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Controlled Aerodynamic Instability Phenomena – An Alternative Approach for Wind Power Generation Systems

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ABSTRACT

In this study the concept of *Controlled Aerodynamic Instability Phenomena* is proposed, as an alternative approach for *Wind Power Generation* systems. The concept is based on the idea that aerodynamic instability phenomena, such as *Karman Vortex Shedding, Flutter, Galloping and Buffeting,* can be driven into a useful motion and be used to extract energy from the flow. A case study using the *flutter* instability is presented and the concept is proved feasible. By using a forced torsional oscillation, the heaving motion is induced in a bluff body, so the energy generated by the heaving motion is estimated by both analytical and experimental processes, converging to the same conclusion. Finally, the results are discussed and alternatives for future developments are introduced.

INTRODUCTION

Nowadays, when a discussion is established around the theme *Wind Power Generation*, what is promptly addressed is the image of a big windmill, with its turbine getting turned by the wind. However, some alternative approaches have already been proposed in the latter decades, showing that the *windmill* is not the only possibility for the exploitation of the wind for power generation purposes.

In 1977 Jeffery [1] developed an oscillating aerofoil system based on a vertically-mounted pivoting wing which flapped in the wind. In contrast, McKinney and DeLaurier [2] in 1981 proposed a system called *Wingmill*, based on a rigid horizontal airfoil with articulated pitching and plunging to extract energy from the flow; this system has stimulated Moores[3] in 2003 to conduct further investigations on applications of such idea.

Following the same trend, other studies have already been carried out, and special remarks should be done to the *Flutter Power Generation System* proposed by Isogai et al.[4] in 2003, which uses the *flutter* instability caused by the wind on an aerofoil to extract energy from the flow. In this branch, Matsumoto et al. [5] went further, proposing enhancements for that system and assessing the feasibility of its usage.

The wind interacts with the obstacles it reaches in its way by transferring a part of its energy to those interactions, which are converted into forces over the bodies, leading them to different levels of motion, which are directly dependant on their aeroelastic and geometric characteristics. A large amount of studies and researches has been conducted concerning these interactions and their dependencies, aiming the understanding of the aerodynamic phenomena that arise due to them, such as *Karman Vortex Shedding*, *Galloping*, *Buffeting* and *Flutter*, mainly regarding *bluff bodies*. By the understanding of such phenomena it is possible to predict instabilities and their consequent motions, feeding the designers with the data they need in order to arrange the structures properly.

In the great majority of the cases – e.g.: in civil buildings – such motions are useless and undesirable, in a manner that all the designing approaches are focused on avoiding them. However these instabilities may also be used in a profitable manner: if they are controlled and driven to a predictable motion, they can provide mechanical power supply to run, for example, turbines, machinery and electricity generators.

So by using the knowledge acquired by now regarding those aerodynamic instabilities and by developing new features, it is possible to propose ways to stimulate them to an optimal state, using them for power generation purposes. That way, alternative approaches to the windmill may be proposed and developed.

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CASE STUDY

The feasibility of using aerodynamic instabilities for power generation purposes is demonstrated in this study by assessing the applicability of the flutter instability for that, as a step towards the development of the *Controlled Aerodynamic Instability* concept.

Flutter is an aerodynamic instability phenomenon induced by the interaction between inertial, damping, elastic and the self-excited aerodynamic forces acting on structures. When a bluff body is subjected to a wind load of a certain critical wind velocity, i.e. flutter onset velocity, the aerodynamic forces, instead of dissipating energy, start to feed the oscillatory system in a divergent motion. This may lead the structure to the collapse and has become a major concern in the designing of long span bridges. Basically, it is a composition of 2 modes of vibration that are presented as heaving and torsional oscillations, and when both eigen-frequencies coincide, very strong vibrations can be noticed.

There are some types of flutter instabilities, and this study is focused on the heaving branch of the coupled flutter mechanism. Previous studies [6] have proved this branch to be an efficient alternative for such a kind of application.

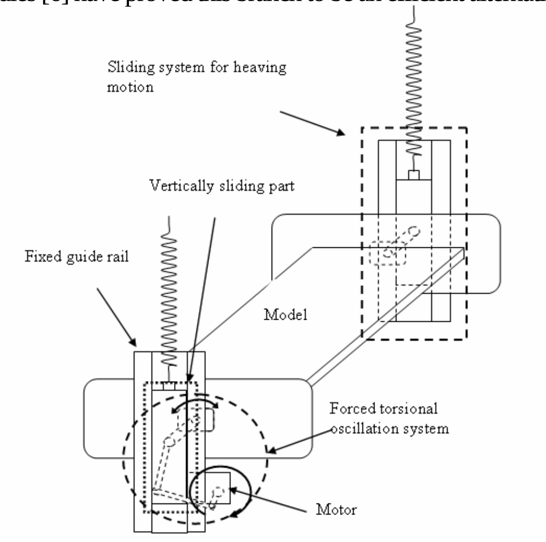

Fig. 1 – Mechanical System

In this type of instability there is interdependence between heaving and torsional motions, which coexist over the onset velocity. The oscillation is characterized by the heaving branch frequency and this interdependence can be exploited by the proposition of a system in which the excitation of one DOF implies in the induction of the other. So the heaving motion is excited by the lift force induced by an initial torsional oscillation, given by an electronic motor with prescribed frequency and amplitude (Fig. 1), through the coupled aerodynamic derivatives H_2^* and H_3^*.

Analytical solutions for calculating the amplitude ratio between both motions, as well as the generated and supplied regarded energy, are presented. These solutions are intended to provide a theoretical base for the understanding of the mechanisms regarded to the use of aerodynamic instability for power generation purposes. Finally, they are compared to experimental data, pursuing the validation of their predictions.

<u>Amplitude Ratio for Forced Torsional Oscillation Mode</u>

The differential equation of heaving motion for a certain wind velocity can be expressed by Eq. 1:

$$m\ddot{\eta} + (C_\eta - \rho b^2 \omega_F H_1^*)\dot{\eta} + (k_\eta - \rho b^2 \omega_F{}^2 H_4^*)\eta = \rho b^3 \omega_F H_2^* \dot{\phi} + \rho b^3 \omega_F{}^2 H_3^* \phi \tag{1}$$

where, η/ϕ : heaving/torsional displacement (downward/nose-up positive), m: mass per unit length, C_η: heaving damping coefficient, k_η: heaving stiffness, ρ : air density, b: half chord length, ω : flutter circular frequency, H_i^* (i=1-4) : aerodynamic derivatives of lift force.

Defining the damping coefficient and the stiffness as $C_\eta = 2m\omega_{\eta 0}\varsigma_{\eta 0}$ and $k_\eta = m\omega_{\eta 0}{}^2$, Eq. (1) takes the form of Eq. (2), where circular frequency and damping ratio under wind velocity are defined as $\omega_\eta{}^* = \sqrt{\omega_{\eta 0}{}^2 - \rho b^2 \omega_F{}^2 H_4^* / m}$ and $\varsigma_\eta^* = (2\varsigma_{\eta 0}\omega_{\eta 0} - \rho b^2 \omega_F H_1^* / m) / 2\omega_\eta^*$.

$$\ddot{\eta} + 2\varsigma_\eta^* \omega_\eta^* \dot{\eta} + \omega_\eta^{*2} \eta = (\rho b^3 / m)\omega_F H_2^* \dot{\phi} + (\rho b^3 / m)\omega_F{}^2 H_3^* \phi \tag{2}$$

Assuming the torsional motion as $\phi = \phi_0 \sin \omega_F t$, the amplitude ratio between heaving and torsional oscillations can be given by Eq. (3).

$$\frac{\eta_0}{\phi_0} = \frac{\rho b^3 \omega_F{}^2 \sqrt{H_2^{*2} + H_3^{*2}}}{m\omega_\eta^{*2}} \cdot \frac{1}{\sqrt{[1-(\omega_F/\omega_\eta^*)^2]^2 + [2\varsigma_\eta^*(\omega_F/\omega_\eta^*)]^2}} \tag{3}$$

in which, the term $\rho b^3 \omega_F{}^2 \sqrt{H_2^{*2} + H_3^{*2}}$ is the amplitude of the lift force driven by the forced torsional oscillation, while the term $1\Big/\sqrt{[1-(\omega_F/\omega_\eta^*)^2]^2 + [2\varsigma_\eta^*(\omega_F/\omega_\eta^*)]^2}$ is the frequency response function.

Generated Energy

In the steady oscillation, the heaving amplitude is constant and the total energy of the system, composed by the potential and the kinetic energies, must also be constant. Therefore, the energy generated by the system is assumed to be the energy exhausted by the free vibration, in this case the heaving motion, which can be considered equal to the work done by the unsteady aerodynamic lift force.

Assuming the heaving motion as $\eta = \eta_0 \sin \omega_F t$, the torsional displacement and its velocity are expressed by the amplitude ratio and phase difference between heaving and torsional motions, as $\phi = \frac{1}{\eta_0/\phi_0}\left(\eta \cos\Psi + \dot{\eta}\frac{\sin\Psi}{\omega_F}\right)$ and $\dot{\phi} = \frac{1}{\eta_0/\phi_0}\left(\dot{\eta}\cos\Psi - \eta\omega_F \sin\Psi\right)$.

Substituting the given torsional displacement and the velocity into Eq. (1), integrating the unsteady aerodynamic lift force for one cycle and dividing it by one period, the energy per unit time generated by the system may be represented by Eq. (4), in which the integral corresponding to the heaving displacement term is zero. Thus the heaving velocity term is considered as the net result for the power generation system.

$$\begin{aligned} W_{GH} &= \int_0^T [\rho b^2 \omega_F H_1^* \dot{\eta} + \rho b^3 \omega_F H_2^* \frac{1}{\eta_0/\phi_0}\left(\dot{\eta}\cos\psi - \eta\omega_F \sin\psi\right) \\ &+ \rho b^3 \omega_F{}^2 H_3^* \frac{1}{\eta_0/\phi_0}\left(\eta\cos\psi + \dot{\eta}\frac{\sin\psi}{\omega_F}\right) + \rho b^2 \omega_F{}^2 H_4^* \eta]\dot{\eta}/T dt \\ &= \left[\rho b^2 \omega_F H_1^* + \rho b^3 \omega_F H_2^* \frac{\phi_0}{\eta_0}\cos\psi + \rho b^3 \omega_F H_3^* \frac{\phi_0}{\eta_0}\sin\psi\right]\eta_0^2 \omega_F \pi / T \end{aligned} \tag{4}$$

Supplied Energy

The energy that should be supplied to the system must compensate the losses originated in the driving devices, such as motor, transmission and so on. Also, it must drive the torsional oscillation itself, counterbalancing the work done by the unsteady pitching moment. As a primary stage, this study will consider only the energy associated to the latter one, assuming a perfect system.

This energy can be represented by Eq. (5), using the given amplitude ratio and phase between heaving and torsional motions.

$$W_{SH} = [\rho b^4 \omega_F A_2^* + \rho b^3 \omega_F A_1^* \frac{\eta_0}{\phi_0}\cos\psi - \rho b^3 \omega_F A_4^* \frac{\eta_0}{\phi_0}\sin\psi]\phi_0{}^2 \omega_F \pi / T \tag{5}$$

Wind Tunnel Tests

The wind tunnel tests were carried out by using a 2D rectangular cylinder with side ratio B/D=20 (B=0.30[m], D=0.015[m]), in a 1DOF system in heaving mode. The wind tunnel used in the experiments is a room circuit Eiffel type, with working section of 1.8 m of height by 1.0 m of width and maximum wind velocity of 30 m/s.

The amplitude ratios between heaving and torsional motions (η_0/ϕ_0), according to the frequencies of the forced torsional oscillation, are represented by Fig.2. For lower wind velocities, the analytical results showed larger values, and for higher wind velocities this trend is the opposite. This happened because of the dependency of the heaving damping on the amplitude of the heaving oscillation, due to imperfections in the mechanical system. In the calculations, it was considered a constant damping value of 0.656. Despite these little discrepancies it is possible to verify an overall agreement between the results of analyses and the wind tunnel tests.

The amplitude ratio increases with the wind velocity because of the increase of the absolute values of aerodynamic derivatives H_2^* and H_3^*, as shown in Fig. 3. As the forced torsional frequency approaches the heaving natural frequency, larger values of amplitude ratio are obtained, for all wind velocity ranges. This can be explained by the increase of frequency response function.

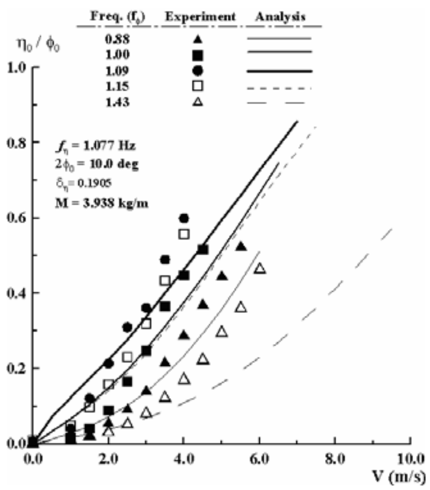

Fig.2 - Amplitude ratios according to the frequencies

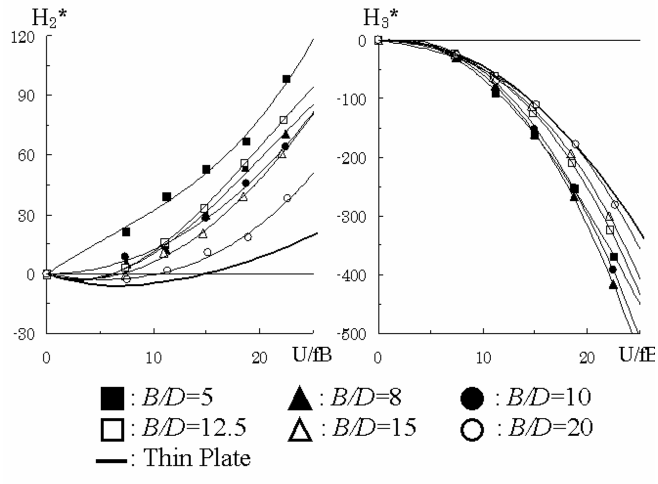

Fig.3 – Aerodynamic derivatives H_2^* and H_3^* of rectangular sections

Apparently there is a positive correlation between the energy that can be extracted from the flow and the absolute values of H_2^* and H_3^*. So by improving the geometrical shape of bodies, towards higher absolute values of H_2^* and H_3^*, may be a good strategy for maximizing the energy output of the system.

CONCLUDING REMARKS

The idea of using aerodynamic instabilities for power generation purposes is still incipient, but the look for environmentally clean solutions through the use of alternative sources of energy, e.g. wind power, bio-mass, bio-gas, geothermal, oceanic tidal, oceanic thermal, has strongly increased. So this proposition finds its justification in this scenario and also in the search of the enhancement of the knowledge in the Wind Engineering, regarding the aerodynamic instability phenomena.

The correlation between the aerodynamic derivatives H_2^* and H_3^* and the energy outcome points a direction to the search of the feasibility of the proposed concept. For this, the usage of active control devices for flow control as well as by taking advantage of the effects of surrounding structures may be good wind power augmentation strategies and should be addressed in further works.

Finally, some points can be remarked:

- Concerning the forced torsional frequency, significant large heaving response can be produced at the vicinity of natural heaving frequency;
- A power generation system based on the flutter instability can be applied to high-speed moving objects, from the point of view of energy saving, since the maximization of the energy is attained in higher wind velocities;
- As future works, the energy efficiency including the effects of power generation devices and their practical realization should be carefully investigated;
- The generated energy by unsteady lift force is larger than the energy supplied to the system only over a certain velocity. So the system should be initiated by an external power supply, to become self-sustainable only after that velocity is reached.

In future works the same approach adopted here should be extended to other aerodynamic instabilities, in the search of the best alternative for the application of the *Controlled Aerodynamic Instability Phenomena* for power generation purposes.

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