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Quasi-steady Across-wind Aerodynamic Damping of Tall Structures

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Abstract

The paper presents a generalization of existing analytical approaches to determine the across-wind aerodynamic damping of tall structures through the quasi-steady theory. The theory takes into account the nature of non-uniform wind, structural mode shapes and the variation of structural parameters. Numerical applications on a prototype high-rise building and a real sculptural tower point out that the common approach may be over simplified, giving rise to inappropriate predictions of the aerodynamic damping. The role of the structural mode shapes, usually being neglected for uniform structures, is then highlighted.

Keywords: aerodynamic damping; across-wind; galloping; high-rise building

1. Introduction

Slender structures such as masts, telecommunication towers, poles, tall buildings are very sensitive to wind actions that may lead to large dynamic vibrations, even aeroelastic instability, e.g. galloping. Due to the interaction between wind and structures, the aerodynamic damping is generated. The positive value is beneficial to the structures as it adds more damping to them. In contrast, the negative one is detrimental because it reduces the total damping of the structures. When the aerodynamic damping is negative with an absolute value smaller than the structural damping, the structure will be unstable, leading the occurrence of galloping.

In along-wind loading, the aerodynamic damping is commonly neglected due to its positive and small value (Boggs 1992). The across-wind aerodynamic damping is interested as it may be negative. Such negative is more evident with more slender and complex shapes of recent and future tall structures that potentially lead to negative slope of the across-wind coefficients (Tanaka et al. 2013). Across-wind aerodynamic damping can be evaluated through wind tunnel tests (e.g. Isyumov et al. 1992; Vickery and Stackley 1993; Watanabe et al. 1997; Gu et al. 2014) or full-scale measurements (e.g. Spencer and Kareem 2014, Stengel et al. 2017). In early design stages, an analytical tool to predict the aerodynamic damping is necessary. Quasi-steady theory has been widely adopted to formulate the problem.

The very early study to derive the quasi-steady across-wind aerodynamic damping, also the condition for the occurrence of transverse galloping, is the Den Hartog's theory (Den Hartog, 1932). Den Hartog criterion has become an important tool and widely used in engineering application. Following the study of Den Hartog, many linear models have been proposed to extend the theory. Macdonald and Larose (2006) generalized the theory to evaluate the aerodynamic damping with the inclusion of Reynolds number effects and relative angles between the wind and structures and then applied it to inclined cables. Nikitas and Macdonald (2014) pointed out some misconceptions in applications of the Den Hartog's theory.

It is worth noting that those studies and most of other analysis in the literature provided formulations to predict the across-wind aerodynamic damping using an assumption that the aerodynamic coefficients, mean wind velocity, mass per unit length and cross sections (dimensions and shapes) are constant along the height of structures. This assumption is valid for uniform structures in uniform wind. For vertical structures, that is not actually the case as wind velocity is varying in height, making the prediction inappropriate, even for uniform structures. In other words, the common analysis may lead to errors, affecting the safety of structures.

This paper reports on an analytical formulation of the across-wind aerodynamic damping for slender tall structures, using the quasi-steady hypothesis. The height-dependent wind and structural parameters such mean wind, aerodynamic coefficients, mass per unit length and mode shapes are taken into account. The effect of vortex-induced vibration and nonlinearity on the aerodynamic damping are not addressed in the paper. Additionally, special cases commonly used in practice are discussed. The theory is then illustrated through applications for a tall building and a sculptural

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tower. Critical remarks are finally discussed.

2. Formulation of across-wind aerodynamic damping

Considering a vertical structure with mass per unit length m and height H subjected to the distributed external load $f(z,t)$, the equation of motion for each vibrational mode can be written in the generalized coordinate as following:

$$\ddot{p}_k(t)+2\xi_k\omega_k\dot{p}_k(t)\omega_k^2 p_k(t)=\frac{1}{m_k}f_k(t) \tag{1}$$

where ω_k and ξ_k are the modal circular frequency and modal damping ratio of the k-th vibrational mode with the mode shape Ψ_k, respectively; p_k, p_k and p_k are the generalized acceleration, velocity and displacement respectively. The generalised mass m_k and generalised force $f_k(t)$ are given by:

$$\begin{cases} m_k=\int_0^H m(z)\,\psi_k^2(z)dz \\ f_k(t)=\int_0^H \psi_k(z)f(z,t)dz \end{cases} \tag{2}$$

Given that the structure exhibits self-excited across-wind oscillation and focusing on the formulation of the aerodynamic damping, by employing the quasi-steady hypothesis, the wind load is given by (Nguyen et al., 2015):

$$f_k(t)=-\frac{1}{2}\rho\int_0^H b(z)U(z)[C_D(z)+C_L'(z)]\Psi_k(z)\dot{p}_k(t)dz \tag{3}$$

where C_D, C'_L, U, b and ρ are the drag coefficient, first derivative of lift coefficient against wind angle, mean wind speed, width of the structure and air density, respectively. The mean wind speed $U(z)$ varies along the structural height and is modelled using the mean wind speed $U(z_e)$ at the reference height z_e as:

$$U(z)=U(z_e)\frac{\mu(z)}{\mu(z)} \tag{4}$$

where $\mu(z)$ is the wind profile function, following a power law or logarithm law (Simiu and Scanlan, 1996).

Substituting Eq. into Eq., and then Eq. into Eq., it yields:

$$\ddot{p}_k(t)+2\omega_k\left[\xi_k+\frac{\rho b(z_e)c_{ka}U(z_e)}{4m_{k,\mathrm{eq}}\omega_k}\right]\dot{p}_k(t)+\omega_k^2 p_k(t)=0 \tag{5}$$

where $m_{k,\mathrm{eq}}$ and c_{ka} are the equivalent mass and normalised aerodynamic damping coefficient related to the k-th mode, respectively:

$$m_{k,eq}=\frac{m_k}{\int_0^H \psi_k^2(z)dz} \tag{6}$$

$$c_{ka}=\frac{\int_0^H b(z)\mu(z)[C_D(z)+C_L'(z)]\psi_k^2(z)dz}{b(z_e)\mu(z_e)\int_0^H \psi_k^2(z)dz} \tag{7}$$

From Eq. (5), the aerodynamic damping ratio related to the k-th mode can be defined as:

$$\xi_{ka}=\frac{\rho b(z_e)U(z_e)c_{ka}}{4m_{k,\mathrm{eq}}\omega_k} \tag{8}$$

For uniform wind and uniform structures with constant mass per unit length and a uniform cross-section along the height, the Eqs.(6)-(8) drastically reduce to:

$$m_{k,\mathrm{eq}}=m \tag{9}$$

$$c_a=C_D+C_L' \tag{10}$$

$$\xi_{ka}=\frac{\rho bU(C_D+C_L')}{4m\omega_k} \tag{11}$$

The aerodynamic damping ratio given in Eq. (11) is commonly adopted and widely used in engineering practice (Dragomirescu, Yamada, and Katsuchi, 2009; Macdonald and Larose, 2006). Strictly speaking, it is not valid, even for uniform structures. This is because, as seeing from Eq. (7), the normalised aerodynamic damping coefficient c_{ka} is dependent on the structural mode shapes due to the inherent variation of the mean wind speed along the height of the structures. Only when both the structures and the mean wind are uniform, the mode shape functions in Eq. (7) cancel out, making Eq. (11) accurate.

On the other hand, negative aerodynamic damping for negative values of C_D+C_L' is detrimental for structures. Eq. (11) provides the largest negative aerodynamic damping at the first structural mode. However, due the dependence on the structural mode shape, Eq. (8) may provide larger negative aerodynamic damping for higher modes. As a result, using the simplified aerodynamic damping ratio may underestimate wind-induced structural response, affecting the safety of structures.

It is interesting for the case when the aerodynamic damping is small that gives rise to the negative of total damping. Then the structure is aerodynamically unstable, i.e. galloping. So ξ_{ka} is the minimum structural damping, including additional damping from external dampers, required

to prevent the occurrence of galloping. It is worth noting that, for the case that an external damper is attached to the structure, the structural modes become complex modes that can modify the stability condition of galloping. This issue is discussed in Nguyen and Macdonald (2017).

Equivalent to find the minimum structural damping to prevent galloping, it is also practically interesting to find the critical on-set wind speed for galloping, which can be derived from Eq. (8):

$$U_{k,\mathrm{cr}}(z_e)=\frac{4m_{k,\mathrm{eq}}\omega_k\xi_k}{\rho b(z_e)c_{ka}} \tag{12}$$

where $U_{k,\mathrm{cr}}$ is the critical galloping velocity at the reference height z_e for the k-th mode. The critical galloping wind velocity varies along the height, which is referred to as the critical galloping wind profile and can be calculated from Eq. (4). For uniform structures in uniform wind, Eq. (12) reduces to:

$$U_{k,cr}=\frac{4m\omega_k\xi_k}{\rho b(C_D+C_L')} \tag{13}$$

It can be realized that with k=1 Eq. (13) is the Den Hartog's criterion that is widely used in many codes and standards.

3. Case studies

3.1. A high-rise building

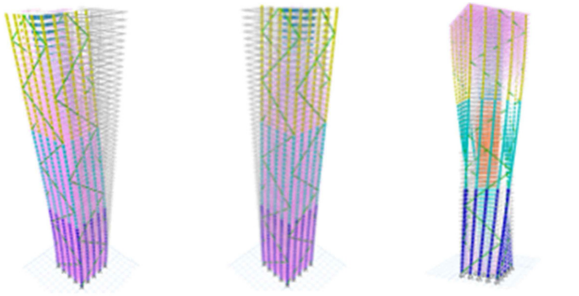
A 60-floor tall building with the dimension of 40 m× 40 m × 240 m is considered (Doan-Sy 2019). The dynamic properties of the building such as modal frequencies, mode shapes are estimated by the finite element model. Fig. 1 shows the first three modes of the building. Table 1 provides other building parameters.

Table 1. Structural parameters of a 60-floor tall building

Parameter	Value
Width (b) × depth (b) × Height (H)	40 m × 40 m × 240 m
Fundamental frequency	0.162 Hz
First mode shape	$(z/H)^{1.2}$
Mass per unit length (m)	440000 kg/m

To obtain the aerodynamic coefficients, wind tunnel tests on a 1:400 model were conducted in a closed-circuit wind tunnel at Yokohama National University, Japan. Model dimensions and setup are shown in Fig. 2 and detailed in Doan-Sy (2019); Doan-Sy et al. (2019).

Fig. 3 shows the drag (C_D) and lift (C_L) coefficients of the building at each height level, obtained by integrating



Mode 1: Longitudinal 0.162 Hz | Mode 2: Lateral 0.162 Hz | Mode 3: Torsional 0.547 Hz

Figure 1. First three modes of the building.

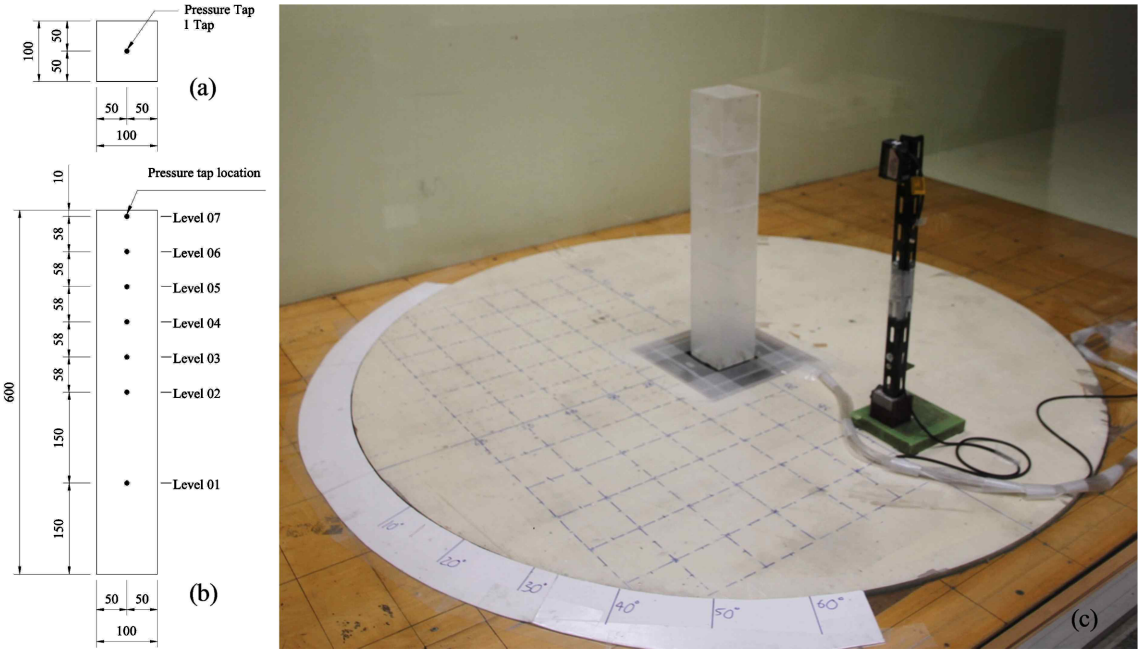


Figure 2. Model dimension and pressure tap location from the top. (a); Model dimension and pressure tap location from the front (b); Model arrangement in the wind tunnel (c)

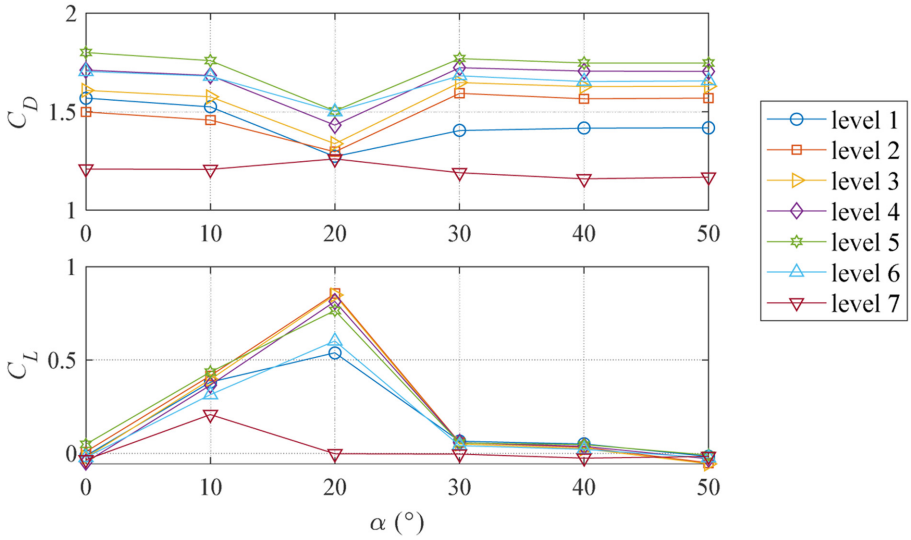


Figure 3. Drag (CD) and lift (CL) coefficients for 7 height levels of the building.

the pressure over the cross section. It can be observed that the drag and lift coefficients at Level 7 are significantly different from the overall pattern of the aerodynamic coefficients at the other height levels. This is due to the existence of flow over the top of the building, which induces distinct flow features compared to lower height levels and reduces drag and lift coefficients. In addition, the pressure taps at Level 7 locate closely to the separation point near the top of building leading to the significant change in pressure coefficients. An example of the flow over the top of building and its effects can be found in Huang et al. (2007). In addition, wind tunnel tests for aerodynamic characteristics of square section tall buildings were conducted by Kim et al. (2015) but with an aspect ratio b:H of 1:5.

Using Eq. (8), and considering only the first vibrational mode which is the most typical for tall buildings, Fig. 4 shows the aerodynamic damping ratio evaluated for the mean wind velocity of 30 m/s at the reference height for different angles of attack α. In addition, using Eq.(11), i.e. the simplified method, the aerodynamic damping ratios are evaluated at each height level (from Levels 1 to 6) and for different angles of attack. The maximum and minimum values at each angle of attack are extracted and compared with the rigorous solution in Fig. 4. The two dashed lines are referred as the upper and lower bounds of the aerodynamic damping calculated with the assumption of a uniform structure in uniform wind. In the analysis, the aerodynamic coefficients are fitted by the spline fitting and the coefficient derivatives are calculated from the fitting lines.

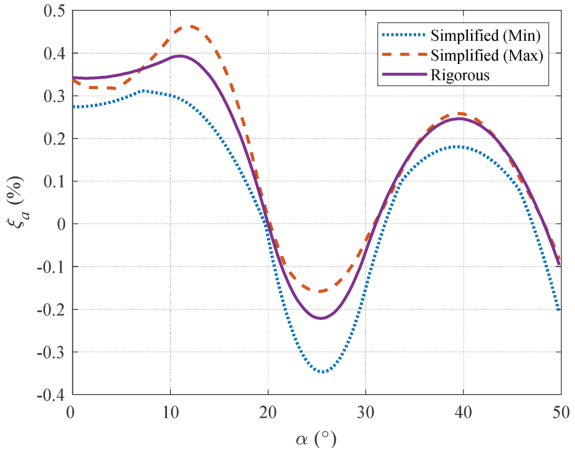


Figure 4. Aerodynamic damping ratios of the building.

As can be seen from the Fig. 4, both simplified and rigorous methods agree on the ranges of the wind direction which are associated with negative or positive aerodynamic damping ratios. On the other hand, there is significant difference in predicting the value of the aerodynamic damping ratio. In engineering practice, the minimum value is interested because of conservative reason. At α=30°, the minimum value is two times smaller than the rigorous value and nearly four-times smaller than the maximum value. This means that the commonly simplified approach is sometimes beneficial but also detrimental to the structure. Importantly, as shown by the large difference between the minimum and maximum values, the simplified approach contains large uncertainty due to the variation of aerodynamic coefficients and wind speed along the structure.

It is usual in practice that the aerodynamic coefficients of a vertical structure are taken as constant with those obtained from sectional wind tunnel tests. As shown in here, this approximation may lead to incorrect determination of the aerodynamic damping.

3.2. A sculptural tower

Another numerical case study is the well-known sculpture "Endless Column" in Romania (Fig. 5). The column, also

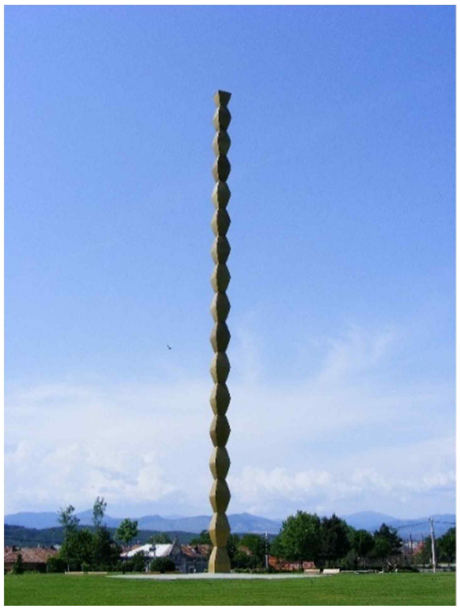


Figure 5. Brancusi column. (source: www.romania-insider.com)

known as Brancusi column, is a symbol of an exceptionally artistic and technical work. Despite of its slenderness, it has never been suffered from any visible instability that has attracted many investigations for the aerodynamic and aeroelastic performances (e.g. Dragomirescu et al., 2009; Lungu et al., 2002; Solari, 2013). The structural parameters are summarized in Table 2.

The drag and lift aerodynamic coefficients for different angles of attack α were estimated through sectional model wind tunnel tests reported in Lungu et al., (2002) and are redrawn in Fig. 6.

Applying Eq. and Eq., Fig. 7 shows the aerodynamic damping ratios obtained from the rigorous and simplified solutions, respectively. Based on the Eurocode and the topography condition of the column location with the roughness length $z_0 = 0.05$ m, the mean wind velocity at the reference height of 10 m is 25.47 m/s. Similar to the case of the tall building, spline fitting is used to interpolate aerodynamic coefficients. The rigorous solution suggests that the aerodynamic damping ratio is negative for the angle of attack from –7° to 9°. The lowest negative ratio is 0.44%, reducing the structural damping by 27.5%. Meanwhile, outside such a range of the angle of attack, the aerodynamic damping is positive, which is beneficial

Table 2. Structural parameters of Brancusi column.

Parameter	Value
Height (H)	29 m
Width (b)	0.9 m
Fundamental frequency	0.513 Hz
First mode shape	$(z/H)^{1.75}$
Structural damping (ξ)	1.6%
Mass per unit length (m)	1069 kg/m

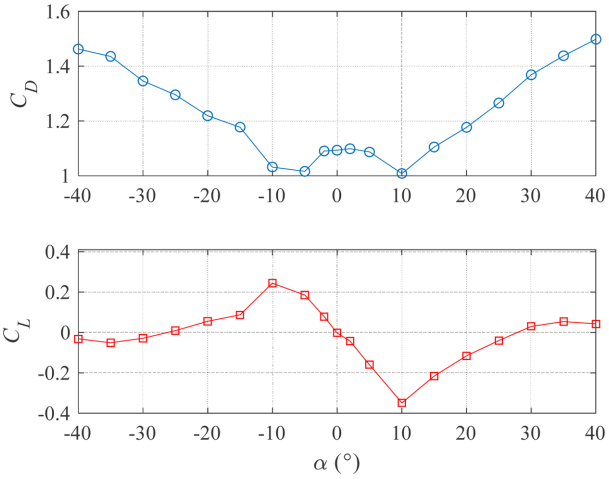


Figure 6. Drag and lift coefficients.

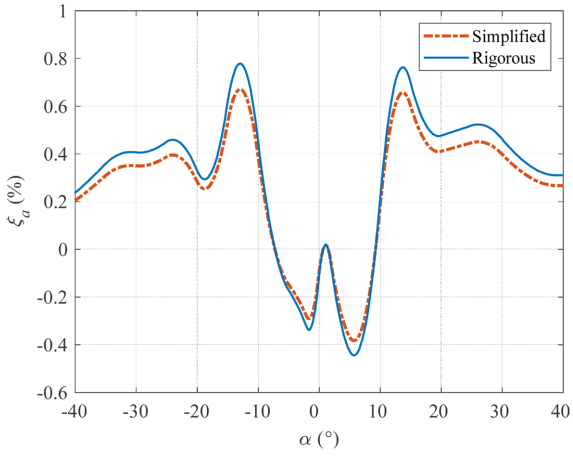


Figure 7. Aerodynamic damping ratio of Brancusi column.

to the structure. The highest positive ratio is 0.78%, increasing the structural damping by 48%. This shows the aerodynamic efficiency in the design of the column, making the structure stable in wind.

In a comparison against the rigorous solution, the simplified solution underestimates up to 14% the aerody-namic damping ratio, both for the lowest negative and highest positive values. Such underestimation in the negative aerodynamic damping is detrimental to the safety and integrity of the structure. Furthermore, as both the solutions treat the column as uniform and as the aerodynamic coefficients are constant, the difference between them indicates a crucial role of the structural mode shapes and the variation of mean wind velocity.

From an aerodynamic point of view, it is shown above that Brancusi column has an effective design with a large range of angle of attack having positive aerodynamic damping. For the negative aerodynamic damping, it is useful to investigate the aeroelastic stability of the structures so that the effectiveness is evaluated more comprehensively. Fig. 8 plots

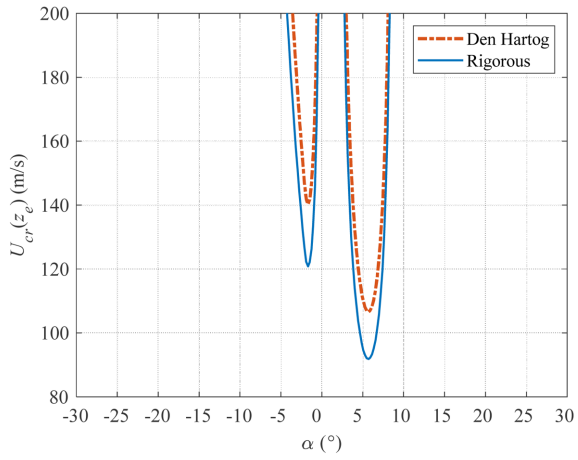


Figure 8. Critical galloping velocity.

the critical galloping velocity at the reference height, where the aerodynamic damping is negative, using the Den Hartog criterion, i.e. simplified solution, and rigorous solution. The critical velocities higher than 200 m/s are excluded from the figure. The lowest critical velocity given by the rigorous solution is 91.87 m/s, which is relatively high and rarely occur at the site. This, again, emphasizes the aerodynamic effectiveness of the design of the structure. On the other hand, the simplified solutions over-estimates the critical wind speed, which is less conservative than the rigorous solution and unsafe for the structure. Although both methods predict very high critical galloping velocities, the difference shows the inadequacy of the use of the Den Hartog criterion.

4. Conclusions

The paper presents a rigorous solution for evaluating the across-wind aerodynamic damping of tall structures using the quasi-steady hypothesis. The theory is applicable for non-uniform structures in non-uniform winds. For particular cases of uniform structures in uniform and in non-uniform wind, closed form solutions are provided.

Two applications on a tall building and a sculptural tower show that the traditional method to evaluate the aerodynamic damping and the onset galloping velocity is over simplified. Such a simplification give rise to unreliable results with large uncertainty, which are sometimes unsafe for the structures. In addition, the non-negligible difference between the rigorous and simplified solution highlights the role of structural mode shapes, which are usually ignored for uniform structures. It is also shown that not only the negative aerodynamic damping should be considered as usual, but also the positive value needs to be considered as it can have significant contribution to the total damping of the structures. In the case of positive aerodynamic damping, structural damping can be reduced to save costs or improve the design.

Finally, the proposed method, on the one hand, provides a useful tool for evaluating the aerodynamic damping ratio. On the other hand, it is helpful for assessing the required structural damping to be added to the structure in order to mitigate the dynamic response or to prevent the occurrence of galloping.

5. Acknowledgement

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