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Adding aerodynamic damping: the wing design for the Third Bosphorus Bridge

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SUMMARY:
This paper is about the design of wing profiles adequate for giving to the Third Bosphorus Brige an additional aerodynamic damping on both vertical bending as well as torsional modes. The additional damping estimate procedure is made through a simplified quasi steady approach. A CFD approach has been used for a preliminary design and optimization of the wing profile and its position over the wind screen at the upwind and downwind locations.

Keywords: Third Bosphorus Bridge, Aerodynamic damping, Winglet, CFD design

1. THIRD BOSPHORUS BRIDGE AERODYNAMIC DESIGN: AN OVERVIEW

The assessment of the aerodynamic performances of the Third Bosphorous Bridge (BB3) has been realized through tests in two different Wind Tunnels, CSTB and Politecnico di Milano (POLIMI) and with different scale factors. A specific focus of the tests was indeed the check of possible Reynolds Number effects on the tests results: the availability of very different scales in the two laboratories gave the opportunity to quantify the uncertainties due to the possible Reynolds dependence, generally affecting the results and usually not addressed in the bridges studies. Models in the following scale factors have been specifically used in the study: 1:100 and 1:25 (sectional models) at CSTB with wind speed up to 50m/s reaching high Reynolds number conditions, 1:180 and 1:50 (sectional and aeroelastic models) at POLIMI. The fundamental sectional aerodynamic static coefficients of the deck were of course compared in the different scaling, but a more in deep analysis has been also specifically planned, finalized at the comparison of the flow field generated by the wind screen flow interaction on the upper surface of the deck as well as finalized at the comparison of the pressure distribution (steady and unsteady) on the deck cross section. This comparison was actually realized on the 1:25 (CSTB) and 1:50 (POLIMI) scale models over a wide range of wind speeds. The fundamental result of the study confirmed that in the range of wind speed addressed by the 1:50 and 1:25 scale models a quite perfect agreement was shown by CSTB and POLIMI tests in terms of velocity profiles and pressure distributions. The further agreement among the static aerodynamic coefficients measured on the different scales deck sections allowed to confirm for the different scales section models an optimum representativeness of the deck section aerodynamics, free from relevant Reynolds number effects.
During the over mentioned experimental campaigns all the quantities that define the deck aerodynamic behaviour have been measured and cross checked between the two laboratories. Static and dynamic wind load have been measured on sectional models, using a full aeroelastic and taut strip models the full bridge dynamic response have been evaluated. Moreover, the pressure field on the deck have been checked on a large (1:50) taut strip model and on the same model we measured the wind profile on different lanes and the wind velocity in the deck wake. All the collected data were fundamental to tune and verify a CFD model, that has been used to check the wind screen efficiency and to design a wing profile to be installed on top of that if some additional damping is needed to reduce the deck response to the wind.

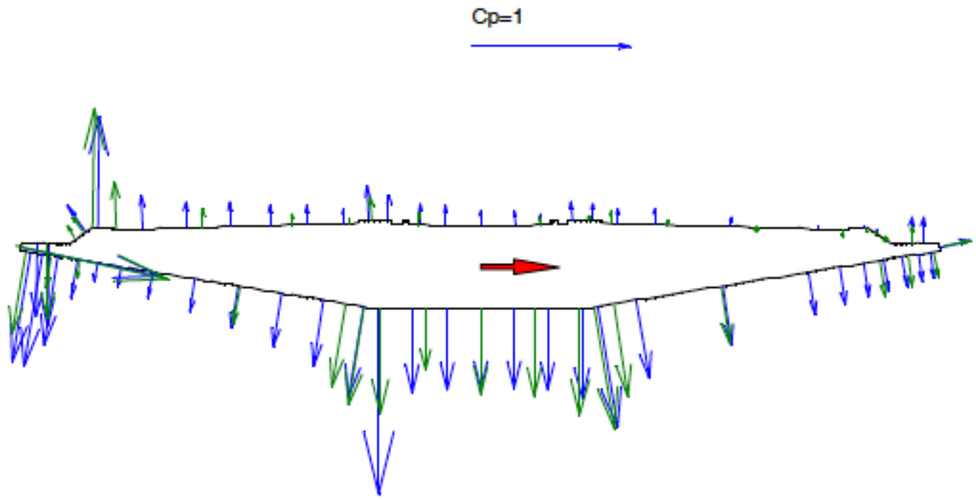

Figure 1. PoliMi (Blue)-CSTB (Green) mean pressure coefficient comparison.

Fig. 1 reports, as an example of the large amount of data collected, a comparison among the mean pressure coefficient measured at POLIMI and at CSTB for 0 angle of attack

2. CFD SIMULATIONS

The large amount of experimental data collected during the experimental campaigns at CSTB and at Polimi has been used as reference for aerodynamic design of the bridge. In particular, the forces and the pressure distribution and the velocity profile on the deck have been measured and they are a very good reference to validate computational the fluid dynamic model, in terms of integral forces and in terms of pressure and velocity on the deck.

Two different set of CFD simulations have been performed.

The aim of the numerical model was to analyse the effect of the wing profile mounted over the wind screen in terms of added aerodynamic damping. The purpose is to check the efficiency of different profile and different angle of attack on the overall damping, on the torsional motion of the deck.

The first CFD model developed is three dimensional and it was finalized at being the reference case for all the CFD models. This model is very complicated and it has a very fine mesh that implies a heavy computational effort summarized by the average number of 9.000.000 (9 million) cells each single run.

The No-Wind deck configuration has been extensively tested both at CSTB and at Polimi, measuring the aerodynamic forces and moment, the pressure distribution and the wind profiles on different lanes. These experimental data have been used as reference for validating the 3D model.

Once this very heavy and time consuming model has been validated it has been used as reference for the simpler and faster 2 dimensional model. This latter, involving a more efficient mesh, with an average number of 200.000 cells each single run, was validated by a check against the reference one, the tested configuration was the the No-Wing, as shown Fig. 2 and Fig. 3, were the mean velocity magnitude has been reported, respectively for the 3D and 2D simulations.

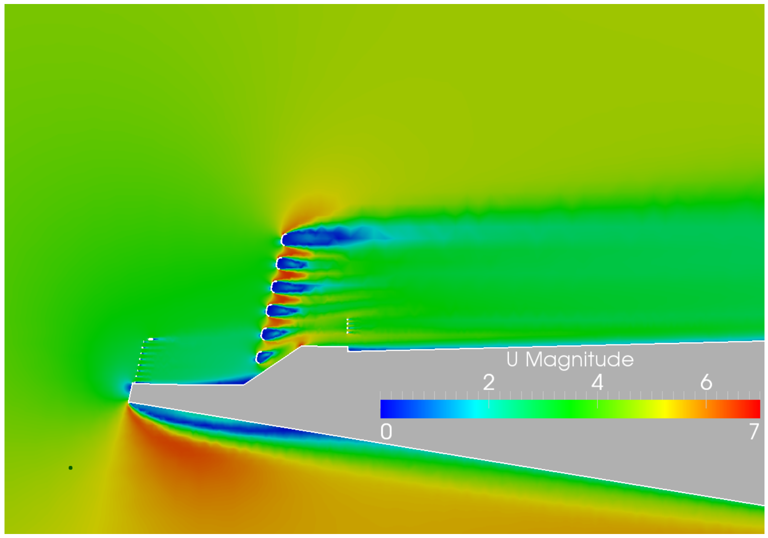

Figure 2. - Mean velocity magnitude. 3D Model.

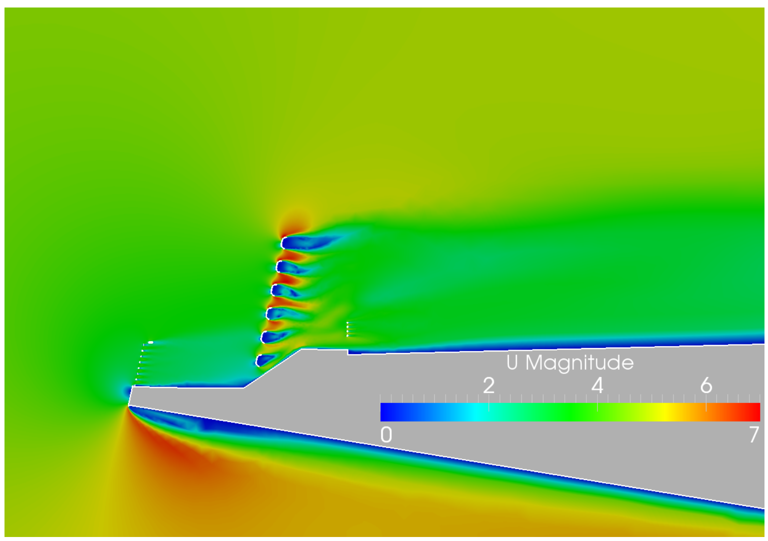

Figure 3. - Mean velocity magnitude. 2D Model

Table 1 describes the 2D model parameters, the total number of cells of each single run is around 200.000 cells, depending on the considered configuration and the average y+ value is 2. Numerical simulations are conducted using a finite volume approach, resolving the steady state RANS equations, with kw-SST closure model.

Table 1. Model parameters.

Row 1	A
Model scale	1:75
Domain size	15 m x4 m
Inlet velocity	5 m/s
Numerical model	RANS kwSST steady

Forces and force coefficients are computed using as reference the undisturbed reference wind velocity and wind incidence angle.

3. WING DESIGN PROCEDURE

The numerical model has been adopted to propose a design procedure to add, if needed, aerodynamic dampers to the BB3 deck design. The focus is to control the vibrations level of the deck itself, or to in other words to control the overall damping level.
In Figure 4, the adopted reference system is reported where F_L is the lift force, F_D the drag force, and z and y the direction of motion of the bridge section, moreover V is the incoming wind direction and α the angle of attack of the section, positive is the nose is going up.

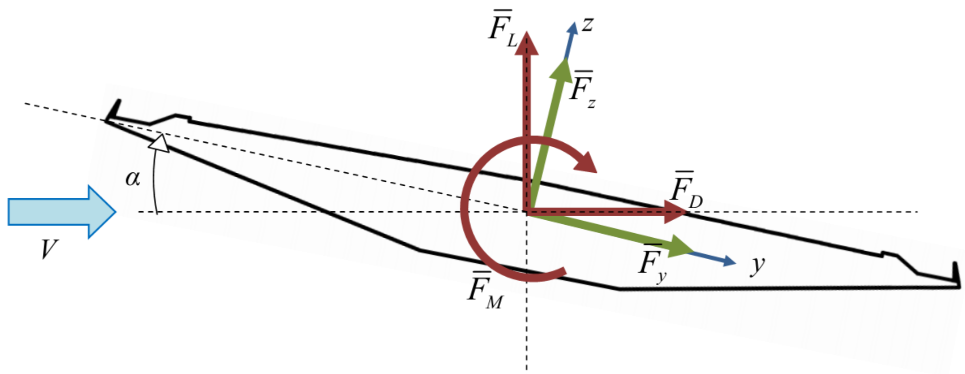

Figure 4. – Adopted reference system

The reference model for the aerodynamic forces is the quasi steady theory and the flutter derivatives as described in (Zasso, 1996).
In particular, with reference to the deck sectional rotational dynamics and its aeroelastic damping it is possible to write the following equation:

$$J\ddot{\vartheta} + R\acute{\vartheta} + K\vartheta = \frac{1}{2}\rho V^2 B^2 \left(\cdots - a_{2D}\frac{\dot{\vartheta}B}{V} + \cdots\right) \qquad (1)$$

where the term on the right-hand side of the equation represents the aerodynamic moment. *J, R, K* are respectively the inertia, structural damping and structural stiffness, whereas ρ is the air density and B the deck chord length.
To evaluate the effectiveness of the wing profiles it is necessary to include their forces into the mathematical modelling, in particular using the subscripts *Up* and *Down*, respectively for the profile mounted on the upwind and downwind edges.

$$F_{z-Up} = \frac{1}{2}\rho V_{Up}^2 B_W (C_{D-W} + K_{L-W})\frac{z_{Up}}{V_{Up}} \qquad (2)$$

$$F_{z-Dw} = \frac{1}{2}\rho V_{Dw}^2 B_W (C_{D-W} + K_{L-W})\frac{z_{Dw}}{V_{Up}} \qquad (3)$$

where C_{D-W} is the drag coefficient and K_{L-W} the lift coefficient first derivative respect to the angle of attack for each profile and B_W is the chord of each added wing.
Under the hypothesis of considering:

$$z_{Up} = z_{Dw} = \vartheta \frac{B_S}{2} \quad (4)$$

where B_S is the distance among the upwind and downwind wing on a typical bridge deck section and Z_{Up} and Z_{Dw} are the vertical displacements, respectively, of the up-wind wing and down-wind wing.
The aerodynamic behaviour of the profile is characterized by its drag, lift and aerodynamic moment coefficient, so the aerodynamic forces can be considered equal on the up-wind and down-wind profiles, or better C_D and K_L are equal on the two wings. To have a practical solution also the differences in the wind velocity can be considered negligible or:

$$V_{Up} = V_{Dw} = V \quad (5)$$

The aerodynamic moment induced on the deck by the wings, associated to the torsional velocity of the deck is described in equation (6), where B_W is the wind chord;

$$M_{Equiv} = -\frac{1}{2}\rho V^2 B_W \frac{B_S}{2} 2(C_{D-W} + K_{L-W}) \frac{\dot{\vartheta}\frac{B}{2}}{V} \quad (6)$$

To obtain the contribution of the aerodynamic dampers to the global torsional damping of the section, the direct damping term on this degree of freedom has to be highlighted. The a_{2D} flutter derivatives represents the aerodynamic contribution to the torsional damping. Equations (7) and (8) describe how to write it as a function of the wing aerodynamic characteristics, drag and lift first derivative, and as a function of the wing chord and wings positions relative to the bridge axis.

$$M_{Equiv} = -\frac{1}{2}\rho V^2 B^2 \frac{B_S}{B}\frac{B_W}{B}(C_{D-W} + K_{L-W}) \frac{\dot{\vartheta} B}{2V} \quad (7)$$

$$a_{2D} = \frac{1}{2}\frac{B_S}{B}\frac{B_W}{B}(C_{D-W} + K_{L-W}) \quad (8)$$

Equation (8) can be solved for $\frac{B_W}{B}$ to have the wing chord respect to the bridge chord:

$$\frac{B_W}{B} = 2a_{2D}\frac{B}{B_S}\frac{1}{(C_{D-W}+K_{L-W})} \quad (9)$$

Equation (9), once the distance between the wing is chosen and the aerodynamic characteristics of the wings are selected, gives to the designer a first estimation of the needed wing dimensions to have the desired aerodynamic damping added to the structural.

3.1. Equivalent Aerodynamic Damping due to Wing Profiles

The procedure described in the previous paragraph could be used to have a direct estimation of the Scruton Number changes due to add the wings.
Equation (1) describes the torsional motion of a generic bridge deck section, introducing in this equation the definition of critical damping, i.e. $R_{Cr} = 2J\omega_T$, where ω_T it the circular frequency of the considered torsional motion.
So that the viscous term in equation (1) can be rewritten as

$$R_{Tot} = \xi 2 J \omega_T + \frac{1}{2}\rho V^2 B^2 a_{2D}\frac{B}{V} \quad (10)$$

In order to have a quantitative indication on what is the influence of the added damping on the bridge deck dynamics, and keeping in mind the definition of Scruton number for torsional motion given in equation (11), equation 12 can be easily written by setting equation (10) equal to 0.

$$Sc_T = \frac{2\pi J \xi}{\rho B^4} \quad (11)$$

$$a_{2D} = -4 Sc_T \frac{1}{V^*_{Critical}} \quad (10)$$

where $V^*_{Critical}$ is the critical reduced velocity for the considered aeroelastic interaction.

4. RESULTS

Using the numerical model described in paragraph 2, different numerical simulations have been carried out to define the wing parameters of interest and to give a first indication for added damping devices to the bridge deck. In particular, as highlighted before, the important parameters to be calculated are: wind drag coefficient, wing lift first derivative, wing chord and wing position.

Starting from the latter, for structural issues only two possible mountings have been considered on the third Bosphorus Bridge, one is internal respect to the wind screens and the second one is external.

The simulations have been performed both with a NACA 0012 and NACA 0006 profiles adequately modified in order to be symmetrical around a transversal axis, so that allowing for wind direction reversal.

The NACA 0012 has been judged too risky in terms of possible VIV wing profile excitation, preferring to consider the NACA 0006 profile as the most suitable.

Risk of separation has been considered, preferring configurations showing a lower lift and a lower negative pressure on the upper surface, due to the rotated (upwash) incoming wind boundary conditions.

The configuration selected as is with a modified NACA 0006 profile, installed 1.5m over the wind screen upper edge (at the 3/4 chord point) with an angle of attack equal to 5 deg (negative upwind / positive downwind).

Table 2 report the main results for some of the considered cases.

Table 2. CFD results.

Wing profile	Mounting Deg and position	Upwind profile Coefficient			Downwind profile Coefficients		
		Drag	Lift	Moment	Drag	Lift	Moment
NACA006	5 deg Ext	0.032	0.17	-0.045	0.022	0.105	0.077
NACA006	5 deg Int	0.032	0.071	-0.05	0.025	0.103	0.068
NACA012	5 deg Ext	0.063	0.101	-0.102	0.026	0.05	0.009
NACA012	5 deg Int	0.046	0.0446	-0.076	0.027	0.075	0.033
NACA006	3 deg Ext	0.026	0.279	-0.027	0.020	0.076	0.048
NACA006	3 deg Int	0.017	0.189	-0.014	0.022	0.071	0.039
NACA012	3deg Ext	0.059	0.156	-0.093	0.026	0.043	0.003

In Table 2 the upwind wing is oriented with a negative angle of attack while the downwind is oriented

with a positive angle of attack. To evaluate K_L a counter-clock wise rotation of the incoming flow has been numerically simulated.
The above results give us all the data to feed the analytical model and hence to obtain the optimized performances of the aerodynamic dampers added to the bridge deck section.
The configuration of the system with the best performances in terms of additional damping to the structure are reported in Table 3

Table 3. Optimized design of the wing.

Wing profile	NACA 006 (modified)
Angle of attack	5 deg (negative upwind/positive downwind)
Wing position	Eternal (1.5 m over the wind screen upper edge connected to wing at ¾ chord
Wing Chord	2.475 m

Figure 5 shows an example of the results obtained with the optimized design, in particular the streamlines for the 0 deg angle of attack are reported.

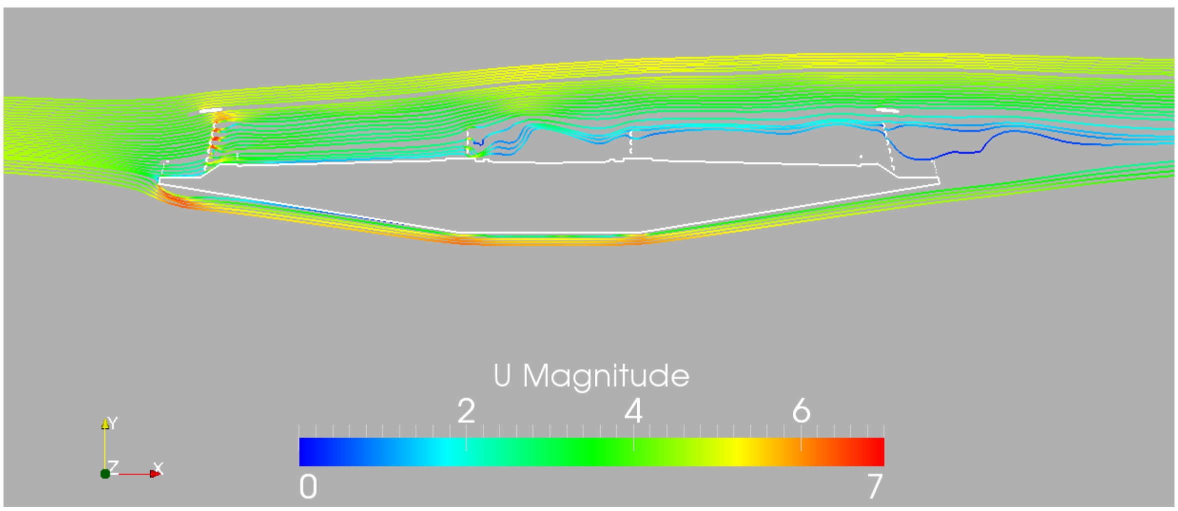

Figure 5. – Streamlines for the optimized solution, the deck angle of attack is equal to 0 deg

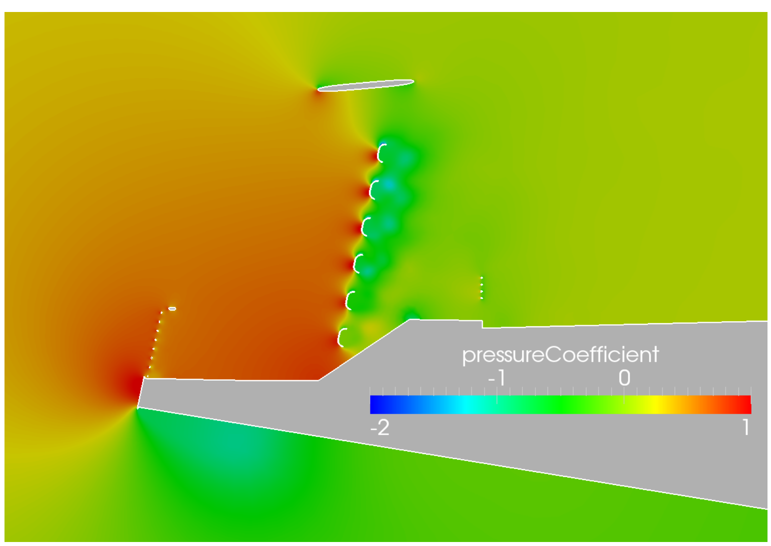

Figure 6 – Streamlines for the optimized solution, the deck angle of attack is equal to 0 deg

Moreover, the CFD analysis makes possible also to define the pressure distribution on the wing and on the wind screens. The static pressure is very useful to have the reference force to dimension the wind screen connection to the girder, Figure 6 shows the static pressure distribution for the optimized case.

3. CONCLUSIONS

Present study proposes a procedure to design aerodynamic dampers to be added on the bridge deck, in particular wing profiles over the wind screens are considered. These are a rational solution among the of possible, being well performing in terms of aerodynamic damping and reasonable, from a realization point of view. The study presents also an analytical procedure to evaluate the effectiveness of the so design profiles on the overall damping performances of the deck; the proposed case is relative to torsional vibrations but it can be easily done also for vertical deflections. If the deck needs such a kind of devices, the procedure should be finalized in terms of detailed investigations of separation issues (referring to full scale size and Reynolds number) as well as in terms of cross check of the aerodynamic design with the structural design of the proposed solution. The presented methodology is not to be considered as the final design of the wing profile for construction purposes, but as a rational choice of possible solution aimed at being well performing in terms of adding aerodynamic damping and "reasonable" from a realization point of view. In case the overall bridge performances will require the actual adoption of such a wing profile, the study should be finalized in terms of more detailed enquiry of separation issues.

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