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Experimental validation of parametric effect of turbulence in buffeting response and flutter stability

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SUMMARY:
This work presents an ongoing wind-tunnel study aimed at validating the turbulence-induced average parametric effect previously isolated numerically by the authors. An elastically suspended two-degree-of-freedom flat-plate model is designed to become unstable in smooth flow where the aerodynamic derivatives are strongly sensitive to the angle of attack. Preliminary simulations predict a measurable reduction of the flutter threshold in grid-generated turbulent flow and guide the forthcoming experiments.

Keywords: flutter instability, turbulent flow, parametric excitation, average parametric effect, stochastic stability

1. INTRODUCTION

There is a common perception in the literature that the role of atmospheric turbulence in flutter stability is still not completely understood. Classical calculations linearize self-excited forces around a steady flow condition, treating turbulence only as an external buffeting excitation. Large-scale fluctuations, however, may also parametrically modify the homogeneous aeroelastic system through kinetic-pressure, reduced-velocity and effective-angle-of-attack variations.

Early stochastic approaches on random flutter stability mainly focused on random kinetic-pressure fluctuations and the associated variation of aerodynamic damping and stiffness (Lin and Ariaratnam, 1980). A complementary line of research, initiated by Diana and co-workers, recognised that large-scale turbulence also changes the instantaneous wind incidence, modulating the self-excited forces through angle-dependent aerodynamic derivatives (Diana et al., 1993); this led to nonlinear buffeting formulations (Diana et al., 2013), time-domain models by Chen and Kareem (2001), and the 2D RFA framework adopted by the authors (Barni and Mannini, 2024; Barni et al., 2022). In this context, Barni and Mannini (2024) and Barni et al. (2024) showed, through Floquet and Lyapunov analyses, that turbulence-induced angle-of-attack fluctuations may reduce flutter stability mainly through two mechanisms: an average parametric effect, associated with the mean shift of aerodynamic stiffness and damping, and possible parametric resonances. Therefore, when a section aerodynamically deteriorates away from its most favourable incidence, usually close to zero, turbulence is expected to reduce the flutter threshold with respect to the classical linearized prediction.

This mechanism has been analysed numerically but not yet observed experimentally in a clear and targeted way. A further open issue concerns which frequencies of the turbulence spectrum, or equivalently which eddy scales, are effective in modulating the self-excited forces, directly affecting the cutoff frequency used to define the slowly varying angle of attack. The present work addresses these points through a flat plate elastically suspended in heave and pitch. The flat plate is particularly suitable because available aerodynamic derivatives show a strong angle-of-attack sensitivity, especially for the torsional damping derivative A_2^* (Wu et al., 2020). Since the wind-tunnel tests have not yet been performed, this abstract presents the experimental strategy and the preliminary numerical predictions used to guide them.

2. NONLINEAR BUFFETING RESPONSE MODEL

The sectional model is described by the vertical displacement $z(t)$ and torsional rotation $\theta(t)$, collected in the vector

$$\mathbf{r}(t) = \begin{bmatrix} z(t) & \theta(t) \end{bmatrix}^T . \tag{1}$$

The incoming flow is decomposed into a mean velocity V_m and turbulent fluctuations $u(t)$ and $w(t)$. The slowly varying angle of attack associated with large-scale turbulence is written as

$$\tilde{\alpha}(t) = \text{atan}\left[\frac{\tilde{w}(t)}{V_m + \tilde{u}(t)}\right], \tag{2}$$

where the tilde denotes the low-frequency part of the turbulent signal.

The aeroelastic equation of motion reads

$$\mathbf{M}\ddot{\mathbf{r}}(t) + \mathbf{C}\dot{\mathbf{r}}(t) + \mathbf{K}\mathbf{r}(t) = \mathbf{q}_{se}(\tilde{\alpha},t) + \mathbf{q}_b(t), \tag{3}$$

where $\mathbf{q}_b$ is obtained by linearizing the quasi-steady buffeting forces, while the self-excited forces vary in time through $\alpha(t)$. According to the 2D RFA formulation,

$$\mathbf{q}_{se}(\tilde{\alpha},t) = \frac{1}{2}\rho V_m^2 \left[\mathbf{A}_1(\tilde{\alpha})\mathbf{r}(t) + \frac{B}{V_m}\mathbf{A}_2(\tilde{\alpha})\dot{\mathbf{r}}(t) + \sum_{l=1}^{N_a} \mathbf{A}_{l+2}(\tilde{\alpha})\boldsymbol{\lambda}_l(t)\right], \tag{4}$$

with aerodynamic lag states

$$\dot{\boldsymbol{\lambda}}_l(t) = -\frac{d_l(\tilde{\alpha})V_m}{B}\boldsymbol{\lambda}_l(t) + \dot{\mathbf{r}}(t), \qquad l = 1,\ldots,N_a. \tag{5}$$

Introducing the structural and aerodynamic states in the vector $\boldsymbol{\gamma}(t)$ gives the linear time-varying system

$$\dot{\boldsymbol{\gamma}}(t) = \boldsymbol{\Omega}[\tilde{\alpha}(t), V_m]\,\boldsymbol{\gamma}(t) + \mathbf{B}_q\mathbf{q}_b(t). \tag{6}$$

The homogeneous part of Eq. (6) governs stability. The full stochastic problem can be studied through Lyapunov or moment Lyapunov exponents, accounting for both average effects and possible parametric resonances. Conversely, the average parametric effect alone can be isolated through the equivalent linear time-invariant procedure proposed by Barni and Mannini (2024). In this approach, the aerodynamic damping and stiffness terms are first averaged over the probability density of the turbulent angle of attack:

$$\overline{\mathbf{C}}_{ae}(V_m) = \mathbb{E}_{\tilde{\alpha}}\left[\mathbf{C}_{ae}(\tilde{\alpha},V_m)\right] = \int \mathbf{C}_{ae}(\tilde{\alpha},V_m)\, p_{\tilde{\alpha}}(\tilde{\alpha})\, d\tilde{\alpha}, \tag{7}$$

$$\overline{\mathbf{K}}_{ae}(V_m) = \mathbb{E}_{\tilde{\alpha}}\left[\mathbf{K}_{ae}(\tilde{\alpha},V_m)\right] = \int \mathbf{K}_{ae}(\tilde{\alpha},V_m)\, p_{\tilde{\alpha}}(\tilde{\alpha})\, d\tilde{\alpha}. \tag{8}$$

Under Gaussian vertical turbulence and negligible longitudinal fluctuations, $p_\alpha(\alpha)$ can be written in closed form by approximating $\tilde{\alpha} \simeq w/V_m$, as detailed in Eqs. (19)–(21) of Barni and Mannini (2024). The averaged aerodynamic terms are then introduced in the RFA-based state-space model, yielding an equivalent time-invariant matrix $\boldsymbol{\Omega}_{\text{eq}}(V_m)$. The average-parametric flutter threshold is finally obtained from the deterministic eigenvalue condition

$$\max_j \left\{\text{Re}\left[\lambda_j\left(\boldsymbol{\Omega}_{\text{eq}}(V_m)\right)\right]\right\} = 0. \tag{9}$$

This equivalent system describes only the mean shift of aerodynamic stiffness and damping, whereas Eq. (6) also includes the dynamic effects of stochastic parametric excitation.

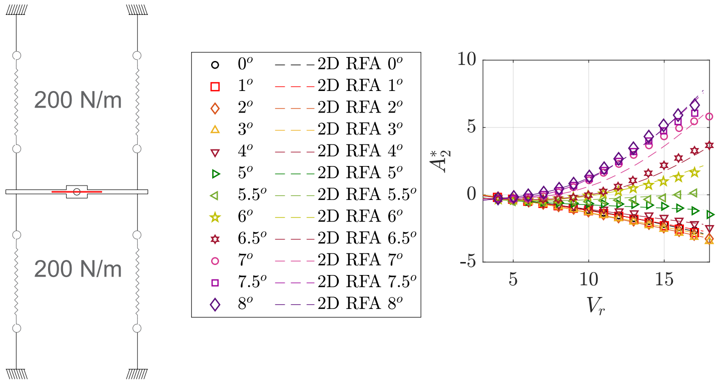

Figure 1. Two-degree-of-freedom flat-plate setup and sensitivity of the torsional aerodynamic derivative A_2^* to the angle of attack, with the 2D RFA fit in the background.

Table 1. Main mechanical properties of the flat-plate setup. The chord-to-thickness ratio is $B/D = 40$.

Quantity	Symbol	Value	Quantity	Symbol	Value
Plate chord	B	0.120 m	Model span	L	1.00 m
Heaving mass	m	1.643 kg	Torsional inertia	I_θ	0.0112 kg m^2/m
Heaving frequency	f_z	4.967 Hz	Torsional frequency	f_θ	6.003 Hz
Heaving damping	ξ_z	0.15 %	Torsional damping	ξ_θ	0.20 %

3. EXPERIMENTAL VALIDATION STRATEGY

The proposed experiment will be carried out in the CRIACIV wind tunnel on a flat plate elastically suspended in heave and pitch (see Fig. 1) The model has chord $B = 120$ mm, thickness $D = 3$ mm and span $L = 1.00$ m. The suspension system is designed so that the smooth-flow flutter critical reduced velocity falls in the interval $V_{r,cr} = 16$–18, where the available flat-plate aerodynamic derivatives show a pronounced dependence on the angle of attack, especially A_2^*. The current design gives $V_{m,cr} = 11.7$ m/s, $V_{r,cr} = 17.11$ and $f_{cr} = 5.72$ Hz in smooth flow.

The first experimental phase will be performed in smooth flow, to identify the still-air modal properties and verify the deterministic flutter prediction. The second phase will be carried out in grid-generated turbulent flow. A large-scale grid previously used in CRIACIV wind-tunnel studies will be considered (Pigolotti et al., 2017), aiming at an integral length scale of the order of one to two plate chords and sufficiently large vertical-turbulence intensity to produce appreciable angle-of-attack fluctuations.

The turbulent-flow tests will be designed to distinguish a true stability reduction from a mere increase of forced buffeting response. To this aim, the elastically suspended setup has been optimized to match the target reduced-velocity range while keeping the pre-critical response amplitude as limited as possible. Long acquisitions are needed because stochastic time-varying systems may exhibit different sample- and moment-stability properties. Stability interpretation will be supported by the assesment of Lyapunov and moment Lyapunov exponents.

4. PRELIMINARY NUMERICAL RESULTS

Preliminary simulations are performed to verify whether the setup is expected to show a measurable turbulence-induced reduction of the flutter threshold. The reference calculation is linear time-invariant, with self-excited forces evaluated at the mean angle of attack; the time-varying calculations instead include the modulation of the 2D RFA coefficients by the low-frequency component of $\tilde{\alpha}(t)$.

Fig. 2 reports the RMS vertical and torsional responses predicted for the target grid-generated

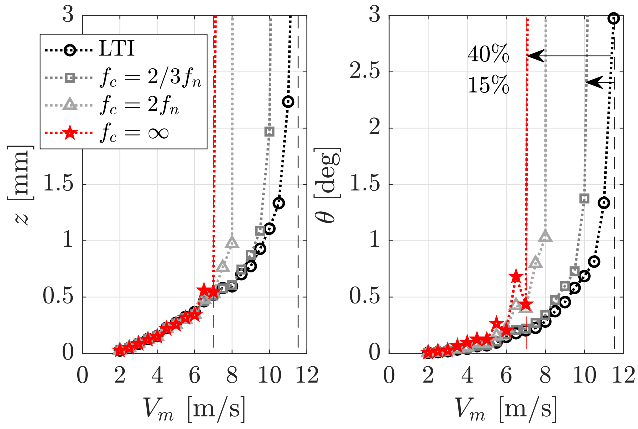

Figure 2. Numerical RMS response in heave and pitch versus mean wind velocity. Black curves: linear time-invariant model. Grey curves: time-varying simulations with different cutoff frequencies. Red curves: no-cutoff case, where the whole turbulent spectrum is assumed to modulate the self-excited forces.

turbulent flow. Turbulence is generated at 10 points along the model span to account for partial correlation, with signal duration $T = 120$ s and sampling frequency $f_s = 80$ Hz.

The grey curves refer to filtered time-varying simulations based on the multiple-cutoff strategy of Barni et al. (2022). The most conservative case, with cutoff frequencies equal to about two thirds of the relevant natural frequencies, is consistent with the range where the modulation of self-excited forces has direct experimental support and already predicts an approximately 15% reduction of the stability threshold. Increasing the cutoff lets more turbulent energy contribute to the parametric modulation and further anticipates the instability.

The red curves represent the limiting no-cutoff case, where the whole turbulent spectrum is assumed to modulate the aerodynamic derivatives, leading to a predicted reduction of about 40%. The forthcoming turbulent-flow experiments are expected to fall between these bounds, thus providing information on the turbulent energy effectively involved in the parametric excitation and on a reasonable cutoff criterion.

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