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Vortex street suppression of a circular cylinder using perforated semi-circular fairing in shallow water

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ABSTRACT

In this study, the effect of perforated fairing on vortex street suppression of a circular cylinder was investigated experimentally in shallow water. In order to investigate the effect of arc angle, α and porosity, β which are the main parameters of the study, three different arc angles ($\alpha = 120°$, $150°$ and $180°$) and six different porosities ($\beta = 0.3$, 0.4, 0.5, 0.6, 0.7 and 0.8) were examined. Perforated fairing was concentrically located with respect to the circular cylinder along its downstream direction. Turbulent statistics (turbulent kinetic energy, TKE and Reynolds shear stress, $\langle u'v' \rangle$) in the wake region were obtained by employing particle image velocimetry (PIV) technique at a Reynolds number of $Re_D = 5 \times 10^3$ based on the circular cylinder diameter, D. The results depicted that the flow structure downstream of bare cylinder was significantly affected by the presence of perforated fairing for the porosity, β values, in the range of $\beta = 0.3$–0.6. It is found that the wake region of the cylinder was elongated substantially along the main flow direction and the vortex shedding frequency, was reduced substantially. Moreover, opposing shear layers lost their strength considerably compared with the bare cylinder case. The peak magnitude of Reynolds shear stress, $\langle u'v' \rangle$ was reduced up to 75% for the arc angle of $\alpha = 180°$ and the location of peak magnitude of Reynolds shear stress, $\langle u'v' \rangle$ moved further downstream regions for all cases. Compared to the bare cylinder case, the most effective flow control was obtained for the case having $\beta = 0.6$ porosity and $\alpha = 180°$ arc angle.

1. Introduction

Vortex shedding downstream of a circular cylinder which causes structural vibration and acoustic noise or resonance, is a well-known phenomenon for engineering applications as well as the natural flows. Therefore, the suppression of the vortex shedding has been attracting much attention and numerous techniques have been developed in order to control the vortex shedding. Vortex shedding control techniques are generally classified into two types as passive and active controls. A distinct difference of the passive control techniques from the active ones is that the passive control techniques do not need externally applied energy. Some illustrative studies can be given for the passive control techniques such as; splitter plate [1,2], small rod [3,4], helical wires or strakes [5–7], roughness elements [8] and O-ring [9]. The application of active flow control techniques have been studied extensively such as; synthetic jets [10–12], rotary oscillations of cylinder [13], wake heating [14].

One of the oldest experimental study about perforated shrouds was carried out by Galbraith [15] where the flow past a particular shrouded cylinder was investigated. He concluded that significant base bleed exists for the shrouded cylinder, fluid is ejected into the free shear layer making it turbulent and thicker, and the formation of vortex street is about twice as far from the shrouded cylinder as that from a plain cylinder. Molin [16] investigated the effect of shrouded cylinder on the flow characteristics for high diameter ratio and small porosity, β numerically. He noted that perforated shroud efficiently suppressed the vortex induced vibrations on the cylinder. Ikeda and Takaishi [17] studied the suppression of Aeolian tone using three types of pantograph horn models; a bare cylinder, a perforated cylinder and a continuous slit cylinder. They showed that the stable wake shear layers of the perforated cylinder and suppression of Aeolian tone are carried out due to the jets emitted from the holes at regular intervals. Zhao and Cheng [18] numerically investigated the effect of porous media on the flow downstream of the circular cylinder at different Reynolds numbers.

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Nomenclature

c_f	bed friction coefficient	St	Strouhal number
D	inner cylinder diameter (m)	S_u	spectrum analysis
D_o	outer cylinder diameter (m)	TKE	dimensionless turbulent kinetic energy
f	vortex shedding frequency (Hz)	U_∞	depth-averaged free stream velocity (m/s)
h_L	laser height (m)	x	streamwise distance (m)
h_w	water depth (m)	y	spanwise distance (m)
Re_D	Reynolds number	β	porosity ratio
Re_{hw}	ambient Reynolds number	α	arc angle (degree)
S	stability number	$\langle u'v' \rangle$	dimensionless Reynolds shear stress

Properly choosing porous media contributed to decrease Strouhal number of the vortex shedding. They noted that the reduction of the lift force is associated with the attenuation of the wake vortices. Kleissl and Georgakis [19] modified the shape of bridge cables, in which one of the shape was a shrouded cylinder, for aerodynamic control. They reported that shrouded cylinder successfully achieved the prevention of vortex formation and the attenuation of fluctuating lift force. Effects of using permeable outer cylinder were investigated on the flow characteristics downstream of a circular cylinder by Ozkan et al. [20]. Results of PIV showed that the presence of permeable cylinder not only significantly changes the flow structure but also remarkably reduces turbulent intensities compared to the bare cylinder. They also indicated that diameter and porosity, β of permeable outer cylinder are the important parameter on the suppression of vortex shedding. Gozmen and Akilli [21] investigated the flow control around circular cylinder using permeable cylinders in deep water. They concluded that both diameter ratio of inner cylinder to the outer permeable cylinder (D/D_o) and porosity are the fundamental parameters in order to suppress large scale vortices. They revealed that the most effective flow control is achieved by the diameter ratio of $D/D_o = 3$ and the porosity of $\beta = 0.7$ in their study. In a similar way, Pinar et al. [22] presented an experimental investigation of flow structure around perforated cylinders in shallow water. They showed that the formation of Karman Vortex Street is prevented by means of jet alike flow through the holes on the cylinder surface. Perforating fairing, which is a thin walled half cylindrical shell, were studied to investigate its effect on the bluff body as a noise control device by Boorsma et al. [23]. In their study, perforated fairing was located in front of the cylinder and perforated shells were partly covered with tape to determine the influence of perforated surfaces on noise control. They indicated that perforating fairing remarkably effects the breakdown of vortex shedding process and the fairing self-noise is reduced.

A shallow flow is generally defined as the situation in which the horizontal length scale of the flow is significantly larger than its depth. Jirka and Uijttewaal [24] show that the definition of turbulent shallow flow in practice need to the two particular conditions which are kinematic condition and dynamic condition. The kinematic condition is defined as the horizontal length scale must be larger than the vertical length scale, h_w (water depth). The dynamic condition is defined as at least one of the bounding surfaces must be shear-supporting, while the other surface is shear-free. Typical examples can be given for the shallow flow applications such as; heat exchanger, columns of bridges and coastal protection structures. The shallow water applications have been considered in some recent studies [25–27]. Chen and Jirka [28] experimentally investigated shallow two-dimensional turbulent wake flows in shallow water for different bluff body. They observed that three different near wake structures produced, which are vortex street type, unsteady bubble and steady bubble, by circular cylinder depend on sufficiently large ambient Reynolds numbers, Re_{hw} ($Re_{hw} \geqslant 1500$ and base on the water depth) and the stability parameter which is defined as $S = c_f D/h_w$ (where c_f is the bed friction coefficient). They noted that transition the vortex street type to the unsteady bubble is characterized by a critical value of $S = 0.2$ and transition the unsteady bubble type to the steady bubble by $S = 0.5$.

Although aforementioned studies have been carried out, the use of various perforated devices are still needed to be developed for vortex street suppression, since their shape, location and Reynolds numbers significantly affect the flow structure and controls the vortex formation. In the present study, the ambient Reynolds number, Re_{hw} and stability parameter, S were kept constant as $Re_{hw} = 5000$ and $S = 0.0066$, respectively, that is, the wake structure of cylinder is the vortex street type with an oscillating vortex shedding mechanism. A parametric study was performed to investigate and optimize the usage of perforating fairing for suppressing the vortex street downstream of the circular cylinder in shallow water. The PIV measurement technique was conducted to obtain velocity vector field and corresponding turbulent statistics (Reynolds shear stress, $\langle u'v' \rangle$ and Turbulent Kinetic Energy). The results were compared with the bare cylinder case in order to point out the control effect.

2. Experimental setup

PIV measurements were performed in a closed-loop water channel having a width of 1000 mm, a length of 8000 mm and a height of 750 mm located at Cukurova University. A solid cylinder (D) made by delrin (polyoxymethylene) material with 50 mm diameter and 1 mm thick perforated cylindrical shells made of chrome-nickel steel (perforated fairing) were used. The porosity, β, which is defined as the ratio of the gap area on the cylindrical shell to the whole cylindrical shell surface area have six different values such as $\beta = 0.3$, 0.4, 0.5, 0.6, 0.7 and 0.8 and they were used to investigate their effects on the unsteady flow structure created in the near wake of the cylinder. Perforated cylindrical shells have three different arc angle values as $\alpha = 120°$, 150° and 180° and they were positioned towards downstream direction, in a concentric way and in the near wake region of the cylinder as shown in Fig. 1. If shells become a whole cylinder, its diameter gets value of $D_o = 100$ mm and diameter ratio, D/D_o is 0.5. The depth-averaged free-stream velocity, U_∞ was kept constant as 100 mm/s which corresponded to a Reynolds number of $Re = 5000$ based on the cylinder diameter (D).

The illumination of measurement field was supplied with a thin and an intense laser light sheet, which was located parallel to the bottom of the platform at a height of $h_L = 25$ mm, by using a pair of double-pulsed Nd:YAG (yttrium aluminum garnet) laser source energy level of 120 mJ at 532 nm wavelength. The time interval