M. Bussiere, D. Nobes, and C. R. Koch. The oscillatory behavior of a symmetric airfoil hinged at its aerodynamic centre in the wake of a circular cylinder. In *23rd Canadian Congress of Applied Mechanics*, page 5, June 2011. CANCAM 2011

Proceedings of the 23rd CANCAM

THE OSCILLATORY BEHAVIOR OF A SYMMETRIC AIRFOIL HINGED AT ITS AERODYNAMIC CENTRE IN THE WAKE OF A CIRCULAR CYLINDER

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ABSTRACT

A NACA 0012 airfoil free to rotate about its aerodynamic center is placed in the wake of a circular cylinder. The cylinder produces a periodic pattern of swirling vortices which cause pressure fluctuations across the airfoil and ultimately cause it to oscillate in a sustained periodic manner. This oscillatory behavior is characterized by the oscillation amplitude and frequency as well as the amplitude and frequency of pressure fluctuations measured on either side of the airfoil. How these characteristics vary with distance along the center of the cylinder wake is described.

INTRODUCTION

Wind turbines are usually clustered together on large sections of land referred to as wind farms or wind power plants. A major challenge in wind farm planning is to make the most effective use of the available land. There are many economic advantages in spacing the wind turbines close together; however, in order to maintain a maximum power output from all wind turbines, a precise turbine spacing scheme is required. This spacing scheme is a function of the wind shear, the turbulence in the wind, the turbulence added by the turbines, and the terrain [1]. It could be advantageous to manipulate the flow by suppressing wake vortices from other wind turbines and hence reduce the required space between wind turbines. The ability to manipulate the natural unsteadiness in the wind could be of practical significance to researchers in the field of wind energy harvesting.

This paper is a preliminary step to investigate methods of oscillation control in flow systems and will describe the oscillatory behavior of a symmetric airfoil hinged at its aerodynamic centre when placed in the wake of a circular cylinder. The results obtained from these experiments will later be used as a basis for future work to develop active control strategies where the hinged wing is actuated by applying a torque about its centre of rotation. The goal of this system will be to either enhance or suppress large scale oscillations in the flow through active closed-loop control.

BACKGROUND

A large scale oscillatory motion can be generated in a laboratory situation by positioning the systems to be studied in the wake of a cylinder. The flow over a circular cylinder is a well documented phenomenon and when the fluid flows past the cylinder with a significant Reynolds number (Re > 40), a distinctive pattern of alternating vortices appear in the wake of the cylinder. This flow field is commonly described as the von Karman vortex street [2] and can be described by the dimensionless Strouhal number defined as:

$$\mathrm{St} = \frac{fd}{V} \tag{1}$$

Here, f is the frequency of vortex shedding, d is the diameter of the cylinder and V is the free stream velocity of fluid passing over the cylinder. For a large range of Reynolds numbers the Strouhal number over a cylinder may be approximated with the following empirical relation [3]:

$$\mathrm{St} = 0.198\left(1 - \frac{19.7}{\mathrm{Re}}\right) \tag{2}$$

This periodic shedding of eddies results in an alternating lift force on the cylindrical structure. If the structure's resonant frequency coincides with the shedding frequency of the vortex street, appreciable vibrations may result [4]. A design solution to suppress vortex shedding consists of a longitudinal rigid splitter plate attached to the trailing edge of the cylinder/structure. Assuming the plate is sufficiently long compared to the cylinder diameter, it is possible to suppress the vortex induced vibrations to safe amplitudes and prevent damage to the structure [5]. Several studies related to the suppression of the von Karman vortex street have taken place. These include the effects of rigid splitter plates on the wake of a circular cylinder [6] both experimentally [5] and numerically [7]. In both cases, communication between the two shear layers of a von Karman vortex street is completely inhibited.

An interesting extension to the rigid splitter plate problem is the use of a hinged splitter plate in the wake of the cylinder. In contrast to the rigid splitter plate scenario, a hinged splitter plate only partially inhibits communication between the two shear layers, thus allowing for some level of interaction between the two vortex sheets. Experimental investigation of a splitter plate hinged at the leading edge showed that the main non-dimensional parameters of importance are the splitter plate length to cylinder diameter ratio, and Re [8]. Other non-dimensional parameters related to the mass and the stiffness of the splitter plate, as well as the internal structural damping of the hinge are assumed to be small and consequently have little effect on the final results. In that study they were able to show that the splitter plate length to cylinder diameter ratio (*L/D*) is crucial in determining the character and magnitude of the splitter plate oscillations. Also, the splitter plate amplitude increases with Reynolds number at low values of Re, but they seem to reach a saturation amplitude level at higher Re [8].

An active flow control concept has been attempted to reposition and alter the strength of vortices shed from an upstream cylinder by appropriately adjusting the phase of an oscillating airfoil positioned in the wake of the cylinder [9]. In this study, open-loop control is used and consequently accurate knowledge of the fluid mechanics of the flow regime is required. It follows that employing an active closed-loop control method to the airfoil would be a compelling addition. This may allow for similar vortex manipulation that isn't limited to the wake conditions generated by a cylinder of fixed diameter. A successful closed-loop control method may lead to the cylinder being replaced by a rotating ellipse which could produce a more complicated non-periodic wake.

EXPERIMENTAL SETUP

The experimental facility consisted of a 0.7x0.4 m (27.5"x16") water channel with low turbulence characteristics [10]. A vertically aligned cylinder was positioned perpendicular to the flow direction on the channel centerline and produced periodic unsteady flow conditions in its wake. Both the cylinder diameter and the free stream velocity can be adjusted to produce a wide range of wake conditions. An airfoil system comprising primarily of a NACA 0012 symmetric extruded aluminum airfoil hinged at the aerodynamic centre was placed in the cylinder wake at known location. The airfoil suspended vertically such that it hangs down into the water channel, perpendicular to the upstream flow direction. A schematic of the flow configuration is shown in Fig.1.

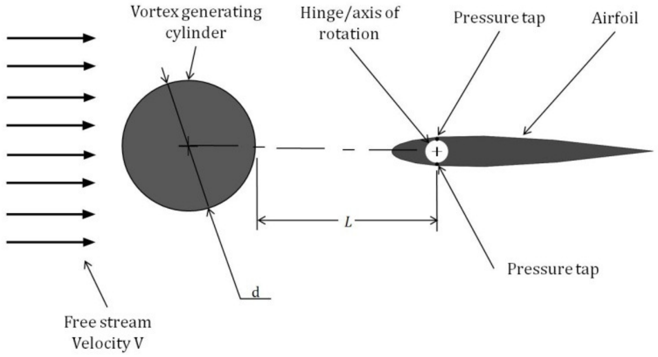

Fig.1: Actuator rotor schematic

Stereo particle image velocimetry (Stereo-PIV) is used to visualize and quantify the flow. The experimental Stereo-PIV setup is illustrated in Fig.2 and consists of two 1376 x 1040 pixels, 12 bit duel-frame CCD cameras (FlowMaster, LaVision) viewing in stereo the region-of-interest. An acrylic sheet was place on the flow surface to remove surface refraction effects. A double-pulse Nd:YAG laser (Solo III-15z, New Wave) illuminated the flow which is seeded with 20μm hollow glass spheres (Sphericel, Potters Industries). The imaging system is placed on a 3D traverse allowing controlled manipulation of the region-of-interest. Images were processed through to velocity vectors using commercial software (DaVis 7.4, LaVision). The experimental setup is illustrated in Fig.2.

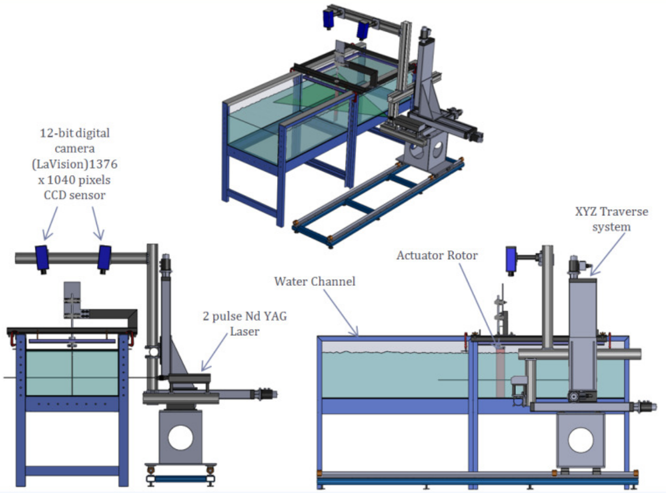

Fig. 2: Orthogonal and isometric view of the working section of the re-circulating water channel with the Stereo-PIV experimental setup

A von Karman vortex street was generated with a d = 80mm diameter smooth cylinder oriented perpendicular to a uniform flow of V = 0.3 m/s. The Reynolds number and Strouhal number are 24,000 and 0.198 respectfully. This particular flow regime ($300 > Re > 3\times10^5$) is referred to as a subcritical regime for flow over a smooth cylinder in steady flow and is characterized by a completely turbulent wake with laminar boundary layer separation [11].

The motion of the aerofoil is characterized using an optical encoder (IH740, W&S Measuring Syst. Ltd.). This data is collected synchronously with pressure information used to characterize the large scale motion in the flow. The differential pressure between two pressure taps located on either side of the airfoil in line with the aerodynamic centre and situated 100 mm beneath the free surface is measured using a differential pressure transducer (IXLdp, Archsoft). All signals are logged to a PC at 200Hz for 240 seconds at a time through a DAQ system (DS1103 PPS controller board, Dspace).

The airfoil system was placed in the wake of the cylinder and data was collected for several positions along the center of the wake. In addition, at every position, data was gathered for both the rigid hinge and free hinge condition. The rigid hinge condition approaches the rigid splitter plate study in [5] and, given the inertia of the rotor assembly, the free hinge scenario lies somewhere between the hinged splitter plate study in [8] and the rigid splitter plate study in [5].

RESULTS

The wake characteristics of the cylinder in a 2D plane sufficiently far from the free surface (100 mm) are examined and compared to theoretical values for flow over a circular cylinder as described by von Karman vortex street theory. A two dimensional velocity vector map of the wake behind a cylinder in a free stream velocity of 1.5 cm/s whose diameter is 12 mm is shown in Fig.3. The trailing edge of the cylinder is located at the top boundary of Fig.3 and the flow is from top to bottom. The white arrows represent the vector difference between the actual velocity and the free stream velocity. This gives rise to a moving reference frame traveling at the same velocity as the undisturbed free stream fluid. The vortices are accentuated by calculating and plotting the swirling strength in the background color map. The distinctive pattern of alternating vortices as predicted by the von Karman vortex street is clearly observed in the figure. The vortices travel downstream at an average velocity of 125 mm/s. This value is obtained by measuring the average distance a vortex will travel within a known time interval (100 images similar to Fig.3 were averaged). Also, the vortices in a similar row are separated on average by 57 mm. The ratio of these two numbers gives a shedding frequency of $f = 0.219$ Hz. Based on equations 1 and 2 and with a Reynolds number of 180, the theoretical shedding frequency is 0.220 Hz. This flow regime (40 > Re > 200) is characterize by a laminar vortex street making it possible to clearly distinguish and locate the centers of the vortices.

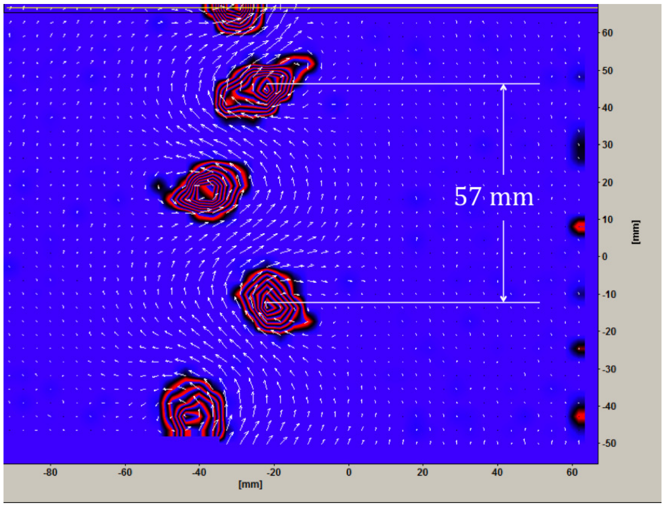

Fig. 3: Velocity vector map with swirling strength

The effect of the large scale motion on the airfoil system was investigated for 8 positions along the centre of the wake. The downstream distance separating the trailing edge of the cylinder and the aerodynamic centre of the airfoil (separation distance) is expressed in dimensionless cylinder diameters *(L/d).* An example time series for the angular position and the differential pressure experienced by the airfoil is shown in Fig.4. Here, the airfoil is free to oscillate and the separation distance is 0.55 *L/d*. The pressure signal leads the position signal and closely replicates variations in position amplitude.

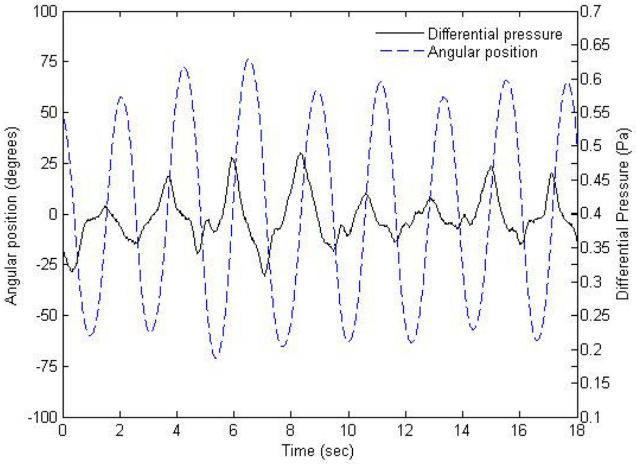

Fig. 4: Time series of the angular position and differential pressure experienced for the free hinge condition.

The effect of separation distance is shown in Figures 5 and 6 where the average frequency and amplitude for both angular position and pressure are plotted. Fig.5 illustrates the relationship between the airfoil's average oscillation amplitude and its distance downstream of the cylinder for the free hinge condition. The downward trend seen in the figure is anticipated since vortex intensity is expected to decay as the vortices travel away from the cylinder airfoil [12]. Fig.6 illustrates the relationship between the average differential pressure amplitude and the distance downstream of the cylinder for both the free hinge and fixed conditions. For the free hinge there appears to be a slight increase from 0.5 to 0.6 *L/d* it then continues along a distinct downward trend up to 0.85 *L/d*. Pressure fluctuations in the free hinge scenario are not only a result of the vortices traveling past the airfoil, but also of the airfoil changing orientation and consequently altering the way in which the pressure taps are aligned to the flow. The oscillating airfoil therefore presents a more complicated relationship with separation distance and further investigation is required. In contrast, for the fixed hinge case the peak-to-peak amplitude has a slight increase with downstream distance. This is believed to be a result of the fixed airfoil acting as a rigid splitter plate and effectively repressing the vortex intensity. As the plate moves away from the cylinder, the degree of vortex suppression is altered and the pressure fluctuations appear larger. This is depicted by [5] where it was shown that a rigid splitter plate of constant length placed in the wake of a cylinder increases vortex suppression up to a critical downstream distance; then, suppression drops of dramatically as the plate is moved further away from the cylinder. The data from Fig.6 indicates that the studied range (0.5-0.85*L/d*) is likely beyond the critical separation distance for this particular system and as a result, vortex suppression steadily decreases with increasing cylinder distance.

The fixed airfoil completely inhibits communication between the two shear layers of the vortex street. Such a system tends to have more of a pre-emptive effect on vortex formation and consequently, vortex suppression is detectable at the pressure taps. In contrast, by allowing some interaction between the shear layers, the hinged airfoil tends to be more effective at rearranging vortices in the wake after they pass by the airfoil's trailing edge. Hence, the pressure taps located at the aerodynamic centre are not intended to directly detect suppression strength but rather to provide a consistent feedback signal to be later used in an active closed-loop control system.

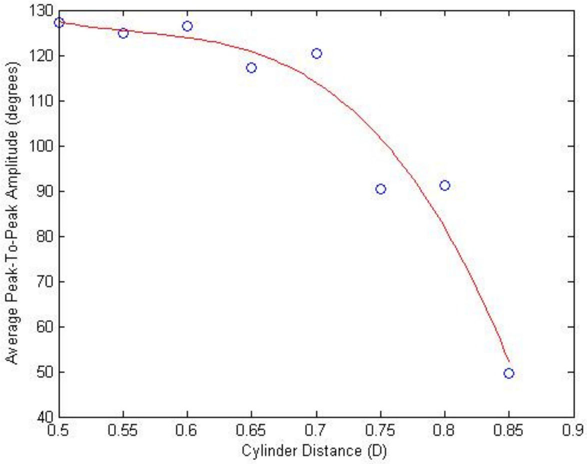

Fig.5: Average peak-to-peak amplitude of angular position vs. cylinder distance *(D)* for the free hinge condition

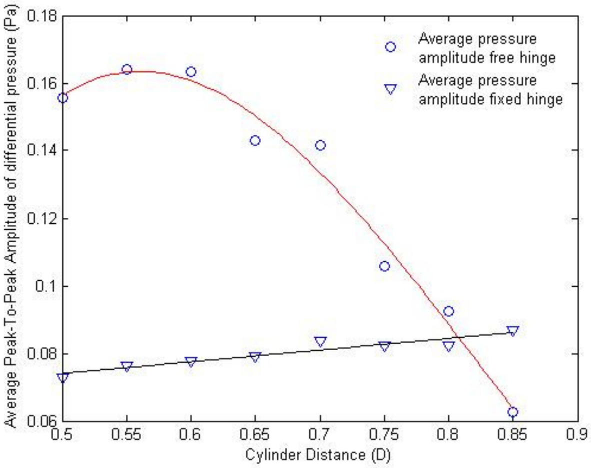

Fig.6: Average peak-to-peak amplitude of differential pressure (Pa) vs. cylinder distance *(D)* for the free hinge condition

The average frequency of oscillations for the free hinge condition remain relatively constant for the various downstream distances ranging from 0.45 Hz to 0.48 Hz with an average value of 0.46 Hz. Similarly, the average frequency of differential pressure for the free hinge scenario ranges from 0.46 Hz to 0.49 Hz with an average of 0.47 Hz. Finally, the average frequency of differential pressure for the fixed hinge scenario ranges from 0.47 Hz to 0.50Hz with an average of 0.48 Hz. This indicates that the frequency of both the pressure signal and the position signal is not affected by downstream position of the actuator rotor. It further specifies that the pressure signals for both of the hinge arrangements share a common frequency and as a result indicates that the frequency is unaffected by the inertia of the actuator rotor.

CONCLUSIONS

Experimental evaluation of flow downstream of a circular cylinder was evaluated and found to be two dimensional. This was accomplished by measuring the in and out of plane velocity components of the flow with Stereo-PIV. The data showed that the out of plane velocity components are small relative to the in plane velocity components.

The oscillatory behavior of a NACA airfoil hinged at its aerodynamic center in the wake of a circular cylinder was studied. Both the angular position and the pressure difference across the thickness of the foil were evaluated for a fixed hinge and a free hinge arrangement. The distance separating the cylinder's trailing edge and the airfoil's axis of rotation is expressed in dimensionless cylinder diameters and data is collected for 8 different separation distances. For the free hinge scenario, the amplitude of differential pressure and of angular position decreases as the separation distance is increased. Interestingly, the amplitude for differential pressure seems to increase between 0.5 and 0.6*D;* then, it decreases as separation distance is increased beyond 0.6*D*. The differential pressure amplitude for the fixed hinge arrangement increases with separation distance indicating that a critical separation distance is likely located before 0.5*D*, and as a result vortex suppression decreases with separation distance. Finally, both separation distance and hinge arrangement seem to have little effect on the average frequency of position and pressure oscillations.

The results from this paper will be used to develop an active closed-loop control system capable of actuating the airfoil and ultimately manipulate the vortex shedding characteristics in the wake of a cylinder or rotating ellipse.

ACKNOWLEDGMENTS

This work has been conducted with the support of the Natural Sciences and Engineering Research Council (NSERC) of Canada and the Discovery and Research Tools and Instruments (RTI) grants.

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