International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 18 (2017) pp. 7329-7339

A Review on cross flow Vibration

K B Rajasekarababu[1], G Vinayagamurthy*[2] and G Ilamurugan[3]

[1]Research Scholar, School of Mechanical and Building science (SMBS), VIT-University, Chennai -600127, India.
[2]Assistant Professor (SG), School of Mechanical and Building science (SMBS), VIT-University, Chennai -600127, India.
[3]Assistant Professor (G III), Department of Computer science, Sri Sairam institute of technology Chennai-600044, India.

[1]Orcid ID: 0000-0001-7790-5228 [2]Scopus Author ID: 56909555700 & [2]Orcid Id : 0000-0003-1960-8270

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 withwindy 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 withanegative 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 alignednormal, 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

Record	A_{RMS}/D	U(m/s)	Re(x10^5)	V_r	V_{nr}*
a	0.099	2.06	0.13	6.4	5.4
b	0.006	9.05	0.55	27.3	23.2
c	0.049	16.9	1.03	49.5	42.0
d	0.006	0.67	0.67	32.9	27.9

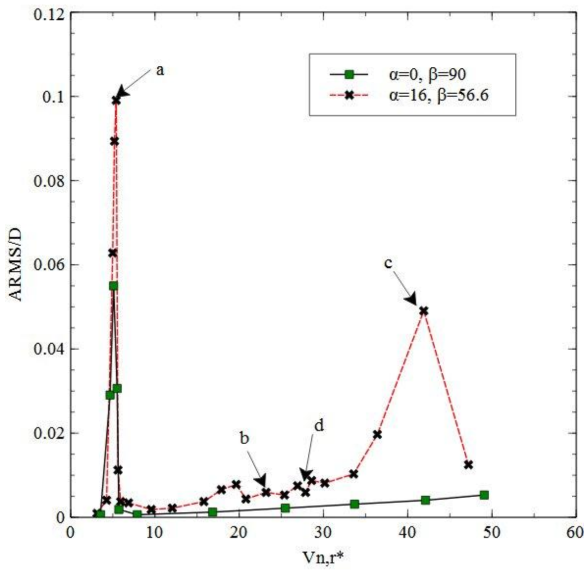


Figure 1: Amplitude Vs Reduced velocity related with wind component perpendicular to the structural axis and AOA for wind tunnel test at different configuration.

Table 2: Wind tunnel test configuration

Config.	α (deg)	β (deg)	β° (deg)	*f*(Hz)	ζ (%)
1	16	56.6	58.3	3.52-3.76	0.35[a]
2	0	90.0	90.0	3.61-3.80	0.35[a]

[a] = average value

.

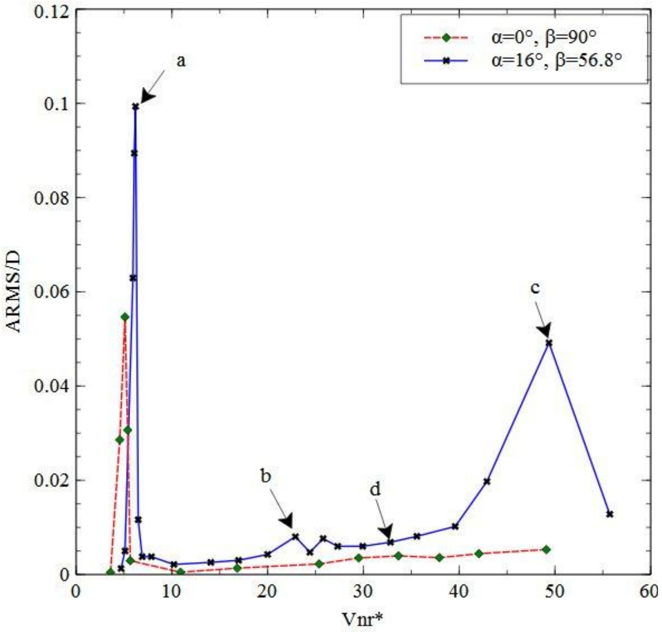
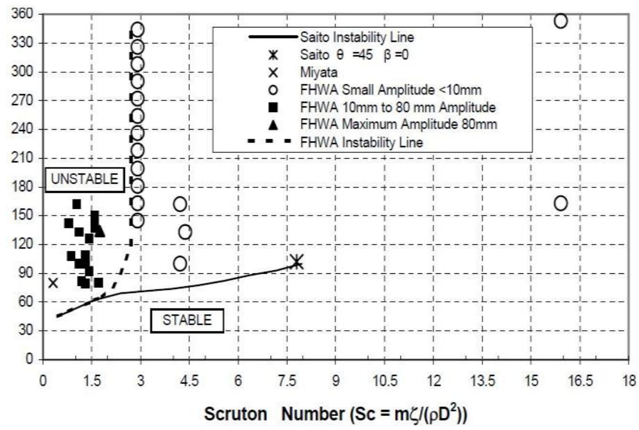


Figure 2: Amplitude Vs Reduced velocity for wind tunnel test of different configuration

(J.J. Ratkowski 1965)Tested nineteen models with ice accretion on cable experimentally and numerically by rotating modelsthrough 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..,



Reduced Wind Velocity Ur vs. the Scruton number Sc

$$U_r = {U_{CRIT}}/{fD}$$

U_{CRIT} = critical velocity for instability

f = natural frequency

D = cable diameter

$$S_c = m\,\zeta / (\rho D^2)$$

m = mass of cable per unit length (kg/m)

ζ = damping ratio of critical damping

ρ = air density (kilograms per meters cubed (kg/m3))

By increase,Sc reduces oscillation amplitude.

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 20º~45º 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 20º~60º 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 0.6×105~2×105 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

International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 18 (2017) pp. 7329-7339

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,thegeometry of a structure wind incidence angle and arrangements and spacing insists the high amplitude vibration (interference wake galloping).It only appearsunevencross sections and grouped structures on the closely placed arrangementof passive and active structures causing high amplitude vibration response on cross winds. Fig: 4 The shear layer separated from the passive structureattaches on tothe 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.

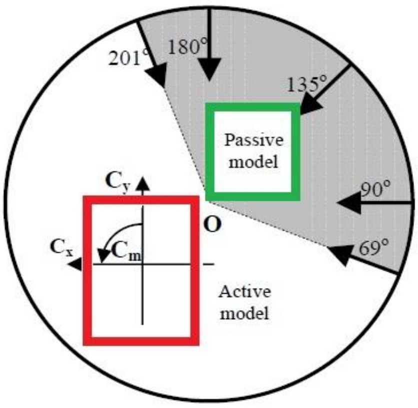


Figure 4: Direction of wind attack interference of active model

Wind Incidence Angle of attack

A wind effect on structure also depends onexposed 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 aero elastic 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 structuresButalso, happen on varying cross-section throughout length or height. In practical sense cables, bridge deck leading edges, antenna, leading edges of tall structuresand 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 atlow angles of attack. The critical velocity decreases and hysteresis range of flow velocities decreases and these effects are verified experimentally and mathematically. However, the incidenceangle of a wind creates the resonance velocity due to the interaction of nearby structures.

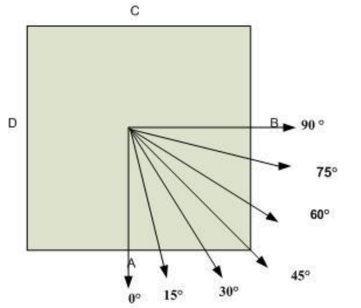


Figure 5: Angle of Attack of model

(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, α, assuming the variation of the angle of attack due to crosswise oscillation around α is small sufficient, galloping instability.

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

where cl = 2l/(ρU2b) is the section Cl, cd = 2d/(ρU2b) the section Cd and α the angle of attack; l and d are the aerodynamic forces, lift and drag, respectively, ρ 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 obtain by wind tunnel testing.(A. Joly,et al, .2011)concentrated to observe the galloping phenomena at low Reynolds numbers using a two-

International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 18 (2017) pp. 7329-7339
© Research India Publications. http://www.ripublication.com

dimensional FEM .A sinusoidal quasi-steady model allows determination of the occurrence of galloping and its amplitude.(MingzheHe, 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-likebehaviour for maintaining an instability zone at any aspect ratio up to close the circular cylinder ($\tau = 1$) 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 andside ratio of a structure. (O. Mahrenholtz 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_o is smaller than Y_o.

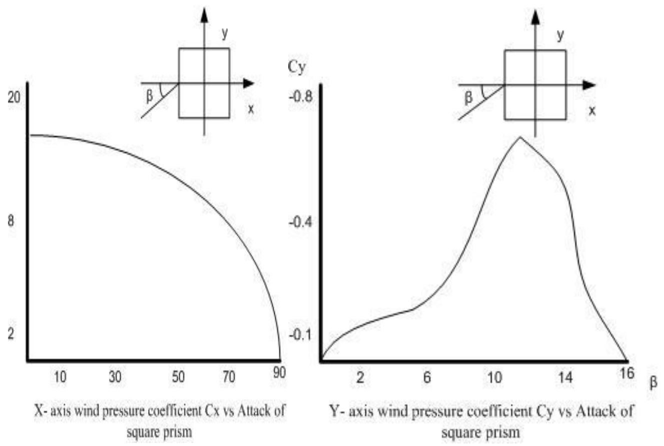


Figure 6: Wind pressure coefficient of square prism

(H. Kawai 1995) examines the amplitude of galloping and VIV effect of AOA on turbulent and smooth flow conditions intherectangular and triangular sectionsof 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 oudheusden2000) 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 revel 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 $159 \leq Re \leq 200$. 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) investigatedhysteresis phenomena of anisosceles triangular cross-section body, focusing on the dynamic response in inflection point in the CL curve at 10^0 to 60^0 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 20105)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 mode are found to be more critical for bending response, first mode lock-in is critical only for displacement response.

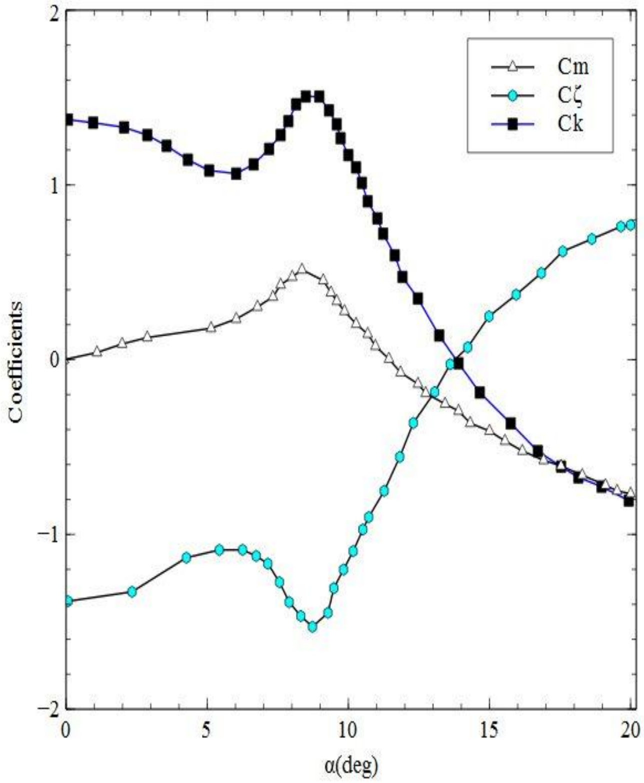


Figure 7: Aerodynamic characteristics of rectangular cross section

Wind loads increasewith the height of the structuresas 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.

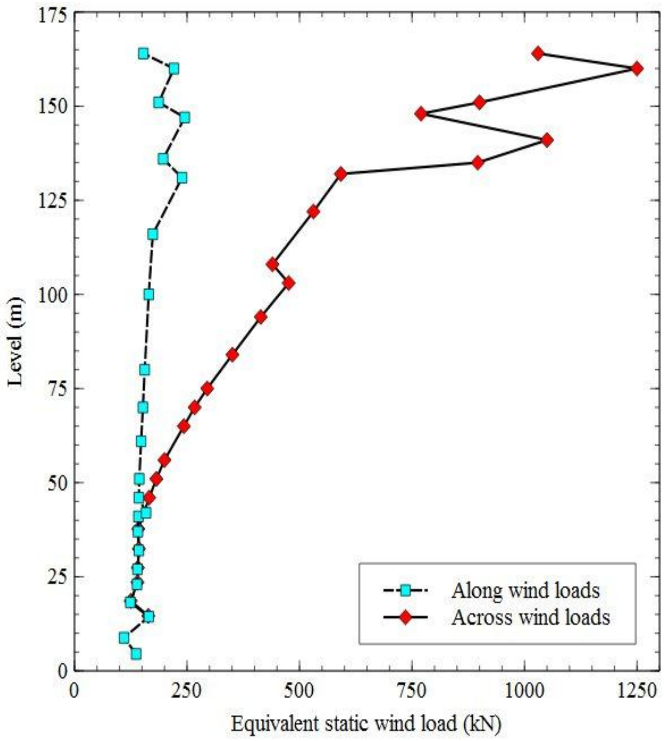


Figure 8: Equivalent static wind load distribution of the original plan

(Luigi Carassale, et al, .2013) examined the corner shaping influence on cross wind oscillation bythe-thequasi-static approach. Fig: 9 explains the fact that the corner shaping producesa 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 7.9x 10^4.(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.

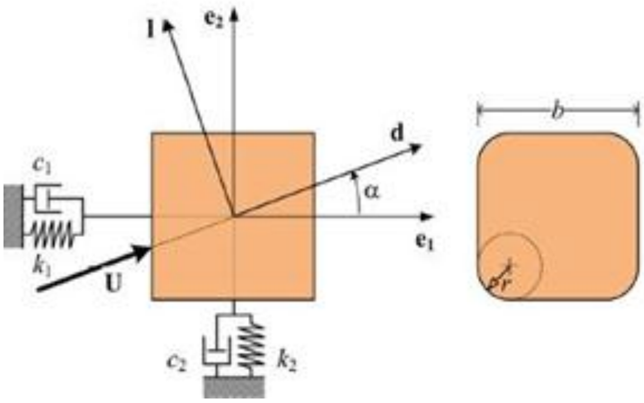


Figure 9: Experimental set of corner shaping

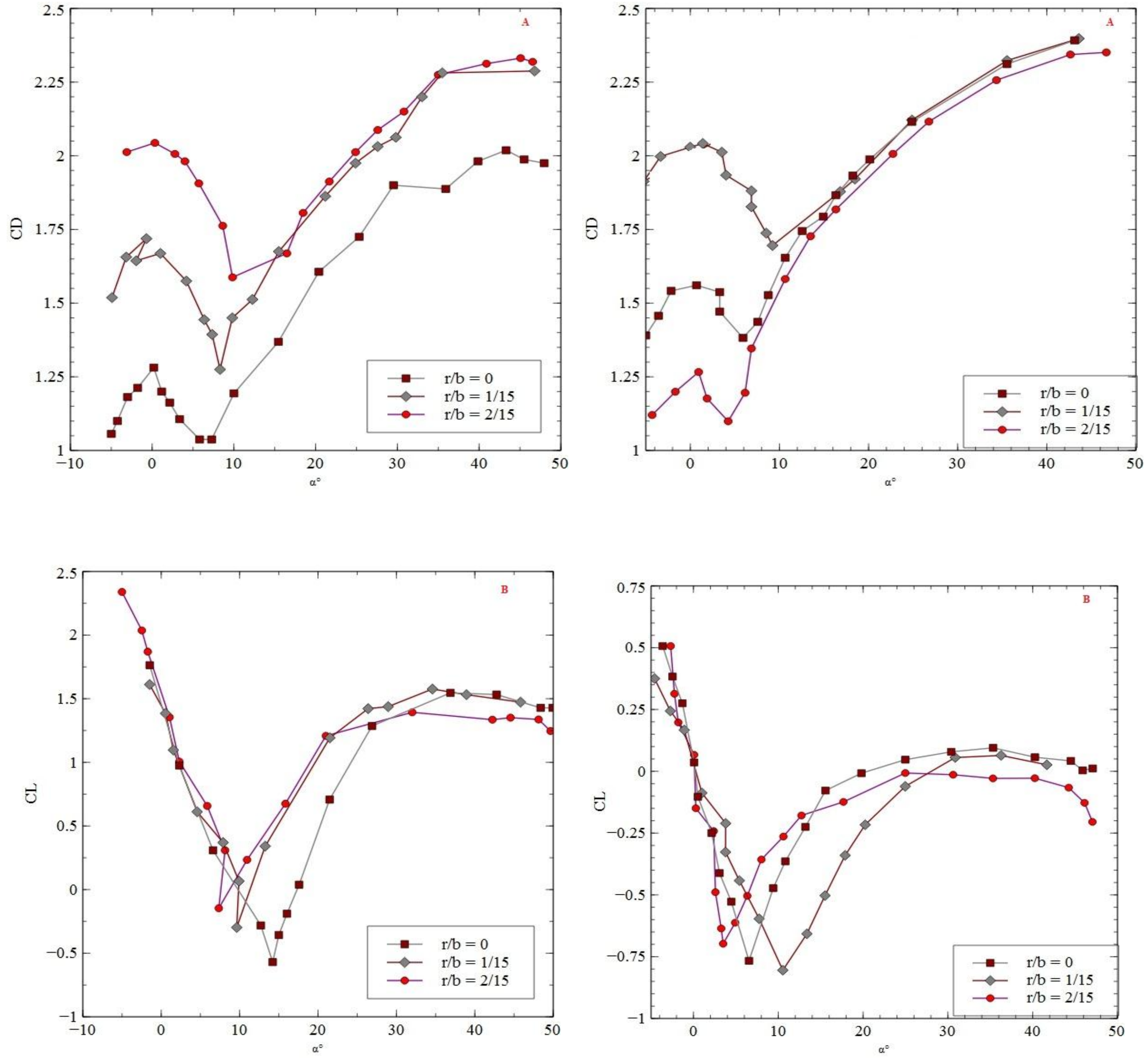


Figure 10: C_D(A)and C_L (B) in laminar and turbulent flow with a different case of r/b.

(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 0^0 and 90^0 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:

Windpressures 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 lowlevel turbulence associated withopen country exposure, fluctuation in the wake of an upstream structure is associated and leads to an improved wind loads on the downstream structure. (Taniike 1991) examined the mutual interaction between neighboring tall structures is an exceedingly turbulent stream over an urban territory. An interference effect reduces exponentially with an increase in turbulent and extinct out when turbulent intensity is increased up to 17-18 %. By upstream terrain presentation from open to suburban, the along and across wind loads on the downstream structure due to upstream structure reduces to about 60-80% of open terrain values, depending on the terrain geometries and natural obstacles. (I.G. Lines, *et al.* 1995) evaluated the risk assessment on building wakes and assessing a set of realistic releases for a real siteto equivalent building using CFD approach. (NarayanK and Gairola A 2014) investigated the isolated roof structure. The wind pressure coefficient was observed as 48% due to interference and other occurs at corner zones.

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 (Sakamotoet 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.

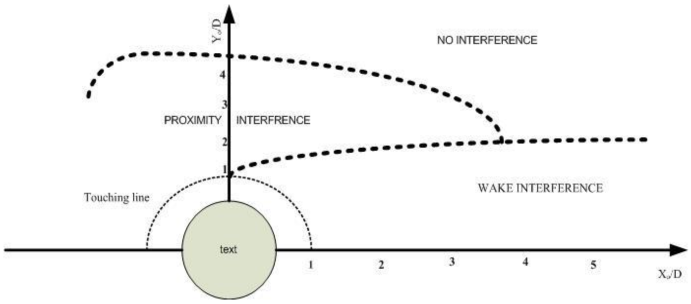


Figure 10: Wake interference regime by Zdravkovich (1987)

(Gu and Sun 1999) explained that separation shear angle of more than 20^0 from an upstream structure doesn't interface with downstream structure. Taking account water channel test for flow separation. (Sumner *et al.* 2000) distinguished nine flow patterns of various centre-to-centre distances at various angles of incidence were obtained experimentally where the numerical analysis to be applied for staggered structures in recent years. (Akbar*et al.* 2005) numerically analysed the flow behaviour of vortex formation for two staggered structure at various L/D ratio and angle of incidence at low Reynolds number. And five flow patterns were known as ‘‘Base-Bleed” (recirculation near base the pressure in this region is lower than free stream pressure), “Shear-Layer Reattachment”(reattachment existence is associated with the periodic lift using boundary layer flow control mechanism), “Vortex Pairing and Enveloping” (the way of vortex coupling with respect to particle dispersion on structure), “Vortex Impingement”(it is evident in corner interaction of a structure) and “Complete Vortex Shedding” (it depends upon the shape of the body, The vortices createlow-pressure zone of a structure)

Tandem arrangement of structures:

Tandem arrange of thestructure 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 = $10^2$and 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 resultedthat critical spacing would be easily affected by Re. (Meneghini et al.2001) Researched tandem and side-by-side arrangement ofthecircular 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 hysteretic effect of fluid force in the range of L/D ratios, at the range of

2<L/D<2.5. The drag coefficients values are different at downstream and upstream structures depending on L/D ratio increased gradually.(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.Itdepicts 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 cylindricalstructure 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 protectedfrom the upstream wake.

Arrangement of Cables	**Phenomena Classified**	**L/D**	**Vibration (Amplitude)**
Single Cable	Vortex-induced vibration	-	Restricted
	Galloping	-	Unlimited where the wind speed exceeds its critical value
	Rain wind Induced vibration	-	Restricted
	Inclined cable vibration	-	Unlimited where the wind speed exceeds its critical value
Two Parallel Cables	Wake galloping	1.5-6	Unlimited where the wind speed exceeds its critical value
	Wake induced flutter	10-20	

(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.

REFERENCES

[1] Identification of aeroelastic forces and static drag coefficients of a twin cable bridge stay from full-scale ambient vibration measurements (A.Acampora, J.H.G.Macdonald, C.T.Georgakis, N.Nikitas)

[2] R.D. Blevins, Flow-Induced Vibrations. 2nd Edition (Van Nostrand Reinhold Company, New York, 1990).

[3] Aeroelastic galloping in one degree of freedom Parkision (1965).

[4] Wind tunnel testing of yawed and inclined circular cylinders in the context offield observations of staycable vibrations (Delong Zuo, NicholasP.Jones).

[5] Experiments with Galloping Spans (J.J. Ratkowski 1965).

[6] Factor Relative to High-Amplitude Galloping (J.J. Ratkowski 1965).

[7] Rain-wind excitation of cables of cable-stayed Higashi–Kobe Bridge and cable vibration control.In: Proceedings of International Conference on Cable-Stayed and Suspension Bridges(Saito, T.,Matsumoto,M.,Kitazawa,M.,1994).

[8] Rain-wind induced vibrations of cables stayed bridges (Hikami, Y., Shiraishi, N., 1988)

[9] Characterization of rain-wind induced stay-cable vibrations from full-scale measurements. (Main, J., Jones, N., Yamaguchi, H., 2001)

[10] Aerodynamic characteristics of an inclined and yawed circular cylinder with artificial rivulet (Xiaoqing Du, MingGu, SurenChen 2013)

[11] Critical conditions of galloping for inclined square cylinders (Giuseppe Piccardo n, LuigiCarassale,AndreaFreda 2011)

[12] Wind-induced loading and dynamic responses of a row of tall buildings under strong interference (K.M. Lam, J.G.Zhao, M.Y.H.Leung 2011)

[13] Galloping of small aspect ratio square cylinder (A. N. Ryabinin and V. D. Lyusin 2015)

[14] Aerodynamic stiffness and damping effects in the rotational galloping of a rectangular cross-section (B. W. VAN OUDHEUSDEN 2000)

[15] An analytical solution for the galloping stability of a 3 degree-of-freedom system based on quasi-steady theory (Mingzhe He, JohnH.G.Macdonald 2015)

[16] Galloping of square cylinders in cross-flow at low Reynolds numbers (A. JolyS.Etienne, D.Pelletier 2011)

[17] An analysis of the dependence on cross section geometry of galloping stability of two-dimensional bodies having either biconvex or rhomboidal cross sections (Gustavo Alonso, Eusebio Valero, José Meseguer 2008)

[18] Galloping response of towers. (G.V. PARKINSON, P.P. SULLIVAN 1979)

[19] Aeroelastic problems at masts and chimneys (O. Mahrenholtz And H. Bardowicks 1979)

[20] An Evaluation of Onset Wind Velocity for 2--D Coupled Galloping Oscillations of Tower Buildings (Liang Shuguo, et al,.1993)

[21] Effects of angle of attack on vortex induced vibration and galloping of tall buildings in smooth and turbulent boundary layer flow (H. Kawai 1995)

[22] Hysteresis phenomenon in the galloping oscillation ofa square cylinder (S.C. Luo, Y.T. Chew, Y.T. Ng2003)

[23] Hysteresis phenomena in transverse galloping of triangular cross-section bodies (G. Alonso , A.Sanz-Lobera,J.Meseguer 2013)

[24] Cross-flow pressure measurement on a 2D square cylinder (Y.F. Li, P.J. Richards, R.G.J. Flay 2001)

[25] Experimental study of wind loading of rectangular sign structures ((Delong Zuo , Douglas A.Smith, Kishor C. Mehta 2014)

[26] Across-wind response of tall circular chimneys to vortex shedding (S. Arunachalam, N. Lakshmanan 2015)

[27] An analytical study of the across-wind response of cylinders due to vortex shedding (T. K. Datta and A. K. Jain 1987)

[28] On the across-wind oscillation of tall buildings (Takeo Matsumoto)

[29] Brief Communication Transverse galloping at low Reynolds numbers (A. Barrero-Gil, A.Sanz-Andre´s, M.Roura 2003)

[30] Across-wind loads and effects of super-tall buildings and structures(GU Ming & QUAN Yong 2011).

[31] Critical conditions of galloping for inclined square cylinders (Giuseppe Piccardo n, LuigiCarassale,AndreaFreda 2011).

[32] The effects of aerodynamic interference on the dynamic response of prismatic structures (Kareem. A. 1984)

[33] A crosswind aerodynamic damping of isolated square-shaped buildings (C.-M. Cheng, P.-C. Lu, M.-S. Tsai. 2002)

[34] Experimental study on transverse flow-induced oscillations of a square-section cylinder at low mass

ratio and low damping (J. Xu-Xu, A. Barrero-Gil, A. Velazquez)

[35] Incorporation of building wake effects into quantified risk assessments (I.G. Lines, D.M. Deaves and R.C. Hall 1995)

[36] Wind interference on single similar gable roof building with overhangs(Narayan K and Gairola A 2014)

[37] . Mathematical model of across wind dynamic loads on rectangular tall buildings (Shuguo Lianga, Shengchun Liu, Q.S. Li, Liangliang Zhang, Ming Gu 2002)

[38] Effects of neighbouring building on wind loads (Kanpyowho, Sungil Hong, Kyu- Seok Hwang 2004)

[39] Along- and cross-wind response of a generic tall building: Comparison of wind-tunnel data with codes and standards (John D. Holmes 2014)

[40] Flow-pattern identification for two staggered circular cylinders in cross-flow, (Sumner, D., Price, S. J. & Païdousis, M. P 2000).

[41] Interference between two circular cylinders, Series of unexpected discontinuities (Zdravkovich, M. M. & Pridden, D. L. 1977),

[42] Flow-induced oscillations of two interfering circular cylinders, Journal of Sound and Vibration. (Zdravkovich, M. M. 1985)

[43] Study on the surface pressure distribution of cubes in cross- wind arrays (Lim, KenjiTsukamoto, MasaakiOhba, Kunio Mizutani 2014)

[44] The effects of interference between circular cylinders in cross-flow, (Zdravkovich, M. M. 1987)

[45] Flow around circular cylinders Vol 1: Fundamentals, Oxford University Press, (Zdravkovich, M. M 1997)

[46] Unsteady incompressible flows past two cylinders in tandem and staggered arrangements (Mittal, S., Kumar, V. & Raghuvanshi,1997)

[47] Flow-induced oscillations of two cylinders in tandem and staggered arrangements (Mittal, S. & Kumar, V 2001)

[48] A study on flow around two circular cylinders in staggered arrangements(Sakamoto, H., Alam, M. M., Kim, S. & Takai, K 2004)

[49] Vortex shedding from two circularcylinders in staggered arrangement, (Kiya, M., Arie, M., Tamura, H. & Mori H 1980).

[50] Numerical investigation of flow patterns for staggered cylinder pairs in cross-flow, (Akbari, M. H. & Price, S. J 2005).

[51] Wake-induced galloping of two interfering circular cylinders, (Bokaian, A. & Geoola, F 1984).

[52] Dynamic response of circular cylinders in cross-flow (B.O. Albedoor a, A. Almusallam 1997)

[53] The flow interaction between a stationary cylinder and a downstream flexible cylinder (Brika, D. & Laneville, 1999).

[54] A study on wake-galloping employing full aeroelastic twin cable model (Tokoro, S., Komatsu, M., Nakasu, M., Mizuguchi, K. & Kasuga, A. 2000).

[55] Aerodynamic characteristics of closely and rigidly connected cables for cable-stayed bridges.(Maeda, H., Kubo, Y., Kato, K. & Fukushima S. 1997)

[56] Wind-induced oscillations of groups of bridge staycables, (Yoshimura, T. & Savage, M.G 1995)

[57] An analytical approach to waking interference effects on circular cylindrical structures. (Rupert, G. et al. 2006)

[58] The interaction between a pair of circular cylinders normal to a stream. (Bearman, P. W. & Wadcock, A. J 1973)

[59] Wake interaction experiments with two flexible circular cylinders in flowing water. (King, R. & Johns, D. J 1976)

[60] Characteristics of the flow around two circular cylinders arranged in tandem (Igarashi, T. 1981)

[61] Characteristics of the flow around two circular cylinders arranged in tandem unique phenomenon at small spacing, (Igarashi T.1984)

[62] Evolution of a single wake behind a pair of bluff bodies. (Williamson, C. H. K. 1985)

[63] Fluctuating pressure on two circular cylinders at high Reynolds numbers, Journal of Wind Engineering and Industrial Aerodynamics.(Sun, T. F., Gu, Z. F., He, D. X. & Zhang, L. L. 1985)

[64] Interference between two circular cylinders in tandem in turbulent flow, (Zhang, H. & Melbourne, W. H. 1992).

[65] (Mittal, S. & Kumar, 2001) Flow-induced oscillations of two cylinders in tandem and staggered arrangements.

[66] (Meneghini, J. R., Saltara, F., Siqueira, C. L. R. & Ferrari Jr, J. A. 2001) Numericalsimulation of flow interference between two circular cylinders in tandem and side-by-side arrangements.

[67] Jester, W. & Kallinderis, Y. Numerical study of incompressible flow about fixed cylinder pairs, Journal of Fluids and Structures 2003.

[68] Vortex- and wake-induced vibrations of a tandem

arrangement of two flexible circular cylinders with far wake interference (F.J. Huera-Huarte, M. Gharib 2011)

[69] Flow around Two Cam Shaped Cylinders in Tandem Arrangement. (Arash Mir Abdolah Lavasani and Hamidreza Bayat 2012)

[70] Modal excitation of a flexible cylinder undergoingVortex-induced vibrations (Harrison P. Zimmer 2014)