

Eco-generation of energy from flutter based on energy-recycling mechanism

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ABSTRACT: This paper presents a harvesting system that extracts electrical energy by effectively using wing flutter, which is called eco-generation or energy-harvesting. This study utilizes the quasi-steady aerodynamic theory and FEM for simulating the dynamics of a plate wing. The use of piezoelectric patches and switching circuits can lead to effective harvesting from supersonic flutter. We evaluated our switching harvesting approach in supersonic flutter. Our harvesting system via wing flutter can generate 10 times more energy than a conventional harvesting system.

KEYWORDS: Eco-Generation, Flutter, Energy-Harvesting, Energy-Recycling, Piezoelectric

1 INTRODUCTION

The interaction between the structural motion of a wing and the aerodynamic load exerted on the wing can cause flutter phenomenon. It is a self-excited aeroelastic phenomenon that occurs in wings, thin walls, and so on. Wing flutter can be found most frequently within a high-speed, i.e., transonic, supersonic, and hypersonic flow (Dowell, 1966).

Eco-generation or energy-harvesting is a process by which energy is extracted from various sources and stored for future use, such as solar energy, tidal energy, piezoelectricity, thermoelectricity, and kinematic energy. Energy-harvesting techniques are expected to be of vital importance in the future when fossil fuel reserves will exhaust completely. Among the various sources mentioned above, this study focuses on harvesting energy from vibrating structures using piezoelectricity. Sodano et al. (2003) reviewed investigations of piezoelectric energy-harvesting techniques. Lesieutre et al. (2003) discussed the damping associated with harvesting electrical energy from a mechanically excited piezoelectric structure. Cornwell et al. (2005) developed an approach to improve energy output by using a tuned auxiliary structure. Because of the interest in the use of wind in harvesting energy, various studies and investigations were conducted by researchers, as discussed below. Erturk et al. (2010) employed the lumped-parameter model that entails energy-harvesting from aeroelastic vibration of a two-degree-of-freedom system. Robbin et al. (2006) discussed vortex-induced oscillations of piezoelectric cantilevers located behind bluff bodies. Isogai et al. (2003) conducted a study on a power generation system that extracts wind energy from flutter of a binary elastic system.

So far, wing flutter has been considered as a phenomenon that should be avoided, especially in aerospace engineering. However, adding electromotor or piezoelectric transducers to wings under aeroelastic vibrations is a feasible method for harvesting energy, as Isogai (2010), verified in simulation and experiments. We introduce an energy-harvesting system that extracts electrical energy from wing flutter using piezoelectric materials and a switching circuit. The effective use of wing flutter changes our perception of it; from being a destructive phenomenon as it was formerly known to be to being useful in various applications.

2 WING FLUTTER MODEL

2.1 Outline of tail wing of rocket

We focus on harvesting energy from wing flutters of sounding rockets (National Research Council Board, 2009). Japan Aerospace Exploration Agency has developed a sounding rocket S-310, which we consider as an example in our research. This rocket is 310 mm in diameter, and can reach an altitude of 150 km. The rocket attains approximately Mach 4.6 in 23 seconds, which indicates that it flies at a supersonic speed during most of its flight. Thus, it can be subject to supersonic flutter during the flight of the sounding rocket. The rocket has four tail wings made of a solid titanium plate (Fig. 1) flying at a supersonic speed. We include a cantilevered-plate wing to investigate the harvesting of energy from wing flutter. Piezoelectric patches are attached to the wing surface to generate electrical energy from the wing motion. In reality, patches attached to the wing surface may adversely affect fluid dynamics because they cause discontinuity of the wing surface. Furthermore, the patches may be adversely affected by the heat generated by aerodynamic interference. However, in this study, we do not consider these issues.

2.2 Derivation of aerodynamic pressure for flutter analysis

The flow velocity field, (u_1, u_2, u_3) , is written as

$$u_1 = 0, \quad u_2 = U + \tilde{u}_2, \quad u_3 = \tilde{u}_3. \quad (1)$$

Here, U is the steady flow in the direction x_2 . It is assumed that the variation of velocity is sufficiently small, compared with the steady flow. The continuous equation is

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_j) = 0. \quad (2)$$

The conservation of momentum is

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i}. \quad (3)$$

The variation of velocity occurs in an adiabatic reversible manner, and the law of conservation of energy in an isentropic process can be written as

$$\frac{1}{2} u_i u_i + \frac{a^2}{\gamma - 1} = \frac{1}{2} U^2 + \frac{a_\infty^2}{\gamma - 1}. \quad (4)$$

The inner-product with u_i of Eq. (3) yields

$$u_i \left(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} \right) = -u_i \left(\frac{1}{\rho} \frac{\partial p}{\partial x_i} \right) = -\frac{u_i}{\rho} \left(\frac{\partial p}{\partial \rho} \right)_s \left(\frac{\partial \rho}{\partial x_i} \right) = -\frac{u_i}{\rho} a^2 \left(\frac{\partial \rho}{\partial x_i} \right). \quad (5)$$

The substitution of Eq. (2) to Eq. (5) becomes

$$u_i \left(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} \right) = a^2 \left(\frac{1}{\rho} \frac{\partial \rho}{\partial t} + \frac{\partial u_k}{\partial x_k} \right). \quad (6)$$

By substituting Eq. (1) in Eq. (6), and exchanging right and left terms, we get

$$a^2 \left(\frac{1}{\rho} \frac{\partial \rho}{\partial t} + \frac{\partial u_2}{\partial x_2} + \frac{\partial u_3}{\partial x_3} \right) = (U + u_2) \left\{ (U + u_2) \frac{\partial u_2}{\partial x_2} + u_3 \frac{\partial u_2}{\partial x_3} \right\} + u_3 \left\{ (U + u_2) \frac{\partial u_3}{\partial x_2} + u_3 \frac{\partial u_3}{\partial x_3} \right\} + (U + u_2) \frac{\partial u_2}{\partial t} + u_3 \frac{\partial u_3}{\partial t}. \quad (7)$$

The variation symbol, $(\tilde{\cdot})$, is removed. The substitution of Eq. (1) to Eq. (4) yields

$$a^2 = a_\infty^2 \left[1 - \frac{\gamma-1}{2} M_\infty^2 \left\{ 2 \frac{u_2}{U} + \left(\frac{u_2}{U} \right)^2 + \left(\frac{u_3}{U} \right)^2 \right\} \right]. \quad (8)$$

By combining Eqs. (7) and (8), we obtain

$$a_\infty^2 \left[1 - \frac{\gamma-1}{2} M_\infty^2 \left\{ 2 \frac{u_2}{U} + \left(\frac{u_2}{U} \right)^2 + \left(\frac{u_3}{U} \right)^2 \right\} \right] \left(\frac{1}{\rho} \frac{\partial \rho}{\partial t} + \frac{\partial u_2}{\partial x_2} + \frac{\partial u_3}{\partial x_3} \right) = (U + u_2) \frac{\partial u_2}{\partial t} + u_3 \frac{\partial u_3}{\partial t} + (U + u_2) \left\{ (U + u_2) \frac{\partial u_2}{\partial x_2} + u_3 \frac{\partial u_2}{\partial x_3} \right\} + u_3 \left\{ (U + u_2) \frac{\partial u_3}{\partial x_2} + u_3 \frac{\partial u_3}{\partial x_3} \right\}. \quad (9)$$

In Eq. (9), we omit higher variation terms than the first-order because $(u_i/U) \ll 1$;

$$(M_\infty^2 - 1) \frac{\partial u_2}{\partial x_2} + M_\infty^2 \frac{\partial u_2}{\partial t} - \frac{\partial u_3}{\partial x_3} = \frac{1}{\rho} \frac{\partial \rho}{\partial t}. \quad (10)$$

The velocity potential, $\phi = \phi(x_2, x_3, t)$, is introduced as

$$\frac{\partial \phi}{\partial x_2} \equiv u_2, \quad \frac{\partial \phi}{\partial x_3} \equiv u_3. \quad (11)$$

By using D'Alembert's method without the time variation, a general solution can be expressed as

$$\phi \equiv F(x_2 - \lambda x_3) + G(x_2 + \lambda x_3), \quad \lambda \equiv \sqrt{M_\infty^2 - 1} \quad (12)$$

These functions F and G hold constant values along lines $x_2 \pm \lambda x_3 = \text{const.}$, respectively, Boundary condition at wing surface $w = 0$ is

$$-\lambda \frac{\partial}{\partial x_2} \{ F(x_2 - \lambda x_3) \} \big|_{w=0} = U \frac{\partial w}{\partial x_2}. \quad (13)$$

Ashley and Zartarian (1956) developed the piston theory under the notion that at high Mach numbers the shock waves and expansion fans on an airfoil form at small angles to the undisturbed flow. The stream wise gradients are small compared to gradients perpendicular to the flow. Normal fluid velocity produced by the wing's motion results from Eq. (13) as

$$u_3 = \frac{\partial w}{\partial t} + \left(U \frac{\partial w}{\partial x_2} \right) \quad (14)$$

Considering Eqs. (3) and (10) to (14), the pressure is expressed as

$$\frac{p}{p_\infty} = \left(1 + \frac{\gamma-1}{2} \frac{w}{a_\infty} \right)^{(2\gamma)/(\gamma-1)} \approx 1 + \gamma \frac{w}{a_\infty} + \frac{\gamma(\gamma+1)}{4} \left(\frac{w}{a_\infty} \right)^2 + \frac{\gamma(\gamma+1)}{12} \left(\frac{w}{a_\infty} \right)^3. \quad (15)$$

When high order terms are truncated, the low-order aerodynamic pressure is described by

$$p - p_\infty = \frac{2q}{\lambda} \left[\frac{\partial w}{\partial x_2} + \left(\frac{\lambda^2 - 1}{\lambda^2} \right) \frac{1}{U} \frac{\partial w}{\partial t} \right]. \quad (16)$$

Other parameters are defined in Appendices A and B. Assuming that the pressure is exerted on both sides of the wing, we can express the resultant pressure $p_a(x, y, t)$ exerted on the wing as

$$p_a(x_1, x_2, t) \equiv -\frac{4q}{\lambda} \left[\frac{\partial w}{\partial x_2} + \left(\frac{\lambda^2 - 1}{\lambda^2} \right) \frac{1}{U} \frac{\partial w}{\partial t} \right]. \quad (17)$$

3 FLUTTER HARVESTING WITH PIEZOELECTRIC PATCHES

3.1 Equations of motion for wing dynamics

Piezoelectric patches shown in Fig. 1 are assumed to be polarized in the thickness direction (x_3 direction) and isotropic in the in-plane direction (x_1 – x_2 plane). Hence, their constitutive equations (Jaffe et al., 1971) are given by

$$\sigma_p = \mathbf{c}_p^D \boldsymbol{\varepsilon}_p - \mathbf{h} D_3, \quad E_3 = -\mathbf{h}^T \boldsymbol{\varepsilon}_p + \beta_{33}^S D_3. \quad (18)$$

The stress–strain relation of a wing is written as

$$\sigma_w = \mathbf{c}_w \boldsymbol{\varepsilon}_w. \quad (19)$$

The linear strain–displacement relation based on the Kirchhoff–Love assumption is

$$\boldsymbol{\varepsilon} = -x_3 \left[\frac{\partial^2}{\partial x_1^2}, \frac{\partial^2}{\partial x_2^2}, 2 \frac{\partial^2}{\partial x_1 \partial x_2} \right]^T w(x_1, x_2, t). \quad (20)$$

On the surface of the wing, n_p pieces of piezoelectric patches are attached, and the j th patch ($1 \leq j \leq n_p$) is attached at positions $x_{1Sj} \leq x_1 \leq x_{1Ej}$, $x_{2Sj} \leq x_2 \leq x_{2Ej}$, and $x_{3Sj} \leq x_3 \leq x_{3Ej}$. To ensure the generality of this theoretical analysis, a multiple-input–multiple-output system is considered. Using Hamilton's principle, we construct

$$\int_{t_1}^{t_2} \left[\delta T_w - \delta U_w + \sum_{j=1}^{n_p} (\delta T_{pj} - \delta U_{pj}) + \delta W \right] dt = 0, \quad (21)$$

where virtual work δW can be written as

$$\delta W \equiv \int_S \delta w [f(x_1, x_2, t) + p_a(x_1, x_2, t)] dS + \sum_{j=1}^{n_p} V_j \int_{S_{pj}} \delta D_{3j} g_j(x_1, x_2, x_3) dS. \quad (22)$$

Here, $f(x_1, x_2, t)$ is the external force normal to the wing and V_j is the voltage applied to the j th piezoelectric patch as a generalized external force. The finite element method (FEM) element proposed by Adini, Clough, and Melosh that is known as the ACM element (Zienkiewicz and Taylor, 1985), which is a four-node non-conforming plate element, is employed to discretize the partial derivative equations of motion. From Eqs. (17)–(22), the equation of motion for the cantilevered wing with multiple piezoelectric patches attached to it can be expressed as

$$\mathbf{M} \ddot{\vec{y}} + (\mathbf{K} + \psi \mathbf{A}) \vec{y} = \mathbf{B} \vec{Q} + \vec{f}, \quad (23)$$

$$\vec{V} = -\mathbf{B}^T \vec{y} + \mathbf{C}^{-1} \vec{Q}. \quad (24)$$

We perform the modal transformation

$$\ddot{\mathbf{y}} = \mathbf{\Phi} \ddot{\mathbf{\eta}}, \quad (25)$$

and introduce the modal damping in Eq. (23) as

$$\ddot{\mathbf{\eta}} + \mathbf{\Xi} \dot{\mathbf{\eta}} + (\mathbf{\Omega} + \psi \mathbf{\Phi}^T \mathbf{A} \mathbf{\Phi}) \mathbf{\eta} = \mathbf{\Phi}^T \mathbf{B} \ddot{\mathbf{Q}} + \mathbf{\Phi}^T \mathbf{f}. \quad (26)$$

This eigenvalue problem is solved for the homogenous part of Eq. (23) with $\psi = 0$.

3.2 Switching eco-generation and circuit enhancement

A conventional energy-harvesting device that employs piezoelectric materials to generate energy includes a vibrating piezoelectric structure and an energy storage system (Priya and Inman, 2003). The energy generator is composed of piezoelectric materials, which are attached to the structure, and a harvesting circuit. Circuit A shown in Fig. 2 is a conventional harvesting circuit consisting of a diode bridge of four diodes. The diode bridge is connected to the piezoelectric materials and it provides a mechanism for current rectification. This harvesting system is used in many vibration systems; however, it does not satisfactorily harvest electrical energy.

To enhance the energy-harvesting performance, we use the energy-recycling semi-active approach (Onoda et al, 2003) as an effective energy-harvesting mechanism. This approach involves the use of Circuit B, which is connected to the piezoelectric material, as shown in Fig. 3. The circuit has only two diodes and a selector switch. The selector switch is connected to point 1 or 2 to control the current flow. According to our previous study (Onoda et al, 2003), the advanced energy-recycling approach can simultaneously manage multiple circuits and piezoelectric patches. This type of energy-harvesting was described in (Makihara et al, 2006). Because our semi-active method just changes the switch connection to point 1 or 2 in Fig. 3, it never increases the vibration energy by its switching action. Hence, our semi-active approach is safer than other active approaches that usually involve a risk of instability such as spillover.

As will be seen later, in flutter problems, modal frequencies can shift according to dynamic pressure. Therefore, sophisticated controls based on modal decomposition are impractical. One way of implementing switching controls without modal information is to adopt an approach based on the direct velocity feedback method (Balas, 1979). The control reads that switching point should be changed according to the strain at the position of piezoelectric patch.

4 NUMERICAL ANALYSIS OF FLUTTER HARVESTING

4.1 Wing flutter design

We carried out numerical simulation of the energy-harvesting on the plate wing (Fig. 1). The wing was made of a titanium alloy (Ti-6Al-4V). This configuration is essentially a simpler model of the S-310's tail wing for explaining the harvesting performance on which we focus in this study. The wing was rigidly supported on one of its boundaries, i.e., $\psi = 0$. A piezoelectric patch was attached at $0 \leq x_1 \leq 0.15$ and $0.28 \leq x_2 \leq 0.46$ on the wing. The total resistance in the circuit was 30Ω , and the piezoelectric capacitance C_p was $1.17 \times 10^{-6} \text{ F}$. Without considering the aerodynamic influence, the first and second mode frequencies of the open circuit (i.e., constant charge) were 43.0 Hz and 84.5 Hz, respectively. The simulation parameters are listed in Table 1. These parameters were determined on the basis of the materials used in the investigation to carry out realistic simulations. This study focuses on the energy harvested from wing flutter via

piezoelectric patches. We here explain the harvesting mechanism shown in Circuit B (Fig. 3) using a single-degree-of-freedom (SDOF) system, as this system is comprehensible. Figure 4 shows a schematic of the single-mode vibration in energy-harvesting.

4.2 Eigenvalue analysis for flutter phenomenon

Equation (23) can be reduced into an eigenvalue problem:

$$|\mathbf{K} + \psi \mathbf{A} - \mu \mathbf{M}| = 0, \quad (27)$$

where μ is a complex eigenvalue. Because the eigen-analysis is performed on a no-control system, the control input and the external disturbance are neglected. Figure 4 plots eigenvalues as a function of the dynamic pressure parameter ψ . The curves of the two values of the real part approach each other as ψ increases. When $\psi = 2.86 \times 10^6$, the two values of the real part can be combined as $\text{Re}[\mu] = 1.86 \times 10^3$. At this critical value of ψ the wing experiences a flutter phenomenon. This figure shows the loci of only the first and second modes. Since this critical value indicates the smallest dynamic pressure among all critical values, we focus on the relation between only two vibration modes.

4.3 Flutter harvesting simulation

We simulated flutter dynamics in the case that a white noise force was exerted on the wing surface. The power spectral density (PSD) per unit frequency of white noise had a constant nonzero value in the range of 30 to 100 Hz and a value of 0 in the rest of the frequency range. Therefore, the frequency range of the nonzero PSD covered the first and second modes.

The history of wing dynamics at a critical dynamic pressure with Circuit B is shown in Fig. 5. The wing tip displacement increases due to the wing flutter phenomenon. Following the displacement, the piezoelectric voltage also increases. Then, the stored voltage increases and harvested energy is accumulated. The stored voltage in the harvesting device is shown to have a step-like curve, which is characteristic of harvesting systems that use diode bridges. Figure 6 shows the magnified view of voltage in the two harvesting systems with Circuit A and Circuit B for $C_s = 1.17 \times 10^{-6}$. The harvesting system with Circuit B outperforms in harvesting energy from wing flutter. Figure 7 presents a comparison of the energy harvested by the two systems with $C_s = 1.17 \times 10^{-6}$. Our harvesting system with Circuit B can generate 10 times more electrical energy than the system with Circuit A. The generation ratio, i.e., 10 times, is quite a striking and attractive number as a powerful energy harvester. Our harvesting system shows potential and is effective because it takes advantage of the wing flutter that has thus far been considered as destructive.

5 CONCLUSIONS

Eco-generation from the flutter phenomenon of a plate wing is studied using the quasi-steady aerodynamic theory and the finite element method. The wing is modeled as sounding rockets' wings. We harvest electrical energy from supersonic flutter by using piezoelectric patches and electric devices. To assess their harvesting performances, we simulate flutter dynamics of the plate wing to which piezoelectric patches are attached. We demonstrate that our harvesting sys-

tem can generate 10 times more electrical energy from wing flutter than conventional harvesting systems can. We expect that our proposed technique will be applicable to various energy-harvesting systems, and we anticipate that it will be the basis for further studies in this field. More experimental validation is essential for assessing the harvesting performances, and an experiment is currently being carried out for this purpose.

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8 APPNDIX A. DEFINITION OF TERMS

$$\begin{aligned}
\sigma_p &\equiv \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix}, \epsilon_p \equiv \begin{Bmatrix} \epsilon_1 \\ \epsilon_2 \\ \gamma_{12} \end{Bmatrix}, \mathbf{h} \equiv \begin{Bmatrix} h_{13} \\ h_{13} \\ 0 \end{Bmatrix}, \mathbf{c}_p^D \equiv \frac{c_p^D}{1-\nu_p^2} \begin{bmatrix} 1 & \nu_p & 0 \\ \nu_p & 1 & 0 \\ 0 & 0 & \frac{1-\nu_p}{2} \end{bmatrix}, \mathbf{c}_w \equiv \frac{c_w}{1-\nu_w^2} \begin{bmatrix} 1 & \nu_w & 0 \\ \nu_w & 1 & 0 \\ 0 & 0 & \frac{1-\nu_w}{2} \end{bmatrix} \\
g_j(x_1, x_2, x_3) &\equiv [H(x_1 - x_{1Sj}) - H(x_1 - x_{2Ej})] \times [H(x_{2j} - x_{2Sj}) - H(x_2 - x_{2Ej})] \\
&\quad \times [H(x_3 - x_{3Sj}) - H(x_3 - x_{3Ej})] \\
T_w &\equiv \int_V \frac{\rho_w}{2} \left(\frac{\partial w}{\partial t} \right)^2 dV, U_w \equiv \int_V \frac{\sigma_w^T \epsilon_w}{2} dV, T_{pj} \equiv \int_{V_{pj}} \frac{\rho_{pj}}{2} \left(\frac{\partial w}{\partial t} \right)^2 g_j dV, U_{pj} \equiv \int_{V_{pj}} \frac{(\sigma_p^T \epsilon_p + E_3 D_3)}{2} dV \\
\mathbf{M} &\equiv \sum_{\text{ele}} \int_{V+V_p} \rho \mathbf{N}_F^T \mathbf{N}_F dV, \mathbf{K} \equiv \sum_{\text{ele}} \int_{V+V_p} x_3^2 \mathbf{B}_F^T \tilde{\mathbf{c}} \mathbf{B}_F dV, \mathbf{A} \equiv \sum_{\text{ele}} \int_S \mathbf{N}_F^T \frac{\partial \mathbf{N}_F}{\partial x_2} dS \\
\mathbf{B} &\equiv \sum_{\text{ele}} \int_{V_p} \left(\frac{x_3}{S_{\text{ele}}} \right) \mathbf{B}_F^T \mathbf{h} dV, \mathbf{C}^{-1} \equiv \sum_{\text{ele}} \int \left(\frac{x_3 \beta_{33}^S}{S_{\text{ele}}} \right) dx_3, \mathbf{B}_F \equiv \left[\frac{\partial^2 \mathbf{N}_F}{\partial x_1^2}, \frac{\partial^2 \mathbf{N}_F}{\partial x_2^2}, 2 \frac{\partial^2 \mathbf{N}_F}{\partial x_1 \partial x_2} \right]^T \\
\psi &\equiv \frac{4q}{\lambda}, \quad q \equiv \frac{1}{2} \rho_\infty U^2, \quad M_\infty \equiv \frac{U}{a_\infty} \\
\Phi &\equiv [\varphi_1, \varphi_2, \dots, \varphi_n], \quad \Omega \equiv \text{diagonal}[\omega_k^2], \quad \Xi \equiv \text{diagonal}[2\zeta\omega_k]
\end{aligned}$$

Table 1. Parameters of titanium wing and piezoelectric patch

	Titanium wing	Piezoelectric	unit
Piezoelectric coefficient	—	4.67	10^8 V/m
Dielectric coefficient	—	1.95	10^7 Vm/C
Density	4.47	8.10	10^3 kg/m ³
Young's modulus	11.3	6.40	10^{10} N/m ²
Poisson's ratio	0.31	0.32	—
Area	370×490	154×175	mm $\times$ mm
Thickness	6.75	0.5	mm

NOMENCLATURE

a_∞	speed of sound in air
c	Young's modulus
D_3, E_3	electric displacement and field
$\vec{f}$	external disturbance vector
$\mathbf{F}$	feedback matrix
h_{13}	piezoelectric coefficient
n_p	number of piezoelectric
$\mathbf{N}_F$	shape function of FEM
p	pressure exerted on plate
p_∞	air pressure
$\vec{\eta}$	modal displacement vector
$\vec{Q}$	electric charge vector
T_w	kinetic energy of wing
T_{pj}	kinetic energy of j th piezoelectric
U	flight speed
U_w	strain energy of wing
U_{pj}	mechanical and electrical energy of j th piezoelectric
$\vec{V}$	voltage vector of piezoelectric
w	x_3 -directional displacement
$\vec{y}$	FEM displacement vector
β_{33}^S	dielectric coefficient
ε, σ	strain and stress vectors
ρ, ν	density and Poisson's ratio
ρ_∞	air density
ζ	modal damping ratio
γ	ratio of specific heat

superscript

D	constant electric displacement
S	constant strain
T	transpose

subscript

p	piezoelectric patch
pj	j th piezoelectric patch
w	wing structure without piezoelectric

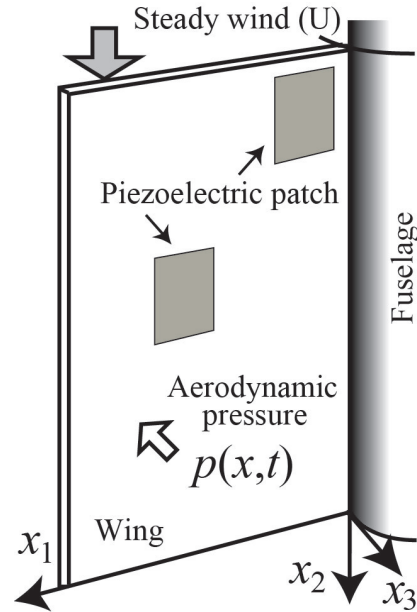


Figure 1. Tail wing subject to flutter and piezoelectric patches attached to wing

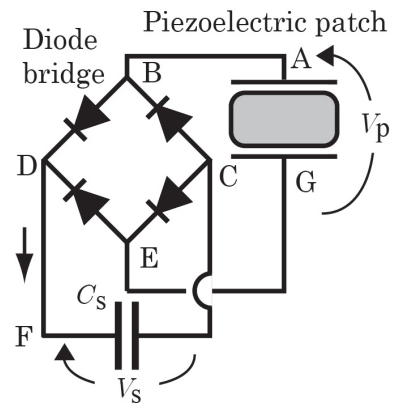


Figure 2. Circuit A: Conventional harvesting

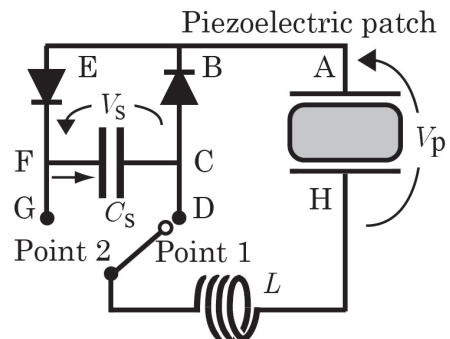


Figure 3. Circuit B: Efficient harvesting with energy-recycling mechanism

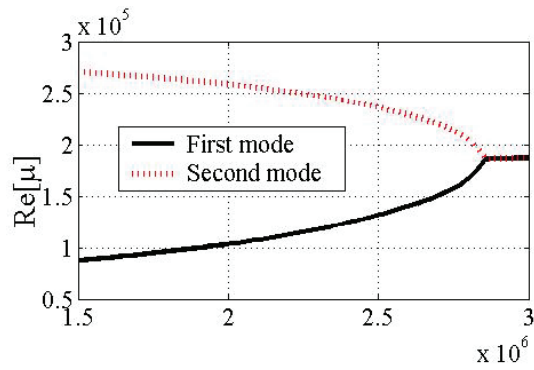


Figure 4. Eigenvalues as a function of dynamic pressure

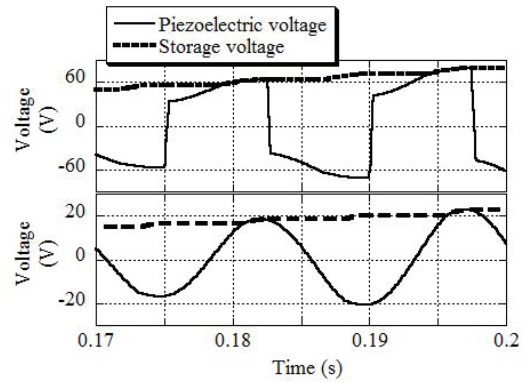


Figure 6. Magnified view of voltages (Upper: energy-harvesting, Lower: conventional)

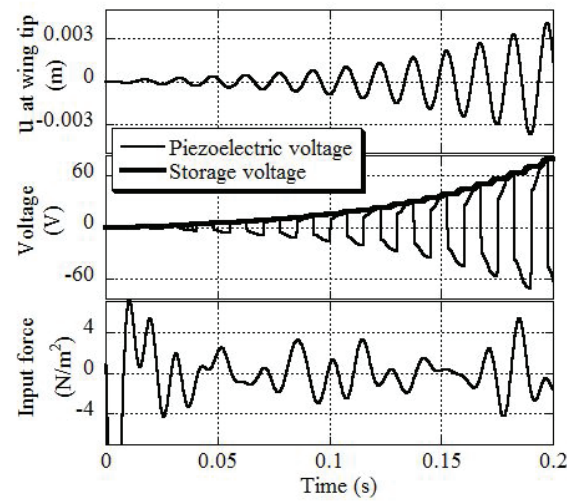


Figure 5. History of wing at critical dynamic pressure with energy-harvesting

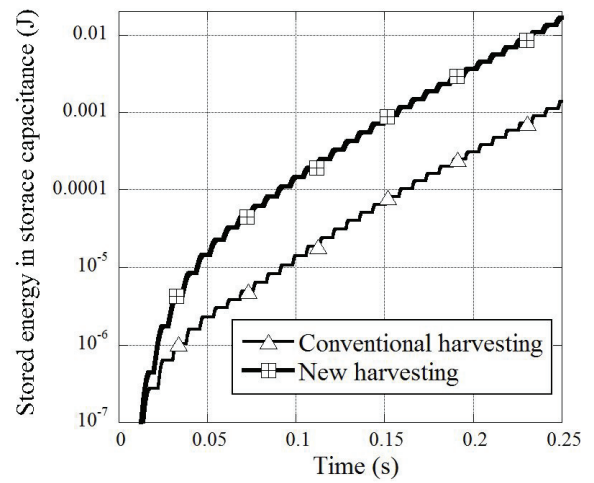


Figure 7. Comparison of stored energy in harvesting systems ($C_s = 1.17 \times 10^{-6}$)

Wind energy harvesting at elevated bridges

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ABSTRACT: This paper presents overall procedure for wind energy harvesting at elevated bridge in order to enable the self powered bridge. The test bed bridge was carefully selected from short term wind data measured at 86 sites considering wind energy potential and safety issues for traffic. The position of wind turbine around bridge girder was chosen from the CFD analysis and wind tunnel tests, where wind speed boosted 17~27% by oncoming wind. Two small wind turbines and associate monitoring system for wind data and electric power have been installed at the concrete girder of an elevated bridge over 57m above ground. Monitoring results for recent two months reveals a high correlation between the wind speed probability distribution and actual generated electric power. Long term monitoring of wind data and electric power is ongoing for further investigation.

KEYWORDS: Wind Energy, Bridge, Wind Turbine, Wind Tunnel Test.

1 INTRODUCTION

In modern bridges, electricity is needed for service and maintenance such as traffic control, lighting, and structural health monitoring. However, it is not easy to supply electricity to bridges in remote area. The cost for electric grid connection is \$50/m in Korea, and is not acceptable for many bridges in rural or mountain area. One feasible way is to provide the harvested electricity from ambient energy sources to rechargeable battery equipped at bridges. Wind has an advantage of a continuous source of energy. The traditional wind turbines convert the ambient wind flows into useful electrical energy.

Elevated bridges are good places for wind energy harvesting because of escalated wind speed from the ground. Wind speed is also increased at elevated bridges which cross a valley or canyon, producing a convergence of streamlines. When wind turbines are installed at bridge girder, the major concerns for bridge are probable wind forces increase, mechanical vibration and wind-induced vibrations. In case of short and mid span bridges, wind induced vibrations and mechanical vibrations may be not significant because of its stiffness. The additional wind forces at the bridges introduced by wind turbines seem to be negligible compared with self load and other live loads.

In the first step for realizing the self powered bridges, an elevated concrete bridge with sufficient stiffness has been selected and equipped two different types of small wind turbines. This paper presents overall numerical and experimental results of site selection, position of wind turbine, monitoring system and short term measurement at field.