A new numerical approach to reproduce bridge aerodynamic non linearities in time domain

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ABSTRACT: A new approach to deal with aerodynamic non linearities in time domain has been developed relying on a rheologic mechanical model. The parameters of the rheologic model have been estimated from specific wind tunnel tests. Once performed the mechanical parameters estimation, the rheologic system allows the reproduction of the aerodynamic forces, starting from the bridge motion and wind velocity inputs, taking into account the non linearities induced by the reduced velocity and by the large changes in the angle of attack that are commonly experienced by the real structure due to the motion and turbulence components.

KEYWORDS: Aerodynamic non linearities, time domain, rheologic model, aerodynamic force hysteresis, numerical simulation.

1 INTRODUCTION

Bridge aeroelasticity is commonly studied by numerical models relying on the experimental aerodynamic coefficients measured in wind tunnel on deck sectional models. The most widely adopted approaches can be divided in time domain [1, 2] and frequency domain [3, 4] approaches. Both of them are based on the definition of aerodynamic transfer functions (flutter derivatives) capable to link the deck motion to the aerodynamic forces at different reduced velocities and angles of attack. The aerodynamic transfer function, that are commonly measured in the frequency domain by wind tunnel tests through free motion or forced motion methods [5], is directly used by the frequency domain models that study the linear behavior of the bridge deck section close to the static angle of attack reached under mean wind conditions. Some time domain approaches translate the reduced frequency dependence of the aerodynamic transfer function in the time domain by means of convolution integrals, always considering the linear problem of the small deck oscillations around the static equilibrium position under mean wind conditions. Experimental evidences [6] outlined that the linear approach hypothesis may be not correct under the operating wind condition in presence of a large fluctuation of the angle of attack induced by turbulent wind velocity components. The non linear effects induced by turbulence have been also outlined and studied by means of wind tunnel tests [7] and an attempt to take into consideration the non linear effects is provided by time domain approaches [2, 7], that still rely on the aerodynamic transfer function but study the problem of the small oscillation around a low frequency varying mean angle of attack. The new approach presented in this paper try to take into account the aerodynamic non linear effects by means of a rheologic model in time domain. The advantage of this approach is that, even if a reduction of the physical interpretation appears, the model is able to contemporary evaluate, in a time domain approach, the aerodynamic forces by the knowledge of the deck motion and wind velocity component reproducing the aerodynamic non linearities induced by the variation of the mean angle of attack, by the variation of the reduced velocity and by the motion amplitude. The parameters of the rheologic mechanical model have been estimated from specific wind tunnel tests consisting in the measure of the aerodynamic forces acting on a deck sectional model driven to vibrate in torsional motion also at high amplitudes. Tests have been performed at different amplitudes and
with different mean angles of attack, analysing a wide range of reduced velocities by varying the
wind velocity and the motion frequency. The investigation of the experimental data allows the
definition of the single components of the rheologic model and of the related parameters.

2 WIND TUNNEL INVESTIGATION

2.1 Experimental set-up
Wind tunnel tests, were performed in the Boundary Layer Wind Tunnel at the Politecnico di
Milano on a 1:60 deck sectional model of the Messina Strait bridge under low turbulence flow
conditions defined by a turbulence intensity index \( I_t = 2\% \).

Referring to [5] for a detailed model description, the global experimental set-up features
are here summarized. The model is made of a central dynamometric part 1 m long and 1 m wide
in the along wind direction allowing the measure of all the 6 aerodynamic force/moment
components. The whole 3 m long sectional model is connected to 3 oil-dynamic actuators
driving the model vertical motion and the rotation around the longitudinal axis. The low mass
and the high stiffness of the model structure allow to perform rigid motion tests at frequencies up
to 5 hz with large amplitudes without exciting the model natural frequencies. The measurement
quality and sensibility allow to perform measurements at very low wind velocities, also on very
slender and aerodynamic optimized deck section like to Messina one, granting an investigation
of a wide reduced velocity field. The measurement system of the model displacement and
acceleration completes the experimental test rig [5].

2.2 Experimental results
The experimental set-up allows to perform both “quasi steady” tests providing a very low
frequency rotation in order to define the static aerodynamic forces at different mean angles
of attack, and “dynamic” tests providing a rotation with a sinusoidal motion law at high frequency
in order to investigate the aeroelastic effects. Changing the wind mean velocity from 4 to 12 m/s
and the motion frequency from 0.02 to 0.8 Hz a wide reduced velocity range was investigated
(from 1 to over 100). At first the definition of the static aerodynamic coefficients trend versus
the mean angle of attack was performed following the procedure described in [5]. Figure 1
shows the drag, lift and aerodynamic optimized deck section like to Messina one, granting an investigation
of a wide reduced velocity field. The measurement system of the model displacement and
acceleration completes the experimental test rig [5].

![Figure 1. Static aerodynamic coefficients and sign convention](image)
Dynamic tests were performed assigning a sinusoidal motion law to the rotational degree of freedom considering different mean angles of attack, different oscillation amplitudes, different motion frequencies and different mean wind speeds. In particular 2 different levels of motion amplitudes are considered equal to 2.5 deg and 5 deg; 3 different mean angle of attack are investigated equal to -3 deg, 0 deg and 3 deg. Combining the motion frequencies and the mean wind velocity a large range of reduced velocities is analyzed. Dynamic tests were performed assigning a sinusoidal motion law to the rotational degree of freedom considering different mean angles of attack, different oscillation amplitudes, different motion frequencies and different mean wind speeds. In particular 2 different levels of motion amplitudes are considered equal to 2.5 deg and 5 deg; 3 different mean angle of attack are investigated equal to -3 deg, 0 deg and 3 deg.

Combining the motion frequencies and the mean wind velocity a large range of reduced velocities is analyzed. As an example of the parametric analysis performed on the experimental data is proposed in Figure 2, on the left, where the comparison of the shape of the aerodynamic hysteresis cycle for the lift force is proposed in terms of force coefficients at the same wind speed \( U \) equal to 11.3 m/s, at 0 deg mean angle of attack \( \theta_0 \), with an oscillation amplitude \( \Delta \theta \) equal to 5 deg, versus the dynamic angle of attack \( \psi \) defined as:

\[
\psi = \theta - \frac{B \dot{\theta}}{U}
\]

where \( \theta \) = rotation around the longitudinal axis; \( \dot{\theta} \) = the angular velocity; \( U \) = the mean wind speed; and \( B \) = a reference dimension. The dependence on the mean angle of attack is shown in Figure 2, on the right, where the lift coefficient hysteresis cycles at three different mean angles of attack is reported at the same reduced velocity. It is clearly visible that the cycles move on the mean static coefficient curve with the angle of attack.

![Figure 2. Lift force hysteresis cycle, \((U = 11.3 m/s; \Delta \theta = 5 \text{ deg}; B = 1)\)](image)

3 RHEOLOGIC MODEL

The rheologic model operates receiving as input the time history of the dynamic angle of attack \( \psi \) that contains all the contribution due to the bridge motion and the wind fluctuations, and provides the aerodynamic force as output by the computation of the force requested by a mechanical system, made of simple damper/spring elements, to react to the assigned input. The basic components of the rheologic model are:

1) a non linear spring, whose stiffness characteristic reproduces the static coefficient trend;
2) an array of damping elements, acting in parallel to the non linear spring, with a damping factor that is inversely proportional to the wind velocity and one end attached to a coulomb friction element to suppress its contribution under particular operating conditions;
3) a mechanical system made of damper and spring acting in parallel to the other elements. The damper and spring parameters are deduced minimizing the error between the numerical results and the experimental data in terms of aerodynamic forces.

### 3.1 Experimental-Numerical comparison

A comparison between experimental and numerical results is reported in Figure 3 for 2 different reduced velocity conditions referring to the lift force coefficient. A good agreement is shown denoting that the model, once the parameters are correctly defined, is able to reproduce the correct relationship between the dynamic angle of attack variation and the aerodynamic force for different reduced velocity conditions. Similar satisfactory comparisons are also achievable for different mean angles of attack and different vibration amplitudes of the motion.

![Figure 3. Numerical-experimental comparison](image)

Figure 3. Numerical-experimental comparison (\(U = 11.3 \text{ m/s} \); \(\vartheta_0 = 0\deg \); \(\Delta \vartheta = 5\deg \); \(B = 1\))

### 4 CONCLUSION

A new numerical approach was applied to define the bridges aeroelastic response taking into account the aerodynamic non-linearities induced by large fluctuation of the angle of attack. The approach is based on a rheologic model and is implemented in the time domain allowing to contemporarily consider the aerodynamic force dependence by the angle of attack and by the reduced velocity. The validation of the proposed model will be performed comparing the results with those one measured in the wind tunnel on the same sectional model elastically suspended on stays and run over by a actively produced turbulence fluctuations generating large variations of the dynamic angle of attack.

### 5 REFERENCES

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