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Nonlinear buffeting modelling of a 2000 m long twin-deck suspension bridge

Niccolò Barni [1], Ole Andre Øiseth [2], Øyvind Wiig Petersen [2], Claudio Mannini [1]

[1] *University of Florence, Florence, Italy.* niccolo.barni@unifi.it, claudio.mannini@unifi.it
[2] *Norwegian University of Science and Technology, Trondheim, Norway.* ole.oiseth@ntnu.no, oyvind.w.petersen@ntnu.no

SUMMARY:
Multiple-box solutions are increasingly used in super-long suspension bridges because of their outstanding aeroelastic performance. However, the aerodynamic properties of the section can significantly change with the angle of attack, making these sections prone to parametric excitation due to large-scale turbulence. A model for buffeting response calculation taking into account large angles of attack is discussed in this paper. A suspension bridge crossing the Halsa Fjord with a main span of 2000 m is used as a case study to investigate the importance of nonlinearities introduced by large-scale turbulence.

Keywords: Nonlinear buffeting, time-variant self-excited forces, twin-deck.

1. INTRODUCTION

Since aeroelastic effects were introduced in buffeting response calculations of suspension bridges, linear unsteady models have widely been used for self-excited forces. However, it has been seen that self-excited forces (either quasi-steady or unsteady) are often sensitive to a variation in the angle of attack, which can be induced by large-scale turbulence. How this nonlinearity affects the dynamic response and aeroelastic stability of a long-span bridge is still not fully clear. Nonlinear aerodynamic force models were developed since the beginning of the '90s, aiming to properly account for the parametric excitation promoted by turbulence (e.g., Chen and Kareem, 2001; Diana et al., 2013; Barni et al., 2021). This effect resulted to be crucial in predicting the dynamic response of bridge sectional models subjected to multi-harmonic gusts (Diana et al., 2020). However, the few applications on real suspension bridges available in the literature (Chen and Kareem, 2003; Ali et al., 2021; Barni et al., 2022) show that turbulence may either stabilise or destabilise the bridge response, and highlight the lack of understanding of the phenomenon.

In this paper, the 2D RFA model presented in Barni et al. (2021) is used to evaluate the nonlinear buffeting response of the Halsafjorden Bridge, which presents a main span of 2000 m and a twin-deck girder. Here, the 2D RFA equations are slightly modified to directly obtain some of the model parameters from the quasi-steady limits of the aerodynamic derivatives. This work aims to increase awareness of the importance of nonlinear effects due to large-scale turbulence and to understand how they affect the structural design of long-span bridges.

2. MATHEMATICAL MODEL

As explained in Barni et al. (2021), the 2D RFA model preserves the small vibration assumption and assumes that the angle of attack due to wind velocity fluctuations varies slowly compared to the bridge motion. Therefore, the time-variant transfer function $\mathbf{G}(K,\tilde{\alpha})$ between the motion vector $\mathbf{r}$ and the self-excited force vector $\mathbf{q}_{se}$ maintains the simple form valid for a linear system, but it becomes a function not only of reduced frequency K but also turbulence-induced slowly-varying angle of attack $\tilde{\alpha}(t)$.

$$\mathbf{q}_{se}(K,\tilde{\alpha}) = \mathbf{G}(K,\tilde{\alpha})\mathbf{R}(K)\ ,\ \ \mathbf{q}_{se} = [q_y \quad q_z \quad q_\theta]^T\ ,\ \ \mathbf{R} = \mathcal{F}[\mathbf{r}] = \mathcal{F}[y \quad z \quad \theta]^T \tag{1}$$

The vector $\mathbf{R}$ represents the Fourier transform $\mathcal{F}$ of the bridge girder motion vector $\mathbf{r}$ (the self-excited forces acting on cables and pylons are neglected), where y, z and θ denote lateral, vertical and torsional displacements, respectively. $K = \omega B / V_m$ is the reduced frequency of oscillation, where V_m is the mean wind velocity, ω the circular motion frequency, and B the width of the deck.

The 2D RFA model describes the self-excited forces in the time domain inspired by Roger's rational approximation. Øiseth et al. (2011) noted that for $K \to 0$ the quasi-steady limit of the imaginary part of Roger's approximation also depends on the contants of the exponential filters. In contrast, with a slight change in the aeroelastic filters, a 2D RFA with a simpler quasi-steady limit can be obtained as follows:

$$\mathbf{G}(K,\tilde{\alpha}) = \frac{1}{2}\rho {V_m}^2 \left(\mathbf{A}_1(\tilde{\alpha}) + \mathbf{A}_2(\tilde{\alpha}) iK + \sum_{l=1}^{N-2} \mathbf{A}_{l+2}(\tilde{\alpha}) \frac{(iK)^2}{iK + d_l(\tilde{\alpha})}\right) \tag{2}$$

Since the 2D RFA is a multivariate transfer function, these quasi-steady limits are functions of the angle of attack:

$$\lim_{K\to 0} K^2 \left\{\mathrm{Re}[\mathbf{G}(K,\tilde{\alpha})] / \left(\frac{1}{2}\rho {V_m}^2 K^2\right)\right\} = \mathbf{A}_1(\tilde{\alpha})\ ;\ \lim_{K\to 0} K \left\{\mathrm{Im}[\mathbf{G}(K,\tilde{\alpha})] / \left(\frac{1}{2}\rho {V_m}^2 K^2\right)\right\} = \mathbf{A}_2(\tilde{\alpha}) \tag{3}$$

In this way, the 2D RFA coefficients $\mathbf{A}_1$ and $\mathbf{A}_2$ can be obtained from a simple linear least square fit to the quasi-steady limits of the aerodynamic derivatives, entrusting the parameters of the aeroelastic filters with the unsteady contribution to self-excited forces. Taking the inverse Fourier transform of Eq. (2), considering $\mathbf{A}_l$ and d_l as frozen-time functions of the angle of attack, after some manipulation, one obtains the following expression of the self-excited forces:

$$\mathbf{q}_{se}(t,\tilde{\alpha}) = \frac{1}{2}\rho {V_m}^2 \Bigg(\underbrace{\mathbf{A}_1(\tilde{\alpha})\mathbf{r}(t) + \frac{B}{V_m}\mathbf{A}_2(\tilde{\alpha})\dot{\mathbf{r}}(t)}_{\text{quasi-steady contribution}} + \underbrace{\sum_{l=1}^{N-2} \mathbf{A}_{l+2}(\tilde{\alpha})\, d_l(\tilde{\alpha}) \boldsymbol{\psi}_l(\tilde{\alpha},t)}_{\text{unsteady contribution}}\Bigg) \tag{4}$$

$$\dot{\boldsymbol{\psi}}_l = -d_l(\tilde{\alpha}) \frac{V_m}{B}\ \boldsymbol{\psi}_l + \dot{\mathbf{r}} \tag{5}$$

Compared to the standard 2D RFA, $\mathbf{A}_1$ and $\mathbf{A}_2$ in Eq. (2) can be forced to respect the quasi-steady limits. Consequently, the model has less free parameters, which may deteriorate the accuracy of the aerodynamic derivative fit, possibly requiring to increase the number of exponential filters. On the other hand, this formulation might be helpful in case of a lack of experimental data in the low-frequency range, preventing unphysical extrapolations that can lead to inaccurate modelling of the low-frequency buffeting contributions, which are essential for the lower modes of long-span suspension bridges.

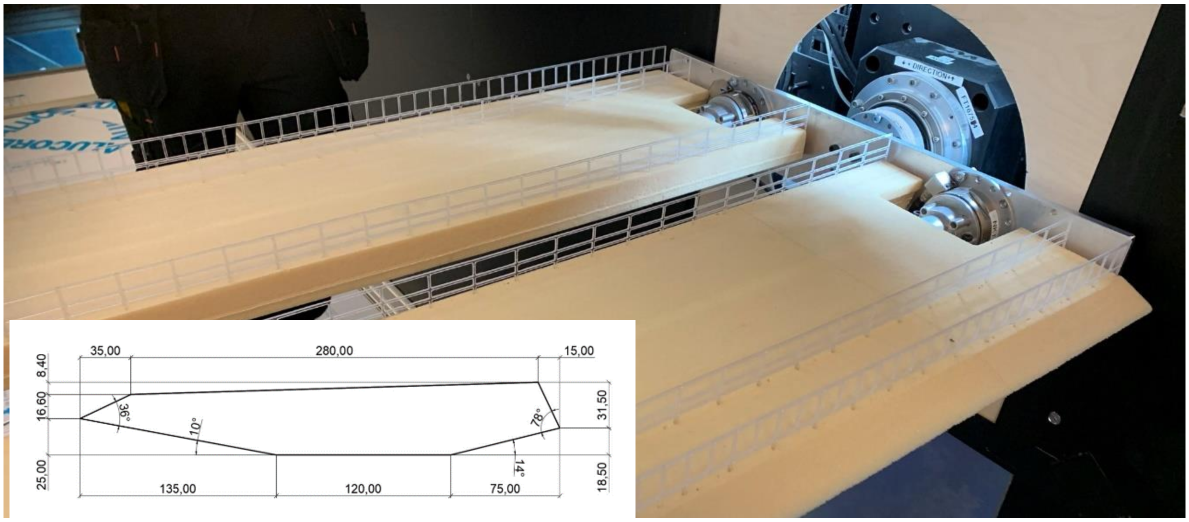

Figure 1: Halsafjorden Bridge section model (1:50 scale) mounted in the wind tunnel

Finally, the self-excited forces in Eq. (4) are implemented in the nonlinear buffeting response framework described in Barni et al. (2022), leading to a time-variant state-space model, expressed in compact form as:

$$\dot{\boldsymbol{\gamma}}(t) = \boldsymbol{\Omega}(t)\boldsymbol{\gamma}(t) + \mathbf{B}\hat{\mathbf{q}}_{ext}(t) \tag{6}$$

$\mathbf{B} = [\mathbf{0} \quad \widehat{\mathbf{M}}^{-1} \quad \mathbf{0}]^T \in \mathbb{R}^{[2N_{mod}+3\cdot(N-2)\cdot N_x]\times N_{mod}}$ is the input matrix, $\boldsymbol{\gamma} \in \mathbb{R}^{2\cdot N_{mod}+3\cdot(N-2)\cdot N_x}$ is the state vector, while $\boldsymbol{\Omega}(t) \in \mathbb{R}^{[2\cdot N_{mod}+3\cdot(N-2)\cdot N_x]\times[2\cdot N_{mod}+3\cdot(N-2)\cdot N_x]}$ is the time-variant state matrix. $\widehat{\mathbf{M}} \in \mathbb{R}^{N_{mod}\times N_{mod}}$ indicates the generalized mass matrix, N_{mod} is the considered number of vibration modes, and N_x the number of nodes used to discretize the bridge deck.

3. CASE STUDY

The self-excited force model is applied to evaluate the wind-induced dynamic response of the Halsafjorden Bridge, a proposed 2000 m-long suspension bridge. The design has two 300 m-tall reinforced concrete towers and a sag-to-length ratio of 8.8. There are 83 hangers on each side of the deck spaced 24 m apart. The girder comprises two steel boxes, each 2.5 m high and 16.5 m wide, with a inner tip-to-tip distance of 14 m. The main cables are spaced 47 m apart. The outer shape of each box is illustrated in Fig. 1.

The 2D RFA model identification requires a set of aerodynamic derivatives for different angles of attack. Their measurement through harmonic forced vibrations tests is underway in the wind tunnel of the Fluid Mechanics Laboratory at NTNU, Norway. The 1:50 scale twin-deck section model (Fig. 1) is 2620 mm long, 740 mm wide and 50 mm high.

The calculation of the nonlinear buffeting response of the bridge also requires that the random wind field at the site of the structure is available in the time domain. Time histories of the fluctuating wind velocity components are therefore artificially generated. Turbulence intensity and integral length scale will be chosen as free parameters to investigate the variation of the nonlinear effects produced by turbulence.

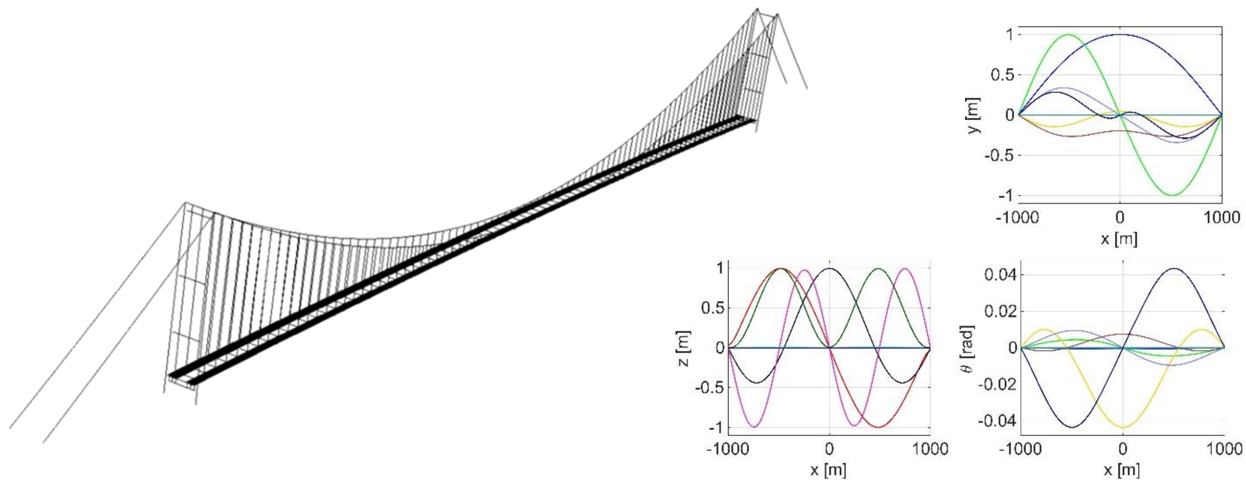

Figure 2. Finite-element model of the Halsafjorden Bridge with the shapes of the most important modes.

A finite element model of the Halsafjorden bridge is generated in the software ABAQUS, where the first 100 undamped vibration modes were obtained. The modal analysis was performed after applying the dead load, accounting for the geometrical stiffness provided by the cables. The buffeting calculations will be performed with 20 modes, and the shapes of the most important ones for the dynamic response are shown in Fig. 2.

4. RESPONSE ANALYSIS AND PROSPECTS

The nonlinear buffeting response of the bridge is calculated up to the flutter instability onset. The influence of turbulence intensity and integral length scale is assessed, as well as the impact of the mean wind velocity inclination. The fundamental role of the nonlinearities in the self-excited forces is highlighted for the present case study comparing linear and nonlinear buffeting responses. It is worth pointing out that the most important feature of the current nonlinear buffeting approach is the modulation of external and self-excited forces due to the spatio-temporal fluctuations of the angle of attack, which also accounts for the loss of spanwise correlation of the wind field.

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