WIND ENERGY HARVESTING FROM AEROELASTIC INSTABILITY

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ABSTRACT

This paper proposes an electromagnetic energy harvester for generating electric power from cross wind. The working principle of the device is based on galloping instability and utilizes permanent magnets and coils for transforming mechanical motion to electricity. A prototype device is tested in a wind tunnel. The device is found to provide a continuous average electrical power from a wind speed of 2 m/s.

Keywords: Energy harvesting, wind energy, galloping, flutter, electromagnetic

Introduction

The wind induced vibrations such as vortex shedding, flutter and galloping have been suggested as an alternate input source for small scale energy harvesters because the natural gust do not provide enough power at low wind speed. The cantilever type oscillator excited by aeroelastic instability has been investigated recently [Kwon (2010), Barrero-Gil et al. (2010) and Bryant et al. (2011)]. This study mostly target for powering small wireless sensor modules by capturing and transforming energy from wind into electricity. Present study presents the experimental and analytical results for maximizing energy production under ambient natural wind with low average speed.

![Schematic diagram](a) Schematic diagram
![Prototype device in the wind tunnel](b) Prototype device in the wind tunnel

Fig. 1 The proposed electromagnetic energy harvester subjected to cross wind

Energy Harvester Model

As shown in Fig 1(a), present wind energy harvester consists of steel plate, tip prism, magnets and coils. The steel plate provides stiffness to the tip prism. We use the tip prism to elicits the translational galloping, a velocity dependent and damping controlled instability. The galloping oscillation is transformed into electricity via electromagnetism.
The geometric arrangement of magnets and coil is shown in Fig. 2(a). Four magnets are attached at each end of the tip prism. These opposite pole arrangement of upper and lower magnets aim to prevent self cancellation of electricity induced at a coil. The copper wire coils are placed between magnets to allow relative motion provided by galloping instability. Note that the coils are separately fixed but the magnets attached at the tip prism are movable. Fig. 2(b) shows the result of FEM based magnetic field analysis using the FEMM 4.2 software. As can be seen in the figure, the magnetic flux vectors are normal to the coil which is beneficial for generating electricity.

Size of the tip prism is 22 mm × 22 mm × 100 mm. A bar magnet is 20 mm wide × 10 mm high × 3 mm thick in size, and is rare earth neodymium iron boron (NdFeB) magnets of 0.307 Tesla in magnetic flux density. Outer diameter, inner diameter and thickness of a coil are respectively 15 mm, 3 mm and 2 mm. Number of turns of a coil is 1200. Internal resistance and inductance of a coil are respectively 101 Ω and 9.67 mH. Two coils are serially connected. Natural frequency and damping ratio are respectively 2.67 Hz and 0.55 %.

(a) Four magnets and a coil
(b) Magnetic flux density

Fig. 2 Magnet arrangement and magnetic field around permanent magnets

Governing Equation

Considering a damped prism oscillator subjected to cross wind, the equation of motion for wind-structural interaction can be expressed as Eq. (1a) which is nonlinear because of the power terms related to velocity [Paidoussis (2010)]. The relation between the induced coil voltage and relative speed between the coil and the magnet is given as Eq. (1b).

\[
m\ddot{y} + 2m\xi\omega_n\dot{y} + m\omega_n^2y = F_{\text{aero}} + F_{\text{em}} = \frac{1}{2}\rho U^2 A \sum_j a_j \left(\frac{\dot{y}}{U}\right)^j + \frac{\phi}{R_L} V
\]

\[
\dot{V} = \frac{R_L}{L_C} \ddot{y} - \frac{R_L}{L_C} V
\]

By combining Eq. (1a) and (1b), the governing equation of motion can be derived in the following state-space form. This nonlinear equation is numerically solved by the fourth order Runge-Kutta method.

\[
\dot{z} = Az + \sum_{j=2} A_j z^j
\]

where \(y\) is transversal displacement, \(m\) is equivalent modal mass, \(\xi\) is damping ratio, \(\omega_n\) is natural frequency, \(U\) is wind speed, \(\rho\) is air density, \(A\) is projection area normal to wind flow,
\( \alpha_j \) is empirical aerodynamic coefficient, \( V \) is electric voltage, \( \phi \) is electromechanical coupling coefficient, \( L_C \) is coil inductance, \( R \) is electric resistance, and \( z = \{ y \ y' \ V \}^T \).

\[
A = \begin{bmatrix}
0 & 1 & 0 \\
-\alpha_j^2 & -2\alpha_j + \frac{\rho A U a_j}{2m} & -\frac{\phi}{m R_L} \\
0 & \phi R_L / L_C & -R_L / L_C
\end{bmatrix}, \quad A_j = \begin{bmatrix}
0 & 1 & 0 \\
0 & \frac{\rho A U_j^2 a_j}{2m U_j} & 0 \\
0 & 0 & 0
\end{bmatrix}
\]

Experimental Setup

The wind tunnel tests were carried at the KOCED Wind Tunnel Center at Chonbuk National University in Korea. The test section size in this open circuit wind tunnel is 1.0 m wide × 1.5 m high. The maximum wind speed is 21 m/s, and the turbulent intensities are less than 0.5%. The dynamic motion of the tip prism was measured by laser displacement transducer. The output voltage was monitored on the Agilent 34410A digital multimeter, and is converted to power from the measured voltage and applied electrical load resistance using the following relation; \( P = \frac{V^2}{R_L} \).

Test Results and Discussion

Fig. 3 shows experimentally obtained peak tip displacement and average power as a function of wind speed and external load resistance. It is obvious from the figure that the cut-in speed (galloping onset speed) gradually move to higher value as external load resistance increases. High power is extracted from the coil at low external load resistance. As a result, the galloping onset speed increases because of the increased electric damping.

Fig. 4 shows the measured output voltage and power over a range of load resistances at different wind velocities. The voltage and power are very sensitive to the external load resistance, and the optimal external load resistance for obtaining maximum power changes with the wind speed. This represents that one specific external load resistance may not be used at entire range of wind speed and should be changed according to wind speed in order to get maximum power.

Fig. 5(a) shows the relation between wind speed and maximum harvested average power in accordance with optimal resistance. The power is proportional to square of wind speed. The relation between the galloping onset speed and the external load resistance is given in Fig. 5(b). As was explained previously, the galloping onset speed increases as higher electric damping caused by low external load resistance.

Conclusions

This study demonstrates an electromagnetic cantilever with tip prism for energy harvesting from a freely available ambient wind flow. The prototype device activated by galloping instability can generate output power from a wind speed of 2 m/s and can provide an average power of 2.52 mW at 9 m/s. The arrangement of several proposed devices has the potential to provide power to a mobile electronic apparatus cost effectively.

References


Fig. 3 Experimental output as a function of wind speed and external load resistance

Fig. 4 Experimental output as a function of electrical load resistance

Fig. 5 Harvested average power and galloping onset speed (cut-in speed)