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Modeling the coupled electro-mechanical response of a torsional-flutter-based wind harvester with a focus on energy efficiency examination

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ABSTRACT

Wind energy is a rapidly evolving field of research because of the need for clean energy resources. Large horizontal axis wind turbines (HAWT) are often employed to increase output power and energy production. On the other hand, "specialized" wind-based energy systems have been proposed to capture the wind energy resource in the low wind speed range and for intermediate-scale applications, e.g., one or few residential housing units. Wind harvesters, triggered by various aeroelastic instability regimes, have been studied in recent years [e.g., Matsumoto et al. (2006)]. Along this line of research, the writer has examined a torsional-flutter-based apparatus for extracting energy from the wind flow. This paper presents some recent advancements, a new fully-coupled electro-mechanical model and the numerical results of an ongoing investigation.

1. Introduction

The exploitation of aeroelastic phenomena for energy production is a relatively new technological area in comparison with other research activities in the field of aeroelasticity. Nevertheless, several new contributions and studies have appeared in the literature. One of the first interesting examples refers to the concept of the *flutter mill* (Tang et al., 2009) for extracting energy from the wind. This conceptual idea has captivated the interest of the research community in the last decades. Various solutions have been proposed and examined by researchers (Ahmadi, 1978; Farthing, 2009; Kwon et al., 2011; Matsumoto et al., 2006; Shimizu et al., 2008; Tang et al., 2009).

Among the most interesting examples, the flapping wing power generator (Shimizu et al., 2008) is based on the principle of the classical flutter of airfoils, involving a combined pitching-heaving motion. Another apparatus, which exploits the two-degree-of-freedom coupled flutter of a streamlined body in plunging and pitching motion, has been investigated both analytically and experimentally for energy extraction (Zhu, 2011). The coupled-mode flutter-mill concept has also been proposed and used for water pumping and irrigation purposes (Farthing, 2009). The configuration of this kind of aeroelastic harvesters is composed of either a rigid blade, mounted on a mobile support (Abdelkefi et al., 2012a) or several flexible blades (Abdelkefi et al., 2012b; Dunnmon et al., 2011; Kwon et al., 2011). If the blade or airfoil is exposed to an air flow speed beyond the critical flutter speed, large vibration can be triggered. The resulting limit-cycle oscillation regime can be exploited and converted to electrical energy (Dowell et al., 2004; Dunnmon et al., 2011). The limit-cycle is influenced by nonlinear aeroelastic effects. Oscillation amplitudes must be controlled both to optimize energy extraction from the flow and facilitate conversion to electrical power. Along the same line, the use of airfoil-like plates equipped with porous screens has been recently proposed as a new development of the flutter mill concept (Pigolotti et al., 2016, 2017).

In most successful applications of the flutter mill concept (Abdelkefi et al., 2012a; Dunnmon et al., 2011) the use of piezo-electric materials has been indicated as a practical technology that converts elastic deformation energy to electricity. Piezo-electric actuators have also been recently used to harvest energy from transverse galloping of square prisms in fluid flow (Abdelkefi et al., 2013, 2014), a mechanism conceptually simpler than coupled flutter, and from flutter-induced vibration of miniature beams, predominantly employed for sensor design (Casadei and Bertoldi, 2014). Capitalizing from some recent advances in the exploitation of piezo-electric materials, a number of design configurations of galloping-based harvesters have also been recently examined and experimentally tested, either at small scale (Tomasini and Giappino, 2016) or miniature scale [e.g., for installations inside air ventilation systems (Biscarini et al., 2016; Gkoumas et al., 2017; Petrini et al., 2014)]. The piezo-electric technology is typically efficient if either

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Nomenclature

The following symbols are used in this study

B	average magnetic flux density of the winding coil [teslas]
b	half-width (half-chord) of the blade-airfoil harvester [m]
$C(k)$	complex Theodorsen function
C_P	dimensionless power coefficient of the harvester
$c_j,\ d_j$	parameters of the Wagner function with $j=\{1,2\}$
e	rotational-axis eccentricity, measured from structural support (Fig. 1)
$F(k)$	real part of Theodorsen function
$f_{\text{e.m.}}$	electro-motive force induced by winding coil on the harvester
$G(k)$	imaginary part of Theodorsen function
I	time-varying induced current in the winding coil (electrical system) [ampères]
$I_{0\alpha}$	total mass moment of inertia of the rotating blade-airfoil [kg·m^2]
$I_{\max}$	Maximum current during limit-cycle post-critical stages (one period) [ampères]
$\hat{\imath}$	imaginary unit
k	reduced frequency
k^*	reduced frequency of the harvester at flutter
k_α	still-air reduced angular frequency of the blade-airfoil mechanism
L_C	inductance of the coil (electrical system) [henries]
ℓ	longitudinal length (span or height) of the blade-airfoil [m]
ℓ_C	effective coil length (electrical system)
M_{0z}	total dimensional torsional moment about pole O [N·m]
$\hat{M}_{0z,ae,u}$	unsteady dimensionless aeroelastic torque about pole O
$M_{\text{e.m.}}$	total dimensional electromotive torque about pole O [N·m]
m	mass of the 1*dof* model illustrating electro-mechanical coupling [kg]
N	number of winding coils (electrical system)
$P_{\text{in}},\ P_{\text{out}}$	Maximum (instantaneous) input and output powers [watts]
p	sliding *dof* of the magnet inside the winding coil (electrical system)
$\mathbf{q}_{\text{em}}(\mathbf{w}_{\text{em}})$	nonlinear vector-function for post-critical simulations
$R_1,\ R_2$	aerodynamic functions needed to solve for flutter
R_C	resistance of the winding coil [ohms]
s	dimensionless time, $s=Ut/b$
t	continuous time [s]
U	wind speed [m/s]
U^*	minimum operational wind speed [m/s]
$\mathbf{w}_{\text{em}}$	State vector of the coupled electro-mechanical system
α	angular rotation of the blade-airfoil about pole O
α_I	initial rotation at time $\tau=0$ (system's release)
$\alpha_{\max}$	maximum rotation amplitude of the blade-airfoil during limit-cycle post-critical stages
γ^*	frequency ratio at flutter $\gamma^*=\omega_\alpha/\omega^*$
ε	generalized inertia parameter, $\varepsilon=\pi\rho b^4\ell(I_{0\alpha})^{-1}$
ζ_p	damping ratio of the 1*dof* model (illustrating coupling)
ζ_α	structural damping ratio of the harvester
ι	time-varying dimensionless induced current of the harvester (electrical system)
$\iota_{\max}$	maximum value (magnitude) of the dimensionless induced current during limit-cycle post-critical stages
κ	nonlinear stiffness coefficient of the torsional spring model
λ_{RL}	generalized impedance coefficient
$\mu_{ae,j},\ \nu_{ae,j}$	aeroelastic states with $j=\{1,2\}$
ρ	air density [kg/m^3]
τ	dimensionless time of the state-space model, $\tau=k_\alpha s$
$\Phi(s)$	aeroelastic load function (indicial function)
$\Phi_{\text{e.m.c.}}$	dimensional electro-mechanical coupling coefficient [N/ampère]
Ψ	Dimensionless electro-mechanical coupling coefficient
ω^*	angular frequency of the harvester at flutter [rad/s]
ω_p	angular frequency of the 1*dof* model (illustrating coupling) [rad/s]
ω_α	Still-air rotational frequency of the blade-airfoil [rad/s]
Operators	
$(\cdot)',\ (\cdot)''$	first and second derivative with respect to s

vibration frequencies are greater than 10 Hz (Priya and Inman, 2009) or the energy transfer is enhanced by repeated impacts (Zhu and Zhang, 2015). Nevertheless, the high cost of piezo-electric materials restricts applications to the scale of small devices.

For applications at a larger scale, the use of vortex-induced vibration of "suspended" circular cylinders, connected by springs to a fixed-base support has been proposed (Bernitsas et al., 2008, 2009; Mehmood et al., 2013). For example, the VIVACE apparatus, designed for underwater applications (Bernitsas et al., 2008, 2009), exploits the lock-in harmonic vibration of the cylinder in the direction orthogonal to the flow. This device is ideal if the anticipated flow speed does not vary considerably. Nevertheless, the overall efficiency can significantly diminish in the case of irregular and turbulent flow conditions, typical of wind flow in the atmospheric boundary layer. Consequently, applications are possibly restricted to a narrow (lock-in) wind speed range.

This paper builds on the results of a previous study that examined the technical feasibility of a wind-based energy harvester, taking advantage of the leading-edge torsional flutter instability of a blade-airfoil (Caracoglia, 2010) for wind energy conversion. Torsional flutter is a single-mode aeroelastic instability phenomenon, which triggers a diverging vibration of a flexible body. Sustained vibration is possible in a post-critical flutter state, stable beyond the critical flutter speed. This phenomenon is a prerogative of long-span bridges with bluff deck girders (Scanlan and Tomko, 1971). It is also possible in the case of streamlined airfoils if the center (axis) of rotation of the airfoil's cross-section coincides with the leading edge of the profile (Bisplinghoff et al., 1955; Kakkavas, 1998).

It is observed that the pitching rotation mechanism of an H-shaped cross section, similar to a bluff bridge deck and prone to torsional flutter, was proposed in the recent past to convert wind power to electric energy (Ahmadi, 1979). An H-shaped cross section is believed to be adequate for its propensity to exhibit torsional flutter. However, it also has several disadvantages. For example, sensitivity to incoming turbulence may lead to non-negligible buffeting vibration prior to the flutter onset, which needs to be avoided to prolong the lifetime of the apparatus. Furthermore, a bluff body would tend to produce larger drag loads, which must be considered while designing the structural support system and torsional-restoring force rotating mechanism. Additionally, larger wakes generated by a bluff body would reduce efficiency if an array of devices were used (for example, staggered from each other).

The blade-airfoil cross-section and apparatus proposed herein are simple, versatile, and compact; they are possibly attractive in comparison