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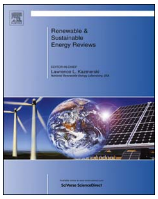

Renewable energy harvesting by vortex-induced motions: Review and benchmarking of technologies

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ABSTRACT

Vortex-induced motions are generally known as destructive phenomena for engineering structures. Nevertheless, they have a positive effect which is their great potential to extract renewable energy from the fluid flow. The phenomenology of vortex-induced motions has been studied and several energy harvesting technologies based on these motions have been reported, separately through literature. However, a comprehensive study that bonds together the phenomenology and the energy extraction technologies does not exist yet. Now that this area has become well established, classification of the relevant phenomena and technologies has become necessary as well. The present paper has two main objectives; The first objective is to classify the whole vortex-induced motion phenomena into several groups which include Flutter, Transverse and Torsional Galloping, Buffeting, Vortex-Induced Vibration (VIV), and Fluttering-Autorotation. The second objective is to review the literature, with the aim of classifying different technologies of renewable energy harvesting based on vortex-induced motion. Also, the performance characteristics and economical costs of these technologies are benchmarked.

1. Introduction and background

From long time ago, human society have used the energy of wind and current to do several activities, such as mill grains and pump waters in the past and generate electricity recently. Traditionally, turbines and watermills have been in use for extracting energy from these resources. Examples of these devices are the reaction turbines such as Francis turbine, impulse turbines such as Pelton wheels, or impulse and reaction turbines such as modern wind turbines. These devices have relatively high efficiency; however there are some remarkable disadvantages in regard to use of these devices.

One of the disadvantages about the traditional turbines and watermills is their requirement to high energy fluid flow for working. For instance, in hydropower turbine, high hydraulic head is needed for running the turbine. Although the hydraulic head can occur naturally, e.g. waterfall, it is not always the case. In most cases, high hydraulic head is created by constructing a dam on a river. The cost of dam construction makes traditional hydroelectric projects difficult to execute. In spite of the cost, building a dam will increase safety risks, such as flash flood caused by a broken dam, and environmental and ecological complications such as silt accumulation in basin.

Other disadvantage, mostly attended to impulse and reaction turbines, is due to their particular design. The inborn structural weakness associated with centrifugal stress necessitates high performance materials and thus the construction costs are increased. Moreover, in conventional designs, e.g. the horizontal axis wind turbines, large translational speed is reached at the tips of the blades. In large wind turbines, this speed approaches the sound barrier causing serious environmental concerns about noise generation as well as the threat they pose to birds [1].

Recently, a new paradigm to extract energy from wind and current has been developed which is based on vortex-induced motions. In this paradigm, the energy of vortices is recovered instead of providing flow with extra energy artificially. A vortex is a rotating region in fluid medium that can be simplified by many concentric circular layers which rotate in different angular velocity [2]. Vortex shedding, due to which vortices are generated and detached from the body, changes the local pressure distribution around the body [12]. This local change in pressure distribution induces motion on the body. Vortex generation repeats periodically and therefore, the body moves continuously.

In the recent decades, a lot of studies have been performed to develop the knowledge and new technologies have been introduced in the field of energy extraction from vortex-induced motion. However, a comprehensive classification to categorize the relevant phenomena and technologies does not exists yet. The objectives of this work are; (1) to classify the whole vortex-induced motion phenomena into several

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groups, and (2) to review the energy extraction technologies related to each class. Also, the technologies are benchmarked by different criteria. The classification and the phenomena description of vortex-induced motion are presented in Section 2. The literature about the energy extraction using the described phenomena is reviewed in Section 3. Section 4 gives the performance and the energy cost benchmarking of the vortex-induced motion phenomena. Also, the cost of vortex-induced motion energy harvesting technologies is compared to other traditional and alternative energy resources. Finally, the conclusion is presented in Section 5.

2. Vortex-induced motions (VIM): classification

Vortex-induced motions (VIM) place into two main groups of oscillation type and rotation type. Oscillation types are classified in two general categories; instability type and resonance type [4,5]. In instability type the forces vary with time as a result of the motion of the structure, and increase the oscillation amplitude. The instability is called Flutter when the resulting oscillation is in two or more coupled degrees of freedom, and Galloping when the oscillation has only one degree of freedom. Galloping, in its turn, has two types; transverse and torsional. On the other hand, in resonance type, the elastic structure begins to oscillate if the frequency of the oscillatory forces corresponds to its natural frequency. The oscillatory force can be either by the oscillating incoming flow, i.e. Buffeting, or induced due to the vortex shedding, i.e. Vortex-Induced Vibration (VIV) and Fluttering.[1] As the inertia increases, Fluttering which is an oscillatory rotation is converted to Autorotation which is continuous rotation. In other words, there is a bifurcation between Fluttering and Autorotation, i.e. rotation type VIMs. A flowchart of flow-induced oscillations is shown in Fig. 1. The phenomenology of VIMs is briefly introduced in the following sections.

2.1. Flutter

Flutter is a self-controlled oscillation due to hydro/aero elastic instability, and usually applies for two degree of freedom aeroelastic oscillation of aircraft wings [6]. A simplified two-dimensional representation of an airfoil is shown in Fig. 2 where the foil is restrained elastically in torsion and vertical bending. The aerodynamic lift forces classically places in one-quarter of the chord aft of the foil leading edge, so-called “Aerodynamic center” [7]. In this figure, the connection point of elastic axis is at the center of rotation. Hydro/aero elastic instability happens when the center of gravity places aft of the center of rotation. On the contrary, the stable condition comes from putting the center of gravity forward of the center of rotation.

In flutter, there is an inertial coupling between the two degrees of freedom [8]. The phase difference is an essential part of the instability in flutter. In this process the two independent translational and torsional frequencies are driven together by aerodynamic stiffness terms. This coupled motion initiates when the encountered flow reaches to special velocity. This velocity is known as cut-in velocity or flutter boundary velocity.

Singh et al. [9] have justified the cut-in speed as the responsible part of the fluid for flutter instability. They have reported that the oscillation happens for a certain range of current speeds regardless to geometry. The interesting point which was reported in their work is that the inviscid part of the fluid is responsible for instability because the inviscid forces cause to finite amplitude oscillations. Also, they have stated that the viscous part of the flow only extends the range of speed corresponding instability without any changes on the fundamental physics of flutter oscillations. Fei and Li [10] have given an empirical equation for critical flutter speed (cut-in velocity), which can be written as:

$$U_C = \frac{1.76\quad r}{B}\sqrt{\frac{m}{\pi\rho}(\omega_P^2 - \omega_H^2)} \tag{1}$$

where r is radius of gyration of the cross-section ($I=mr^2$); m is the mass per unit length; B is the structure width; ρ is the flow density; ω_P and ω_H are the angular frequencies in rotational direction (pitch motion) and translational direction (heave), respectively.

By observing nonlinear bifurcations, aeroelastic responses can be determined in the vicinity of the flutter boundary. This nonlinear analysis can determine the LCO stability. In Fig. 3a general bifurcation plot depicts two different LCO responses [11]. It can be clearly seen that when weak nonlinearities are present in the aero/hydro elastic system the LCO quickly reaches large amplitude with a consequent divergent behavior. Conversely, strong nonlinearities create a more stable LCO response.

Flutter includes various types such as torsion-plunge coupled instability (flutter), unstable torsion (divergence), and single degree of freedom oscillation (stall flutter)[14].

2.2. Galloping

Suppose an elastic body stirs up when placed in fluid flow. The fluid forces, generated by relative motion of the body and fluid, cause that the oscillation amplitude descends and body remains stable, or ascends and motion becomes unstable. Therefore, the stability or instability of the body depends on the ratio between the transmitting energy to vibrating body due to the forces and the dissipated energy from the system that is named energy ratio. Hence, the body becomes unstable if the energy ratio is greater than 1 and in the contrary, becomes stable if the ratio of energy being less than 1.

Galloping is known as dynamic instability that is induced in an elastic structure due to internal turbulence of the fluid or any other reason which provides initial disturbance. Therefore, galloping enhances any initial small motion of the structure and turns it to an oscillation. The oscillation occurs in a plane normal to the oncoming flow velocity. Some references define it as a velocity-dependent, damping-controlled instability, which unlike Flutter is a one degree-of-freedom [13,4,14]. This instability gives rise to Transverse (translational) galloping or torsional galloping and has relatively high amplitude.

2.2.1. Transverse galloping

Consider a prismatic body connected to a linear spring, subjected to an incoming flow in the transverse direction, with a mass per unit length m, mechanical damping ratio ζ, and natural circular frequency of oscillation ω_n (see Fig. 4). The only degree-of-freedom of such structure is transverse oscillation. Moreover, the body is sufficiently slender to consider bi-dimensional flow, and the incident flow is free of turbulence. Then, the equation governing the dynamics of the system is

$$m(\ddot{y}+2\zeta\omega_n\dot{y} + \omega_n{}^2 y) = F_y = \frac{1}{2}\rho U^2 D C_y \tag{2}$$

where y denotes the vertical position, ρ is the fluid density, U is the undisturbed velocity of the incident flow, D is the characteristic dimension of the body normal to the flow, F_y is the fluid force per unit length in the normal direction to the incident flow, C_y is the instantaneous fluid force coefficient also in the transverse direction to the incident flow, and the dot symbol stands for differentiation with respect to time t. Fig. 4 implies that

$$F_y = -F_D sin\alpha - F_L cos\alpha \tag{3}$$

Any increase in the vertical velocity of the body ($\Delta\dot{y}>0$) will result in $\Delta\alpha > 0$. Besides, the system would be stable if $dF_y/d\alpha<0$, because $\Delta\dot{y}>0$ and $dF_y<0$, and hence the transverse oscillation will decay. On the other hand, for $dF_y/d\alpha>0$ the transverse oscillation will grow and lead to

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[1] Note that there is difference between *flutter* and *fluttering*.