WIND – INDUCED INSTABILITY OF COMPLEX LIGHTING POLES AND ANTENNAS MASTS: STATIC AND AEROELASTIC EXPERIMENTAL STUDY

Cung Huy Nguyen¹, Andrea Freda², Giovanni Solari³, Federica Tubino⁴
¹Postdoctoral Researcher, DICCA, University of Genoa, Italy, cung.nguyenhuy@unige.it
²Technician, DICCA, University of Genoa, Italy, andrea.freda@unige.it
³Professor, DICCA, University of Genoa, Italy, solari@dicat.unige.it
⁴Assistant Professor, DICCA, University of Genoa, Italy, federica.tubino@unige.it

ABSTRACT

In a previous paper authors studied the aeroelastic behavior of complex lighting poles and antennas masts by carrying out static sectional model tests, determining aerodynamic coefficients and using them in the framework of quasi-steady theory. This paper continues the above research by illustrating the results of aeroelastic sectional model tests aimed at verifying the precision and reliability of the previous approach. The aeroelastic experiments are conducted by increasing and decreasing the mean wind velocity in order to check the presence of hysteresis phenomena.

Keywords: Aeroelastic test, hysteresis, lighting pole, antenna mast, wind-induced instability

Introduction

Lighting poles and antenna masts (Fig.1) are built in such a large and growing number, to represent a relevant economic issue in spite of a low single cost. Being characterized by increasing height, lightness, slenderness and impressive shape, they are very sensitive to wind-excited response and aeroelastic phenomena. The impressive number of damages and collapses that increasingly involve such constructions, frequently due to wind-excited fatigue, emphasizes their susceptibility to wind actions and their potentially dangerous role in the territory (Repetto and Solari 2010).

(a) (b) (c)

Fig. 1. Typical lighting poles and antennas masts

In engineering applications lighting poles and antennas masts are usually modeled as cantilever beams with circular or polygonal section. Such approach is often not correct due to several peculiar features of these structures, namely stairs, cable bundles and solar panels,
usually applied to the shaft, as well as lighting devices, top balcony, antennas and parabolas that create a situation of structural complexity both from the mechanical and aerodynamic viewpoint; in turn, this may lead to potential instability and very intense wind-induced vibrations.

The Authors have recently carried out a quasi-steady stability analysis on this structural type, considering all the above irregular features, multiple modal couplings in the alongwind and crosswind directions, and the variations of mass, width of cross section, aerodynamic coefficients, eccentricity, and mean wind velocity along the height of the structure (Nguyen et al. 2012). This study, developed through static wind tunnel tests on sectional models, has highlighted the importance of the aerodynamic coefficients. Especially, it has pointed out the potentiality for galloping instability occurrence, which is unpredictable for non-prismatic structures by means of classic models and calculations based on Den Hartog’s criterion (Den Hartog 1932).

Based on quasi-steady hypothesis but taking into account non-linear terms, Parkinson and Smith (1964) and Novak (1969) pointed out the existence of galloping hysteresis, in which the structural amplitudes are different at a given wind velocity, depending on whether the wind velocity is increasing or decreasing. In addition, they mentioned a “universal curve”, which represents galloping amplitudes independently of the structural parameters such as natural frequencies, structural mass, stiffness and damping. Later, a number of theoretical and numerical approaches, e.g. Lou et al. (2003), Vio et al. (2007), Barrero-Gil et al. (2009), have been presented to better understand hysteresis. Alonso et al. (2012) detected the hysteresis based on aeroelastic wind tunnel tests on triangular cross-section models, but this phenomenon was not always found during the tests. Recently, aeroelastic wind tunnel tests on blunt bodies carried out by Kluger et al. 2013 have reported hysteresis.

This paper presents the study of the aerodynamic and aeroelastic behavior of a real telecommunication antennas mast by means of wind tunnel experiments. Starting from the previous study (Nguyen et al. 2012), static sectional model tests have been carried out for several Reynolds numbers, namely \( \text{Re}=5.6 \cdot 10^4, \text{Re}=8.6 \cdot 10^4, \) and \( \text{Re}=1.2 \cdot 10^5 \), in order to derive the aerodynamic coefficients that allow evaluating the critical galloping based on quasi-steady theory. Besides, aeroelastic sectional model tests have been conducted to verify the validity of quasi-steady hypothesis; a wide discussion is developed on this delicate issue. During the aeroelastic tests, the hysteresis phenomenon has been deeply studied for different structural parameters.

**Quasi-steady approach for galloping analysis**

Let us consider a structure immersed in a wind flow field and its vibration in a translational crosswind direction \( y \). Adopting quasi-steady hypothesis, the equation of motion is given by:

\[
m \ddot{y} + 2m \omega \xi \dot{y} + k y + \frac{1}{2} \rho C_{Fy} (\alpha) U^2 b = 0
\]

where \( m, \xi, \rho, k, \alpha, C_{Fy}, \alpha, U, \) and \( b \) are mass per unit length, structural damping, air density, structural circular frequency, structural stiffness, aerodynamic force coefficient, angle of attack, mean wind velocity, and width of cross-section.

The coefficient \( C_{Fy} \) depends on the angle of attack \( \alpha \) and can be evaluated through static wind tunnel sectional tests. Such a coefficient can be expressed as a Maclaurin series of the angle of attack:

\[
C_{Fy} = \sum_{k=0}^{\infty} \left. \frac{\partial^k C_{Fy}}{\partial \alpha^k} \right|_{\alpha=0} \alpha^k
\]
Neglecting the static term (with \( k=0 \)) and focusing on small angles of attack \( \alpha \), i.e. retaining only the linear component (with \( k=1 \)) and assuming \( \alpha = \dot{y} / U \), the equation of motion (1) can be rewritten as:

\[
\ddot{y} + \left[ 2\alpha \dot{\xi} + \frac{\rho b U C'_y}{2m} \right] \dot{y} + \omega^2 y = 0 \tag{3}
\]

The structure is unstable if the term \( \left[ 2\alpha \dot{\xi} + \frac{\rho b U C'_y}{2m} \right] \) in Eq. (3) is negative, i.e. the total damping is negative. The necessary condition of instability is then given by:

\[
C'_y = C_D + C'_l < 0 \tag{4}
\]

where \( C_D \) and \( C'_l \) are, respectively, the drag coefficient and the prime derivative of the lift coefficient.

The condition given in Eq. (4) is well known as Den Hartog necessary condition for galloping occurrence. Then the critical velocity \( U_{cr} \) is given by:

\[
U_{cr} = -\frac{4\alpha \dot{\xi} m}{\rho b (C_D + C'_l)} \tag{5}
\]

Taking into account the non-linear terms in Eq. (2), Parkinson and Smith (1964) provided the solution of Eq. (1), evaluating the amplitudes of structural oscillations. In their study, the experiments on a square section cylinder showed the existence of galloping hysteresis phenomenon. Extending the study of Parkinson and Smith, Novak (1969) provided the analytical solutions of the structural amplitudes in the hysteresis zone.

It is important to mention that according to Parkinson and Smith (1964) and Novak (1969), at each angle of attack, the structural oscillation amplitudes for various values of the structural damping fall down on a unique so-called “universal curve” in a coordinate system \((\lambda U_r, \lambda \dot{y}_r)\), where:

\[
\lambda = \begin{cases} 
\lambda_{PS} = \frac{n(C_D + C'_l)}{2\dot{\xi}} & : \text{Parkinson-Smith's coefficient} \\
\lambda_N = \frac{n}{2\dot{\xi}} & : \text{Novak's coefficient} 
\end{cases} \tag{6}
\]

\[
U_r = \frac{U}{ab}; \quad \dot{y}_r = \frac{y}{b}; \quad n = \frac{\rho b^2}{2m} \tag{7}
\]

According to those studies, this curve represents the galloping amplitudes and is independent of the structural parameters such as natural frequencies, structural mass, stiffness and damping; in other words, for a given cross-section bluff body, the galloping amplitudes for various structural parameters collapse on such “universal curve”. The experimental results carried out on square section (Parkinson and Smith 1964), L-section (Slater 1969), rectangular section (Novak 1972) matched with the theoretical “universal curve”. Using a different analytical approach, the recent paper of Kluger et al. (2013) has confirmed such an agreement.

A crucial point to be highlighted is that in those studies the aerodynamic coefficients are unaffected by Reynolds number. If the aerodynamic coefficients change with respect to the wind velocity, the hysteresis regime is modified; this may lead to some doubts on the existence of the “universal curve”.

**Wind tunnel tests**

Static and aeroelastic experiments on a sectional model have been conducted in the Wind Tunnel at DICCA (University of Genoa), with a cross-section of 1700x1350 mm. Static tests
are aimed to derive the aerodynamic coefficients as functions of the angle of attack; from here, quasi-steady theory provides the necessary condition for galloping occurrence. Aeroelastic tests are carried out in order to obtain the amplitude of structural motion for different wind velocities; in this case the stability conditions of the model are directly found.

Fig. 2 shows the sectional model of the shaft of an antennas mast with eccentric stairs and cable bundles, used for both static and aeroelastic wind tunnel tests with geometric scale 1:5. The cable system is modeled by a rectangle cylinder which sectional dimension 60 mm x 30 mm. The models are realized through the assemblage of aluminum profiles, and have a span length \( l = 500 \) mm. The stair is modeled by a steel bar with length 80 mm. Static tests have been conducted for angles of attack varying from 0° to 350° with step 10°; two specific domains of the angle of attack (106°–113° and 265°–275°) are investigated with step 1°.

In the static tests, the models are mounted in cross-flow configuration on a force balance realized by six resistive load cells. End plates are installed at the extremities of the models to maintain a two-dimensional flow condition and separate the model from the boundary layer on the wind-tunnel walls.

The force balance measurements are used to evaluate the static aerodynamic drag and lift coefficients, defined as:

\[
C_D = \frac{E[F_D]}{0.5\rho blU^2}; \quad C_L = \frac{E[F_L]}{0.5\rho blU^2}
\]

where \( E[\cdot] \) is the statistic average operator, implemented as a time average adopting the hypothesis of ergodic behavior; \( b \) is the characteristic width of cross-section of the model; \( l \) is the span length of the model; \( F_D \) and \( F_L \) are, respectively, the measured drag and lift forces; \( U \) is the undisturbed mean wind velocity. No data correction is adopted due to the low value (<2.5%) of the blockage ratio. The influence of the Reynolds number is investigated by changing the wind velocity \( U \) in the range 5 – 25 m/s.

In the aeroelastic tests, the models are mounted on a system of springs. For each experimental setup, the structural damping and natural frequency of model are evaluated during the test. They are measured based on the time history of the decaying vibration, after disturbing the model from the equilibrium condition in absence of wind flow. The body displacements are recorded through a system of four laser distance sensors.

**Static tests results**

Fig. 3a-c show, respectively, the variation of \( C_D \), \( C_L \) and \( (C_D + C_L') \) with respect to the angle of attack for the Reynolds numbers \( Re = 5.6 \times 10^4 \) and \( Re = 8.6 \times 10^4 \). The angles of attack are changing from 0° to 350° with step 10°. The derivative of lift coefficients with respect to the
angle of attack is obtained by using a smoothing spline approximation. The shadow areas in Fig. 3c correspond to the domains in which \((C_D + C'_L)\) values are negative, i.e. the structure may be unstable according to Den Hartog’s criterion given in Eq. (4). From these figures, it can be inferred that the aerodynamic coefficients are extremely variable for small changes of the angle of attack. It is worth noting that the step 10\(^\circ\) is not enough to derive the most correct aerodynamic coefficients since the cross-section has a very complex shape.

Due to the above reasons, further static tests have been carried out for more Reynolds numbers \((Re = 5.6 \cdot 10^4, Re = 8.6 \cdot 10^4\), and \(Re = 1.2 \cdot 10^5\)), changing the angles of attack with step 1\(^\circ\) in two domains: from 106\(^\circ\) to 113\(^\circ\), where \((C_D + C'_L)\) values are positive (Fig. 4), and from 265\(^\circ\) to 275\(^\circ\), where \((C_D + C'_L)\) values are negative (Fig. 5). The refined \((C_D + C'_L)\) values obtained from static tests for the above two domains of the angle of attack provides a very different prospect from what pointed out using step 10\(^\circ\) (Fig. 3). At angles of attack from 106\(^\circ\) to 113\(^\circ\), Fig. 4 shows that the Reynolds number slightly affects both the drag and lift coefficients and the \((C_D + C'_L)\) value. On the other hand, at angles of attack from 265\(^\circ\) to 275\(^\circ\), Fig. 5 reveals that the influence of the Reynolds number is clearer. For example, from Fig. 5c, at angle 269.5\(^\circ\), \(C_D + C'_L = -26.7\) for \(Re=8.6 \cdot 10^4\) while \(C_D + C'_L = -20.7\) for \(Re=1.2 \cdot 10^5\). Such large difference has a deep impact on evaluating the critical velocity according to Eq. (5).

It is worth noting that the values of \((C_D + C'_L)\) strictly depend on how the aerodynamic coefficients are fitted. A little change of the fitting curve can noticeably modify the \((C_D + C'_L)\) value. Furthermore, from Fig. 5c, it can be deduced that the domains where \((C_D + C'_L)\) is negative are very sharp, and \((C_D + C'_L)\) drastically changes its value for tiny changes of the angle of attack. This means that the Den Hartog critical velocities are very sensitive to small variations of the angle of attack; for instance, at \(Re = 1.2 \cdot 10^5\), \(C_D + C'_L\) varies from -20.7 to -8.8 for a small range of angle of attack from 269.5\(^\circ\) to 270\(^\circ\) (Fig. 5). It should be pointed out that, due to possible small bias in the measurement of the angle of attack, static test results may result slightly biased.
Aeroelastic tests results

To verify the reliability of the quasi-steady theory prediction, aeroelastic tests have been carried out at angles of attack $110^\circ$, where $(C_D + C'_L)$ is positive (Fig.4c), $269^\circ$ and $270^\circ$, where $(C_D + C'_L)$ is negative (Fig.5c). For each attack angle, the tests have been conducted by increasing and decreasing wind velocities.

Table 1 shows the values of the model mass per unit length $m$, structural damping $\xi$, and corresponding natural frequencies $f$ for different setups.

<table>
<thead>
<tr>
<th>$m$ (kg/m)</th>
<th>$\xi$ (%)</th>
<th>$f$ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>110°</td>
<td>269°</td>
</tr>
<tr>
<td>7.88</td>
<td>0.13</td>
<td>4.46×10^{-2}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.55×10^{-2}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.20×10^{-2}</td>
</tr>
</tbody>
</table>
Fig. 6 plots the dimensionless amplitudes $y_r$ versus the reduced velocity $U_r$ at the three angles of attack $110^\circ$, $269^\circ$ and $270^\circ$, for the different setups described in Table 1. From the figure, for $\alpha=269^\circ$ and $\alpha=270^\circ$, the amplitudes at $U_r=0.5-0.8$ are related to vortex-induced vibration; those at higher $U_r$ correspond to buffeting-excited or galloping oscillation. The two types of vibration are well-separated. Outside the vortex shedding regime, the oscillation amplitudes at the angle of attack $110^\circ$ are considerably smaller than those at the angles of attack $269^\circ$ and $270^\circ$; here, the galloping occurs for $U_r>2.2$. This confirms the validity of using the coefficient $C_D +C_L'$, i.e. the quasi-steady hypothesis, to predict the critical wind direction giving rise to galloping. The hysteresis galloping has been found at both the angles of attack $269^\circ$ and $270^\circ$.

![Figure 6. Reduced amplitude – Velocity at angle 110°, 269° and 270°](image)

Fig. 7a shows the reduced amplitudes at the angle of attack $269^\circ$ for three setups corresponding to the values of the structural damping $\xi=0.0446\%$, $0.04\%$, and $0.062\%$. It can be witnessed that, at the lowest structural damping ($\xi=0.0446\%$), the oscillation amplitudes increase linearly on increasing the reduced velocity. At higher structural damping, instead, such linearity disappears and galloping hysteresis occurs. When the wind velocity is increased, the structural model starts vibrating with very large amplitudes at the reduced velocity 6.3. Meanwhile, when the wind velocity is decreased, the amplitudes of structural motion still remain very large and start decreasing at lower reduced velocity. Comparing the results for different setups, it is worth noting that the hysteresis regime is larger for higher structural damping.

Fig. 7b shows the reduced amplitudes at the angle of attack $270^\circ$, for three setups corresponding to the values of the structural damping $\xi=0.0357\%$, $0.059\%$, and $0.13\%$. It can be observed that, similarly to the situation related to the angle of attack $269^\circ$ (Fig. 7a), oscillation amplitudes increase linearly with respect to increasing the reduced velocity at the lowest structural damping ($\xi=0.0357\%$), while the galloping hysteresis occurs at higher structural damping ($\xi=0.059\%$, and $0.13\%$). In addition, the hysteresis regime is larger for higher structural damping.
The above observations stress the significant influence of structural damping not only on the structural amplitudes but also on the possibility of the hysteresis occurrence. At a given angle of attack, i.e. at a certain aerodynamic coefficient derived from static wind tunnel tests, the aeroelastic behavior is completely different for different structural damping values. This contradicts the results provided by Luo et al. (2003) and Barrero-Gil et al. (2009), which stated that the occurrence of galloping hysteresis depends on the inflection points of the curve $C_y(\alpha)$, and by Kluger et al. (2013), which states that only the aerodynamic force coefficients affect to the existence of hysteresis.

It is worth mentioning that scaling the axes $(U_r, y_r)$ in Fig. 6–7 as defined in Eq. (6) ($\lambda U_r, \lambda y_r$), as done by Parkinson and Smith (1964) and Novak (1969), does not let all the results collapse on a “universal curve”, neither for $\lambda=\lambda_{PS}$ nor for $\lambda=\lambda_{PS}$, since the galloping amplitudes for $\xi=0.046\%$ ($\alpha=269^\circ$) and $\xi=0.0357\%$ ($\alpha=270^\circ$) vary linearly with respect to the reduced velocity (Fig. 7). It should be emphasized that in the study of Parkinson and Smith (1964), the force coefficients were independent of the Reynolds number and the experiments were conducted at structural damping values much higher than those in this paper. If the coefficient $\lambda_{PS}$ is dependent on the Reynolds number, the hysteresis regions are modified in such a way as to avoid the collapse of oscillation amplitudes.

Comparison between static and aeroelastic tests

Den Hartog’s theory has been widely applied due to its simplicity. This section provides a verification of this theory for the case study considered, based on the results obtained from static and aeroelastic tests.

First of all, Fig. 8 compares the reduced amplitudes at the angles of attack 269°, for $\xi=0.0357\%$, and 270°, for $\xi=0.0446\%$. It can be seen that the critical velocity ranges of such two cases are very similar. However, based on Eq. (5), the critical velocity at 269° should be substantially lower than that corresponding at 270° since the aerodynamic damping coefficient ($C_D + C_L'$) at 269° is much lower than that at 270° (Fig.5c). Consequently, for the present cross-section shape, although the Den Hartog’s theory is correct for the galloping necessary condition provided by Eq. (4), it is not successful to predict the critical velocity.
For more details, Table 2 shows the comparison between the reduced critical velocities obtained from static and aeroelastic tests at the two angles of attack 269° and 270°, for different values of the structural damping. As mentioned in the previous section, since \((C_D + C_L')\) considerably varies for small changes of the angle of attack, the reduced critical velocity provided by Den Hartog’s criterion (denoted as \(U_{rDH}\)) also changes very much with respect to the angle of attack. Therefore, the values of \(U_{rDH}\) in the domain of the angles of attack from 268.5° to 269.5°, i.e. ± 0.5° around 269°, are compared with the value of \(U_r\) at the angle of attack 269°. For the comparison at the angle of attack 270°, \(U_{rDH}\) is taken in the domain from 269.5° to 270.5°. It can be realized from the table that, around the angle of attack 269°, the critical velocity \(U_{rDH}\) provided by Den Hartog’s criterion is extremely lower than the \(U_r\) value given by the aeroelastic tests. Around the attack angle 270°, \(U_r\) is in the range of \(U_{rDH}\) for the domain from 269.5° to 270.5°

<table>
<thead>
<tr>
<th>(\xi(%))</th>
<th>(C_D + C_L')</th>
<th>(U_{rDH}) (static test)</th>
<th>(U_r) (aeroelastic test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.46x10</td>
<td>3.57x10</td>
<td>268.5° - 269.5°</td>
<td>20.7 – 0.4</td>
</tr>
<tr>
<td>5.55x10</td>
<td>5.90x10</td>
<td>20.3 – 20.7</td>
<td>0.07 - 0.11</td>
</tr>
<tr>
<td>6.20x10</td>
<td>13.0x10</td>
<td>268.5° - 269.5°</td>
<td>0.08 - 0.12</td>
</tr>
</tbody>
</table>

### Conclusions

The paper studies the aerodynamic behavior of lighting poles and antennas masts through static and aeroelastic wind tunnel experiments conducted on a complex cylinder sectional model. The results of the static tests show the influence of the Reynolds number and of the angle of attack on the coefficients \((C_D + C_L')\). The aeroelastic tests carried out for various values of structural parameters and angles of attack are aimed to verify the possibility of using the quasi-steady hypothesis. The results provide several critical remarks.

First, in spite of a very complex cross-section shape, Den Hartog’s theory is able to predict the galloping instability occurrence in correspondence of a very narrow domain of the angles of attack of the wind. However, probably due to the extreme dependence of \((C_D + C_L')\) on the angle of attack, such theory does not provide suitable values of the critical velocity.

Second, the amplitudes of the structural oscillations vary linearly with respect to the wind velocity at low structural damping values. Instead, at higher structural damping values,
galloping hysteresis is found. Importantly, this investigation shows that the vibration amplitudes and the existence of hysteresis strictly depend on the structural damping and that the “universal curve” does not exist for the examined sectional model. These observations are not clearly documented in literature.

The obtained results point out several problems of engineering nature. This research started with the aim of elucidating the role of the mechanical and aerodynamic eccentricities frequently present but usually disregarded in the calculation of lighting poles and antennas masts, also in the light of a lot of damages and collapses not easy to understand. Quasi-steady analyses based on static tests on sectional models highlighted the existence of specific configurations such as to create unstable phenomena and strong dynamic responses. The present analyses carried out by means of aeroelastic tests on sectional models confirm the existence of such phenomena, just in the situations revealed by quasi-steady theory; in the meanwhile, they raise several doubts on the possibility of predicting suitable values of the critical galloping velocities through simplified engineering models. The problem deserves to be further studied.

References


