

A review of cases of vortex shedding excitation in bridges: Sectional models testing

J. Á. Jurado^a, R. Sánchez^b, S. Hernández^c, F. Nieto^d, I. Kusano^e

^{a,b,c,d,e} *School of Civil Engineering, University of La Coruña, Campus Elviña 15071
La Coruña, Spain*

ABSTRACT: Vortex shedding excitation frequently occurs in cable supported bridges. Even other types of bridges such as beam or arch bridges suffer this phenomenon during or after construction. It is well-known that a bluff body sheds alternating vortices with frequency n , which mainly depends on the Reynolds number and body geometry. Vortices induce transverse forces on the body with the same frequency. In many cases of flexible and slender structures with a small damping, these forces may produce unacceptable vibrations. This paper reviews several bridges where this phenomenon was important and explains the approaches used to study the instability and the solutions to improve the behavior of the structures. Then several sectional models of long span bridges have been tested in the wind tunnel of the School of Civil Engineering at the University of La Coruña for the vortex shedding excitation.

KEYWORDS: Vortex shedding, Bridges, Deck Sectional Models, Wind Tunnel

1 VORTEX SHEDDING FUNDAMENTALS

Vortex shedding is perhaps one of the most studied phenomena of fluid mechanics, especially its interaction with circular cylinders; see for example Goswami *et al.* [1]. When a vortex is formed on one side of a body, it immediately increases flow velocity on the opposite side, which results, according to Bernoulli theory, in a pressure reduction. Under certain conditions such as a case of a cylinder, the vorticity in the shear layers of the body becomes periodic forming alternating vortices downstream. The periodic vortex street causes a fluctuating force on the body. If it is flexible or supported flexibly, an interaction takes place between downstream flow and body displacements. These periodic vortices are called Von Karman Vortex Street, named after Von Karman who studies the phenomenon around 1910. The fundamentals of this phenomenon can be found in classical literature such as Simiu & Scanlan [2] and Dyrbye & Hansen [3].

Vortex shedding can not be explained without taking into account of air viscosity. Air particles in contact with the body surface adhere to it, which produces the boundary layer; however, due to its mass, air undergoes inertial effect according to Newton's law and Navier-Stokes equations. The relationship between inertial and viscous effects is defined by Reynolds number, $Re = \rho UL / \mu$ (ρ , air density, μ , air viscosity, L , main dimension, U , velocity). The separation point of the boundary layer is the key to explain the body behavior immersed in a flow. When there is a surface body with high curvature, such as circular cylinder, the separation point changes with regard to Re , which produces very

different effects. The structures in civil engineering generally use bluff body sections that have separation points always at sharp corners, and therefore vortex shedding does not vary with Re . Although some bridge decks consisted of aerodynamic boxes with curved edges have different behavior when Re changes. This is a problem for carrying out wind tunnel testing, and it obliges us to use large scale models.

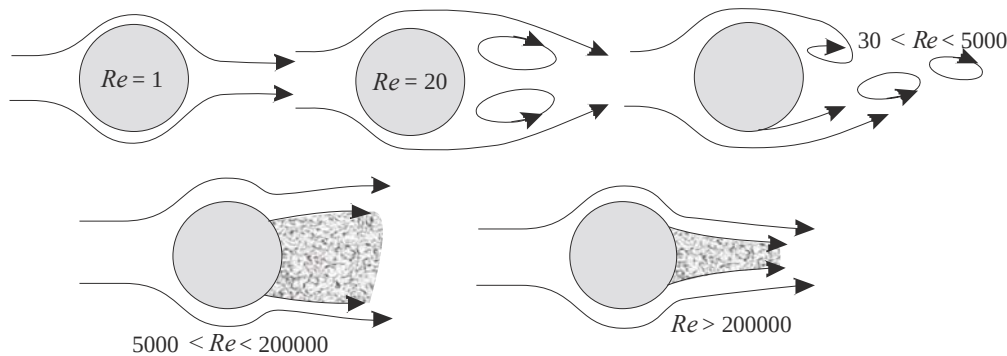


Figure 1. Reynolds dependency of the cylinder wake

Another determining parameter in order to study vortex shedding phenomenon is the Strouhal number $St = nD/U$ (n , vortex frequency). It is of a particular interest to establish a relationship between flow velocity and the frequency of the fluctuating forces on the body, which will permit the definition of a critical velocity at which vortex shedding frequency is close to a natural frequency of the structure. The Strouhal number is approximately constant. It has been evaluated for a great number of cross sections, and it takes values from 0.2 and 0.1 depending on the geometry. The value is greater if the section is rounded like a circular cylinder and lower if it is square like a flat plate. In the cases of flexible structures with a small damping, these forces can produce large vibrations. The greatest displacement occurs when the vortex frequency is close to the structural natural frequency. When this coupling takes place, the vortex shedding frequency does not change with the wind velocity in a significant range, which is called lock-in.

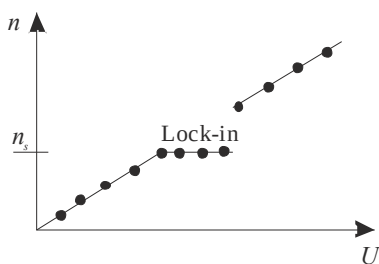


Figure 2. Lock-in effect when vortex frequency n is close to natural frequency of the body n_s .

Relating structural damping and mass with vibrations due to vortex shedding and air displaced, the Scrouton number can be established as $Sc = 2\delta m / (\rho L^2)$. (δ , logarithm decrement damping, m , vibrating structural mass). This parameter is used to determine whenever structures are prone to suffer vibrations due to vortex shedding. Whenever Sc is high, structural damping and mass prevail over displaced air, so the structure should not have problems of vibrations. As soon as Sc reduces, the displaced air may induce negative

damping that nullifies the structural damping and induces stationary vibrations with high amplitude.

Other factors such as the turbulent scale of wind or the number and the shape of near bodies play an important role on wake behavior and structural excitation by vortex shedding. Long-scale turbulence means that wind velocity varies with a slow fluctuation, not allowing the vibrations to grow. When bodies are placed in a way that one follows the other such as the case of twin box decks (see Figure 3), or set of cables, the possibilities of vortex shedding increase, which also depends on the separation between bodies. The bodies may behave as a single body if the separation is small, while they behave as different bodies if the separation is sufficiently large. There are intermediate cases depending on the turbulence.

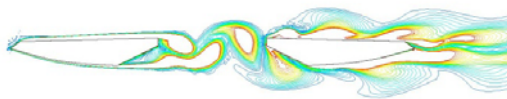


Figure 3. Vortex shedding of a twin box

2 VORTEX SHEDDING EXCITATION IN BRIDGES

Historically, many bridges have had vortex shedding vibration problems (Jurado et al. [4]). The first example was the clear vertical oscillations that the old Tacoma Narrows Bridge showed days before the collapse caused by flutter instability. Another veteran bridge like the Golden Gate Bridge suffered also this effect previously to its deck reinforcement. More modern bridge like Kessock Bridge, a cable stayed bridge in Scotland or Great Belt suspension bridge in Denmark showed this behavior. Not only cable supported bridges but also, continuous truss bridges like the one over Niterói River in Brasil showed this interaction with the wind. Moreover, the arch of Alconétar Bridge in Spain had big oscillations during the construction. A review of these cases helps us to explain the details of the phenomenon showing the best solutions to mitigate the vibrations.



Figure 4. From left to right: Kessock Brige, Great Belt Bridge, Niterói Bridge, Alconétar Bridge

Kessok Bridge has two planes of cable stayed and a 240 m of main span with an open cross section deck shown in figure 5. Since vibrations of large amplitude appeared during its construction, tuned mass dumpers (TMD) were installed. At the beginning of 90's monitoring measurements were registered and several events with large peak dynamic displacements were observed. For a wind velocity of about 21 m/s, the first mode of 0.51

Hz frequency were excited with large amplitude. Also in another occasion, the first torsional mode of 0.74 Hz frequency was excited. The Owen at al. [5] investigation concluded that TMDs did not succeed in limiting the response of the bridge to the desired level.

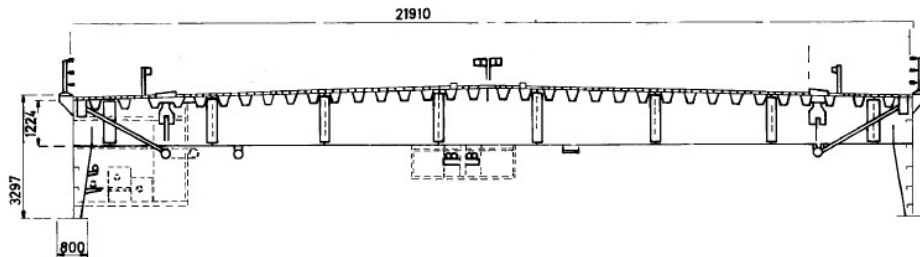


Figure 5. Open cross section of the Kessock Bridge

The Great Belt Suspension Bridge in Denmark also suffered vortex-shedding oscillations during last construction phases of the girder, before the application of the roadway surfacing. In January of 1998 a monitoring structural system of several accelerometers was installed (Larsen at al. [6]). At the same time the wind conditions at the bridge site were measured. The registered events of vortex shedding were for a mean velocity of $5 < U < 13$ m/s. The excited vertical modes were the third (0.13 Hz), the fifth (0.209 Hz), and the sixth (0.242 Hz). All the events had a reduce velocity $1 < U/nB < 1.5$. Its deck width measured $B = 31$ m. These results were in agreement with the 1/80 sectional model. The structural analysis indicated that the vibrations were insignificant for structural safety, although they could cause bad sensations for the users. Thus a system of guide vanes was designed for mitigating the oscillations (see Figure 6). The rms of the vertical displacements of a 1/60 sectional model with guide vanes resulted almost null.

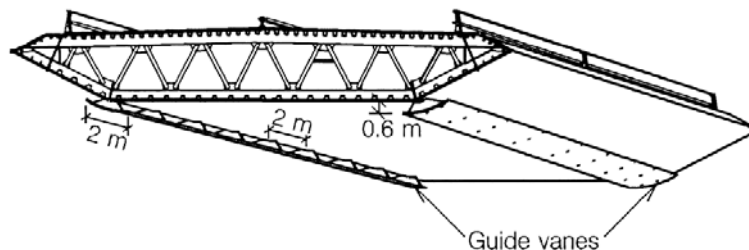


Figure 6. Bridge deck of Great Belt Bridge with guide vanes

The Rio Niterói Bridge has three continuous spans (200/300/200 m) of steel twin-box-girder. Since its opening to traffic in 1973, this non-cable-supported bridge also suffered several vortex shedding oscillation events for mean wind velocities close to 60 km/h. The figure 7 shows the bluff body cross section of the bridge deck which causes lock-in instability with big amplitudes. Considering that the natural frequency of the first excited bending mode is 0.32Hz, the Strouhal number results in around 0.14. An interested study for reducing the oscillation by active and passive control devices using TMDs was conducted by Battista & Pfeil [7]. They used structural optimization to design the TMD properties, achieving to avoid the coupling between the vortices and the structural motions.

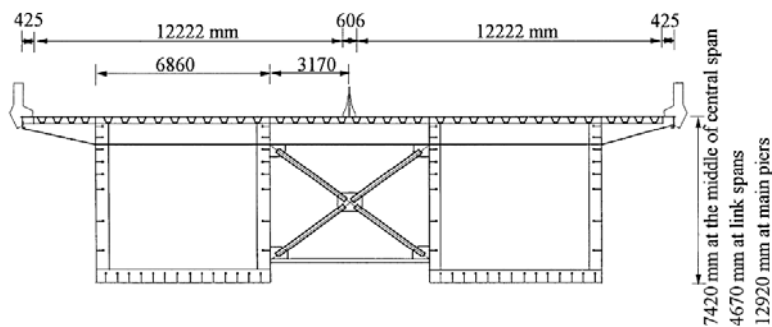


Figure 7. Steel twin-box-girder of Rio Niterói Bridge

The vortex shedding excitation also took place during the construction of the Alconétar Arch. As can be observed in figure 8, the bridge has two arches supporting two superior decks with 220 m of span length. The oscillations occurred when the first arch was closed, before the columns and deck were built. The mean wind velocity was estimated around 30 Km/h and the excited vibration mode was non-symmetrical with a frequency of 0.70 Hz. A 1/20 fixed sectional model, and 1/15 elastic model were tested in an aerodynamic wind tunnel; see Barrero et al. [8]. These experiments showed that the Strouhal number for the twin box section was 0.15. The solution to avoid the vibrations was to install guide vanes, which are small plates welded to the steel boxes. This type of aerodynamic appendages resulted easy to build and it reduced the oscillation amplitudes to an acceptable level. The complete arch bridge has no problems of wind structure interaction because its stiffness and damping of the complete structure is much greater than the isolate arches.



Figure 8. Arches of Alconétar Bridge.

The observation of these examples shows that non-aerodynamic sections of the Kessock Bridge, Niterói Bridge and Alconétar Arch, with twin boxes sections in the Niterói and Alconétar cases have tendency to vortex shedding excitation. Also the more aerodynamic

deck of the Great Belt Bridge generates the effect, but not a dangerous amplitude for the structure. TMDs installation is a suitable solution for bridges with bluff body sections in spite of maintenance problems; however, it is generally recommendable to use aerodynamic appendages. It is the case of the guide vanes of the Great Belt Bridge, or the welded plates of Alconétar arch section.

3 WIND TUNNEL TESTING

There are several ways to determine the wind speed for vortex shedding excitation and to evaluate if the oscillation amplitude is dangerous for the structure. Numerical methods based on CFD analysis have nowadays great expectation and give rapid results, but wind tunnel testing has been the most reliable way of studying the phenomenon. There are researches using complete models, taut-strip models and sectional models. Full models have to maintain the Froud number $Fr = U^2/Dg$ (g is the gravity), resulting that the velocity scale is the root of scale length; thus the velocity is very low in the wind tunnel. This generates low Reynolds numbers and inaccurate results for vortex shedding simulation. Taut-strip models are complicated compared to sectional models that are the most common way of studying vortex excitation. Larsen et al. [5] shows results for the Great Belt Bridge vortex shedding using three types of testing.

The sectional model validity is based on the dynamic similarity. The results in the wind tunnel can be apply to the real bridge if there is a geometric similarity and Reynolds number related to the air flow around the real obstacle is the same. The differential equation of the body displacement oscillating laterally respect to the air flow can be written:

$$m \left(\frac{d^2 y}{dt^2} + 2\pi n \xi \frac{dy}{dt} + (2\pi n)^2 y \right) = F \left(\rho, \mu, U, D, n, y, \frac{dy}{dt}, \frac{d^2 y}{dt^2} \right) \quad (1)$$

Where m is the mass per unit length, y is the lateral displacement, t the time, n the structural frequency, ξ the damping ratio, F the force per unit length which depends on the fluid properties. Using dimensionless parameters, it can be written:

$$\frac{d^2 \eta}{d\tau^2} + 2\pi \xi \frac{d\eta}{d\tau} + (2\pi)^2 \eta = \frac{\frac{1}{2} \rho U^2}{m n^2} F \left(Re, \frac{nD}{U}, \eta, \frac{d\eta}{d\tau}, \frac{d^2 \eta}{d\tau^2} \right) \quad (2)$$

The Reynolds number dependency is small if the body has sharp corners, so the problem depends of the reduce frequency nD/U and of the parameter $\rho U^2/(mn^2)$. As ρ is the same value in model and real prototype, the velocity, mass and frequency scales must verify $(\lambda_U)^2 = \lambda_m (\lambda_n)^2$ and keep nD/U , $\lambda_U = \lambda_n \lambda_L$. Both relations set up that mass scale must be the square of length scale $\lambda_m = (\lambda_L)^2$. For example, these similarity requirements were considered in the sectional model of the Alconétar Bridge arch [7] (see figure 9). When the length scale was fixed as $\lambda_L = 1/15$ because of the wind tunnel dimensions, the mass scale was defined as $\lambda_m = 1/225$. Then the stiffness of the suspension system determines that $\lambda_n = 3.31$ and the velocity scale was calculated by $\lambda_U = \lambda_n \lambda_L = 1/4.5$.



Figure 9. Sectional model of the arch with guide vanes

An interesting research about vortex shedding excitation for the twin box deck of the Stonecutters Bridge (Figure 10) in Hong Kong was done by Larose et al. [9]. In the study, a greater than usual sectional model scale of 1/20 was tested. The aim was to achieve a greater Reynolds number to compare the results with that of smaller scale. The results showed considerable differences with respect to a previous study using a 1/80 sectional model, mainly when the model is tested with aerodynamic appendages. If the wind velocity is the same, and the scale model is greater, the required frequency of the model at vortex shedding excitation decreases because the reduced frequency, nB/U should be constant during the phenomenon. The model weight was 215 Kg with the aspect ratio of 5:1, and the suspension system could vary the vertical frequency between 7 and 10 Hz. The damping was 1% log. dec. The tests were carried out in a smooth flow at 0° attack angle in a 9m x 9m wind tunnel of the National Research Council of Canada. The results showed clear vortex shedding peak at 0.35 of reduce velocity. The Strouhal number measured in the wake had two peaks for 0.20 and 0.14. The sectional model also was tested with guide vanes and it was checked that these aerodynamic appendages successfully mitigated the excitation.

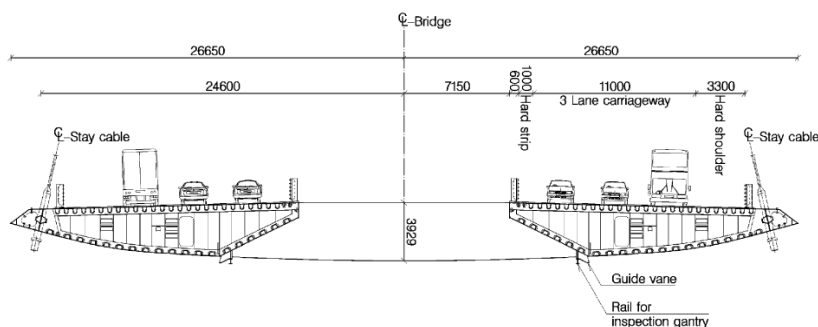


Figure 10. Stonecutters Bridge deck cross section.

4 SECTIONAL MODELS TESTED AT THE UNIVERSITY OF LA CORUÑA

Several experiments of vortex shedding on sectional models have been carried out in the wind tunnel of the School of Civil Engineering at the University of La Coruña. For determining the Strouhal number, it is useful to test the sectional model supported by a very

stiff system built by bars connected to load cells. A Fourier transform of the alternating forces measured by load cells permits to identify the force peak for vortex shedding and the greatest peak force at the natural frequency of the model. As figure 11 shows, both peaks values increase with the wind velocity. At lock-in both peaks overlap and the highest amplitude force appears.

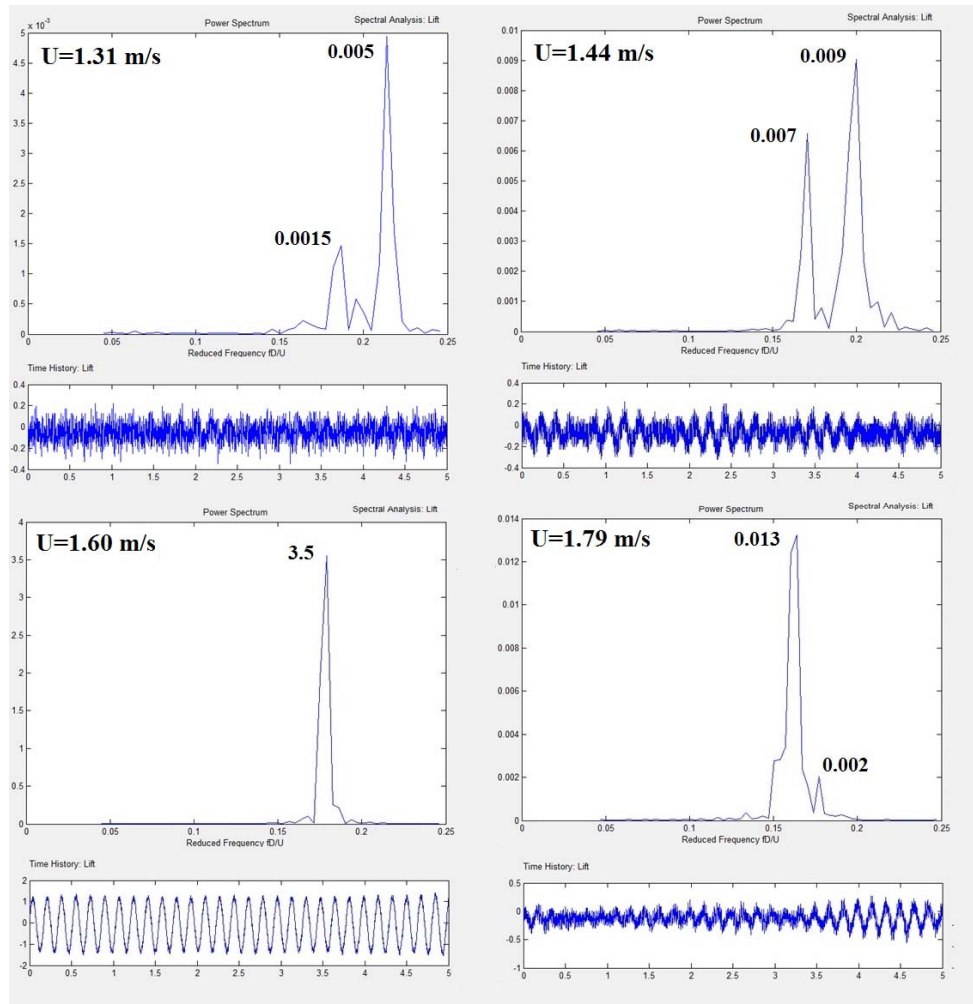
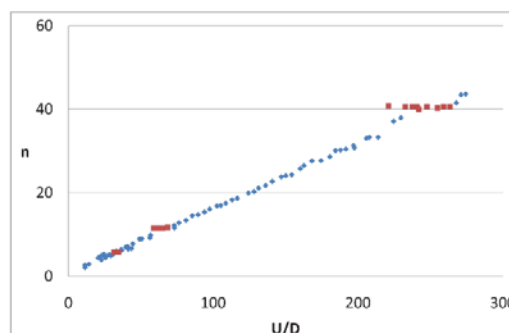
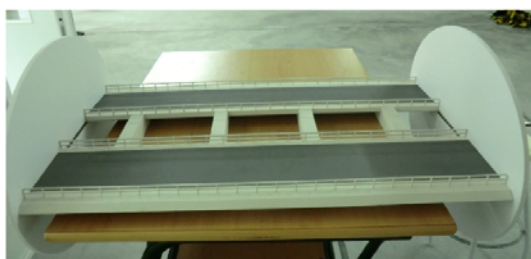


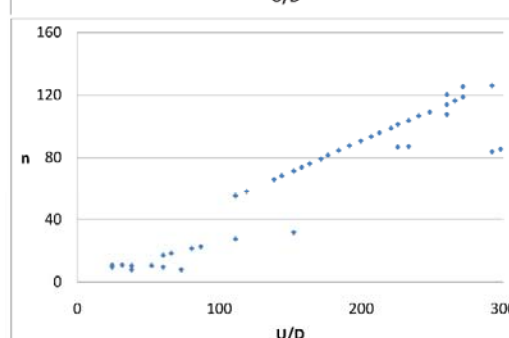
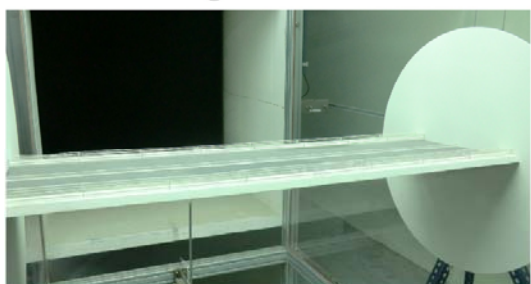
Figure 11. Vertical force Fourier transform on a sectional model with rigid support.

A graph that represents the vortex shedding frequency peaks as function of the value U/D permits the calculation of the Strouhal number value, which is the slope of the line. The figure 12 shows three sectional models: the twin-box deck of the Stonecutters Bridge ($\lambda_L = 1/80$), the single-box of the Miradoiros Project Bridge in La Coruña (Spain) ($\lambda_L = 1/100$) (Jurado et al. [10]), and the stress ribbon footbridge of Cuenca in Spain ($\lambda_L = 1/10$) (Jurado et al. [11]). For the case of the twin-box sectional model, the table 1 indicates a good agreement for the lift peaks at lock-in with regards to the results of Larose et al. [8]

Stonecutters Bridge



Miradoiros Bridge



Cuenca Footbridge

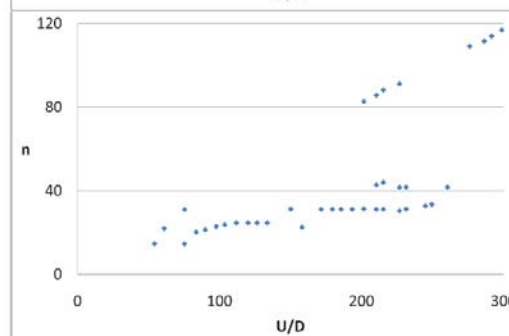


Figure 12. Frequency n of vortex shedding with regard to U/D for three sectional models.

Table 1. Strouhal number for the twin-box deck.

	U	n	D	St	$(St \text{ Larose et al. [8]})$
	(m/s)	(Hz)	(m)		
First Lock-in	1.604	5.859	0.049	0.179	0.20
Second Lock-in	3.586	11.597	0.049	0.158	0.14

5 CONCLUSIONS

Vortex shedding fundamentals have been explained to understand several cases of bridges that suffered this effect.

The observation of these examples shows that non-aerodynamic sections, mainly with twin boxes have tendency for vortex shedding excitation. Also more aerodynamic sections could generate the phenomenon, as in the case of the Great Belt Bridge deck.

TMDs installation is a suitable solution for bridges, but it creates maintenance problems. It is generally recommendable to use aerodynamic appendages as guide vanes.

Testing sectional models is the most common way of studying vortex excitation. Several cases have been explained.

The Fourier transform of the lift force on a stiff sectional model is useful to determine the frequency of vortex shedding and the lock-in effect. The procedure has been used with several sectional models in the wind tunnel of the School of Civil Engineering at the University of La Coruña.

6 ACKNOWLEDGMENTS

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