LARGE GALLOPING OSCILLATIONS OF A SQUARE SECTION CYLINDER IN WIND TUNNEL

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ABSTRACT

This paper reports an experimental study of galloping of a 2D square section cylinder flexibly mounted in a wind tunnel. The long term purpose deals with the evaluation of such a system for energy harvesting. Preliminary a deeper study is needed for large amplitude motions which are not well known. We present here two kinds of results, the oscillations amplitude measurements and the wake velocity investigation. An interesting feature is observed with the cylinder inclined by 10° from the axis: for high wind velocity the oscillation amplitude presents a saturation indicating the presence of a self-limited mechanism. Wake velocity profiles show that the vortex shedding remains present but independent of the galloping response due to the system design parameter.

NOMENCLATURE

D	width of the cylinder section, D = 17.1mm
f_1	frequency of vortex shedding (Hz)
f_2	natural frequency of cylinder motion (Hz)
f_r	reduced frequency, $f_r = f_2 D/U_{ref}$
h	vertical coordinate in the wind tunnel frame (m)
M	total mass of the cylinder (kg)
m	mass per unit length of the cylinder (kg/m)
Re	Reynolds number, $Re = U_{ref} D/\nu$
S	Span of the cylinder, S = 170 mm
S_c	Scruton number, $S_c = 2\eta m/\rho D^2$
St	Strouhal number, $St = f_1 D/U_{ref}$
U	mean velocity (m/s)
U_{ref}	mean reference velocity of the wind tunnel (m/s)
U_r,	reduced velocity, $U_r = 1/f_r$,
u	RMS velocity (m/s)
u_1	RMS velocity at vortex shedding frequency (m/s)
u_2	RMS velocity at cylinder motion frequency (m/s)
x	longitudinal coordinate in the wind tunnel frame,
$z(t)$	vertical displacement of the cylinder (m)
z	RMS vertical displacement of the cylinder (m)
θ	rotation angle of the cylinder (°)
η	reduced damping, referred to critical damping
ρ	air density (kg/m^3)
ω	angular frequency, $\omega = 2\pi f$ rad/s

INTRODUCTION

Galloping is an aeroelastic coupling mechanism between an airflow and a flexible structure, often a cylinder normal to the flow. It is described as a one degree of freedom instability where the flow-structure coupling generates a negative added damping that induces the oscillations of the cylinder. This occurs above a critical velocity of the flow and oscillations amplitude may reach very large values, as for instance those observed on electric lines [1].

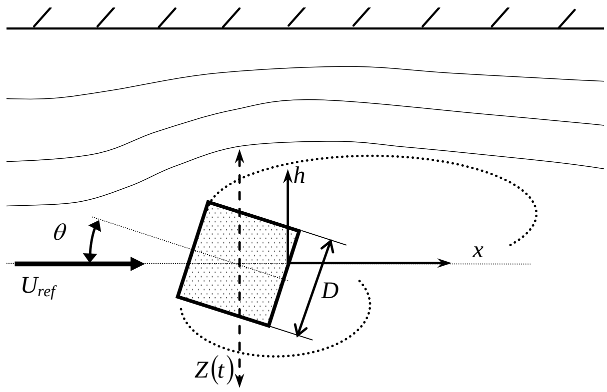

FIGURE 1. THE STUDIED CONFIGURATION.

The long term objective of the current project is to evaluate the energy harvesting potential of the galloping mechanism. Although it has been previously studied analytically [2, 3], the deep understanding of the phenomenon should be improved. Especially large amplitude galloping oscillations are not so well known in simple configuration such as a rigid cylinder, *i.e.* in an almost 2D configuration.

We present here the experiments performed with a square section cylinder as shown Fig. 1 and 2. First we describe the experimental setup, then the amplitude of oscillations are presented. Finally the wake investigation is shown, focusing on the unsteady characteristics.

1. EXPERIMENTAL SETUP

A flexibly mounted square cylinder is placed in a wind tunnel with a square test section (see Fig. 2 & 3).

The upstream velocity has a longitudinal turbulence intensity less than 1 % over a wide range of frequency. The reference velocity is measured with a Pitot tube connected to a pressure manometer. Corrections take into account atmospheric pressure and temperature and global accuracy is better than 1 %.

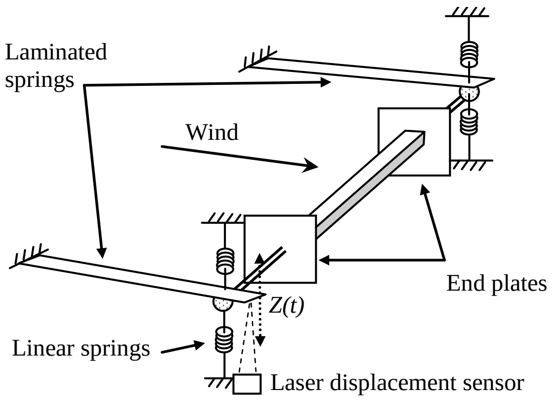

FIGURE 2. PRINCIPLE OF THE EXPERIMENTAL SETUP

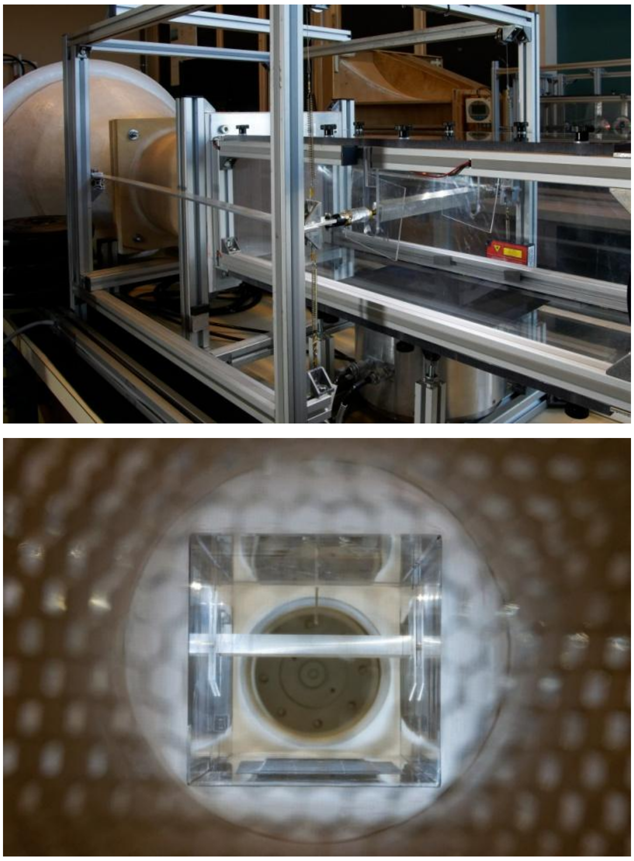

FIGURE 3. PHOTOS OF THE EXPERIMENTAL SETUP

The vertical displacement of the cylinder is measured by a laser sensor, *i.e.* without contact that could corrupt damping of the system. All measured signals are connected to the acquisition system (resolution 24 bits, sampling frequency 512 Hz) providing time histories of the signal and simultaneous spectral analysis. Typically a record is 45 s long and the frequency resolution is 1/8 Hz.

The cylinder is equipped with two end plates which are supposed to keep the airflow 2D as much as possible. The shape has been adjusted on a milling machine ensuring very sharp edges. Stiffness is provided by combination of linear and laminated springs, suitably mounted in order to produce a very low structural damping. These springs are mounted outside the test section, via two vertical fences (see Fig. 2 & 3). Length of laminated springs is large (0.75 m) compared to the expected cylinder vertical displacement so that the system can be considered as linear in the range of use.

The structural data are determined experimentally without wind. First the stiffness is measured by static calibration using reference masses. Then the eigenfrequency is measured by spectral analysis. The total mass of the cylinder is deduced and expressed as a mass per unit length by dividing by the cylinder span. The damping is measured through the free decay of the vibrations after an initial excitation. The resulting Scruton number being large, the risk of vortex induced vibration is expected to be very small. Two cases have been studied by adding or not small masses on the cylinder. Summary of characteristics is given in Table 1.

TABLE 1. STRUCTURAL CHARACTERISTICS OF THE CYLINDER

	Case A	Case B
f_2 (Hz)	5.875	5.25
M (kg)	0.320	0.400
η (%)	0.177 ± 0.013	0.178 ± 0.006
k (N/m)	435.8	435.8
S_c	19.1	24.2

2. AMPLITUDE OF OSCILLATIONS

Amplitude of oscillations are measured for different wind velocities. As widely reported in the literature the square cylinder has a subcritical branch which leads to different limit cycles depending on the initial excitation or perturbation. In this study the high amplitudes are sought. In all results reported here, the hysteresis effect has been removed and the limit cycle amplitudes are obtained after an initial “strong” excitation manually operated. Each point in Figures 4 and 5 should be considered independent from each other.

To ensure that there is no transient effect, each record is started after the stabilization of the motion and at least one minute of stable oscillations. In all tests, the frequency of motion remained the one measured without wind.

Since Den Hartog it is well known that the galloping instability is possible when the lift derivative Cz' of the cylinder is negative. In the case of square section this is true around $\theta = 0$ (see Fig. 1) up to a value about 15° depending on the free stream conditions [3, 4, 5]. When the upstream turbulence is low, as it is the case here, the steady lift gradient shows also a minimum around $\theta = 10°$ which leads to larger sensitivity to galloping with this rotation angle.

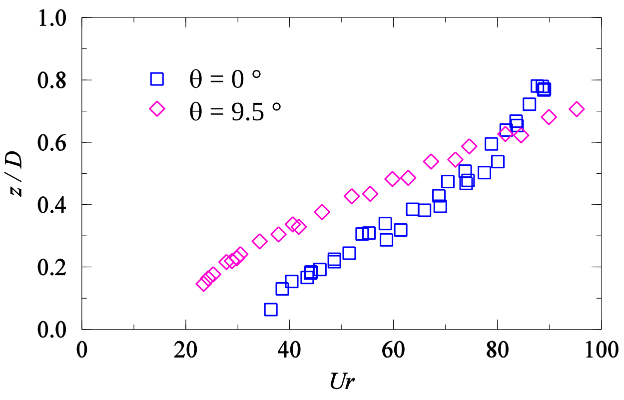

FIGURE 4. OSCILLATIONS AMPLITUDE VERSUS VELOCITY, CASE A.

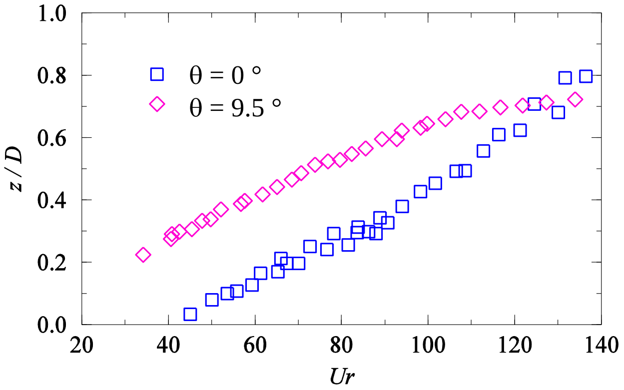

FIGURE 5. OSCILLATIONS AMPLITUDE VERSUS VELOCITY, CASE B.

Then the two cylinders A and B have been tested with two values of θ, 0 and 9.5° as reported in Fig. 4 and 5. Preliminary to these measurements the quasi-steady lift gradient of the cylinder has been estimated by measuring the total damping versus wind velocity. By remaining in stable conditions it is possible indeed by free decay tests to obtain the lift gradient Cz' using the quasi-steady relation of the added damping:

$$\eta_a = \frac{\rho D U}{2 m 2\pi f_2} Cz' . \qquad (1)$$

The resulting values listed in Tab. 2 are in good agreement with those encountered in the literature, especially for $\theta = 0°$ [3, 6].

It is interesting to note that the amplitude response of the cylinder is much higher for $\theta = 9.5°$ than for $\theta = 0°$ at low wind velocities. However, for $\theta = 0°$ the maximum amplitude at high velocities is larger than for $\theta = 9.5°$. Moreover one observes that the amplitude reaches a kind of saturation for $\theta = 9.5°$ at high velocities, as clearly seen in Fig. 5. Even this was expected it is very interesting in the sense that such a system used as an energy harvesting starts to oscillate in low wind but is self-limited in amplitude in high wind. Note that the amplitude saturation is due to aeroelastic effect, not to the structural setup, as the oscillation amplitude for $\theta = 0°$ reaches larger values without visible perturbation.

TABLE 2. AEROELASTIC CHARACTERISTIC OF THE SQUARE CYLINDER

	$\theta = 0°$	$\theta = 9.5°$
Cz'	-2.92 ± 0.3	-8.0 ± 0.3

Obviously the difference between the two cases $\theta = 0°$ and $\theta = 9.5°$ lies in the fact that geometrical symmetry is present for $\theta = 0°$: during the oscillation the effective angle of attack seen by the cylinder in motion oscillates around its mean value $\theta = 0°$. Since the lift curve is symmetric around 0° the galloping force is symmetric also.

But for $\theta = 9.5°$ symmetry is lost which causes amplitude saturation because the effective angle of attack reaches large values for which the lift derivative becomes positive. Then saturation is the result of an equilibrium in which during one period of oscillation the cylinder gains energy for small effective angles of attack but losses energy at high angles of attack. Although this remark implies a kind of quasi-steady assumption, the present experiment proves that it is valid, at least qualitatively.

3. WAKE ANALYSIS

A single component hot wire sensor can be mounted in the wake of the cylinder. It can be moved vertically for measuring velocity profiles. Calibration was performed with a Pitot tube and a reference manometer. Accuracy is globally around 5 %. Length of records is typically 60 s with a sampling frequency of 1024 Hz. Accurate Fourier analysis of the signals provides the different components of the velocities due to vortex shedding (u_1) and to the cylinder oscillations (u_2) at the frequency f_2.

First we measure the Strouhal number, as presented Fig. 6. It has a mean value of 0.147, which corresponds to a wind velocity of lock-in with the cylinder of 0.68 m/s. Agreement with [7] for instance is good.

Note that the blockage effect in the test section leads to a reference velocity lower than that around the cylinder. Geometrically this velocity is 10 % higher, resulting in a corrected Strouhal number 10% lower.

The important point here is that the frequency of vortex shedding is very different from the frequency of the cylinder oscillations due to galloping. Then during the measurements of wake velocity profiles, the reference velocity was set to 8.5 m/s (Ur = 85 with cylinder A). Then the vortex shedding frequency, according to Strouhal law, is 73 Hz, to be compared to 5.875 Hz for the cylinder oscillations.

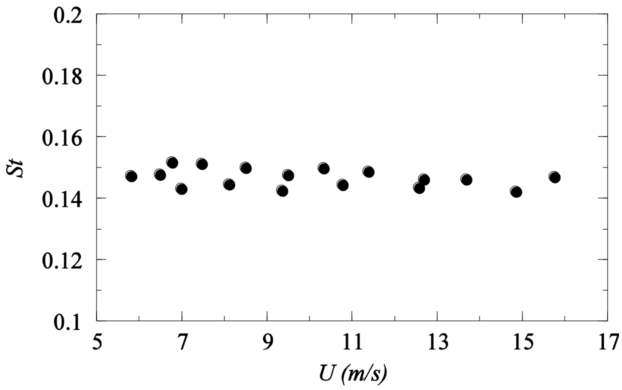

FIGURE 6. MEASURED STROUHAL NUMBER VERSUS VELOCITY FOR STATIC CYLINDER

The velocity profiles have been measured at three different distance from the cylinder rear face, 1.3 D, 0.7 D and 0.23 D. In the first position the entire wake has been investigated, showing symmetry along the axis, see Fig. 7, so that only one side has been measured for the two other distances Fig. 8 and 9.

In each case, the mean velocity U, its RMS value u and the two components u_1 and u_2 are plotted. In the case of u_2 it was found more significant and reliable to reduce the component by the oscillation velocity of the cylinder $\dot{z}$. Indeed these experiments were quite long and perfect stability of the oscillations was not exactly respected for such a long time. Then amplitude of u_2, obviously related to oscillation amplitude, could have changed otherwise.

The first remark is that the oscillations of the cylinder do not modify the main characteristics of the wake. Mean and RMS velocities remain the same in amplitude and distribution. This is also the case for the component at the frequency of vortex shedding, although more noisy signals. It means that the cylinder motion, at a frequency much lower than that of vortex shedding does not perturb the natural shed of vortices which remains present during oscillations. It can be explained by the quasi-steady assumption for which the cylinder motion is so slow that its aerodynamic behaviour remains the same than if there were no motion at all.

But a difference in the phenomena can be observed when considering the expansion of the wake along the distance behind the cylinder. The spatial evolution of the unsteady wake is shown in Fig. 10 where the positions of the maxima of the two velocities u_1 and u_2 are plotted versus the distance x / D behind the cylinder. The expansion of the wake width due to the cylinder oscillation is clear, with a rate of 0.19 (corresponding to an angle 10.75°), although the wake resulting from the alternate vortex shedding remains parallel in the observed region.

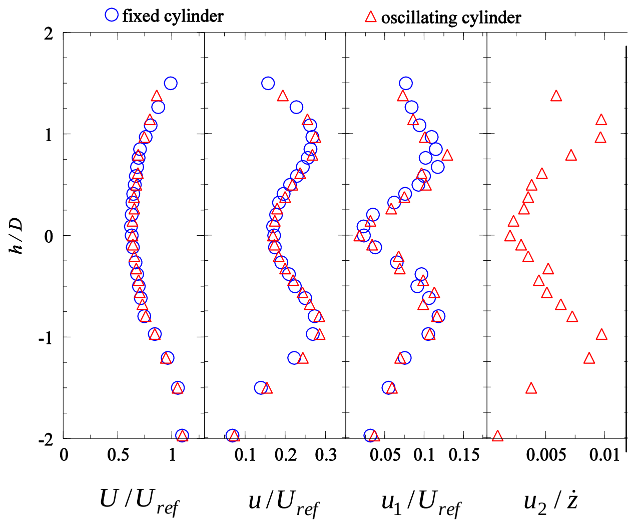

FIGURE 7. VELOCITY PROFILES IN THE WAKE AT x =*1.3D* FOR FIXED AND OSCILLATING CYLINDER AT U_r = 85, CASE A WITH θ=*0*.

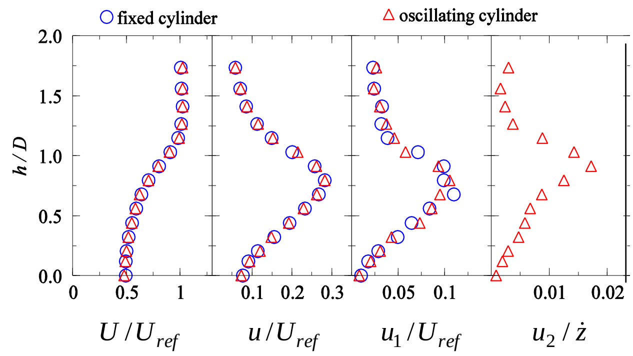

FIGURE 8. VELOCITY PROFILES IN THE WAKE AT x =*0.7D* FOR FIXED AND OSCILLATING CYLINDER AT U_r = 85, CASE A WITH θ=*0*.

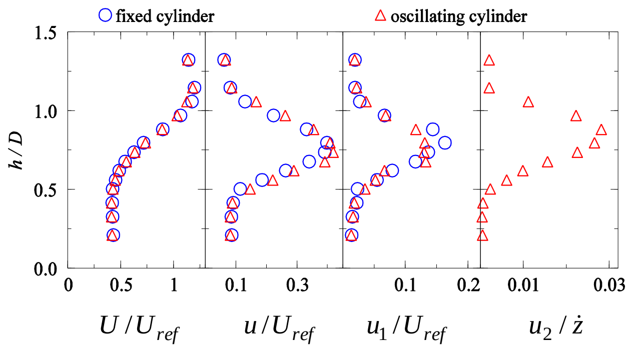

FIGURE 9. VELOCITY PROFILES IN THE WAKE AT x =*0.23D* FOR FIXED AND OSCILLATING CYLINDER AT U_r = 85, CASE A WITH θ=*0*.

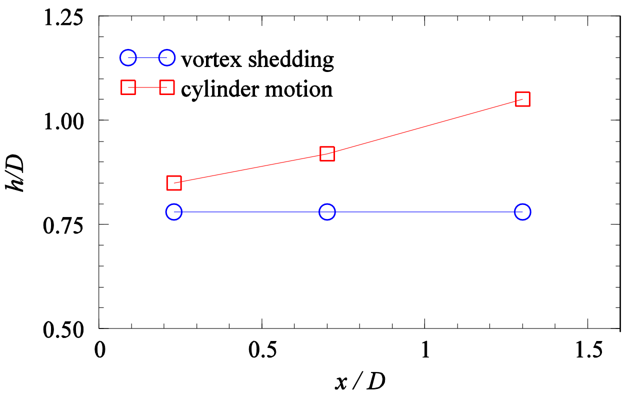

FIGURE 10. VERTICAL POSITIONS *h / D* OF THE MAXIMA OF THE FLUCTUATING VELOCITIES VERSUS THE DISTANCE *x / D* BEHIND THE VIBRATING CYLINDER AT $U_r = 85$.

CONCLUSION

Experiments have been conducted with a mostly 2D square section rigid cylinder flexibly mounted in wind tunnel. The setup allows large amplitude oscillations due to galloping instability. Vortex shedding, although always present, does not lead to excitation because of its very different frequency from the cylinder natural frequency.

Results of oscillations amplitude shows that it is possible to design a system that can start to oscillate at a low wind velocity. Moreover the same system in high wind presents a saturation of oscillations amplitude, suggesting that it is self-limited naturally by its aeroelastic properties. Then the long term objective of the study which is the development of an energy harvesting simple system is still valid and needs further investigations.

Experimental results presented can serve for instance for the validation of analytical models including large nonlinear amplitude features.

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