Closed-loop flutter control using strain actuation

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ABSTRACT

The present work investigates feedback control of flutter using piezoceramic strain actuators. A two degree-of-freedom oscillating airfoil model with the air loads simulated assuming unsteady aerodynamics is considered. Various feedback measurement combinations for SISO feedback control and strain actuation in the heave and pitch direction are studied to quantify their effect on flutter. The effect of sensor placement on the airfoil, for combined pitch and heave measurement feedback, is also studied. The results show that for a given aeroelastic system, sensor location is an important parameter in realizing an increase in the flutter speed. It is demonstrated that the flutter speed can be increased by more than 50% through strain actuation in the pitch direction.

NOMENCLATURE

$C(k)$	Theodorsen's function
C_L and C_M	lift and moment coefficients (acting at the elastic axis)
$\bar{q} = U_\alpha^2/\pi\mu r_\alpha^2$	normalised dynamic pressure
r_a	dimensionless radius of gyration
u_h	gain X (force generated by PZT in heave)/K_h b
u_a	gain X (moment generated by PZT in pitch)/K_h b^2
$U_\alpha = U/\omega_\alpha b$	normalised airspeed
x_α	normalised (with respect to semi-chord) distance from the elastic axis to the c.g.
a	position of elastic axis with respect to mid-chord (normalised with respect to semi-chord)
x_s	normalised (with respect to semi-chord) distance from the elastic axis to the sensor
X	$(\omega_\alpha/\omega)^2$
ω_h	uncoupled natural frequency in heave (rad/s)
ω_α	uncoupled natural frequency in pitch (rad/s
$\bar{\omega}_h = \omega_h/\omega_\alpha$	bending to torsional frequency ratio

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. Aeroelastic 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[1-3]. Past research in flutter feedback control laws have investigated changes to

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flutter speed using various combination of measurement feedback versus control force actuation[4,5]. Horikawa and Dowell[4] performed simple feedback control simulations on a two degree-of-freedom (dof) aerofoil system and studied the effectiveness 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 *et al*[5] 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. Controllability of various measurement feedback and control actuation combinations by studying the open-loop transfer function pole-zero locations at an airspeed below the flutter speed was investigated and explained. The above two studies[4,5] are very illustrative in describing the effect of different control strategies on the flutter stability boundary. Heeg and co-workers[6,7], demonstrated analytically as well as experimentally, flutter control using piezoceramic actuation. A maximum increase of 20% in the flutter speed was realized. Reich and others at MIT[8] investigated piezoceramic actuation as a means to realise flutter control in an aeroelastic wing model. The PARTI program at NASA[9] conducted proof-of-concept investigations on a five-foot span composite wing with piezoceramic patches bonded to 60% of the inboard span. A maximum 12% increase in flutter speed was experimentally observed.

The present work considers a two degree of freedom model of aeroelastic flutter of a wing section. Flutter feedback control is realized using strain actuation in the pitching and plunging directions. This problem is similar to that studied earlier by Heeg[6,7]. Here, we investigate the effect on flutter speed due to strain actuation in pitch and heave with feedback from pitch and heave measurements under a SISO framework. The effect of control gain on different input-output combinations is studied. Further, the influence of of sensor placement on a 2D wing section for heave and pitch measurement is also investigated under a SISO framework.

2.0 STRAIN ACTUATED FLUTTER CONTROL

Typical section models are commonly used to explain the fundamental mechanics of aeroelastic phenomena, and justification for their use is given by Bisplinghoff[10] and Fung[11]. The sketch of a typical section model is shown in Figure 1. The typical section has two degrees of freedom, namely heave h, and pitch α. The typical section model used here includes force and moments acting on it as a result of induced strain actuation from the piezoceramic actuators[12]. An aeroelastic analysis of a two dof aerofoil model, with the unsteady aerodynamic forces modeled using Theodorsen's theory[10,11] is presented here. Feedback control schemes using strain actuation in heave and pitch are assumed. The typical section model incorporates forces u_h and u_α in the heave and pitch directions, acting at and about the elastic axis, respectively. Forces and moments generated by strain actuators are derived using Euler-Bernoulli beam theory[12]. It is assumed that the piezoceramic actuators are bonded to leaf springs that elastically restrain the aerofoil section in heave and pitch, as shown in Fig. 2. The governing equation of motion for a 2D aerofoil with strain actuation is then,

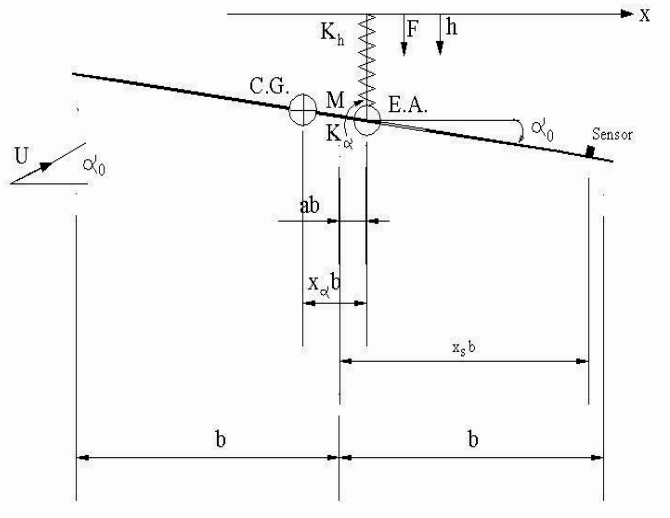


Figure 1. 2D aerofoil section model.

$$\begin{pmatrix} \mu(\bar{\omega}_h^2 X-1)-1+\dfrac{2C(k)i}{k} & -\mu x_\alpha + a + \dfrac{i}{k} + \dfrac{2C(k)[1+ik(0{\cdot}5-a)]}{k^2} \\ -\mu x_\alpha + a - 2(0{\cdot}5+a)\dfrac{C(k)i}{k} & -\mu r_\alpha^2 + \mu r_\alpha^2 X - a^2 + i(0.5-a)\dfrac{i}{k} - \dfrac{1}{8} \\ & -2(0{\cdot}5+a)C(k)[1+ik(0{\cdot}5-a)]\dfrac{1}{k^2} \end{pmatrix} \begin{pmatrix} \bar{h} \\ \alpha \end{pmatrix}$$

$$= \begin{pmatrix} \mu X \bar{\omega}_h^2 u_h \\ \mu X \bar{\omega}_h^2 u_\alpha \end{pmatrix} \quad \ldots (1)$$

The characteristic equation is given by

$$\begin{aligned} \nabla(X) = {} & (0{\cdot}125k^2 + C(k) - 0{\cdot}5ik + 0{\cdot}125\mu k^2 + \mu C(k) + \mu k^2 a^2 - 0{\cdot}5\mu ki + 0{\cdot}25C(k)ik \\ & + 2\mu C(k)a + \mu kia - \mu k^2 \bar{\omega}^2 Xa^2 + 0{\cdot}5\mu k\bar{\omega}^2 Xi - \mu k\bar{\omega}^2 Xia - 0{\cdot}125\mu k^2\bar{\omega}^2 X - 2{\cdot}0C(k) \\ & + 0{\cdot}5\mu kC(k)i - 2\mu kC(k)ia^2 - 0{\cdot}5\mu k\bar{\omega}^2 XC(k)i - 2\mu\bar{\omega}^2 XC(k)a + 2\mu k\bar{\omega}^2 XC(k)ia^2 \\ & - \mu\bar{\omega}^2 XC(k) + \mu r_\alpha^2 k^2 - \mu r_\alpha^2 Xk^2 - x_\alpha^2\mu^2 k^2 + 2C(k)x_\alpha\mu + \mu^2 k^2 r_\alpha^2 - \mu^2 k^2 r_\alpha^2 X \\ & - \mu^2 k^2\bar{\omega}^2 Xr_\alpha^2 + \mu^2 k^2\bar{\omega}^2 X^2 r_\alpha^2 + 2x_\alpha\mu k^2 a + ikx_\alpha\mu - 2C(k)i\mu r_\alpha^2 k + 2C(k)i\mu r_\alpha^2 Xk \\ & - 4x_\alpha\mu kC(k)ia)/k^2 \end{aligned} \quad \ldots (2)$$

The control input transfer functions can be represented as

$$\begin{pmatrix} \bar{h} \\ \alpha \end{pmatrix} = \frac{r_\alpha^2}{\nabla(X)} \begin{bmatrix} n_{hh}(X) & n_{h\alpha}(X) \\ n_{\alpha h}(X) & n_{\alpha\alpha}(X) \end{bmatrix} \begin{pmatrix} u_h \\ u_\alpha \end{pmatrix} \quad \ldots (3)$$

The elements of the matrix in Equation (3), that is, the individual SISO transfer functions from the strain actuation in heave direction, u_h, and strain actuation in pitch direction, u_α, to the two output variables, heave h, and pitch α, are given by,

$$\begin{aligned} n_{hh}(X) = {} & -\mu r_\alpha^2 k^2 + \mu r_\alpha^2 Xk^2 - a^2 k^2 + 0{\cdot}5ik - ika - 0{\cdot}125k^2 - C(k) - 0{\cdot}5ikC(k) \\ & - 2C(k)a + 2C(k)ika^2 \end{aligned} \quad \ldots (4)$$

$$n_{h\alpha}(X) = x_\alpha\mu k^2 - ak^2 - ik - 2C(k) - ikC(k) + 2ikaC(k) \quad \ldots (5)$$

$$n_{\alpha h}(X) = k(x_\alpha\mu k - ak + C(k)i + 2iaC(k)) \quad \ldots (6)$$

$$n_{\alpha\alpha}(X) = k(-\mu k + \mu k\bar{\omega}_h^2 X - k + 2iC(k)) \quad \ldots (7)$$

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Table 1
2D Typical section aerofoil parameters

Properties	Symbol	Value
Section geometry	a	-0·2
	x_α	0·2
	μ	10
	r_α	0·45
	$t/2b$	0·12
Wing parameters	$\bar{\omega}_h$	0·46
	L/b	7·74
Steady aerodynamic coefficients	C_L	2π
	C_M	1·885

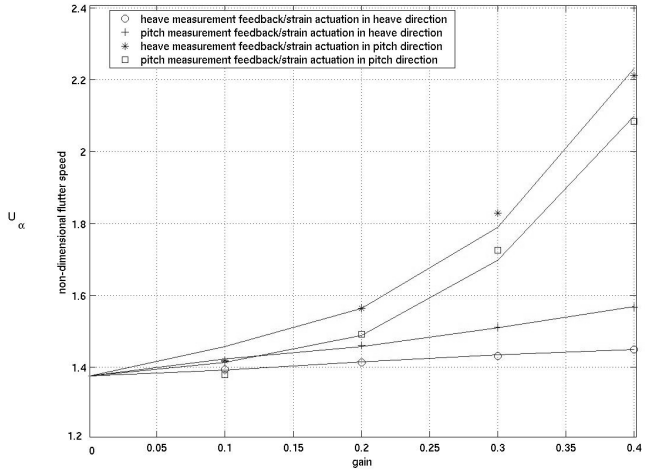


Figure 3. Effect of closed-loop control gain on flutter.

The zeros of each individual SISO transfer function are determined by setting n_{ij} (X) to zero. The system pole and zero locations are important for determining the manner in which the system can be controlled, and is a prerequisite for control system design. In an aeroelastic system, in general, the poles and zeroes are functions of the airspeed. This implies that a control law appropriate at one flight condition may not necessarily be appropriate at others.

3.0 RESULTS AND DISCUSSIONS

Properties of the 2D airfoil section used in this analysis are listed in Table 1. The elastic restraint in the heave direction is basically simulated by four leaf springs, and the elastic restraint in the pitch direction is also simulated by a pair of leaf springs, as shown in Fig. 2. The PZTs are bonded to these leaf springs to provide strain actuation in the heave and pitch direction[6,7,12].

The open-loop flutter speed was determined by solving Equation (2) using the U-g method. For the given aeroelastic model, flutter occurred at a non-dimensional airspeed value $U_\alpha = 1{\cdot}37$.

The effect of increasing control gain on flutter speed is examined first. These results are shown in Fig. 3. Four cases are illustrated. In all of these four, pure heave or pitch mode of aerofoil motion is assumed to be measured. Therefore, the issue of sensor location does not enter into the consideration. Of these four, heave measurement feedback-strain actuation in heave, and pitch measurement feedback-strain actuation in heave, result in a maximum 14% increase in flutter speed. This is not much when compared with the increase in flutter speed one obtains with strain actuation in the pitch direction. The increase in flutter for the case of strain actuation in pitch with heave measurement feedback is a maximum 57% at a gain value 0·4. Pitch measurement feedback and strain actuation in pitch results only in a maximum 50% increase in flutter speed at a gain value of 0·4. This result is of some interest. Feedback of heave measurement to strain actuation in pitch affects the mass offset term in the second part of Equation (1). A positive control gain effectively reduces the mass offset term x_α even making it negative. For $a = -0{\cdot}2$, the location of the mass offset such that $x_\alpha + a < -0{\cdot}2$ results in a large increase in the flutter speed[10, pp 543]. Pitch measurement feedback with strain actuation in pitch increases the stiffness in pitch which results in the increase in flutter speed. In summary, these results imply that strain actuation in heave is not very effective irrespective of whether pitch or heave motion being measured and fed back. On the other hand, strain actuation in the pitch direction, either with pitch or heave measurement feedback, will be most effective in increasing flutter speed for a given aeroelastic system.

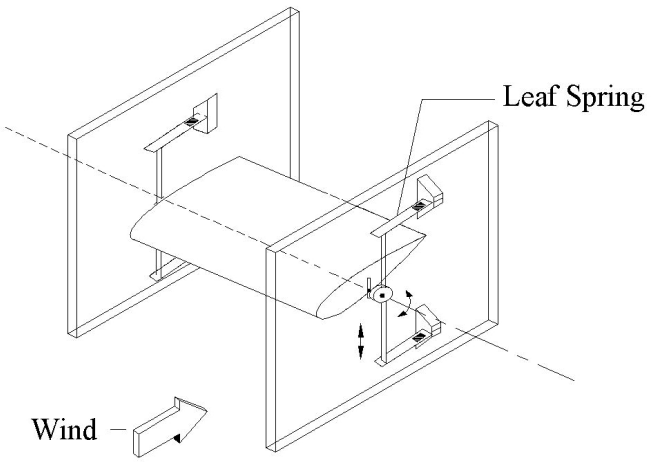


Figure 2. 2D aerofoil model with PZT in leaf spring.

The effect of sensor position along the chord of the wing section on feedback control of flutter is now investigated. A sensor placed at any point on the chord line other than the elastic axis will measure both heave and pitch. That is:

$$y = \bar{h} + x_s \alpha \qquad \ldots (8)$$

The sensor position x_s should be selected in such a way that the SISO transfer function has a zero in between the open-loop poles. Then, the system can be stabilised using rate feedback of the output variable y. A sensor position x_s can be found that yields the desired SISO transfer function zeros for each method of actuation. However, x_s can only be chosen to be between +1 and –1, since the sensor must be placed on the airfoil. The case of combined heave and pitch measurement that is used as feedback for strain actuation in pitch and heave is now explored separately.

In Fig. 4, the variation of flutter speed with sensor location along the chord of the wing section for negative values of gain is presented. Strain actuation is in the pitching direction. For control gain values between –0·2 to 0·0, the flutter speed increased as the sensor was moved from fore to aft of the airfoil chord. However for a control gain value equal to –0·3, the flutter speed decreased and then increased as the sensor was moved from fore to aft of the airfoil with reference to the mid-chord. The maximum flutter speed occurred when the sensor was placed at the trailing edge, and was nearly 40%

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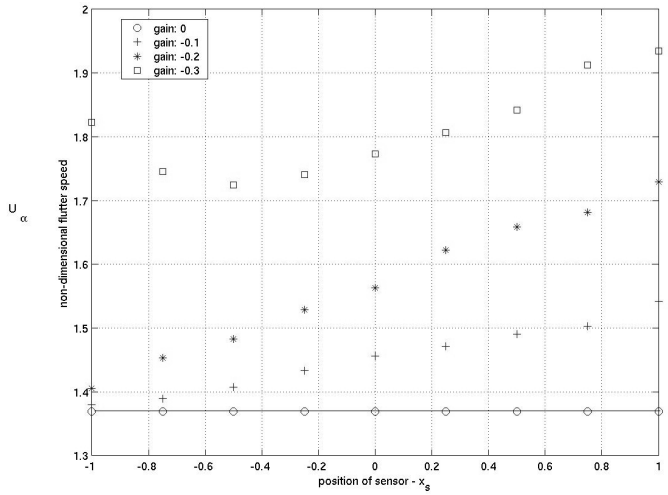


Figure 4. Effect of sensor position of combined heave and pitch measurement feedback on the flutter speed for negative values of control gain; strain actuation in pitch.

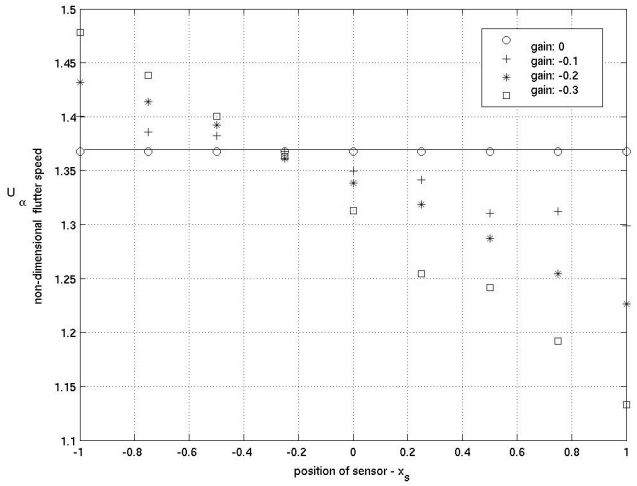


Figure 6. Effect of sensor position of combined heave and pitch measurement feedback on the flutter speed for negative values of control gain; strain actuation in heave.

of the open-loop flutter value. Strain actuation in the pitch direction affects the second part of Equation (1). Negative gain feedback of combined pitch and heave motion apparently increased the mass offset and the torsional stiffness. Increasing mass offset decreased the flutter speed, but increasing torsional stiffness increased the flutter speed. The combined effect, at a gain value of –0·3 and below, shows the trend in flutter speed as observed[10]. In general though, this type of behavior will depend on the characteristics of the aeroelastic system under consideration, especially the value of the mass offset, axis location a, and $\bar{\omega}_h$. For positive values of control gain, as shown in Fig. 5, the flutter speed, for non-zero values of the gain, decreased as the sensor was moved from fore to aft of the wing-section chord line. The rate of decrease was greater, higher the value of the control gain.

In Figs 6 and 7, the effect of sensor position on flutter speed, for the combination of heave and pitch measurement feedback, but with strain actuation in the heave direction, is presented. In Fig. 6, the variation of flutter speed with sensor position for negative values of the control gain parameter is shown. The flutter speed decreased as the sensor position was moved fore to aft of the airfoil chord. Note

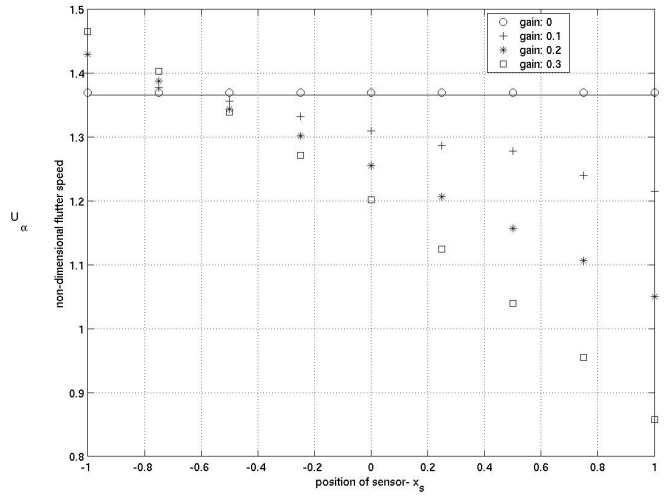


Figure 5. Effect of sensor position of combined heave and pitch measurement feedback on the flutter speed for positive values of control gain; strain actuation in pitch.

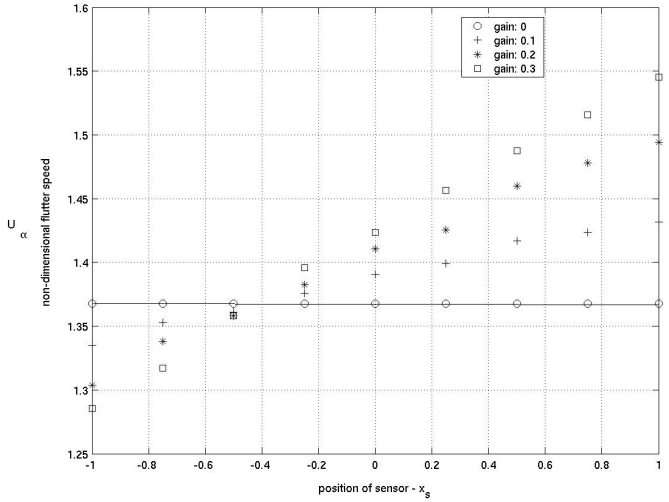


Figure 7. Effect of sensor position of combined heave and pitch measurement feedback on the flutter speed for positive values of control gain; strain actuation in heave.

that the sensor position $x_s = –0·2$ has very little effect on the flutter speed at all whatever the value of the control gain parameter. Indeed, this position is the location of the elastic axis, and when the sensor was placed at this location, it measured only heave motion. Accordingly, strain actuation in heave using heave measurement feedback for negative values of the control gain parameter has very little effect on the flutter speed, as seen in Fig. 3. The variation of flutter speed for positive values of the control gain parameter is shown in Fig. 7. The flutter speed increased as the sensor position was moved from the fore to aft of the wing section chord line. When the sensor was moved from the leading edge of the wing section up to $x_s = –0·4$, the flutter speed increases from a value below the zero-gain flutter speed to a value equal to the zero-gain flutter speed. When the sensor position moved to the trailing edge, the flutter speed increased for all positive values of the control gain parameter. For a gain value of 0·3, the increase in flutter speed relative to the zero-gain flutter speed was nearly 13%.

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4.0 CONCLUSIONS

The present work considers a two degree of freedom model of aeroelastic flutter of a wing section. Flutter feedback control was realised using strain actuation in the pitching and plunging directions. The effect on flutter speed due to strain actuation in pitch and heave with feedback from pitch and heave measurements under a SISO framework was investigated. The effect of control gain on different input-output combinations was studied. Strain actuation in pitch with pure heave or pure pitch measurement resulted in an increase in flutter speed of more than 50% with reference to the open-loop flutter speed. Furthermore, the influence of sensor placement on a 2D wing section for combined heave and pitch measurement was also investigated under a SISO framework. The results presented here show that for a given feedback control gain value, sensor placement along the chord line is a critical parameter in realising an appreciable increase in the closed-loop flutter speed. Finally, strain actuation in the pitch direction is the most effective means for feedback control of flutter using either pitch or heave, or combined heave and pitch measurement.

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