Flutter control using resistively shunted piezoceramics

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ABSTRACT

This paper investigates the feasibility of flutter control using resistively shunted piezoceramics. 2D aerofoil model is elastically restrained in heave and pitch by a set of leaf springs modeled as Bernoulli-Euler beams. The piezoceramic transducers are bonded to the leaf springs. Unsteady aerodynamic theory is used to solve the flutter determinant incorporating the additive damping terms due to resistive shunting. Tuned dampers realised by resistive shunted piezoceramics in heave and pitch springs could enhance flutter speed in the range 25-50 % based on additive damping of 10 % achieved due to resistive shunting of piezoceramics in either pitch spring, heave spring or both.

NOMENCLATURE

L_h, L_α and M_α	aerodynamic functions of reduced frequency
r_α	dimensionless radius of gyration
b	semi chord of aerofoil section
m	mass per unit span of aerofoil section
ρ	density of the aerofoil
μ	density ratio of the aerofoil ($m/\pi\rho b^2$)
x_α	normalised (with respect to semi-chord) distance from the elastic axis to the c.g.
a_h	position of elastic axis with respect to mid-chord (normalised with semi-chord) $X = (\omega_\alpha/\omega)^2$
ω_h	uncoupled natural frequency in heave (rad/s)
ω_α	uncoupled natural frequency in pitch (rad/s) $\overline{\omega}_h = \omega_h/\omega_\alpha$
T	thickness ratio (leaf spring (beam) thickness/PZT thickness)
R_i	resistance across the piezoceramics
C_{pi}	Capacitance of piezoceramics
ω_n^{SC}	natural frequency of the beam with PZT shorted
K_{ij}	generalised electromechanical coupling coefficient

1.0 INTRODUCTION

Swept-back wings of aircraft are prone to dynamic aeroelastic instabilities such as flutter. Since most modern combat aircraft have swept-back wings, active flutter control therapies have become attractive. Several options exist for implementing the aeroelastic control schemes such as active and passive control. With development of smart materials and intelligent systems it is possible to control the aeroelastic instabilities. Aeroelastic active control may be effected by altering the aerodynamic forces acting on the wing through articulation of leading or trailing edge control surfaces, or, as in recent proof-of-concept investigations, using strain actuators such as piezoceramics that directly deform the structure through electromechanical coupling demonstrated by Crawley[1] and Horikawa *et al*[2] performed simple feedback control simulations on a two degree-of-freedom (dof) aerofoil system and studied the effec-

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tiveness of these control laws in changing the flutter speed. Stability analysis with these feedback controls in place was also performed. Control realisation was assumed to be through trailing-edge actuator. Lazarus and Crawley[3] considered a four-dof aerofoil system with trailing and leading edge controls. Besides articulated control force realisation, strain actuators, such as piezoceramics and magnetostrictives, were also considered. Nitzsche *et al*[4] demonstrated the application of closed-loop control system on a full scale fighter aircraft vertical fin using piezoelectric actuators. The dynamic response study of high aspect ratio (16·7) wing with PZT patches and its control for first five modes by Abramovich *et al*[5] is a practical example for achieving strain actuation capability of piezoceramic patches. Tuzscu and Meirovitch[6] used dispersed piezoelectric actuators to control flying flexible aircraft using control surfaces. However passive control of flutter is also possible with current smart materials, PZTs in particular as emphasised by Chopra[7] and Hurlebaus *et al*[8].

The present work considers passive control of a two degree of freedom model of aeroelastic flutter of a wing section using resistively shunted piezoceramics. The piezoceramic materials are transformers that convert mechanical energy to electrical energy and vice-versa. When these piezoceramics are bonded to a structure, the mechanical strain energy generated in piezoceramics is converted to electrical voltage across the poling direction of the piezoceramic device. This voltage or electrical energy is dissipated or shunted to another frequency bandwidth using electrical networks connected to the terminals of piezoceramics, which acts as passive vibration control tool[9,10]. The analysis of power output for piezoelectric energy harvesting system by Shu and Lien[11] highlights the judicious application of shunted PZTs in both active and passive control using the electrical energy generated during the mechanical deformation of the structure under dynamic loads. Tang and Wang[12] demonstrated the combined utilisation of active and passive vibration control with hybrid piezoelectric networks. These applications could be effectively utilised in flutter control where, both the benefits of active and passive control could be combined. Agneni *et al*[13] has investigated the efficacy of shunted piezoceramics in elastic and aeroelastic gust control. The study on a fully composite glider wing with shunted PZTs to improve the stability margin establishes the capability in controlling the aeroelastic instabilities. Various feed back measurement combinations demonstrated by the authors[14] on a two degree-of-freedom oscillating aerofoil model with SISO feed back control and strain actuation in heave and pitch directions could increase the flutter speed by 50%. An autonomous shunt circuit suggested by Niederberger and Morari[15] for vibration control further strengthen the application of shunted PZTs. The stable damping performance could be achieved by these autonomous shunt circuits at environmental conditions where temperature variations are predominant.

2.0 SHUNTED PZT AS PASSIVE VIBRATION CONTROL DEVICE

Resistively shunted piezoceramic transducers enhance the damping characteristics of the host structure. Optimal thickness and length ratios (Kandagal and Kartik Venkatraman, 2004b) of the PZT and host-beam structure were used in application of damping enhancement and hence to increase the flutter speed of the wing section. Note that flutter is a dynamic instability caused due to a combination of coupling of bending and torsional oscillations, as well as aerodynamic damping. The aerodynamic damping is a function of the airspeed, and increases with airspeed. The net damping in the aeroelastic system is an algebraic sum of the structural and aerodynamic damping. Therefore, as the airspeed increases, the negative aerodynamic damping will increase, and the net damping will bifurcate from a positive damping to a negative damping system. The flutter speed then is that airspeed where this net damping changes from positive to negative. Thus, the additive

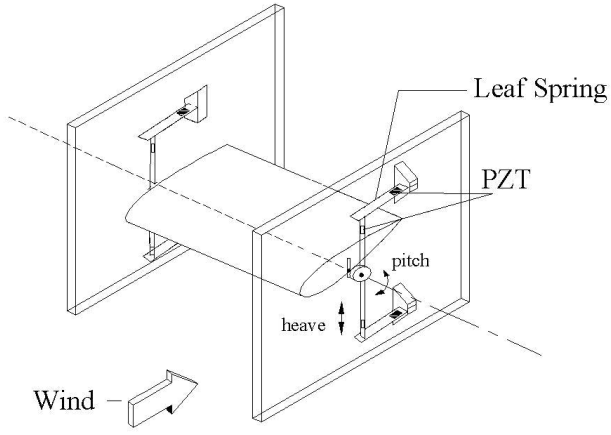


Figure 1. 2D aerofoil model with PZT in leaf springs.

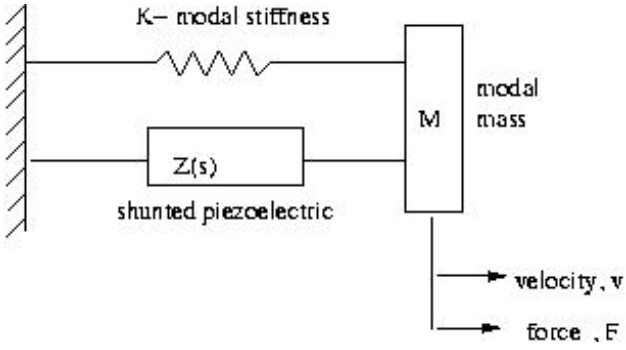


Figure 2. SDOF system model with shunted piezoelectric element in parallel with the system modal mass.

damping due to resistive shunting of a piezoceramic transducer will increase the flutter speed.

As already mentioned the 2D aerofoil model is elastically restrained in heave and pitch by a set of leaf springs. These leaf springs can be modeled as Bernoulli-Euler beams. The piezoceramic transducers are bonded to the leaf springs. The location of the piezoceramics is shown in Fig. 1.

3.0 FORMLUATION

The 2D aerofoil has bending and pitching motions simulated by leaf springs. These leaf springs (aluminum beams) are modeled as Bernoulli-Euler beams. The piezoceramic transducers are bonded to these beams. The effectiveness of piezo-resistive shunting in controlling the dynamics of a vibrating system can be modeled by a single vibration mode as shown in Fig. 2. The modal velocity[9] of the vibrating system with piezoceramic can be expressed in Laplace domain as

$$v(s) = \frac{F(s)}{Ms + (K/s) + Z_{jj}^{ME}(s)} \quad \ldots (1)$$

Where Ms is the impedance associated with modal mass of the host structure. K/s is the impedance associated with the modal stiffness of the host structure, and $Z_{jj}^{RES}(s)$ is the impedance associated with the resistively shunted piezoceramics. The transfer function for the mechanical system shown in Fig. 2 can expressed as follows

$$\frac{x}{x_{st}} = \frac{(r\gamma + 1)}{(r\gamma^3 + \gamma^2 + r(1 + K_{ij}^2)\gamma + 1)} \quad \ldots (2)$$

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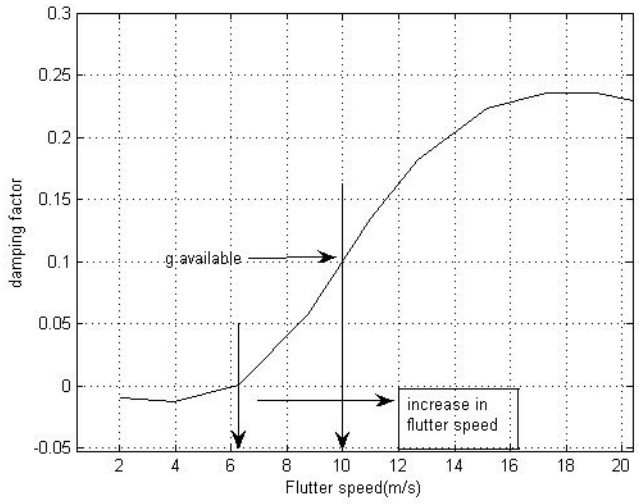


Figure 3. Effect of damping factor on flutter speed.

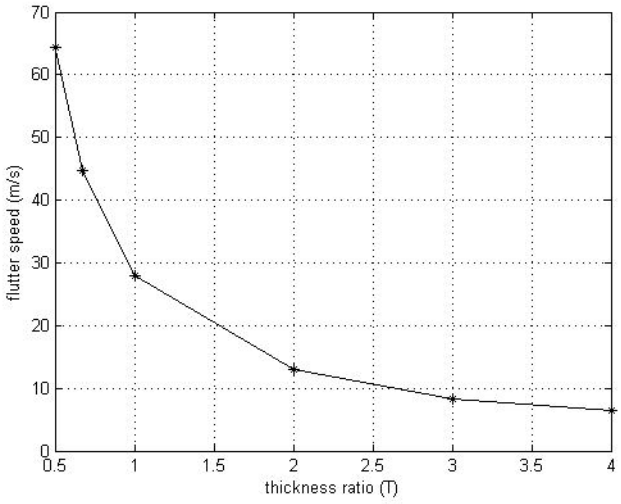


Figure 4. Flutter speed variation with respect to thickness ratio for zero damping.

The generalised electromechanical coupling coefficient, K_{ij} is obtained from

$$K_{ij}^2 = \left(\frac{K_{pzt}}{K + K_{pzt}}\right)\left(\frac{k_{ij}^2}{1-k_{ij}^2}\right) \quad \ldots (3)$$

Where x_{st} represents F/K_{tot}, and K_{tot} is the sum of base system modal stiffness (K) and the piezoelectric short-circuit modal stiffness (K_{pzt}). The electromechanical coupling coefficient (k_{ij}) of the piezoceramic patch is 0·35 as provided by the PZT patch manufacturer (Sparkler Ceramics, Pune, India). The non-dimensional frequency and electrical damping ratio are, respectively

$$\gamma = s/\omega_n^{SC}$$
$$r = R_l C_{pl} \omega_n^{SC} \quad \ldots (4)$$

The added damping to the system is estimated by the solution of the denominator term in Equation (2). The maximum additive damping is achieved for optimal thickness ratio of the beam thickness to the PZT thickness[16]. The leaf springs represented by Aluminum beams have thickness of 1·6mm and length of 155mm and PZT has 0·5mm thickness. The ratio of beam thickness to PZT thickness being 3, which is close to 2·73, the exact optimal thickness ratio for Aluminum as host material. In this paper the effect of thickness ratio affecting the bending frequency (ω_h) and pitch frequency (ω_α) in association with damping variation due to resistive shunting on flutter speed is investigated.

The aerofoil selected has section geometry parameters as a_h = –0·2, x_α = 0·2, μ = 10, r_α = 0·45, $t/2b$ = 0·12, wing parameters as $\bar{\omega}_h$ = 0·46, L/b = 7·74. The flutter determinant with unsteady aerodynamic theory incorporating the additive damping terms due to resistive shunting is derived and represented in the governing equation of motion for a 2D aerofoil as

$$\begin{pmatrix} \mu(1-\bar{\omega}_h^2 X(1+ig_h))+L_h & \mu x_\alpha + L_\alpha - L_h(0\cdot5+a_h) \\ \mu x_\alpha + 0\cdot5 - L_h(0\cdot5+a_h) & \mu r_\alpha^2[1-X(1+ig_h)] - 0\cdot5(0\cdot5+a_h) + \\ & M_\alpha - L_\alpha(0\cdot5+a_h) + L_h(0\cdot5+a_h)^2 \end{pmatrix} \begin{pmatrix} \bar{h} \\ \alpha \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \quad \ldots (5)$$

where, g_h and g_α are the additive damping terms in heave and pitch, respectively estimated from Equation (2)

Flutter determinant in Equation (5) is solved using V-g method for flutter speed estimation[17] for various cases involving heave and pitch spring (realised through aluminum beams) in association with damping achieved by shunting the PZT patches.

4.0 RESULTS AND DISCUSSIONS

The effect of additive structural damping due to piezoceramic resistive shunting on the flutter speed is studied. The resistor shunted across the PZT patch is varied physically for its optimal resistance to achieve the added damping. Figure 3 shows the variation of the net structural damping with airspeed.

Note that the flutter condition is when the net structural damping factor g is zero. Below the flutter speed, the net damping is negative. This is so because we have assumed the motion to be of the form $\exp(i\frac{\omega_\alpha}{\omega}(1+ig)t)$ This figure also indicates that there is a 66% increase in flutter speed if the structural damping is augmented by 10%. Now we investigate the effect of resistive shunting of piezoceramic transducers on flutter speed for the two degree of freedom model of Fig. 1. There are three cases of interest here. Resistive shunting of the piezoceramic transducers bonded to the leaf springs elastically restraining the heave motion, those bonded to the leaf springs elastically restraining the pitch motion, and resistive shunting of the PZTs in heave and pitch springs for combined participation. In flutter control methods, enhancing the flutter speed is given prime importance. Flutter speed is dependent on the ratio of uncoupled natural frequencies in heave and pitch ω_h/ω_α. The flutter speed variation with respect to thickness ratio is shown in Fig. 4.

Flutter speed drops quite significantly as the frequency ratio approaches unity due to large thickness ratio. The low flutter speeds are most in need of flutter control and also most amenable to improvement of the flutter speed. This could be achieved by resistive shunting.

The variation in flutter speed as a function of damping factor due to resistive shunting of PZTs in pitch springs is shown in Fig. 5.

Here, for higher thickness ratios, and consequently higher values of ω_h/ω_α, the percentage increase in flutter speed is more. For a thickness ratio of 4, there is 25% increase in flutter speed when the added damping due to resistive shunting is 10%. Figure 6 shows the percentage variation of flutter speed with resistively shunted piezoceramic transducers bonded to the leaf springs in heave motion.

The trends are similar to that of additive damping in the pitching direction. Note however, that the percentage increase in flutter speed is greater than in the pitching case. For an additive damping factor of 10%, the increase in flutter speed is as high as 37% for a thickness ratio of 4 as seen in Fig 6. The effect on flutter speed of combined resistive shunting of the piezoceramic transducers in the heave and pitching directions, $g_h = g_\alpha$, is shown in Fig 7. Besides the fact that the increase in flutter speed with increase in damping factor shows

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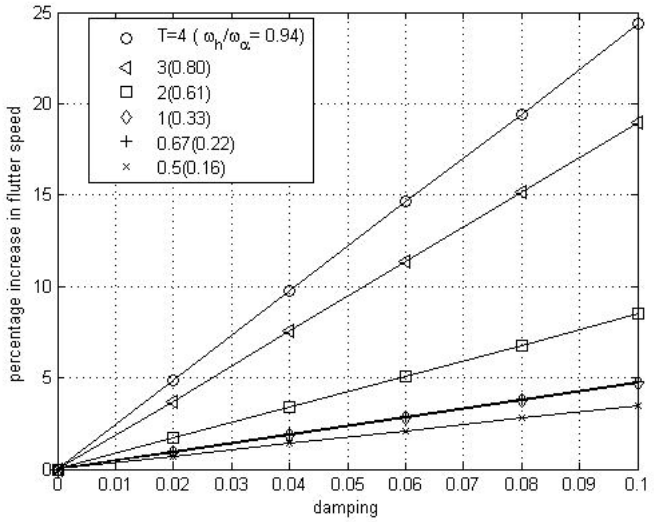


Figure 5. Percentage increase in flutter speed as a function of damping factor due to resistive shunting of PZTs in pitch springs.

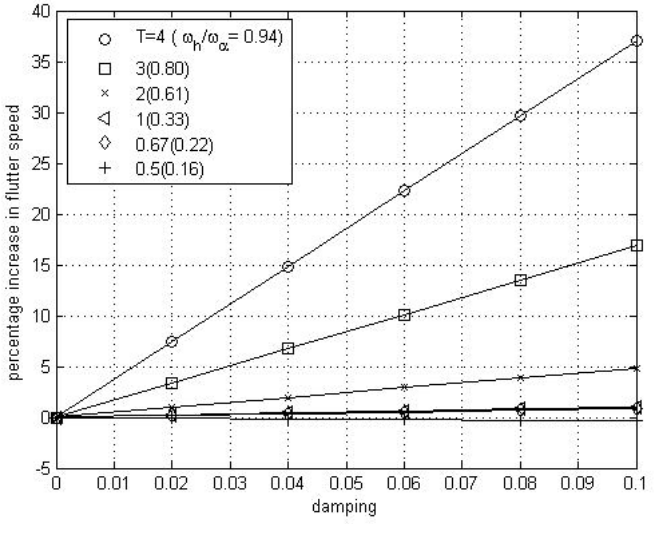


Figure 6. Percentage increase in flutter speed as a function of damping factor due to resistive shunting of PZT in heave direction.

the same trend as in the earlier two cases, the percentage increase in flutter speed is much higher. For a thickness ratio of 4, there is a 52% increase in flutter speed at a combined damping factor value of 0·1 as observed in Fig 7.

5.0 CONCLUSIONS

Resistive shunting of piezoceramic transducers bonded to lifting surfaces can be used as a passive flutter control technique to increase the flutter speed. In this case, the piezoceramic transducers bonded to the leaf springs that provided elastic restraint in the heave and pitch directions are considered. Resistive shunting of the PZT transducers bonded to the heave and pitch leaf springs separately and together were studied. Tuned dampers realised by resistively shunted piezoceramics in heave and pitch springs could enhance the flutter speed in the range of 25-50% based on additive damping of 10% achieved due to resistive shunting of piezoceramic in either pitch spring, heave spring or both.

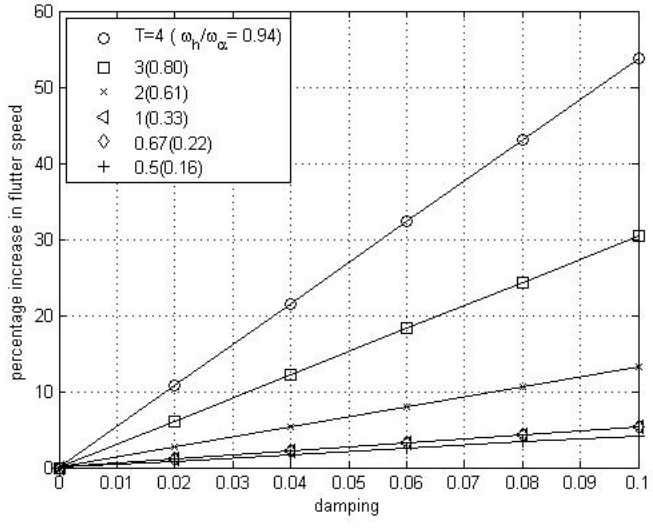


Figure 7. Percentage increase in flutter speed as a function of damping factor due to resistive shunting of PZT in both heave and pitch directions.

REFERENCES

1. CRAWLEY, E.F. Intelligent structures for aerospace: A technology overview and assessment, *AIAA J*, 1994, **32**, (8), pp 1689-1699.
2. HORIKAWA, H. and DOWELL, E.H. An elementary explanation of the flutter mechanism with active feedback controls, *J Aircr*, 1979, **16**, (4), pp 225-232.
3. LAZARUS, K.B, CRAWLEY, E.F. and LIN, C.Y. Fundamental mechanics of aeroelastic control with control surface and strain actuation, *J Guidance, Control and Dynamics*, 1995, **18**, (1), pp 10-17.
4. NITZSCHE, F., LIBERATORE, S. and ZIMCIK Theoretical and experimental investigations on an active control system for vertical fin buffeting alleviation using strain actuation, *Aeronaut J*, 2001, **105**, (1047), pp 277-285.
5. ABRAMOVICH, H, WELLER, T. and PING, S.Y. Dynamic Response of a high aspect ratio wing equipped with PZT patches — A theoretical and experimental study, *J Int Mat Systems and Structures*, 2005, **16,** pp 919-923.
6. TUZSCU, I. and MEIROVITCH, L. Control of flying flexible aircraft using control surfaces and dispersed piezoelectric actuators, *Smart Materials and Structures*, 2006, **15**, pp 893-903.
7. CHOPRA, I. Review of the state of the art of smart structures and integrated systems, *AIAA J*, 2002, **40**, (11), pp 2145-2187.
8. HURLEBAUS, S. and GAUL, L. Smart structure dynamics, *Mech Systems and Signal Processing*, 2006, **20**, pp 255-281.
9. HAGOOD, N.W. and FLOTOW, A. VON. Damping of structural vibrations with piezoelectric materials and passive electrical networks, *J Sound Vib*, 1991, **146**, (2), pp 243-268.
10. MOHEIMANI, S.O. A survey of recent innovations in vibration damping and control using shunted piezoelectric transducer, *IEEE Trans on Control Systems Technology*, 2003, **11**, pp 482-494.
11. SHU, Y.C. and LIEN, I.C. Analysis of power output for piezoelectric energy harvesting systems, *Smart Materials and Structures*, 2006, **15**, pp 1499-1512.
12. TANG, J. and WANG, K.W. Active and Passive hybrid piezoelectric networks for vibration control comparison and improvement, *Smart Materials and Structures*, 2001, **10**, pp 794-806.
13. AGNENI, A. MASTRODDI, F. and POLLI, G.M. Shunted piezoelectric patches in elastic and aeroelastic vibrations, *Computers and Structures*, 2003, **81**, pp 91-105.
14. KANDAGAL, S.B. and VENKATRAMAN, K. Closed-loop flutter control using strain actuation, *Aeronaut J*, 2004, **108**, (1083), pp 271-275.
15. NIEDERBERGER, D. and MORARI, M. An autonomous shunt circuit for vibration damping, *Smart Materials and Structures*, 2006, **15**, pp 359-364.
16. KANDAGAL, S.B. and VENKATRAMAN, K. Form factors for vibration control of beams using resistively shunted piezoceramics, *J Sound Vib* 2004, **274**, pp 1123-1133.
17. BISPLINGHOFF, R.L., ASHLEY, H. and HALFMAN, R.L. *Aeroelasticity*, 1955, Addison-Wesley Publishing, Cambridge, UK.

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