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Piezoaeroelastic energy harvesting based on an airfoil with double plunge degrees of freedom: Modeling and numerical analysis

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HIGHLIGHTS

- A double-plunge airfoil-based piezoaeroelastic energy harvester is proposed.
- The dynamic equations of the proposed harvester are derived.
- The proposed harvester outperforms its pitch–plunge counterpart.
- A thorough case study is performed on the effects of the system parameters.

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ABSTRACT

In this paper, a piezoaeroelastic energy harvester based on an airfoil with double plunge degrees of freedom is proposed to additionally take advantage of the vibrational energy of the airfoil pitch motion. The analytical model of the proposed harvester is built, and an equivalent model using the well-explored pitch–plunge configuration is presented. The nonlinear aerodynamics is calculated based on the dynamic stall model. The dynamic response, average power output, energy harvesting efficiency, and cut-in speed (flutter speed) of the proposed harvester are numerically studied. It is demonstrated that the harvester with double-plunge configuration outperforms its equivalent pitch–plunge counterpart in terms of both the power output and energy harvesting efficiency beyond the flutter boundary. In addition, case studies are performed to reduce the cut-in speed and to enhance the energy harvesting efficiency of the proposed harvester, including the airfoil mass characteristics, the configuration, mass, damping, and stiffness characteristics of the two plunge supporting devices, and the load resistances in the external circuits. It is shown that the cut-in speed is greatly reduced by increasing the airfoil mass while tuning the mass eccentricity. The mass of the first (windward) supporting device should be a bit smaller than that of the second one for an applicable cut-in speed and a high-energy harvesting efficiency. Besides, the decrease of airfoil mass moment of inertia or the damping of the supporting devices is shown to be beneficial for the energy harvesting performance. In addition, the optimal location of the first supporting device is found to be at the airfoil leading edge. Decreasing the distance between the two supporting devices reduces the cut-in speed. The load resistances affect the cut-in speed slightly, and optimal values are found to maximize the energy harvesting efficiency.

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Nomenclature

Symbols

a	Dimensionless offset of the elastic axis measured from the half-chord axis.
A_f	Frontal area of the harvester in operation.
A_h, A_α	Resultant aerodynamics acting on the elastic axis.
b	Airfoil semi-chord.
c_1, c_2	Damping coefficients of 1st and 2nd plunge devices.
c_h, c_α	Damping coefficients of the plunge and pitch supporting devices of the equivalent model.
C_p	Equivalent capacitance of the transducers.
d	Dimensionless offset of 2nd plunge spring measured from 1st one.
d_1	Dimensionless offset of 1st plunge spring measured from half-chord axis.
D	Aerodynamic drag.
F_{p1}, F_{p2}	Electric forces by the transducers of 1st and 2nd supporting devices.
h	Plunge displacement of the elastic axis.
h_1, h_2	Plunge displacements of 1st and 2nd supporting devices.
h_c	Plunge displacement of the gravity center axis.
$\dot{h}_{1/4}$	Airfoil one-quarter-chord plunge velocity.
J	Airfoil mass moment of inertia about the gravity center axis of the equivalent model.
J_c	Airfoil mass moment of inertia about the gravity center axis.
k_1, k_2	Linear stiffness coefficients of 1st and 2nd plunge devices.
k_h, k_α	Linear stiffness coefficients of the plunge and pitch supporting devices of the equivalent model.
k_p	Linear stiffness coefficient of the transducers.
k_{s10}, k_{s20}	Linear stiffness coefficients of 1st and 2nd plunge springs.
k_{s12}, k_{s22}	Nonlinear stiffness coefficients of 1st and 2nd plunge springs.
l	Airfoil spanwise length.
L	Aerodynamic lift.
m	Airfoil mass.
m_1, m_2	Mass of 1st and 2nd plunge supporting devices.
m_T	Total mass of the airfoil with the supporting devices of the equivalent system.
M	Aerodynamic moment.
$\bar{P}$	Average power output.
$\bar{P}_f$	Total mechanical power available in a uniform flow.
Q_1, Q_2	Quantities of electric charge of 1st and 2nd transducers.
R_1, R_2	Load resistances in 1st and 2nd external circuits.
t	Time.
T	Kinetic energy of the system.
$\mathbf{T}$	Transfer matrix.
U	Flow velocity.
U_p	Potential energy of the system.
V_1, V_2	Voltage outputs of 1st and 2nd transducers.
W_p	Electrical energy of the system.
x_α	Dimensionless offset of the gravity center axis measured from the elastic axis.
α	Airfoil pitch rotation.
α_{eff}	Effective angle of attack.
$\delta W_1, \delta W_2$	Generalized virtual forces corresponding to h_1 and h_2.
δW_e	Virtual work with respect to the electrical generalized force.
μ	Energy harvesting efficiency.
ρ	Air density.
θ	Electromechanical coupling factor of the piezoelectric transducers.

Superscripts

$\cdot$	Derivative with respect to time.
$'$	Derivative with respect to dimensionless time.

Subscripts

z	z can be l or m denoting aerodynamic lift or moment in the ONERA model.

Abbreviations