IN-VENTO 2026
International Conference of the Italian Association for Wind Engineering
Bari, September 13th – 16th, 2026

Long-term extreme bridge buffeting response accounting for parametric effects of turbulence

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SUMMARY:
A frequency-domain framework is presented for long-term extreme wind-induced response analysis of suspension bridges, including static response, flutter stability and parametric effects of turbulence associated with fluctuations in the wind angle of attack. Integrating the conditional distribution of response maxima over the population of environmental wind states (mean wind speed, turbulence intensities, etc.), long-term analysis addresses the limitations of classical short-term calculations. The method is applied to a 2000 m-main span suspension bridge under three different wind scenarios. Results show that the stochastic variability in turbulence intensity and turbulence-induced reduction in torsional aerodynamic damping can significantly increase the long-term torsional response associated with high return periods.

Keywords: Suspension bridges, buffeting response, extreme response, long-term analysis, flutter stability, turbulence

1. INTRODUCTION

Wind-induced extremes of long-span bridges are often estimated through a calculation performed at the design mean wind speed associated with the target return period for a stationary event of a duration complying with the wind spectral gap (short-term analysis). This classical route follows the framework introduced by Davenport, in which Rice's crossing theory and a Poisson model for response maxima are used to evaluate the peak of a stationary Gaussian process (Davenport, 1961; Rice, 1944). This classical approach has several limitations. First, for very flexible bridges, the distribution of response maxima conditioned to the mean wind velocity is not expected to be very narrow; therefore, the choice of the suitable percentile is an issue. Moreover, the calculated peak response significantly depends on the assumed duration of the short-term event (for instance, extending the observation time from 10 min to one hour can lead to differences in the estimated peak response of up to 20%–30%). Finally, the response associated with a given return period may be governed by different combinations of mean wind speed and turbulence characteristics, rather than by the design wind speed alone (especially if an omnidirectional analysis is carried out).

Full long-term analysis addresses the abovementioned limitations by integrating the short-term distribution of maxima over the probability distribution of all environmental variables considered (Næss, 1984; Næss and Moan, 2013). The resulting formulation is closely related to structural reliability and performance-based wind engineering, because the bridge response can be regarded as an engineering demand parameter conditioned on an environmental vector. The important difference is that the integration is performed over the population distribution of the short-term wind states, instead of only over the annual distribution of a selected intensity measure (Barni et al., 2026; Ciampoli et al., 2011; Melchers and Beck, 2018). In the present work, for the first time, the contributions of wind-induced static response and flutter instability to the probability of non-exceedance of the total response are included in the long-term analysis in a consistent way.

A further difficulty is that atmospheric turbulence modifies the instantaneous angle of attack of the deck. When the aerodynamic derivatives are sensitive to wind incidence, these fluctuations produce time-varying aerodynamic damping and stiffness (Barni et al., 2022; Chen and Kareem, 2003; Diana et al., 2013). Fully accounting for this mechanism generally requires time-domain simulations for each short-term wind state. The aim of this work is instead to include the most relevant turbulence-induced parametric effect within a computationally feasible frequency-domain long-term formulation.

2. LONG-TERM FORMULATION

Let $R(t)$ be a bridge response component, such as lateral, vertical or torsional deck displacement. Over a short interval T in th wind spectral gap, the wind state is assumed constant and the response is treated as stationary. If high-level crossings are independent, the short-term non-exceedance probability is:

$$F_{\hat{R}(T)}(r) = \exp\left[-\nu_R^+(r)T\right] \tag{1}$$

where $\nu_R^+(r)$ is the mean upcrossing rate of threshold r. For a Gaussian process with mean value μ_R, the upcrossing rate is given by:

$$\nu_R^+(r) = \nu_{R0}^+ \exp\left[-\frac{1}{2}\frac{(r-\mu_R)^2}{m_{R0}}\right], \qquad \nu_{R0}^+ = \frac{1}{2\pi}\sqrt{\frac{m_{R2}}{m_{R0}}} \tag{2}$$

where m_{R0} and m_{R2} are the zeroth and second spectral moments of the response. The static wind-induced displacement is included through μ_R and therefore directly changes the crossing probability, rather than being added after the dynamic calculation.

For a long-term duration $T_{LT} = NT$, let $\mathbf{w} \in \mathbf{W}$ collect the environmental random variables (for instance the mean wind velocity V_m, and the longitudinal and vertical turbulence intensities, I_u and I_w, respectively) with joint density $f_{\mathbf{W}}(\mathbf{w})$. Then, the long-term non-exceedance probability can be written as:

$$P\left[\hat{R}(T_{LT}) \leq r\right] = \left\{\int_{\mathbf{W}} \exp\left[-\nu_R^+(r|\mathbf{w})T\right] f_{\mathbf{W}}(\mathbf{w})\, d\mathbf{w}\right\}^N. \tag{3}$$

This form is adopted because it can handle zero conditional non-exceedance probabilities without further manipulation. Indeed, if $\mu_R(\mathbf{w}) \geq r$, the static response alone exceeds the considered threshold, and $F_{\hat{R}(T)}(r|\mathbf{w})$ is set to zero. Similarly, aeroelastic stability is checked for each wind state through the frequency-domain impedance matrix used in the buffeting calculation. The unstable states define a flutter sub-domain $\mathbf{W}_f \subset \mathbf{W}$; for $\mathbf{w} \in \mathbf{W}_f$, a conservative linear-divergence assumption is adopted, namely $F_{\hat{R}(T)}(r|\mathbf{w}) = 0$ for response thresholds of practical interest.

3. PARAMETRIC EFFECT OF TURBULENCE

It was shown in Barni and Mannini (2024) that the most important parametric effect of turbulence is by far the so-called average parametric effect. Such a nonlinear effect is considered in the present analysis by replacing the aerodynamic derivatives evaluated at the mean angle of attack with those averaged over the turbulence-induced angle-of-attack distribution. Therefore, for a generic aerodynamic derivative $AD(V_r, \alpha)$, where V_r is the reduced wind velocity,

$$\overline{AD}(V_r, \alpha_m, I_w) = \int AD(V_r, \alpha) f_\alpha(\alpha, \alpha_m, I_w)\, d\alpha \tag{4}$$

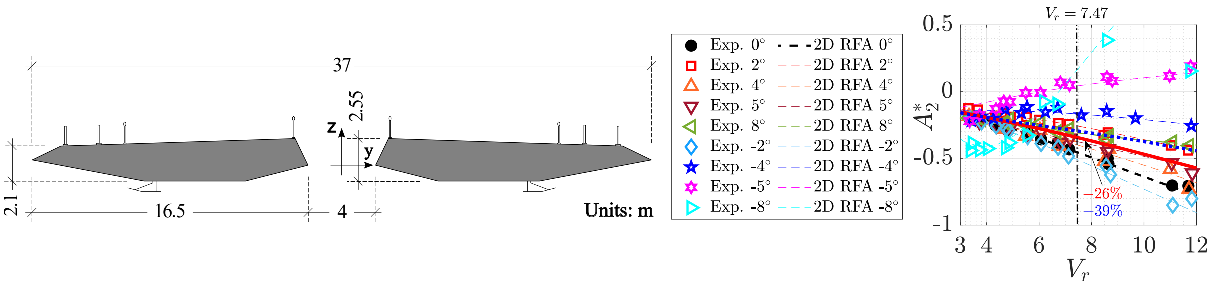


Figure 1. Sketch of the Halsafjorden Bridge deck section with units in meters (left); aerodynamic derivative A_2^* measured in the wind tunnel for various angles of attack (right). The averages around $\alpha_m = 0°$ are shown for vertical turbulence intensities $I_w = 5.6\%$ (dashed blue line) and 8.3% (solid red line).

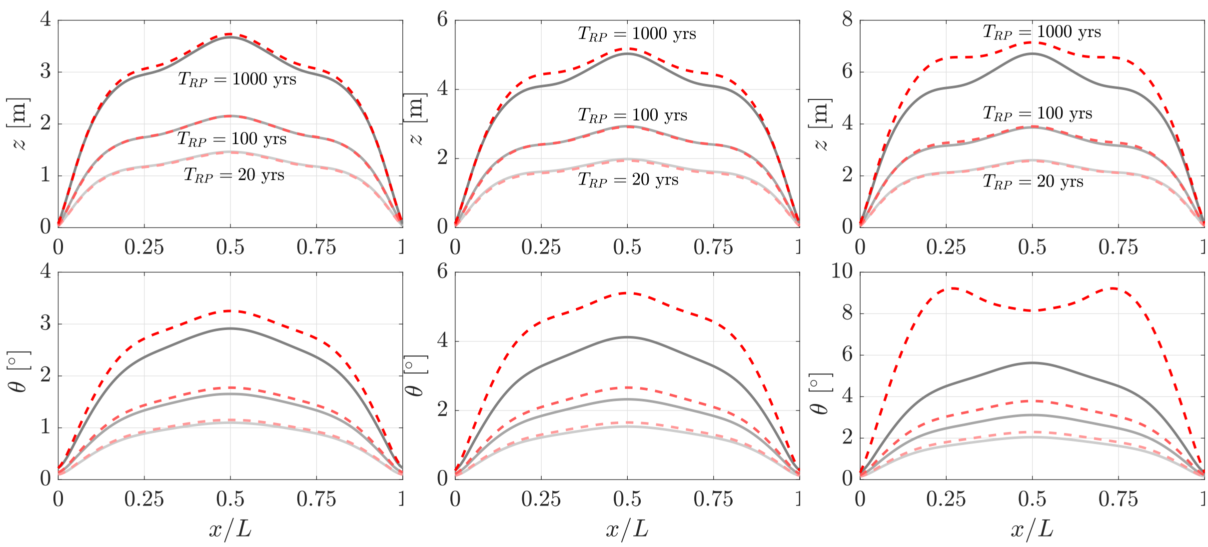
where α_m includes the mean wind inclination and the static deck rotation. Assuming $\alpha(t) \simeq w(t)/V_m$, being $w(t)$ the Gaussian vertical turbulent velocity fluctuation,

$$f_\alpha(\alpha, \alpha_m, I_w) = \frac{1}{I_w\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\alpha - \alpha_m}{I_w}\right)^2\right]. \tag{5}$$

The average derivatives are then used in the same frequency-domain buffeting and flutter analyses as the mean-angle case, so that the response spectral moments and the upcrossing rate in Eq. (2) become functions of the turbulence parameters entering Eq. (4). Fig. 1 illustrates why this operation is relevant for a suspension bridge deck: the important aerodynamic derivative A_2^*, directly contributing to torsional aerodynamic damping, is often highly sensitive to angle-of-attack variations and therefore to an averaging over α.

4. APPLICATION TO THE HALSAFJORDEN BRIDGE

The presented framework is applied to the planned Halsafjorden Bridge, Norway, with a main span L of 2000 m (Fig. 1). Three wind scenarios are considered: a reference wind climate for the Halsafjord (A), increased turbulence intensities tipical of another norwegian fjord (B), and increased turbulence combined with a more severe mean-wind distribution (C). In the complete



(a) Wind scenario A
(b) Wind scenario B
(c) Wind scenario C

Figure 2. Vertical and torsional extreme response of the Halsafjorden Bridge along the span with and without the average parametric effect, for different return periods.

study, long-term analyses are repeated by progressively increasing the number of environmental random variables: first only V_m, then V_m and I_w, and finally V_m, I_u and I_w (Barni et al., 2026).

The results for the analysis in which both V_m and I_w are treated as random variables are reported in Fig. 2. The total response includes both static and dynamic components through Eq. (2). The parametric effect of turbulence impacts especially on the torsional response and for exceedance probabilities associated with high return periods T_{RP}. The change in the shape of the response along the span for $T_{RP} = 1000$ years is due to the contribution of the antisimmetric mode, which becomes low damped approaching the flutter critical wind speed.

5. CONCLUSIONS

For the considered case study, the following main conclusions can be drawn.

- If the mean wind speed is the sole environmental random variable, the difference between the long-term response and that obtained using the classical Davenport short-term approach is only minor. In contrast, the difference noticeably increases when the vertical turbulence intensity is treated as a random variable.
- The average parametric effect of turbulence may significantly influence the long-term bridge response, especially for high return periods when the aerodynamic damping plays a significant role in the bridge dynamics.
- The impact of the average parametric effect of turbulence is practically identical on the long-term and classical short-term approach for low-to-medium return periods (e.g., up to 100 years). In contrast, this nonlinear effect of turbulence has a stronger influence on the long-term response for high return periods (e.g., 1000 years).
- The rigorous inclusion of static response and flutter instability in the long-term analysis non-negligibly affects the probability of excedance of given response thresholds.

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