

Aeroelastic behavior of complex lighting poles and antenna masts

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ABSTRACT: This paper presents the analytical and experimental studies of aeroelastic behavior of slender structures, particularly of lighting poles and antenna masts with distributed eccentricities. Critical conditions of coupled galloping and of generalized Den Hartog's criterion are derived in closed form. An application of the method on a real structure indicates the significance of the aerodynamic eccentricities, upper vibration modes, and coupling between the translational components of the motion. Additionally, in case of such a structure, it is pointed out that carrying out the classic simplified SDOF (single degree of freedom) stability analysis may lead to considerable errors in the prediction of instability conditions.

KEYWORDS: Aeroelasticity, steady-state theory, galloping, tubular poles, antenna masts, critical velocity, wind-tunnel test

1 INTRODUCTION

Tubular poles may appear as simple structures that can be modeled, very easily, by a cantilever beam with one or more concentrated masses usually at their top; unfortunately, this is often the concept that inspires the usual static engineering calculations. A deeper reflection on this structural type, however, points out totally different characteristics. The structures are built in such a large and growing number to represent a relevant economic problem in spite of a low single cost. They are characterized by an increasing height, lightness, slenderness and complicated shapes that make them extremely sensitive to complex wind-excited and aeroelastic responses and require refined analyses to capture their physical behavior (Fig.1). An impressive number of collapses that increasingly involve these constructions, frequently due to wind-excited fatigue [1], emphasize their susceptibility to wind actions and their potentially dangerous role in the anthropogenic territory.

A dominant property that joins engineering calculations and refined evaluations carried out in the literature on tubular poles is their idealization as polar symmetric structures. This is definitely not correct due to several peculiar features of these structures, such as stairs, cable bundles, or solar panels, usually applied to the shaft, lighting devices, top balcony, antennas and parabolas that are often put eccentrically with respect to the axis of the shaft, and cylinder hulls, which ever more frequently cover the transmission devices, endowed with non circular sections due to construction imperfections. One or the whole of these situations give rise to mass and shape eccentricities, which make these structures complex, both in mechanical and in aerodynamic terms, and sensitive to potential instabilities due to aeroelastic critical phenomena.

Review in literature shows that there are few studies on this issue, both in theoretical and experimental aspects. Solari and Pagnini [2] analyzed the wind-excited response and the galloping of lighting poles and antenna masts with distributed concentrated masses, upper modes and coupling between alongwind and crosswind vibrations, without considering eccentricities. Cara-

coglia and Jones [3] studied the galloping and buffeting responses of poles with a luminaire at the top; the effect of eccentric aerodynamic loads at the level of the luminaire is taken into account, but the main pole is considered as polar symmetric structure.

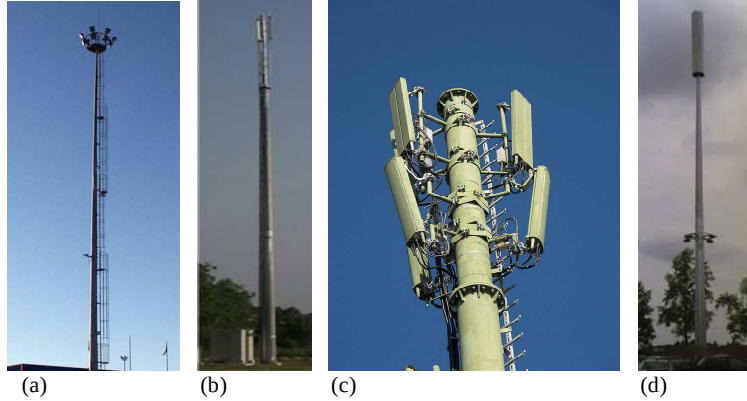


Figure 1. Typical lighting poles and antennas masts

To clarify the role and the importance of the above remarks, this paper introduces a theoretical framework to evaluate the aeroelastic performance of slender structures with distributed eccentricities, particularly of lighting poles and antenna masts. A quasi-steady theory is first developed that takes into account the variations of mass, width of cross section, aerodynamic coefficients, eccentricity, and wind velocity along the structure; besides, upper modes of vibration and coupling effects among such modes are considered; aeroelastic instability conditions are determined in the state space. Starting from this formulation, and introducing suitable conditions, analytical solutions for the critical velocity of coupled and uncoupled systems are then derived.

As an example, this formulation is applied to a real telecommunication antenna mast, in which typical distributed eccentricities, such as stairs, cable bundles and masts are considered. This structure reveals the occurrence of unusual aeroelastic instabilities that emphasize the role of the upper modes, of the coupling between crosswind and alongwind vibrations, of the distribution of the eccentricities along the structural height.

2 GENERAL FORMULATIONS

Let us consider a vertical tubular pole idealized as a vertical cantilever beam with longitudinal axis z passing through the stiffness center of the cross section. The structural motion at height z is defined by two horizontal displacements x and y and a torsional rotation θ . The structure has height L , mass per unit length $m(z)$, width of cross section $b(z)$. The wind direction is horizontal and makes an angle α with axis x (Fig.2).

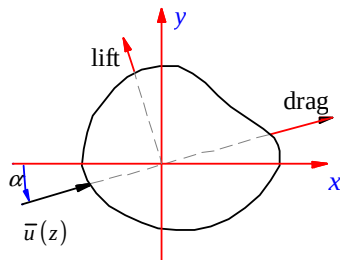


Figure 2. Wind action on a structural body.

To perform the stability analysis, the forces given rise from the mean wind velocity, atmospheric turbulence and vortex shedding are ignored. Then, the equations of motion can be expressed in principal coordinates as follows [4]:

$$\tilde{\mathbf{M}}\ddot{\mathbf{P}}(t) + \tilde{\mathbf{C}}\dot{\mathbf{P}}(t) + \tilde{\mathbf{K}}\mathbf{P}(t) = \tilde{\mathbf{F}}_a(t) \quad (1)$$

where $\mathbf{P}(t)$ is the generalized displacements vector; $\tilde{\mathbf{M}} = \text{diag}(\tilde{m}_i)$, $\tilde{\mathbf{C}} = \text{diag}(2\tilde{m}_i\zeta_i\omega_i)$, and $\tilde{\mathbf{K}} = \text{diag}(\tilde{m}_i\omega_i^2)$ are respectively the generalized mass, structural damping, stiffness matrices, in which $\tilde{m}_i$, ζ_i , ω_i are correspondingly the generalized mass, structural damping coefficient, and natural frequency associated with i -th mode ($i=1,2,\dots$); whereas $\tilde{\mathbf{F}}_a(t)$ is the vector of generalized aeroelastic wind actions:

$$\tilde{\mathbf{F}}_a(t) = \int_0^L \boldsymbol{\Psi}^T(z) \mathbf{f}_a(z, t) dz \quad (2)$$

in which $\boldsymbol{\Psi}(z) = [\boldsymbol{\Psi}_1(z) \ \boldsymbol{\Psi}_2(z) \ \dots]$ is the modal matrix where $\boldsymbol{\Psi}_k(z) = [\psi_{kx}(z) \ \psi_{ky}(z) \ \psi_{k\theta}(z)]^T$; $\mathbf{f}_a(z, t) = [f_{ax}(z) \ f_{ay}(z) \ f_{a\theta}(z)]^T$ is the vector of aeroelastic wind actions. By adopting the quasi-steady theory, it follows that:

$$\mathbf{f}_a(z, t) = -\frac{1}{2} \rho \bar{u}^2(z) b(z) \mathbf{R}^T \mathbf{c}_a(z) \mathbf{R} \boldsymbol{\Psi}(z) \dot{\mathbf{P}}(t) \quad (3)$$

where ρ is the air density, $\bar{u}(z)$ is the mean wind velocity profile; $\mathbf{c}_a(z)$ and $\mathbf{R}$ are the aerodynamic coefficient and rotation matrices, respectively:

$$\mathbf{c}_a(z) = \begin{bmatrix} 2c_d(z) & c'_d(z) - c_l(z) & -R_0(z)(c'_d(z) - c_l(z)) \\ 2c_l(z) & c_d(z) + c'_l(z) & -R_0(z)(c_d(z) + c'_l(z)) \\ 2b(z)c_m(z) & b(z)c'_m(z) & R_0(z)b(z)c'_m(z) \end{bmatrix}; \quad \mathbf{R} = \begin{bmatrix} \cos \alpha & \sin \alpha & 0 \\ -\sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (4)$$

in which $c_d(z)$, $c_l(z)$, and $c_m(z)$ are the mean drag, lift, and torsional moment coefficients, respectively, estimated through static tests in wind tunnel; $R_0(z)$ is the characteristic radius of the cross section; dealing with a compact section, it is reasonably assumed as equal to zero [5-6].

Substituting Eq.(3) into Eq.(2), then Eq.(2) into Eq.(1) and rearranging in state space form, it leads to:

$$\dot{\mathbf{p}} = \tilde{\mathbf{A}}\mathbf{p} \quad (5)$$

where

$$\mathbf{p} = \begin{bmatrix} \mathbf{P} \\ \dot{\mathbf{P}} \end{bmatrix}; \quad \tilde{\mathbf{A}} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\tilde{\mathbf{M}}^{-1}\tilde{\mathbf{K}} & -\tilde{\mathbf{M}}^{-1}(\tilde{\mathbf{C}} + \tilde{\mathbf{C}}_a) \end{bmatrix} \quad (6)$$

in which $\tilde{\mathbf{C}}_a$ is the generalized aerodynamic damping matrix:

$$\tilde{\mathbf{C}}_a = \frac{1}{2} \rho \int_0^L \bar{u}(z) b(z) \boldsymbol{\Psi}^T(z) \mathbf{R}^T(z) \mathbf{c}_a(z) \mathbf{R} \boldsymbol{\Psi}(z) dz \quad (7)$$

The dynamical system represented by Eq.(5) is asymptotically stable if and only if all the real part of the eigenvalues of matrix $\tilde{\mathbf{A}}$ are negative [7]. Such an eigenvalue problem to find the con-

dition for the instability occurrence is normally solved through a numerical procedure. Particularly, neglecting the torsional rotation component and assuming that the resultant 2 DOFs coupled system is endowed with a set of couples of orthogonal modes having the same frequencies, i.e. $\omega_{2k-1} = \omega_{2k}$ ($k = 1, 2, \dots$), this problem can be solved in closed form and the eigenvalues of the matrix $\tilde{\mathbf{A}}$ are given by [4, 8]:

$$\begin{aligned}\lambda_{1,2} &= i - \xi_{2k} + \frac{\rho b(z_e) \bar{u}(z_e)}{8\tilde{m}_{2k,eq} \omega_{2k}} \left(-\text{tr} \tilde{\mathbf{C}}_{a,2k,eq} \pm \sqrt{\text{tr}^2 \tilde{\mathbf{C}}_{a,2k,eq} - 4 \det \tilde{\mathbf{C}}_{a,2k,eq}} \right) \\ \lambda_{3,4} &= -i - \xi_{2k} + \frac{\rho b(z_e) \bar{u}(z_e)}{8\tilde{m}_{2k,eq} \omega_{2k}} \left(-\text{tr} \tilde{\mathbf{C}}_{a,2k,eq} \pm \sqrt{\text{tr}^2 \tilde{\mathbf{C}}_{a,2k,eq} - 4 \det \tilde{\mathbf{C}}_{a,2k,eq}} \right)\end{aligned}\quad (8)$$

where i is the imaginary unit; z_e is a reference height; $\tilde{m}_{2k,eq}$ and $\tilde{\mathbf{C}}_{a,2k,eq}$ are the equivalent mass and aerodynamic matrix related to mode $2k$ -th, respectively:

$$\tilde{m}_{2k,eq} = \frac{\int_0^L m(z) \|\Psi_{2k}(z)\|^2 dz}{\int_0^L \|\Psi_{2k}(z)\|^2 dz} ; \quad \tilde{\mathbf{C}}_{a,2k,eq} = \int_0^L \mathbf{\Pi}_{2k}^T(z) \mathbf{c}_a(z) \mathbf{\Pi}_{2k}(z) dz \quad (9)$$

in which $\mathbf{c}_a$ is the aerodynamic matrix achieved by dropping the third column and row in the aerodynamic matrix $\mathbf{c}_a(z)$ given in Eq.(4), and $\mathbf{\Pi}_{2k}(z)$ is a functional matrix associated with the $2k$ -th mode given by:

$$\mathbf{\Pi}_{2k}(z) = \sqrt{\frac{\bar{\mu}(z) b(z)}{\bar{\mu}(z_e) b(z_e) \int_0^L \|\Psi_{2k}(z)\|^2 dz}} \mathbf{R} \Psi_{2k}(z) \quad (10)$$

where $\|\Psi_{2k}(z)\|$ denotes the norm of the mode shape $\Psi_{2k}(z)$ and $\bar{\mu}(z)$ is a suitable non-dimensional function expressing the shape of the mean wind velocity profile, e.g. a power or logarithm law:

$$\bar{u}(z) = \bar{u}(z_e) \frac{\bar{\mu}(z)}{\bar{\mu}(z_e)} \quad (11)$$

As a result, the necessary condition for instability is represented by the simultaneous satisfaction of the following two equations:

$$\text{i) } \text{tr} \tilde{\mathbf{C}}_{a,2k,eq} < 0 \quad (12)$$

$$\text{ii) } \text{tr} \tilde{\mathbf{C}}_{a,2k,eq} \geq 0 > \det \tilde{\mathbf{C}}_{a,2k,eq} \quad (13)$$

The critical velocity at the reference height z_e associated with such two conditions is given by:

$$i) \bar{u}_{cr,2k}(z_e) = \begin{cases} -\frac{8\omega_{2k}\xi_{2k}\tilde{m}_{2k,eq}}{\rho b(z_e) \operatorname{tr} \tilde{\mathbf{C}}_{a,2k,eq}} & \text{for } \operatorname{tr}^2 \tilde{\mathbf{C}}_{a,2k,eq} - 4\det \tilde{\mathbf{C}}_{a,2k,eq} \leq 0 \\ -\frac{8\omega_{2k}\xi_{2k}\tilde{m}_{2k,eq}}{\rho b(z_e) \left[\operatorname{tr} \tilde{\mathbf{C}}_{a,2k,eq} - \sqrt{\operatorname{tr}^2 \tilde{\mathbf{C}}_{a,2k,eq} - 4\det \tilde{\mathbf{C}}_{a,2k,eq}} \right]} & \text{for } \operatorname{tr}^2 \tilde{\mathbf{C}}_{a,2k,eq} - 4\det \tilde{\mathbf{C}}_{a,2k,eq} > 0 \end{cases} \quad (14)$$

$$ii) \bar{u}_{cr,2k}(z_e) = -\frac{8\omega_{2k}\xi_{2k}\tilde{m}_{2k,eq}}{\rho b(z_e) \left[\operatorname{tr} \tilde{\mathbf{C}}_{a,2k,eq} - \sqrt{\operatorname{tr}^2 \tilde{\mathbf{C}}_{a,2k,eq} - 4\det \tilde{\mathbf{C}}_{a,2k,eq}} \right]} \quad (15)$$

It is worth noting that the eigenvalues derived in Eq.(8) and the instability conditions given in Eq. (12)-(15) take into account the variation along the whole structures of the width of cross section $b(z)$, mass per unit length $m(z)$, aerodynamic coefficients $\mathbf{c}_a(z)$, and mean wind velocity $\bar{u}(z)$. So, they constitute the generalization of the solutions given in literature, e.g. in [8], in which those structural and aerodynamic parameters were assumed to be constant. Moreover, focusing on the sole oscillation corresponding to crosswind modes, the galloping analysis of a SDOF system can be derived as a particular case of Eqs.(12) and (13). This can be done by setting $\alpha=0$ and by considering only the element (2,2) of matrix $\tilde{\mathbf{C}}_{a,2k,eq}$. Consequently, the necessary condition for galloping occurrence in the k -th mode in the crosswind direction results:

$$(c_d + c'_l)_{k,eq} < 0 \quad (16)$$

where $(c_d + c'_l)_{k,eq}$ is the equivalent galloping coefficient in the k -th mode obtained from the second equation of Eq.(9):

$$(c_d + c'_l)_{k,eq} = \int_0^L [c_d(z) + c'_l(z)] \Pi_k(z) dz \quad (17)$$

in which $\Pi_k(z)$ is a function related to the k -th mode:

$$\Pi_k(z) = \frac{\bar{\mu}(z)b(z)\psi_k^2(z)}{\bar{\mu}(z_e)b(z_e) \int_0^L \psi_k^2(z) dz} \quad (18)$$

The critical velocity corresponding to k -th mode at the reference height z_e is provided by:

$$\bar{u}_{cr,k}(z_e) = -\frac{4\omega_k\xi_k\tilde{m}_{k,eq}}{\rho b(z_e)(c_d + c'_l)_{k,eq}} \quad (19)$$

For a particular case in which $m(z)$, $b(z)$, $c_d(z)$, $c'_l(z)$, and $\bar{u}(z)$ are constant, then $(c_d + c'_l)_{k,eq}$ is equal to $(c_d + c'_l)$; furthermore, the critical velocity related to the first crosswind mode is resulted in:

$$\bar{u}_{cr,1} = -\frac{4\omega_1\xi_1 m}{\rho b(c_d + c'_l)} \quad (20)$$

which is the one given by Den Hartog.

Consequently, Eq.(16) and Eq.(19) are the generalizations of the classical galloping analysis.

It is worth noting that once the critical wind velocity at the reference height z_e is determined, thanks to Eq.(11), a critical wind profile is established.

3 CASE STUDY

An infinite series of different lighting poles and antennas masts exists in reality. The theoretical framework described above is applied herein to study the aeroelastic behavior of a particular type of real structure. This structure is an antenna mast whose total height is $h = 30$ m and it is composed by two steel shafts with circular sections (Fig.3). The first shaft, which is referred to as main shaft, is 24 m long. The outer diameter of its section, whose thickness is 5 mm, varies from 950 mm at the bottom to 350 mm at the top. The cables attached along this shaft have a distributed mass per unit length 5 kg/m. The second shaft, put above the first one, is 6 m long, and it carries 6 antennas; the total weight of this shaft is 540 kg. Its section has constant outer diameter 193.7 mm, and it is 7.1 mm thick. A stair is placed along the whole structure and has a unit mass per length 7 kg/m. The structural damping for each mode is assumed as 0.5%. The additional stuffs such as the stair, cables, and antennas give rise to a distributed mass eccentricity; instead, they are assumed to be ineffective to the structural stiffness. Besides, the pole is located at a terrain characterized by a roughness length $z_0 = 0.3$ m, and the mean wind velocity is assumed to follow the logarithm law.

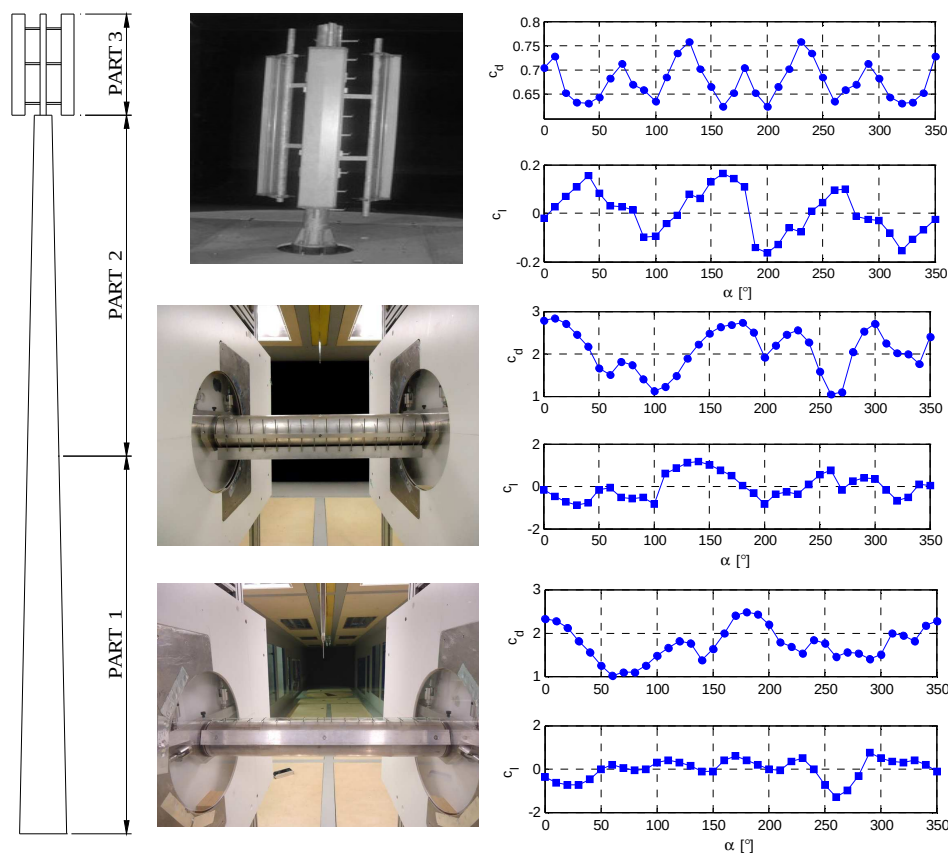


Figure 3. Sectional models of wind tunnel test and aerodynamic coefficients.

The static aerodynamic coefficients have been determined by wind tunnel tests. The tests on the main shaft have been conducted in the wind tunnel of the Faculty of Engineering of the University of Genoa. Since the outer diameter of the main shaft varies significantly from 950 mm to 350 mm, measurements have been carried out by dividing this shaft into two uniform parts with geometric scales 1:5 and 1:10. The angle of attack has been varied with 10° steps. For the top shaft, the results achieved from previous experiments performed in the wind tunnel of Milan Polytechnic have been used. All results pointed out that the Reynolds numbers do not affect considerably the aerodynamic coefficients. Fig.3 shows the drag and lift coefficients for each part of the pole.

4 NUMERICAL RESULTS AND DISCUSSIONS

The modal analysis provides the first four natural frequencies: $n_{1,2}=0.774$ Hz, $n_{3,4}=3.628$ Hz. The corresponding mode shapes are plotted in Fig.4. The eccentricity does not change the substantial similarity between couples of natural frequencies in translational directions, but it couples the corresponding mode shapes.

In the stability analysis, the Den Hartog's criterion is preliminarily utilized for each of three parts of the pole. Next, the instability conditions presented in the previous section for the SDOF and the 2DOF systems, i.e. uncoupled and coupled vibrations, are applied.

The analysis is carried out by taking into account the variation along the whole structure of the mass, width, mean wind velocity and aerodynamic coefficients. Two cases are considered, namely the shaft without eccentricity and with an eccentricity varying along its height. By employing Eq.(9), it results in that $\text{tr}\tilde{C}_{a,2k,eq}$ is always positive. Then Eqs.(13), (15), (16), and (19) are applied to determine the instability conditions and the critical velocities for both SDOF and 2DOF systems. The critical velocity is evaluated at the reference height fixed $z_e=10$ m. Any critical velocity larger than 200 m/s is disregarded. It is found that, on one hand, the presence of the distributed eccentricity, which is small as compared with the pole diameter, does not influence the aeroelastic response. On the other hand, the following remarks are highlighted.

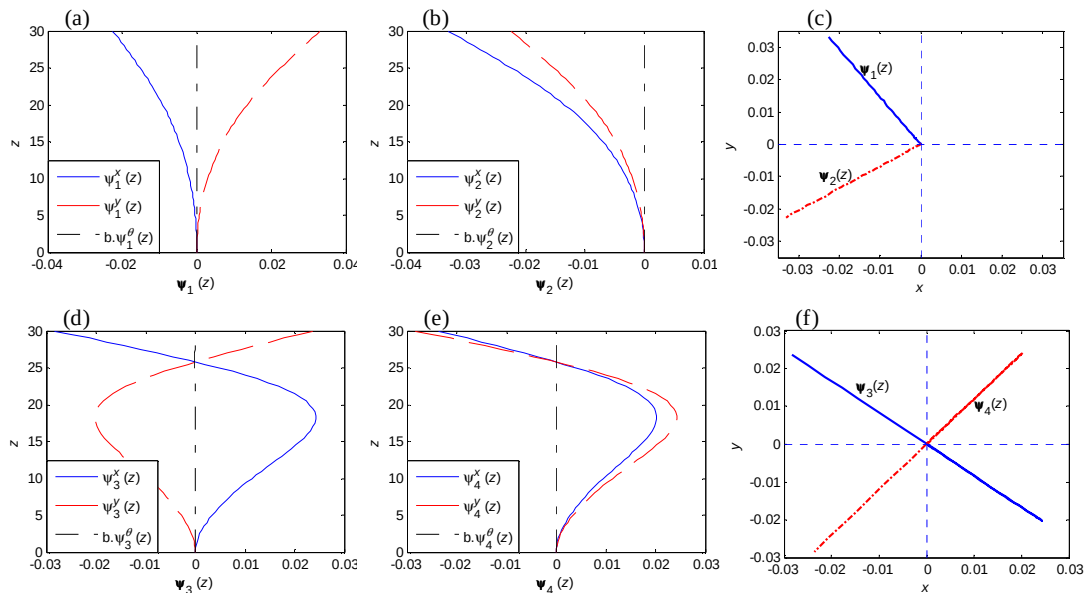


Figure 4. First four mode shapes : (a) first mode; (b) second mode; (c) first and second modes top view; (d) third mode; (e) fourth mode; (f) third and fourth modes top view

Firstly, Fig.5a shows the values of $(c_d + c'_l)$ for each of the three parts of the pole; Fig. 5b shows the values of $(c_d + c'_l)_{k,eq}$ provided in Eq.(17) for the first two crosswind modes. It can be seen that, according to the Den Hartog's criterion for each of three single parts, part 1 can gallop at wind attack angles 240° and 250° ; part 2 at 0° , 100° , 120° , and 240° ; part 3 at 180° and 190° . However, applying the generalized Den Hartog's criterion given by Eq.(16), in which the shaft is considered in its whole, the structure can gallop at only 3 wind attack angles 180° , 190° and 240° . Moreover, the structure can be unstable not only in the first crosswind mode (mode 2 in Fig.2) but also in the second crosswind mode (mode 4 in Fig. 2). This latter case occurs for the angle of attack 240° where it cannot gallop in the first crosswind mode. Therefore, carrying out the galloping analysis only for first crosswind mode of a SDOF system can be unsafe.

Secondly, Fig.6a shows the necessary condition for instability of a 2DOF system, i.e. $\det \tilde{C}_{a,2k,eq} < 0$, and Fig.6b presents the critical velocities for the 2DOF coupled system (Eq.(15)) in comparison with those for the SDOF uncoupled one (Eq.(19)). That the instability can occur in the third and fourth coupled modes reconfirms the importance of the higher modes in the stability analysis. Moreover, at the angle 180° , the SDOF model provides the critical velocity 37.03 m/s, while the 2DOF model gives a higher value, 40.52 m/s; in this case, carrying out a SDOF galloping analysis, as in the common practice, provides a result on the safe side. The situation changes at the angle 190° , where the critical velocity of a 2DOF system is 23.87 m/s, considerably lower than the value 36.12 m/s provided by a SDOF galloping analysis. This huge error (34%) stresses the significance of coupling the crosswind component of the motion with the alongwind one. In other words, neglecting such coupling as usual may give rise to unsafe evaluations. The difference between the above two critical velocities may result from the internal resonance due to the equality of two translational modes.

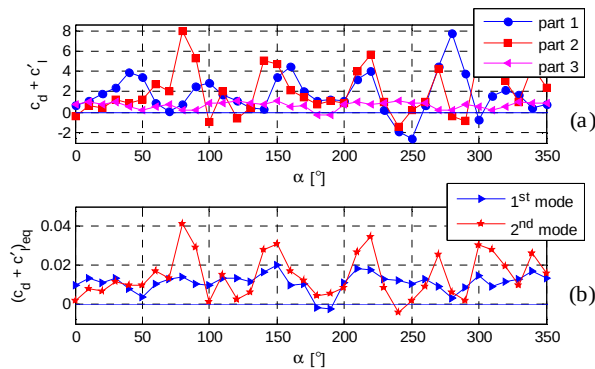


Figure 5: Galloping condition for SDOF system: Den Hartog's criterion (a); generalized Den Hartog's criterion (b)

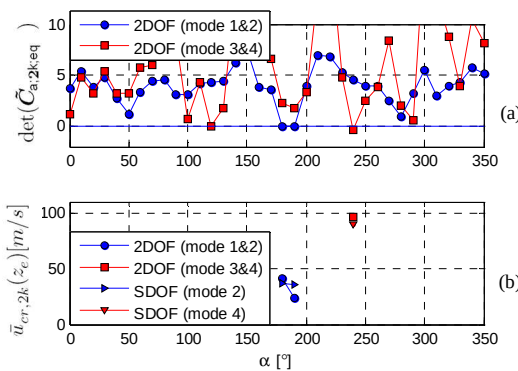


Figure 6. (a) Necessary conditions for 2DOF galloping; (b) Critical velocities.

Thirdly, in the first crosswind mode of a SDOF system, and in the first two modes of a 2DOF system, the galloping occurs only at the angles 180° and 190° , at which the top antennas part (part 3) is potentially unstable. This emphasizes the role of the antennas in the instability of the whole structure. To investigate deeper this role, the analysis is replicated by rotating the top part with an angle θ varying from 0° to 350° , with respect to the main pole, with an increment of 10° . Fig.7a shows, for each the angles of attack α , the minimum critical velocity corresponding to all the rotation angles θ . It can be witnessed that the structure is potentially unstable with different critical velocities for different position of the antennas part. In the meanwhile, for each angle θ , Fig.7b plots the minimum critical velocity corresponding to all the attack angles α . From this, the worst position of the top part respect to the main shaft that the critical velocity is smallest corresponds to $\theta=310^\circ$. This means that the antennas should not be put in such a position during the construction. In addition, due to the resonant coupling between the first two translational modes, the critical velocities of a 2DOF system are not always close to those of a SDOF system; even more, in some cases, e.g. at $\theta=0^\circ$, 140° , 150° , they are seriously lower than those of a SDOF system. Besides, the structure is unstable in the 4th uncoupled mode and in the 3rd and 4th coupled modes at all rotating angles θ while it is still stable in the lower modes at θ equal to 30° , 40° , 100° , 110° , 200° , 230° , 240° , and 330° . In summary, this study points out that, on one hand, the effect of the top antennas part on the stability of whole pole is noteworthy. On the other hand, it is confirmed that neglecting the alongwind component of the response, i.e. considering only the crosswind SDOF instability with different modes may lead to remarkable errors being fatal to the structure.

Lastly, to understand deeper the influence of the antennas part on the structural stability, the analysis is repeated by covering the antennas with a cylinder, as it is shown in Fig.1d. For this cylinder, $c_d=0.74$, and $c_l=c'_d=c'_l=0$. Fig.8a plots the necessary instability conditions ($\text{tr}\hat{C}_{a,2k,eq}$ is absent in this figure since it is positive for every k) while Fig.8b shows the critical velocities for the 2DOF coupled system in comparison with those for the SDOF uncoupled one. It can be seen that the instability phenomenon occurs only at 240° for the second crosswind mode in the case of a SDOF system and in the second two modes in the case of a 2DOF system. This phenomenon disappears at the lower modes. Furthermore, the critical velocities given by the SDOF and 2DOF models are coincident with the value 64.3 m/s. It can be concluded that the cover cylinder does not only create a positive aerodynamic damping that makes the structure more stable, but it can also decouple the aeroelastic motions in translational directions. It should be observed, however, that these considerations apply to perfectly circular cylinders. Recent experiences showed that this situation is definitely not guaranteed. In some limit cases values of the lift coefficient in the order of 0.4 have been detected. This creates a further sort of complexity that can modify also the stability conditions of the pole.

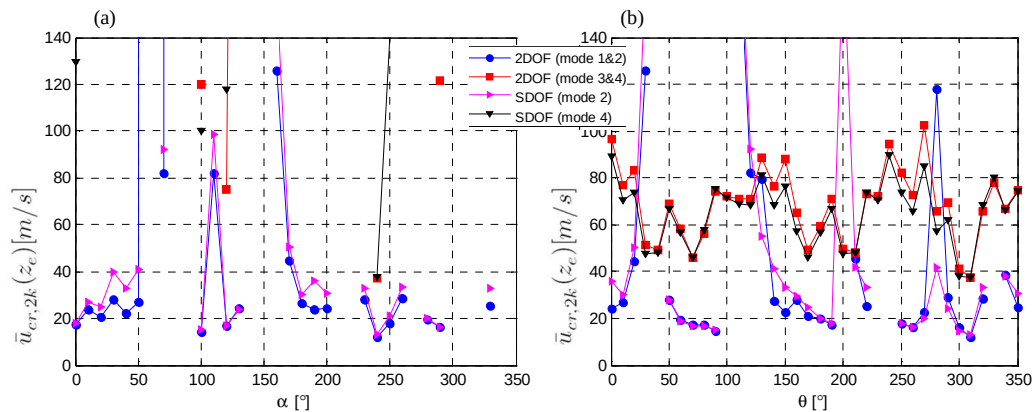


Figure 7. Minimum critical velocity by rotating the antennas part

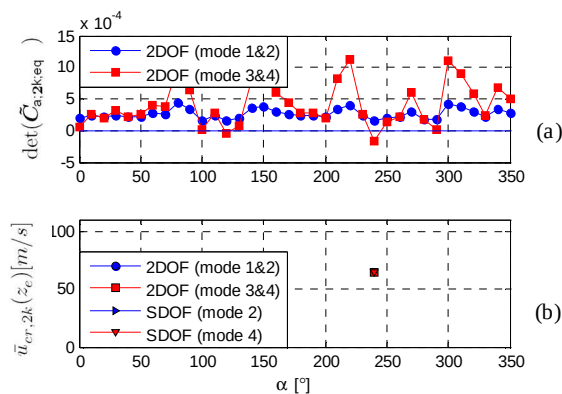


Figure 8. Conditions for 2DOF galloping with the cover cylinder: necessary condition (a); critical velocity (b)

5 CONCLUSIONS AND PERSPECTIVES

This paper establishes a general theoretical framework to study the aeroelastic instability of slender structures with distributed eccentricities. Neglecting torsion and focusing on the internal resonance of translational oscillations, an analytical solution for coupled instability conditions is formulated, which generalizes some previous results available in literature. The classic galloping condition for a SDOF system vibrating in the crosswind direction is obtained as a particular case.

An application of presented method to a real telecommunication antenna mast points out the importance of the aerodynamic eccentricities, of the upper modes of oscillation, and of the coupling between the crosswind and alongwind components of the motion. A comparison between the results provided herein and the classical engineering approaches emphasizes that relevant errors may occur, especially for particular sets of parameters and specific configurations. In such conditions the structure may exhibit very low critical galloping velocity able to produce unexpected damages and collapses. This might explains a lot of damages and collapses that these structures often suffer without clear and suitable explanations.

Showing the potentiality for the occurrence of critical situations unpredictable by means of classic models, this paper can be regarded as a preliminary step towards more refined analyses that may confirm the results provided herein.

The first and most important point is to study the reliability of the proposed theory by carrying out suitable aeroelastic wind tunnel tests and comparing the results obtained with monitored structures and the engineering evidence. Such study cannot avoid the investigation of the role of the turbulence, neglected herein by considering only smooth flows.

A second point to be inspected is a generalization of this study from the aeroelastic instability conditions to the wind-excited response [9, 10] and fatigue [11, 12]. Even far from unstable behavior, slender structures with distributed eccentricities are traditionally calculated without considering such eccentricities, crosswind response and upper modes. The results provided in this paper point out that all these aspects might strongly increase design wind loads, making the current design approaches for these structures seriously unsafe.

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