Dynamic Analysis of Slender Buildings under Wind Loading

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Abstract. This work aims to understand and compare methods that simulate the dynamic characteristics of atmospheric wind loads acting on slender structures, with a focus on NBR 6123 and the Synthetic Wind Method. The amount of research conducted on this topic since the 1960s has led to significant advancements in understanding the dynamic behaviour of wind. This progress has facilitated the development of methodologies for quantifying its impact on buildings and the continuous refinement of these methodologies up to the present day. In this context, it is worthwhile mentioning two approaches: NBR 6123:2023 [1], developed by the Brazilian Association of Technical Standards, and the Synthetic Wind Method, initially proposed by Franco in 1993 [2]. The Brazilian standard provides two methods to determine maximum values of variables such as acceleration, displacement, and forces for structures subjected to wind, without describing how these values vary over time. Despite advances in wind engineering studies and methodologies, the procedure described in the 1988 version of the standard remained unchanged in its 2023 update. On the other hand, the Synthetic Wind Method, first published in 1993 and subsequently refined until 2014, works by decomposing the fluctuating component of wind into harmonic functions. This approach not only allows to obtain absolute maximum values but also provides the structural response over time. To address these issues, this work carries a comparative study between NBR 6123:2023 [1] and the most updated version of the Synthetic Wind Method.

Keywords: Slender structures, Characteristics of wind loading, NBR 6123:2023, Synthetic Wind Method

1 Introduction

The unpredictable nature of wind loads motivates the development of various studies and methods to consider their effects on structures. Alan Davenport was a pioneer in this field, writing relevant publications in the 1960s [3]. Davenport's work laid the foundation for various international design codes, including the Brazilian standard [4]. Regarding the Brazilian standard, there have been no significant updates to the calculation of dynamic wind analysis for the past 35 years, even in the latest version published in 2023. On the other hand, the Synthetic Wind Method, developed by Franco [2], is a more refined approach that originated from NBR 6123:1988 [5] and has continuously been improved since then. In the next two sections, one presents an overview of each method.

2 NBR 6123:2023 [1]

The NBR 6123 is currently at its second version, being the NBR 6123:1988 [5] the first and the NBR 6123:2023 [1] the second one. Although the gap between them is 35 years, the calculation procedure, in it's essence, remains the same. The difference lies mainly in the limitation of the structures to which the method can be applied and in the maximum number of vibration modes.

The Brazilian standard treats dynamic wind response as the superposition of an average response and a fluctuating response. Thus, the standard defines the mean and fluctuating static forces that lead to a static response representing the maximum amplitude of dynamic oscillation. To achieve it, a discrete method described is defined to find this result.

2.1 Wind velocity

The NBR 6123:2023 [1] defines a Project Velocity $\bar{V}_p$ that is the average wind speed over a 10 minutes period at a height of 10 meters above ground level given by

$$\bar{V}_p = V_0 \, S_1 \, S_3, \tag{1}$$

in which V_0 is the basic wind velocity that occurs over a 3 seconds period at a height of 10 meters, S_1 represents a topographic factor and S_3 is based on statistical concepts.

2.2 Discrete model

The discrete model according to NBR 6123:2023 [1] is schematically represented in fig. 1, where x_i is the modal shape amplitude at coordinate i, A_i represents the influence area associated to coordinate i, m_i is the discrete mass associated to coordinate i, C_{ai} is the drag coefficient, z_i is the height of the coordinate i, and n represents the number of degrees of freedom.

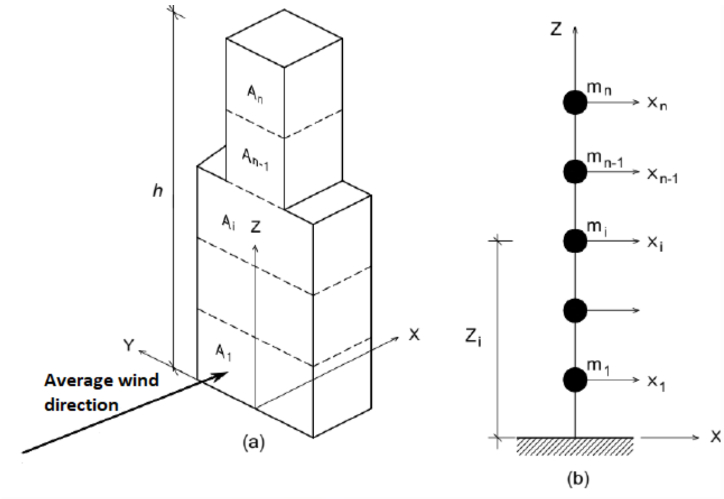

Figure 1. Discrete model. (modified from NBR 6123:2023 [1])

From this model, the natural frequencies of the structure are determined. According to normative guidelines, up to two bending modes can be used, depending on the engineer's judgment. The use of additional modes falls outside the scope of the standard.

2.3 Dynamic response along wind direction

The total force X_i to be applied at the coordinate point due to the wind consists of two components, as follows

$$X_i = \bar{X}_i + \widehat{X}_i, \tag{2}$$

in which the first component $\bar{X}_i$ is the mean force and $\widehat{X}_i$ the maximum amplitude of the fluctuating force component given, respectively, by

$$\bar{X}_i = \bar{q}_0 b_m^2 C_{ai} A_i \left(\frac{z_i}{z_r} \right)^{2p} \qquad \text{and} \qquad \widehat{X}_i = F_H \Psi_i x_i, \tag{3}$$

where

$$\Psi_i = m_i/m_0, \qquad F_H = \bar{q}_0 b_m^2 A_0 \frac{\sum_{i=1}^{n} \beta_i x_i}{\sum_{i=1}^{n} \Psi_i x_i^2} \xi, \qquad \beta_i = C_{ai} \frac{A_i}{A_0} \left(\frac{z_i}{z_r} \right)^p . \tag{4}$$

In eq. (3) and eq. (4), the following parameters are presented: an arbitrary reference mass m_0 and area A_0, the dynamic factor ξ whose value is obtained from NBR 6123:2023 [1], the normative parameters p and b_m, and the pressure $q_0 = 0.613\bar{V}_p^2$ (where q_0 is in N/m² and $\bar{V}_p$ is in m/s).

2.4 Assessment of human comfort

For any stress or geometry variable denoted by $\widehat{Q}$, the combined effect of the first and second vibration modes is obtained by $\widehat{Q} = \sqrt{\widehat{Q}_1^2 + \widehat{Q}_2^2}$. This approach accounts for the simultaneous influence of both modes on the response.

Thus, human comfort can be assessed based on the results obtained for the maximum acceleration amplitude and vibration frequency for a specific vibration mode j, given by

$$a_j = 4\pi^2 f_j^2 u_j, \tag{5}$$

in which u_j represents the maximum displacement amplitude at a height z due to the action of the force $\widehat{X}$.

With the acceleration and vibration frequency, it is possible to conclude the human comfort analysis using the graph presented in fig. 2. All pairs of acceleration and frequency that fall below the presented curves are approved in terms of comfort.

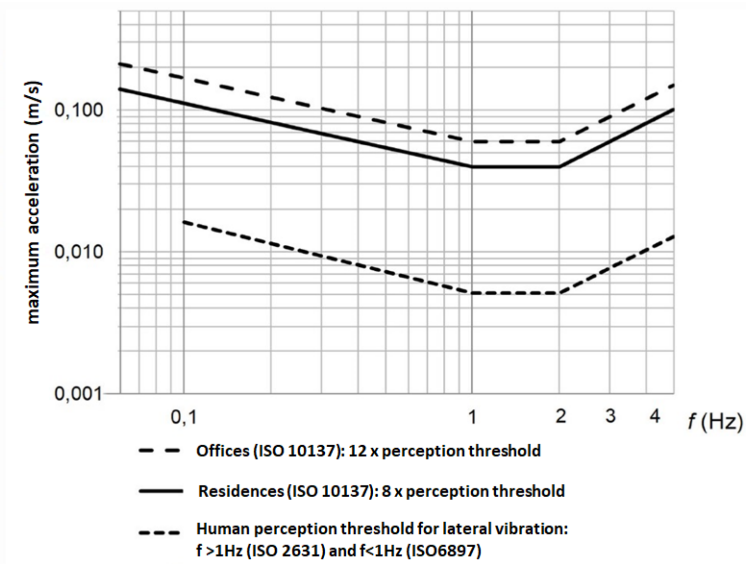

Figure 2. Human comfort. (modified from NBR 6123:2023 [1])

3 Synthetic Wind Method

The Synthetic Wind Method (SWM) was initially published by Franco [2] in 1993 and later updated by Franco [6] and Franco and Medeiros [7]. These updates incorporated suggestions from other studies, enhancing the energy and statistical treatment, and expanding computational applications. Here, one presents the most up-to-date version.

The Synthetic Wind Method (SWM) is based on the assumptions of NBR 6123:2023 [1], which involves superimposing the mean and fluctuating portions to obtain the dynamic response. This method aims to approximate the fluctuating wind component by combining time-dependent harmonic functions. Franco [6] established a minimum of 11 harmonics for each combination, with a minimum of 20 combinations.

3.1 Frequencies of the harmonic functions

The harmonic functions frequencies are determined following a geometric progression of ratio r based on the fundamental periods of the first (T_1) and second (T_2) vibration modes. When using 11 harmonics, Franco [6] suggests that these modes occupy the fourth and second positions, respectively.

3.2 Amplitude of the harmonic functions

The amplitudes of harmonic functions are determined by decomposing the reduced power spectrum into a number of parts equal to the preselected number of harmonics. Each amplitude is obtained by multiplying the fluctuating pressure q_{flut} by a coefficient $\bar{c}_k$, which distributes its magnitude among the amplitudes of these functions, i.e.,

$$(\text{Amplitude})_k = \bar{c}_k q_{flut} \tag{6}$$

where k is the index of the harmonic function ranging from 1 to m, with m being the preselected number of harmonics. The pressure q_{flut} comes from the NBR 6123:2023 [1] and represents the difference between pressures with measurement interval of 3 seconds (peak) and 3600 seconds (average). The coefficient $\bar{c}_k$ comes from the reduced power spectrum ($S_r(f)$) decomposition as exemplified in fig. 3.

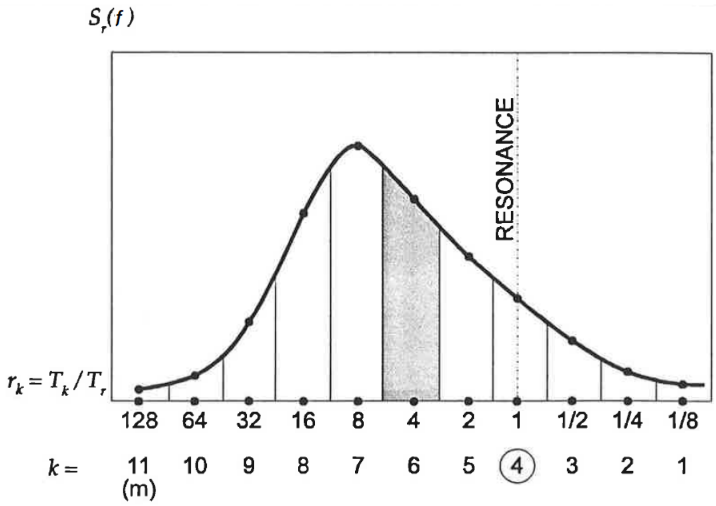

Figure 3. Reduced power spectrum decomposition into 11 parts (Franco [2]).

3.3 Phase angle of the harmonic functions

Franco [6] recommends that 20 or more combinations of the 11 harmonic functions should be performed. In each of these combinations, the phase angle θ_k should be generated by a pseudo-random processes.

Thus, with the frequency, amplitude, and phase angle of each of the harmonic functions, the time-dependent fluctuating pressure for a given combination is written as

$$q_{flut}(t) = \sum_{k=1}^{m} \bar{c}_k \; q_{flut} \cos\left(2\pi f_k \; t - \theta_k\right). \tag{7}$$

3.4 Spatial correlations

As discussed by Franco [6], when a wind gust hits a building, it does not happen simultaneously across the entire structure. Thus, the gust center is defined as the point z_{cr} where the maximum wind velocity occurs at a given instant, with decreasing intensity as one moves away from z_{cr}, as shown in fig. 4.

The influence range of gusts Δz is given by $\Delta z_k = \frac{U_0}{7n_k}$, where U_0 represents the average wind at a height of 10 meter in an open field.

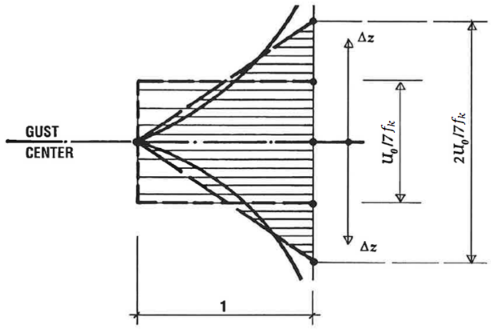

Figure 4. Spatial correlation (Franco [2]).

According to Franco [6], the gust center is determined in such a way that it positions the resonant gust ($k = 4$, if Franco's suggestion is followed) as high as possible. After this determination, the remaining gusts are positioned around the gust center.

3.5 Characteristic response

With the combination's results in hand, the most probale maximum value $\bar{R}$ is determined from Gumbel's distribution. According to Franco [6], it is also acceptable to adopt a Gaussian distribution with 5% quantile, i.e., $\bar{R} = R_M + 1.65\sigma$ with R_M and σ representing the mean response and standard deviation of the responses obtained in the combinations, respectively. Thus, the characteristic combination is the one closest to $\bar{R}$ and is considered to be the one that provides the best fit for all parameters of interest, such as accelerations, velocities, loads and displacements.

4 Methodology

The simulations of the presented methods were carried out using the structural calculation software TQS. This software contains the procedures from the NRB 6123 and from the most updated version of the Synthetic Wind Method [7]. Although the SWM is incorporated to TQS, the statistical analysis is not performed by the software and require an outside calculation in order to define the characteristic results of the method.

After defining the wind proprieties and modelling the structure, the comparison between the NBR 6123:2023 [1] and the SWM is established by analysing the acceleration in the load direction. As the NBR 6123:2023 [1] just provides the analysis' maximum acceleration, without describing how it changes over time, this comparison is perform solely based on the highest absolute value of this parameter.

5 Practical application and results

The application of these methods for comparative purposes is carried out using an arbitrary building that is slender in one direction and non-slender in the other, allowing to verify the limits of the SWM with a single structure. The building consists of 20 floors, with a ceiling height of three meters and a structural plan presented in Fig. 5. The structural arrangement configures a slender building for winds acting in the Y direction and non-slender when facing the X direction. The slenderness of the structure is evaluated by inspecting a slenderness ratio, which is calculated based on the area and inertia of the arrangement of the pillars in the floor plan and based on the approximation of the building as a cantilever, along with the instability parameter γ_z. These parameters indicate the susceptibility of the structure to horizontal displacements.

Thus, the building presents a slenderness ratio of 53 in the Y direction and 15 for the X direction. In addition, the building exhibited a instability parameter $\gamma_z = 1.28$ in the Y direction and $\gamma_z = 1.15$ in the X direction, indicating a considerable displacement under horizontal loads, specially in the Y direction.

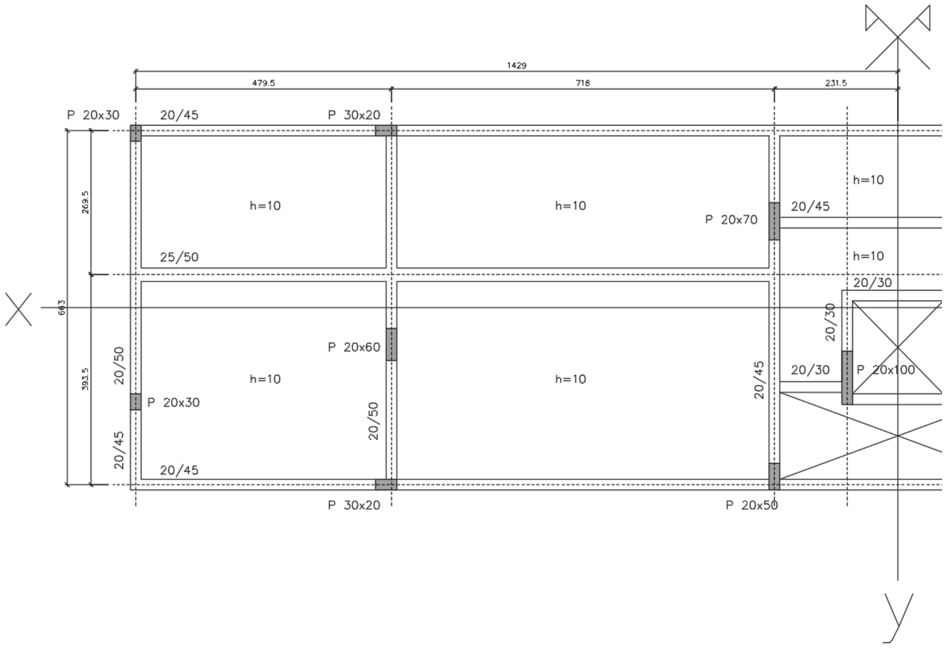

Figure 5. Structure Plan

The adopted building is considered to be made of concrete with a characteristic compressive strength (f_{ck}) of 30 MPa and is fixed at the base of the pillars. It is also assumed that wind acts on it with a basic velocity of 45 m/s, and the gust center varies in height to each direction.

The obtained results indicates that the absolute maximum acceleration occurs at the top of the structure. Therefore, presented results are colected from the highest floor. For the 20 wind gusts generated for each direction of the SWM, totalling 40 gusts, the accelerations were determined and are described in Table 1.

Table 1. Absolute maximum accelerations of each gust (SWM)

Acceleration	Gusts									
(m/s^2)	1	2	3	4	5	6	7	8	9	10
a_x	0.387	0.398	0.386	0.387	0.401	0.399	0.399	0.401	0.397	0.403
a_y	1.336	1.323	1.339	1.293	1.313	1.328	1.323	1.342	1.323	1.326
Acceleration	Gusts									
(m/s^2)	11	12	13	14	15	16	17	18	19	20
a_x	0.389	0.395	0.400	0.401	0.400	0.394	0.405	0.389	0.403	0.401
a_y	1.316	1.316	1.333	1.330	1.320	1.316	1.330	1.334	1.333	1.337

From the probable values found through statistical analysis of accelerations in each direction, the characteristic gust was defined as Gust 17 in the X direction and Gust 8 in the Y direction. After this process, the results obtained with the SWM can be compared to those from NBR 6123, as shown in Table 2.

Table 2. Maximum accelerations (m/s^2) by NBR 6123:2023 [1] and SWM

	Direction X	Direction Y
NBR 6123	0.340	1.438
SWM	0.405	1.342
Variation	7%	-19%

6 Conclusions

Regarding the results of each method, it is expected that the values obtained from the NBR 6123:2023 [1] prescriptions are higher than those from the SWM, as the standard lacks a description of acceleration over time and needs to safeguard itself in this aspect. The results presented in the Table 2 may reflect the assumption of the SWM proposal that the structure is slender. In the Y direction, where the SWM is valid according to its own proposition, the result shows a significant reduction of 19% in maximum values. This suggests that user comfort is addressed while ensuring greater cost savings. On the other hand, in the X direction, since it is a non-slender direction and no dynamic phenomena such as resonance occurred, the maximum acceleration may be overestimated, exceeding the standard value by 7%.

Future research will focus in the verification of the drawn conclusions for other structures, as well as include new techniques for estimate wind loads such as Computational Fluid Dynamics and Fluid-Structure Interaction and other spectral decomposition approaches.

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