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A non-linear approach to compute the aeroelastic response of a long-span bridge subjected to a non-synoptic wind

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SUMMARY
In the recent years, extreme climate events such as thunderstorms and downburst are becoming more and more intense and frequent. The numerical simulation of the aerodynamic response of long-span bridges subjected to these phenomena is not an easy task and requires the employment of non-linear methods which take into account time-variant mean wind speed and the effect of large wind angles of attack. In this work, a new time domain model is presented. Specifically, the method combines the non-linear corrected quasi steady theory with a rheological model, which allows to translate in time the information contained in the flutter derivatives and in the admittance functions, typically identified in frequency with specific wind tunnel tests. Moreover, at each integration step, the rheological model is modulated by the low frequency angle of attack. The new numerical procedure is here investigated applying to a suspension bridge case of study a non-synoptic wind scenario. After a brief presentation of the method, the results will be presented and compared with those obtained by the application of a more standard synoptic wind.

Keywords: Non-linear aerodynamics, time domain integration, non-synoptic winds, rheological model.

1. INTRODUCTION

In the last years, the technological advancement in full-scale monitoring on long-span bridges allowed to observe more and more extreme climate phenomena such as thunderstorms and downbursts. These events are typically characterized by large wind angles of attack which, combined with sudden variations of the mean wind speed, could have a significant impact on the aerodynamic forces acting on a bridge deck. Specifically, the latter are inherently non-linear and dependent both on the motion of the structure and on the wind turbulence. In this context, the identification of accurate non-linear numerical procedures to predict the aeroelastic response of long-span bridges is of fundamental importance.

Different numerical methods, which deal with the aforementioned non-linearities, are available in the literature to evaluate the time response of long-span bridges excited by turbulent winds [1, 2, 3, 4]. Nevertheless, the development of a reliable procedure to reproduce the non-linear behavior of the aerodynamic forces is still an open problem. The latter are analytically defined by the quasi-steady theory (QST) which nevertheless, well describe the wind non-linearities only at reduced velocities $V^* > 20$ ($V^* = V/(fB)$, where V is the mean wind speed, f is the frequency of motion and B the deck chord length). Therefore, to overcome this problem and simultaneously take into account large variations of the wind angle of attack and of the mean wind speed, a new numerical procedure is here proposed. The method, accurately described and validated through wind tunnel tests in [5], employs the QSTC (Corrected QST) and a rheological approach, which reflect in the time domain the information of the flutter derivatives and of the admittance functions experimentally identified in frequency domain, to calculate the complete response of a bridge accounting for the non-linear effect on the aerodynamic forces.

In the present abstract, the method is briefly introduced and applied to the Messina Strait Bridge considering a real non-synoptic wind scenario, which is characterized by an unsteady mean wind speed and a significant variation of the wind angle of attack. In the extended version of the work, the results will be presented and compared with those obtained by the application of a more standard case characterized by a synoptic wind.

2. THE NON-LINEAR APPROACH

The method proposed combines the QSTC and a rheological model to compute the complete aeroelastic response of a bridge. Specifically, considering the sign convention reported in Figure 1, the QST defines the aerodynamic drag F_D, lift F_L and moment M as

$$F_D = \frac{1}{2}\rho V_{Rel}^2 BLC_D(\alpha)$$
$$F_L = \frac{1}{2}\rho V_{Rel}^2 BLC_L(\alpha) \quad (1)$$
$$M = \frac{1}{2}\rho V_{Rel}^2 B^2 LC_M(\alpha)$$

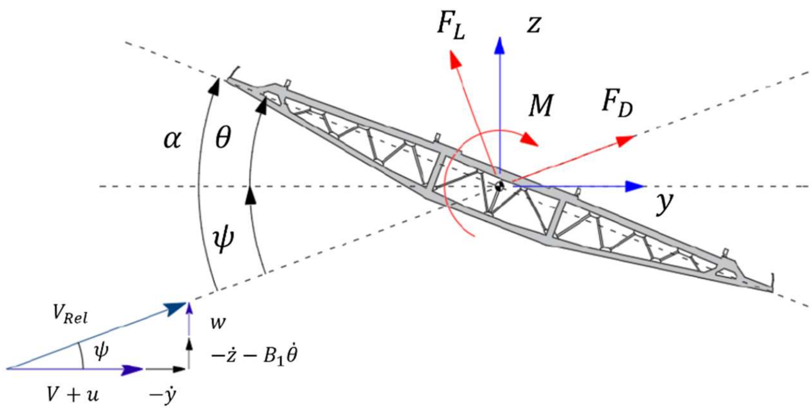

Figure 1. Deck forces and displacements sign convention and relative wind velocity.

where ρ is the air density, L is the bridge section longitudinal length while C_D, C_L and C_M are the static aerodynamic coefficients. Furthermore, V_{Rel} is the instantaneous relative velocity, ψ is the angle of V_{Rel} and α is the effective angle of attack. These parameters are respectively defined as follows

$$V_{Rel}^2 = (V + u - \dot{y})^2 + (w - \dot{z} - B_{1i}\dot{\vartheta})^2, with\ i = y, z, \theta$$
$$\psi = atan\left(\frac{w - \dot{z} - B_{1i}\dot{\vartheta}}{V + u - \dot{y}}\right), with\ i = y, z, \theta \quad (2)$$
$$\alpha = \psi + \theta$$

with $\dot{y}$ and $\dot{z}$ respectively lateral and vertical velocity of the bridge deck. The coefficient B_{1i} represent the correction of the QST and it is experimentally determined through the knowledge of the aerodynamic derivatives. As already mentioned, the non-linear QSTC well describes the wind forces in correspondence of $V^* > 20$. To overcome the problem, the method here presented employes a rheological approach to correct the non-linear QST at low reduced velocities. Specifically, the dependency on V^* is typically identified in frequency domain using the flutter derivatives and the admittance functions, which are experimentally measured with specific wind tunnel tests. These coefficients allow to define, in a linearized framework, the self-excited and the buffeting forces. Therefore the rheological models, which consist in a series of simple mechanical oscillators, i.e. masses, dampers and springs properly tuned, implement in time domain the aerodynamic transfers functions of the self-excited and of the buffeting forces. Figure 2 shows the models used. Moreover, at each integration step, the rheological models are modulated with the low frequency instantaneous effective wind angle attack α. A more detailed description of the model is reported in [5].

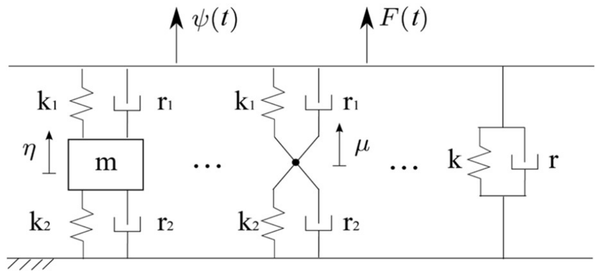

Figure 2. Mechanical oscillators used to describe in time domain the aerodynamic transfer functions.

3. CASE OF STUDY

The non-linear model previously described is here applied to determine the dynamic response of the Messina Strait Bridge subjected to a non-synoptic wind case of study, which is characterized by significant variation of the mean wind speed and of the wind angle of attack. The results will be subsequently compared with a more standard synoptic wind case.

The real non-synoptic wind scenario was identified from the monitoring campaign of the Hardanger Bridge [6]. Specifically, the numerical wind was generated multiplying the full-scale recordings by a constant equal to V_d/V, where $V_d = 60m/s$ is the design wind speed of the Messina Strait Bridge while, V is the mean wind speed over the last ten minutes of the time history in exam. An example is reported in Figure 3. The second scenario is a more standard case of synoptic wind, characterized by a mean wind speed equal to V_d and generated employing the parameters reported in Table 1. Figure 4 illustrates the longitudinal component and the wind angle of attack of one of the applied synthetic time histories.

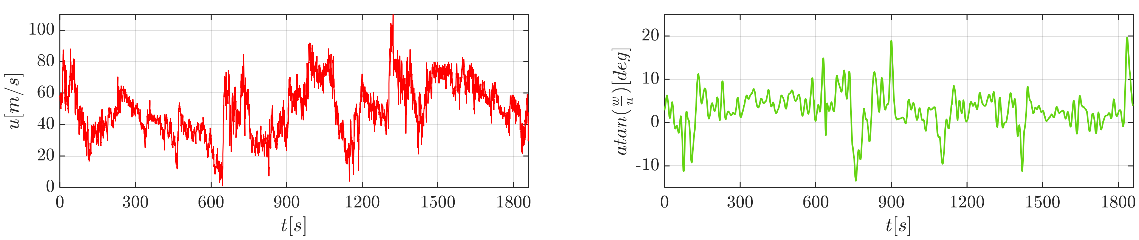

Figure 3. Non-synoptic time histories of the horizontal wind component and of the low-pass filtered angle of attack.

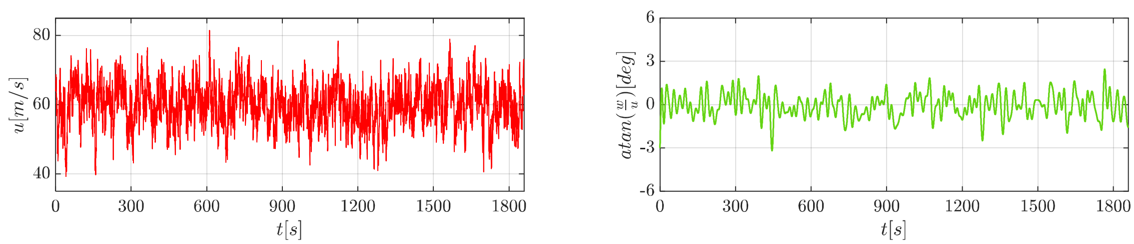

Figure 4. Synoptic time histories of the horizontal wind component and of the low-pass filtered angle of attack.

Wind speed	$V = 60\ m/s$
Air density	$\rho = 1.22\ kg/m^3$
Turbulence intensity	$I_u = \sigma_u/V = 0.10;\ I_w = \sigma_w/V = 0.05$
Integral length scale	${}^xL_u = 200\ m;\ \ {}^xL_w = 20\ m$

Table 1. Parameters employed for the synoptic wind time histories generation.

The Messina Bridge is characterized by a span length equal to 3300 m and a multi-box girder with $B = 60m$. The frequencies of the main deck modes are reported in Table 2. The aerodynamic properties were identified performing specific tests carried out in the Politecnico di Milano wind tunnel. Specifically, the identification was performed around a range of static angles between -6° and 6° and for values of V^* between 2 and 25.6. Figure 5 illustrates the a_2 and a_3 coefficients in PoliMi notation [7].

Mode	Frequency [Hz]
LS1	0.031
LA1	0.056
VA1	0.060
VS1	0.080
TA1	0.080
TS1	0.096

Table 2. Main modal frequencies of the Messina Strait Bridge.

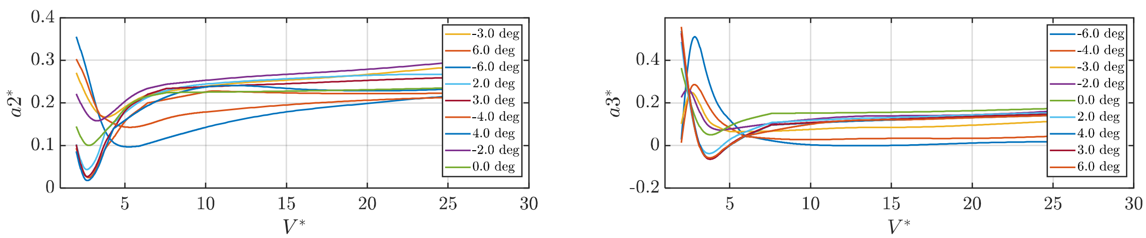

Figure 5. a_2 and a_3 aerodynamic derivatives, measured around different static angles of rotation.

4. CONCLUSIONS

In the present abstract, a new non-linear method to predict the aerodynamic response of long-span bridges is proposed and applied to the Messina Strait Bridge, considering two wind scenarios: the first characterized by a non-synoptic wind while the second by a more standard synoptic one. Specifically, the new non-linear method allows to take into account the time variant mean wind speed and the large wind angles of attack which typically characterize non-synoptic phenomena. In the full-version of the work, the results of the two wind scenarios will be compared and discussed.

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A more extensive and adequate bibliography can be found in all the previous publications.