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Analysis of Vortex Shedding Frecuencies, in Curved Buildings

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Abstract: *The Curved buildings are a challenge for structural engineers, either because there are no standards for this purpose, such as the need to resort to scale tests in wind tunnels.*
This work presents a number of wind tunnel tests of a curved building with circular arc profile, which was subjected to different angles of attack of the wind, to obtain the frequency of vortex shedding, in order to determine if the number of Strouhal remains constant or varies with the angle of attack of the wind.
The tunnel where the tests were carried out is of atmospheric boundary layer, with a wind profile for a type IV urban environment (according to CIRSOC 102, ASCE 7 standards) and Reynolds numbers between $6x10^4$ and 10^5. The speeds were measured in the wake, at the coordinate point Y = 3.5.C, X = 0.4.C.Sen α (C is the chord and α is the angle of attack). With the data we proceeded to do a spectral analysis to calculate the corresponding Strouhal number.
The main results obtained indicate that the main frequency of vortex shedding varies strongly according to the angle of incidence, therefore also the Strouhal number does, a result that is different from those obtained by C. Knisely (1990) in cylinders of rectangular base, where for those buildings the number of Strouhal varies only in the first 10 degrees producing a slight increase, and then remains constant.
Keywords: *Curved building, circular-arc profile, wind tunnel test*

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I. Introduction

There are no stationary loads on the buildings, due to the nature of the wind, which is totally turbulent, so the wind loads are fluctuating.When a construction is very rigid, oscillating loads may appear, due to the variation of the wind, or to a fluctuating flow pattern around sections of certain characteristics, or due to a combination of both causes. The methodology for the analysis of these cases (constructions of very high rigidity) is to assume that their movements are negligible and study them in a quasi-static manner, with pressure and velocity values averaged or integrated over time, and with maximum design loads with a low probability of occurrence in a time, greater than the expected useful life for the construction.In Argentina, the calculation of wind loads in these cases is described in the CIRSOC 102 regulation.

When the rigidity of the construction is low, three different but related situations can occur:
1) If the lowest natural frequency (the first fundamental mode) of the construction is of the order of the turbulence frequencies in its wake, resonance and feedback mechanisms will be produced.
2) Due to the low rigidity of the structure, this allows greater displacements, and in certain cases, the forces acting on the displaced construction are different from those acting in the original position, giving rise to aeroelastic phenomena (flutter).
3) Both phenomena are coupled with a third: the lower the rigidity, the greater the amplitude of the movement and the greater the acceleration, so that the inertial forces can even exceed the aerodynamic forces.

1.1. Separation of the boundary layer

We know that the air flow in the boundary layer loses momentum due to frictional forces. When the external pressure gradient is favourable, the outer fluid layers continuously transfer momentum to the layers adjacent to the obstacle, so that the air in the boundary layer maintains a positive velocity. However, in an adverse pressure gradient, this transfer is less, and it reaches a point where the lower layers have lost all their momentum and stop. The layers adjacent to these must flow on stationary air, and consequently separate from the surface. This is the phenomenon called "separation", which plays an important role in the development of wind configurations around buildings and the consequent forces on them (as illustrated in Fig. 1).

In cylindrical or rounded sections, the point of separation depends among other things on whether the boundary layer is laminar or turbulent, and this is determined by three factors: the Reynolds number, the wind turbulence,and the roughness of the surface.

The critical value of the Reynolds number at which the laminar to turbulent transition is triggered is approximately $3.5x10^5$ for cylinders in air without turbulence and a surface without roughness. If the wind contains turbulence and the surface of the object is rough, then the critical Reynolds is reduced to values on the order of 10^4.

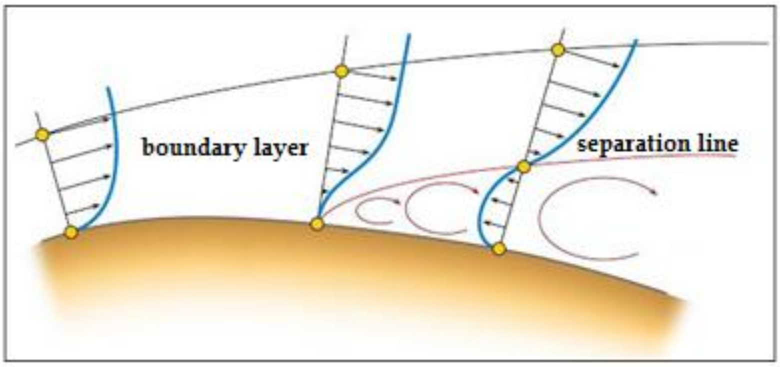

Figure 1. Separation of boundary layer.

The flow pattern that follows the separation of the boundary layer is very important in the study of forces on buildings. The point at which this displacement occurs depends on the wind speed, the level of turbulence, the surface roughness and the geometry of the same. This greatly complicates the studies carried out in wind tunnels because the Reynolds number of the prototype will be one to two orders of magnitude higher than those that can be obtained in the wind tunnel with the models.

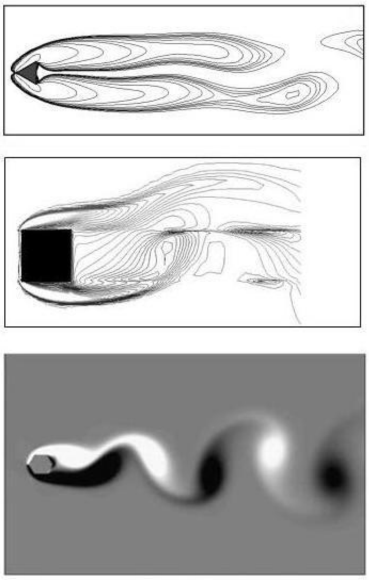

Figure 2. Example of different bodies with sharp edges. It is observed that the separation occurs in the first edge.

Fortunately, it is very common in civil constructions, the use of sections of sharp edges (not rounded). For these sections, the separation occurs at the first edge that should surround the flow, regardless of the Reynolds number, surface roughness and wind characteristics (Fig. 2 illustrates this type of landslides that generate the wake of the body). So the action of the wind on these constructions can be investigated in the tunnel with reliable results, since the different configurations can be reproduced.

1.2. Wake of a building

The layer in which viscous forces are important, when adjacent to a surface, is called the "boundary layer". Downstream of the separation point, this layer moves into the free flow and is called the "shear layer". It divides the wake of the body from the free flow that surrounds it (see Fig. 3). An important feature of the cutting layers is that they incorporate fluid from both the flow and the wake.

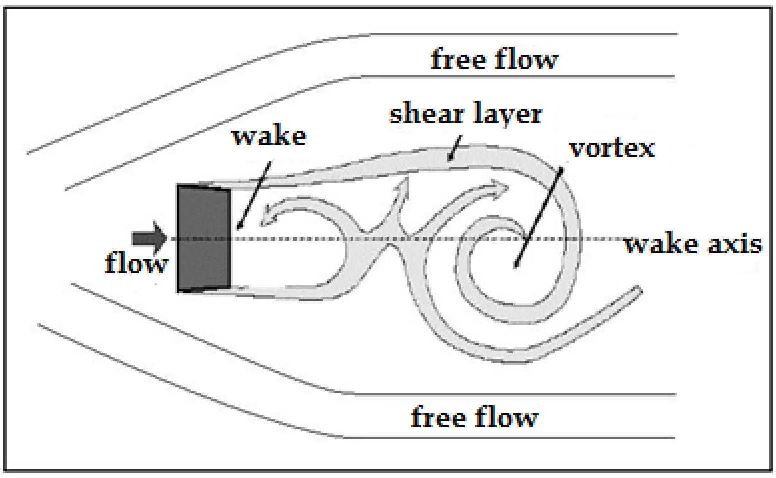

Figure 3. Vortex shedding in a parallelepiped type body.

For this configuration to be stable, it is necessary that these major vortices alternate between both layers. This configuration is known as "Von Karman vortex street", as illustrated in Fig. 4 (Von Karman, T., and Rubach, 1912).

Figure 4. Streets of Von Karman generated behind a cylinder, consisting of vortices separated alternately.

With its growth, a group of vortexes gradually incorporate vortices of the opposite layer, which have a different direction of rotation, and therefore tend to reduce the vorticity of the group. When the vorticity increase rate of the vortex adjacent to the wall is canceled, it falls off and travels downstream. This originates in the immediate area to the wall the growth of a vortex of the opposite layer, which grows until its vorticity stops increasing and falls off, repeating the cycle. This phenomenon is called "vortex shedding".

1.3. Oscillation frequency and Strouhal number

The Strouhal number is a dimensionless parameter that relates vibrations to inertia and is defined as:

$$St = \frac{L \cdot Fc}{V}$$

St : Strouhal number
L : Structural diameter or distance between the edges where separation occurs
V :Wind velocity
Fc :Frequency of vortex shedding

The Strouhal number for vortex shedding is a function of the shape of the section of the structure (Fig. 5), and in cases of rounded sections, it also depends on the Reynolds number, atmospheric turbulence and surface roughness.

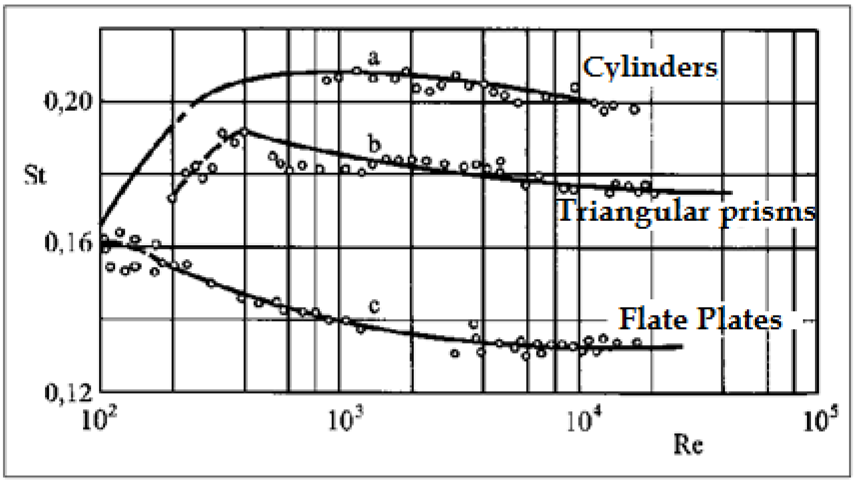

Figure 5. Variation of the Strouhal number with the Reynolds number for three different bodies.

1.4. Number of Strouhal in cylinders of rectangular and square base

Knisely (1990) makes a literature review about the Strouhal number in cylinders of rectangular and square base, and with wind tunnel tests provides new data in this regard. Fig. 6 shows the variation of the number of Strouhal as a function of the angle of attack of the wind on a cylindrical body of square base, where it is observed that for angles between 0° and 12° there is a linear increasing variation of the St, then it remains constant up to 78° and decays to 90° (there is a symmetry from 45° to 90°).

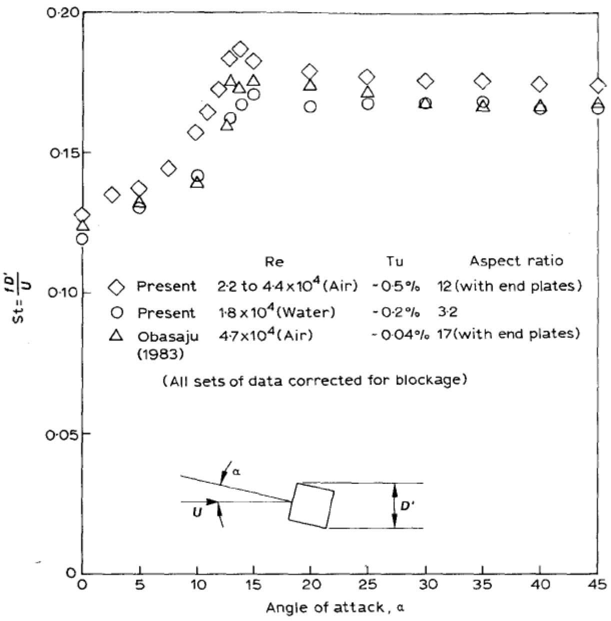

Figure 6. Variation of Strouhal number with the angle of attack of the wind (extracted from reference 1).

1.5. Vortex shedding in curved buildings

In the case of constructions with significant curvatures, the separation of the vortices is not done at the vertices of the buildings, but depends on the point where the adverse pressure gradient reverses the circulation of the boundary layer on the surface of the same (as shown illustrated in Fig. 1).

Therefore, this type of vortex shedding will be more similar to how the aerodynamic profiles behave, than to that presented by Knisely (1990).

Due to this, a bibliography was located where the vortices were separated in symmetrical aerodynamic profiles type NACA 00XX, as the work done by Yarusevych and Boutilier (2010).

Yarusevych et all (2009) studied the wake of a NACA 0025 profile and concluded for angles of incidence between 0° and 10°, that the Strouhal number increased with the increase of the Reynolds number in the range of $5x10^4$ - $15x10^4$, and then it stayed constant.

On the other hand Mahbub Alam et al (2010), observed for a NACA 0012 profile that the Strouhal number is dependent on the angle of incidence of the wind on the profile, and for Reynolds numbers between 10^4 and $6x10^4$ it remains practically constant.

How this study is part of the development of a Doctoral Thesis, in this paper we present the first part of the study, which consisted in determining how the number of Strouhal varies on a Circular Arch profile of a thickness of 20%, which are used in many architectural works such as curved buildings, airport roofs and bus terminals.

II. Material And Testing

In order to carry out the tests, a circular arc profile model of 20% thickness was built and tested in an atmospheric boundary wind tunnel, with a wind profile for an urban type IV environment (according to CIRSOC 102, ASCE 7 standards), the tests were performed for Reynolds numbers between $6x10^4$ and 10^5.

The velocities were measured in the wake, at the coordinate point Y = 3.5.C (three point five times the profile chord), X = 0.4.C.Senα (four tenths of a times the profile chord through the angle of incidence) as outlined in Fig. 7.

For this test, Pitot tubes connected to piezoelectric sensors were used and data were recorded by means of a data logger. The frequency of data acquisition was 1000 Hz for 10 seconds. Then we proceeded to perform a spectral analysis with this information to obtain the vortex shedding frecuencies.

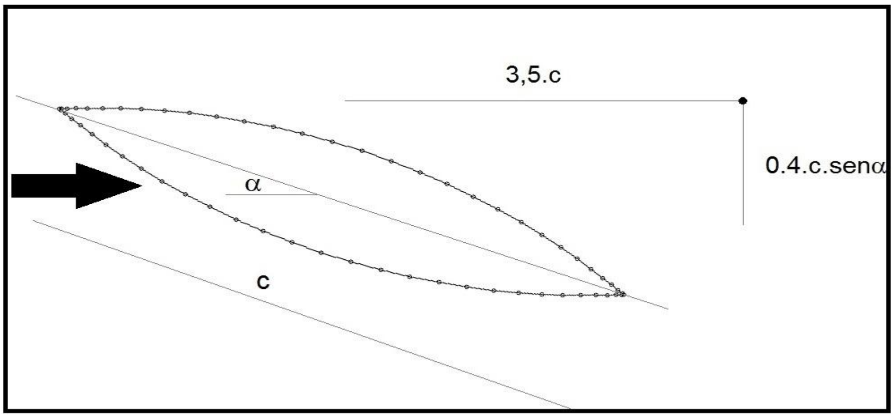

Figure 7. Dimensions of the profile and location of the measurement point of the vortex shedding.

III. Results And Conclusions

The main vortex shedding frecuency was analyzed. The following graphs shows the peaks of frecuencies in the power spectral density function for some angles of attack.

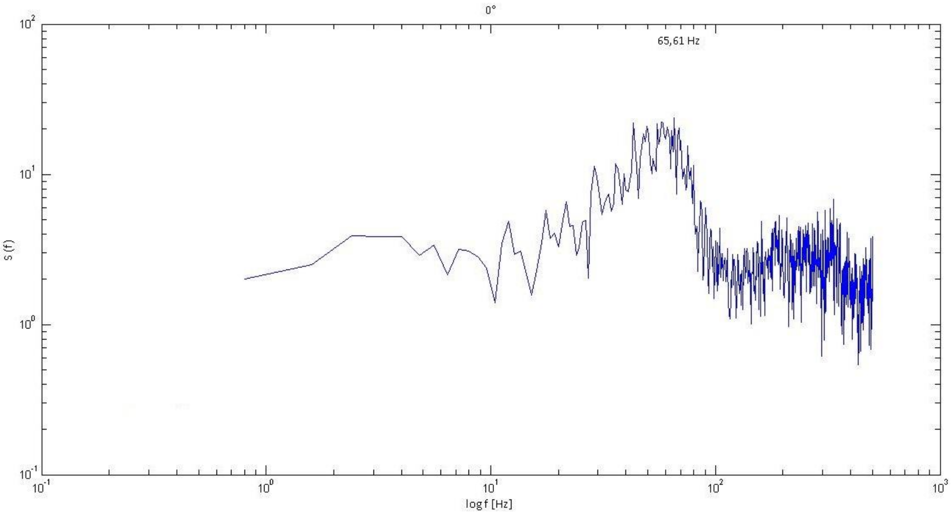

Figure 8. Power spectral density. Peak of 65.61 Hz at α = 0°.

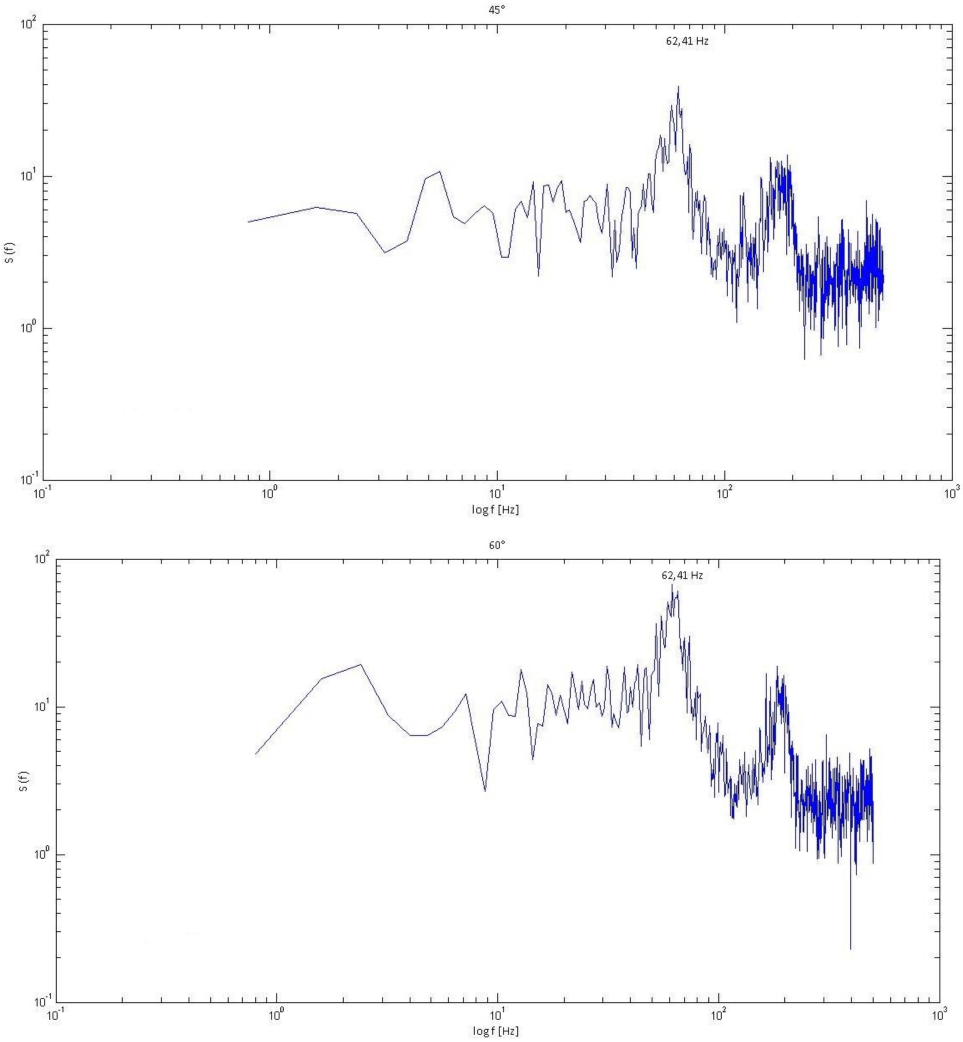

Figure 9. Power spectral density. The same peaks of 62.41 Hz at $\alpha = 45°$ and $\alpha = 60°$.

With them the Strouhal number was calculated according to the angle of attack. In Fig. 8 the results are presented.

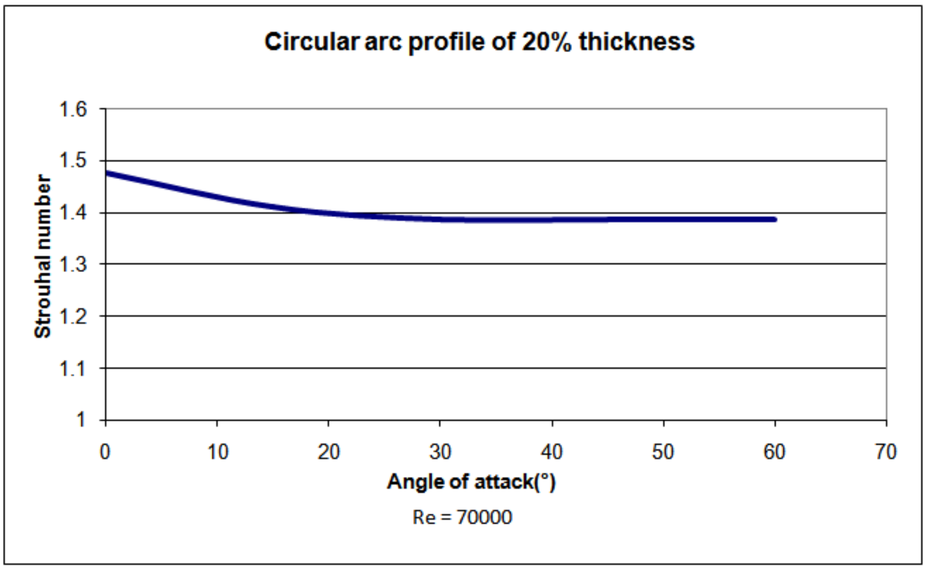

Figure 10. Variation of Strouhal number with the angle of attack in a circular arc profile of 20% thickness tested at $Re = 7x10^4$.

Comparing with Fig. 6, a similar behavior is observed, but instead of a growth in the first grades, there is a decrease. While in Fig. 6, for cylinders of rectangular base, there is a linear variation increasing in angles of attack between 0° and 12°, in Fig. 8, for the circular arc profile of 20% of thickness, a linear variation decreasing between 0° and 25°. It is observed that from 25° the Strouhal number remains constant around 1.39. On the other hand, coincidence with the references cited above for symmetrical aerodynamic profiles type NACA 00XX is observed, in that as the angle of attack increases, the value of the Strouhal number remains constant.

Taking the maximum value of Strouhal number of 1.39 obtained in the test, the frequency of vibration is calculated in a circular arc profile building of 50 m of rope, according to different values of wind speed, as can be seen in Table 1.

Table 1. Vibration frequency as a function of wind velocity

v (m/s)	f (Hz)
10	0.28
20	0.56
30	0.83
40	1.11

Acknowledgments

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