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AN INNOVATIVE AEROELASTIC MODEL OF THE THIRD BOSPORUS BRIDGE TO STUDY VORTEX INDUCED VIBRATIONS

G. Diana[1], T. Argentini[1], M. Belloli[1], S. Muggiasca[1], L. Rosa[1]

ABSTRACT

This paper presents the results of the investigation on vortex-induced vibrations using a 1:50 sectional aeroelastic model of the Third Bosporus Bridge deck. These tests are included in the complete project of the Third Bosporus Bridge (BB3) developed by M. Virlogeux and T-Engineering International SA and they are part of a wide experimental campaign performed in the Politecnico di Milano wind tunnel, to investigate the aerodynamic behavior of the bridge. In particular this model has been design to study vortex shedding phenomena in multi-modal excitation conditions. It is actually able to reproduce correctly the response behavior of the first modes of the bridge, as usually does an aeroelastic model but with a large geometrical scale as usually does a sectional rigid model. The large model scale allows to reproduce the shape of the deck, barriers, and geometric details with accuracy, on the other hand the use of an aeroelastic deformable model allows to study the vortex induced response for different modes of vibration. The large model scale allowed also to use high wind velocities avoiding the typical problems found in the wind tunnel tests at low wind speeds. Many different configurations were studied to evaluate the sensitivity of the deck to the fittings. No vortex induced vibrations were observed in the tested operating conditions. In order to evaluate the potentialities of this innovative set up a test case was defined considering the deck in the presence of a train on it: the naked configuration with train showed very high oscillation amplitudes.

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[1] Dept. of Mechanichal Engineering, Politecnico di Milano, Via La Masa 1, 20156, Milano, Italy

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This paper presents the results of the investigation on vortex-induced vibrations using a 1:50 sectional aeroelastic model of the Third Bosporus Bridge deck. These tests are included in the complete project of the Third Bosporus Bridge (BB3) developed by M. Virlogeux and T-Engineering International SA and they are part of a wide experimental campaign performed in the Politecnico di Milano wind tunnel, to investigate the aerodynamic behavior of the bridge. In particular this model has been design to study vortex shedding phenomena in multi-modal excitation conditions. It is actually able to reproduce correctly the response behavior of the first modes of the bridge, as usually does an aeroelastic model but with a large geometrical scale as usually does a sectional rigid model. The large model scale allows to reproduce the shape of the deck, barriers, and geometric details with accuracy, on the other hand the use of an aeroelastic deformable model allows to study the vortex induced response for different modes of vibration. The large model scale allowed also to use high wind velocities avoiding the typical problems found in the wind tunnel tests at low wind speeds. Many different configurations were studied to evaluate the sensitivity of the deck to the fittings. No vortex induced vibrations were observed in the tested operating conditions. In order to evaluate the potentialities of this innovative set up a test case was defined considering the deck in the presence of a train on it: the naked configuration with train showed very high oscillation amplitudes.

Introduction

Nowadays longer and longer spans have been realized for suspension and cable stayed bridges designing slender and flexible structures. On the other hand this kind of structures showed an higher sensitivity to the wind excitation. In particular vibrations induced by vortex shedding phenomena can become relevant at moderate wind velocities as observed in different kind of flexible structure ([1],[2],[3],[4]). In order to avoid higher level of vibration, the aerodynamic design of a bridge deck has to be taken in strong consideration. Indeed, a correct definition of the deck shape is surely preferable than adding devices to control the phenomenon. In [5], the effect of guide vanes to mitigate vortex shedding is showed: this solution permits to solve the problem in an already built bridge but it requires more money and maintenance than to correctly projected in advance the deck from an aerodynamic point of view. An example of a correct shaping on a trapezoidal box girder bridge deck is shown in [6]. The interest in studying the phenomenon is finalized to control or eliminate the vibrations induced by vortex shedding: avoiding significant level of vibration it is important not only for the structure safety but also for the comfort and the safety sensation of the drivers on the bridge. In these studies a key role is played by the wind tunnel tests, that are finally become a standard tool in bridge design ([7],[8],[9],[10]).

Vortex shedding phenomenon is usually studied in wind tunnel using sectional rigid suspended models. For these models all the sections are characterized by the same aerodynamic behavior that is the one observed in correspondence of the antinode of flexible structures. As observed studying flexible cylinders [11], the tests performed on sectional

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[1] Dept. of Mechanichal Engineering, Politecnico di Milano, Via La Masa 1, 20156, Milano, Italy

models can be restrictive because they do not consider neither the effects related to the modal shape nor the effects due to the multimodal excitation, as an aeroelastic model could do. On the other hand, aeroelastic models are generally realized in small geometrical scales with low level of accuracy in reproducing the geometric details.

The present paper describes a new aeroelastic model able to sum up the advantages of an aeroelastic model and the ones of a rigid sectional model. It has been realized in a large scale in order reproduce the shape of the deck, barriers, and geometric details with accuracy and, at the same time, its flexibility allowed to study the vortex induced response for different modes of vibration. The large model scale allowed also to use high wind velocities avoiding the typical problems found in the wind tunnel tests at low wind speeds. Moreover this particular set up may be very little damped, whereas with traditional full aeroelastic models it is difficult to obtain very low level of structural damping i.e. Scruton Number.

The experimental tests on the model were performed in the Politecnico di Milano Wind Tunnel Boundary Layer test section. The new set up was used to reproduce the Third Bosporus Bridge (BB3) that is a trapezoidal box girder bridge deck with external road lanes and central rail lanes scaled 1:50 (see Figure 3). The dynamic response of the model, for different operating configurations, was studied considering also the effect of the presence of a train. In particular the configurations with train have been used as test case to investigate the potentiality of the new set up.

Experimental set-up

The experimental campaign was performed in the Boundary Layer test section of the Politecnico di Milano Wind Tunnel. The aeroelastic model was realized as an equivalent “spine” model of the deck section: a non-structural exterior skin reproduces the external correct geometry of the deck while the stiffness characteristics are obtained using an internal steel tube with a circular section. The internal spine is fixed to each module as shown in Figure 1 taking care to separate the modules with a gap of 1 mm: a single module is 0.4 m long and is made by carbon fiber in order to be as stiff and light as possible.

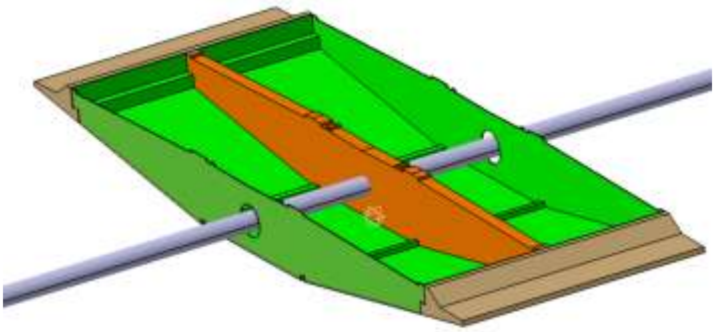

Figure 1. Sketch of one module without the top skin.

The complete model was composed by 20 modules for a total length of 8 m, giving an aspect ratio equal to 6.9. The different tested configurations had required the use of windshields and guardrails, made in carbon fiber and glued on the modules.

Figure 2 shows the complete model placed in the wind tunnel test section. The spine of the sectional model was fixed, in correspondence of its ends, at two rigid frames, 1.5 m far from the ground (see Figure 3). The model was placed on the turntable, allowing the change of the exposition angle β very easily without change any set-up, see Figure 2 (right). Figure 4 shows the complete model in the wind tunnel.

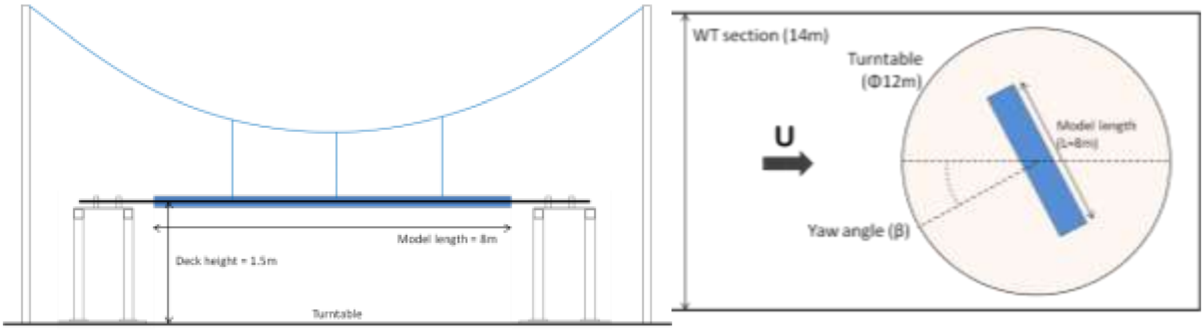

Figure 2. (left) Test set-up. Cross wind configuration, β=0°; (right) Test set-up. Top view

Figure 3 Detail of the model in the wind tunnel, attack angle α=-3deg

In order to sustain the model, two catenaries with three hangers each were used. This system was designed avoiding to change frequency and damping of the torsional modes.

Figure 4 The complete model in the wind tunnel test section

The deck was studied in three different operating configurations:

- NAKED (Figure 5 (a)),
- 2WS i.e. two wind screens (Figure 5 (b))
- 2WS + WING i.e. two wind screens and wings on the top (Figure 5 (c)).

Figure 5 Operating configurations: (a) NAKED, (b) 2WS, (c) 2WS + WING

The bridge in the naked configuration is not provided with wind screens, but just with guard-rails. The guard-rails are present in all the configurations. In the configuration "2WS" the wind screens for the road lanes are installed on the bridge. In the configuration named "2WS+WING", the wind screens for the road are installed together with the wings.

The same operating conditions were considered with a train model placed in the rail lane (see Figure 6): this group of configurations was considered as a test case to investigate the potentiality of the set up in vortex shedding analysis.

Figure 6 2WS+WING configuration with train

The model was instrumented through accelerometers placed along the deck to define its dynamic response (Figure 7): the number and the positions of the accelerometers were chosen in order to correctly reproduce the first modes of the bridge.

Figure 7 Sketch of the accelerometers arrangement on the deck

Model characteristics

The aeroelastic model was designed to simulate the first three torsional modes of the structure. In particular the model was tuned in order to obtained those frequencies in a range easily excitable by the wind velocities simulated in the wind tunnel (up to 15 m/s).

Table 1 shows the modal frequencies and nondimensional damping factors obtained.

It is possible to note that the frequencies are quite high for an aeroelastic model so not so low wind velocities could excite it: this is important in order to be sure that the energy imparted by the wind could be considered enough high as in the real conditions. On the other hand the damping factors are enough low to lead to Scruton Number lower or comparable with the full scale. The Scruton Number is calculated for the flexural modes as:

$$Sc = \frac{2\pi m_L \xi_{str}}{\rho B^2} \tag{1}$$

and for the torsional modes as:

$$Sc = \frac{2\pi J \xi_{str}}{\rho B^4} \tag{2}$$

where m_L is the linear mass of the section (m_L=14.2 kg/m), J is the linear moment of inertia (J=1.6 kgm), ρ is the air density and B is the deck chord (B=1.16 m). The Scruton number obtained is lower than 0.16 for the flexural modes and lower than 0.014 for the torsional modes. These values are comparable with the ones expected for the real bridge. That means that the dynamic response can be considered representative of the expected dynamic response for the real bridge.

Mode	f (Hz) [min-max]	Deformation	ξstr (-) [min-max]
1	1.3	1st flexural	0.35-0.40%
2	3.1	2nd flexural	0.24-0.25%
3	3.9	1st torsional	0.14-0.15%
4	6.0	3rd flexural	0.16-0.17%
5	7.8	2nd torsional	0.12-0.30%
6	9.8	4th flexural	-
7	11.4	3rd torsional	0.15-0.30%

Table 1. Model characterization: frequencies and nondimensional damping

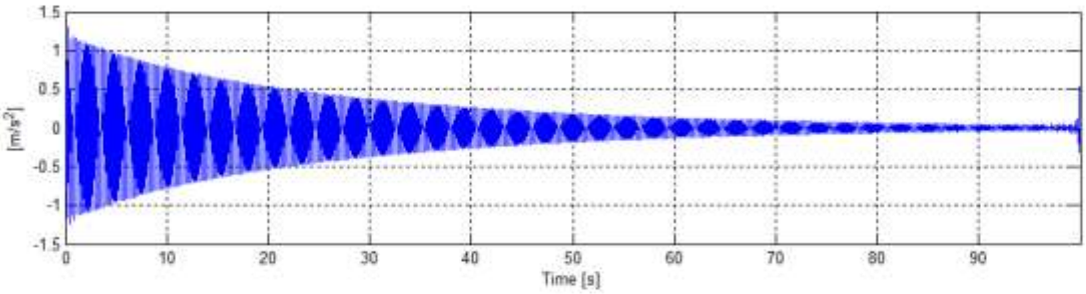

Figure 8 Decay test: First torsional mode at quarter span

The nondimensional damping was defined through decay tests in still air. In Figure 8 is shown, as an example, the time history measured at a quarter span for a decay tests relative to the first torsional mode. The corresponding nondimensional damping as a function of the displacement of the leading edge is reported in Figure 9.

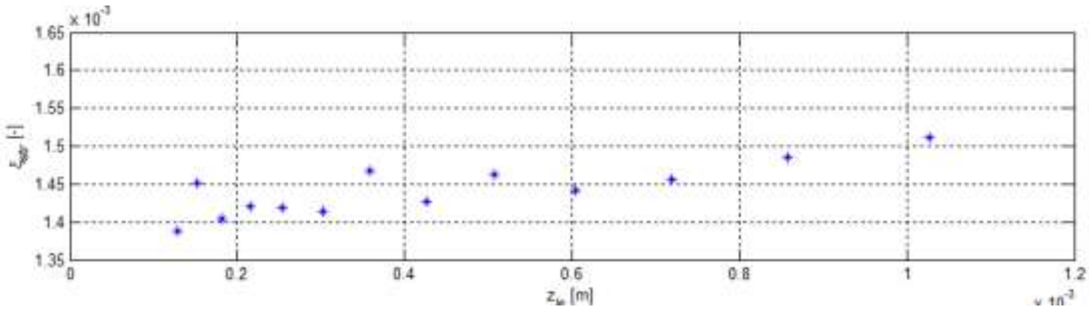

Figure 9 Decay test: Nondimensional damping for the first torsional mode

Experimental results

In order to study vortex shedding phenomenon, the dynamic response of the model was studied as a function of the wind velocity: the velocity was changed in order to excite the first flexural and torsional modes of the model. The response has been analyzed considering the half-sum or the half-difference between the two accelerometers placed in each section upwind and downwind. The half-sum permits to put on evidence the contribution due to bending modes, on the contrary, the half-difference permits to put on evidence the contribution due to torsional modes. In particular the half-difference has been referred at the leading edge of the deck. In the following figures the half-sum will be called *z acceleration* (z) and the half difference *θ equivalent acceleration* (θ_{eq}).

Operating conditions tests

The model was tested in the expected operating conditions i.e. naked and with two different wind screens. The deck was investigated also changing the angle of attack α and the yaw angle β.

In all these configurations no relevant oscillations were observed. In Figure 10 and in Figure 11 there are reported the standard deviations of the θ_{eq} and of the z acceleration respectively, in correspondence of the ¾ span, as a function of the wind velocity. Some configurations are shown: naked deck, 2 wind screens deck for three different angles of attack (-3 deg, 0 deg, +3 deg), 2 wind screens and wings. Figure 11 highlights that no flexural excitation can be observed: the standard deviation slightly grows with the wind velocity with a parabolic law. In Figure 10 a small peak can be noticed at about U=2.4 m/s especially for the configuration 2WS (2 wind screens) at 0 deg and -3 deg as angle of attack. A very narrow lock-in region is defined around the peak and it corresponds to an excitation of the second torsional mode. The reduced velocity correspondent to the peak is equal to $U^* = U/fB = 0.27$.

In Figure 12 it is shown the spectrum of the θ_{eq} acceleration for the configuration 2W at 0 deg and -3 deg: it is possible to note that a clear peak in correspondence of the second torsional frequency is present (7.9 Hz). Anyway the absolute value of the peak is very small and negligible for the design of the deck

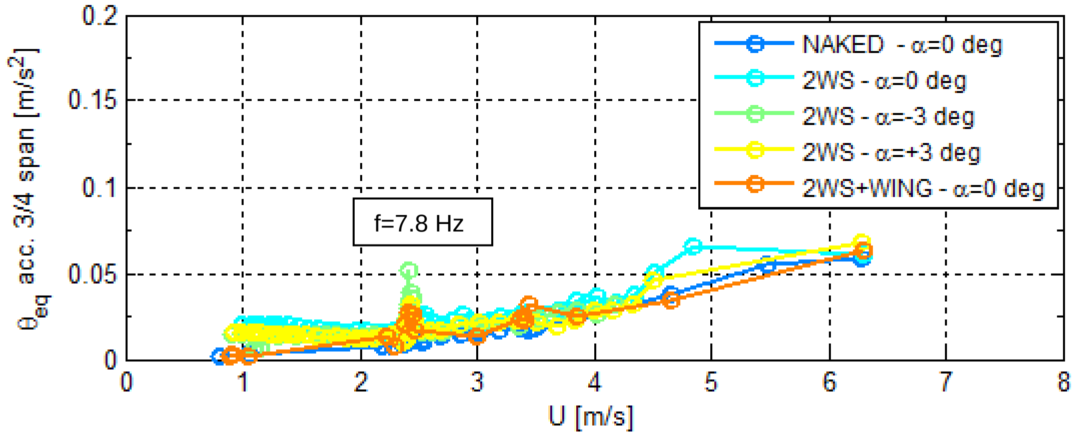

Figure 10 Standard deviation of the half-difference acceleration at ¾ span (θ_{eq}) as a function of the wind velocity for different operating conditions

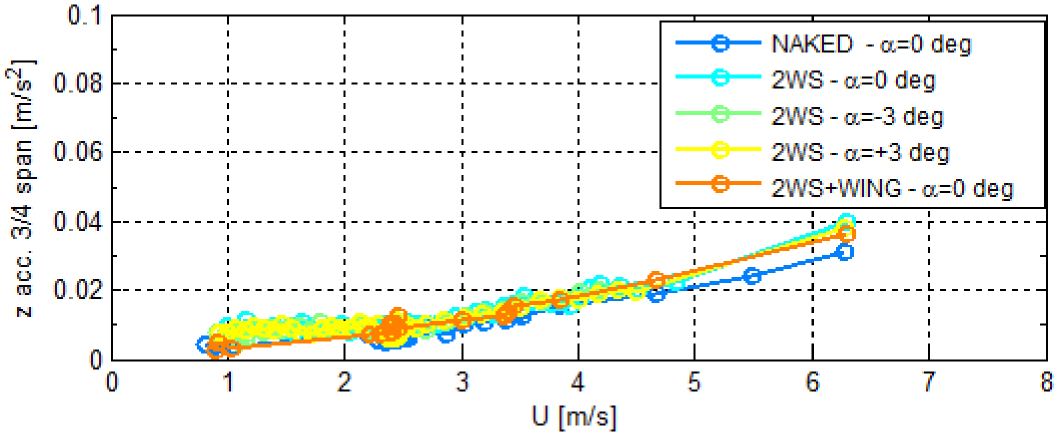

Figure 11 Standard deviation of the half-sum acceleration at ¾ span (z) as a function of the wind velocity for different operating conditions

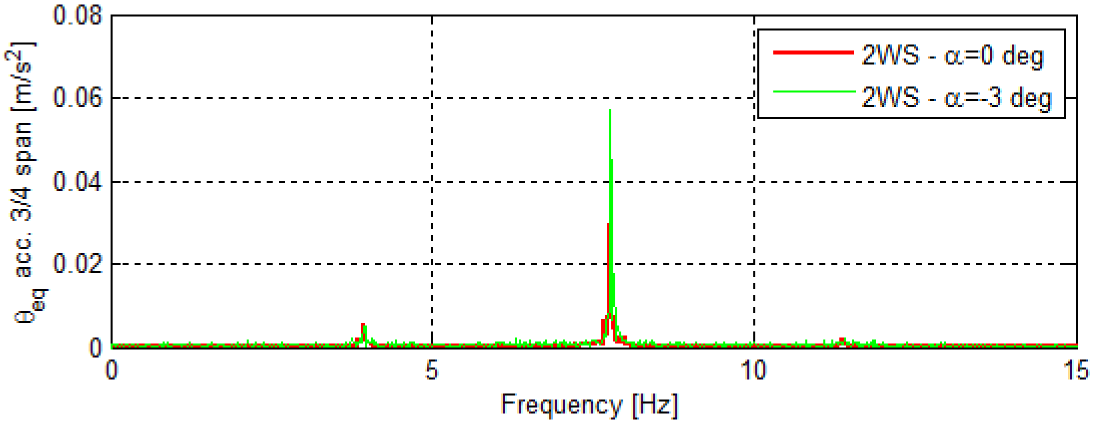

Figure 12 Spectrum of the half-difference acceleration at ¾ span (θ_{eq}) for U=2.44 m/s

Test case (deck with train)

The model was tested in the previous defined configurations also in presence of a train in the rail lane. The configurations with wind screens seem not to show significant differences due to the presence of the train, on the contrary the naked configuration has a completely different aerodynamic behavior. As it is possible to see in Figure 13 and in Figure 14 more than one mode has been excited reaching significant level of acceleration. In the wind velocity range investigated the first torsional mode (Figure 13) has been excited at about U=3.9 m/s (U^*=0.86), while the first three flexural modes have been excited at about U=1.1 m/s, U=2.6 m/s and U=5.3 m/s respectively, at a reduced velocity equal to U^*=0.7 for all the modes. The lock-in regions for each mode are quite wide and the spectra of the accelerometers highlight well defined peaks with significant magnitude (see Figure 15 and Figure 16). In this condition the phenomenon is completely controlled by the train, in fact the reduced velocity at which the excitation occurs is different to the one observed without the train. The wind screens, with or without wings, suppress the vortex shedding changing the characteristics of the flow around the train: in particular the turbulence intensity increases from 2% to 10 %.

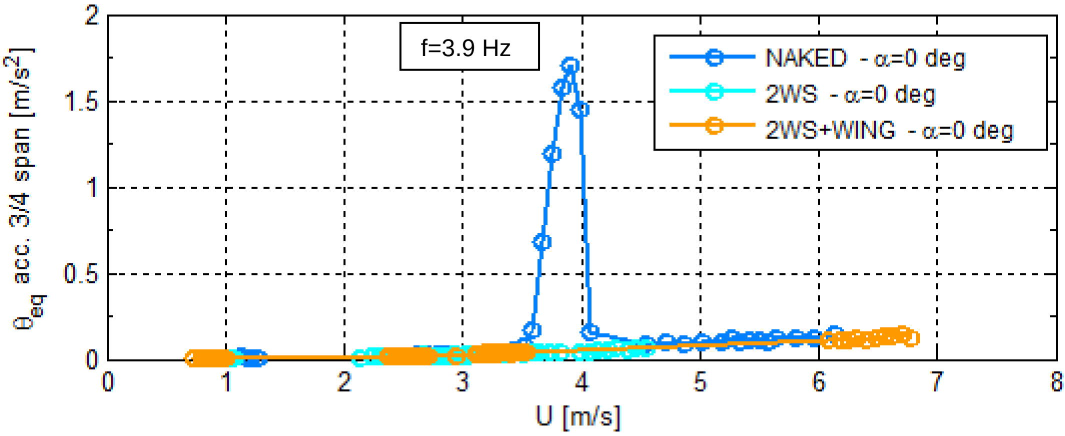

Figure 13 Standard deviation of the half-difference acceleration at ¾ span (θ_{eq}) as a function of the wind velocity for different operating conditions in presence of the train

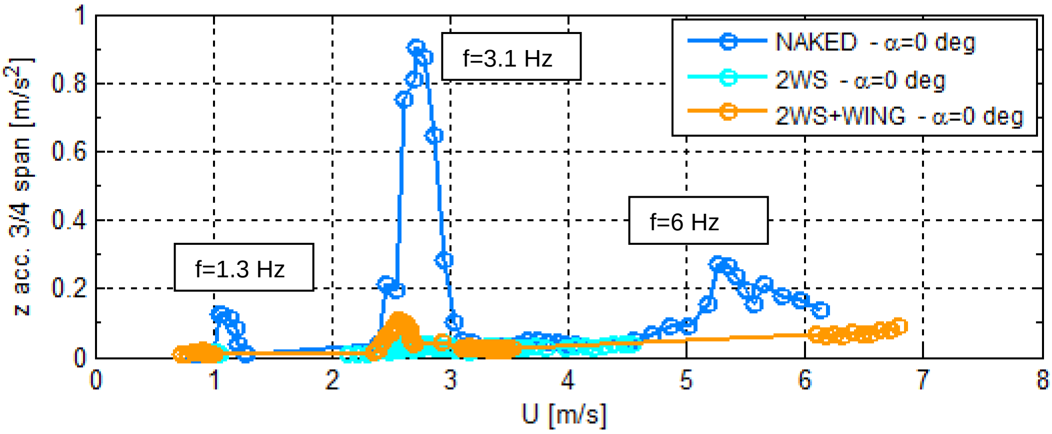

Figure 14 Standard deviation of the half-sum acceleration at ¾ span (z) as a function of the wind velocity for different operating conditions in presence of the train

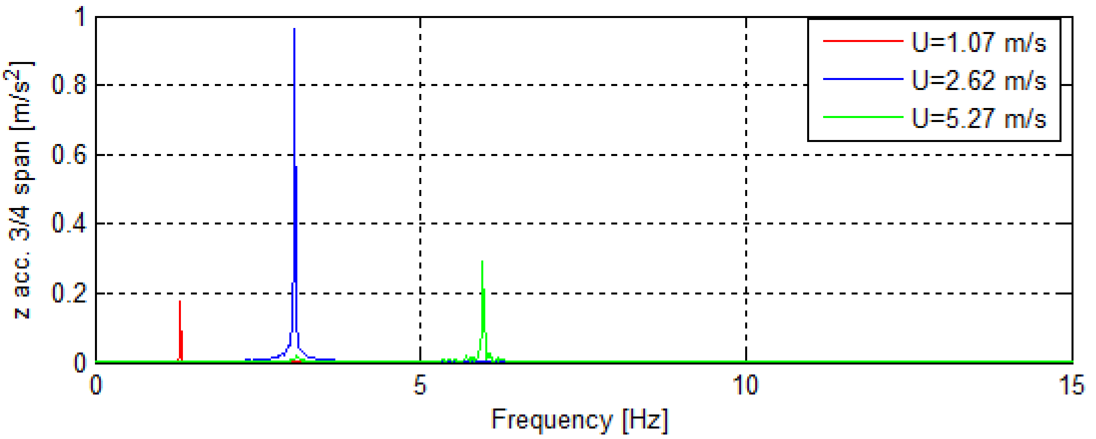

Figure 15 Spectra of the half-sum acceleration at ¾ span (z) for three wind velocities, naked configuration with train

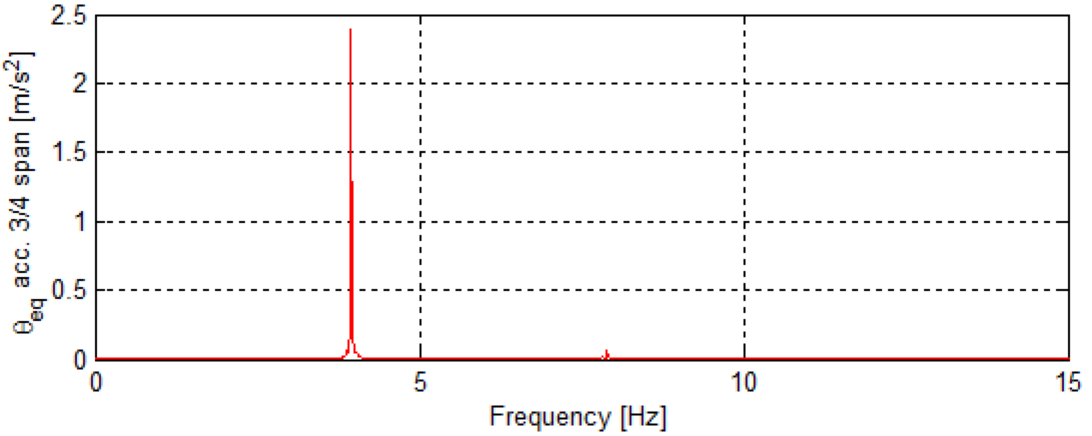

Figure 16 Spectra of the half-difference acceleration at ¾ span (θ_{eq}) at U=3.91 m/s, naked configuration with train

Conclusions

The original set up presented in the paper shows good potentialities in studying vortex induced vibration on deck bridges. It permits to reproduce more than one mode of the bridge, taking into account the deformable shape of each mode as a classical aeroelastic model, and it permits also to reproduce geometrical details with accuracy and to reach very low nondimensional damping i.e. Scruton number as a rigid sectional suspended model. Moreover, its frequencies can be tuned in order to be excited by not too low wind velocities.
The studied deck (Third Bosporus Bridge) does not show significant vortex shedding problems: the phenomenon can be observed but induced accelerations are negligible. Only the naked deck with the train shows high oscillation amplitude but the presence of the wind screens can eliminate the phenomenon: this configuration has been used to investigate the set-up capability in reproducing and measuring vortex shedding.

References

1. Belloli M., Fossati F., Giappino S., Muggiasca S., Villani M. On the aerodynamic and aeroelastic response of a bridge tower. *Journal of Wind Engineering and Industrial Aerodynamics* 2011, **99**, 729–733

2. Belloli M., Giappino S., Muggiasca S., Zasso A. Force and wake analysis on a single circular cylinder subjected to vortex induced vibrations at high mass ratio and high Reynolds number. *Journal of Wind Engineering and Industrial Aerodynamics* 2012, **103**, 96–106

3. Fossati F., Muggiasca S., Giappino S., Squicciarini G., Ozkan E., Belloli M. Wind Induced Vibrations On Bridge Towers: Vortex Shedding Investigation Using Sectional Models, *Proceedings of the 9th UK Conference on Wind Engineering WES - Bristol UK*, September 20–22 2010

4. Zasso A., Belloli M., Giappino S., Muggiasca S. Pressure field analysis on oscillating circular cylinder. *Journal of Fluids and Structures* 2008, **24**, 628–650

5. Larsen A., Esdahl S., Andersen J. E., Vejrum T. Storebælt suspension bridge - vortex shedding excitation and mitigation by guide vanes. *Journal of Wind Engineering and Industrial Aerodynamics* 2000, **88**, 283–296

6. Larsen A., Wall A. Shaping of bridge box girders to avoid vortex shedding response. *Journal of Wind Engineering and Industrial Aerodynamics* 2012, **104–106**, 159–165

7. Belloli M., Fossati F., Giappino S., Muggiasca S. Vortex induce vibrations of a bridge deck: dynamic response and surface pressure distribution, *12th Americas Conference on Wind Engineering* – Seattle USA, June 16-20, 2013

8. Diana G., Resta F., Belloli M., Rocchi D., On the vortex shedding forcing on suspension bridge deck. *Journal of Wind Engineering and Industrial Aerodynamics* 2006, **94**, 341–363

9. Kwok K.C.S, Qin X.R., Fok C.H., Hitchcock P.A. Wind-induced pressures around a sectional twin-deck bridg emodel: Effects of gap-width on the aerodynamic forces and vortex shedding mechanisms. *Journal of Wind Engineering and Industrial Aerodynamics* 2012, **110**, 50–61

10. Laima S., Li H., Chen W., Li F., Investigation and control of vortex-induced vibration of twin box girders. *Journal of Fluids and Structures* 2013, **39**, 205–221

11. Diana G., Belloli M., Muggiasca S., Zasso A. Experimental analysis of VIV on rigid and flexible circular cylinder. 12th ICWE, International Conference On Wind Engineering, Cairns, Australia, July 1-6, 2007