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A CFD Study on the Influence of Free-stream Deterministic Gusts on the Critical Flutter Velocity of Streamlined Bridge Decks

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1 Abstract

In the design of super-long-span bridges, the wind actions are commonly a governing criterion. Critical design checks for wind-induced vibrations involve experimental and numerical procedures for determination of the flutter instability threshold, commonly under laminar free-stream. The influence of free-stream turbulence on the critical flutter velocity of bridge decks still represents an open topic in bridge aerodynamics. This paper presents an investigation of the influence of free-stream deterministic gusts on the critical flutter velocity using Computational Fluid Dynamics (CFD). Deterministic free-stream harmonic gusts are simulated by modelling the wake of two flapping airfoils using the two-dimensional Vortex Particle Method (VPM). These gusts are then applied to a streamlined bridge deck and the oscillation amplitudes are studied for various gust amplitudes and frequencies. The results indicate that the critical flutter velocity is reduced for harmonic gusts with a frequency similar to the critical frequency under laminar free-stream, while it is not in affect for gust frequencies corresponding to the structural frequencies. By dissecting the random free-stream into harmonic gusts, this study aims to provide a deeper understanding of the physical processes occurring in the fluid-structure interaction near the instability threshold.

Keywords: Flutter, Long-span bridges, CFD.

2 Introduction

Since the Tacoma Narrows incident back in 1940, engineers have been trying to understand flutter as a phenomenon that causes violent bridge vibrations at potential design wind speeds. Much research has been done on the front of flutter for laminar free-stream in the past few decades; however, the influence of free-stream turbulence yet remains not fully understood. Experimental tests have shown results that turbulence can both increase and decrease the critical flutter wind speed, depending on the ratio between the turbulent length scales and span/width of the deck [1,2]. Most of the studies agree that the 3D effects are a key factor; however, it is complicated to separate their influence from the 2D turbulent effects experimentally for a dynamic model.

Apart from experimental tests, simulation models based on CFD has also become an important tool to investigate the fluid-structure interaction. As one of the numerical discretization schemes, the 2D VPM has been extensively used to under both laminar and turbulent free-stream [3,4]. The VPM discretizes the Navier-Stokes equations by circulation-carrying particles.

In this paper, we utilize a recently developed method for simulation of deterministic free-stream turbulence [5], based on the VPM, to study the influence of incoming sinusoidal gusts on the critical flutter velocity. By dissecting the frequency content of the free-stream turbulence, an attempt is made to study its influence on the flutter limit.

3 Deterministic Gusts

The concept of simulating incoming deterministic gusts is based the idea of Active Turbulence Generator (ATG) used in experiments, and is depicted in Fig. 1. An ATG represents a set of flapping airfoils, oscillating in- or out-of-phase. For the in-phase case, a sinusoidal vertical gust is generated along the centerline. If a body with width B is positioned downstream, such gust will yield sinusoidal forces.

Within the employed CFD method for simulating free-stream sinusoidal gusts, the wakes of the airfoils are modeled by inflow vortex particles that carry concentrated circulation Γ_F^{in}. These particles are released in the CFD domain at two locations upstream of the section and are converted downstream by the mean wind speed U solving. The fluid equations are solved by using the VPM. Assuming non-interacting wakes and that the particles are converted along horizontal line (planar wake assumption), this ultimately results in a sinusoidal vertical gust w with a frequency f_{gust}. Since the fictitious airfoils are oscillating in a sinusoidal manner, the discrete inflow circulation is also sinusoidal. Thus, two particles are released each time-step j with strength $\Gamma_{F,j}^{in}$, obtained as

$$\Gamma_{F_A,j}^{in} = \Gamma_{F_B,j}^{in} = \Gamma_{F,j}^{in} = \Gamma_{F0}^{in} e^{i2kj\Delta\tau_F}, \qquad (1)$$

where $i = \sqrt{-1}$; $k = 2\pi f_{gust} B/(2U)$ is the reduced frequency based on the airfoil width B (assumed similar as the deck width); $\Delta\tau_F = \Delta t_F U/B$ is the reduced time-step, based on the dimensional time-step Δt_F of particle injection.

To relate the circulation amplitude Γ_{F0}^{in} with the gust amplitude along the centerline w_{c0}, in [5] the following relation was derived:

$$\Gamma_{F0}^{in} = \left| \frac{w_{c0}\pi B\, H_1^{(2)}(k)}{4(k-1i)} e^{\frac{k l_R}{B}} \left(e^{-i2k\Delta\tau_F} - 1\right) \right| \qquad (2)$$

where $H_1^{(2)}$ is Hankel function of second kind and l_R is the distance between the two particle locations (cf. Fig. 1).

Next, the flow field is studied for a sinusoidal gust that will be used in the following section. For the present study, relative gust amplitudes ($I = w_0/U$) of 2.5 and 5% are targeted with reduced velocities $V_r = U/(f_{gust}B)$ in the range $7 < V_r < 30$. The selected CFD domain is $20B \times 20B$ with $l_R = 1.5B$, for $B = 31$ m.

Figure 2 (left) presents time-histories of the vertical w and horizontal fluctuations u at the center of the domain at $V_r = 25$ and $I = 5$, including the corresponding Fast Fourier Transforms (FFT). A clear vertical sinusoid can be observed at the target reduced velocity; however, a slight reduction in the amplitude is noted. This discrepancy is due to the violation of the planar wake assumption, which can be directly observed from the instantaneous particle map in Fig.3 (left).

As noted in [5], the reduction between the target and obtained gust amplitude can be up to 25%, proportionally depended on the reduced velocity. The instantaneous field of the velocity magnitude (cf. Fig 3, right) depicts a sinusoidal behavior across the domain as well.

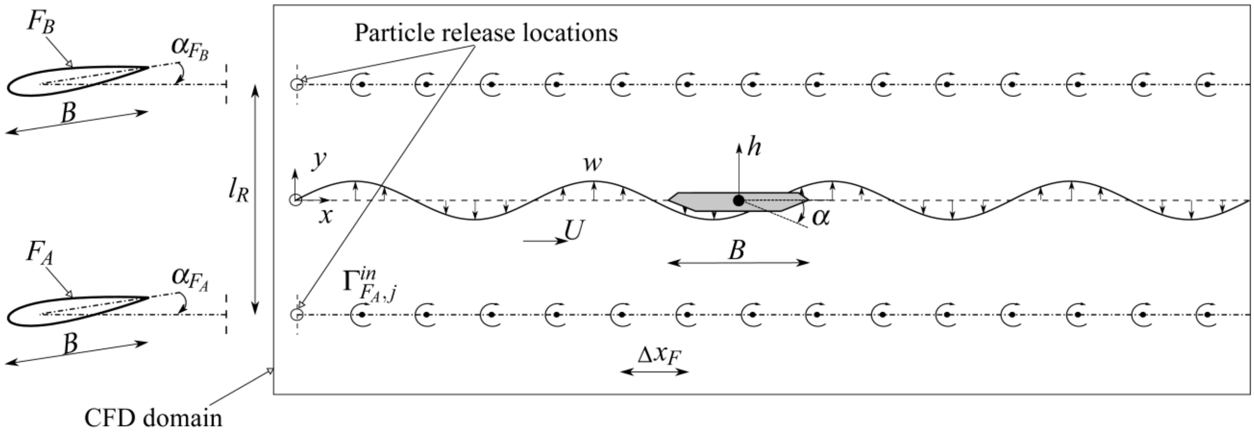

Figure 1. Concept of numerical ATG for generation of deterministic free-stream turbulence using the VPM

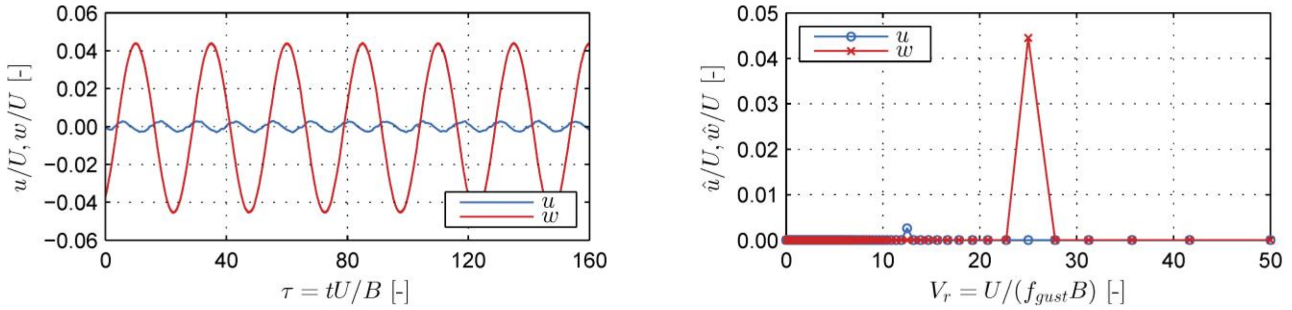

Figure 2. *: Time-histories of the velocity fluctuations (left) and their corresponding FFTs (right) at* $V_r = 25$ *and* $I = 5\%$

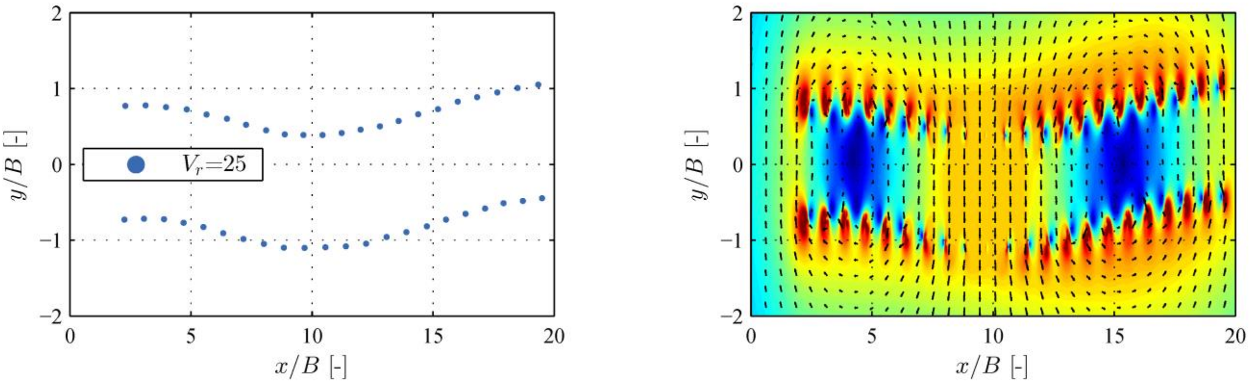

Figure 3. *Instantaneous particle maps (left) and instantaneous velocity vector field at* $V_r = 25$ *(right)*

4 Flutter

Having studied the sinusoidal gusts in the previously, they are applied to a 2D bridge deck, performing vertical h and rotational α oscillations. The deck is selected to be the one of the Great Belt Bridge (cf. Fig.1), with the following parameters: width $B = 31$m; vertical and rotational frequencies $f_h = 0.1$ Hz and $f_\alpha = 0.278$ Hz, respectively; mass $m = 22.74$ t/m and inertial mass $m = 2.47 \times 10^3$ tm^2/m; damping ratio 0.5%.

The laminar critical flutter velocity $U_{cr}^{Lam} = 72.2\,m/s$ was determined and reported in a previous study [4]. Figure 4 (top) depicts the time-histories at and below U_{cr}^{Lam}. The critical frequency of the initial part ($t \approx 0 - 100$ s) was found to be $f_{cr}^{1} = 0.218$ Hz, which shifted to $f_{cr}^{2} = 0.25$ Hz in the limit cycle oscillation regime ($t \approx 150 - 250$ s), due to large separation (cf. [4] for detailed discussion and validation).

Next, the flutter velocity is identified for sinusoidal gusts with target amplitudes $I_{1t} = 2.5\%$ and $I_{2t} = 5\%$. For the gust frequencies, the gust amplitudes recorded at 2B upstream of the section yielded $I_1 = 1.8 - 3.5$ % and $I_2 = 3.7 - 7$ % (the over-/underestimation was corresponding). Figure 4 (top-center, center-bottom and bottom) depicts the time-histories of the displacements at and below the turbulent critical flutter velocity U_{cr}^{Turb}, for gust frequencies corresponding to f_h, f_{cr}^{1}, f_α, respectively. Small change in or U_{cr} is observed at resonant frequencies f_h and f_α. It is interesting to notice that there is kind of resonant oscillation that snaps to a critical regime at U_{cr}^{Turb}. The vertical oscillation amplitudes for $f_{gust} = f_h$ are in the same range for $U < U_{cr}^{Turb}$ as in $U = U_{cr}^{Turb}$; however, the frequency is different.

In case of $f_{gust} = f_{cr}^{1}$, the oscillation behavior is different than for the one for gusts with frequencies corresponding to the natural frequencies. Below the determined critical velocity, there are oscillations with large amplitudes for the rotation; however, they seem to be stabilizing. This is not the case at the selected U_{cr}^{Turb}. As the section experiences kind of soft-flutter regime, it was difficult to identify the U_{cr}^{Turb}. It is also noted that for very large ($\alpha > 25$ deg), issues were noted in the vortex release algorithm; hence, the results might lack of numerical accuracy. Nevertheless, the vertical and torsional frequencies synchronized at U_{cr}^{Turb}.

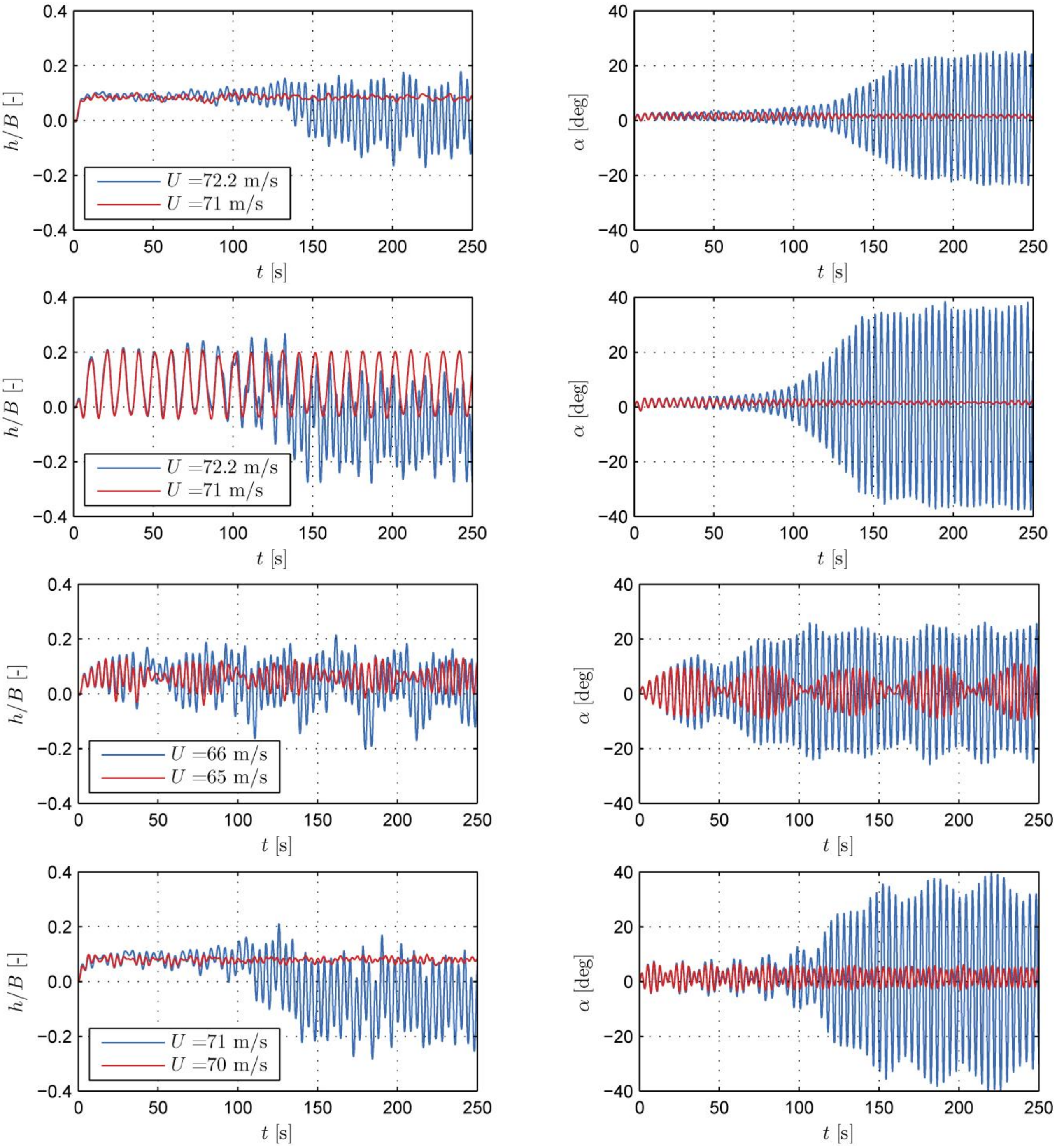

Figure 4. Vertical (left) and rotation (right) oscillations below (blue) and at critical wind speed (red): from top-to-bottom: laminar; $f_{gust} = f_h$ *at* I_1; $f_{gust} = f_{cr}^1$ *at* I_1; $f_{gust} = f_\alpha$ *at* I_2

Figure 5 depicts instantaneous particle maps corresponding to an oscillation cycle for the fluttering velocity for gust with $f_{gust} = f_{cr}^1$. Separating flow structures can be observed at the leading edge at maximum rotation. It should be noted that in case of oscillating body, the body does not cross the airfoil wakes path.

Finally, the ratio between the turbulent and laminar flutter velocity is given in Fig. 6 for the two turbulent cases. It can be observed that only for the resonant cases, there was no or minor influence of the gust on the critical speed.

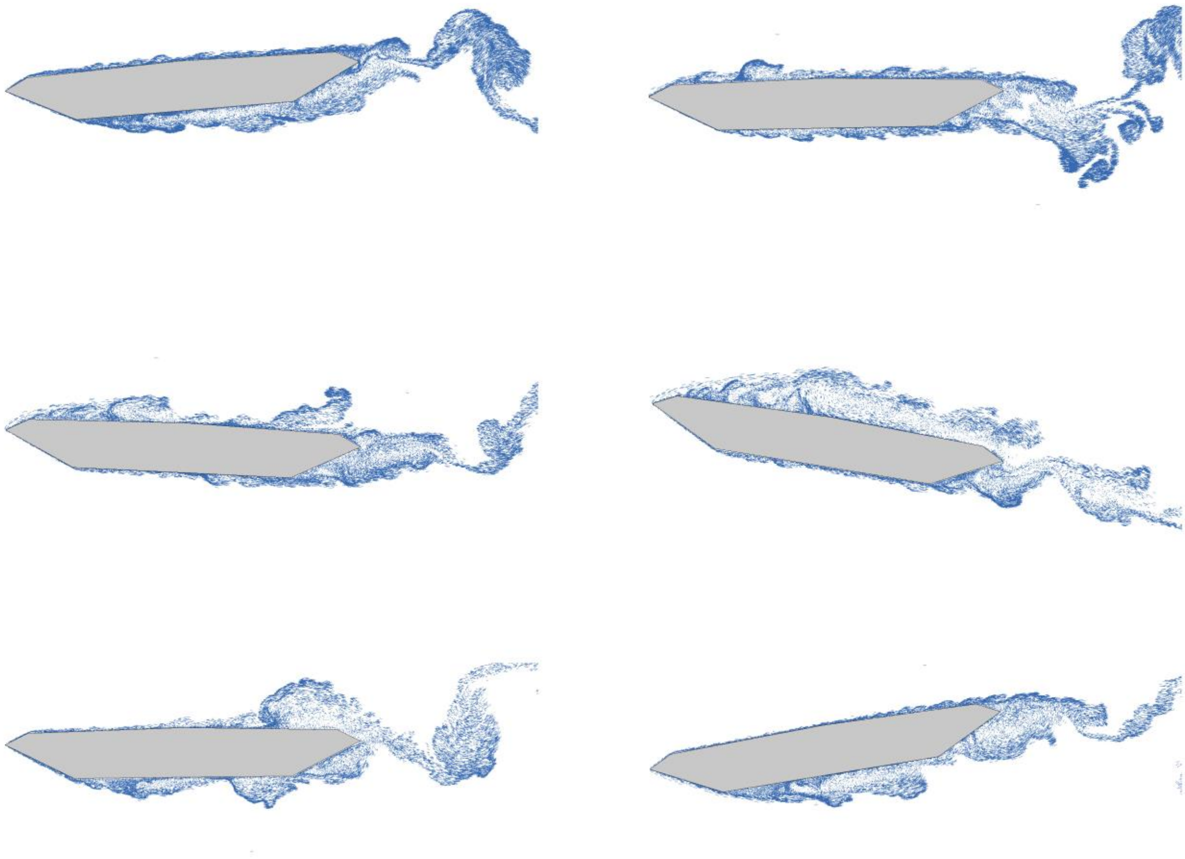

Figure 5. Instantaneous particle maps of an oscillation cycle (left-right; top-bottom) at U_{cr}^{Turb} *and* $f_{gust} = f_{cr}^{1}$

In the other cases, particularly around $f_{gust} = f_{cr}^{1}$, the free-stream turbulence has a destabilizing effect for increasing gust intensity. Another particularity that can be noticed is that at $f_{gust} = f_{cr}^{2}$, the critical flutter velocity for the I_2 case resulted in lower values (it was not determined precisely).

5 Conclusions

The influence of 2D incoming sinusoidal vertical gusts on the critical flutter velocity was studied. Apart for gust frequencies corresponding to the natural frequencies, the analyses showed that the sinusoidal gusts have a destabilizing effect. On the other hand, the resonant behavior seemed to have a stabilizing effect.

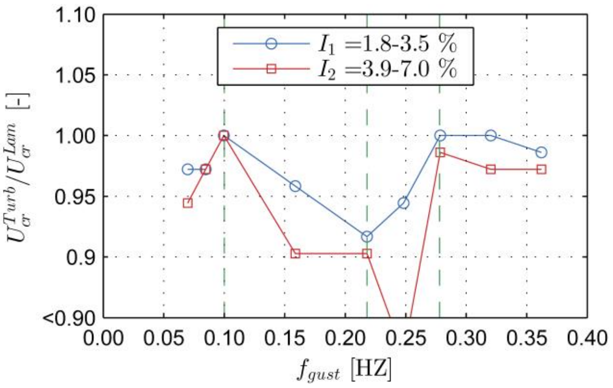

Figure 6. Influence of vertical gusts on flutter. The dashed green lines denote the vertical, critical (laminar) and rotational frequencies, from left-to-right, respectively

6 References

[1] R.L. Wardlaw, H. Tanaaka, H. Utsunomiya, "Wind Tunnel Experiments on the Effects of Turbulence on the Aerodynamic Behavior of Bridge Road Decks*," Journal of Wind Engineering and Industrial Aerodynamics*, vol 14, pp 247-257, 1983.

[2] G. Bartoli, M. Righi, "Flutter Mechanism for Rectangular Prisms in Smooth and Turbulent Flow*," Journal of Wind Engineering and Industrial Aerodynamics*, vol 94, pp 275-291, 2006.

[3] G. Morgenthal, J. Walther, "An Immersed Interface Method for the Vortex-In-Cell Algorithm*," Computers & Structures*, vol 85, pp 712-726, 2006.

[4] I. Kavrakov, G. Morgenthal, "A Synergistic Study of a CFD and Semi-analytical Models for Aeroelastic Analysis of Bridges in Turbulent Wind Conditions*," Journal of Fluids and Structures*, vol 82, pp 59-85, 2018.

[5] I. Kavrakov, T. Argentini, S. Omarini, D. Rocchi, G. Morgenthal, "An Active Turbulence Generator based on the Vortex Method for Simulation of a Complex Aerodynamic Admittance for Bridge Decks," in Proc. 7th CWE, Seoul, 2018.