

# Experimental Study of Frequency Behavior for a Circular Cylinder behind an Airfoil

S. Bajalan, A. Shadaram, N. Hedayat, A. Shams Taleghani

**Abstract**—The interaction between wakes of bluff body and airfoil have profound influences on system performance in many industrial applications, e.g., turbo-machinery and cooling fan. The present work investigates the effect of configuration include; airfoil's angle of attack, transverse and inline spacing of the models, on frequency behavior of the cylinder's near-wake. The experiments carried on under subcritical flow regime, using the hot-wire anemometry (HWA). The relationship between the Strouhal numbers and arrangements provide an insight into the global physical processes of wake interaction and vortex shedding.

**Keywords**—Airfoil, Cylinder, Strouhal, Wake interaction

## I. INTRODUCTION

**A**ERODYNAMIC interference between two closely separated structures give rise to flow separation, reattachment, vortex shedding, recirculation and quasi-periodic vortices. In this situation, interactions between the shear layers, wakes, and Karman vortex shedding of the structures have profound influences on system performance. Several practical configurations of Slender and bluff bodies can be found in groups with close proximity, for example turbo machineries, cooling systems, offshore structures and screens, in both air and water flow. Since, wake flows at a sufficiently large Reynolds number give rise to periodic shedding of vortices in the familiar von Karman Vortex Street; an important subject of research about near-wake is unsteady flow in this region. a dominant frequency of alternating vortices formation, usually expressed in terms of the dimensionless Strouhal number  $S=fL/U_\infty$ , where  $f$  is the shedding frequency,  $L$  is the cross-stream length scale of the body and  $U_\infty$  is the free-stream velocity. This unsteady flow and periodicity may cause structural vibrations, acoustic noise, or resonance. An example application in which frequency behavior has direct engineering significance is the profile of a rotor-stator in cooling fans which the periodicity associated with wakes is

undesirable. Combination of a circular cylinder behind an airfoil provides a good model to understand the physics of flow around such configuration. The most topics available in the literature concern the wake interaction of two or more cylinders for different configurations. Effects of complex interactions have been compiled in articles by Zdravkovich [1, 2, 3, and 4]. Akosile & Summer [5] measured experimentally the vortex shedding frequencies for staggered two circular cylinders. They found that the behavior of the Strouhal number data depended on whether the cylinders were closely, moderately, or widely spaced. Also, an airfoil in the wake of a circular cylinder receives attention since a slender body stabilizes the unsteady forces acting on the upstream bluff body [4, 6]. But, the configuration consisting of a fixed airfoil and a downstream circular cylinder, despite its practical importance, except for a few cases, has been subjected to only a limited number of studies. Zhang and Zhou[7] studied experimentally the aerodynamic characteristics of a circular cylinder in the presence of an upstream cambered airfoil. They studied the effect of spacing on critical Reynolds number for an airfoil and unsteady forces. A numerical study by Zhou et al. [8] produces results in accordance with the experimental studies. Yildirim and co-workers [9] obtained time dependent flow fields of near wake around this configuration via Digital Particle Image Velocimetry. Basic parameters of this investigation were the angle of attack of the airfoil and the vertical distance between the airfoil and the cylinder. The remarkable point is that most of above mentioned approaches have been made via experimental methods and conducted in low-turbulence flow in the subcritical flow regime, with  $Re < 10^5$ .

So, a detailed investigation of wake development downstream a cylinder behind an airfoil by means of an experimental method has many important practical applications. This work aims to experimentally study the effect of airfoil's angle of attack and inline and transverse position of cylinder on the aerodynamic interaction and vortex generation mechanism based on frequency behavior. The interacting flow has been investigated via Hot-Wire Anemometry (HWA). The objectives are to present a detailed investigation of Strouhal numbers, flow structures and interaction mechanism of wakes under low turbulence, subcritical flow conditions. The relationship between the Strouhal numbers and arrangements has been showed. The

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ensemble results provide an insight into the global physical processes of wake interaction and vortex shedding.

## II. EXPERIMENTAL SETUP

The experiment was carried out in a low-speed open-circuit wind tunnel. The test section was 300 mm x 300 mm cross-section and 600 mm length. Measurements were carried out by constant temperature anemometry (CTA) using 2-D wire probe model 55P62 from Dantec Co to study the velocity fluctuations. The probe was mounted on a traversing mechanism that facilitated two orthogonal movements. The signals from the hot wire anemometer were recorded at a sampling frequency of 1 kHz. The fluctuating velocity characteristics were obtained using about 12000 samples. A schematic diagram of the experimental setup is shown in Fig. 1. The airfoil was a NACA 4412 with a chord length  $c=100$  mm and the diameter of cylinder was  $D=14$  mm and the corresponding  $D/C$  were 0.14. According to fig. 1, the cylinder was installed behind the airfoil at a cross-stream offset of  $T$ , and inline space of  $L$ .  $T=0$  being the chord line at zero angle of attack and  $L$  is the distance between the trailing edge of the upstream airfoil and center of the downstream cylinder. Five values of  $T/D = 0, \pm d, \pm 2d$  at  $L/D=1.5$  (fixed) and three values  $L/D=1.5, 3.5$  and  $5.5$  at  $T/D=0$  (fixed) were investigated by employing three different angles of attack. The effect of the angle of attack has been studied for three cases,  $\alpha=0^\circ, 5^\circ$  and  $10^\circ$ . The axis of airfoil's rotation is located at  $0.25C$  from the leading edge of the airfoil, where the thickness of the airfoil reaches its maximum. The turbulent intensity was present work is 1.1% at this free-stream velocity and the maximum blockage ratio was 5.7%.

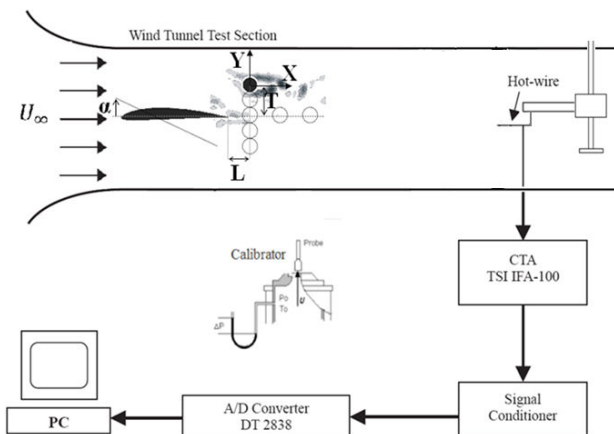


Fig. 1 Typically experimental setup

## III. RESULTS

The Fourier transform produces averaged spectral coefficients that are useful to identify dominant frequencies in a signal. In this study, the Strouhal number of each case is defined by the frequency with the largest power of streamwise velocity.

### A. Validation

For verification, the Strouhal number of the single cylinder and the airfoil are measured and compared with the previous studies. Also these measurements are useful for the subsequent studies of interaction between cylinder and airfoil. Fig. 2 shows the power spectral function of streamwise velocity for the single cylinder and the 2D section of NACA4412 at different angles of attack for  $x/d=1.5$  downstream of the models. Note that the normalization of frequencies based on  $D$  is for the convenience of comparison only.

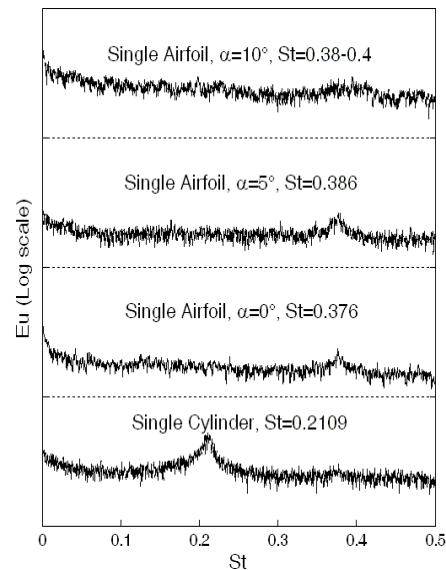


Fig. 2 Power spectral function of streamwise velocity,  $E_u$  measured for single cylinder and single airfoil with  $\alpha=0^\circ, 5^\circ$ , and  $10^\circ$  at  $X/D=1.5$  and  $Y/D=1$

The power spectrum diagrams display pronounced sharp peaks at the Strouhal numbers of 0.2109, 0.376 and 0.386 respectively for the single cylinder and single airfoil at  $\alpha=0^\circ$  and  $5^\circ$  (fig. 2). As  $\alpha$  increase, further vortices shed forming the vortex street and the size of vortices appears smaller. However, the vortex street is qualitatively unchanged, but the separation point moves upwards from the trailing edge as  $\alpha$  increases and separation region becomes larger. Therefore, increasing  $\alpha$ , the band width increases and the sharp peak at  $\alpha=10^\circ$  is barely identifiable. Since, the angle of stall for such low Reynolds number ( $Re_c \approx 5 \times 10^4$ ) is as small as  $7.5^\circ$  [10], so the enlargement of the separation region on the upper surface of the airfoil is a good justification for  $\alpha=10^\circ$ . But a broad band peaks occur near the normalized frequency between 0.38 and 0.4. These results are in accordance with the other references [7, 8, and 11].

### B. Dependence of $St$ on $L/D$

Fig 3 shows the power spectrum diagrams for different  $L/D$  values with  $\alpha=0^\circ$  at  $X/D=1.5$  and  $Y/D=1$ .

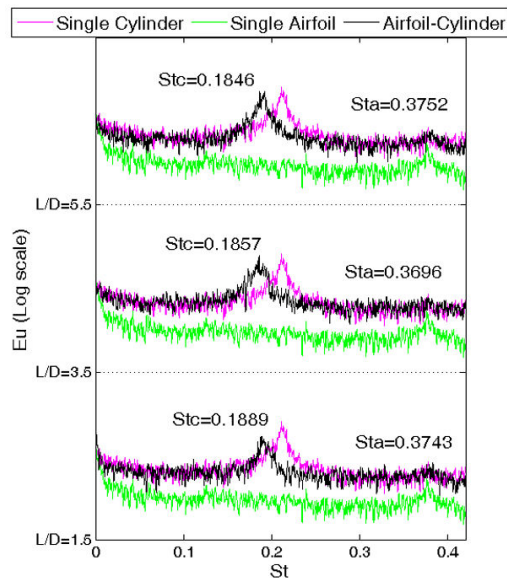


Fig. 3 Power spectral function of streamwise velocity,  $Eu$ , measured at various inline location of cylinder behind at  $X/D=1.5$  and  $Y/D=1$  with  $\alpha=0^\circ$

For  $L/D=1.5$ , there are two evident Strouhal numbers with discontinues changes respect to Spacing ratio (Fig. 7). Separated free shear layers from the airfoil reattach on to the surface of the cylinder. But, from the existing power spectrum results, it is not clear whether the two frequencies,  $St_a$  and  $St_c$ , co-exist or emerge individually. The gap flow is unknown and vortices may form in the gap between the models. This mechanism is known as Critical pattern (CP).  $St_c$  is smaller than  $St$  of isolated single cylinder and that's due to exposing cylinder in the upper separation region of airfoil. For larger spacing, shear layer reattachment on the cylinder can no longer be maintained. For  $L/D=3.5$  and  $5.5$ , the shedding pattern is Co-shedding (CSP) and vortex shed street of the airfoil forms in the gap and impinges on the cylinder, the wake width of the cylinder increase and velocity deficit effect and frequent shedding decrease. The  $St_c$  is less than  $St$  of the single cylinder for all  $L/D$  measured. As the Spacing ratio reaches  $L/D=5.5$ , the cylinder is now sufficiently far removed and the near-wake region of the upstream cylinder form less restricted, more similar to a single, isolated airfoil. The power spectral functions of streamwise velocity in the near-wake of the cylinder obtained for different inline positions of the cylinder for  $\alpha=5^\circ$ , are presented in Fig 4.

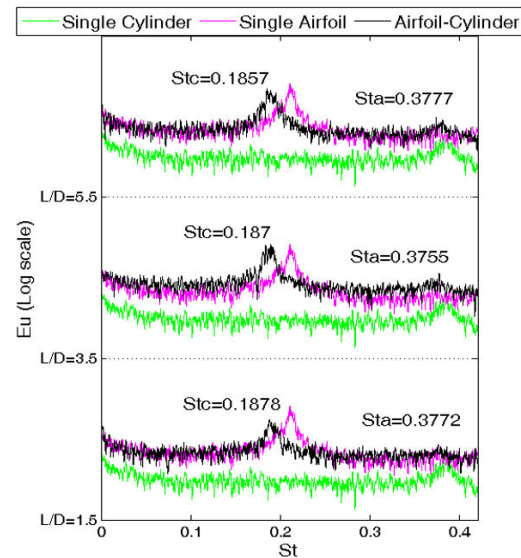


Fig. 4 Power spectral function of streamwise velocity,  $Eu$ , measured at various inline location of cylinder behind at  $X/D=1.5$  and  $Y/D=1$  with  $\alpha=5^\circ$

For  $L/D=1.5$ , at slightly greater angles of incidence, shear layer reattachment can no longer be Maintained and the vortices arising from the upper surface of the airfoil penetrates to the gap. In its place, a small near-wake region forms behind the upstream cylinder; this small region is highly constrained within the gap.  $St_c$  and  $St_a$  have identical changes; in the other hand, Variation of  $St_c$  relative to  $St_a$  is opposite the other cases. This pattern is named Critical Pattern (CP). At  $L/D=3.5$  and  $5.5$ , the peak of the airfoil shedding frequency in the spectra is more distinct. Restricted wake region of the airfoil and interaction of Vortex Street with the downstream cylinder cause the wider airfoil's wake and lower  $St_a$  than the Strouhal number of a single Airfoil.

Two evident Strouhal numbers are essentially identical for all  $L/D$  values (CSP). The upstream shear layer of the airfoil impinges onto the both sides of the cylinder and due to large size of separation region or dead fluid zone, this effect endures long distance. But strongly interact and induced separation of gap flow increase the models wakes widths.

Fig 5 shows the power spectrum diagrams for different  $L/D$  values for  $\alpha=10^\circ$ .

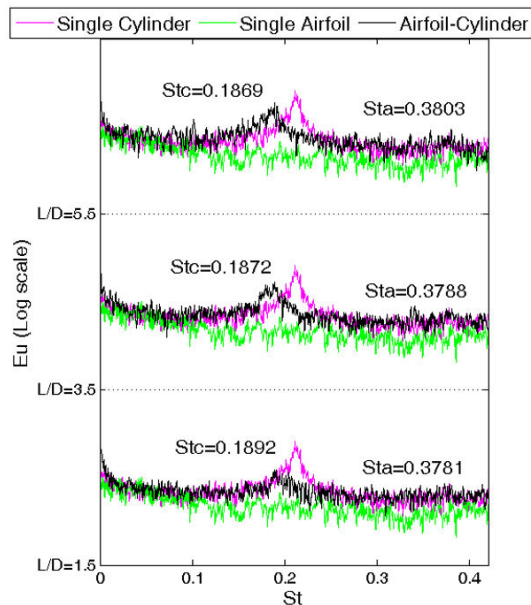


Fig. 5 Power spectral function of streamwise velocity,  $Eu$ , measured at various inline location of cylinder behind at  $X/D=1.5$  and  $Y/D=1$  with  $\alpha=10^\circ$

#### C. Dependence of $St$ on $L/D$ and $\alpha$

Fig 6 and 7 show the dependence of  $St_c$  and  $St_a$  on  $L/D$  and  $\alpha$ .

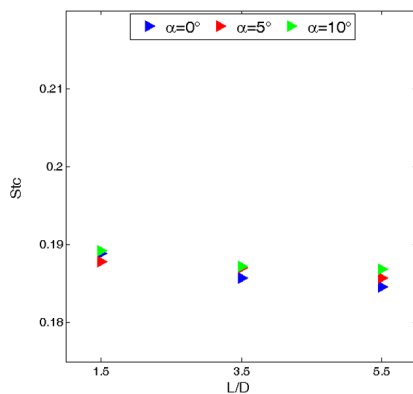


Fig. 6 Dependence of  $St_c$  on  $L/D$  and  $\alpha$

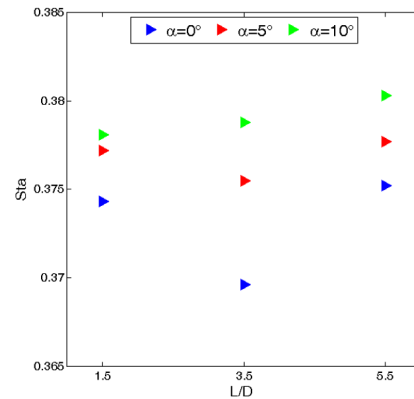


Fig. 7 Dependence of  $St_a$  on  $L/D$  and  $\alpha$

As seen in the fig. 6 and 7, the frequency of vortex shedding from the cylinder ( $St_c$ ) treats in reversed manner respect to the airfoil's frequency ( $St_a$ ), probably because the downstream cylinder acts to slow down the flow around the airfoil. On the other hand, the dimensionless frequency,  $St_c$ , of vortex shedding from the cylinder increases due to an increase in the incident flow velocity to this cylinder. With increasing  $T/D$ ,  $St_c$  increase and  $St_a$  decreases (Other than configuration associated with critical geometry). Increasing  $T/D$ , the dimensionless frequency,  $St_a$ , of vortex shedding from the airfoil declines progressively, and  $St_c$  increase (Other than configuration associated with critical geometry). Increase of the interaction effect and the overspread of the cylinder wake width is the reason of this behavior. Increasing  $L/D$ , the dimensionless frequency of vortex shedding from the airfoil,  $St_a$ , increase progressively, and  $St_c$  decrease (Other than discontinues changes due to transition). The reason is that increasing  $\alpha$ , velocity deficit implying on the downstream cylinder withstand farther. As shown in Fig 12, for  $\alpha=0^\circ$  and  $5^\circ$  at  $L/D=3.5$ , an abrupt change in  $St_a$  and  $St_c$  occurs; due to the transition to co-shedding pattern. Increasing angle of attack,  $St_c$  increase and  $St_a$  decrease. It's due to enlargement of the separation zone and elongation of formation region.

#### IV. CONCLUSION

The downstream cylinder interferes with the wake dynamics and vortex formation region of the upstream airfoil. The two models may behave as a single body or as two independent bodies, depending on the spacing between them. Generally, three distinct flow patterns govern the interaction mechanism. They are: (1) Extended-Body Pattern for small spacing ratios; (2) Critical pattern for intermediate spacing and, (3) Co-Shedding Pattern or free oscillations of shear layers at large spacing ratios. Pattern change between the Critical and the others is associated with abrupt change of Strouhal values. It was observed that the inline position of the cylinder in the near-wake of the airfoil, affects  $St_a$  more than  $St_c$ . Also,  $St_c$  and  $St_a$  vary contrary toward change of spacing ratios. For smaller  $\alpha$  velocity deficit implying on the

downstream cylinder is higher but for higher  $\alpha$ , this recovery rate withstand farther.

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