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EVALUATION OF ALONGWIND RESPONSE AND CROSSWIND FORCES FOR LIGHTING MASTS AT IAŞI INTERNATIONAL AIRPORT

BY

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Abstract. Lighting masts are used for illumination of highways, airports or many types of platforms. Due to their slenderness, these structures are mainly sensitive to the action of turbulent wind and have a high potential of aeroelastic instability. The paper investigates the alongwind response of lighting masts by applying the 3D Gust Effect Factor technique to a real 30m high lighting mast located at Iasi airport. Results are then compared to those obtained using several relevant European wind codes. An evaluation of crosswind equivalent forces generated by vortex shedding on the lighting mast was also carried out. Results show the need of evaluation for cross-wind forces associated with superior mode shapes and the lack of interaction between vortex shedding and galloping.

Keywords: lighting mast; wind loading codes; gust effect factor; alongwind-induced loads and effects; aeroelastic phenomena.

1. Introduction

Lighting or telecom mono-tubular masts have a reduced construction cost, their importance consisting in their functionality, for example ensuring

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illumination of airport platforms, or as part of GSM communication systems. Despite their basic static scheme and seemingly simple design process, the physical phenomena associated with the action of turbulent wind could prove quite complex. Alongwind induced load effects (Davenport, 1961, 1967, Solari, 1999) and crosswind vibrations (Vickery & Clark, 1972, Vickery & Basu, 1983) were progressively studied during last decades, mainly beginning with 1960's. Gust buffeting and aeroelastic behaviour of single section tubular masts were investigated, for instance by Solari & Pagnini (1999), while alongwind load effects on free-standing lattice towers were analysed, for instance by Calotescu & Solari (2016). Vortex shedding represents a transition between dynamic and aeroelastic responses of structures, whereas galloping, a typical aeroelastic phenomenon, represents the vanishing of the total damping.

The paper investigates the response of slender structures such as lighting masts to wind loading by means of a practical application. The alongwind response of a typical 30m high airport lighting mast was evaluated within the framework of the 3D Gust Effect Factor technique (Piccardo & Solari, 2002) which represents a generalization of the original gust response factor technique as introduced by Davenport (1961, 1967). The results were then compared with those obtained using the European (Eurocode 1 Part 1-4), the Romanian (CR1-1-4/2012) and the Italian (CNR-DT207/2008) wind codes. Crosswind forces produced by vortex shedding, corresponding to first and second mode shapes were evaluated according to Italian code and potential interaction between vortex shedding and galloping was also investigated.

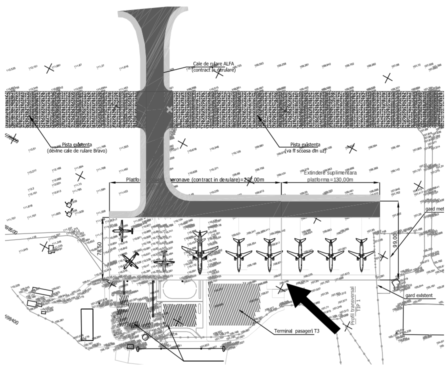
In Section **1** a brief introduction is presented. Section **2** presents general information about the case study, location and characteristics of the 30m steel airport lighting masts, whereas Sections **3** and **4** focus on the evaluation of the wind induced response of these slender lighting masts and evaluation of crosswind forces induced by vortex shedding, respectively. Conclusions present the main findings of the study.

2. Characteristics of the Steel Lighting Masts

Iaşi International Airport, the main North-Eastern airport of Romania is located in the North-Eastern part of the City of Iasi, near Ciric Lakes. First private flight took place on a grass runway in 1905 and first timetable for commercial flights became official in 1926. Currently, the airport has 3 passenger terminals with two of them fully operational after 2012, reporting 890,800 passengers last year. For this year, the airport reported for the first time in November 2017 a total of 1 million processed passengers. The presented case study refers to a group of 25 and 30 m high mono-tubular steel lighting masts erected in 2014 and 2015 on the new airport apron, as part of the Iasi

International Airport modernisation and development program (Figs. 1 *a* and 1 *b*).

a



b

Fig. 1 – *a* – Erection of a 30 m high lighting mast at Iasi Airport; *b* – Map showing the extension and modernisation works at the Iaşi Airport.

The structure analysed within this paper is a 30m high airport lighting mast which is part of the group of lighting masts mentioned above. The mast has a polygonal cross-section with 16 sides, the base diameter is 1,009 mm whereas the top diameter is 247 mm. The cross-sectional thickness is and 10 mm for the first 10.5 m and 8 mm to top. The material used for the mast is steel S355. A modal analysis was carried out using FEM software, eigenvector method and three distinct types of modelling such as non-prismatic elements, cylinder segments and shell elements. The obtained mode shapes were similar, with periods and frequencies of: $T_1 = T_2 = 1.33$ sec; $f_{1,2} = 0.75$ Hz; $T_3 = T_4 =$ $= 0.35$ sec; $f_{3,4} = 2.88$ Hz.

3. Alongwind Induced Response of Lighting Masts

Consider a Cartesian coordinate system *x o z*, where *x* represents the alongwind direction, *y* crosswind direction and *z* represents the height coordinate. A first step towards the generalized a 3-D Gust Effect Factor technique was the 3-D Gust Response Factor approach, a method which represented the extension of classic evaluation concerning just alongwind displacement response to crosswind displacement response and torsion response, replacing *x* direction with $\alpha = x, y, \theta$ (Piccardo & Solari, 2000).

According to 3-D Gust Effect Factor technique (Piccardo & Solari, 2002), the generalized effect *e* (bending moment $e = b$, shear force $e = s$ and generalized displacement $e = d$) corresponding to direction $\alpha = x, y, \theta$ is given by:

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

where: $\bar{e}_\alpha$ is the mean value and e'_α is the nil mean fluctuation of e_α.

The mean maximum value of effect is defined as:

$$\bar{e}_{(\alpha,\max)}(r) = \bar{e}^x_\alpha(r) G^e{}_\alpha(r) \tag{2}$$

where: $\bar{e}^x_\alpha$ is the static effect caused by the action of generalised wind force in the α direction at an associated height r and G^e_α is the 3-D gust effect factor given by:

$$G^e_\alpha(r) = 1 + g^e_\alpha(r)\sqrt{Q^e_\alpha(r) + D^e_\alpha(r)} \tag{3}$$

where: $\bar{e}_\alpha$ is the mean part of e_α, G^e_α is the GEF, g^e_α is the peak factor, Q^e_α quasi-static part and D^e_α resonant part are given by:

$$Q^e_\alpha(r) = \frac{\left[\sigma^e_{Q_\alpha}(r)\right]^2}{\left[\bar{e}_\alpha(r)\right]^2}; \quad D^e_\alpha(r) = \frac{\left[\sigma^e_{D_\alpha}(r)\right]^2}{\left[\bar{e}_\alpha(r)\right]^2} \quad (\alpha = x, y) \tag{4}$$

$\sigma^e_{Q\alpha}$ and $\sigma^e_{D\alpha}$ being the standard deviations of the quasi-static and resonant parts of e'_α.

The generalized equivalent static force associated with effect e_α is given by:

$$F^e{}_{\alpha eq}(z,r) = \lambda_\alpha G^e{}_\alpha(r)\bar{F}_x(z) \tag{5}$$

where $\lambda_\alpha = 1$ for $\alpha = x, y$ and $\bar{F}_x(z)$ is the mean alongwind force.

In case of displacement effect ($e = d$), Eq. 5 becomes:

$$F_{\alpha eq}(z) = \lambda_\alpha G_\alpha \bar{F}_x(z) \tag{6}$$

which means 3-D Gust Response Factor approach ($G_\alpha = G^d{}_\alpha$). Furthermore, in case of $\alpha = x$, Eq. 6 is transformed into Davenport initial relation:

$$F_{xeq}(z) = G_x \bar{F}_x(z) \tag{7}$$

The generalized mean wind force is expressed by (Piccardo & Solari, 2002):

$$\bar{F}_\alpha(z) = (1/2)\rho \bar{u}^2(z) b \lambda_\alpha c_{\alpha u} \gamma_{\alpha u}(z) \tag{8}$$

where: ρ is the air density, $\bar{u}$ is the mean wind speed, $b$is the reference dimension of cross-section, $c_{\alpha u}$ is the generalized aerodynamic force coefficient and $\gamma_{\alpha u}(z)$ is a non-dimensional function of z, with value of 1. According to Eq. 8, the alongwind (α=x) mean wind force becomes:

$$\bar{F}_x(z) = (1/2)\rho \bar{u}^2(z) b c_{fx} \tag{9}$$

For the evaluation of alongwind forces on masts, three relevant design codes were applied, EN1991-1-4 (EC1), CR1-1-4/2012 (Romania) and CNR-DT207/2008 (Italy). The mean wind velocity profile used in all the above stated wind codes is the logarithmic profile defined as:

$$U(z) = \frac{1}{k} u_* \ln\left(\frac{z}{z_0}\right) \tag{10}$$

where: $U(z)$ is mean wind speed, k is Von Karman constant, z is the height above ground level, z_0 is the roughness length and u_* is shear velocity.

The evaluation of base reactions revealed that highest values were obtained using Italian code CNR-DT, almost 7% above CR1-1-4 results. Also, the icing effect (10 mm) was found to have a reduced influence on this type of structure. The maximum base reactions resulted: axial force N = 80.4 kN, base shear force V = 76.8 kN and base bending moment M = 1,325.9 kNm. According to all three design codes, the dynamic response coefficient c_d, resulted equal to 1.15. The first and second mode shapes of the mast are presented in Fig. 2.

The equivalent mass per unit length of the mast is given by:

$$m_{e,i} = \frac{m_i}{\int_0^l \phi_i^2(z)\mathrm{d}z} \tag{11}$$

where: m_i is generalised mass of the structure for i-th vibration mode $\phi_i^2(z)$ and l is the height of the structure. The equivalent mass per unit length corresponding to first and second vibration modes resulted $m_{e,1}$ = 76.52 kg/m and $m_{e,2}$ = 102.61 kg/m.

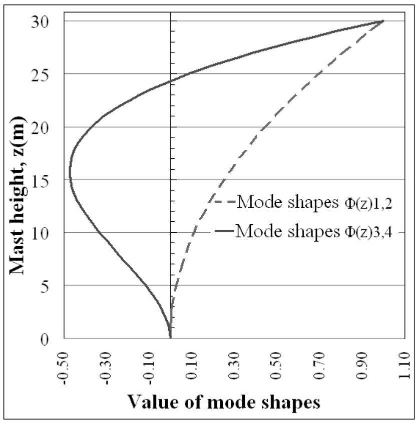
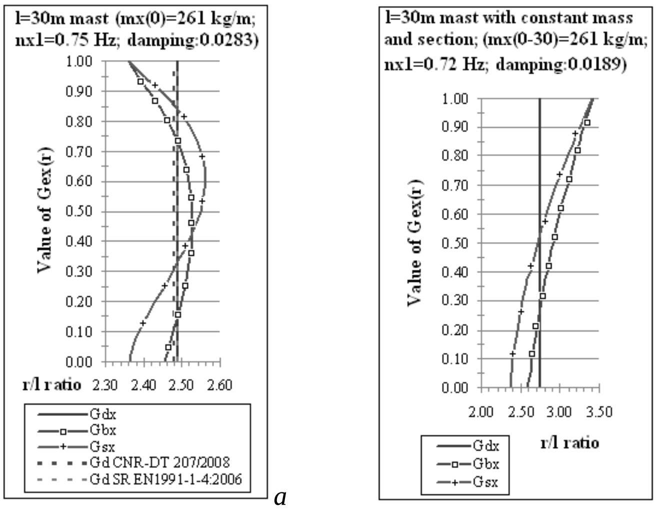


Fig. 2 – First and second mode shapes of the 30 m high steel mast.

Fig. 3 shows the variation of the displacement (G^d_x), bending moment (G^b_x) and shear force (G^s_x) gust effect factors corresponding to the alongwind direction ($\alpha = x$). It might be noticed that the displacement gust factor provides an overestimation of alongwind response parameters at the base, while with increasing height in a certain interval it underestimates the response. Fig. 3 *a* also shows, for the sake of comparison, the displacement gust factor as obtained by the Italian wind code as well as Eurocode 1 Part 1-4.

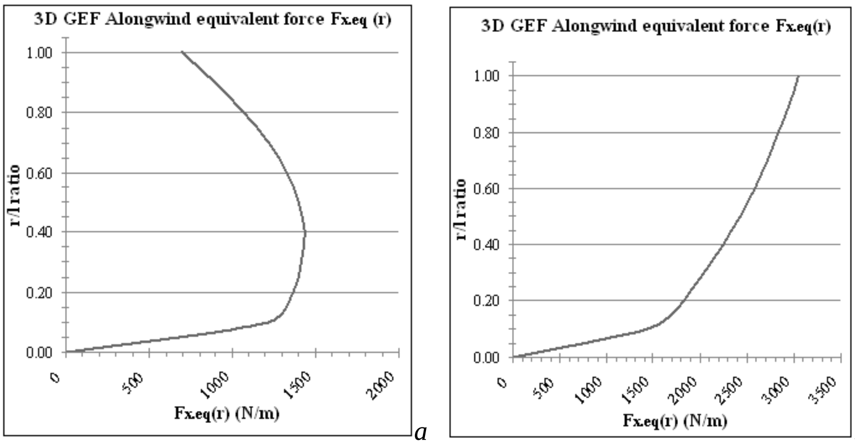


a *b*

Fig. 3 – Gust Effect Factor for displacement ($e = d$), bending moment ($e = b$), shear force ($e = s$) in the alongwind direction: *a* – for the real 30m mast; comparison with EU, Italian codes and *b* – for a 30m mast with constant mass and cross-section.

The 3-D GEF method was further applied in case of a potential steel mast with constant mass and cross-section section (base mass and section from original lighting mast). Results are presented in Fig. 3 *b* showing the distribution with height of the displacement (G^d_x), bending moment (G^b_x) and shear force (G^s_x) gust effect factors corresponding to the alongwind direction ($\alpha = x$). Again, it might be observed that, at the base level, the bending and shear gust effect factors are smaller than the displacement gust factor by approximately 6% for bending moment and 13% for shear force, implying a reduction of these effects at base.

The alongwind equivalent forces for displacement effect $e = d$ were calculated for the real 30 m lighting mast with variable mass and cross-section and for another 30 m mast with constant mass and cross-section, as represented in Fig. 4. Forces vary with height and differences may be observed due to variation of wind exposed cross-sections.



a *b*

Fig. 4 − Equivalent static force for displacement effect ($e = d$): *a* – for real 30 m lighting mast with variable mass and cross-section and *b* – for a 30 m mast with constant mass and cross-section $v = 33.5$ m/s.

4. Vortex Shedding Crosswind Action on Lighting Masts

The appearance of the vortex shedding as a transition between dynamic and aeroelastic responses, in case of slender structures like lighting masts is a very specific phenomenon and an important research subject in wind engineering. It is well known that critical conditions appear when vortex shedding frequency is very close to the structural frequency corresponding to crosswind vibration modes and is negatively influenced by smooth flow and low turbulence. In most cases the Strouhal law shows the linear variation of vortex shedding frequency with mean speed, whereas in case of small Scruton numbers, in a certain interval of wind speed this is cancelled and self-control appears. In this sense, the Scruton number Sc, which for a certain mode shape, depends on equivalent mass, structural damping, air density and cross-sectional dimension is a dimensionless parameter that usually indicates the type of response (Vickery & Basu, 1983). For the particular case of the 30m Iasi Airport lighting masts, S_c = 25.27 for first mode and 33.89 for second vibration mode, while Strouhal number St=0.19 (acc. CNR-DT207/2008). The cross wind equivalent static force $F_{L,i}(z)$ produced by vortex shedding, according to the Ruscheweyh model (1990), is expressed by:

$$F_{L,i}(z) = m(z)\left(2\pi n_{i,y}\right)^2 \phi_{i,y}(z) y_{F\max} \tag{12}$$

where z is height coordinate, $m(z)$ mass per unit length, $n_{i,y}$ i-th cross wind natural structural frequency, $\phi_{i,y}(z)$, i-th cross wind mode shape which has value of 1 at the position of maximum displacement, $y_{F\max}$ peak structural deflection. Peak deflections were calculated using both the spectral and the harmonic methods. The obtained mass dependent cross wind static equivalent forces for first and second mode shapes of the Iasi lighting masts are shown in Fig. 5.

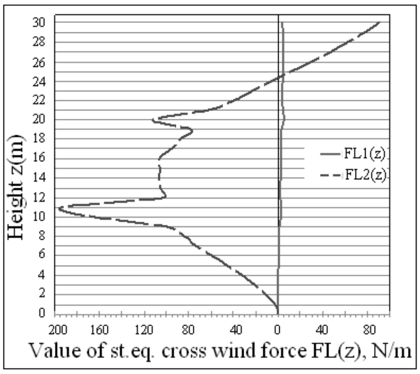


Fig. 5 – Cross wind forces for first and second modes of the 30m high steel mast, generated by vortex shedding.

Another specific phenomenon investigated in the paper is the possible interaction between vortex shedding and galloping, defined by the condition (CNR-DT207/2008):

$$0.7 < \frac{v_{G,i}}{v_{cr,i}} < 1.5 \tag{13}$$

where $v_{G,i}$ is the critical galloping speed and $v_{cr,i}$ is the critical vortex shedding speed. In case of Iasi Airport lighting masts, this phenomenon was avoided.
Galloping as pure aeroelastic phenomenon that may appear in case of structures without circular section is defined by the necessary condition (Glauert, 1919 & Den Hartog, 1932):

$$c_D + c'_L \leq 0 \tag{14}$$

where: c_D is the drag coefficient and c'_L is the first derivative of the lift coefficient. The sufficient condition for galloping is the vanishing of total damping ξ_t. Recent experimental analyses in Boundary Layer Wind Tunnel on similar slender steel telecom/lighting masts concerning the potential appearance of aeroelastic phenomena revealed that external power cables or the external maintenance ladder are changing the polar symmetry of masts, favouring the appearance of galloping and contributing to aeroelastic instability of masts. (Nguyen *et al*., 2015).

5. Conclusions

A case study concerning Iasi Airport 30 m lighting masts was carried out. A modal analysis was performed and along-wind static equivalent forces according to EU, Romanian ad Italian design codes were evaluated, comparing the obtained results. The base reactions obtained using Italian code, were almost 7% above those obtained using Romanian code. The 3-D GEF method was applied and results were compared with those obtained using design codes. The alongwind displacement gust factor evaluated according 3-D GEF method was compared with those obtained according to Italian code and EU code, results being very similar. The reduction of gust factors in case of bending moments and shear forces compared with classic displacement, at the column base means a reduction of these effects at base. The alongwind equivalent static forces as a product between displacement gust factor and mean alongwind force were calculated for both cases variable and constant masses and cross-sections, observing variation with height. These results are similar with those from other previous studies provided by literature, validating once again these methods in practice and confirming their efficiency.

The cross-wind effects of aeroelastic phenomena, such as vortex shedding or galloping, on slender lighting masts were also analysed. An increased cross-wind force produced by vortex shedding associated with second mode shape was observed, compared with fundamental mode shape. This fact is stressing the need of evaluation for cross-wind forces associated with superior mode shapes. In case of Iaşi Airport lighting masts, the interaction between vortex shedding and galloping was not present.

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EVALUAREA RĂSPUNSULUI PE DIRECȚIA ACȚIUNII VÂNTULUI ŞI AL FORȚELOR PERPENDICULARE PE DIRECȚIA ACESTUIA PENTRU PILONII DE ILUMINAT DE LA AEROPORTUL INTERNAȚIONAL IAŞI

(Rezumat)

Pilonii de iluminat sunt utilizați în special pentru iluminatul nodurilor autostrăzilor, aeroporturilor sau diferitelor tipuri de platforme. Pilonii de iluminat prezintă o sensibilitate la acțiunea vântului turbulent, datorată în mare parte zvelteții şi pot prezenta în anumite condiții instabilitate aeroelastică. Această lucrare analizează răspunsul unui pilon de iluminat cu o înălțime de 30 m, montat în incinta Aeroportului Iaşi, sub acțiunea vântului şi pe direcția acestuia, prin aplicarea metodei Factorului Generalizat de Efect la Rafală. Rezultatele au fost comparate cu cele obținute ca urmare a aplicării unor coduri europene de proiectare. În acelaşi timp, pentru pilonul de iluminat, s-au evaluat forțele echivalente pe direcție transversală a vântului, generate de fenomenul de desprindere a vârtejurilor, precum şi potențiala apariție a fenomenului de galopare. În cazul pilonului analizat, rezultatele au arătat necesitatea evaluării forțelor pe direcție transversală aferente modurilor superioare de vibrație, precum şi lipsa interferenței fenomenului de desprindere a vârtejurilor cu cel de galopare.