A novel electro-magneto-aeroelastic energy harvester is proposed employing the single degree of freedom flutter mechanism, in which a free pitching airfoil is augmented with an inductive energy harvesting system including a permanent magnet attached to the trailing edge of the airfoil and a fixed coil. Due to stall aerodynamics in divergent motion after the onset of flutter, such a system will exhibit nonlinear flutter phenomenon, such as LCOs, which can be used to generate energy by the induction effect. To address such a physical problem in energy harvesting, a nonlinear electro-magneto-aeroelastic system model is developed, taking the stall aerodynamics nonlinearity and the electromechanical coupling into account. With given parameters, the nonlinear electro-magneto-aeroelastic behaviour is studied by the time domain simulation approach. A preliminary study reveals the nonlinear aeroelastic behaviour and energy harvesting performance of the present aeroelastic energy harvester.

Keywords: electro-magneto-aeroelastic, energy harvesting, LCO, inductive, stall

1. Introduction

Aeroelastic flutter energy harvesting is a rich mine attracting many researchers to make of ambient wind energy, e.g. power wireless sensors [1,2]. In previous works of the authors [3,4], a novel Magneto-Aeroelastic Flutter Energy Harvesting (MAFEH) device was designed and tested, and an enhanced MAFEH prototype is proposed later with much lower cut-in airspeed. MAFEH is a more practical aeroelastic flutter energy harvester that can with stand long term limit cycle oscillations (LCOs) after flutter onset, in comparison with other type of harvesters that include elastic components [5,6].

In the present paper, a novel electro-magneto-aeroelastic energy harvester is proposed by employing the single degree of freedom flutter mechanism of a free pitching airfoil, which is augmented with an inductive energy harvesting system including a permanent magnet attached to the trailing edge of the airfoil and a ground coil. The mathematical model of the proposed harvester is developed considering quasi steady stall aerodynamics combined with the unsteady aerodynamics using Wagner function. The electromechanical coupling is also taken into account. Time simulation is carried out in the preliminary study, which reveals the nonlinear aeroelastic behaviour and energy harvesting performance of the present aeroelastic energy harvester.
2. Mathematical model development

The sketch of the proposed aeroelastic energy harvester is shown in Fig. 1 with only part of the airfoil, which is composed of

- A single degree of freedom free pitching airfoil supported by a ground hinge at both ends. The nondimensional location of the hinge line (elastic center) aft the mid chord is \( a \).
- A permanent magnet attached to the trailing edge of the airfoil with the average magnetic field intensity of \( B \).
- A ground coil. The number of coil turns is \( N \), and the internal resistance of the coil is \( R_t \).
- An external resistive load with resistance of \( R_L \).

According to [7], the single degree of freedom flutter could develop for a proper design of the airfoil structural dynamics. Usually the elastic center should near the leading edge, and the moment of inertia of the airfoil should be large enough. In the current model, the elastic center is located at the leading edge, i.e. \( a = -1 \). Different from the previous studies about single degree of freedom flutter, there is no pitch spring in the present model, hence no corresponding fatigue problem will be raised.

![Figure 1: Sketch of the aeroelastic energy harvester.](image)

2.1 Electromechanical coupling

2.1.1 Equation for the electrical circuit

The equation for the electrical circuit is derived by applying Kirchoff’s law to the electrical energy harvesting circuit of Fig. 1,

\[
i( R_L + R_t ) - K \dot{\alpha} = 0
\]

where \( i \) is the electrical current, and \( K \) is the electromechanical coupling coefficient. \( K \) can be expressed as \( K = nbNBl \) where \( l \) is the coil length and \( n \) is the non dimensional location of the center of the magnet aft the elastic center by semi chord \( b \).

2.1.2 Moments due to electrical damping

The electrical damping moments can be determined according to Lenz’s law,

\[
M_e = Ki = \frac{K^2}{( R_L + R_t )} \dot{\alpha}
\]

2.2 Aeroelastic equation of motion

Consider the electromechanical coupling, the nondimensional aeroelastic equation of motion for the airfoil in Fig. 1 can be formulated as
\[ \ddot{\alpha} + 2 \frac{\xi}{V^*} \dot{\alpha} + \frac{\zeta}{V^*} \alpha = \frac{2}{\pi \mu r^2} C_M(\tau) \]  

(3)

where (\cdot) denotes derivative with respect to \( \tau \), \( V^* = V/(b \omega) \) and \( \zeta = K^2/(R_L + R_I) \). Note there is no term of restoring moment for a free pitch airfoil, so \( \omega = 1 \) is chosen for convenience.

The aerodynamic moment coefficient \( C_M \) can be derived by linear unsteady aerodynamics theories such as Wagner function for small amplitude motion, while stall aerodynamics can be applied to large amplitude motion.

### 2.3 Quasi steady stall aerodynamics

In this work, the piecewise linear function is employed to model the aerodynamic force considering the stall effect once the amplitude exceeds 10 degree. The quasi steady formulation is expressed as:

\[ C_M = \frac{1}{\pi \mu r^2} \left( \frac{1}{2} + a \right) C_L \left( \alpha_{\text{eff}} \right) - \frac{1}{\mu r^2} \frac{d\alpha}{d\tau} \]  

(4)

\[ \alpha_{\text{eff}} = \alpha + \left( \frac{1}{2} - a \right) \frac{d\alpha}{d\tau} \]  

(5)

where \( C_L \) is well documented in [8].

Combine Eq. (1-5), we could study the nonlinear behaviour of the present harvester using some numerical technique.

### 3. Numerical simulation of nonlinear aeroelastic energy harvesting

For nondimensional airspeed of \( V^* = 3 \), time response histories of the proposed harvester are obtained by ode tool in Matlab. Some preliminary results are presented as follows.

The time histories of the pitching angle is shown in Fig. 2. The corresponding phase plot is depicted in Fig. 3. The LCO behaviour is clearly obtained as shown in Fig. 3.
Figure 2: Time history of pitching angle.

Figure 3: Phase plot of pitching rate v.s. pitching angle.
The harvested voltage in the external load is shown in Fig. 4. For the applied parameters, the peak-peak voltage generated is about 4 mV.

![Voltage Graph](image)

**Figure 4:** Voltage harvested by the external load.

4. **Concluding remarks**

   A new type of electro-magneto-aeroelastic energy harvester is proposed with no elastic component that will not suffer from fatigue problem. The mathematical model was developed for this single degree of freedom aeroelastic energy harvester. Quasi steady stall effect and the electromechanical coupling are considered in the EOM. Preliminary numerical simulation shows that the current model could obtain LCO phenomenon and predict harvested voltage. Detailed parametric design should be investigated with experimental validation followed in the future.

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**REFERENCES**


