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3-D Gust Effect Factor including aeroelastic effects

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Abstract

Slender structures and structural elements are sensitive to both aerodynamic and aeroelastic excitations which are a dominant factor in their design. However, a unified method of handling these problems doesn't exist. In the context of the three-dimensional gust effect factor technique, till now mainly addressed to the aerodynamic response, the present paper proposes some advances in the formulation in order to include aeroelastic effects (vortex-induced response, in particular) and to arrive at a unified vision in the evaluation of wind-induced effects on slender structures and structural elements.

Introduction

The action of wind on structures leads to vibrations in the longitudinal (alongwind), lateral (crosswind) and torsional direction. The atmospheric turbulence causes forced excitations, whereas particular aeroelastic phenomena, such as vortex shedding and galloping oscillations, can overlap gust actions at certain values of the mean wind velocity. Slender structures and structural elements, typically present in industrial buildings, are particularly sensitive to this kind of action. In addition to chimneys, relevant examples are elements of cranes for industrial lifting and for the uses in harbor areas, which can be realized in a wide range of different types, depending on the use and the amplitude of the area to be handled (Figure 1). A new generation of super tall buildings (Figure 2) also shows a dynamic behaviour much closer to that of a slender element (like a chimney) rather than to a classic tall building. All of these structures can benefit from a unified analysis procedure that can be very important in the initial design stage.

Figure 1. Example of harbor cranes.

The evaluation of vibrations and stresses induced by the wind on slender structures and structural elements is crucial in evaluating both the serviceability and the ultimate limit state design. During the last two decades, the research group in Wind Engineering at the University of Genoa has developed a number of procedures for the calculation of the response based on the three-dimensional (3-D) gust factor technique. At first, a complete closed-form solution of vibrations in longitudinal, lateral and torsional direction was supplied through the generalized gust factor technique (GGF; [1,2]) considering a sole significant vibration mode in the evaluation of both quasi-static and resonant part of the dynamic response. Later, the 3-D gust effect factor (3-D GEF; [3]) was introduced in closed form for vertical slender cantilevers. In particular, the examined effects are generalized displacements and internal stresses; they were obtained by recovering the higher modes in the static and quasi-static components of dynamic response through the use of the influence functions of the load. In this context, a unitary numerical procedure has recently been developed, partially removing some approximations necessary to obtain the closed-form solution, in order to evaluate the wind-induced effects of a generic slender structural element, variously inclined and constrained [4].

All the cited formulations represent gust- and wake-induced excitations by suitable spectral functions in a purely random field. This approach leaves out possible aeroelastic phenomena depending on motion-dependent components such as galloping and Vortex-Induced Vibrations (VIV). The authors [5] very recently proposed a step towards a unitary procedure for the evaluation of the wind-induced response of slender within the GGF framework. Using an equivalent aerodynamic damping for aeroelastic effects, it supplies the structural response (RMS and peak value) at the varying of the mean wind velocity, including galloping phenomenon (taken into account in a linearized way only) and VIV excitation.

Figure 2. Example of the new generation of super tall buildings.

The present paper focuses the attention on the GEF formulation introducing some advances in its framework, with the attempt to introduce a unified vision in the assessment of wind-induced effects on slender structures and structural elements. The procedure considers aeroelastic effects induced by galloping and VIV excitations and can include higher vibration modes (i.e., it is not limited to the fundamental mode). Without intending to predictively reproduce experimental results, the capability of the proposed formulation to reproduce experimental values is then investigated with reference to literature examples.

Theoretical model

The structural element considered has general boundary conditions, is inclined and elevated above the ground (Figure 3), has a linear visco-elastic behaviour. It is modelled through three uncoupled components of motions ($\alpha=x,y,\theta$). Since the wind loading is schematized as a tri-variate two-dimensional stochastic stationary normal process, the generic structural effect e_α at height r along z (Figure 3), associated with the generalized direction α, is a stochastic stationary normal process:

$$e_\alpha(r;t) = \bar{e}_\alpha(r;t) + e'_\alpha(r;t) \tag{1}$$

being $0 \le r \le L$, L the element length, t the time, $\bar{e}_\alpha$ the mean value and e'_α the nil mean fluctuation of e_α around $\bar{e}_\alpha$. The solution is developed in integral form through the influence functions $\eta^e_\alpha(r;z)$ (e.g., [4]), which represent the value of the generic effect e at height r due to a unit static generalized force applied at height z in the direction α.

The expression of the mean value is:

$$\bar{e}_\alpha(r) = \int_0^\ell \bar{F}_\alpha(z)\,\eta^e_\alpha(r,z)\,dz \tag{2}$$

where $\bar{F}_\alpha$ is the mean value of the wind loading F_α, that can be expressed as (e.g., [2]):

$$\bar{F}_\alpha(z) = \frac{1}{2}\rho U^2(z) b \lambda_\alpha c_{\alpha u} \gamma_{\alpha u}(z) \tag{3}$$

ρ being the air density, U the mean wind velocity, b the reference size of the cross-section, $\lambda_x=\lambda_y=1$, $\lambda_\theta=b$, $c_{\alpha u}$ the drag, lift, torsional moment coefficients, respectively, depending on the element cross-section shape, $\gamma_{\alpha u}$ a non-dimensional function of z able to consider variable mechanical and/or aerodynamic properties along the element length.

Applying a suitable loading model (e.g., [2,6]) to the equations governing the structural response, the standard deviation of the generic effect can be obtained by the following straightforward expression:

$$\sigma^e_\alpha(r) = \bar{e}^x_\alpha(r)\sqrt{Q^e_\alpha(r) + D^e_\alpha(r)} \tag{4}$$

where $\bar{e}^x_\alpha$ is the static effect due to the application of the generalized wind mean force in the α direction, Q^e_α and D^e_α are the quasi-static and resonant dimensionless components of the response in terms of variance. The explicit expressions are:

$$\bar{e}^x_\alpha(r) = \frac{1}{2}\rho U^2(\bar{z}) b \ell \lambda_\alpha c_{xu} \bar{K}^e_{\alpha x}(r) \tag{5}$$

$$Q^e_\alpha(r) = \sum_\varepsilon \sum_\eta \chi^e_{\alpha\varepsilon}(r)\,\chi^e_{\alpha\eta}(r)\,Q^e_{\alpha\varepsilon\eta}(r) \tag{6}$$

$$D^e_\alpha(r) = \sum_\varepsilon \sum_\eta \phi^e_{\alpha\varepsilon}(r)\,\phi^e_{\alpha\eta}(r)\,D^d_{\alpha\varepsilon\eta}(r) \tag{7}$$

where $\bar{z}$ is an arbitrary value of z in the range 0-L, $c_{\alpha\varepsilon}$ is the matrix collecting the aerodynamic coefficients (taking into account the possible inclination φ of the model, Fig. 3), $\varepsilon,\eta=(u,v,w,s)$ are indices associated to the three turbulence components and wake excitations, respectively, $\bar{K}^e_{\alpha x}$, $\chi^e_{\alpha\varepsilon}$, $\phi^e_{\alpha\varepsilon}$ are coefficients necessary to perform the evaluation. The core of the procedure concerns the calculation of the generic component of the quasi-static and resonant part of the response:

$$Q^e_{\alpha\varepsilon\eta}(r) = \int_0^{n_{\alpha 1}} I^e_{\alpha\varepsilon\eta}(r;n)\,dn \tag{8}$$

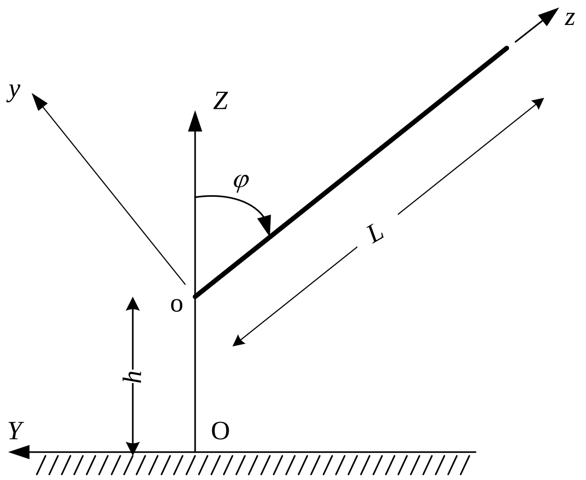

Figure 3. Structural model with its reference systems (X,x entering the page).

$$D^d_{\alpha\varepsilon\eta}(r) = \sum_{k=1}^{N} \frac{\pi n_{\alpha k}}{4\xi_{\alpha k}} I^d_{\alpha\varepsilon\eta}(r;n_{\alpha k}) \tag{9}$$

$$I^e_{\alpha\varepsilon\eta}(r;n) = \frac{\begin{aligned}&\int_0^\ell\int_0^\ell U^2(z)U^2(z')\,J_\varepsilon(z)J_\eta(z')\,\cdot\\ &\gamma_{\alpha\varepsilon}(z)\gamma_{\alpha\eta}(z')\,\eta^e_\alpha(r,z)\eta^e_\alpha(r,z')\cdot\\ &S^*_{\alpha\varepsilon\eta}(z,z';n)\,dz\,dz'\end{aligned}}{\begin{aligned}&\int_0^L U^2(z)\,J_\varepsilon(z)\,\gamma_{\alpha\varepsilon}(z)\,\eta^e_\alpha(r,z)\,dz\,\cdot\\ &\int_0^L U^2(z')\,J_\eta(z')\,\gamma_{\alpha\eta}(z')\,\eta^e_\alpha(r,z')\,dz'\end{aligned}} \tag{10}$$

where J_ε, J_η are terms related to turbulence intensities, $\gamma_{\alpha\varepsilon}$, $\gamma_{\alpha\eta}$ are non-dimensional functions able to consider variable mechanical and/or aerodynamic properties along the element length, $S^*_{\alpha\varepsilon\eta}$ is the cross-power density function of turbulence and wake reduced components. The double integral in Eq. (10) represents the most delicate step of the numerical procedure because of the two-dimensional nature of the loading process combined with the sharp shape of the coherence function.

The presence of influence functions $\eta^e_\alpha(r,z)$ ensures that the quasi-static component is able to take into account all the structural modes. Conversely, the resonant component is deduced by modal analysis considering the displacement influence functions (as specified by the superscript d). Thus, the possible effect of multiple modes (generally significant only for the wake term s) is highlighted by a summation of the N vibration modes considered, $n_{\alpha k}$ and $\xi_{\alpha k}$ being the frequency and damping ratio of the k-th modal shape in the α direction.

When considering turbulence terms, the damping ratio $\xi_{\alpha k}$ is supplemented by the aerodynamic portion calculated through the classic quasi-steady approach (e.g., [5,7]). Therefore, the galloping critical condition is automatically taken into account. The VIV effect can be included in the described context as both forced response and transitory/self-excited (lock-in) condition. This seems possible in an equivalent manner, within the linear random dynamics, following the derivation first proposed by Vickery & Basu [8], using an equivalent damping coefficient that is dependent upon the mean-square cross-wind displacement averaged over a long period. A similar procedure has been recently proposed by the authors [4] within the GGF framework. In this way, at the varying of the mean wind velocity, the wake contribution on the generic structural effect e_α at height r is calculated considering the possible different shedding points depending on the structural mode involved. With regard to this assessment, some aspects take on a great deal of importance in order to obtain reliable assessments of the structural response, as widely discussed in [4]. Among them, the choice of the limiting RMS amplitude stands out as it governs the van der Pol nonlinearity in the equivalent damping expression, whereas it is usually set equal to $0.4 \cdot b$ (e.g., [9]) regardless of both structure and flow characteristics.

According to the GEF technique, the mean maximum value (in modulus) of the generic effect e_α during the period T over which the mean wind velocity U is averaged (usually 10 minutes) is defined as:

$$\bar{e}_{\alpha,\max}\left(r\right)=\bar{e}_{\alpha}^{x}\left(r\right)G_{\alpha}^{e}\left(r\right) \tag{11}$$

where $\bar{e}_{\alpha}^{x}$ is the static effect due to the application of the generalized force $\lambda_\alpha \bar{F}_x$ in the α direction and G_α^e is a non-dimensional quantity referred to as the 3-D GEF [3]:

$$G_{\alpha}^{e}\left(r\right)=\mu_{\alpha}^{e}(r)+\sqrt{Q_{\alpha}^{ep}(r)+D_{\alpha}^{ep}(r)} \tag{12}$$

where $\mu_\alpha{}^e$ represents the static non-dimensional component of the response, while Q_α^{ep} and Q_α^{ep} supply the quasi-static and resonant peak components in terms of variance. They can be defined as overall quantities comprehensive of suitable peak factors related to each excitation components, as in the following:

$$Q_{\alpha}^{ep}(r)=\sum\nolimits_{\varepsilon}\sum\nolimits_{\eta}\chi_{\alpha\varepsilon}^{e}(r)\,\chi_{\alpha\eta}^{e}(r)\,g_{Q\alpha\varepsilon\eta}^{2}\,Q_{\alpha\varepsilon\eta}^{e}(r) \tag{13}$$

$$D_{\alpha}^{e}(r)=\sum\nolimits_{\varepsilon}\sum\nolimits_{\eta}\phi_{\alpha\varepsilon}^{e}(r)\,\phi_{\alpha\eta}^{e}(r)\,g_{D\alpha\varepsilon\eta}^{2}D_{\alpha\varepsilon\eta}^{d}(r) \tag{14}$$

Classic expressions for *g'*s coefficients (see, e.g., [1]) seem to fit peak factors related to buffeting excitations. On the contrary, the definition of the peak factor related to VIV excitations is a challenging issue: it can strongly influence the assessment of the maximum response as discussed in [5].

Work in progress

The described procedure has been implemented in a computer program developed in Fortran code by suitably extending the steps described in [4]. Currently two study cases are being selected. The first concerns a real chimney with recorded structural effects. The second one is related to the slender brace of an existing harbor crane. In these cases, both buffeting and VIV effects can play a decisive role in the serviceability and ultimate limit state design.

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