

# VIV resonant wind generators

David Jesús Yáñez Villarreal  
Vortex Bladeless S.L.  
[www.vortexbladeless.com](http://www.vortexbladeless.com)

**Summary.** *New wind generators with different characteristics compared with conventional wind turbines can improve the exploitation of this clean energy source. Aeroelastic resonance phenomena are usually considered a problem, but they can also constitute the basis of a technology for wind energy transformation. This paper is a condensed synopsis of the most general aspects of an alternative technology based on VIV fluid-structure interaction that avoids the use of gears or shafts. The application of magnetic forces to the resonant structure allows to passively modify the structure rigidity, which leads to an increase of the lock-in range and consequently a higher number of working hours per year. Electromagnetic induction is also one of the available strategies to transform the energy of the oscillatory movement into electricity.*

## 1 Introduction

The efficiency of renewable energies has grown significantly in recent years and wind energy has been one of the most important responsables. The increasing size of wind turbines is making wind power to be one of the most relevant energy source. However, in the distributed energy sector, where energy is generated close to the point of use, the most remarkable technology may be photovoltaic solar energy. The lacking of mobile mechanical parts allows to collect energy from the sun with minimal maintenance and no environmental noise impact. In addition, it is well known that the combined use of different renewable energy sources is synergistic due to mutual compensation in periods of absence of wind, sunlight, etc. The development of a new wind generator can be very useful if it is able to emulate the features that have made photovoltaics the main energy source in the distributed energy sector.

In relation to large-scale wind power, the offshore technology (turbines installed in the ocean) is very promising. One of the faced problems is the aggressiveness of marine environments, especially the corrosion of mobile mechanical parts of the mills. Therefore the absence of gears, bearings, etc. in a device capable of collecting wind energy can also be an important advantage.

The influence on wildlife (mainly birds), the visual impact, the cause of EMI phenomena with antennas or radars, the costs, and many other factors must also be considered when developing a new wind generation device.

## 2 Resonance

One of the most well known events produced by aerodynamic resonance is the collapse of the Tacoma Narrows bridge [1]. Resonance phenomenon arises when an oscillation is reinforced by a periodic movement. In aeroelasticity, the air can induce an oscillatory movement in a body if its natural resonance frequency and the vortex shedding's wake frequency are similar. The vibrations induced in a body by vortices are known as VIV phenomena [2]. The vortex shedding (figure 1) happens with periodicity, with forces perpendicular to the incident wind flow direction. There is a constant of proportionality  $St$  between the average velocity of the incident wind flow  $v$ , the inverse of its characteristic length  $\Phi$  and the frequency of vortex shedding  $f$ :

$$f = \frac{St \cdot v}{\Phi} \quad (1)$$

The resonance phenomena often appears associated with the normal mode of oscillation.

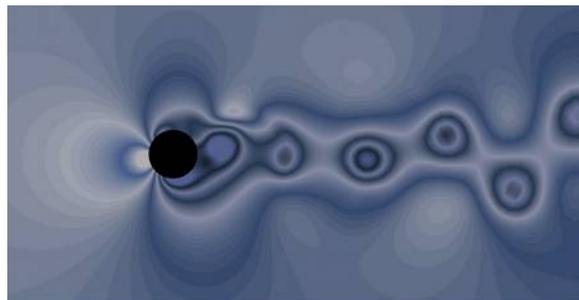


Figure 1. 2D VIV contour of pressures, CFD for a DNS model,  $Re = 416$  y  $A/D = 0,2$  (AcuSolve v14, HyperWorks®, Altair®).

Generally, the wind direction is variable. The cross section of a device without mechanical shafts and always well oriented to the wind direction has to be circular. Vortex shedding formation, unlike other dynamic phenomena such as fluttering or galloping, are easily formed in circular section bodies. On the other hand, normally the higher you are from the ground, the more increases the gradient of wind velocities. The Hellmann's exponential law [3] is a well studied approximation to this fact. Due to the aforementioned reasons, a vertical, slender and circular cross section structure seems to be adequate to collect wind energy without requiring mechanical shafts.

The performance in the conversion of wind's kinetic energy into mechanical energy should be as close as possible to the Betz limit [4]. Regarding this, the mast is the rigid part of the structure directly interacting with the wind. As showed below, we can reach a synchronised vortex shedding along the whole mast by modifying the diameter according to height. In this way, the perpendicular forces to the wind flow direction do work in phase all together, reaching a higher performance than if they did not.

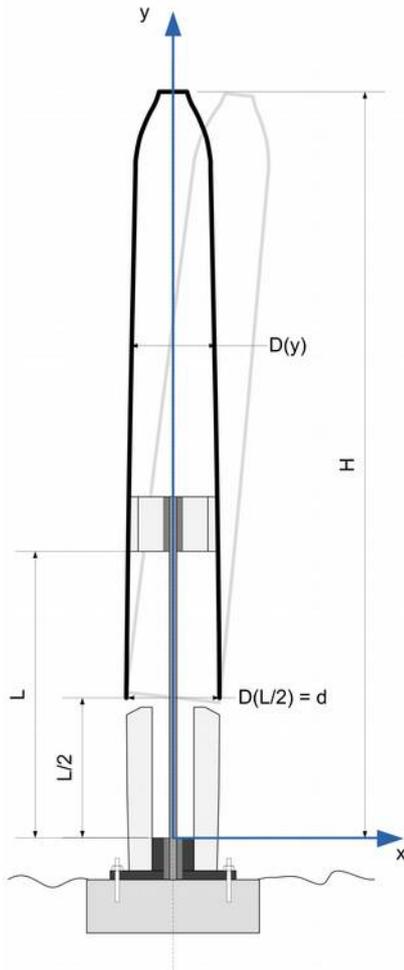


Figure 2. Evolution of the mast diameter according to height.

The characteristic length of cylindrical structures mentioned in equation (1) takes the value from the structure's diameter. This approach fits well for static structures, but with structures whose oscillation is not negligible, it can be proven that a better fit is obtained with:

$$\Phi = D + a \cdot X \quad (2)$$

Where the characteristic length  $\Phi$  is the sum of the diameter of the mast and the amplitude of its oscillation  $X$  multiplied by an adjustment factor which is Reynolds' Number dependent. A correct adjustment of this factor allows an orderly vortex shedding.

Suppose a flexible and free length  $L$  rod (figure 2) embedded in the mast (upper part) and in the ground (lower part). Considering the mast as a rigid solid able to oscillate small angles, it is acceptable to assume that the amplitude of oscillation  $x$  is null [5] at the height of  $y = L/2$ . In this position the characteristic length according to (2) matches the diameter of the mast  $\Phi = D(L/2) = d$  and the vortex shedding frequency  $f$  with wind velocity  $v_\infty(L/2)$  is:

$$f = \frac{S_t \cdot v_\infty(L/2)}{d} \quad (3)$$

In any other section of the mast, where the oscillation value is not negligible, the frequency of vortex shedding results:

$$f(y) = \frac{S_t \cdot v_\infty(y)}{D(y) + a \cdot X(y)} \quad (4)$$

Where  $v_\infty(y)$  and  $X(y)$  are the velocity of the fluid and the oscillation amplitude of the mast at each height  $y$ , respectively. Therefore,  $H$  is the distance between the ground anchor of the flexible rod and the highest part of the device. If the displacement in the upper part of the device is  $\gamma$  times the mast diameter at its lowest part, as a result:

$$X(y) = \frac{y - L/2}{H - L/2} \cdot \gamma \cdot d \quad (5)$$

As the vortex shedding frequency is the same throughout the length of the mast, we finally obtain:

$$D(y) = d \cdot \frac{v_\infty(y)}{v_\infty(L/2)} - a \cdot X(y) \quad (6)$$

A proper estimation of the velocity gradient, including the discontinuity effect in the highest part of the mast, should serve to find the same vortex shedding frequency along the whole mast. In order to reach the desired resonance, this frequency has to be

coincident with the one of the whole structure's normal oscillation mode.

### 3 Tuning system

As seen above, the frequency of vortex shedding is proportional to the wind speed which is not constant. On the other hand, the range of wind velocities within the structure resonates (lock-in range) [6] is narrow due to the fact that the normal oscillation frequency of a structure is a single one. To increase the number of equivalent working hours per year, we have to increase this range of useful wind velocities. A strategy that allows us to avoid mechanical shafts is shown below.

Figure 3 shows the damped harmonic oscillator diagram where a mass  $m$  oscillates under the action of a force  $F$  and it is connected to a spring of elasticity constant  $k$  and a damper of constant  $c$ .

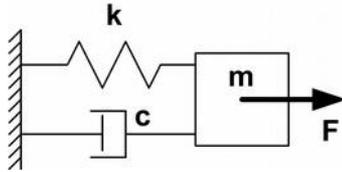


Figure 3. Damped harmonic oscillator diagram.

The behavior of a VIV resonant aerogenerator without built-in tuning system can be understood regarding to this model. The mass of a mast is supported by a rod with a certain rigidity and the system is damped by the alternator and other power losses. This whole system will resonate if the oscillatory force induced by the wind has the following frequency:

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{m} - \left(\frac{c}{2m}\right)^2} \quad (7)$$

An available strategy to increase the range of working wind velocities (resonance) can be illustrated as follows:

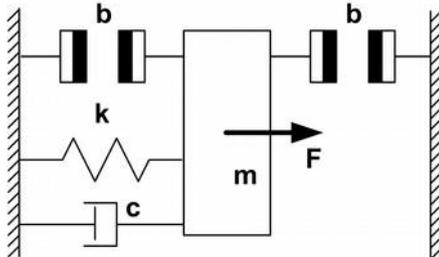


Figure 4. Oscillator with a magnetic tuning system diagram.

Two pairs of permanent magnets  $b$  have been added to the damped harmonic oscillator. The same poles are facing each other. These pair of magnets has one

fixed to the oscillating mass and the other fixed to the ground. The magnetic force that appears between two permanent magnets is inversely proportional to the square of the average distance between their poles, in a way that they behave like a compression spring with non-constant elasticity dependent on the displacement. As they get closer, the growth of the repulsive force between them grows higher than a linear order. So, now the frequency of oscillation is increasing with the oscillation amplitude:

$$f(x) = \frac{1}{2\pi} \sqrt{\frac{(k+k'(x))}{m} - \left(\frac{c}{2m}\right)^2} \quad (8)$$

Where  $k'$  represents the amount of elasticity corresponding to the magnetic repulsion.

As already mentioned, in the design of the device a complete axial symmetry is sought with the aim of having an independent behavior of the wind flow direction. The desired effect can be implemented with one or more pairs of permanent magnets rings, where the one with smaller diameter is the fixed one and it is magnetically confined inside of the one with bigger diameter. As an example, its polarization can be axial (figure 5a) or radial (figure 5b), etc.

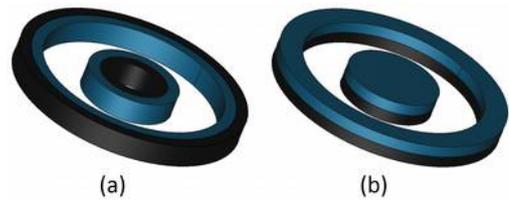


Figure 5. Possible arrangement of permanent magnet rings used for tuning the system. Outer ring is fixed to the mast (oscillator) and the inner ring is fixed to the ground (stator).

As an example, figure 6 shows the temporal evolution of forces in a complete oscillation of a lab model mast.

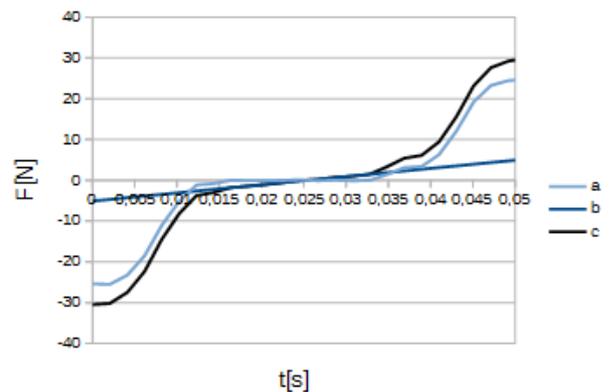


Figure 6. Temporal evolution of forces due to the elasticity of the rod and magnetic repulsion of tuning system according to any oscillation amplitude.

The force  $a$  is magnetically originated. The evolution of the force  $b$  is due to the elasticity of the rod. The resultant force  $c$  (sum of  $a$  and  $b$  forces) is the one that the mast perceives.

A wind speed increase causes an augmentation of oscillation amplitude. As the oscillation amplitude grows, the potential energy accumulated in a flexion grows faster than if it were a linear spring, so the oscillation frequency of the whole system increases. Hence, without the use of any actuator, the lock-in range (figure 7b) reaches higher values on the horizontal axis than those achieved with a classic lock-in (figure 7a).

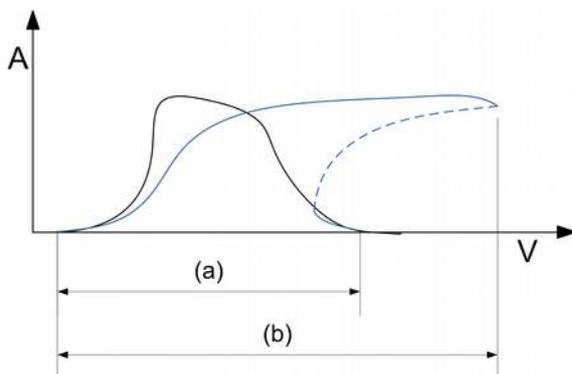


Figure 7. Simplified illustration of lock-in evolution (amplitude vs wind velocity) according to a device with no tuning system (a) and a device with it (b).

It has been observed in wind tunnel tests that when the a model with built-in tuning system exceeds the lock-in range it stops working suddenly (figure 8). As a result, braking systems are not necessary to deal with strong winds.



Figure 8. Testing device in the wind tunnel Acla16 in the CIDA (IDR/UPM). 1m height model, max. mast diam. 95mm and supported by a solid, circular section, 10cm diam., pultruded carbon fiber rod (February, 2018).

## 4 Alternator

The conversion of structural energy into electricity can be made by different methods. As the oscillation

of the device is very close to a cantilever, the use of materials with strong electromechanical coupling is very suggestive. If the resistance to fatigue and the power density of these materials improves in the future, VIV resonant aerogenerators will be able to integrate them.

Currently, the most developed option to obtain electrical energy is electromagnetic induction, especially by using a permanent-magnets alternator. The imposition of excluding mobile shafts and the spherical/variable character of the mast movement condition the design of a suitable alternator for this technology. In a first approximation, and due to the fact that the maximum mast velocity take place where it passes over the oscillation neutral position, it seems to be attractive from an electromagnetic point of view that the interaction between magnets and coils occurs with the mast in a vertical position. It has been proven that this strategy leads us to circular and weakened trajectories of the mast or even the disappearance of resonance. This happens because the system logically searches a minimum energy trajectory. On the other hand, the interaction between magnets and coils in position of maximum bending and even the induced forces between magnets and electric iron cores are allowed by the system dynamics.

Another important aspect to be taken into account in the design of the alternator is the need to maintain a complete axial symmetry. The device must behave identically independent of the wind direction. Thus, the use of permanent magnets arranged in a ring and fixed to the mast are the most indicated strategy again. Finally, the aerodynamic benefits related to a light mast should be highlighted (mast amplitude and lock-in range) [7]. The simultaneous use of the mobile ring for power generation and tuning of the structure saves weight and costs.

Figure 9 shows the different components of the alternator. The permanent magnet rings  $b$  are fixed to the mast. As the mast flexes, the interaction with the coils and tuning magnets fixed to the stator  $a$  increases. The stator part of the alternator is supported by the structure  $c$  fixed to the ground.

Conventional rectifying, filtering and electrical regulation methods are equally applicable as expected. As on other alternators electric power output is AC with variable amplitude and frequency. After rectification and filtering it is transformed into DC.

Other more exotic strategies of conversion of mechanical energy into electrical energy have not been evaluated for the time being.

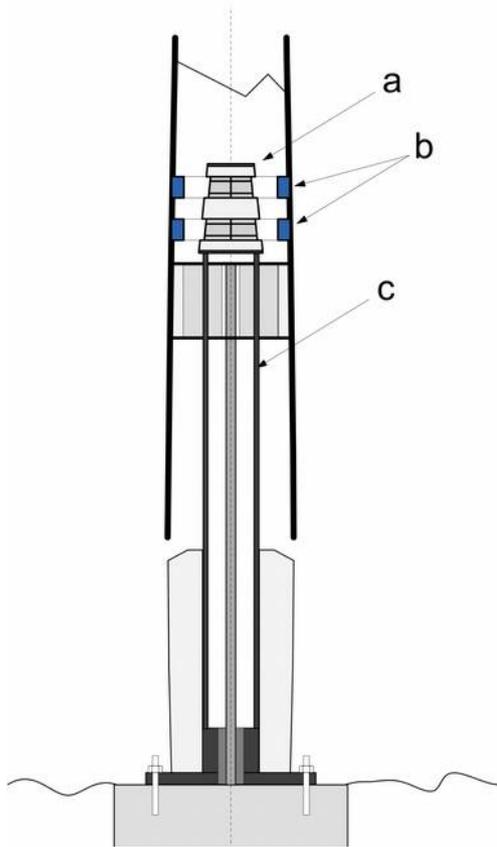


Figure 9. Arrangement of the alternator and tuning system.

## 5 Fatigue

The VIV resonant wind generators are characterized by the lack of mechanical components that can be deteriorated by friction. However, the device has a carbon fiber rod subjected to a dynamic cyclic bending load. This type of demand usually causes the material failure due to fatigue. A brief preliminary analysis will help us to approach its magnitude.

In line with the principle of prudence it is considered a device whose bending was always on the same plane, with a maximum angle and 5Hz uninterrupted working frequency. The classic formulation:

$$S_f = a \cdot N^b \quad (9)$$

with  $S_{ut} = 500$  Mpa,  $S'_e = 252$  MPa and factors  $K_a = 0,96$ ,  $K_b = 0,94$ ,  $K_q = 0,98$ ,  $K_d = 1$ ,  $K_e = 0,98$ ,  $K_g = 0,97$  y  $K_c = 0,897$ , it lead us to an expected operational lifespan of 19,83 years.

## 6 Discussion

The calculation of the cost of any electric generation system (LCoE) relates the total investment that is faced in its manufacture, installation, maintenance and scrapping / recycling and the energy generated during its lifespan. Many aspects influence the final

value of this ratio. The influence of the wake on the behavior of neighboring devices determines the minimum distance that there should be between two installed devices. A shorter required distance is favorable to a reduction in the energy cost. Preliminary experiments in this area allow us to anticipate the appearance of synchrony phenomena between neighboring devices and other typical emergent properties of chaotic systems. A distance between devices of half their height will not cause a dramatic performance reduction but more rigorous studies must be carried out in this regard.

The ability of the device to withstand high winds is important in many areas of the planet. To safeguard their integrity, conventional windmills are designed to face high wind speeds by using a braking and a pitch systems. In the case of VIV resonant wind generators, strong winds produce a decoupling between the structural oscillation frequency and the appearance of vortices. Thus, the resonance and oscillation disappear and lift forces become less important than drag forces. Preliminary tests in this respect point to a remarkable tolerance to strong winds and a low resistance to the collision with objects projected by them. More rigorous studies must be carried out in this regard.

The visual and environmental impacts will influence the cost and acceptance of the device as a new energy generation device, especially in urban emplacements.

## 7 Conclusions

The implementation of a wind generation device based on aeroelastic resonance is feasible. It has been suggested that it is desirable to collect wind energy with a device that minimizes maintenance needs, especially as far as distributed generation is concerned. A slender and circular cross section wind generator whose diameter is variable according to height is proposed for achieve this mission. To maintain the resonance in a wider range of wind speeds, a strategy based on magnetic repulsion by using permanent magnets has been shown. Finally, regarding to the conversion of mechanical energy into electricity, the use of permanent magnets alternators whose stator is fixed to the ground and its mobile part is fixed to the oscillating structure part has been illustrated. No mechanical components susceptible to wear due to friction are required.

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