Influence of parameters on VIV spectral approach for circular cylinders

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SUMMARY:
The present paper addresses the application of the VIV spectral model for the evaluation of the vortex-induced vibrations of circular-shaped structures excited by the wind, focusing on the parameters whose choice is crucial in the response calculation of lightweight, low-damped systems. It is shown that uncertainties inherent in the model parameters and in the calculation models (the limiting amplitude and the peak factor in particular) give rise to major criticisms in the neighbourhoods of the critical vortex-shedding velocity. A wind tunnel experimentation was carried out in the "Giovanni Solari" Wind Tunnel of the University of Genoa on a smooth cylinder in smooth flow conditions in order to obtain new data to add to those already available in the literature. With the aim of improving the application of the spectral model, possible trends and relationships are investigated, useful for the proper estimate of the model parameters, in order to achieve reliable estimates of VIV response.

Keywords: VIV spectral model, VIV limiting amplitude, VIV peak coefficient

1. INTRODUCTION

Vortex-induced vibrations (VIV) are a fundamental topic in wind engineering problems. They arise from a combination of forces induced by pressure fluctuations associated with the shedding of vortices and additional motion-dependent forces, which may cause large across-wind oscillations when the shedding frequency is close to a natural frequency of the structure. A typical result of vortex resonance is the lock-in effect which usually occurs in lightweight, low-damped structures when the vortex shedding becomes synchronized with the vibration frequency at sufficiently large amplitudes, violating the Strouhal law over a specific range of wind velocity (e.g., Ruscheweyh, 1994). It is an inherently nonlinear self-governed phenomenon, the knowledge of which needs to interlace physical and numerical experiments (Sarpkaya, 2004). Vortex-induced phenomenon usually occurs at wind velocities lower than design values; therefore, it must be assessed in structural verifications (e.g., serviceability, ultimate limit state, fatigue). The wind tunnel tests carried out by Wooton (1970) on vertical stack models still represent a reference case for technical studies on this topic.

VIV calculation procedures commonly used in engineering evaluation (e.g., CNR, 2019; EN 1991-1-4, 2010) are based on semi-empirical models such as the spectral model proposed by

Vickery and Basu (1983) and the harmonic model proposed by Ruscheweyh (1994). The former, based on a fluid-elastic conception of the phenomenon, supplies an analytical expression for the equivalent aerodynamic damping derived from a modified van der Pol oscillator; in this context, technical developments have been proposed by Hansen (1999; 2007). The latter, deduced from a simple forced-system model, supplies an exciting force governed by the so-called 'effective correlation length' of vortex-induced forces, which increases with the vibration amplitude. Other advanced models, such as coupling of structure and wake oscillators, allow to better capture the essential features of VIV also in complex geometries but have, at the moment, few technical applications on real structures. Recent papers (e.g., Lupi et al., 2021) confirm the suitability of spectral methods to predict VIV but question a van der Pol aerodynamic damping proposing a different modeling fitting by experimental tests. On the other hand, one of the most important of these unanswered questions about VIV is the relationship between the maximum cylinder response amplitude and the system mass and damping (Govardhan and Williamson, 2006). These diagrams, commonly called Griffin plots, they may attempt to answer this question and may support (or, in some cases, avoid) the use of technical approaches.

Recently Pagnini and Piccardo (2017) and Pagnini et al. (2020) have proposed a thorough investigation of the spectral model pointing out several issues to be explored for the purpose of its correct application. The present paper intends to pursue this research objective by investigating some aspects that may lead to considerable uncertainties in the assessment of the VIV response on circular-shaped cylinders.

2. VIV SPECTRAL APPROACH

Within a VIV spectral approach, assuming that the resonant stochastic response is governed by the classic solution for low-damped single degree-of-freedom linear systems, a closed-form expression for the standard deviation of the crosswind response can be derived (e.g., Pagnini and Piccardo, 2017):

$$\sigma_y = \sqrt{c_{1F} + \sqrt{c_{1F}^2 + c_{2F}}} \tag{1}$$

where

$$c_{1F} = \frac{b^2}{2\kappa^2 \psi_y^2(\hat{z})}\left[1 - \frac{Sc}{4\pi C_1^a}\right], \quad c_{2F} = \frac{m_{ye} C_f^a}{\rho \kappa^2 \psi_y^2(\hat{z}) C_1^a} \tag{2}$$

$$C_f^a = \frac{\pi n_y}{4 m_y^2 \left(2\pi n_y\right)^4}\left(\frac{\rho b \tilde{c}_{ls}}{2}\right)^2 \int_0^L \int_0^L U^2(z) U^2(z') \gamma_{ys}(z) \gamma_{ys}(z') \psi_y(z) \psi_y(z') S_{yss}^*(z,z';n)\, dz\, dz' \tag{3}$$

$$C_1^a = \int_0^L \gamma^a(z) K_{a0}(z) \psi_y^2(z) dz \Big/ \int_0^L \psi_y^2(z) dz \tag{4}$$

$\tilde{c}_{ls}$ being the RMS lift wake coefficient, $Sc=4\pi m_{ye}\xi_y^m/\rho b^2$ the Scruton number, ρ the air density, n_y, ψ_y, m_y the frequency, modal shape and mass of the fundamental crosswind mode, $\hat{z}$ the position of the maximum modal displacement, $1/\kappa$ a suitable fraction of b, m_{ye} the effective mass per unit length in the y direction, S^*_{yss} the cross-power spectral density function of the wake excitation, $\gamma_{ys}(z)$ a non-dimensional function accounting for possible cross-section reference size variation along the structural axis z. C_1^a is the linear modal aerodynamic damping, in which $K_{a0}(z)$ is the so-called "aerodynamic damping parameter at small amplitude", depending on both the ratio U/U_{VS} and the Reynolds number Re, U_{VS} being the vortex shedding critical velocity, $U_{VS}=n_y b/St$ (St=Strouhal number). In the present approach (see Pagnini et al., 2020), consistently with the definition of the modal aerodynamic damping, the limiting RMS amplitude $\sigma_L(z)$ is modulated by the maximum amplitude of the modal shape, $\sigma_L(z)=\psi_y(z)/\psi_y(\hat{z})\cdot b/\kappa$.

Concerning the maximum VIV response, it is obtained through a suitable peak coefficient g_{yVS} which must be applied to the RMS response, Eq. (1). Basu (1983) and Vickery and Basu (1983) first represented the peak factor related to the cross-wind vortex-shedding excitation as a function of the ratio $Sc/(4\pi\cdot K_{a0})$ using numerical results obtained by three different slenderness ratio. In this way, when the ratio $Sc/(4\pi\cdot K_{a0})$ is close to zero, the system vibrates according to a deterministic harmonic oscillation and the peak factor g_{yVS} is close to $\sqrt{2}$. At large $Sc/(4\pi\cdot K_{a0})$ values, the response is definitely Gaussian narrow-band random and g_{yVS} is about 4. On the basis of the same functional relationship and relying on purely empirical derivation, CNR (2019) and EN 1991-1-4 (2010) show two different expressions for g_{yVS}. The relationship in CNR (2019) seems more reliable according to the in-depth analysis by Chen (2014).

3. PARAMETER SENSITIVITY ANALYSIS

The application of the spectral model highlights major criticisms in the neighbourhood of the critical vortex-shedding velocity, pointing out uncertainties inherent in the model parameters (the limiting RMS amplitude in particular) and in the calculation models (the peak factor in particular). Investigations over these quantities have been quite neglected in the literature until recent years (e.g., Hansen, 2013 and Chen, 2014, respectively), without particular evolutions in codes and guidelines. They are, indeed, as crucial as the aerodynamic damping parameter K_{a0} which, on the contrary, have attracted much more attention (e.g., Lupi et al., 2021). A further set of important parameters affecting the VIV response include the Scruton number, the correlation length, the Strouhal number, the fluctuating lift coefficient. Considering uncertainties over all these parameters involved in VIV response, it appears evident the need to enrich the VIV data base to obtain complete and reliable information at this concern.

The limiting RMS amplitude, that triggers the nonlinear vibration-amplitude-dependent part of the vortex-induced aerodynamic damping, is crucial in the response prediction from a quantitative point of view, both in the transition and in the lock-in regime (see, e.g., examples reported in Pagnini and Piccardo, 2017). It is Reynolds dependent and it is probably related to structural factors, although it does not seem to depend on the aspect ratio as tentatively discussed by Basu (1983). Despite this, it is usually assumed according to purely tentative values. Regarding circular cylinders, all the literature seems crystallized on the limiting RMS value of 0.4b, although Basu (1983) indicates different possibilities in his pioneering work.

Formulations of the VIV peak factor in codes and standards (used also in the scientific literature) rely on few, poorly documented numerical tests (see the Appendix A in Basu, 1983). Chen (2014) has recently reopened the debate through extensive numerical simulations showing validations with full-scale data from traffic-signal-support structures. His proposal, however, does not seem to solve problems that may arise in the transition regime.

4. ON-GOING WORK

With the aim of improving the reliability of the spectral approach for the assessment of VIV response, the on-going work is investigating the items highlighted in the previous Section. The research is mainly organized according to the following activities: collection of reliable data concerning experimental measures on real chimneys reported by the literature; investigation of possible relationships for the limiting RMS amplitude, also using reliable data from wind tunnel experiments; (c) analysis of the peak coefficient based on extensive numerical Monte Carlo simulations. Experimental tests have also recently been carried out in the "Giovanni Solari" Wind tunnel of the University of Genoa on a smooth circular cylinder in smooth flow conditions (Figure 1) for additional sensitivity on maximum cylinder response amplitude versus system mass and damping characteristics.

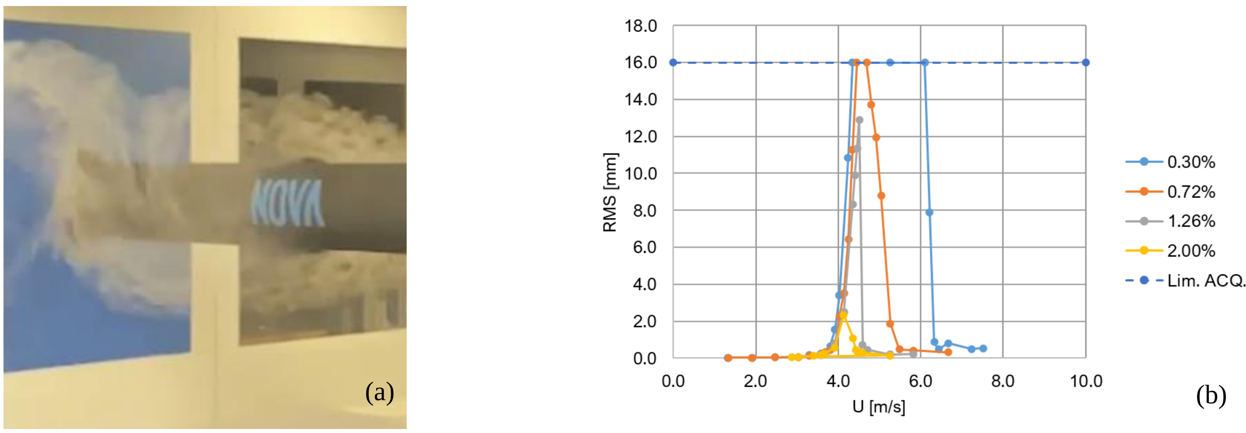

Figure 1. (a) Model in the “Giovanni Solari” WT; (b) RMS response varying the damping ratio (Re≅2.5-9×10[4]).

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