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Non-stationary wind buffeting response of long-span bridges using a nonlinear 2D RFA formulation

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SUMMARY:
A time-domain formulation is presented for the buffeting response of long-span bridges under non-stationary turbulent wind. The method extends a two-dimensional Rational Function Approximation (2D RFA) model to transient events in which mean velocity and wind incidence angle evolve in time. A multivariate non-stationary wind field is generated with prescribed spectral properties and spatial coherence, and the response is computed through a time-varying state-space model. The approach is applied to the Halsafjorden Bridge, comparing a reference calculation with a fully time-varying aerodynamic formulation.

Keywords: suspension bridges, non-stationary wind, buffeting response, time-varying aeroelasticity, 2D RFA, aerodynamic nonlinearities

1. INTRODUCTION

The aeroelastic response of long-span bridges under transient and non-stationary winds is currently attracting increasing attention. Classical buffeting formulations usually rely on a stationary flow description and on aerodynamic forces linearized around a steady bridge position. This assumption becomes restrictive when the incoming flow exhibits pronounced low-frequency variations of mean velocity, turbulence properties and wind incidence, as in non-synoptic events. This limitation has motivated a growing research effort on non-synoptic bridge buffeting, from nonlinear time-domain modelling to benchmark and full-scale validation studies, with the common aim of following the slowly evolving aerodynamic state during severe transient events (Barni and Mannini, 2024; Calamelli et al., 2024; Diana et al., 2025).

This viewpoint is especially relevant when the bridge section aerodynamics is sensitive to the angle of attack (AoA). Low-frequency wind variations modify the local wind incidence angle seen by the deck; if aerodynamic derivatives and admittance functions vary with it and reduced velocity, the unsteadiness in both both self-excited and buffeting forces become time-dependent. Previous work based on the two-dimensional Rational Function Approximation (2D RFA) showed that self-excited-force modulation can affect buffeting response and flutter stability, with angle-of-attack effects generally more important than the sole variation of kinetic pressure or reduced velocity (Barni and Mannini, 2024). Here, the same rationale is extended to the unsteady buffeting formulation through a 2D RFA representation of the aerodynamic admittance and applied to a transient wind condition induced by a non-synoptic-like event.

The present work applies this framework to a numerically generated non-stationary turbulent wind field. The slowly varying wind defines the local aerodynamic operating point, i.e. the condition about which the aerodynamic forces are linearized and treated quasi-steadily at low frequency, whereas the high-frequency fluctuations drive the unsteady self-excited and buffeting forces. The case study is the Halsafjorden Bridge, subjected to a thunderstorm-like mean-velocity modulation whose time scale is inspired by recorded non-synoptic events.

2. METHODOLOGY

Let $U(x,t)$ and $w(x,t)$ be the along-wind and vertical incoming-flow components, and let $\mathbf{r}(x,t) = [y\ z\ \theta]^T$ be the sectional displacement vector. Omitting the dependence on x, wind and structural response are decomposed into slowly varying and high-frequency components:

$$U = \tilde{U} + u_{HF}, \qquad w = \tilde{w} + w_{HF}, \qquad \mathbf{r} = \tilde{\mathbf{r}} + \mathbf{r}_{HF}, \qquad \dot{\mathbf{r}} = \dot{\tilde{\mathbf{r}}} + \dot{\mathbf{r}}_{HF}. \tag{1}$$

The slowly varying flow and motion define the instantaneous aerodynamic operating point. The corresponding relative velocity and apparent angle of attack are written as

$$\tilde{V} = \sqrt{(\tilde{U} - \dot{\tilde{y}})^2 + (\tilde{w} - \dot{\tilde{z}} + \beta B \dot{\tilde{\theta}})^2}, \qquad \tilde{\alpha} = \tan^{-1}\left(\frac{\tilde{w} - \dot{\tilde{z}} + \beta B \dot{\tilde{\theta}}}{\tilde{U} - \dot{\tilde{y}}}\right), \tag{2}$$

where B is the deck width and β identifies the point where the rotational velocity contribution is evaluated. The effective angle entering the aerodynamic coefficients is $\tilde{\alpha}_e = \tilde{\alpha} + \tilde{\theta} + \theta_{st}$.

The sectional aerodynamic force is treated as a nonlinear function $\mathbf{q}_f = \mathbf{f}_q(U, w, \mathbf{r}, \dot{\mathbf{r}})$. Linearization about the slowly varying operating point gives $\mathbf{q}_f(t) \approx \tilde{\mathbf{q}}^{QS}(t) + \mathbf{q}_{se}^{unst}(t) + \mathbf{q}_b^{unst}(t)$, where $\tilde{\mathbf{q}}^{QS}$ is the quasi-steady contribution of the slow dynamics, while $\mathbf{q}_{se}^{unst}$ and $\mathbf{q}_b^{unst}$ are the unsteady self-excited and buffeting forces due to the fast motion and fast turbulence.

The self-excited forces are described through the 2D RFA, whose coefficients depend on the instantaneous effective incidence. In the time domain,

$$\begin{cases} \mathbf{q}_{se}^{unst}(t) = \frac{1}{2}\rho \tilde{V}^2 \left[\mathbf{A}_1(\tilde{\alpha}_e)\mathbf{r}_{HF} + \frac{B}{\tilde{V}}\mathbf{A}_2(\tilde{\alpha}_e)\dot{\mathbf{r}}_{HF} + \sum_{l=1}^{N_a} \mathbf{A}_{l+2}(\tilde{\alpha}_e)\boldsymbol{\lambda}_l \right], \\ \dot{\boldsymbol{\lambda}}_l = -\frac{d_l(\tilde{\alpha}_e)\tilde{V}}{B}\boldsymbol{\lambda}_l + \dot{\mathbf{r}}_{HF}, \qquad l = 1, \ldots, N_a. \end{cases} \tag{3}$$

Here $\mathbf{A}_j(\tilde{\alpha}_e)$ and $d_l(\tilde{\alpha}_e)$ are angle-dependent RFA coefficients identified from the aerodynamic derivatives. The formulation remains linear in the fast motion and self-excited forces, while aerodynamic stiffness, damping and memory terms vary in time through $\tilde{V}$ and $\tilde{\alpha}_e$.

The buffeting forces are obtained by linearizing the quasi-steady load with respect to u_{HF} and w_{HF}, and by introducing aerodynamic-admittance as follows:

$$\begin{cases} \mathbf{q}_b^{unst}(t) = \frac{1}{2}\rho \tilde{U}\mathbf{B}\left[\left(\mathbf{C}_f'(\tilde{\alpha}, \tilde{\alpha}_e) \circ \left[\mathbf{C}_1(\tilde{\alpha}_e) + \sum_{j=1}^{n_b-1} \mathbf{C}_{j+1}(\tilde{\alpha}_e) \right] \right) \mathbf{v}_{HF} \right. \\ \qquad \left. - \sum_{j=1}^{n_b-1} \frac{h_j \tilde{V}}{B} \left(\mathbf{C}_f'(\tilde{\alpha}, \tilde{\alpha}_e) \circ \mathbf{C}_{j+1}(\tilde{\alpha}_e) \right) \boldsymbol{\psi}_j \right], \\ \dot{\boldsymbol{\psi}}_j = -\frac{h_j \tilde{V}}{B}\boldsymbol{\psi}_j + \mathbf{v}_{HF}, \qquad j = 1, \ldots, n_b - 1. \end{cases} \tag{4}$$

$\mathbf{v}_{HF} = [u_{HF}\ w_{HF}]^T$ the high-frequency velocity vector, the symbol $\circ$ denotes the Hadamard product. The matrix $\mathbf{C}_f'$ contains the sensitivities of the quasi-steady load to the turbulent velocity fluctuations, while $\mathbf{C}_j$ and h_j define the RFA coefficients of the aerodynamic admittance.

At bridge level, the sectional formulation is applied along the deck and coupled with the structural model through the modal expansion $\mathbf{r}(x,t) = \Phi(x)\boldsymbol{\eta}(t)$. The resulting problem can be

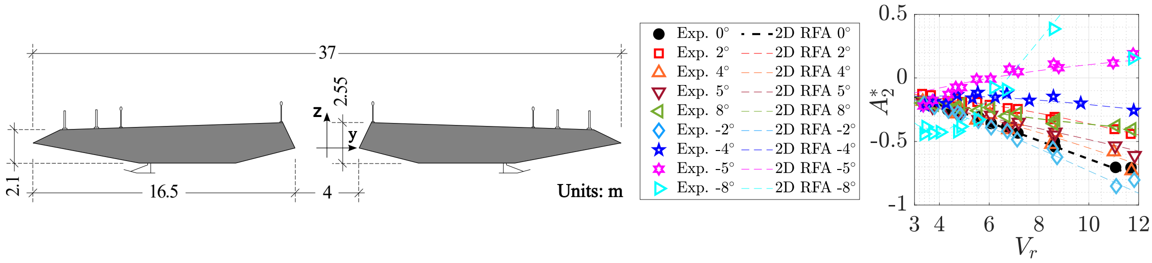

Figure 1. Halsafjorden Bridge twin-box deck section and sensitivity of the aerodynamic derivative A_2^* to the AoA with the 2D RFA fit in the background.

assembled in generalized coordinates and written as a linear time-varying state-space system,

$$\dot{\boldsymbol{\gamma}}(t) = \boldsymbol{\Omega}\left(\tilde{V}(x,t), \tilde{\alpha}_e(x,t)\right) \boldsymbol{\gamma}(t) + \mathbf{B}_{QS}\hat{\mathbf{q}}^{QS}(t) + \mathbf{B}_b\hat{\mathbf{q}}_b^{unst}(t), \tag{5}$$

where $\boldsymbol{\gamma}$ collects structural and aerodynamic states. Thus, the system remains linear with respect to the fast structural response, but the state matrix evolves with the local non-stationary wind conditions. The definition of the slow and fast components follows previous work and is not repeated here (Barni, 2022; Barni and Mannini, 2024).

3. BRIDGE CASE STUDY AND WIND FIELD SIMULATION

The methodology is applied to the Halsafjorden Bridge, a planned 2000-m-span suspension bridge. The structural model is formulated in generalized coordinates, while aerodynamic input comes from wind-tunnel tests (Barni et al., 2026). As shown in Fig. 1, the case is especially relevant because A_2^*, directly related to torsional aerodynamic damping, is highly AoA-sensitive.

The non-stationary turbulent field is generated along the deck as a multivariate process with prescribed evolutionary spectra and spatial coherence, using the stochastic-wave approach by Peng et al. (2017), well suited to many spatial points along a line. Turbulence and spectral properties are taken from wind scenario B of the Halsafjorden study (Barni et al., 2026). The slowly varying mean velocity follows Model II by Roncallo and Tubino (2023), with $\gamma^* = 0.474$ and $T = 75$ s, rising from about 30 m/s to approximately 63 m/s. In this preliminary application, turbulence intensity is kept constant. These parameters reproduce the flow acceleration observed during Storm Tor at the Hardanger Bridge site in late January 2016.

Two response models are compared. The reference calculation includes only the slow mean-velocity modulation $\bar{U}$ (Fig. 2), suppressing AoA modulation of the self-excited forces and keeping the aerodynamic admittance fixed. The fully time-varying calculation lets the local slowly varying velocity and effective AoA modulate the 2D RFA self-excited forces along the span, so that kinetic pressure, reduced velocity and aerodynamic-derivative variations are consistently included in the aeroelastic state matrix.

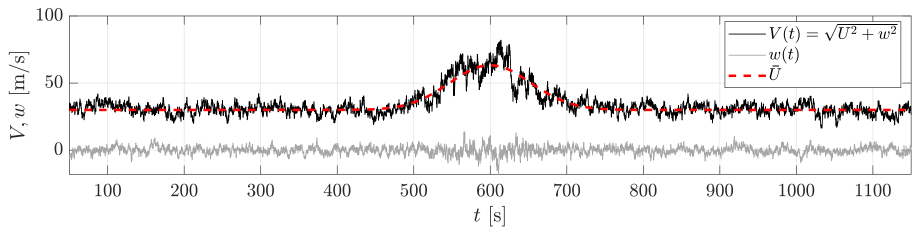

Figure 2. Example of simulated non-stationary wind at a deck section. The slowly-varying modulated mean wind velocity is also reported (dashed red line).

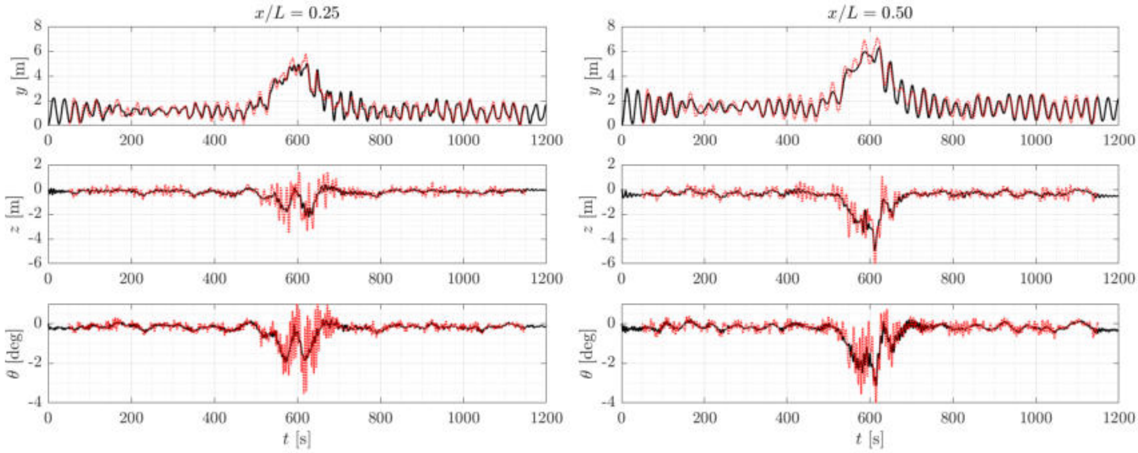

Figure 3. Comparison between the reference (in black) and the fully time-varying (dotted red line) response time histories at mid- and quarter-span for the simulated non-stationary event. Sway y, heave z and pitch θ are shown.

4. PRELIMINARY RESULTS AND CONCLUSIONS

Fig. 3 compares the reference and fully time-varying responses at quarter span and midspan. In the reference case, the gust produces a clear transient amplification: sway mainly follows the increased buffeting load, while heave and pitch are more affected by the dynamic response around the velocity peak. When the fully time-varying formulation is used, the sway response remains comparable, whereas heave and especially pitch fluctuations increase markedly during the most intense part of the event.

This amplification stems from the time-varying self-excited forces. As velocity increases, the effective AoA becomes strongly negative and A_2^* may become positive, as shown in Fig. 1. The resulting reduction in torsional aerodynamic damping can drive short intervals of transient instability, directly identified by mapping the maximum real part of the eigenvalues of the instantaneous state matrix $\mathbf{\Omega}(\tilde{V}, \tilde{\alpha}_e)$.

REFERENCES

Barni, N. (2022). Nonlinear buffeting response of suspension bridges considering time-variant self-excited forces. phdthesis, University of Florence, Norwegian University of Science, and Technology.

Barni, N. and C. Mannini (2024). Parametric effects of turbulence on the flutter stability of suspension bridges. Journal of Wind Engineering and Industrial Aerodynamics 245, 105615.

Barni, N., O. A. Øiseth, Ø. W. Petersen, and C. Mannini (2026). Long-term wind-induced response of suspension bridges including static response, flutter stability, and parametric effects of turbulence. Journal of Wind Engineering and Industrial Aerodynamics. submitted / in preparation; bibliographic details to be updated.

Calamelli, F., R. Rossi, T. Argentini, D. Rocchi, and G. Diana (2024). A nonlinear approach for the simulation of the buffeting response of long span bridges under non-synoptic storm winds. Journal of Wind Engineering and Industrial Aerodynamics 247, 105681.

Diana, G., S. Stoyanoff, T. Argentini, N. Barni, F. Calamelli, S. Hernández, A. Larsen, C. Mannini, D. Rocchi, R. Rossi, et al. (2025). IABSE TG3. 1 final analysis: Comparison between full-scale measurements and numerical simulations of a long-span bridge during a non-synoptic event. Proceedings of IABSE Congress Ghent 2025–The Essence of Structural Engineering for Society, 2111–2119.

Peng, L., G. Huang, X. Chen, and A. Kareem (2017). Simulation of multivariate nonstationary random processes: Hybrid stochastic wave and proper orthogonal decomposition approach. Journal of Engineering Mechanics 143, 04017064.

Roncallo, L. and F. Tubino (2023). Thunderstorm gust response factor: General tendencies and sensitivity analysis. Journal of Wind Engineering and Industrial Aerodynamics 236, 105376.