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Passive flow control in the near wake of a circular cylinder using attached permeable and inclined short plates

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ABSTRACT

The main objective of this study is to assess the effectiveness of attached permeable plates in suppressing nominally two-dimensional vortex shedding from a fixed cylinder. The permeable plate along the entire span of the cylinder was made of a chrome-nickel screen and was attached normal to the cylinder surface. The main parameters of the study are porosity of the permeable plate, β, and the plate angle of the cylinder-plate arrangement, θ, with respect to the freestream. Experiments were performed using Particle Image Velocimetry (PIV) and Flow Visualization Techniques. Additionally, drag force measurements were carried out in a wind tunnel to analyze the effects of permeable plates on drag coefficient of the circular cylinder. The results revealed that the use of a permeable plate successfully suppresses the vortex shedding downstream of the circular cylinder by reducing the velocity fluctuations in the wake, elongating the vortex formation region further downstream and attenuating the vortex shedding frequency. The porosity values of β=0.4 and 0.5 with plate angles in the range of $35° \le \theta \le 90°$ were found to be effective on suppressing the vortex shedding. Furthermore, both the drag coefficients of the cylinder-plate arrangement and the $<TKE>_{\max}$ were reduced almost for all porosity ratios for $\theta < 30°$.

1. Introduction

The shedding of vortices generated from a bluff body has been of great interest for many researchers since it continuously results in serious problems in a wide range of engineering applications. The physical mechanism of vortex shedding generates vortex-induced vibrations (VIV) and high unsteady loadings which could damage the structural integrity of even huge constructions. The vortical formation behind bluff bodies also directly affects the amount of drag and lift forces exerted on the body. Some examples for the engineering applications concerning the vortex shedding are risers in offshore engineering, high-rise buildings, bridge piers, chimney stacks, cooling towers. In recent years investigations have focused on applications in offshore engineering since oil risers (made of steel pipes) break like thin wires due to large amplitude VIVs caused by the deep ocean currents. Ocean engineers pay special attention to this problem because riser systems cost one-third of an entire offshore production unit. Due to its great importance, bluff body wakes and vortex shedding regimes have been attractive research areas. Considering only the circular cylinder wake as a bluff body have been preferred (Williamson, 1996; Gabbai and Benaroya, 2005; Bearman, 2011 may be cited among many others) due to its tempting simplicity in setting up such an arrangement in experimental or computational laboratory.

Various flow control techniques to eliminate and/or reduce the adverse effects of vortex shedding were reviewed extensively by Choi et al. (2008). They introduced recent major achievements in bluff- body based flow controls such as 3D forcing, active feedback control, control based on local and global instability, and control with a synthetic jet. They also classified the controls as boundary-layer controls and direct-wake modifications and discussed important features associated with these control methods. More recently, the review of Rashidi et al. (2016) exhibited a different perspective on the control methods including their advantages and limitations. They classified the existing flow control methods into nine different categories and gave useful conclusions and recommendations. With a broader perspective, a general classification of the methods of vortex shedding control is known as active and passive techniques. Some geometrical modifications without energy consumption is valid for passive control methods, whereas an energy input is required to control the vortical structure in an active manner. Generally, introducing a passive control method is easier to implement and less costly since no energy input is needed. Zdravkovich (1981) classified the passive control techniques in three

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ways: impacting separated shear layers or separation lines with protrusion devices such as helical strakes, wires, studs or spheres; affecting the shear layer emanating from both sides of a bluff body with devices such as shrouds; and preventing the interaction of the entrainment layers with some devices such as splitter plate and base bleed. A selective review of various aerodynamic passive control measures which could be adopted to reduce vortex-induced vibrations (most general type of flow-induced vibration) is presented by Kumar et al. (2008). They introduced recent patents on this topic and concluding notes on the current and future developments expected in the passive control of VIV. Throughout the passive control methods, splitter plate has attracted the attention of most researchers starting with Roshko (1955) who indicated that the use of a splitter plate with a length of 5D (D is the cylinder diameter) at $Re=1.45\times10^4$ results in a complete suppression of vortex shedding, consequently decrease in drag force due to increase in base pressure. According to the results of Roshko (1954, 1955), many researchers started to use splitter plates as flow control devices for suppressing the vortex shedding (Bearman, 1965; Gerrard, 1966; Apelt et al., 1973, Apelt and West, 1975; Unal and Rockwell, 1987; Nakamura, 1996; Anderson and Szewczyk, 1997; Ozono, 1999, Hwang and Yang, 2007; Akilli et al., 2008, Shukla et al., 2009; Gu et al., 2012; Gozmen et al., 2013; Assi et al., 2014; Huera-Huarte, 2014; Barman and Bhattacharyya, 2015; Zhang and Weiping, 2016). The study of Bearman (1965) investigated the flow behind a two-dimensional model with a blunt trailing edge and fitted with splitter plates at Reynolds numbers between 140,000 and 256,000. He measured the base pressure and shedding frequency and showed that the existence of a splitter plate increases the base pressure significantly (thereby reducing the pressure drag), even for very short plate length. He also found that a splitter plate length of 2D completely suppresses the vortex shedding for the given Reynolds numbers. A lower Reynolds-number-study was performed by Gerrard (1966) who studied the mechanism of vortex generation behind a cylinder at $Re_D=2\times10^4$. He showed that the Strouhal number is decreased when the length of the splitter plate was smaller than cylinder diameter, D but it increased for $D < L < 2D$. Akilli et al. (2008) experimentally investigated the passive control of vortex shedding behind a circular cylinder by splitter plates of various lengths attached on the cylinder base in shallow water flow at Re=6300. They found that the flow characteristics in the wake region of circular cylinder sharply change up to the splitter plate length of L/D=1.0 and large-scale vortex shedding behind cylinder has completely disappeared for $L/D > 1.2$. Assi et al. (2009) presented a variation of control methods using plates; free-to-rotate splitter plate, double splitter plate, parallel plates and parallel plates with gap. Within these control methods, they achieved a drag reduction of 38% by using parallel plates. They also reported that a free-to-rotate splitter plate also suppresses VIV, however a mean transverse force was generated which should be eliminated. Cardell (1993) brought a new approach to splitter plate studies by examining the permeable wake splitter plate spanning in the wake center plane. He defined the permeability by means of solidity (which is opposite of the term porosity) and derived it using the pressure drop across the permeable plates which are made from woven screens available in the market (β=0.35, 0.51, 0.65, 0.71, 0.78, 0.81). He used infinitely long permeable plates to examine their effects on wake structures for various solidities and used flow visualization followed with the hot wire, pressure and drag measurements for a Reynolds number range of $2500\leq Re\leq18,000$. He concluded that the use of a low permeable splitter plate separates the large scale vortical structures in the near wake of the cylinder whereas the wake structure for a high permeable splitter plate preserves its basic form similar to the no-splitter plate case. According to the discussions of Cardell (1993) it can be said that the use of permeable materials brings out new alternatives to current techniques on flow control since the control elements such as a woven metal screen are readily available in the market. However, Cardell (1993) used very long splitter plates in the experiments, 16D in length, which is quite difficult to adopt for various engineering applications. In addition, the splitter plates oriented only at 0° with respect to the oncoming flow i.e. the effects of the plate angle on the flow characteristics were not investigated. These shortcomings contribute to the rationale for the present study. A recent study of Assi and Bearman (2015) showed the flow-induced vibration (FIV) response of elastically-mounted circular cylinders fitted with non-rotating, three different geometries of splitter plates: short solid (0.5 diameter in length), long solid (1 diameter in length) and slotted (1 diameter in length and 70% solidity). It was said that the splitter plates seemed to keep the drag below that observed during the VIV of plain cylinder, even though vibrating with much larger transverse displacements in the Re range of 3000–7000. They also revealed that the cylinders fitted with splitter plates show a continuous increase in y-displacement compared with the plain cylinder as Re increased, and that the response curves of the cylinders with solid splitter plates are steeper than those of the slotted one. Their study clearly showed that when compared with the impermeable (solid) plate, permeability (porosity) offers some advantages from the point of view of reducing the amplitude of vibration.

It can be noted that permeable (porous) material was not only used as an attached splitter plate but also used as a detached plate to suppress the vortex shedding behind a circular cylinder in shallow water flow (Negretti et al., 2005), as a cover to control the flow noise generated by a set of cylinders that consist of a rigid core cylinder covered by different porous material in cross-flow (Geyer and Sarradj, 2016), as a thin outer shell (shroud) to suppress the vortex shedding from the inner solid cylinder in cross-flow (Bruneau and Mortavazi, 2006; Bhattacharyya and Singh, 2009; Ozkan et al., 2012, 2013, 2015; Gozmen and Akilli, 2014), as a cover to enhance the heat transfer from the heated cylinder in cross-flow (Al-Salem et al., 2011), a perforated cylinder to attenuate large-scale vortex formation in the wake of it in shallow water flow (Pinar et al., 2015; Durhasan et al., 2016).

In this study, the unsteady vortical flow structure downstream of a circular cylinder was controlled using a permeable plate by varying plate angles and porosity ratios. The permeable plate is made of a woven screen which is commercially available and easy to implement. Among the wide-range research including splitter plate applications, the combination of permeability and splitter plate was considered within this study for a large parameter interval.

2. Experimental details

2.1. Flow facilities

During the course of this study, a close-circuit water channel (located in the Mechanical Engineering Department of Çukurova University) and an open circuit low-speed wind tunnel (located in the Mechanical Engineering Department of Niğde University) were used. The water channel with a test section of 750 mm×1000 mm×8000 mm (height, width and length, respectively) was used for obtaining instantaneous, two-dimensional, whole field velocity measurements using the Particle Image Velocimetry (PIV) technique, and for capturing the dye streaklines in the near wake of the models by dye injection. These experiments were performed considering deep water flow conditions (Fig. 1). The height of the water level and freestream velocity were kept constant as h_w=600 mm and U_∞=95.2 mm/s, respectively. The Reynolds number, based on D (diameter of the cylinder), was about 5000. The freestream turbulence intensity (Tu_x) was less than 2%. The walls of the test section were made of Plexiglas material to allow optical access to the desired part of the flow in channel. A 15 kW centrifugal pump was used to drive the water through the close-circuit channel. The impeller speed of the pump can be controlled by a frequency converter.

Force measurements were performed in the suction-type, open-circuit, subsonic wind tunnel with a test section of 570 mm high, 570 mm wide and 1000 mm long (Fig. 2). The walls of test section (also