Determination of the alongwind dynamic response of the CAARC standard tall building

Hugo G. Castro[1], Mario E. De Bortoli[2], Jorge O. Marighetti[2], Rodrigo R. Paz[3]

[1] Grupo de Investigación en Mecánica de Fluidos (GIMEF), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Universidad Tecnológica Nacional (UTN), Facultad Regional Resistencia, (H3500CHJ) Chaco, Argentina.
[2] Facultad de Ingeniería de la Universidad Nacional del Nordeste (UNNE), Resistencia, Chaco, Argentina.
[3] Livermore Software Technology Corporation (LSTC), USA, Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina.

email: castrohgui@gmail.com, m_debortoli@yahoo.com.ar, jomaringha@gmail.com, rodrigo.r.paz@gmail.com

ABSTRACT: Usually the structural behavior under wind action is evaluated by the Gust Factor Technique (GFT) which provides equivalent static forces acting on the structure. However, it is not possible to develop a more detailed dynamic analysis. Frequency domain analysis provides a clear description of the dynamic aspects involved, being this methodology widely used in research. Time domain analysis allows a detailed study of the phenomenon, even under a non-linear structural behavior.

However, the analytical methods used for determining the wind action structural response generally lead to unreliable results when applied to tall structures with unconventional geometries or structural surrounding. In these situations, wind tunnel tests are an accurate and robust tool to study the dynamic behavior of structures.

In this work, a simplified numerical procedure and an experimental methodology for the determination of the dynamic longitudinal response of high structures under the atmospheric boundary layer wind action is implemented and discussed. The simplified numerical approach consists in simulating velocity time series, which define the wind velocity field and are subsequently transformed into nodal forces by a quasi-static assessment model. Longitudinal dynamic response of the structure in the time domain is obtained by the use of the Finite Element Method (FEM). Wind tunnel experimental evaluation was performed with the aid of a base-pivoted rigid model balance and the longitudinal fluctuating response was measured. In order to compare these different approaches, both procedures were applied to the determination of the longitudinal dynamic response of the CAARC Standard Tall Building.

KEYWORDS: CAARC; Tall Buildings; Along-wind Dynamic Response; Wind Tunnel Tests; Numerical Methods.

1 INTRODUCTION

The oscillations of tall structures are produced by fluctuating lift and drag forces caused by the wind. Wind turbulence, vortex shedding, flow separation and the effects of interference with surrounding buildings generates these dynamic forces. Usually, building wind loads are considered as composed by a static and a fluctuating component, being the later caused by the interaction of the wind flow with the geometry of the structure.

It is well known that significant dynamic response is obtained when the frequency of the more energetic gusts matches the first structural modes (lower natural frequencies). This is particularly important in high and slender structures with low stiffness and damping. Lower structural stiffness decreases the natural frequency to values that could be excited by the wind since low-frequency gusts can cover large areas of a building, producing greater pressures. Alongwind response is mainly caused by pressure fluctuations on the windward and leeward faces of the building which, in the low frequency range, follows the fluctuations in the incident flow [1].

When the structural dimensions, stiffness or shape are unconventional, the codes of practice, like the Argentinean Code of Wind Action over Structures (CIRSOC 102 -2005), suggest that the wind loads must be predicted through experimental tests on a boundary layer wind tunnel [2]. These tests are performed with reduced models, where similarity laws must be fulfilled in order to apply dimensionless coefficients to the corresponding full scale building or prototype. Usually, it is impossible to achieve a complete representation of every physical variable and therefore is a common procedure to relaxing the similarity requirements.

Wind tunnel tests with balance technique are designed to simulate the first modes, providing information about the structual response. Mass, damping and stiffness properties can be reproduced by different techniques [1, 3, 4]. In complex scenarios, analytical models cannot take into consideration all these variables and therefore wind tunnel testing with reduced models are currently one of the most reliable tool available. Nevertheless, wind engineering problems generally requires a combined use of different techniques. Analyses are often made through theoretical formulations, numerical algorithms, wind tunnel tests and recommendations of regulations. Moreover, there has been a technological breakthrough that made possible the wide-spreading of the computational modeling research area. Computational Wind Engineering (CWE) is a subject which impressive growth is a result of the use of Computational Fluid Dynamics (CFD) and other computer approaches in wind engineering [5].

This paper deals with the simplified numerical and experimental analysis of the along-wind dynamic response of an isolated tall structure of regular shape, exposed to the wind flow in the atmospheric boundary layer. The Commonwealth Aeronautical Advisory Research Council (CAARC) standard tall building was selected as building model since this model has been focus of many previous studies [6, 7, 8, 9].

The numerical approach used in this work is a simplified one, treating the problem as two-dimensional with the wind load applied on the nodes of the discretized structure [10]. Wind velocity field was simulated using the spectral representation method (SRM) [11] and the structural response was obtained by the application of the finite element method (FEM). The experimental tests were performed in the Jaceck Gorecki Wind Tunnel located at the National University of the Northeast, Resistencia, Chaco, Argentina. Dynamic responses of the model were obtained through the use of a balance which was based on previous designs [12], specifically built for these tests.

2 Numerical method

2.1 Atmospheric boundary layer parameters

The determination of the along-wind dynamic response of structures requires a detailed modeling of the wind field. This is generally accomplished by decomposing the wind velocity into its mean value and its fluctuations around the mean, considering an undisturbed flow direction and discarding the turbulence orthogonal components. Mean atmospheric wind is represented by averaging a velocity field that varies spatially, described by an empirical expression (exponential law) or by a theoretical expression (logarithmic law). The literature provides an extensive group of experimental data, empirical representations, semi-empirical and theoretical values for different aspects of the atmospheric turbulence structure.

Mean wind velocity produces static effects, assuming both direction and mean velocity value remain constant for a time interval less than 10 minutes, with small instantaneous variations. Gusty wind on slender and high flexible structures, with low damping, could produce significant oscillations. Therefore, the total structural response can also be seen as composed by a mean and a fluctuating component.

In this work, the vertical distribution of the mean wind velocity, $\overline{U}(z)$, is given by

$$\frac{\overline{U}_z}{\overline{U}_{10}} = \left(\frac{z}{10}\right)^{\alpha} \tag{1}$$

known as wind profile power law, where $\overline{U}_z$ is the mean velocity at z height, $\overline{U}_{10}$ is the mean velocity at 10 m high and α is an exponent characterizing the surface roughness.

The instantaneous velocity fluctuations (turbulence structure) are described in the frequency domain by the spectral density function or power spectral density (PSD), which links the eddie sizes with their energy content [13]. Thus, turbulence is considered composed by random eddies of different sizes, overlapping each other, with periodic movements associated to wave numbers.

In 1948, von Kármán performed experiments on a turbulent air flow and suggested a spectral function for the longitudinal fluctuating component. Batchelor, in 1953, using principles formulated by Kolmogorov, proposed a spectral equation based on the similarity laws, which defines the energy content variation in the inertial subrange. Later on, Solari [14] performed a review of available models for the turbulent longitudinal component and presented expressions for the spectral density and coherence functions. These expressions are suitable for the assessment of the dynamic longitudinal response of structures. The spectral density function is given by

$$\frac{nS_{(z,n)}}{\sigma_u^2} = \frac{6.868nL_u(z)/\overline{U}(z)}{[1+10.32nL_u(z)/\overline{U}(z)]^{5/3}} \tag{2}$$

where z is the height above the ground (m), n is the frequency (Hz), $L_u(z)$ the integral length scale (m) and σ_u the variance of u.

Other important parameter is the turbulence integral scale. This scale is a measure of the eddy sizes on the turbulent flow [15]. The available wind velocity measurements used for the estimation of turbulence integral scales, show a wide dispersion. Based on wind velocity records obtained experimentally, Solari and Piccardo [16] proposed the following expression for the turbulence integral scale:

$$L_u^x = 300\left(\frac{z}{200}\right)^{\nu} \qquad \nu = 0.67 + 0.05\ln(z_0) \tag{3}$$

where z_0 is the roughness length. The variance of the longitudinal fluctuating component depends mainly on the roughness length and quantifies the turbulence intensity. The proposed expression by Solari and Piccardo [16] is

$$\sigma_u^2 = \{6 - 1.1\arctan[\ln(z_0 + 1.75)]\}u_*^2 \tag{4}$$

Finally, the coherence function quantifies the cross-correlation between analogous wind fluctuating components, which is computed using the following expression:

$$Coh(x,z,x',z',n) = \exp\left\{-\frac{\sqrt{C_x^2(x-x')^2 + C_z^2(z-z')^2}}{\overline{U}(z)+\overline{U}(z')}\right\} \tag{5}$$

where C_x and C_z are the turbulence decay coefficients.

2.2 Wind loading

Numerical modeling of the wind velocity field was performed by using SRM, which generates Gaussian stochastic processes by means of the PSD matrix decomposition as a product of two matrices. The Cholesky (lower triangular) procedure was used in this work. Defining the alongwind turbulence component, u_j, as a multivariate Gaussian stochastic velocity field, depending on time t:

$$u_j\,(t) = \sum_{k=1}^{m}\sum_{n=1}^{N} |H_{jk}(\omega_n)|\,\sqrt{2\Delta\omega}\cos\left[\omega_n t + \Phi_{kn}\right] \tag{6}$$

where N is the number of $\Delta\omega$ intervals of the frequency domain $[0,\ldots,\omega_n,\ldots,\omega_c]$, Φ_{kn} are independent random phase angles uniformly distributed over the interval $[0, 2\pi]$ and $H_{jk}(\omega_n)$ is an element of the lower triangular matrix $\mathbf{H}(\omega)$ obtained from the decomposition of the PSD matrix $\mathbf{S}(\omega)$ by the Cholesky factorization method. $H_{jk}(\omega_n)$ is a real function because $\mathbf{S}(\omega)$ is a semi-definite positive real matrix [23].

Once the spatial and temporal distribution of the wind velocity field is obtained, the following step is to compute the time history of the fluctuating wind force in order to implement the structural dynamic response analysis. As the structural elements considered in this analysis are assumed to be line-like, the overall loading effects are caused by the oncoming flow (buffeting). Thus, vortex shedding and fluid-structure interaction forces are disregarded. Following this approach, the alongwind forces can be computed in the frequency domain as:

$$S_F(z;n) = [\rho C_D A \overline{U}(z)]^2 \left|\chi(z,n)\right|^2 S_u(z,n) \tag{7}$$

where $|\chi(z,n)|^2$ is the aerodynamic admittance which behaves as a "spatial filter" on the temporal series; $S_F(z;n)$ is the power spectral density of the drag force fluctuation, C_D the drag coefficient, ρ the air density and A the reference area. For a more detailed description, the reader can refer to the work of Castro et al. [10].

The structure analyzed in this work is the CAARC (Commonwealth Advisory Aeronautical Council) standard tall building, figure (1). This structure is a rectangular prism with full scale dimensions of 30 m $\times$ 45 m and 180 m high. The model was proposed in 1969 for comparison different techniques used in wind tunnels. Also the boundary layer profile and dynamic properties were specified. The atmospheric boundary layer is representative of a suburban terrain with buildings mean height between 6 m and 15 m. The power law exponent suggested was α = 0.28 [17]. Only the fundamental vibration mode was considered. Its modal shape was assumed to be linear, rotating around a point at ground level. The natural frequency was 0.2 Hz in both orthogonal directions. The mass distribution is considered uniform, with a rate of 160 kg/m^3. The structural damping, given by the relationship of critical damping is ξ = 1% (logarithmic decrement of 0.063).

In this work, the structure was idealized as a vertical line-like structure and replaced for a shearing mode model with a mass-spring-damper system of ten degrees of freedom, figure (1.c). The finite element method (FEM) was used for the computation of the structure dynamic response.

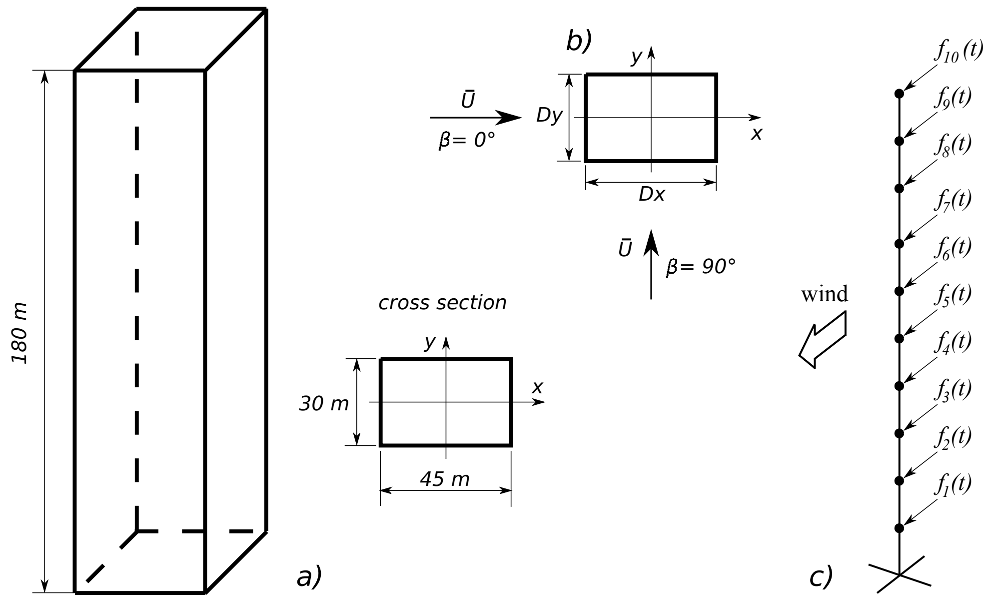


Figure 1. CAARC standard tall building dimensions (a, b) and discretized structure (c).

In order to perform a statistical study on the dynamic structural response, the FEM model was solved several times with different load series. Thirty time histories of the fluctuating drag force were generated for each of the ten nodal points of the structure, which were used for the dynamic response analysis. In figure (2) two samples of the nodal forces (18 m and 180 m) are shown.

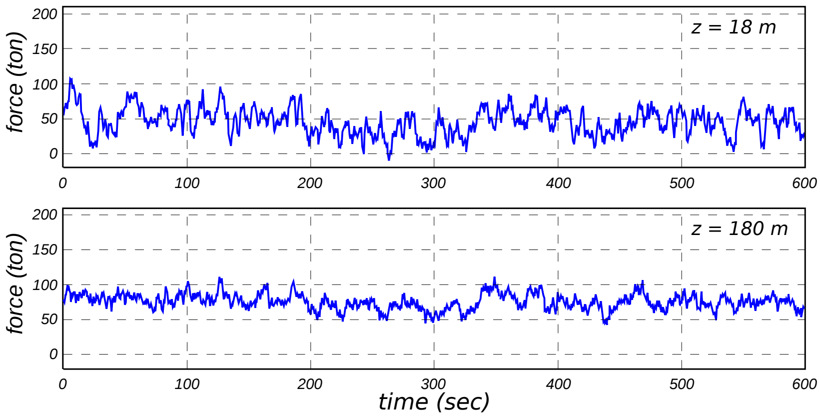


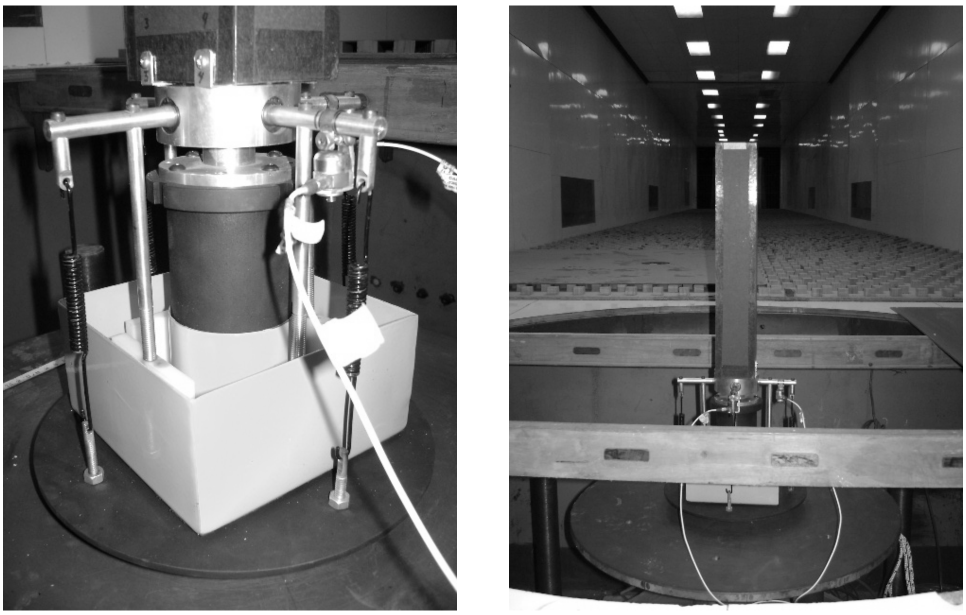
Figure 2. CAARC standard tall building.

2.3 Wind tunnel tests

An accurate wind loading on a model is obtained when the wind and the structure are fully modeled. Under this condition, the model would respond in the same way as the prototype, though in most cases all the the necessary modeling criteria are impossible to fulfill. This relaxation or distortion of the similarity requirements introduces uncertainties in the measurements.

Rigid-body aeroelastic modeling of tall structures is based on three basic assumptions [18]: *a)* the dynamic response in torsion can be neglected, *b)* dynamic sway responses with natural frequencies higher than the first in each orthogonal direction can be neglected, *c)* the modal shape of the sway modes can be assumed as linear functions of height. Under these considerations, the motion of a rigid model that pivots at a point near the ground level, in a wind tunnel with mean and fluctuating wind velocity correctly simulated, can be regarded as representative of the real structure.

In this work, a base-pivoted rigid model testing was performed using a balance that allows the response of the model in two orthogonal sway directions, figure (3.a). The design of the balance was based on a measure system used in previous works [12, 19, 20].



(a) Base-pivoted rigid model. (b) Dynamic balance in the wind tunnel.

Figure 3. Wind tunnel setting.

The wind tunnel test was conducted at the Wind Tunnel Facility of the National University of the Northeast (UNNE). The 1:450 geometric scale was obtained by the method proposed by Cook [21] and the boundary layer was simulated through the use of roughness, barrier and vortex generators, as suggested by Counihan [22]. Gradient height (z_g) of 1.16 m, roughness length (z_0) of 2.6×10^{-3} m, a power law exponent (α) of 2.6 and a turbulence intensity at the top of model I_u = 0.08 were used as characteristic parameters.

The fluctuating responses in the two orthogonal directions were measured with two piezoelectric accelerometers Isotron 7254A-10, coupled to a 102 Isotron signal conditioner and a power source 109 Isotron. A high-speed analog and digital I/O board PCI-DAS1602/16 was used with an acquisition frequency of 1000 Hz during an interval of 20 seconds.

3 RESULTS AND CONCLUSIONS

In Table (1) the longitudinal dynamic response analysis obtained by the simplified numerical method is summarized. Displacement in the x direction is given by a wind incidence angle $\beta = 0°$ and $\beta = 90°$ for the y direction. Furthermore, the following symbols were adopted: $\bar{x}$, σ_x, mean value and standard deviation, respectively, of the displacement on the top of the structure (z = 180 m), and $\bar{x}_{max}$, $\sigma_{x\ max}$, the mean value and standard deviation, respectively, of the maximum values extracted from each dynamic response history. The same considerations were made for the wind incidence angle $\beta = 90°$. In figure (4) these results are compared against several reported experimental tests. Mean and rms responses were normalized by the building dimensions ($\bar{x}/D_x, \sigma_x/D_x, \bar{y}/D_y, \sigma_y/D_y$).

	$\bar{x}$	σ_x	$\bar{x}_{max}$	σ_{xmax}
$\beta = 0°$	0.1927	0.0838	0.4410	0.0396
	$\bar{y}$	σ_y	$\bar{y}_{max}$	σ_{ymax}
$\beta = 90°$	0.3238	0.1369	0.7333	0.0643

Table 1. Statistical results of the dynamic response in z = 180 m.

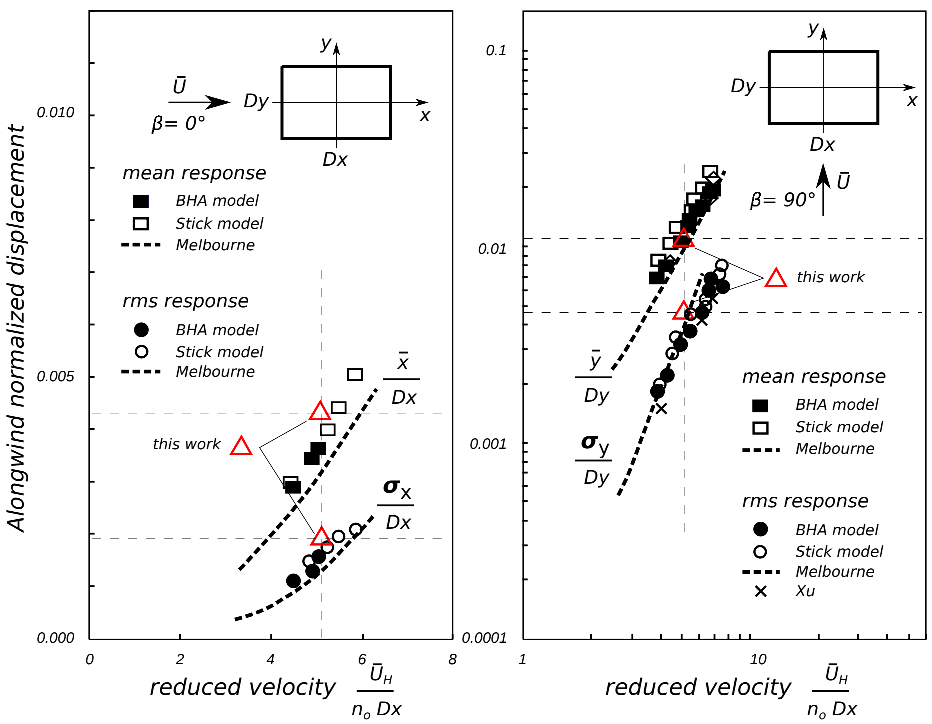


Figure 4. Mean and rms normalized response on the top of the model as a function of the reduced velocity, for $\beta = 0$ and $\beta = 90°$.

Regarding to the experimental tests, the rms normalized displacements are presented as a function of the reduced velocity in figure (5) and compared with the experimental results of the work of Melbourne [17], Thepmongkorn et al. [3], Miguel [19] and Oliveira [20]. The Thepmongkorn et al. [3] values correspond to a flat, open terrain simulation, with a power law exponent α = 0.15 and a turbulence intensity at the top model of I_u = 0.10; whereas in the work of Miguel [19] and Oliveira [20] the exponent was α = 0.19 and a turbulence intensity of I_u = 0.046. Values reported by Melbourne [17] were also included with α = 0.28 (representative of an urban environment) and I_u = 0.10.

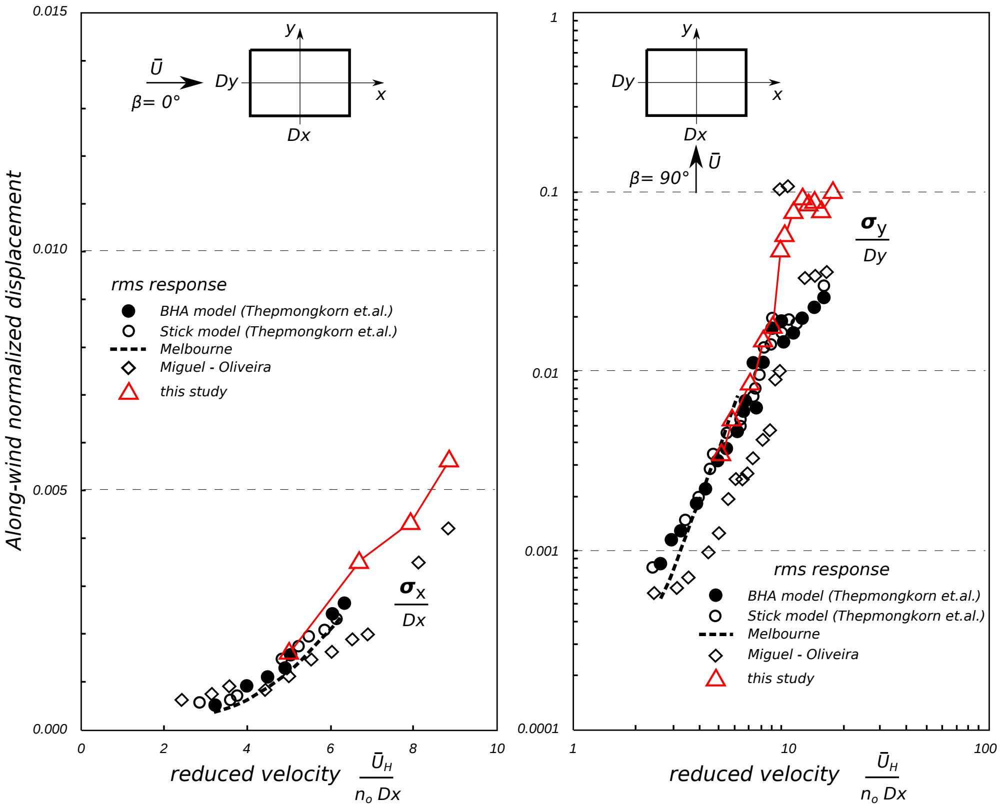


Figure 5. Longitudinal displacements on the top of the model as a function of the reduced velocity, for $\beta = 0$ and $\beta = 90°$.

Results for $\beta = 0°$ are in agreenment with the general tendency of the referenced experimental tests, while for $\beta = 90°$ the obtained rms displacements in the range of reduced velocities higher than 10 are greater than those reported in the references cited above, except for the work of Miguel [19] and Oliveira [20]. With respect to these later studies, the difference is expected since the turbulence intensities are about 50% lower than the one used in this work.

Regarding the y direction ($\beta = 90°$) the longitudinal response agrees with the rms values reported by Thepmongkorn et al. [3] and Melbourne [17] for reduced velocities lower than the critical velocity value associated with vortex shedding. Both authors related this peak in the alongwind response with a coupling generated by an energy transfer from crosswind to alongwind direction, since the natural frequencies in those directions matches. This peak is also reproduced in this work, but with different characteristics. Within the range of velocities tested, there is no evidence of a significant attenuation of the response once the critical reduced speed is surpassed. This is probably due to the particular characteristics of the base-pivoted rigid model, which does not allows that the response decays rapidly.

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