FLUTTER CONTROL OF WIND TUNNEL MODEL USING A SINGLE ELEMENT OF PIEZO-CERAMIC ACTUATOR

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Abstract

A single element of piezo ceramics is used in this study, instead of conventional actuators such as a hydraulic actuator or electric motor, as an actuator in order to control flutter. This study aims at confirming that the free vibration in the still air and the flutter in the wind tunnel, of an aluminum plate wing, can actually be controlled by a single element of a piezo-ceramic actuator. The wing model of a rectangular aluminum plate (270.0 × 90.0 × 0.5mm) has one piezo ceramic element PZT (40.0×20.0×0.1mm) attached on its one side. We used proportional control for free vibration and flutter in order to confirm the fundamental effect of PZT. The control here uses positive voltage alone in order not to decrease the piezo-electric effect of PZT, which is so-called control of one-sided effect. However, even a single element of piezo-ceramic actuator was confirmed to be effective enough to control flutter.

1 Introduction

Currently airplane prevents flutter by a sufficient stiffness of the main wings or mass balancing. However in recent years, research of the active control technology for aeroelasticity is advanced in many countries. In active flutter control research control surfaces driven by hydraulic actuators or electric motors are mainly used for controlling flutter actively.1). As opposed to it, in this research, the wing itself is made to deform by attaching piezoelectric material on the wing for making the flutter control actively. Therefore the piezo ceramics is used for the actuator, instead of a hydraulic actuator or electric motor. Since this research aims at weight mitigation of the airframe.

Piezo ceramics has small size and lightweight so that it can install in a small place suitable for a sensor/actuator. Therefore, its application to sensing the oscillation and controlling the vibration of structures will increase rapidly in future. Actually the research using piezo ceramics aiming at reducing buffet2), or at controlling flutter3) have been carried out. The present study deals with active flutter control using a piezoceramic actuator. Making use of an adverse piezoelectric effect, which is one of the electrodynamic characteristics of PZT, we control free vibration and flutter by imposing the strain produced by voltage to the aluminum plate wing model. It examines where piezo ceramics are to be attached first, and then whether free vibration and flutter of aluminum plate wing model can be suppressed using proportional control.

2 Flutter Control Model

2.1 Aluminum Plate Wing Model

A wing model used in the vibration control tests is an aluminum palate wing shown in Fig. 1. The wing model of aluminum rectangular plate whose aspect ratio is 3 has a single piezo ceramic element PZT attached on its one side. The size of the aluminum rectangular plate was determined as 270.0 mm*90.0 mm*0.5 mm as shown in Fig. 1 considering the sectional size of the wind tunnel outflow of 300 mm * 300 mm square and the maximum wind speed of 25*m/s*.

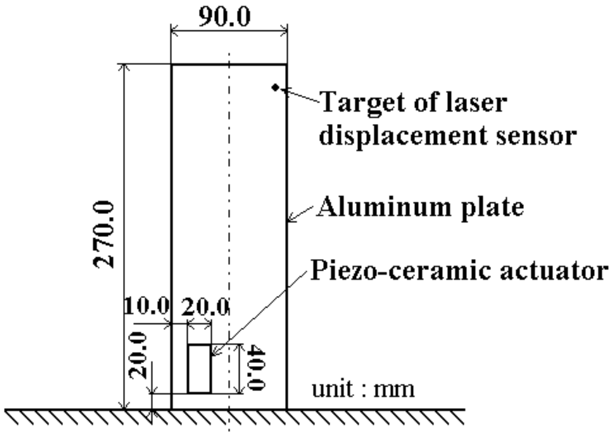


Fig. 1. PZT actuators placed on a model wing spar

2.2 PZT Actuator

In order to control free vibration and flutter by imposing the strain produced by voltage to the aluminum plate wing model large surface strain for PZT is needed. Piezoelectric relation of PZT attached at wing model is shown in Fig. 2. The surface strain x for PZT is defined by piezoelectric charge constants d_{ij} and an electric field strength E_i as:

$$\begin{Bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \end{Bmatrix} = \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{31} \\ 0 & 0 & d_{33} \\ 0 & d_{15} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} E_1 \\ E_2 \\ E_3 \end{Bmatrix} \tag{1}$$

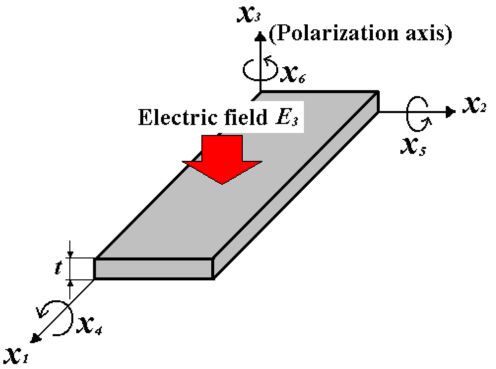


Fig. 2. Piezoelectric relation of PZT

where strain x_4, x_5 and x_6 is sharing strain of rotation of 1 axis, 2 axis and 3 axis.

The direction of polarization is toward x_3 axis since we make use of distortion along the x_1 and x_2 axis. An electric field strength is expressed by the imposed voltage V by $E=V/t$ and the surface strain x can be expressed as follows.

$$\begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = d_{31}\frac{V}{t} \tag{2}$$

Since the large surface strain is desirable for PZT, piezoelectric charge constants d_{31} should be large and thickness t should be small.

Young's modulus E should be large in order to get a large exerted force. Therefore, PZT of the material properties shown in table 1 was selected and the size of PZT was determined as 40.0 mm*20.0 mm*0.1 mm. We used a laser displacement sensor to measure the displacement of a wing tip. The position to measure is shown as a target in Fig. 1 where bending as well as torsion deformation can be detected.

Table. 1. Physical constants of PZT at normal temperature

Density	$8.1\times10^3\ kg/m^3$
Dielectric constants	4900
Piezoelectric charge constants	$-375\times10^{-12}\ m/V$
Young's modulus	$6.4\times10^{10}\ N/m^2$
Poisson's ratio	0.32

For simplicity and as a challenge, we decided to use only a single element of PZT. PZT actuators can excite simple bending, simple torsion deformation, or those combinations to the aluminum rectangular plate depending on the position and the direction of the actuators. The amount of deflection also depends on them. The position and the direction were determined such that both bending and torsion can be excited and deflection can be as large as possible[3)]. Figure 3 shows the actual arrangement of PZT on the aluminum plate.

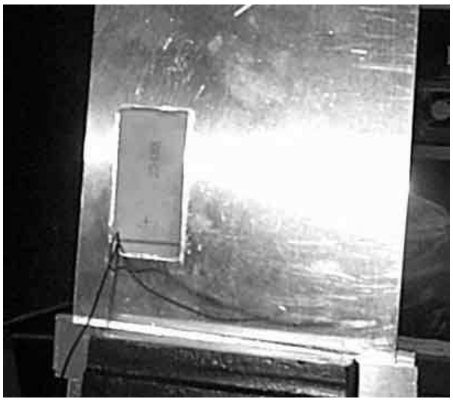


Fig. 3. Aluminum wing model with PZT attached

2.3 Vibration Characteristics of Wing Model

In order to obtain natural frequencies and mode shapes of the wing model, we performed finite element method structural analysis. The finite element model used in analysis is shown in Fig. 4. In this figure, the wing is fixed at the bottom. In analytical results, the first two natural frequencies and mode shapes are shown in Fig. 5. Natural frequencies of a bending dominant first mode and a torsion dominant second mode are 5.80Hz and 34.9Hz, respectively. Notice that the difference between the frequencies of the bending mode and the torsion mode is about 6 times in the original model.

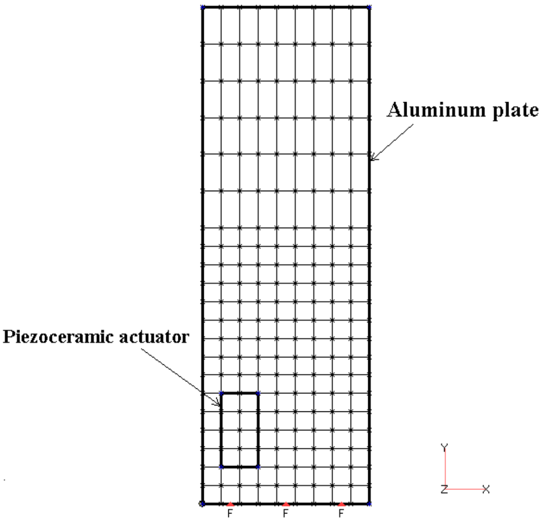
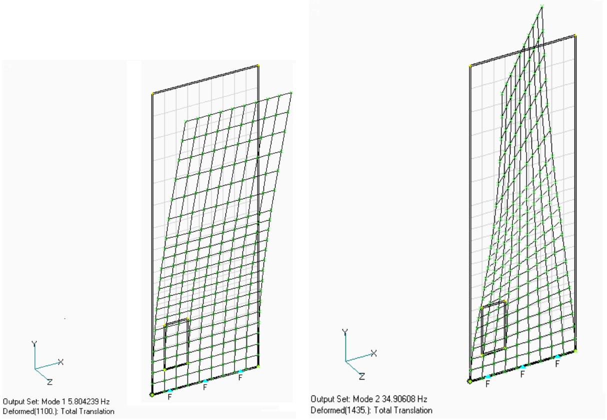


Fig. 4. Finite Element Model



(a) Mode 1 5.80 Hz (b) Mode 2 34.9 Hz

Fig. 5. Mode shape and natural frequency

3 Control of Free Vibration

The free vibration control test was performed with the test set-up shown in Fig. 6. This test composition is a single input single output system since only single element of PZT actuator is attached on the aluminum plate. The displacement of wing tip is measured by CCD laser displacement sensor and this signal is taken in the AD converter board incorporated the personal computer through charge amplifier. A sampling frequency is 1kHz. The signal output from DA converter board is amplified 24 times with power amplifier, and is imposed on PZT actuator. Maximum-output voltage is 240V.

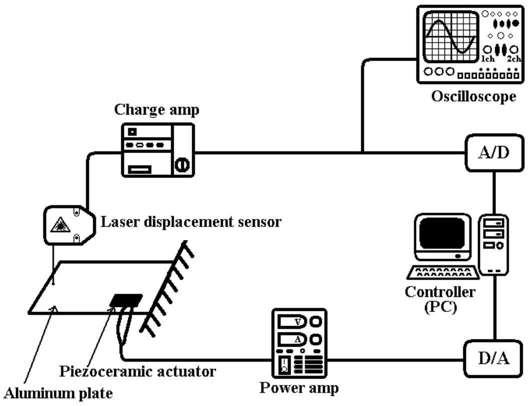
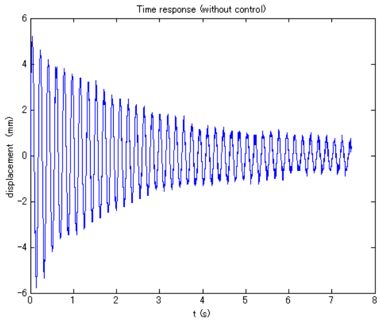


Fig. 6. Schematic diagram of the test set-up

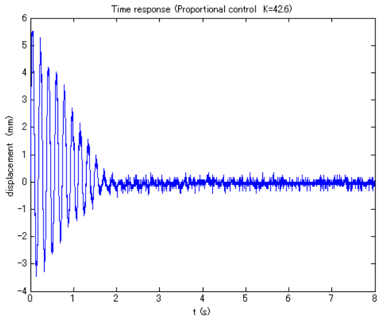
We used proportional control for free vibration in order to confirm the fundamental effect of PZT actuator. When the free end of a wing model was flipped by hand, the time response when not performing proportional control is shown in Fig. 7(a), while the time response when performing control is shown in Fig. 7(b). Figure 7(b) shows the time response of the proportional control,

$$u = -Ky \tag{3}$$

where the displacement y [*mm*] is fed back to the PZT command signal u [*V*] with the proportional gain K=42.6 [*V/mm*].



(a) Without control



(b) Controlled with a gain (K=42.6)

Fig. 7. Time response for free vibration

We compared damping characteristics of the system without control and with performing control. The damping has increased greatly by vibration control with the PZT actuator. The control voltage used here was strictly kept positive in order not to decrease the piezo-electric effect of PZT, which is so-called control of one-sided effect. However, it was confirmed that it is still effective enough.

4 Flutter Control Experiment

We fixed the wing model to the wind tunnel outflow and applied the air, but the flutter did not occur on the original model. Because flutter is bending-torsion coupling phenomenon and the frequencies of the first two modes separate too far. Therefore, the natural frequency in the mode 2 was decided to decrease, and the center of gravity of a wing model was moved behind an elastic axis by attaching an additional mass at free end trailing edge of the wing model as shown in Fig. 8. As a result, flutter succeeded in starting at a wind speed of 14.5 *m/s*. The size of additional mass (aluminum) is 20.0 mm∗150.0 mm∗0.5 mm.

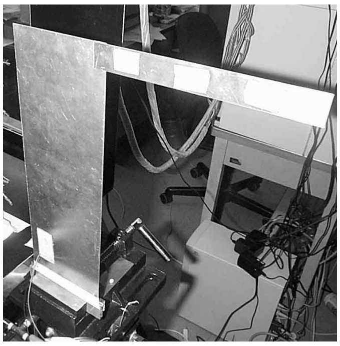
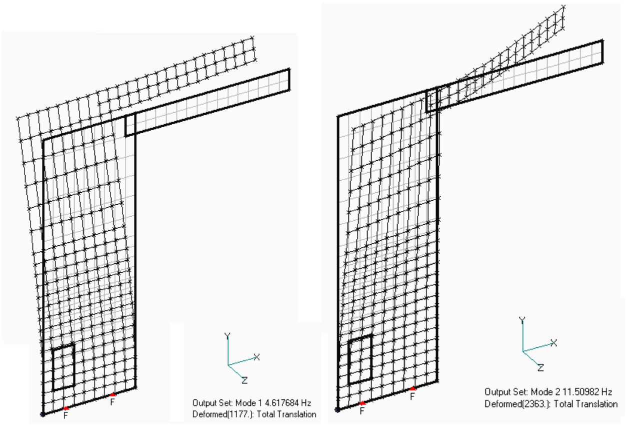


Fig. 8. Flutter model with a PZT actuator attached

In order to confirm how much the natural frequencies were improved, we performed finite element method structural analysis. The finite element model used in analysis is shown in Fig. 9.



(a) Mode 1 4.62 Hz (b) Mode 2 11.5 Hz

Fig. 9. Mode shape and natural frequency of the wing with added mass

The first two natural frequencies of bending dominant first mode and torsion dominant second mode are 4.62Hz and 11.5Hz, respectively. We found that although bending dominant first mode is not so much decreasing, torsion dominant second mode is decreasing to one third. Therefore the distance of the bending mode and the torsion mode is reduced by about a half in the improved model.

Figure 10 shows the frequency response of a wing model obtained by the vibration test. The wing model was vibrated by imposing the voltage of sine wave of constant amplitude to PZT actuator. We obtained frequency response from the voltage imposed on PZT actuator as an input to the displacement of wing tip as an output. The response of changing the input frequency at interval of 0.5Hz is shown in Fig. 10. In this figure, the natural frequency of the first mode is about 4Hz and the second mode is about 10Hz. Therefore we found that the result of FEM analysis is fundamentally confirmed. A small difference between the FEM results and the tests is considered to be the influence of support conditions. This figure will be used when the mathematical model is constructed at the next stage of the study identifying the vibration parameters.

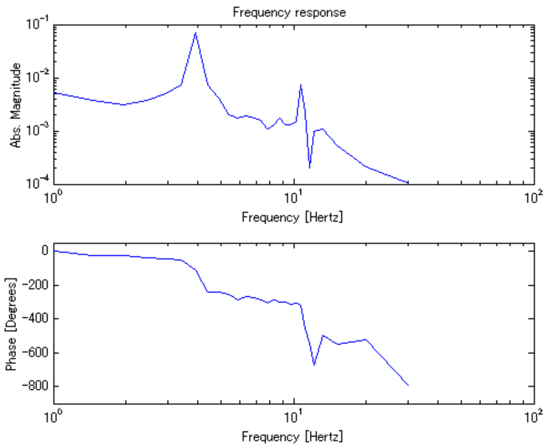
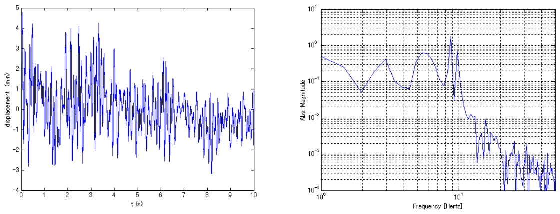


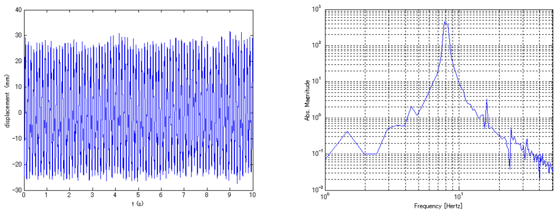
Fig. 10. Frequency response

Comparison of the response before flutter and during flutter is shown in Fig. 11. The time domain is shown in Fig. 11(a), while the frequency domain is shown in Fig. 11(b), and the response before flutter is shown in Fig. 11(1), while the during flutter is shown in Fig. 11(2). In time domain, vibration of bigger amplitude than before flutter has occurred at flutter. The amplitude of flutter is about 6 times larger than the amplitude before flutter and is continuously at constant value. In frequency domain, the bending mode and the torsion mode can be distinguished yet before flutter. When flutter occurs, two frequencies have merged.



(a) Time domain (b) Frequency domain

(1) Response just before flutter
(wind velocity 13m/s)

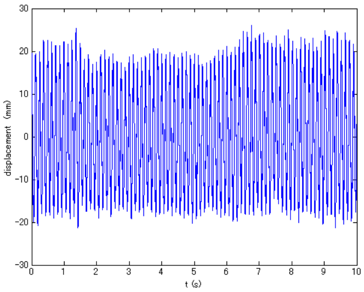


(a) Time domain (b) Frequency domain

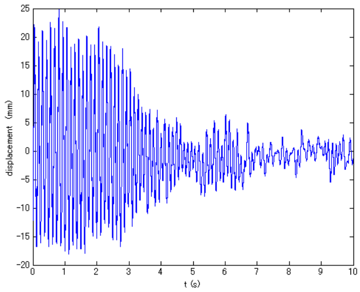
(2) Response during flutter
(wind velocity 15m/s)

Fig. 11: Comparison of the response before flutter and during flutter

In order to control flutter, we performed the proportional control as the preceding experiment for free vibration. Since flutter is bending-torsion coupling phenomenon, if control can separate two frequencies, flutter may be suppressed. We took the proportional gain contrary to the case of the free vibration control experiment. The result in the time domain is shown in Fig. 12. In this figure, actually we were able to confirm that the wing model escaped from flutter when this control was engaged.



(a) Without control



(b) Proportional control (K=-42.6)
Fig. 12. Time response for flutter

The result in the frequency domain is shown in Fig. 13. In this figure, it can be confirmed that two modes are decoupled and their frequencies are separated. We conjecture that flutter was controlled since the two natural frequencies of bending dominant mode and torsion dominant mode were separated by proportional control.

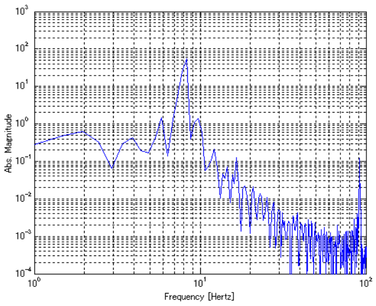


Fig. 13. Controlled flutter in frequency domain

5 Conclusions

It was confirmed that PZT actuator is effective even with a single element in vibration control of the aluminum plate as well as in flutter control.

6 Future Work

It is required to build the mathematical model of a wing model to design a control law by the LQG method etc. in order to perform more precise control. In this proportional control, the voltage imposed on a PZT actuators have saturated, we have to design a control law so that the maximum voltage may not reach to the limit. In this research, we used the laser displacement sensor. Since from a practical view point, should be attached on a wing, we have to consider the use of the an accelerometer or a PVDF film.

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