

Full-scale measurement of wind pressure on the surface of a circular cylinder

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ABSTRACT: An experimental campaign was conducted to measure wind pressure acting on the surface of a full-scale circular cylinder. The pressure measurements were used with measurements of cylinder acceleration to investigate the interaction between the cylinder and turbulent wind. Different characteristics of this interaction were revealed for different wind regimes.

KEYWORDS: Circular cylinder, wind-induced vibration, full-scale pressure measurement.

1 INTRODUCTION

Slender structural members with circular cross-sections are often susceptible to wind excitation. For example, cables of cable-stayed bridges are known to vibrate at large amplitudes under the excitation of wind with simultaneous occurrence of rainfall and, in certain situations, only wind (e.g., [1]). Also, traffic signal support structures having mast arms with circular cross-sections have exhibit problematic vibration (e.g., [2]). A number of full-scale studies (e.g., [1-4]) have been conducted to understand the characteristics of the vibrations and their correlation with wind and, in the case of cable vibration, with wind and rain. These studies revealed that large amplitude vibrations can be induced both by vortex-shedding and by wind oblique to the cylinder with reduced velocity that are much higher than those associated with classical vortex-induced circular cylinder vibration. As complements to full-scale studies, circular cylinders have been tested in wind tunnels (e.g., [5-7]). In particular, a number of experiments were conducted to expressly explore the potential inherent susceptibility of yawed or inclined dry circular cylinders to wind excitation. The findings from these studies have varied, with some suggesting the importance of an axial flow component in the wake of the cylinder in generating three-dimensional flow around the cylinder and initiating large-amplitude vibration at high reduced velocity ([7, 8]), and the others focusing on the potential of instability in the critical Reynolds number range (e.g., [6, 9]). In addition to the experimental studies, numerical investigations based on computational fluid dynamics (e.g., [10]) suggested that the three-dimensional nature of the flow can play a key role in the excitation mechanism. This paper presents the outcome of a full-scale study conducted to measure wind pressure on the surface of a circular cylinder. It facilitates a characterization of the mean and fluctuating wind loading on an oscillating slender circular cylinder when it is subjected to wind of various mean and turbulent characteristics.

2 EXPERIMENTAL CONFIGURATION

The specimen was a 7.62 m long circular pipe of 22.4 cm in diameter and 0.8 cm in wall thickness. It consisted of a 6.40 m long steel pipe and a 1.22 m long PVC pipe. As shown in Figure 1,

the steel portion was rigidly mounted horizontally near the top of a tapered circular aluminum pole, which was 30.5 and 36.8 cm in diameter at the top and the base, respectively, and had a wall thickness of 1 cm. A ring of 32 pressure taps evenly spaced at 11.25° intervals, as depicted in Figure 2, was installed at a cross-section that is 2.1 m from the free end of the cylinder; four additional taps were installed on the sides of this ring at locations indicated in Figure 2. The taps were connected to pressure transducers with a range of ± 1.245 kPa through tubings of 0.91 m in length and 0.6 cm in diameter. With this configuration, the pressure taps were at least 8 diameters and 23 diameters of the cylinder, respectively, from the free and fixed ends. To minimize undesirable end effects on the flow near the pressure taps, a spherical cap was installed at the free end. Besides pressure measurement, a tri-axial accelerometer with a range of ± 4 g was installed adjacent to the pressure tap ring to monitor vibration; an ultrasonic anemometer was installed at a height of 1.5 m above the centerline of the cylinder to monitor the wind, and temperature, relative humidity, and barometric pressure sensors were used to provide measurements for calculation of air density. The data acquisition system recorded 10-minute records at 32 Hz. Two additional 10-second records were sampled before and after each 10-minute record for calibration of the pressure transducers. Due to the inability of the pressure measurement system to function properly in rain, the taps were covered in advance when rainfall was anticipated.



Figure 1 Circular cylinder subjected to study

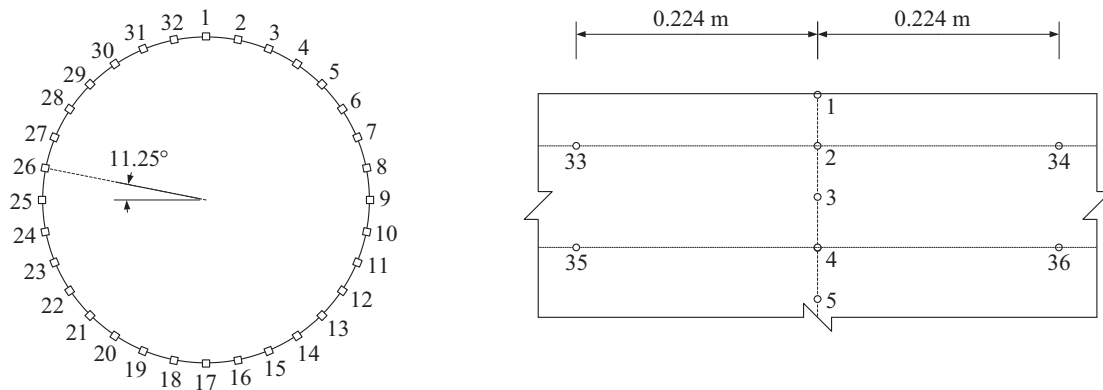


Figure 2 Configuration of pressure taps (not to scale)

3 CHARACTERISTICS OF CYLINDER RESPONSE

To characterize the vibration of the cylinder, the acceleration measurements are numerically integrated to estimate the displacement at the location of the accelerometer. After each integration process, a 5th order high-pass Butterworth filter with a cut-off frequency of 0.2 Hz is applied to

eliminate the spurious effect of low frequency noise. The displacement are then band-pass filtered using a 5th order Butterworth filter to estimate the response in the first two modes of the structure in the in-plane and out-of-plane directions, whose frequencies are identified based on the estimated power spectral density functions of acceleration records. The pass bands of the filter are 0.5 Hz frequency bands centered at the natural frequencies. Finally, the Hilbert transform is applied to the modal displacement to assess the evolution of the amplitude and frequency. The data suggested that during the measurement, the vibration of the cylinder is predominantly in the first in-plane and out-of-plane modes at 2.44 Hz and 2.17 Hz, respectively.

Figure 3 shows the 10-minute mean displacement amplitudes in the first in-plane (A_z) and out-of-plane (A_x) modes against mean speed of the wind component normal to the cylinder axis (V_n). It is seen that the cylinder exhibited significant vibration in the cross-wind direction over a restricted range of wind speeds. This is a clear characteristic of classical vortex-induced vibration. The figure also suggests that at higher wind speeds, the vibration amplitudes increased in both directions with wind speed. This is typical for vibration due to buffeting. Figure 4 shows the mean in-plane vibration amplitude against the reduced velocity (V_r) and the longitudinal turbulence intensity (I_u). The reduced velocity is computed as $V_r = V_n / (fD)$, where f is the mean vibration frequency, and D is the cylinder diameter. It can be seen that vortex-induced vibration occurred over a reduced velocity range centered at a value greater than 5, which is equivalent to the nominal Strouhal number of 0.2 for circular cylinders normal to smooth flow. This can be primarily attributed to two facts. Firstly, according to measurements by an adjacent meteorological tower, the wind speed measured by the anemometer can be 1% to 10% higher than that at the height of the cylinder, depending on the stability of the atmospheric boundary layer. Secondly, according to previous wind tunnel tests [11], organized vortex shedding over circular cylinders can occur over a broad range of Strouhal number, depending on the turbulence intensity of the free stream wind. According to Figure 4, significant vortex-induced vibration did occur over a broad range of longitudinal turbulence intensity.

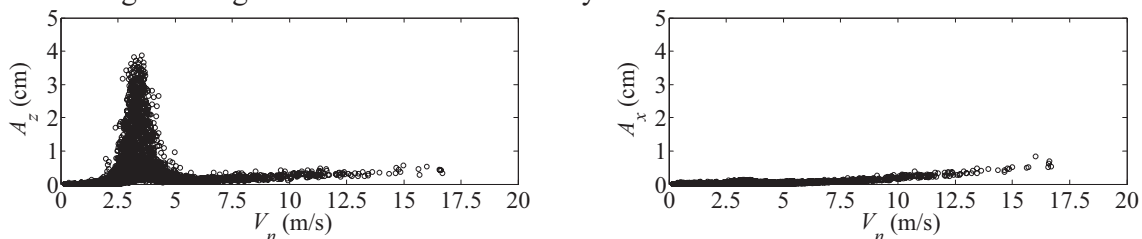


Figure 3 Mean displacement amplitudes in the first in-plane and out-of-plane modes vs. mean wind speed

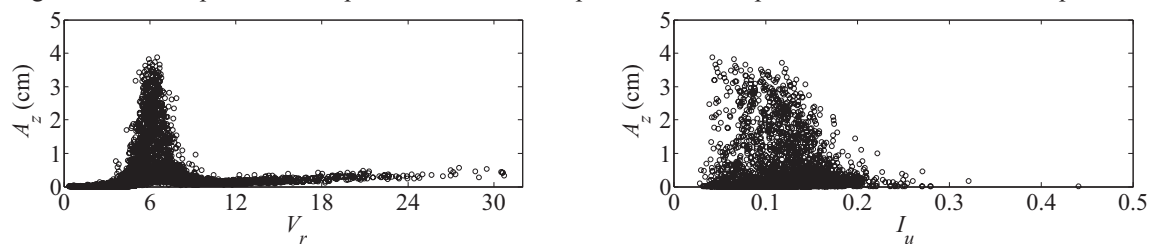


Figure 4 Mean in-plane displacement amplitude vs. reduced velocity and along-wind turbulence intensity

4 INTERPRETATION OF PRESSURE MEASUREMENTS

Incorporation of the measurements by the pressure transducers and the accelerometer have revealed some distinct characteristics of wind loading on the circular cylinder in different wind regimes and different types of wind-structure interaction.

Figure 5 shows the estimated mean drag (C_D) and lift (C_L) coefficients of the cylinder against mean wind speed (V) and the corresponding Reynolds number (Re) for a mean wind direction range of 85° to 95° relative to the cylinder axis. Only records with wind direction variation not exceeding 60° are used here. The Reynolds number is computed based on the mean wind speed, an assumed kinematic viscosity value of $1.5 \times 10^{-5} \text{ m}^2/\text{s}$ and the cylinder diameter as the reference dimension. It can be seen that when wind is almost normal to the cylinder, the transition from the subcritical to the critical Reynolds number range starts at mean wind speeds between 5 m/s and 7.5 m/s, corresponding to a Reynolds number range of 0.75×10^5 to 1.12×10^5 , which is much lower than the Reynolds number (about 2×10^5) at which the transition occurs in smooth flow. Such shifting of critical Reynolds number range is due to the presence of turbulence in the free stream flow, which has been well documented by previous wind tunnel studies (e.g., [11, 12]), although the integral length scale of the wind in these studies were often much smaller than what proper scaling requires for full-scale cylinders such as the one subjected to study herein. Figure 5 also suggests that when the flow is in the subcritical Reynolds number range, the mean lift coefficients are close to zero and that in the critical Reynolds number range, the mean lift coefficients as a trend deviate more from zero. This is also consistent with previous reports (e.g., [9]).

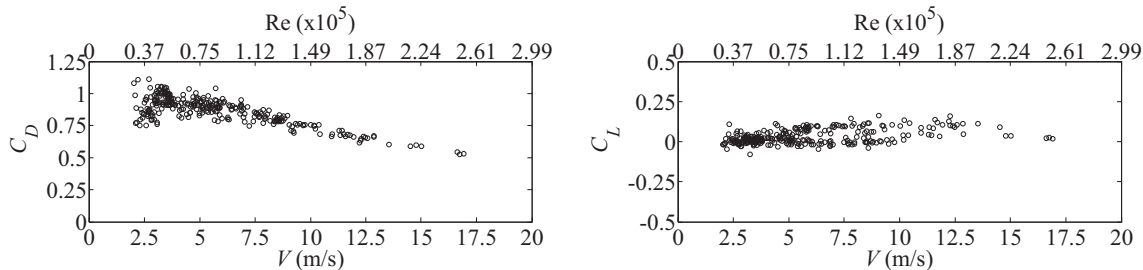


Figure 5 Mean drag and lift coefficients associated winds approximately normal to cylinder axis

It is noteworthy that the mean force coefficients exhibit considerable scatter for low wind speeds. This is partly due to the fact that at these wind speeds, the flow in the lower atmospheric boundary layer is significantly affected by atmospheric stability. The stability state affects not only the ratio of the mean measured wind speed to that at the height of the cylinder, therefore the reference mean dynamic pressure of the wind used for computation of the pressure coefficients, but also the level of shear in the free stream wind, hence the flow-cylinder interaction.

In the following, three representative records with 10-minute mean wind speed and direction (β) as well as turbulence intensity (I_u) listed in Table 1 will be used to illustrate the interaction between the wind and the cylinder when the wind is close to normal to the cylinder.

Table 1 Characteristics of wind of example records with wind approximately normal to cylinder axis

Record Number	V (m/s)	β ($^\circ$)	I_u
1	3.70	93.40	0.055
2	5.00	89.42	0.140
3	12.22	93.06	0.148

Figure 6 shows the drag and lift coefficients of the cylinder estimated based on the wind and pressure measurements in record 1 and the corresponding spectra. It is evident that the lift coefficient is of narrow band and dominated by a frequency component at 2.43 Hz, indicating organized vortex shedding off the cylinder at this frequency. It also can be seen that the drag coefficient has a significant frequency component at 4.86 Hz, which is twice the dominant frequency of the lift coefficient. This is expected for wind loading of circular cylinders in the along-wind direction due to alternating shedding of vortices at the upper and lower surface of the cylinder. It is of interest to notice, however, that the drag coefficient is also dominated by a frequency of 2.43 Hz. This would not have been expected for stationary circular cylinders.

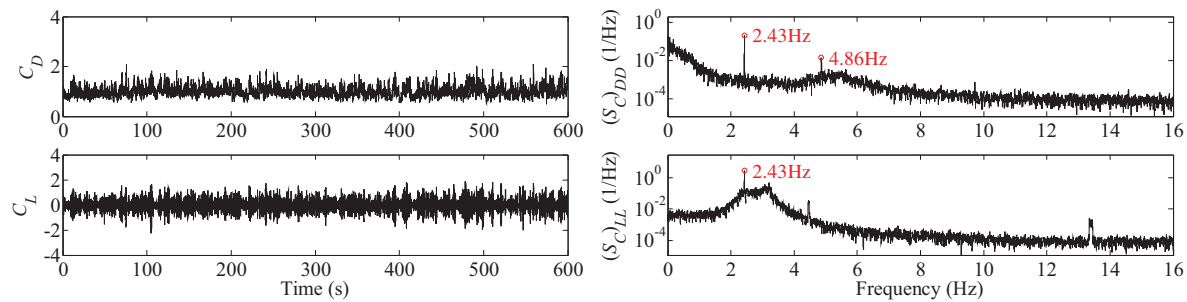


Figure 6 Drag and lift coefficients of the cylinder and the corresponding spectra: record 1

Figure 7 shows the acceleration of the cylinder due to wind loading shown in Figure 6 and the corresponding power spectra. The primarily in-plane vibration (a_z and a_y) is identified to be due to vortex shedding locked-in with the vibration of the structure. It is noteworthy that, in addition to the dominant frequency component at 2.43 Hz, the in-plane vibration also has a component at 4.86 Hz, which is twice the vortex-shedding frequency, despite the fact that this frequency is neither a natural frequency of the structure nor the vortex-shedding frequency. It is believed, therefore, that the in-plane vibration at 4.86 Hz is due to a super-harmonic of the excitation at 2.43 Hz. It is of interest to notice that, since the drag coefficient has a significant frequency component at 2.43 Hz, the insignificant along-wind, out-of-plane, vibration also consists of a component at this frequency, which is not a natural frequency of the structure in this direction.

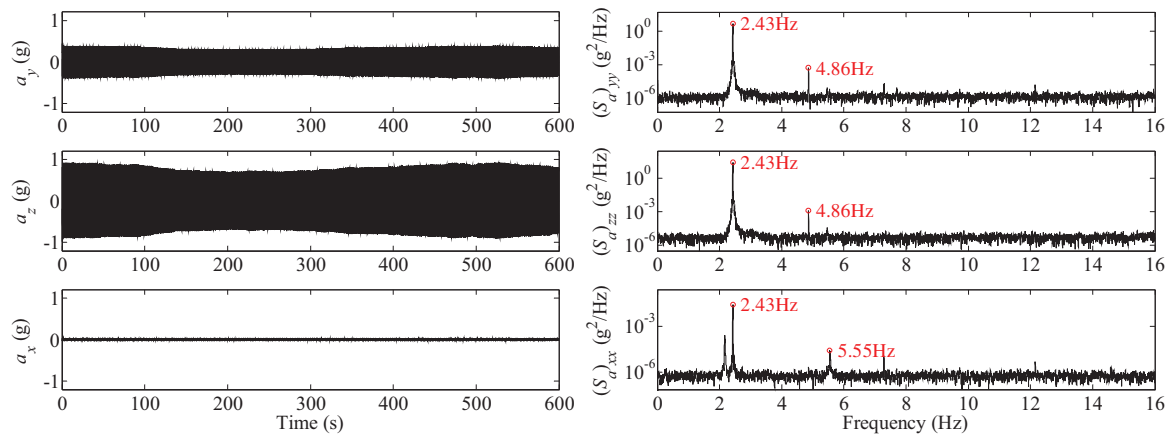


Figure 7 Acceleration time histories and the corresponding spectra: record 1

By comparing the lift coefficient time history shown in Figure 6 and the in-plane acceleration time histories shown in Figure 7, it is apparent that although the response of the structure is quite steady, the lift force acting on the cylinder at the pressure tap ring is not. This is further illustrated in Figure 8, in which can be seen that the lift force and the displacement at the location of the pressure tap ring are only intermittently synchronized due to the interaction of the cylinder and the turbulent wind.

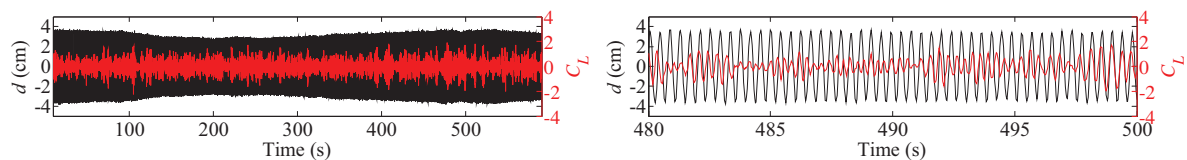


Figure 8 Cylinder displacement and lift coefficient at location of pressure tap ring: record 1

Figure 9 shows the cross-correlation coefficients of the pressures at 5 taps along two axial lines of the cylinder over a time lag of 5 seconds. The subscripts indicate the tap numbers. The measurement by tap number 36 is not used because this tap is determined to have malfunctioned. The coefficients are clearly those of narrow band processes with the same center frequency.

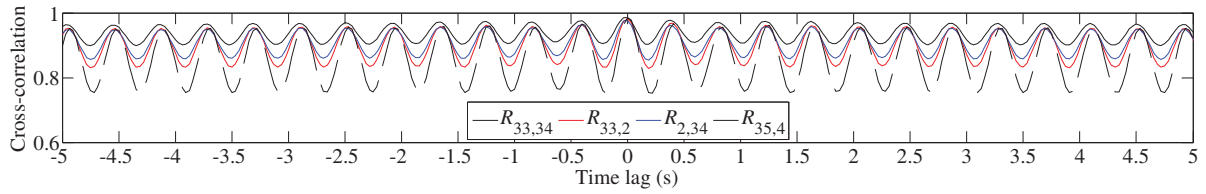


Figure 9 Cross-correlations of pressure measured along the axial direction of the cylinder: record 1

Figure 10 illustrates approximately one cycle of vibration at the pressure tap ring location and the corresponding pressure distribution on the surface of the cylinder, when the vibration and the lift force are nearly synchronized. It is apparent that the pressure distribution on the ring when the cylinder is at symmetric positions during upward and downward movements can be quite different, indicating different vortex shedding patterns from the upper and lower surface primarily due to the existence of turbulence. Figure 11 illustrate the distribution of the mean pressure coefficients (C_p) over the 10-minute duration. It can be seen that for this particular record, the distribution of the mean pressure is quite symmetric about the horizontal plane through the centerline of the cylinder. It must be noted that, the pressure distributions illustrated in Figure 10 and Figure 11 might be biased by the reference pressure measured at the ground level and may be different from the static pressure at the height of the cylinder in a stable boundary layer, which is quite likely in this case as low turbulence intensity is a signature of stable boundary layers.

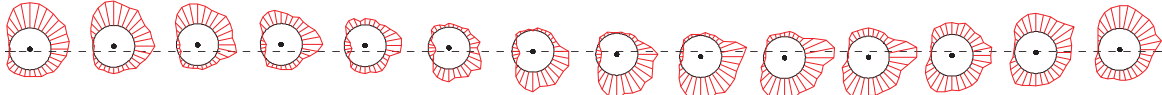


Figure 10 Synchronization of vortex-shedding with cylinder vibration: record 1

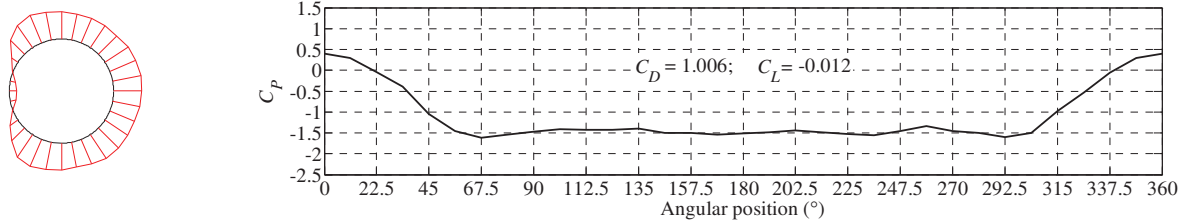


Figure 11 Mean pressure distribution at the pressure tap ring: record 1

According to Figure 5, the mean wind speed over the duration of record 2 is in the subcritical Reynolds number range. Figure 12 shows the drag and lift coefficients of the cylinder for this record and the corresponding spectra. It can be seen that neither the drag force nor the lift force acting at the location of the pressure tap ring have a dominant frequency component, but the lift force does have considerable contribution from components over a frequency band centered between 4 Hz and 5 Hz. This frequency band represents that of unorganized vortex-shedding off the surface of the cylinder. Figure 13 shows the acceleration response of the cylinder. It can be seen that the vibrations in both the in-plane and the out-of-plane directions are at small amplitudes, primarily in the first two modes in these directions.

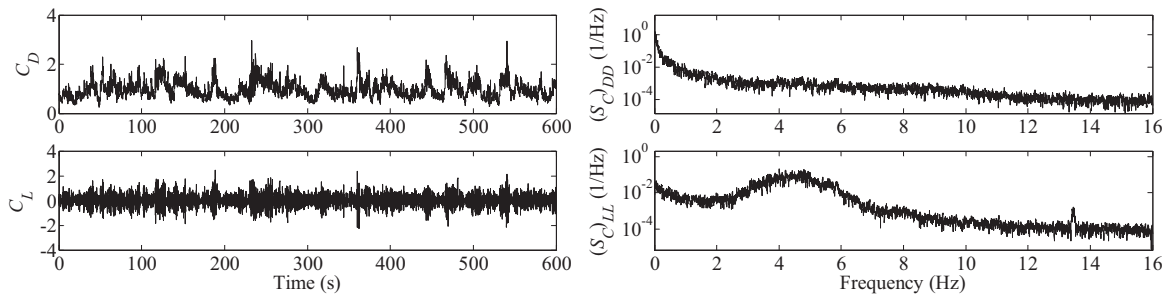


Figure 12 Drag and lift coefficients of the cylinder and the corresponding spectra: record 2

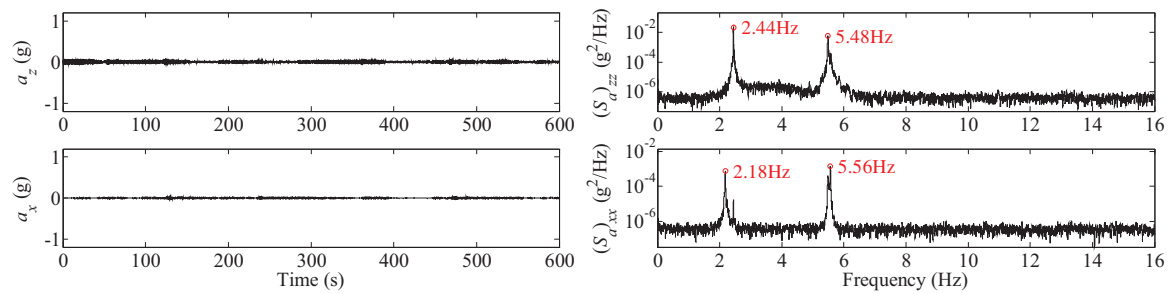


Figure 13 Acceleration time histories and the corresponding spectra: record 2

Figure 14 shows the cross correlation coefficients of the pressures at 5 taps along two axial lines along the cylinder over a time lag of 5 seconds. As expected, the pressures at the locations of the taps are the most correlated when the time lag is zero. The ripples at small time lags indicate the existence of the frequency band centered between 4 Hz and 5 Hz, which, as indicated by the spectra of the lift coefficient shown in Figure 12, is due to unorganized vortex shedding.

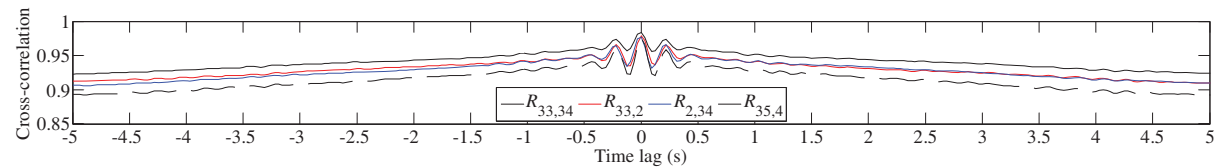


Figure 14 Cross-correlations of pressure measured along the axial direction of the cylinder: record 2

Figure 15 illustrate the distribution of the mean pressure coefficients for the duration of record 2. The angular position is measured clockwise relative to the would-be stagnation point if the cylinder were held stationary. An approximately symmetric pattern is again observed, indicating, on average, approximate symmetric separation of the flow from the upper and lower part of the cylinder during the duration of the record.

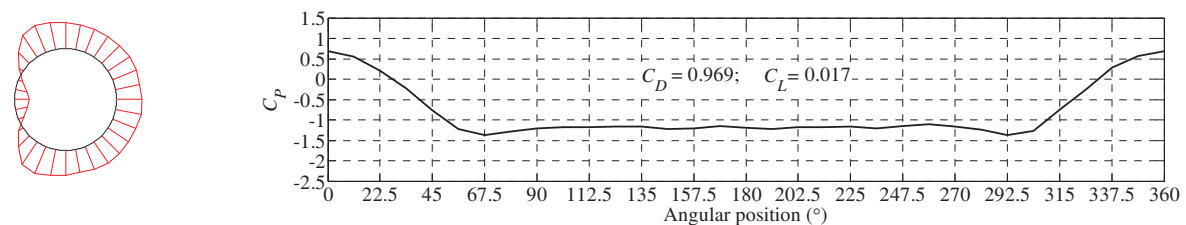


Figure 15 Mean pressure distribution at the pressure tap ring: record 2

According to Figure 5, the mean wind speed over the duration of record 3 is in the critical Reynolds number range. Figure 16 shows the drag and lift coefficients for this record and the corresponding spectra. The spectra of the coefficients show no sign of vortex-shedding, suggesting turbulent separation of the flow off the cylinder surface. Figure 17 shows the acceleration response of the cylinder. It can be seen that the vibrations in both the in-plane and out-of-plane directions are again dominated by the first two modes of the structure in these two directions.

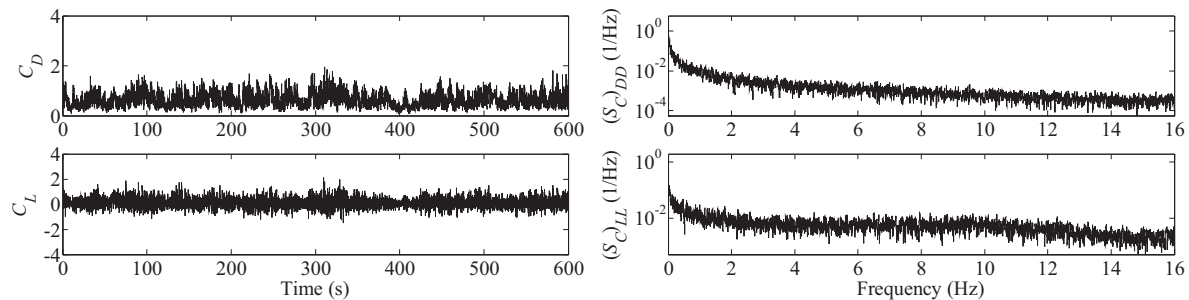


Figure 16 Drag and lift coefficients of the cylinder and the corresponding spectra: record 3

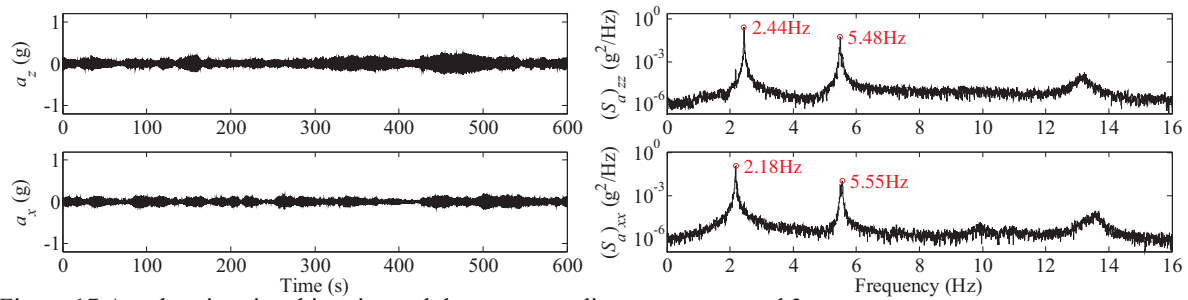


Figure 17 Acceleration time histories and the corresponding spectra: record 3

Figure 18 shows the cross-correlation correlations of the pressures at 5 taps along two axial lines of the cylinder over a time lag of 5 seconds. These are typical of the cross-correlations of correlated broadband processes.

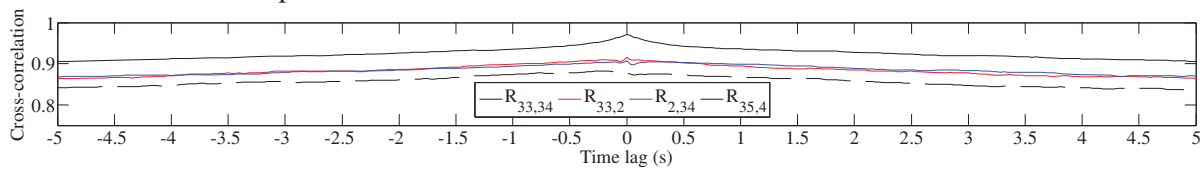


Figure 18 Cross-correlations of pressure measured along the axial direction of the cylinder: record 3

Figure 19 shows the distribution of the mean pressure coefficients for the duration of record 3. It is apparent that the mean pressures acting on the upper and lower parts of the cylinder are not symmetric. This indicates, on average, asymmetric separation of the flow from the oscillating cylinder in the critical Reynolds number range although the wind is approximately perpendicular to the cylinder axis.

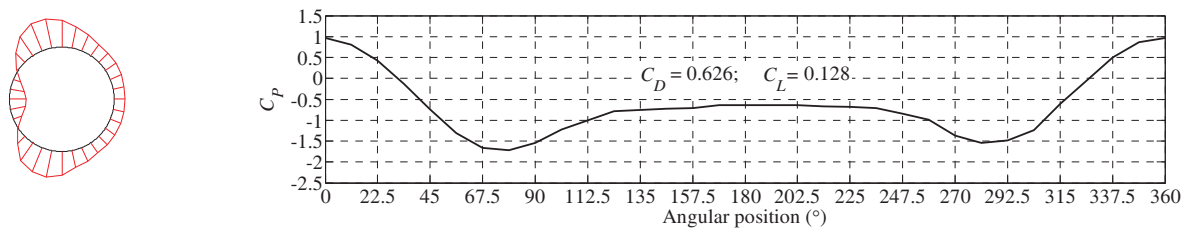


Figure 19 Mean pressure distribution at the pressure tap ring: record 3

The data show that the loading induced by wind oblique to the cylinder can have different characteristics from those of the loading by wind normal to the cylinder. As an illustration, Figure 20 shows the mean drag and lift coefficients against mean wind speed and the corresponding Reynolds number for a mean wind direction range of 55° to 65° relative to the cylinder. Both the force coefficients and the Reynolds number are computed based on the mean free-stream wind speed. The force coefficients show large scatter for low wind speeds. The reason for this scatter has not been positively identified and will be subjected to further investigation. The data does show, however, that the drag coefficient as a trend decrease consistently with wind speed when wind speed is higher than about 7.5 m/s, indicating that the critical Reynolds number range started at about this wind speed, which corresponds to a Reynolds number of 1.12×10^5 .

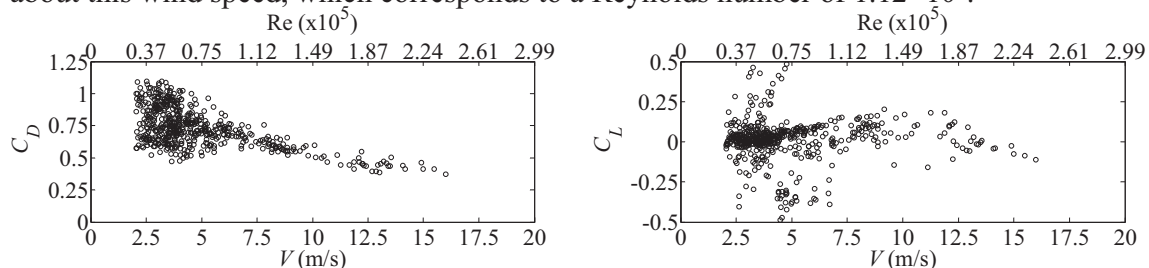


Figure 20 Mean drag and lift coefficients associated oblique to cylinder axis

In the following, a record with $V=11.27$ m/s, $\beta=64.5^\circ$ and $I_u=0.171$, which is designated record 4, will be used to illustrate the interaction between the cylinder and oblique wind approaching from this direction. Figure 21 shows the time histories and the spectra of the drag and lift coefficients at the pressure tap ring. The spectra indicate that, in this case, the separation of the flow is also turbulent without regular vortex shedding. Figure 22 shows the acceleration response of the cylinder at the pressure tap ring. It can be seen that the low-amplitude response is dominated by the two lowest modes of the structure in the in-plane and out-of-plane directions.

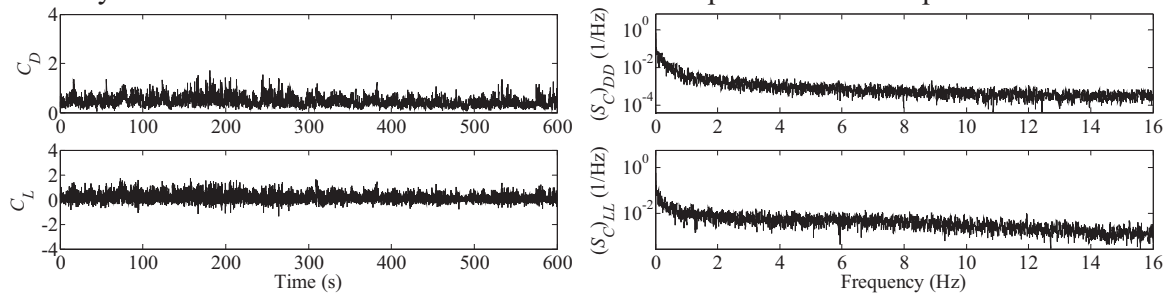


Figure 21 Drag and lift coefficients of the cylinder and the corresponding spectra: Record 4

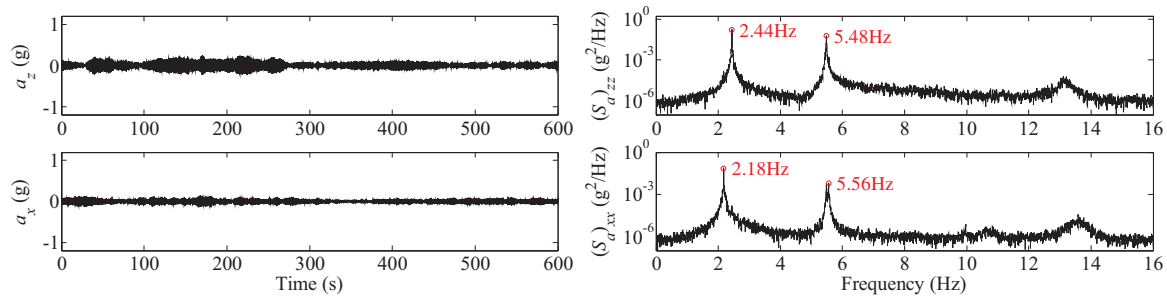


Figure 22 Acceleration time histories of and the corresponding spectra: record 4

Figure 23 shows the cross-correlation coefficients of the pressures at 5 taps along two axial lines of the cylinder over a time lag of 5 seconds. It is evident that the pressures at taps 33, 2 and 34 are the most correlated for zero time lag, indicating no apparent organized flow structure along these three taps. The figure also shows, however, that the maximum correlation between the pressures at taps 35 and 4 occurred for a time lag of ± 0.125 second. This indicates the potential existence of an axial flow component along this line.

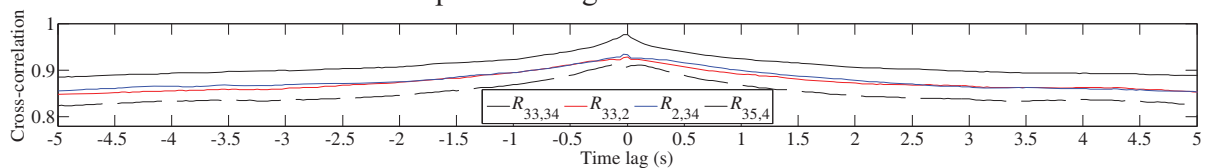


Figure 23 Cross-correlations of pressure measured along the axial direction of the cylinder: record 4

Figure 24 shows the distribution of the mean pressure for the duration of record 4. In this case, the mean pressures acting on the upper part and the lower part of the cylinder are not symmetric, indicating, on average, asymmetric separation of the flow from the oscillating circular cylinder when the oblique wind had mean wind speed in the critical Reynolds number range.

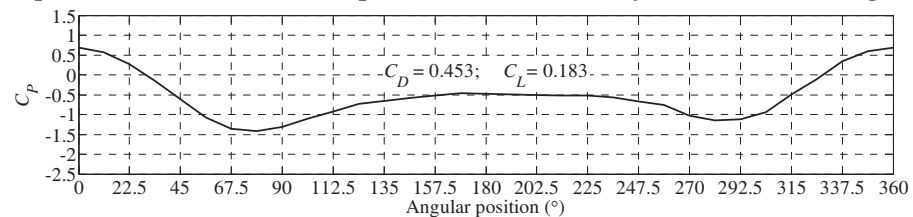
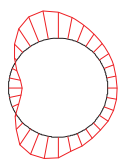


Figure 24 Mean pressure distribution at the pressure tap ring: record 4

5 CONCLUSIONS

A full-scale measurement campaign was conducted to study the dynamic interaction between wind and a circular cylinder. It is revealed that for wind both normal and oblique to the cylinder axis, the presence of turbulence in the free-stream wind shifts the transition from subcritical to critical Reynolds number range toward much lower Reynolds number than that at which the transition occurs in smooth flow. It was observed that when subjected to turbulent wind in the critical Reynolds number range, vortex-shedding does not occur and that in this Reynolds number range, the average flow separation lines on the upper and lower part of the circular cylinder surface are asymmetric about the horizontal plane through the centerline of the cylinder. The data also indicates the potential existence of an axial flow component in the wake of the cylinder when the wind is oblique to the cylinder axis.

6 ACKNOWLEDGEMENTS

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