A Review on cross flow Vibration

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Abstract
Wind loads have become a progressively significant factor in the structural design. The interaction between galloping and vortex resonance for long structures and cables is a decisive issue in cross flow-induced oscillation. This high amplitude oscillation frequently occurs in a tall building structure and cables due to changing cross section and wind-induced angle, increase in wind speed. This paper is aimed to review the significant features of the galloping instability - VIV and wake interference in structures and cables. The parameters influencing the cross flow oscillation phenomena are Geometrical parameters, Aerodynamic parameters and Interference wake effects. The impacts of this parameter are analyzed in empirical, computational and experimental methods. This review article relates the approaches used to study the effects of cross wind in instability of a structure and cables.

Keywords: Cross wind excitation; Wind-induced vibration; Galloping; Interference effects;

INTRODUCTION
In recent trends, tall and slender structures sensitive to wind are associated high amplitude vibration with windy conditions. A typical example progressive vibration of transmission line with high amplitude. The possible causes are accretion of ice on cable, windy conditions, wake, thearrangement of structures (interference effect), changing cross section. This high amplitude mechanism drives change in cross section, vortex shedding, rain-induced vibration, cable deck tower interaction and high reduced velocity vortex shedding (A.Acampora et al., 2013) stated that the aerodynamic instability of a tall and slender structure at relatively low-frequency oscillation phenomena is acted upon across the winds. When the natural frequency of a structure responds lower than the frequency of vortex shedding, it’s called as galloping. Galloping is frequent natural phenomena in which bluff body reaches aerodynamic instability resulting in high amplitude, low-frequency oscillation (Blevins, R.D., 1990) worked on wind galloping in cables, slender structures and bridges; instability is initiated by a turbulent wind blowing transversely across the cross sections. When the section vibrates crosswise in a steady wind velocity, increase in AOA with negative slope cause a negative in lift force, then the structure is unstable and galloping occurs. The result of aerodynamic damping associated with anegative slope of the normal force coefficient with respect to AOA

(Parkinson 1965) explains high amplitude vibration of a cables and structures are not galloped when they are aligned normal, tothe windward, but in the condition of inclined cables leads to large amplitude oscillations of long cables which could potentially arise on bridge cables during a freezing rain storm. (Delong and Nicholas P. Jones. 2009) observes two frequency components such as Karman vortex shedding lower than the stroll frequency, with an angle of the cable (wind tunnel alignment) (fig2) and wind-induced angle. Karman vortex induced vibration with the highest amplitude occurred at close to reducing velocity at 5 (fig1) which concerns about the possible presence of inclined cable galloping.

Rain induced galloping is a potential risk to structural aspects of electrical and cable stay bridges were initiated aerodynamic instability.

Table: 1

<table>
<thead>
<tr>
<th>Record</th>
<th>Arms/D</th>
<th>U(m/s)</th>
<th>Re(x10^5)</th>
<th>Vr</th>
<th>Vnr*</th>
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</thead>
<tbody>
<tr>
<td>a</td>
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<td>2.06</td>
<td>0.13</td>
<td>6.4</td>
<td>5.4</td>
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<td>b</td>
<td>0.006</td>
<td>9.05</td>
<td>0.55</td>
<td>27.3</td>
<td>23.2</td>
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<td>16.9</td>
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<td>49.5</td>
<td>42.0</td>
</tr>
<tr>
<td>d</td>
<td>0.006</td>
<td>0.67</td>
<td>0.67</td>
<td>32.9</td>
<td>27.9</td>
</tr>
</tbody>
</table>

Figure 1: Amplitude Vs Reduced velocity related with wind component perpendicular to the structural axis and AOA for wind tunnel test at different configuration.
Table 2: Wind tunnel test configuration

<table>
<thead>
<tr>
<th>Config</th>
<th>α (deg)</th>
<th>β (deg)</th>
<th>β° (deg)</th>
<th>f (Hz)</th>
<th>ζ (%)</th>
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<tbody>
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<td>56.6</td>
<td>58.3</td>
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</tr>
<tr>
<td>2</td>
<td>0</td>
<td>90.0</td>
<td>90.0</td>
<td>3.61-3.80</td>
<td>0.35a</td>
</tr>
</tbody>
</table>

* = average value

Figure 2: Amplitude Vs Reduced velocity for wind tunnel test of different configuration

(J.J. Ratkowski 1965) Tested nineteen models with ice accretion on cable experimentally and numerically by rotating model through angular steps and, using an energy method. He found three general types of galloping each exists due to distinctive conditions which start the galloping. The first type is the vertical torsion-free galloping which does not require torsional rotation to start vibrating. The second type is the elliptical torsionally modified galloping which does not require a torsional motion to maintain vibration, but the eccentric cross section develops torsional motion which modifies the motion of cable structure. The third type is the elliptical, torsionally controlled galloping which requires a torsional motion to maintain galloping. The atmospheric wind icing causes influential damage on cables reduces their constancy during critical winter periods. Ice accretion indefinite phenomenon and ice loads are varying cross section depend upon ice accretion on span wise. (Saito et al., 1994) Experimentally studied on ice-coated power transmission line galloping. Verifying the instability criteria during the test, low amplitude high-speed frequency vortex shedding was observed large vibration found at a lowest damping ratio (ζ<0.001). In the structural approach the structural parameter like stiffness, mass and damping ratio etc...

Rain wind induced vibration:

The first documentation of rain-wind-induced vibration was by Hikami (1986) where severe vibration was observed on the stay cables of the Meiko-Nishi Bridge in Japan. Further studies (Main and Jones, 1999; Main et al., 2001; Matsumoto et al., 1998, 2001) suggest that this phenomenon is normally associated with the following conditions: a) the stay cables have an inclination angle of 20°~45° and decline with the wind direction; b) typical diameter of the cables being 14~20cm; c) vibration amplitudes up to a few meters; d) wind skew angle of 20°~60° relative to the cable plane; e) associated critical wind speed range is usually 8~12 m/s (generally for 6~18 m/s), the corresponding Reynolds number range is thus 0.6×10^5~2×10^5 which falls into the subcritical regime (Main and Jones, 1999, Main et al., 2001; Matsumoto et al., 1998, 2001). The cross-sectional shape of the cable is modified due to the existence of water rivulet making it asymmetric. This effect is known to alter the aerodynamic forces acting on the cable and which could trigger excessive oscillations.(Xiaoqing Duet al., 2013) Investigation of wind pressures and aerodynamic forces of an inclined and yawed circular cylinder with and without an

\[ U_r = \frac{U_{CRIT}}{fD} \]

\[ U_{CRIT} \] = critical velocity for instability
\[ f = \text{natural frequency} \]
\[ D = \text{cable diameter} \]
\[ S_c = \frac{m \zeta}{(\rho D^2)} \]
\[ m = \text{mass of cable per unit length (kg/m)} \]
\[ \zeta = \text{damping ratio of critical damping} \]
\[ \rho = \text{air density (kilograms per meters cubed (kg/m3))} \]

By increase, Sc reduces oscillation amplitude.
artificial upper rivulet, on rain wind induced vibration (RWIV), the position of the rivulet influences the aerodynamic forces, vortex shedding and reattachments are notice in three different flow patterns.

**Interference effects on structures:**

The attention paid to the parameter affecting interference on the structure are upstream terrain wake, the geometry of a structure wind incidence angle and arrangements and spacing insists the high amplitude vibration (interference wake galloping). It only appears on unenclosed sections and grouped structures on the closely placed arrangement of passive and active structures causing high amplitude vibration response on cross winds. Fig: 4 The shear layer separated from the passive structure attaches to the active downstream structure, this shear layer interaction has some energy causes to vibrate the structure and subsequently initiate to high amplitude vibration. (K.M. Lamet al., 2011) investigates wind-induced interference on a row of five tall buildings arranged in parallel. Diamond shaped. Structure and dynamic responses on the basis of reduced velocity over the range between 5 and 12. The envelope interference factor (EIF) is adopted to quantify the interference effects.

*Figure 4: Direction of wind attack interference of active model*

**Wind Incidence Angle of attack**

A wind effect on structure also depends on exposed angle of a structure and incidence angle of attack that influences the slow galloping on structures. (Giuseppe Piccardo on, et al., 2011) researched mathematically about the aeroelastic instability of inclined square cylinder (13°) at the cross flow critical condition, shows a very vigorous galloping oscillation just in the holding of the incidence and twist angles relating the minimum value of the critical velocity. While numerically inspecting the small aspect ratio cylinder for galloping with and without end plates, it’s found that the cylinders with lesser aspect ratio can’t oscillate with a small amplitude at a slight excess of the critical flow velocity. The critical flow velocity for the cylinders of low aspect ratio is at the right border of the hysteresis range. Wind incidence complications are not only on inclined structures but also, happen on varying cross-section throughout length or height. In practical sense cables, bridge deck leading edges, antenna, leading edges of tall structures and guy masts are strong effects changing cross section due to ice accretion (A.N. Ryabinin and V. D. Lysine 2015) the cylinder equipped with end plates that avoid air coursing through the closures, changes the dependence of the normal force on the angle of attack at low angles of attack. The critical velocity decreases and hysteresis range of flow velocities decreases and these effects are verified experimentally and mathematically.

However, the incidence angle of a wind creates the resonance velocity due to the interaction of nearby structures.

*Figure 5: Angle of Attack of model*

(Delong Zuo, et al.2014) evaluated cross wind loads on rectangular box signs structure of various configuration. The influence of aspect and clearance ratios gives impact on wind induced mean pressure torque.

**Geometrical Parameters Effects**

The Glauert–Den Hartog criterion for galloping instability states that for an assumed configuration of the body, $\alpha$, assuming the variation of the angle of attack due to crosswise oscillation around $\alpha$ is small sufficient, galloping instability.

$$ \left( \frac{dc_l}{d\alpha_l} + c_d \right) \bigg|_{\alpha_2 = \alpha} < 0 $$

where $c_l = 2l/(\rho U^2 b)$ is the section $Cl$, $c_d = 2d/(\rho U^2 b)$ the section $Cd$ and $\alpha$ the angle of attack; $l$ and $d$ are the aerodynamic forces, lift and drag, respectively, $\rho$ the fluid density, $U$ the upstream flow velocity and $b$ is a cross-flow distinctive length of the body. (B. W. Vanoudheusden 2000) has predicted prediction of both damping and stiffness effects on single degree of rotation of a rectangular cross-section. Galloping actions has been investigated based on a quasi-steady modelling of the aerodynamic forces obtained by wind tunnel testing. (A. Joly, et al., 2011) concentrated to observe the galloping phenomena at low Reynolds numbers using a two-
dimensional FEM. A sinusoidal quasi-steady model allows determination of the occurrence of galloping and its amplitude. (Mingzhe He, et al., 2015) proposed 3DOF model aims to identify the galloping stability of a body of a random rigid cross-section of square, rectangular (aspect ratio 3) and equilateral triangular sections and a lightly iced cable, and they are compared with results solutions for 2DOF translational and 1DOF pure torsional galloping. (Gustavo Alonso, et al., 2008) proved biconvex and rhomboidal cross sections are prone to high AOA and influence of the aspect ratio, rhomboidal cross sections profiles developing from a flat plate-like behaviour for maintaining an instability zone at any aspect ratio up to close the circular cylinder (r = 1) then instability disappear.

Aspect ratio influence galloping on the critical cross wind, prism-like towers are constant aspect ratio throughout height, it is effective on cross wind loads. (G.V. Parkinson, P.P. Sullivan, 1979) defines the extension method to finite-height prisms in a three-dimensional turbulent boundary-layer flow, simulating towers exposed to natural wind variations of sectional lateral force over the height of the tower and predict variations of galloping amplitude with wind speed were tested. Crosswind vibration is varying with aspect ratio and side ratio of a structure. (O. Mahrenholz and H. Bardowicks 1979) scrutinized on the vortex induced vibration and the galloping of tall slender structures with aspect ratio, with side ratios, D/B= 1/2 to 3 are examine in a smooth flow and turbulent boundary layer flows over open terrains and urban areas. They resolved that leading edge type of the vibration is still observed for D/B=3 in the turbulent flow, but is suppressed for D/B=2. And D/B=2 and 3 the vibration triggered by the leading edge vortices which are induced by the vibration slower than the resonant velocity. (Liang Shuguo, et al., 1993) formulated the analytical method is for approximating the onset wind velocity for 2D coupled galloping motion. For Appling buildings with square section characteristic of wind pressure coefficient, Cx & Cy results at small attack angle, Fig: 6 the amplitude of X_0 is smaller than Y_0.

(H. Kawai 1995) examines the amplitude of galloping and VIV effect of AOA on turbulent and smooth flow conditions in the rectangular and triangular sections of an open terrain wind normal to the face. Fig: 6 shows the AOA is increased the vibration become weak as in the account of building with the shallow rectangular area. (B. W. Van Oudheusden 2000) investigated galloping instability of rectangular single rotational degree of freedom mathematically and experimentally by using aerodynamic parameters (displacement, stiffness & damping) (Fig: 7. A galloping instability to facilitate frights from rest (soft galloping) are originate to arise rectangular profiles where the depth-to-height ratio D/H lies between 0.75 and 3 of a rectangular section. Researchers show variety of approaches hysteresis using Aerodynamic, geometrical and stiffness parameters. Reynolds number, PSD and AOA are consequence in oscillation of a structure (S.C. Luo, et al., 2003) simulated a flow over a stationary square cylinder at Incidence at 4° and Reynolds number of 250 and 1000. They computed point of inflection at various Reynolds number. There work extend to reveal shear layer reattachment and fluctuation in inflation of square cylinder. (A. Barrero-Gil, et al., 2009) carried out an analysis based on numerical simulations confirms the possibility of galloping at low Reynolds number for Re > 159. Moreover, hysteresis range study was also calculated under range of 159 < Re < 200. This analysis shows that there is no hysteresis in the galloping response for a certain 159 ≤ Re ≤ 200. The amplitude of oscillations grows from zero to steady oscillation of finite amplitude with constant frequency. Another effective method is Cross section like square, triangle, rectangle etc. (G. Alonso, et al., 2013) investigated hysteresis phenomena of anisocles triangular cross-section body, focusing on the dynamic response in inflection point in the CL curve at 10^6 to 60^6 AOA. Result provide that the body produces transverse galloping instability and hysteresis starts appear at 30^0 onwards. (Delong Zuo, et al., 2014) evaluated cross wind loads on rectangular box structure of various configuration. The influence of aspect and clearance ratios gives impact on wind induced mean pressure torque. (Y.F. Li et al., 2001) discussed Power spectra, cross-spectra, coherence and normalised co-spectra signals were calculated lateral surface on the 2D cylinder at 3 different turbulence levels, They found that increasing turbulence causes a reduction in the normalised co-spectra at low frequencies and a reduction in the peak of power spectra at the shedding frequency. (S. Arunachalam, N. Lakshmanan 2015) suggested method using ‘fact’ non-dimensional parameter is taken account for enhanced response during lock-in region in that parameter by using the structural damping with the principles of conventional structural dynamics, is used to evaluate the response equally for applicable both for steel and concrete chimneys. (T.K. Datta et al., 2002) explained the lock in response of tall chimney choice of the critical diameter used for the determining the critical wind velocity and aerodynamic coefficients. It also emphasizes the importance lock-in conditions in the second

**Figure 6:** Wind pressure coefficient of square prism
mode are found to be more critical for bending response, first mode lock-in is critical only for displacement response.

Figure 7: Aerodynamic characteristics of rectangular cross section

Wind loads increase with the height of the structure as it responds with along and across wind direction. Along the wind loads were reduced by increasing the height of the upstream structure due to shielding. (Takeo Matsumoto) analytically investigated the across wind oscillation of tall building, depth/width ratio of cross section, and four kinds of flow are taken to account to find the Vortex exited oscillation. (GU Ming & Quan Yong 2011) experimented rectangular buildings, corner-modified square buildings, and buildings with continuous shrinkage cross section were modelled and tested under four categories of terrain conditions and its observed modified plan and original plan of building. Fig: 8 shows that over static wind load on across and along response in terms of base shear and base bending moment.

Figure 8: Equivalent static wind load distribution of the original plan

(Luigi Carassale, et al. 2013) examined the corner shaping influence on cross wind oscillation by the quasi-static approach. Fig: 9 explains the fact that the corner shaping produces a significant reduction of the onset galloping velocity drop of drag coefficient and free stream and corner radius with different Reynolds number 3.7x10^4, 2.7x10^4 and 7.9x10^4. (Shuguo Lianga, et al. 2002) presented an empirical formula of across wind force spectra, RMS lift coefficients and Strouhal numbers of rectangular tall cylinder with various side ratio at normal AOA, evaluates wind induced across wind response using frequency domain.

Figure 9: Experimental set of corner shaping
(John D. Holmes 2014) predicted cross-wind base moments and resultant accelerations of tall structures with damping of 2 to 2½% in moment and 1% damping in resultant acceleration with 0° and 90° wind direction in accordance with the Australian/New Zealand standards. But in the case of isolated tall building, more damping is experienced (C.-M. Cheng et al., 2002) experimentally performed across wind vibration of an isolated square shaped building and responses are categorized based on a building’s mass-damping coefficient. (J. Xu-Xu, et al.) experimented square cylinder square-section cylinder for values of the mass ratio, low mechanical damping. Results characterized by reduced velocity confirms the amplitude of oscillations start at a reduced velocity which depends on the mass ratio are linearly dependent on the reduced velocity.

**Upstream Terrain Wake Effects:**

Wind pressures on structures are affected by terrain roughness causes strong turbulent flows. In the case of an isolated structure with incremented circumventing obstructions the mean wind pressures acting on the structure decreases while the unsteady pressures increases. (Kareem, A. 1987) investigated inference effects in different conditions (Open, Suburban and urban) and concluded that inference effects were most evident in an open country exposed. Due to low-
Structure Arrangements and Spacing wake Effects:

Wind loads on structures depend on both wind velocities and aerodynamic parameters sparing between two tall structures and cables of structures. Common senses suggest that the arrangement and spacing ratios of structures should be increasing by decreasing shear layer separation distance. (Kanpyo Cho et al, 2004) focused on geometry, arrangement of structure, orientation and upstream conditions. The flows around the multiple structures are highly unpredictability phenomena. The flow over a cylindrical structure in various arrangements (Staggered and Tandem arrangements).

Staggered Arrangement:

Numerous computational and experimental investigation of two cylindrical structures in staggered procedure have been made by (Kiya et al. 1980), (Zdravkovich 1997, 2003), (GU and Sun. 1999), (Sumner et al. 2000), (Mittal et al. 2001) and (Sakamoto et al. 2004) are discovered substantial complexity depending on centre to centre distance proportion, L/D (L: centre-to-centre distance between the cylinders, D: cylinder section diameter), and the angle of incidence α, for the structure in staggered arrangement. (Zdravkovich 1985, 1987, 1997 and 2003) completely reviewed on the wake induced vibration due to flow around two cylindrical structures. (Lim, et al. 2014) studied the pressure variation effect due gap effect, interference effects on equally spaced cubical buildings on cross wind.

Tandem arrangement of structures:

Tandem arrange of the structure have been experimentally performed by (King & Johns 1976), (Igarashi 1981, 1984), (Bearman&Wadcock 1973), (Williamson 1985), (Sun et al. 1992) and (Zhang & Melbourne 1992) in which flow around two stationary cylindrical structures are analysed using FEM strategy. (Mittal et al. 1997) performed 2D numerical simulation at Re = 10^2 and 10^3. In the tandem arrangement with L/D = 2.5, vortices are not observed on the upstream structure till Re = 10^3and its observed when Re = 1000. It has experimentally verified that no separate wake vortex is shed from the upstream cylindrical structure if L/D is less than 3-4. The simulation result that critical spacing would be easily affected by Re. (Meneghini et al. 2001) Researched tandem and side-by-side arrangement of hecircular cylinder using 2D FEM at Re = 10^2 and 2 × 10^2. In side by side arrangement revealed the spacing is sensitive to flutter phenomena due to wake. (Jester &Kallinderis 2003) observed the hysteresic effect of fluid force in the range of L/D ratios, at the range of

Figure 10: Wake interference regime by Zdravkovich (1987)
The drag coefficients values are different at downstream and upstream structures depending on L/D ratio. (F.J. Huera-Quartet al. 2011) experimented tandem configurations of flexible cylinders in cross-flow, the results demonstrated that response of upstream structure shows classical VIV behavior and the response of downstream structure is developed because of the VIV resonance at reduced velocities or wake induced vibration if the reduced velocities are beside the resonance cause large amplitude vibration due to vortices in the crevice area. (Arash Mir et al. 2012) computationally examined the cam shaped structures in tandem arrangement at 2< L/D < 6. It depicts that the structures depends on pitch ratio whereas coefficients of the downstream structure are more dependable on pitch ratio.

**Downstream Elastic model:**
On the account of cylindrical structure vibrating in the wake of another fixed cylinder, the interaction between the wake stream and the oscillating cylinder becomes complex problem (Bokaian et al. 1984 )considered the case of fixed upstream structure and flexible downstream structure. It is observed at a sensitive aspect ratio of L/D, vortex resonance occurs alone for L/D>3 and galloping occurs L/D<7 at high Reynolds number. In the downstream elastic model, galloping progressively occurs at cables and its arrangements. The cable arrangement characterized by L/D ratio that varies from 4.3 – 8.7 specifically relates to the value between the critical condition state of wake galloping, in the case of L/D = 4.3 wake galloping was observed. Shows the categorization of cable aerodynamics. (B.O. Albedooret al.1997) conducted experiment to evaluate the effects of an interfering stationary cylinder, located downstream with two different surface conditions, The interference effects were studied extensively by changing the diameter ratios (d/D) of the two cylinders and the gap spacing (g/D) understand the nature of the interaction. (Maeda et al. 1997) proposed the solution for wake galloping on closely and rigidly connected cables. The cables are connected each other in the rigid arrangement as the result cables are protected from the upstream wake.

<table>
<thead>
<tr>
<th>Arrangement of Cables</th>
<th>Phenomena Classified</th>
<th>L/D</th>
<th>Vibration (Amplitude)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Cable</td>
<td>Vortex-induced vibration</td>
<td>-</td>
<td>Restricted</td>
</tr>
<tr>
<td></td>
<td>Galloping</td>
<td>-</td>
<td>Unlimited where the wind speed exceeds its critical value</td>
</tr>
<tr>
<td></td>
<td>Rain wind Induced vibration</td>
<td>-</td>
<td>Restricted</td>
</tr>
</tbody>
</table>

(Yoshimura et al. 1995) experimented on spacer between cable structures, it experience several instabilities at reduced velocity and related with wake galloping. The nature of instabilities depends upon the separation flow of an upstream. The upstream structure forms a strong wake-switching instability was observed. Experimental studied for wake galloping of the closely spaced triple circular cylindrical structure were conceded by (Nagao et al.2003) in which the centre circular cylindrical structure indicates same as a downstream cylinder and also has similar properties in large staggered angles. An analytical method to wake interference effects on cylindrical structures were studied by (Rupert. et al.2006) considered three dominant regions in his research on the advanced interference model. They are proximity interference region, galloping region and wake interference.

In Proximity interference regions, a phase shift in the response of the downstream structure is predicted on the account of 1.0 < L/D < 1.1. In galloping region, the shear layers from the upstream cylinder began to reattach themselves to the front of the rear cylinder and are in phase with the vortex shedding frequency of the rear from the upstream cylinder in case of 1.1 < L/D < 3.8. The downstream cylinder continues to shed vortices periodically. In wake interference, the vortex on the two structures develops regularized and the vortex trail of the upstream cylinder produces wake. It causes a vibration amplitude of the downstream cylinder in case of L/D > 3.8. 3D the numerical studies turbulence is dominating on the flows and has a critical result on fluid forces. In the case of multiple structures, the 3D flow computational technique is required.

**CONCLUSION**
This review clearly explains the design and vibration characteristics concerning two- and three-dimensional cylindrical structures with a various side ratio, cables with rivulets and results are extracted from analytical, computational and experimental models. The impact of aerodynamic and geometrical nonlinearities, interference and wake effects are taken in account to conduct an in depth investigation and researches on oscillation of cables and structures in a chronological order.
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