Flow around twin rough cylinders at low wind incidence: bi-stability and gap flow

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SUMMARY
Wind tunnel experiments are performed on twin rough cylinders with a centre-to-centre spacing ratio L/D = 1.2 at two different Reynolds numbers, Re = 45k and 275k, corresponding to the sub- and post-critical flow regimes, respectively. The wind incidence is varied from 0° to 10°. A strong gap flow is observed for the largest incidences in both flow regimes and appears at the same wind incidence in the sub- or post-critical flow regimes. The frequency analysis of the lift forces reveals the existence of bi-stabilities before the appearance of the gap flow.

Keywords: Two cylinders, bi-stability, gap flow.

1. INTRODUCTION

Cylinder-like structures can be found in many engineering applications. Therefore, fluid flows around circular cylinder have been extensively studied in the past. Such flows occur in the case of heat exchangers, chimneys, power lines, buildings, offshore structures, struts, landing gears, cables, etc. A part of those applications corresponds to multiple-cylinder configurations. The particular case of two cylinders lying in a flow field was subjected to many studies throughout the years but most of them have been limited to the sub-critical flow regime, as pointed out by Sumner (2010). Because of the continuous increase of the dimensions of engineering structures, it is also necessary to extend the understanding of the flow around two cylinders to the post-critical flow regime. In this regime, the boundary layers, separated shear layers and eddies are all turbulent. The twin-tube tracks of the Hyperloop concept (Fig. 1) represent a particular illustration of a two-cylinder configuration in the post-critical flow regime. The present study investigates the unsteady flow around two closely spaced rough cylinders at small wind incidence in the sub- and post-critical flow regimes.

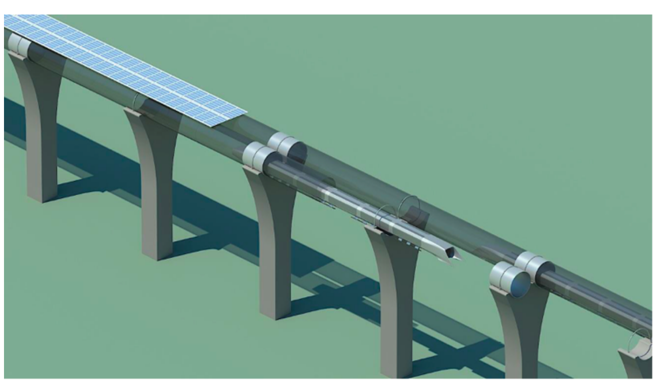

Figure 1. Twin-tube structure of the Hyperloop project (Hyperloop Alpha (2013)).

2. METHODOLOGY

The approach consists in an experimental test campaign on two static rough cylinders in the low-subsonic wind tunnel of the University of Liège. The experimental set-up is shown in Fig. 2 and is extensively described by Dubois and Andrianne (2022). Surface roughness are added to the cylinders in order to reach the post-critical flow regime at lower Reynolds numbers. The experiments are performed at two different Reynolds numbers, Re = 45k and 275k, which respectively correspond to the sub- and post-critical flow regimes. The wind incidence is accurately varied from 0° to 10° by using the turn-table of the wind tunnel. In this study, the cylinders are closely spaced: $L/D = 1.2$. L is the centre-to-centre distance between the cylinders and D is the external diameter. Pressure measurements are performed on each cylinder at 48 taps linearly distributed at mid-span with a sampling frequency of 600 Hz. The flow is characterised by a low level of turbulence (<0.2%).

Figure 2. Experimental set-up installed in the wind tunnel of the University of Liège.

3. LIFT FORCE COEFFICIENTS

Fig. 3(a-b) shows the variation of the time-averaged lift coefficient of each cylinder with the wind incidence in the sub- and post-critical flow regimes. Sub-figures (c-f) also show the *Power Spectral* Density (*PSD*) of the fluctuating lift signal of each cylinder as a function of the wind incidence in both flow regimes. The fluctuating lift signals are initially normalised by their respective standard deviation to allow the comparison of the frequency content at different wind incidences. The dimensionless Strouhal number $St=f\,D/U$ is used as the frequency variable. It takes values in the range $0 < St < 1$ in the present analysis. The superimposed black lines with different markers correspond to the different non-harmonic peaks observed in the spectra. Within the tested range of wind incidences, three different flow behaviours can be identified in the sub- or post-critical flow regime.

The first behaviour is observed at low wind incidences (α = 0° - 2°). In both flow regimes, the time-averaged lift coefficient of each cylinder remains close to zero, as shown in Fig. 3(a-b). It reveals that the flow around the twin-cylinder configuration is rather symmetric. Nevertheless, it can be observed that the lift coefficient of the front cylinder becomes slightly negative while the one of the rear cylinder becomes positive when increasing the wind incidence. The two flow regimes differ in the frequency contents of the lift signals. In the sub-critical flow regime, a strong peak is observed at $St \approx 0.14$. A second and weaker peak is also identified as an harmonic frequency of the fundamental one, $St \approx 0.28$ (see Fig. 3(c-d)). This observation was done by Dubois and Andrianne (2022) in the tandem configuration of cylinders (α = 0°). The presence of harmonic components was inferred to the alternate re-attachment of the separated shear layers from the front cylinder onto the rear cylinder, as shown by Alam et al. (2003). In the post-critical flow regime, the frequency contents also reveal two peaks. However, those peaks are not identified at harmonic frequencies. This observation was done for the tandem configuration. Dubois and Andrianne (2022) concluded that it corresponds to a bi-stability due to the intermittent re-attachment of the separated shear layers from the front cylinder onto the rear cylinder.

A second behaviour is observed at intermediate wind incidences (α = 4° - 6°). Similarly to the low wind incidences, the lift coefficient of each cylinder remains small in both flow regimes. When increasing the wind incidence angle, the lift coefficient of the front cylinder slightly decreases and the one of the rear cylinder slightly increases. In the sub-critical flow regime, two peaks are still observed in the spectra of the lift signals (see Fig. 3(c-d)). Unlike the previous range of wind incidences, the peaks are identified at non-harmonic frequencies (*St* ≈ 0.14 and 0.25). It is therefore assumed that they do emanate from two distinct processes. A bi-stability between two flow patterns takes place, leading to two different Strouhal numbers. The lowest identified Strouhal number increases when the wind incidence angle is increased from 4° to 6° while the other Strouhal number decreases. In the post-critical flow regime, a single peak is observed in the spectra at St ≈ 0.24 (Fig. 3(e-f)). This peak corresponds to the highest Strouhal number identified in the previous sub-range of wind incidence angles. Thus, it is stated that only the eddy shedding process related to this Strouhal number is present in this configuration.

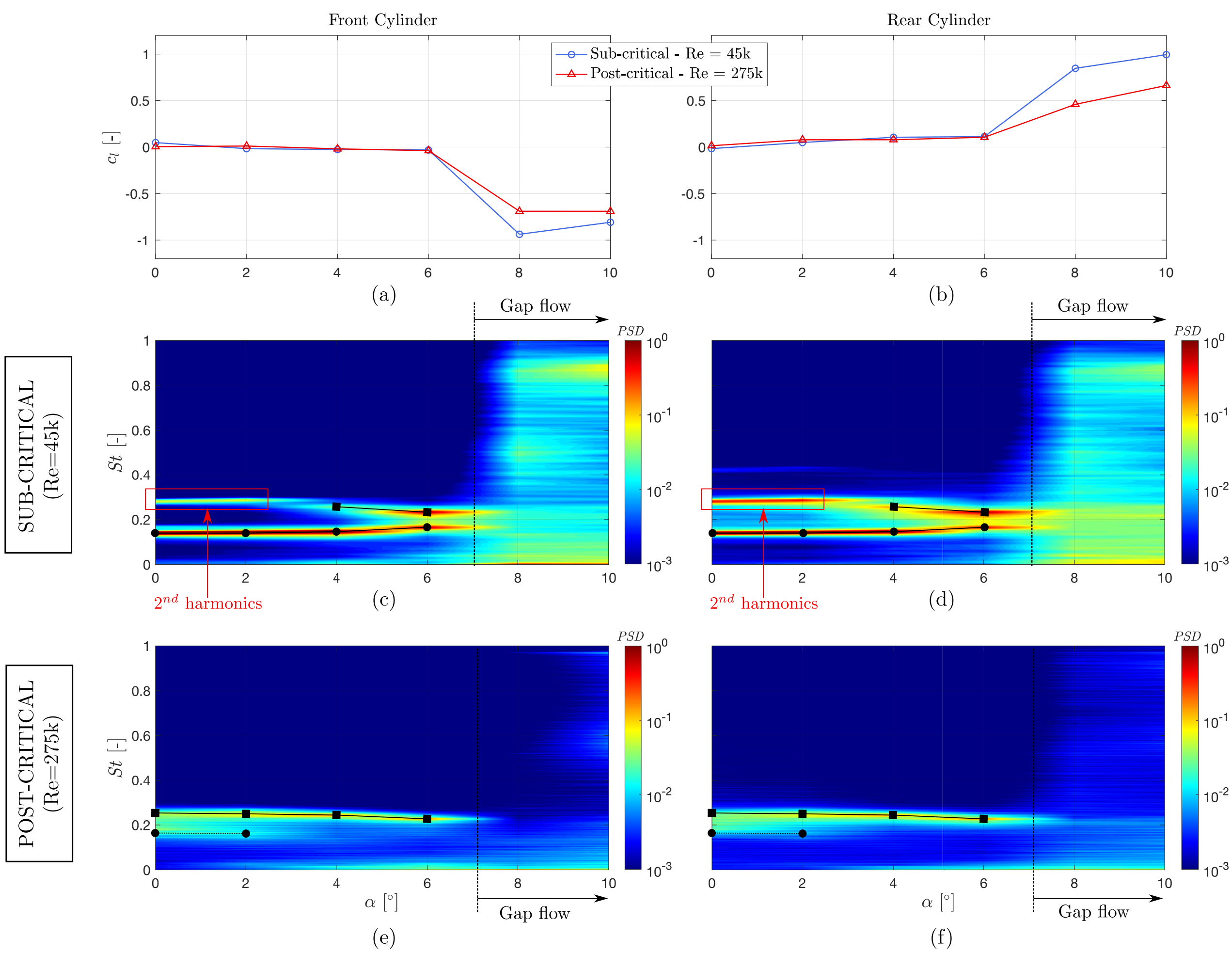

Figure 3. Variation of the time-averaged value and frequency content of the lift coefficient of each cylinder with the wind incidence in the sub- and post-critical flow regimes.

A third behaviour is observed at higher wind incidences (α = 8° - 10°). The time-averaged lift coefficients of the front and rear cylinders take large negative and positive values, respectively. The appearance of these large lift forces has already been observed in previous studies in the sub-critical flow regime (Zdravkovich (1987), among others) and is referred to the "inner" lift force. Those large lift forces are induced by a strong gap flow between the two cylinders. The gap flow occurs in the sub- and post-critical flow regime, as observed in Fig. 3(a-b). Based on the absolute values of the lift coefficients, it can be stated that the gap flow is stronger in the sub- than in the post-critical flow regime. The exact wind incidence angle at which the gap flow appears cannot be identified but it is expected between α = 6° and 8° for both flow regimes. Concerning the frequency content of the lift signals, it is observed that it is broadband within this range of wind incidences (see Fig. 3(c-f)). In both flow regimes, the occurrence of the broadband spectra coincides with the presence of a strong gap flow. Based on this observation, it can be stated that the gap flow strongly impacts the eddy shedding process behind the twin-cylinder configuration.

4. CONCLUSIONS & FURTHER WORK

Pressure measurements are performed on static twin rough cylinders in the sub- and post-critical flow regimes. The analysis of the variation of the time-averaged force coefficients highlights the appearance of a strong gap flow at a particular wind incidence. The latter is the same in the post-critical flow regime than in the sub-critical flow regime. Then, the analysis of the frequency contents of the lift force shows the presence of bi-stabilities at particular wind incidences: two peaks at non-harmonic frequencies appear in the spectra. It is assumed that two flow patterns co-exist in these particular cases. When the strong gap flow occurs, the frequency content becomes broadband.

The analysis of the present results will be completed by a thorough investigation of the pressure distributions in order to extract the different flow patterns around the cylinders.

This work is performed in the scope of the analysis of the wind effects on large twin cylinders with a focus on post-critical flow regime.

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