonding the piezoelectric patch on a structure, it can be used as an actuator or sensor by straining the piezoelectric material. Research on the use of piezoelectric material for vibration suppression has been extensive [4].

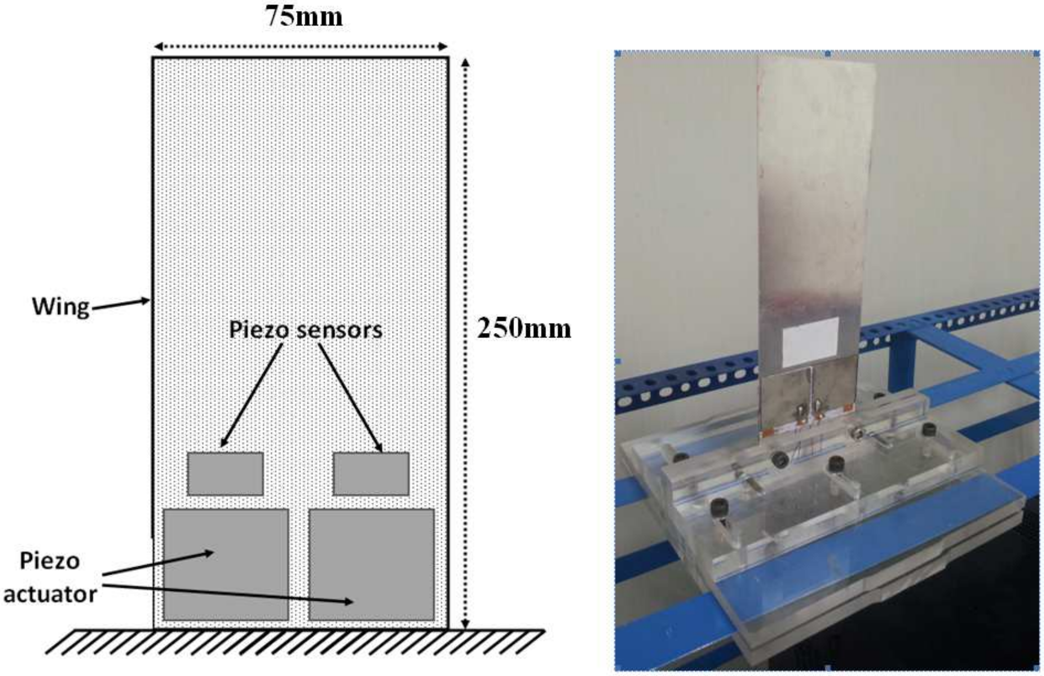


Figure 2: Wing dimension and bonded piezoelectric patches location

Vibration suppression using piezoelectric material can be divided into two main approaches: active and passive. Passive suppression usually involves shunt circuit where the energy produces by the piezoelectric patches is dissipated by resistor, capacitor and inductor circuit [5]. Typically, large value of inductor is required; it can be substituted using synthetic inductor using operational amplifier circuit. Active and passive vibration suppression have been widely studied. Most findings show many advantages using active techniques over passive techniques. There are a few available active control approaches that can be employed for vibration suppression using piezoelectric patches such as output feedback and state feedback.

Physical Properties	Wing
Density	2710kg/m^3
Young Modulus	69000Mpa
Poisson ratio	0.3

Table 1: Wing material properties

The purpose of the present work is to investigate the use of piezoelectric material as means to suppress oscillation manifesting from aeroelastic phenomenon. The phenomenon in question is self-excited oscillation of flutter. The work employs aluminum flat plate as representation of flexible wing structure. Piezoelectric patches were then bonded to the wing structure. The oscillation was then simulated and suppressed using piezoelectric patches bonded to the wing. The control law adopted is the output feedback method. By actuating the piezoelectric patches to increase the structural damping, flutter oscillation amplitude is suppressed.

2 EXPERIMENTAL SETUP

The wind tunnel testing is performed in Science Engineering Centre (SERC) laboratory of Universiti Sains Malaysia, Engineering Campus. The wind tunnel is a closed-circuit tunnel with an effective velocity ranges from 5 to 80 m/sec. It features a test section measured 1.0m x 1.0 x 0.8m in width, length and height. The average turbulence level of the flow in the test section is 0.18%. Fig. 1 shows the cantilever wing setup in the wind tunnel test section. The wing is fixed to the floor of the test section using 10mm Perspex plates. The plates also secured the wing at the wing root. To prevent the wing from breaking free and flying off into the test section during testing, two bolts are fastened through the wing and the base plates.

The wing planform selected for this study is a straight rectangular wing. Two wings are fabricated. The first wing acts as the control point and this wing is coined clean wing. The second wing is bonded symmetrically with piezoelectric patches on both sides. The bonded wing is called patched wing. The location and arrangement of the piezoelectric patches are shown in figure 2. The wing has a span of 250mm and a chord of 75mm, respectively. The wings are made from 1100 aluminum alloy with thickness measured 0.5mm. The wing fixture is made from 10mm Perspex plate.

Physical Properties	Piezo ceramic
Density	7800kg/m^3
Young Modulus	5.2 x 10^{10}
Dielectric constant	1800
Piezoelectric charge constants	390 x 10^{-12} m/V

Table 2: 5A4E piezoelectric properties.

2.1 Piezoelectric patches

Six piezoelectric patches are bonded on the wing's surface. Four of the patches are used as actuators. These are bonded symmetrically on each side of the wing. The size of the actuator patches is 35mm in width and 40mm in height. The other two similar size patches are used for sensing and only bonded on one side of the wing. The bonds between the aluminum plate and piezoelectric patches are realized using epoxy glue since firm contact between piezoelectric patches and the wing is crucial. Weak bonding would result in reduce performance of the actuator. Piezoelectric material chosen for this study is PSI-5A4E made by PIEZO SYSTEM INC. 5A4E sheet has low current leakage and low magnetic permeability. It is temperature insensitive and can operate at wide range of temperature. The sheet was manually cut to the desired sizes before being bonded to the wing. The Piezoelectric sheet is very fragile and must be handled with care. A few sheets have been damaged in the process. After the sheet has been cut and bonded to the wing, electrical cables were soldered to the piezoelectric patches. This turned out to be a challenging process as in many cases, the solder refused to adhere to the patch surface. The material properties of the piezoelectric material are presented in table 2.

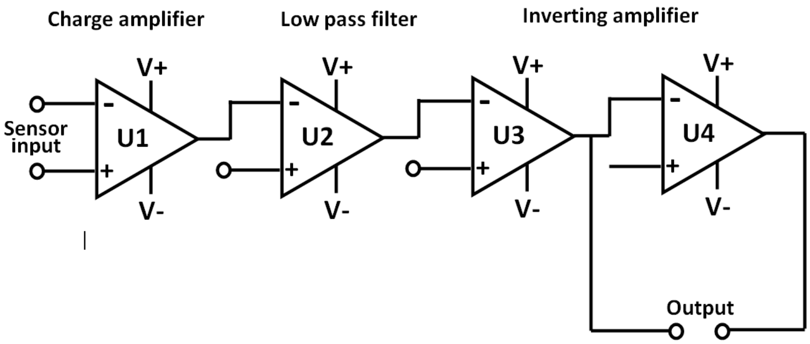


Figure 3: Four stages operational amplifier circuit

3 CONTROL SYSTEM

In this work, constant gain negative velocity feedback is applied. In this technique of control, the sensor signal is differentiated so that the strain signal which is related to the velocity signal is obtained. The actuator is then provided with the velocity feedback. The velocity feedback augments the system damping which effectively control the oscillation amplitude. As the oscillation amplitude decays, the feedback signal voltage also proportionally decreases [9]. This reduction in voltage input also decreases the effectiveness at low vibration amplitude for a given voltage limit. This method was chosen because of its simplicity. It is suitable for preliminary testing of the whole setup.

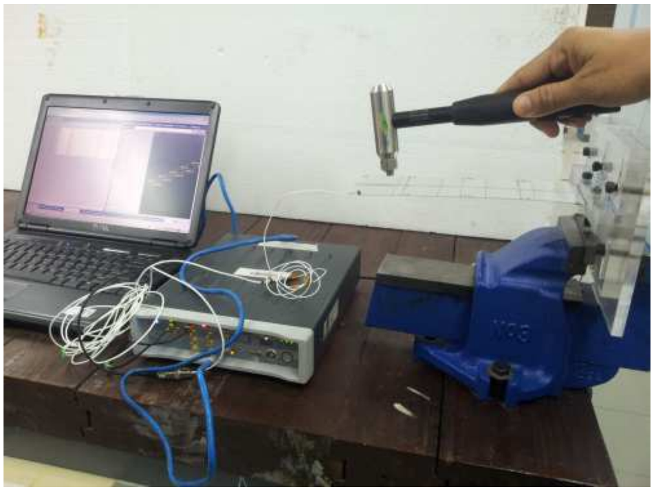
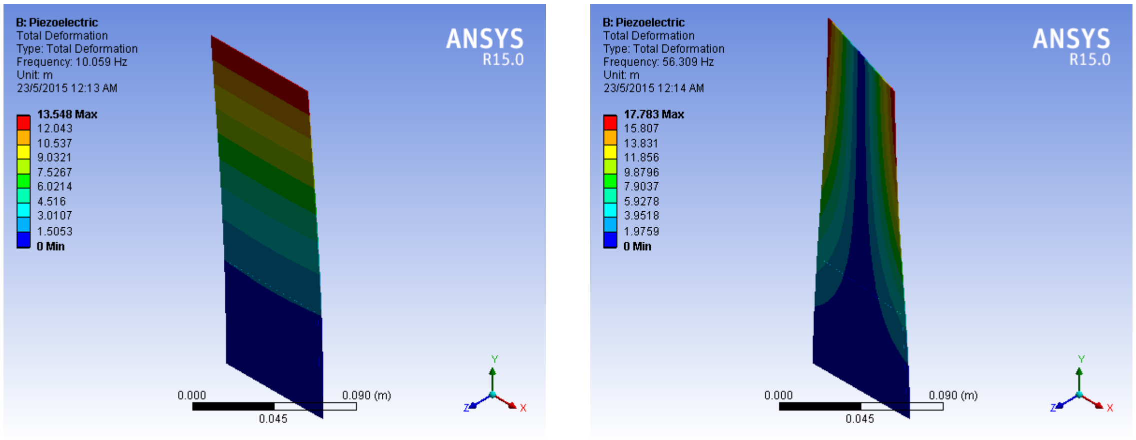
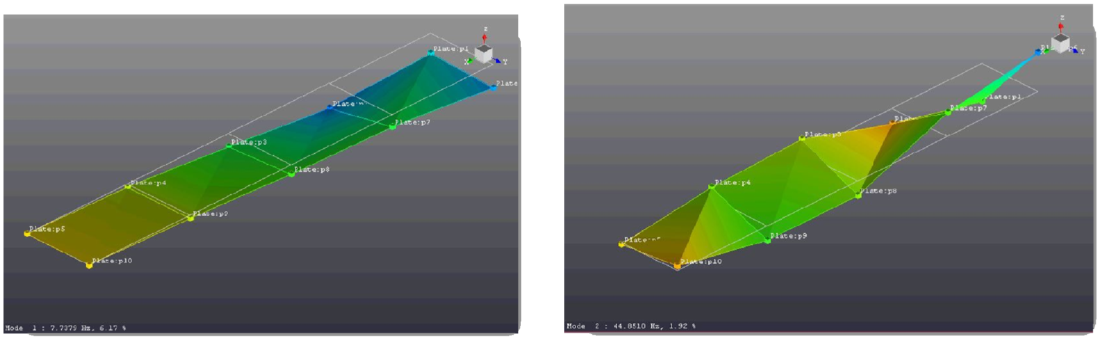


Figure 3: Modal analysis test setup

The negative velocity feedback was realized using a four stage operational amplifier. The signal input is fed through a charge amplifier where electrical signal is converted into voltage. Then it is passed through low pass filter to filter out high frequencies signals. Then the signal is amplified by a constant gain and inverted before being fed into the piezoelectric actuator for suppression. The low pass filter is stage is crucial to avoid any high frequencies signal being amplified in the output signal. The diagram for the operational amplifier is shown in figure 3.



(a) 1st Bending (ANSYS) (b) 1st twisting (ANSYS)



(c)1st Bending (experiment) (d) 1st twisting (experiment)

Figure 4: Mode shapes of the patched wing structure

4 MODAL ANALYSIS

The tests are divided into 3 phases. The first phase involves identifying the structural characteristic of the system. The natural frequencies, mode shapes and damping ratios were obtained through ANSYS 15.0 finite element software and experimental modal analysis. Figure 3 shows the modal analysis setup. The setup employed an impact hammer, teardrop accelerometer and LMS modal analysis data acquisition and software. The results are tabulated in the table 3.0. The table shows that piezoelectric patches bonded to the wing increased the natural frequencies of the structure. The first bending natural frequency rose from 7.73 Hz to 10.06 Hz. 1st twisting mode natural frequency also increased. Bonding of piezoelectric patches to the wing contributed to the overall stiffness of the wing structure. The 1st and 2nd mode shapes for the patched wing is shown in figure 4. There is no discernible change in the mode shape for the patched wing with respect to the clean wing. Only the values of the natural frequencies increased noticeably.

Mode	Clean wing	Patched wing
1st bending	7.7379 Hz	10.06 Hz
1st twisting	50.393Hz	56.31Hz

Table 3: Natural frequency for clean and patched wing

5 WIND TUNNEL TEST

The second stage involved testing the wing structure in the wind tunnel. A clean wing was tested in the wind tunnel. The test was meant to identify the critical flutter speed of the clean wing and obtaining flutter characteristics. The airspeed tested starts from 10m/s up to 34m/s. There was no excitation applied to the wing during the flutter test. Turbulence flow of the wind tunnel is used as the source of excitation. The clean wing was instrumented with strain gauges, connected to signal conditioner and National Instrument data acquisition system. The strain gauges were calibrated with respect to the wing tip oscillation amplitude. Self-excited oscillation was observed when the airspeed is at 32.5m/s. The type of oscillation observed is oscillation limited in amplitude as shown in figure 5. Increasing the airspeed led to an increase in the oscillation amplitude.

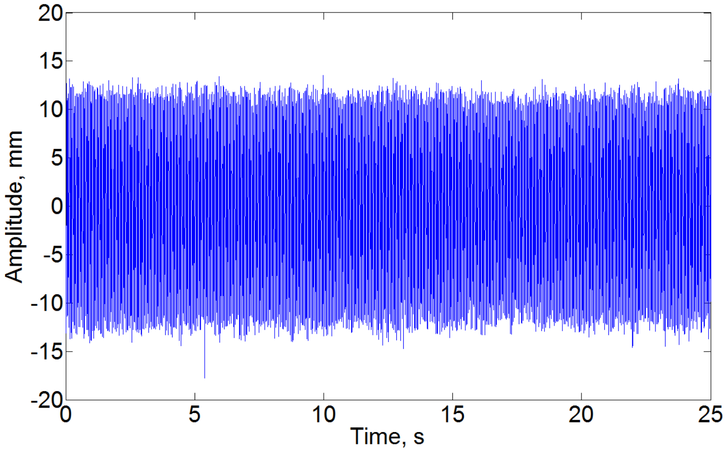
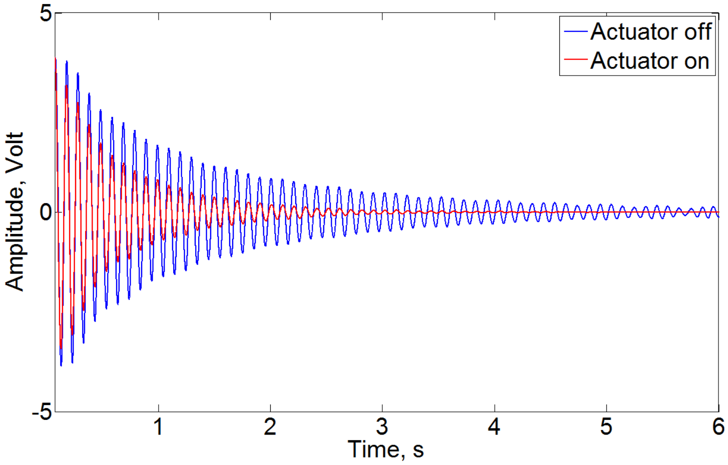


Figure 5: LCO response measured at 32.5m/s

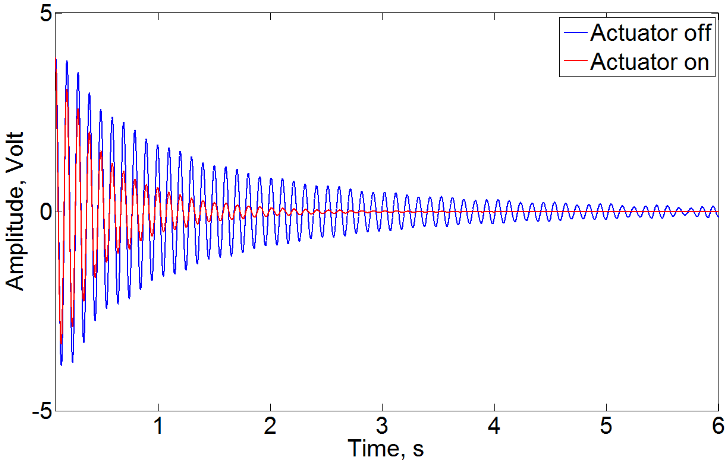
6 ACTIVE CONTROL

6.1 Free response

The last stage of the test involved obtaining free vibration response and simulated self-excited response of the patched wing. The objective is to evaluate the damping ratio of the structure with and without active control suppression. The test was performed by applying similar impulse amplitude to the patched wing and recorded the bending mode responses with the controller switched off and on. The results are shown in figure 6. Figure 6(a) shows the responses when only one piezoelectric patch is utilized. The structure oscillates with 1st bending frequency. The blue line represents when the controller is in the off mode while the red line represent controller in active mode. The plot illustrates the increase in damping for the patched wing when control is applied. This is observed from the earlier decay of the response obtained when the controller is switched on. Figure 6b shows responses when two of the piezoelectric actuator patches were utilized to suppress the free vibration response of the wing structure. By utilizing two piezoelectric patch. The oscillation decayed faster when compared to single piezoelectric actuator. The damping ratio measured for this configuration is 0.0284. This is higher than first configuration where the damping ratio is measured at 0.0227. When the actuator is turned off, the damping ratio of 0.0149 was recorded.



(a) Single patch



(b) Double patch

Figure 6: Patched wing free responses

6.2 Simulated self-excited response

Before testing the patched wing active control performance in the wind tunnel, simulated test were performed. The test is to verify the ability of the piezoelectric patches to suppress self excited oscillation. The simulated test is made possible by changing the roles of two of the four piezoelectric patches bonded to the wing. Two of the bonded patches were used as actuator to simulate self-excited oscillation. The mode of oscillation selected was bending mode. The other two patches were used for suppression role. The simulated self-excited oscillation is achieved by exciting two of the piezoelectric patches with signal measured during the clean wing flutter test. The signal was fed to a high voltage amplifier and channeled to the appropriate piezoelectric patches. The gain of the high voltage amplifier was tuned to achieve the desired response amplitude recorded using strain gauges. This could be achieved because the signals generated by the strain gauges were calibrated to the wing tip deflection. This process was repeated when matching the wing tip deflection excited using piezoelectric patches and for obtaining the right gain value to be applied to the high voltage amplifier.

After the gain value for the high voltage amplifier has been obtained, the simulated self-excited oscillation was performed. The result is shown in figure 7. The test started with the patched wing structure excited to the desired tip oscillation amplitude. It takes a few seconds for the wing to reach the desired amplitude. After the oscillation has stabilized, active control was switched on. This is repeated to ensure the active control part is working as intended. Figure 6 shows the simulated response amplitude of the patched wing before and after the active control was switched on. After active control was switched on, the response amplitude of the structure reduces from 11.5mm to around 2.5mm. It takes around 1.5 seconds for the amplitude to reach the minimum value.

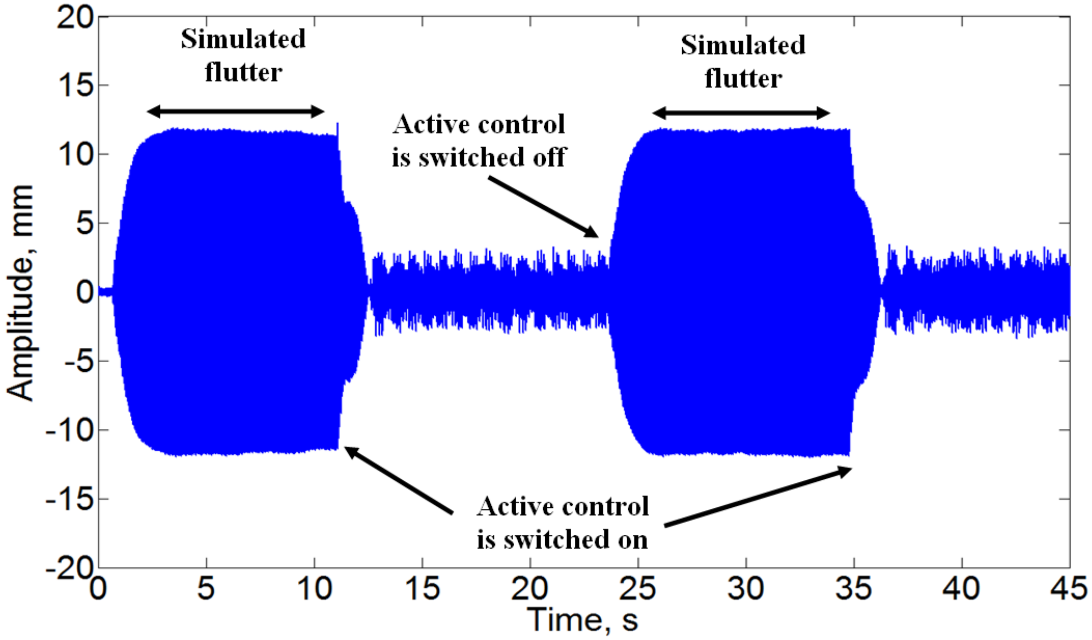


Figure 7: Patched wing simulated self-excited response and

Complete suppression of the simulated response amplitude could not be achieved. This is because the structure was excited in the open loop configuration as opposed to closed loop. Close loop should be more realistic because of the fluid structure interaction. It is also due to the negative velocity feedback approach where it suffers from reduction in its effectiveness at low vibration amplitude. The limitation lies in the nature of the output feedback of the control law. Future works will consider state feedback control approach for better control performance and wind tunnel testing. It should be noted that piezoelectric patch has limitation in exciting high amplitude oscillation. It is also susceptible to saturation when it is operating at its maximum voltage [10].

7 CONCLUSION

This paper reports on simulated active flutter suppression of a lifting surface using piezoelectric actuation and sensing. The control law employed is the negative velocity feedback using single input, single output approach. Self-excited oscillation was simulated using piezoelectric patches. Simulated excitation signal used was the response obtained from measurement during wind tunnel tests. The simulated oscillation was then suppressed using different piezoelectric patches bonded to the wing structure. The Input signal for controlling the oscillation was also provided by piezoelectric patches. The active control manages to suppress the simulated flutter oscillation amplitude to a lower oscillation amplitude values.

8 ACKNOWLEDGEMENT

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