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VORTEX INDUCED VIBRATIONS OF A SQUARE CYLINDER IN A WIND TUNNEL

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ABSTRACT

An experimental study of the vortex-induced vibrations of a rigid square cylinder, mounted flexibly, in a wind tunnel is presented. Special attention is paid to keep the structural damping as low as possible. Structural supports are assumed to behave linearly through out the amplitude envelope. Experimental data comprises of amplitude curves and transient slopes. The experimental procedure was repeated to study the cylinder behaviour both under the memory effect and without it. The classical mode switch can be pointed out in both the cases. Hysteresis is however found only in the former case.

Measurements consist of the time histories of oscillations using laser displacement sensors. Structural parameters are estimated without airflow. Time evolution of energy of the square cylinder is recorded and later manipulated to calculate the growth rate of oscillation amplitude in the transient regime.

INTRODUCTION

Vortex shedding excitation of a cylinder is probably one of the most studied problems in flow induced vibrations. This mechanism, referred to as Vortex-Induced Vibration (VIV), occurs when the vortices which develop in the wake can couple with the dynamics of the cylinder. It can be seen roughly as a resonance mechanism appearing when the frequency of the vortex shedding, controlled by the fluid flow, is close to the natural frequency of the cylinder. However the physics of the interaction between the flow and the cylinder transverse motion is not simply linear. Mathematical modeling of this problem in order to predict the amplitude of the cylinder motion has become a widely studied problem in engineering.

Wilkinson (1974), Otsuki et al (1974) and Nakamura et al (1975) presented some experimental data on the forced oscillations of square section cylinders. Sarpkaya T. (1979) presented a selective review of the then existing knowledge bank about vortex induced oscillations. Bearman & Obasaju (1982) studied the pressure fluctuations on both fixed and forced oscillating square cylinders. They determined that the amplification of the fluctuating lift coefficient for a square cylinder at lock-in was much less than that of a circular cylinder subjected to similar conditions. Ongoren et al (1988) have studied the effects of cylinder inclination with respect to the mean free stream, using a forced circular cylinder in a water channel. Williamson et al (1988) provided the mechanism of vortex formation and the underlying physics for mode shifts. Parkinson G. (1989) resumed the phenomenology and the theoretical modeling tools available to understand the vortex induced oscillations and the galloping instability in case of flow past bluff bodies. Brika et al (1993) studied a hollow slender cylinder in a wind tunnel and showed that the cylinder's steady response was hysteretic. Each branch in the hysteresis loop is associated to either the 2S or the 2P mode of vortex shedding. Abrupt change in the amplitude curve is attributed to the sudden mode shift. Govardhan et al (2000) presented the transverse vortex induced oscillations of an elastically mounted rigid cylinder in a fluid flow. The authors point out that in a classical high mass ratio system the initial and lower amplitude branches can be distinctly identified due to a discontinuous mode transition. In case of lower mass ratio systems a further upper amplitude branch is clearly identifiable attributed to a second instance of mode transition. Hemon et al (2002) submitted experimental and numerical results on the aeroelastic behavior of slender rectangular and square cylinders subjected to a cross flow. Morse et al (2009) discovered the $2P_{overlap}$ mode using high resolution data from a forced oscillating cylinder at a fixed Reynold's number.

As catalogued above, vortex induced oscillations of a cylinder are being investigated with great zeal. Mechanisms of vortex shedding and phase jump at lock-in are being intensely scrutinized. However, almost all of the work being done is largely focused on forced oscillations of circular cylinders in setups with lower mass ratio. Very little attention has been paid to bluff bodies with cross sections other then circular. Ongoren et al (1988) conducted some experiments with square and triangular cross section cylinders. Their experimental setup involved all the cylinders being vertically submerged in a water channel. Some other authors have also submitted their experimental findings on forced square section cylinders in [12], [15] and [18]. We would liked to point out here that almost all the experimental data on square cylinders has either been obtained with lower mass ratio configurations or with forced oscillations mechanisms. Brika et al [3] have submitted experimental findings of a freely oscillating hollow slender cylinder. We strongly feel that the present knowledge base lacks sufficient experimental evidence regarding cylinders with non-circular cross sections allowed to oscillate freely in high mass ratio configurations. This experimental study shall add considerable value to the already expanding scientific knowledge in this field. This work contributes also in the sense that we submit experimental results for a realistic configuration which relays directly to practical real life, civil engineering projects for example. Also, experimental data concerning transient regime is virtually non-existent to this point.

The objective of this paper is to present new experimental results obtained in a wind tunnel for an elastically mounted rigid square cylinder restrained to move in the transverse-wind direction. Such measured data can serve for validation of predictive models. The behavior of the vortex-induced oscillation is studied using two configurations. In the first case, the cylinder was brought to rest and then allowed to oscillate freely for each increment in velocity. In the second case however, the cylinder was not brought to rest for any velocity increment so as to study the memory effects on the cylinder amplitude.

When the cylinder experiences vortex shedding oscillations, its response $z(t)$ exhibits a transient regime, where the oscillations amplitude increases exponentially and a limit cycle oscillations regime (LCO), where the amplitude remains almost constant. Experimental data are presented in terms of values of the main characteristics of the vortex-induced vibrations, *i.e.* the growth rate of the oscillations amplitude in the transient regime, the amplitude $\hat{z}$ of the LCO, and the associated frequency *f*, as a function of the reduced velocity.

EXPERIMENTAL SETUP

Wind Tunnel and Flexibly Mounted Cylinder

Experiments are performed in a small vertical Eiffel-type wind tunnel with a closed circular test section of diameter 200 mm. A rigid square cylinder of span-wise length L = 150 mm and breadth (cross section dimension) D=20 mm is elastically mounted (see Fig. 1) using four linear springs mounted outside the test section. Specific chord wiring is also used in order to restrain the cylinder to move transverse to the flow (see Fig. 1). This specific arrangement is suitably fitted in order to produce very low structural damping.

Mean-velocity and turbulence intensity distributions of the on-coming airflow have been measured. Over the velocity range of the experiments (ranging from 1.5 to 6 m/s) the wall-region of strong mean-velocity gradient is less than 15 mm. According to the length L of the cylinder (150 mm) compared to the diameter of the test section (200 mm) the cylinder is submitted to the flow in this core region where the non-uniformity of the mean-velocity is less than 5% and the turbulence intensity is less than 1 % over the velocity range of the experiments.

No endplates have been used in the experiments. Due to the aspect ratio of the cylinder (L/D=7.5) flow around the end of the cylinder could then have a significant effect on the vortex dynamics, the correlation of the induced fluid forces on the body and thus the vibrations. Meanwhile the proximity of both the ends of the cylinder with the test section wall could reduce the effect of end condition. Indeed, as reported by Morse et al [10] for a circular cylinder the vortex-induced vibrations for attached and un-attached endplates are nearly the same.

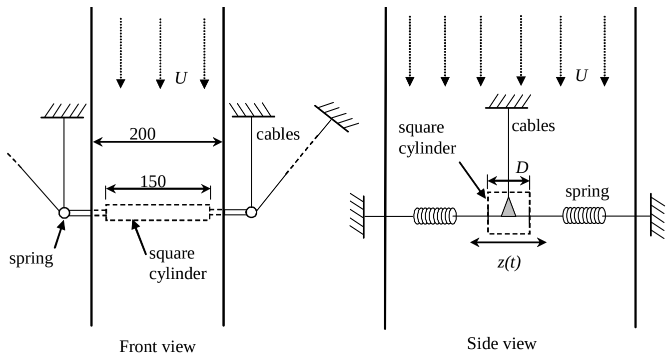

Figure 1. Sketch of the Experimental Setup

Measurement System

A nozzle is mounted down-stream of the test section, in order to accurately measure the reference velocity of the wind tunnel by using two sets of four static pressure taps, one in the test section and the second in the lowest section part of the nozzle. Mean flow velocity in the test section is deduced with Bernoulli's law between the two sections. Correction due to air temperature variation is performed using a thermocouple. This technique allows to measure very low velocities needed in these experiments with accuracy better than 1 %.

The transverse displacement *z(t)* of the cylinder is measured by a laser displacement sensor. The measurement resolution is 40 μm and the accuracy is better than *1%* over the full-scale range (*± 10mm*). The output signals are digitized with a 24 bits resolution acquisition system provided by Muller-BBM. The sampling resolution is *1024Hz* and the duration of the acquisition is typically 60 seconds.

Parameters of the Experiments

Structural parameters are estimated without airflow. Structural supports are assumed to behave linearly through out the amplitude envelope. Parameters of the experiments are resumed in Table I. Pertinent non dimensional parameters are also reported in Table II. One can notice that the system has a high mass ratio $m^* \approx 905$ associated with a very low damping ratio $\eta \approx 0.0828$ *%*. Very low damping leads to a relatively small Scruton number, $Sc \approx 1.5$ which is the key parameter in the observation of vortex shedding vibrations.

Unsteady wake measurements have also been performed in order to measure the Strouhal number of the cylinder at rest. It was found to be *0.127* over the velocity range of the vortex shedding oscillation regime, which is in accordance with Norberg's data for low Reynolds number, [13].

RESULTS

Reduced RMS amplitude of the limit cycle oscillation $Z^* = \hat{z}/D$ is presented in Fig.2 as a function of the reduced velocity for a cylinder starting from rest for each incremental value of velocity. No significant oscillations occur for reduced velocity below *6*. However, a typical VIV amplitude response can be observed for U_r ranging from *6* up to *13*. At higher reduced velocity galloping oscillations appear which are not studied here. Hysteretic transition cannot be observed in this case. However, long time analysis of the limit cycle regime clearly showed mode switching between the upper and the lower branches for $U_r \sim 10$. Different symbols in the figure signify different experimental runs conducted at different times to ensure repeatability of the experimental procedure. Apart from the obvious dispersion of experimental points at higher reduced velocities we can safely assume that the resonant frequencies lie approximately in the same reduced velocity range for each experimental run.

In the VIV regime the amplitude data shown in Fig.2 are very similar to those carried out by Feng [6] for a circular cylinder in airflow. Results obtained by Feng (1968) show two amplitude branches, which were later named as the *"initial"* and the *"lower"* branch by Khalak & Williamson [9].

The maximum oscillation amplitude occurs on the initial branch for a reduced velocity close to *10* which is significantly above the pure resonant point expected for a reduced frequency close to *8* (≈ 1/*St*).

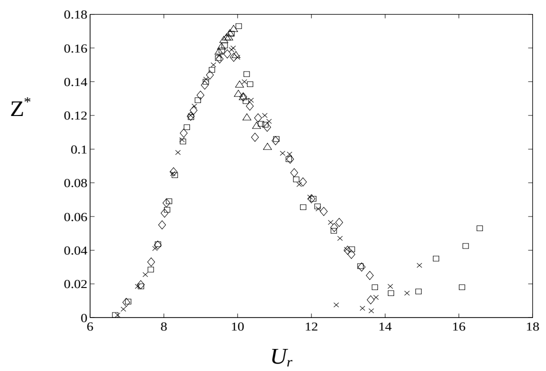

Figure 2. Reduced RMS amplitude of the limit cycle oscillations versus reduced velocity, cylinder starting from rest.

For the "starting from rest" configuration, Fig.2, the transient behaviour of the cylinder oscillation has been characterized by measuring the growth rate of the oscillations amplitude. Results are reported in Fig.3 where the growth rate is presented (as percentage of the cylinder critical damping) as a function of the reduced velocity. It must be noted that the growth rate values have not been corrected by the damping ratio of the cylinder motion in still fluid. To do so and to express a growth rate due to pure aerodynamics effect one has to subtract the damping ratio value η = 0.0828 % to the growth rate data presented in Fig.3.

Results show a sharp increase at the beginning of the lock-in, with a maximum slightly below *0.2%* for a reduced velocity corresponding to the matching of the oscillations frequency with the vortex shedding frequency ($U_r \approx 1/St \approx 8$). Beyond, the growth rate then decreases in a slightly smoother way. This growth-rate behavior can be highlighted using classical couple mode-flutter analysis between the cylinder dynamics and the wake dynamics. This has been theoretically reported by de Langre [5] using linearized VIV dynamic modeling.

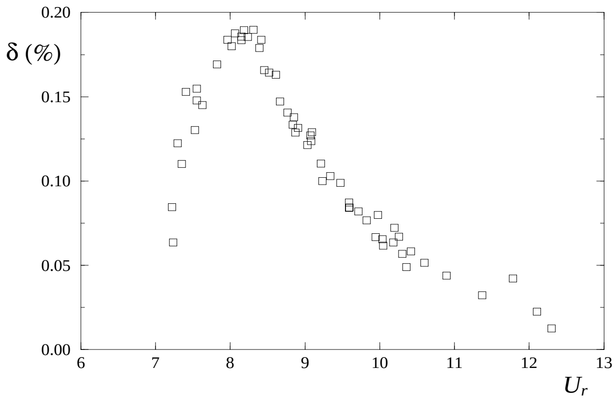

Figure 3. Reduced growth rate of the oscillations versus reduced velocity, cylinder starting from rest (percentage of the critical damping)

A second series of experiments were conducted where the cylinder was not brought to rest so as to study the memory effects on the cylinder amplitude. Results are reported in Fig.4, where circular points represent experimental data recorded while increasing the velocity by a fixed increment and cross points represent data accumulated while decreasing the free stream velocity using a fixed decrement.

Results, obtained from the experiments which allowed the memory effect, exhibit an upper and a lower branch with an abrupt transition for a reduced velocity ~ *9.3*. Williamson and Roshko (1988) used visualisations attributing the sudden change in magnitude to an abrupt mode switch which in turn can be explained by the abrupt shift in phase angle between the vortex shedding frequency and the cylinder oscillating frequency. They showed that the fluid stream just below the critical reduced velocity is extremely sensitive and a very small disturbance is enough for the system to go from one equilibrium state to another thereby causing an abrupt change in formation named as 'the mode-jump'. Brika & Laneville (1993) found that these amplitude branches correspond to different synchronized vortex wake patterns. The 'upper' branch in the amplitude response lies in the von Karman type *2S* mode of the Williamson-Roshko map of wake patterns. The 'lower' branch however lies in the *2P* mode regime in which two vortices of opposite sign are shed from each side of the cylinder at every oscillation cycle. The probability of the existence of *2S* mode decreases as U_r is increased. A slight hysteretic effect can be observed for $U_r \sim 9.5$. Following the circular points as the reduced velocity is increased by a fixed increment, a relatively smooth mode switch to the lower branch can be noticed for a reduced velocity slightly above *9.5*. Following the cross points while decreasing the free stream velocity using a fixed decrement, an abrupt mode switch takes place at reduced velocity slightly lower than *9.5*. The maximum oscillation amplitude found in this case is clearly less than *0.20D*. This maximum amplitude is smaller than the maximum amplitude predicted for a circular cylinder in air flow by Brika & Laneville (1993) and later catalogued by Khalak & Williamson (1999). The amplitude levels presented in Fig.4 are also significantly lower than for the starting from rest configuration.

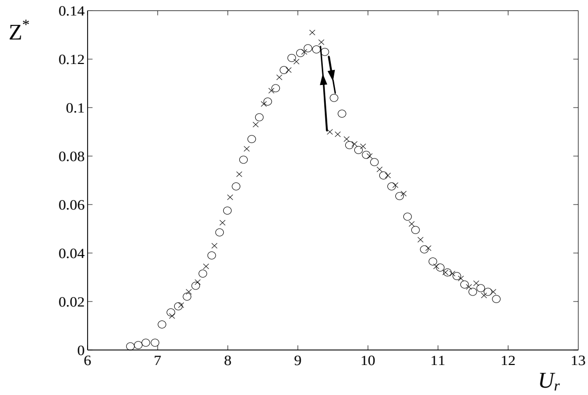

Figure 4. Reduced RMS amplitude of the limit cycle oscillations versus reduced velocity showing hysteretic effect, increasing velocity (o), decreasing velocity (x).

CONCLUSION

An experimental study on the vortex-induced transverse oscillations of a flexibly mounted rigid square cylinder in a uniform airflow has been presented. Unlike much of the experimental data already available as pointed out earlier, our system allows the cylinder to oscillate freely in a high mass ratio configuration. Structural damping was kept as low as possible. New experimental data is provided in terms of amplitudes of the limit cycle oscillations and growth rate of the oscillations amplitude in the transient regime.

Growth-rate results show a sharp increase at the beginning of the lock-in, with a maximum for a reduced velocity corresponding to the matching of the oscillations frequency with the vortex shedding frequency ($Ur \approx 1/St \approx 8$). Upper and lower branches have been highlighted in the amplitude of the limit cycle oscillations with a mode switch between the two branches, similar to the experimental findings submitted by Feng [6] and later Brika et al (1993), [3]. A slight hysteretic effect has also been highlighted in the mode switch area, i.e. for a reduced velocity closed to *9.5*. Moreover a higher amplitude of the LCO is achieved with the cylinder starting from rest for each increment in velocity.

SYSTEM PARAMETERS

TABLE I. PHYSICAL PARAMETERS OF THE EXPERIMENTS

Diameter of the cylinder	D	20	Mm
Length of the cylinder	L	150	Mm
Stiffness of the setup	k	597.6 ± 35	N/m
Mass of the cylinder	m	0.0654 ± 0.004	Kg
Critical damping	cc	12.5 ± 0.75	N.s/m
Structural damping	c	0.0104 ± 0.0008	N.s/m
Natural frequency	f_o	15.21875 ± 0.01563	Hz
Wind tunnel velocity	U	1.5 – 6.0	m/s
Air density	ρ	1.205	kg/m^3
Kinematic viscosity	ν	15 e-6	m^2/s

TABLE II. NON DIMENSIONAL PARAMETERS

Reynolds number	Re	$U\,D/\nu$	2000 – 8000
Mass ratio	m*	$m/\rho\,D^2\,L$	905
Damping ratio	η	c/c_c	0.000828 ± 0.000014
Scruton number	Sc	$2\,\eta\,m*$	1.498
Strouhal number	St	$f_w\,D/U$	0.127
Skop-Griffin parameter	SG	$4\pi^2\,St^2\,Sc$	0.954
Reduced velocity	Ur	$U/f_0\,D$	6 – 20

REFERENCES

[1] Bearman P. W., Obasaju E. D., An experimental study of pressure fluctuations on fixed and oscillating square-section cylinders, *Journal of Fluid Mechanics*. 119 (1982) 297-321.

[2] Bearman P. W., Vortex shedding from oscillating bluff bodies, *Annual Review of Fluid Mechanics*. 16 (1984) 195-222.

[3] Brika D., Laneville A., Vortex-induced vibrations of a long flexible cylinder, *Journal of Fluid Mechanics*., 250 (1993) 481-508.

[4] Cheng L., Zhou Y., Zhang M. M., Perturbed interaction between vortex shedding and induced vibration, *Journal of Fluids and Structures*, 17 (2003) 887-901.

[5] de Langre E., Frequency lock-in is caused by coupled-mode flutter, *Journal of Fluids and Structures*, 22 (2006) 783-791.

[6] Feng C. C., The measurement of vortex induced effects in flow past stationary and oscillating circular and d-section cylinders, Master’s Thesis, Department of Mechanical Engineering, The University of British Columbia, Canada, 1968.

[7] Govardhan R., Williamson C. H. K., Modes of Vortex Formation and Frequency Response of a Free Vibrating Cylinder, *Journal of Fluid Mechanics*. (2000) 420, 85-130.

[8] Hemon P., Santi F., On the Aeroelastic Behaviour of Rectangular Cylinders in Cross Flow. *Journal of Fluids and Structures*. (2002) 16(7), 855-889.

[9] Khalak A., Williamson C. H. K., Dynamics of a hydroelastic cylinder with very low mass and damping, *Journal of Fluids and Structures*, 10 (1996) 455-472.

[10] Morse T. L., Govardhan R., Williamson C. H. K., The effect of end conditions on the vortex-induced vibration of cylinders, *Journal of Fluids and Structures*, 24 (2008) 1227-1239.

[11] Morse T. L., Williamson C. H. K., Fluid Forcing, Wake Modes and Transitions for a Cylinder undergoing Controlled Oscillations. *Journal of Fluids and Structures*. (2009) 25, 697-712.

[12] Nakamura Y., Mizota T., Unsteady Lifts and Wakes of Oscillating Rectangular Prisms. *Proceedings of the ASCE*. 101 (EM6), 855-871 .

[13] Norberg C., Flow around rectangular cylinders: Pressure forces and wake frequencies, *Journal of Wind Engineering and Industrial Aerodynamics*, 49 (1993) 187-196.

[14] Ongoren A., Rockwell D., Flow Structure from an Oscillating Cylinder Part-II. Mode Competition in the Near Wake. *Journal of Fluid Mechanics*. (1988) 191, 225-245.

[15] Otsuki Y., Washizu K., Tomizawa H., Ohya A., A Note on the Aeroelastic Instability of a Prismatic Bar with Square Section. *Journal of Sound and Vibration*. (1974) 34, 233-248.

[16] Parkinson G., Phenomena and Modelling of Flow Induced Vibrations of Bluff Bodies. *Progress in Aerospace Science*. (1989) 26, 169-224.

[17] Sarpkaya T., Vortex Induced Oscillations, A Selective Review. *Journal of Applied Mechanics*. (1979) 46, 241-258.

[18] Wilkinson R. H., On the Vortex Induced Loading on Long Bluff Cylinders. (PhD Thesis) \textit{Faculty of Engineering, University of Bristol, England,} 1974.

[19] Williamson C. H. K., Roshko A., Vortex Formation in the Wake of an Oscillating Cylinder. *Journal of Fluids and Structures*. (1988) 2, 355-381.

[20] Williamson C. H. K., Govardhan R., Vortex Induced Vibrations. *Annual Review of Fluid Mechanics.* 36 (2004) 413-455.