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Effect of Parameters in Power Harvesting From Piezoaeroelastic System

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ABSTRACT: *Vibration-based energy harvesting is achieved commonly using electromagnetic, electrostatic and piezoelectric or a combination of these transduction mechanisms. The new studies have focused on harvesting energy from aeroelastic systems, in which energy is harvested from the airfoil section which is connected to a torsional bar which act as a cantilever beam because it is fixed at one end. For harvesting the energy, the piezo patches are lay down over the torsional bar. The power is harvested when the wind passes through the aerofoil and when the wind velocity crosses the critical speed which is called flutter speed. We investigate the effects of varying the eccentricity between the gravity axis and the elastic axis on the level of energy harvested from a piezoaeroelastic energy harvester consisting of a pitching and plunging motions of rigid airfoil simulated by linear spring supports. The amount of energy that can be extracted from a piezoaeroelastic system depends on its parameters and the wind speed.*

Keywords: *Aerodynamic lift, Plunge and pitch, Energy harvester, Coupling coefficient, Flutter-Speed,*

ABBREVIATIONS:

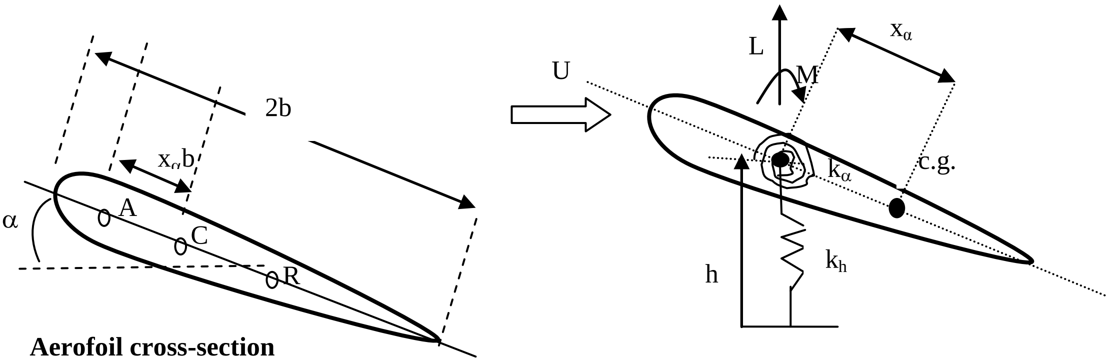
m_T = The total mass of the wing including its support structure
m_w = The wing mass alone
c_h and c_α = The plunge and pitch structural damping coefficients;
k_h and k_α = The linear structural stiffnesses for the plunge and pitch degrees of freedom
k_{h2} and $k_{\alpha 2}$ = The nonlinear stiffnesses of the plunge and pitch degrees of freedom
θ and χ = Electromechanical coupling terms
I_α = Mass moment of inertia about the elastic axis
b = The half chord length
V = Voltage
L and M = aerodynamic lift and moment about the elastic axis
R = Load resistance
c_p =Capacitance of piezoelectric layer
x_α = Eccentricity between centre of mass and elastic axis
U = Free stream Velocity

I. INTRODUCTION

Conversion of vibration into usable form of energy is a topic of interest for long time. Vibration-based energy harvesters can be achieved using either electromagnetic, electrostatic, piezoelectric or a combination of these transduction mechanisms. Piezoelectric energy harvesters have received the most attention because they have a wider operating range than other transductors. Previous studies have, in general, focused on harvesting energy from base vibrations. It is the new technique of harvesting energy from the airfoils. In present work, a piezoaeroelastic energy harvester consisting of a rigid airfoil constrained to pitch and plunge is considered and supported by torsional and flexural springs with a piezoelectric coupling attached to the plunge degree of freedom. When wind passes through this aerofoil section, an aerodynamic lift forces are generated opposite to the deflection of aerofoil which creates an oscillation in the aerofoil which is transmitted to the torsional bar very nicely. This oscillation is sensed by the piezo-patches which then converted into electrical power by the help of electrical circuit attached to it. Erturk et al. [1] used a lumped parameter wing-section model to determine the effects of piezoelectric power generation on the linear flutter speed. De Marqui et al. [2] used a finite element method to analyze piezo aeroelastic energy harvesters. Bryant et al. [3] demonstrated experimentally that energy can be harvested from aeroelastic vibrations using an airfoil section attached to a cantilever. Erturk et al. [4] used a lumped-parameter wing-section model to investigate the effect of piezoelectric power generation on the linear flutter speed. For the purpose of energy harvesting, it is important to generate energy at low wind speeds and, as such, to decrease the flutter speed. To harvest more energy, it would be better to minimize the energy distribution to the pitch motion when harvesting power from the plunge motion.

II. MATHEMATICAL MODELING

There are several articles in literature [5-9] for modelling of aerofoil cross-sections. We consider a piezoaeroelastic energy harvester consisting of a rigid airfoil having two degree of freedom i.e. constrained to pitch and plunge, as shown in Fig.1, and supported by linear and nonlinear torsional and flexural springs with a piezoelectric coupling attached to the plunge degree of freedom. There is in the wing a linear spring is oriented along the plunge displacement direction and a rotational spring along the pitch angle, and corresponding dampers. Hence, in the presence of a flow field, the wing at a free stream velocity exhibits oscillations along a plunge displacement direction, and a rotation at the pitch angle around the elastic axis.



(a) Aerofoil cross-section
(b) An aeroelastic system model with 2 degree of freedom The plunge displacement and pitch angle
Fig. 1 Schematic of a piezoaeroelastic system under uniform airflow

Fig.1 (a) shows the cross-sectional view of an aero foil with all the centers i.e. A is an aerodynamic center(elastic axis), C is a geometric mass center and R is a reference point. 2b is a chord length of the aero foil. Fig.1 (b) shows a two degree freedom of model i.e. plunge direction (h) and pitch angle (α). It also shows the lift force(L) opposite to the direction of deflection of aero foil with a moment(M) of aero foil.
The equations of motion of this system are written as [5]:

$$m_T \ddot{h} + m_w x_\alpha b\ddot{\alpha} + c_h \dot{h} + (k_h + k_{h2}h^2)h - \theta V = -L \quad (1)$$

$$m_w x_\alpha b\ddot{h} + I_\alpha \ddot{\alpha} + c_\alpha \dot{\alpha} + (k_\alpha + k_{\alpha 2}\alpha^2)\alpha = M \quad (2)$$

$$c_p \dot{V} + \frac{V}{R} + \chi \dot{h} = 0 \quad (3)$$

Aerodynamic lift L=$\rho A U^2 b c_{l\alpha} \alpha_{effective}$ (4)

Aerodynamic Moment M= $\rho U^2 b^2 c_{m\alpha} \alpha_{effective}$ (5)

$$\alpha_{effective} = \alpha + \frac{\dot{h}}{U} + \left(\frac{1}{2} - a\right) b \frac{\dot{\alpha}}{U} \quad (6)$$

The co-efficint matrix obtained from solving the above differential equation and breaking the equation into state space form-

$$[A] = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ -\frac{I_\alpha k_h}{d} & -(c_1+d_1U) & -(k_1U^2-\frac{m_w x_\alpha b k_h}{d}) & -(c_2+d_2U) & \theta_1 \\ \frac{m_w x_\alpha b k_h}{d} & -(c_3+d_3U) & -(k_2U^2+\frac{k_\alpha m_t}{d}) & -(c_4+d_4U) & \theta_2 \\ 0 & 0 & -\frac{\chi}{c_p} & 0 & -\frac{1}{Rc_p} \end{bmatrix} \quad (7)$$

where constants are:

$d = m_t I_\alpha - (m_w x_\alpha b)^2$,

$c_1 = I_\alpha (c_h - k_h)/d$,

$d_1 = \dfrac{I_\alpha \rho b c_{l\alpha} + \rho b^3 m_w x_\alpha c_{m\alpha}}{d}$,

$c_2 = \dfrac{-m_w x_\alpha b(c_\alpha - k_\alpha)}{d}$,

$d_2 = -\dfrac{I_\alpha \rho b^2 c_{l\alpha}(1/2-a) + m_w x_\alpha b^4 \rho c_{m\alpha}(1/2-a)}{d}$,

$c_3 = \dfrac{-m_w x_\alpha b(c_h - k_h)}{d}$

$d_3 = (-m_w x_\alpha b^2 \rho c_{l\alpha} - m_t c_{m\alpha} \rho b^2)/d$,

$c_4 = m_t (c_\alpha - k_\alpha)/d$,

$d_4 = \dfrac{-m_t b^3 \rho c_{m\alpha}(1/2-a) - m_w x_\alpha b^3 \rho c_{l\alpha}(1/2-a)}{d}$,

$k_1 = \dfrac{I_\alpha \rho b c_{l\alpha} + m_w x_\alpha b^3 \rho c_{m\alpha}}{d}$,

$k_2 = \dfrac{-(\rho b^2 c_{l\alpha} m_w x_\alpha + m_t \rho b^2 c_{m\alpha})}{d}$,

$\theta_1 = \dfrac{I_\alpha \theta}{d}$, $\theta_2 = \dfrac{-m_w x_\alpha b \theta}{d}$

III. RESULTS AND DISCUSSION

Table-I shows the data for analysis. The airfoil cross-section and coupling terms are selected from Ref [5]. The matrix [A] has a set of five eigenvalues. The first four are similar to those of a pure aeroelastic system in the absence of the piezoelectricity effect. The fifth eigenvalue is a result of the electromechanical coupling. This fifth eigenvalue is always real negative as in the case of piezoelectric systems subjected to base excitations. The first four eigenvalues are complex conjugates. The real part of these eigenvalues represent the damping co-efficient and positive imaginary part corresponds to a global natural frequencies of the piezoaeroelastic system. Because λ_5 is always real negative the stability of the trivial solution depends upon the only first four Eigen values.

Table-I Simulation Parameters for an Aero-elastic System [5]

Parameters	Value	Parameters	Value
A	-0.6719	b	0.1905 meter
c_α	0.016 m^2/sec	c_h	27.43 kg/sec
$c_{l\alpha}$	6.757	$c_{m\alpha}$	0
I_α	$m_w x_\alpha^2 b^2 + 0.009039$ kg/m2	k_α	$12.77 + (1003\, x_3^2)$ N-m
k_h	2844.4 N/m	m_t	15.52 kg
m_w	4.34 kg	x_α	-(0.0998+a)
ρ (density of air)	1.225`kg/m3	Resistance(R)	1 MΩ

Fig.3 and Fig.4 show the variation of voltage and power respectively with the time. The excitation is provided in the form of sinusoidal so that's why the response curve obtained in sinusoidal manner. These are obtained by solving the equation (7) in MATLAB by ODE(45) and we got a variation of power and voltage with respect to time.

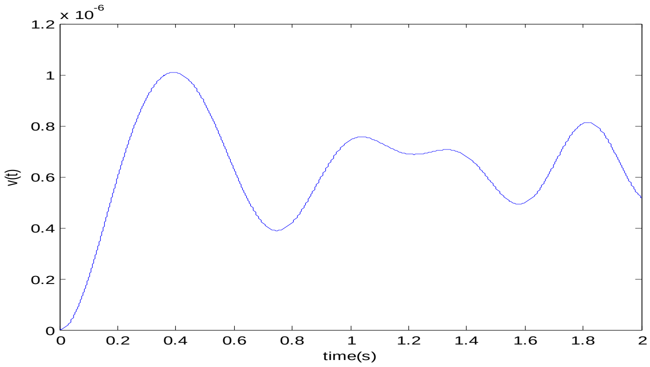


Fig.3- Variation between voltage and time at x_α=0.25 and Flutter speed=6.26m/sec

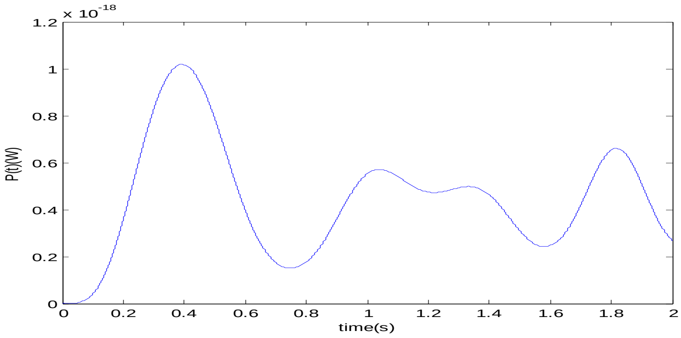


Fig.4- Variation between Power and time at x_α=0.25 and Flutter speed=6.26m/sec

The result of variation of flutter speed with eccentricity is shown in Fig.5.

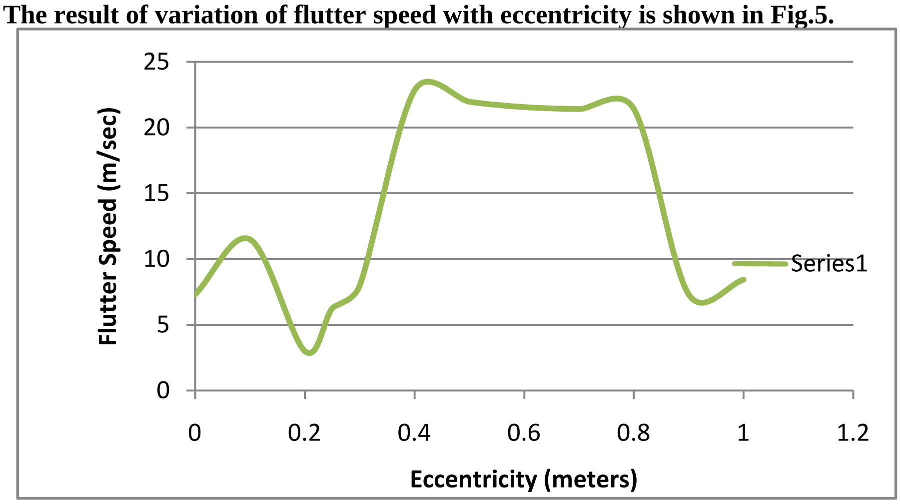


Figure-5 (variation between Flutter speed and eccentricity)

By varying the value eccentricity we get different flutter speeds as shown in Table-II.

Table-II Variation of flutter speed with eccentricity

x_α	0	0.1	0.2	0.25	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
U_f(m/sec)	7.32	11.5	3	6.26	7.98	22.84	21.98	21.57	21.42	21.43	7.32	8.4

As we see that from the figure, at lower eccentricity the flutter speed is lower but after some specific value (i.e. 0.3) the flutter speed is going to increase rapidly for a specific range (upto 0.4) and then after there is a very slight variation in flutter speed with increase in eccentricity .As we know that from the above theory the maximum power is harvested at lower flutter speed i.e. the lower flutter speed is obtained at low value of eccentricity so for harvesting maximum amount of energy we need a small eccentricity between elastic axis and centre of mass.

IV. CONCLUSIONS

We have considered the design aspect of piezoelectric energy harvesters at low wind speeds. The amount of energy that can be harvested from a piezoaeroelastic system a pitching and plunging rigid aero foil supported by linear springs depends on its parameter and wind speed. The aeroelastic system is designed with small structural damping, so we choose linear spring co-efficients to produce flutter at and hence generate energy at low wind speed. The analysis shows the harvested power can be increased by choosing the low eccentricity value and this is obtained at lowers flutter speeds. In the another analysis it is shown that the sinusoidal excitation is provided to the aerofoil due to which the response curve of displacement and power are obtained in sinusoidal manner.

APPENDIX

Combining the equation (1),(2) and (3) and after putting down the lift force (L) value and moment(M) value and assuming the following value,

$$h = h_0 e^{j\omega t} \quad , \quad \alpha = \alpha_0 e^{j\omega t} \quad , \quad V = V_0 e^{j\omega t} \qquad (a_1)$$

Mass matrix, Stiffness Matrix,

$$[M]=\begin{bmatrix} m_t & m_w b x_\alpha \\ m_w b x_\alpha & I_\alpha \end{bmatrix} \qquad [K]=\begin{bmatrix} k_h & \rho U^2 b c_l l \\ 0 & (k_\alpha - \rho U^2 b^2 c_m) \end{bmatrix}$$

Damping matrix,

$$[C]=\begin{bmatrix} (c_h + \rho U b c_l l) & \rho U b^2 c_l l(\frac{1}{2} - a) \\ -\rho U b^2 c_m & (c_\alpha - \rho U b^3 c_m (\frac{1}{2} - a) \end{bmatrix} \qquad (a_2)$$

Solving the above simultaneous differential equation we got,

$$\begin{bmatrix} \dot{h} \\ \dot{\alpha} \\ \ddot{h} \\ \ddot{\alpha} \\ \dot{V} \end{bmatrix} = \begin{bmatrix} o & & I & & 0 \\ & & & & 0 \\ -M^{-1}k & & -M^{-1}c & & \theta_1 \\ & & & & \theta_2 \\ 0 & 0 & \frac{-\chi}{c_p} & 0 & \frac{-1}{c_p R} \end{bmatrix} \begin{bmatrix} h \\ \alpha \\ \dot{h} \\ \dot{\alpha} \\ V \end{bmatrix} \qquad (a_3)$$

where

$$\theta_1 = \frac{I_\alpha \theta}{d} \quad , \theta_2 = \frac{-m_w x_\alpha b\theta}{d} \qquad (a_4)$$

O= Null matrix , I=Identity matrix of [2x2]

[$M^{-1}k$] and [$M^{-1}c$] =Matrix of [2x2]. Solution is obtained by solving the simultaneous differential equations (equation 10) in MATLAB by ode45.

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