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Passive Drag Reduction Techniques for Modulating the Effects of Vortex Shedding

Raed I. Bourisli

***Abstract*—Over a wide range of Reynolds numbers, the phenomenon of vortex shedding and the associated fluctuations in drag and lift, and the possible vibration in the structure, can be a formidable problem in many applications. Attempts have been made to control, reduce, or altogether eliminate these vortex-induced fluctuations in flow properties. In this study, unsteady laminar flow around a circular cylinder is numerically simulated using the finite volume method. The passive technique of introducing simple slits at specified locations around the cylinder for the purpose of modulating the effect of vortex shedding is investigated. It was found that at a Reynolds number of 1000 the reduction in the coefficient of drag is over 14%, which decreases in Nusselt number, and thus the total heat transfer from the cylinder, of 15.5% and 4.44%, respectively. Physical insight is given to explain the source of the phenomenon, and the advantages of applying such passive techniques to control free flows are discussed.**

***Index Terms*—Vortex shedding, passive drag reduction, slit cylinder, CFD.**

I. INTRODUCTION

Vortex shedding is an intrinsic part of fluid flow around object over a wide range of Reynolds numbers and fluid properties. Such phenomena are relevant to a wide range of applications such as flow around off-shore structures, heat exchangers, nuclear reactor fuel rods, and steel cables used in suspension bridges. Many challenges, both physical and numerical, stem from this phenomenon including fluctuations in drag and lift coefficients, the associated vortex-induced vibration, and the transient nature of the governing equations which might pose a problem for numerical algorithms. The main focus when modeling such flows as of late seems to be the attempt to reduce the drag force experienced by structures by way of modifying either the topology of the structure or the flow characteristics.

One of the key parameters that have a direct effect on the intensity of many flow quantities such as lift and drag is the Strouhal number, interpreted as a dimensionless frequency of the vortex shedding from a stationary object in uniform flow. Vortex shedding appears naturally, forcing the lift coefficient to fluctuate at some frequency and the drag coefficient to fluctuate at twice that frequency. Superimposing external changes to the flow specifically to modify the response to oscillations in flow quantities or capitalize on them for other purposes, such as enhancing heat transfer, was tried by a number of researchers. For example, a number of researchers investigated forcing a circular cylinders to oscillate in the horizontal (inline) direction, which is equivalent to pulsating the flow over it [1], [2]. Meanwhile, others substituted or added a vertical (cross-flow) oscillation to the flow/cylinder and studied changes to averaged lift and drag as well as effects on heat transfer [3]-[5]. It was repeatedly found that in the lock-on region, when the forcing frequency is in the neighborhood of the natural frequency of vortex shedding, the latter is suppressed significantly, leading to noticeable reductions in the drag coefficient. In general, it was concluded that forcing frequency modulates the vortex shedding while forcing amplitude modulates the vortex overall interaction [6].

Combining the two directions of oscillation, Al-Mdallal [7] studied the flow past a circular cylinder with combined streamwise and transverse oscillations. The development of the physical properties of the flow at early times is captured and used to explain observed changes in flow quantities such as lift and drag coefficients. Fu and Tong [8] and Ghazanfarian and Nobari [9] also showed that heat transfer from any downstream heated blocks can also benefit greatly from that optimum oscillation frequency of the cylinder.

Other attempts at controlling vortex shedding to reduce drag and/or enhance heat transfer came in the form of rotating the structure itself. Suppression of vortex shedding from a cylinder was investigated by Dol *et al.* [10]. Optimum rates of rotation were reported at a specific Reynolds number and insight was given as to the mechanism by which vortex shedding is modulated. A number of other researchers also investigated the effect of rotary motion on natural convection heat transfer [11] and the effect of Prandtl number on the process [12]. The idea of introducing a rotary oscillation component to the motion of the cylinder was introduced as early as the early nineties, as experimentally reported by Tokumaru and Dimotakis [13] and then numerically investigated by Baek and Sung [14]. Detailed studies were performed by many researchers to explore the rotation amplitude, frequency, amplitude, as well as the frequency of any occasional pulsating of the flow itself [15]-[17]. Enhancement of the process via optimal control of the rotary oscillations was also investigated [18], [19]. The same dependence of vortex shedding, drag, lift, and heat transfer on being near the lock-on region of oscillation was observed.

While the previous techniques generally result in significant drag reductions, reaching 50% or more, the dynamic nature of the phenomenon and the sensitivity of the flow to external factors take away from their robustness. Added to that is the need for external controls and/or topological manipulation that can be difficult if not impossible to achieve. Among other techniques are can be considered "passive" in nature, and can thus be installed once

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R. I. Bourisli is with the Mechanical Engineering Department, Kuwait University, PO Box 5969 Safat, Kuwait (e-mail: raed.bourisli@ku.edu.kw).

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and forgotten, are (especially stationary) splitter plates and slits on the surface of objects. The use of splitter plates to dissect the downstream, and sometimes upstream, flow regions have been investigated by Hwang and Yang [20]. Recent applications of such technique by Wu and Shu [21] and by Sudhakar and Vengadesan [22] also used the dynamic flapping motion of the plates to oscillate the flow around the circular cylinders.

More recently, Peng *et al.* [23] used a slit that goes through the entire cylinder normal to a uniform flow and experimentally studied the impact of the slit width on the measured vortex shedding signal. No attention was given to any possible reduction in overall drag, however. An optimum range of 0.1–0.15, where is the diameter of the cylinder, was found to to also yield a linear relationship between the Strouhal and Reynolds numbers. In this study, slits with finite widths of 0.05 and lengths of 0.1 are used on the top and bottom of a cylinder in uniform flow and the associated reduction in drag is quantified.

II. GOVERNING EQUATIONS AND BOUNDARY CONDITIONS

The flows of fluid and energy around the cylinder are governed by the transient, 2D form of the continuity, Navier-Stokes, and energy equations. These equations are non-dimensionalized using the following variables,

$$u^* \equiv \frac{u}{U},\quad v^* \equiv \frac{v}{U},\quad x^* \equiv \frac{x}{H},\quad y^* \equiv \frac{y}{H},\quad t^* \equiv \frac{tU}{H},$$

$$p^* \equiv \frac{pH}{\mu U},\quad \theta \equiv \frac{T - T_{in}}{q'' H / k_f},\quad Re_H \equiv \frac{\rho U H}{\mu},\quad Pr \equiv \frac{c_p \mu}{k_f}$$

where U=1 is the uniform upstream velocity, and c_p, ρ and μ are the specific heat, density and dynamic viscosity of the fluid, respectively. The resulting equations are,

$$\frac{\partial u^*}{\partial x^*} + \frac{\partial v^*}{\partial y^*} = 0 \tag{1}$$

$$Re_H\left(\frac{\partial u^*}{\partial t^*} + u^*\frac{\partial u^*}{\partial x^*} + v^*\frac{\partial u^*}{\partial y^*}\right) = -\frac{\partial p^*}{\partial x^*} + \frac{\partial^2 u^*}{\partial x^{*2}} + \frac{\partial^2 u^*}{\partial y^{*2}} \tag{2}$$

$$Re_H\left(\frac{\partial v^*}{\partial t^*} + u^*\frac{\partial v^*}{\partial x^*} + v^*\frac{\partial v^*}{\partial y^*}\right) = -\frac{\partial p^*}{\partial y^*} + \frac{\partial^2 v^*}{\partial x^{*2}} + \frac{\partial^2 v^*}{\partial y^{*2}} \tag{3}$$

$$\frac{\partial \theta_f}{\partial t^*} + u^*\frac{\partial \theta_f}{\partial x^*} + v^*\frac{\partial \theta_f}{\partial y^*} = \frac{1}{Re_H\, Pr_f}\left(\frac{\partial^2 \theta_f}{\partial x^{*2}} + \frac{\partial^2 \theta_f}{\partial y^{*2}}\right) \tag{4}$$

Fig. 1 shows a sample mesh of the problem. A fluid with Prandtl number Pr and thermal conductivity is uniform far upstream of the cylinder with a temperature of 300 K. The surface of the cylinder (including the grooves) is kept at a constant temperature of 400 K.

The governing equations and boundary conditions were discretized using the finite volume technique [24]. The power law scheme was used to discretize the momentum and energy equations while a first-order upwind scheme was used for the continuity (pressure) equation [25]. Pressure-velocity coupling was provided by the Pressure-Implicit with Splitting of Operators (PISO) scheme.

The grid was examined at a Reynolds number of 1000 using four different mesh densities. Results based on the coefficient of lift, coefficient of drag and the friction coefficient at the surface of the cylinder ceased to change significantly (by more than 1%) past the 70,000 cells mesh. Results reported here use just over that number of cells. Naturally, the consistency of the numerical algorithm was tested by comparing the Strouhal number of a proper cylinder to the data in the literature. Agreements there were superb at two different Reynolds numbers of 500 and 1000.

III. RESULTS

Simulations were done for a proper, un-slit cylinder and then for a comparable slitted one, at a Reynolds number of 1000. Cyclically-steady conditions were reached before any output was recorded. The temperature contours through one complete periods of oscillations around a slit cylinder at Re = 1000 are shown in Fig. 2. One critical observation made here is that the intensity of vortex shedding is quite smaller than that for the comparable un-slit cylinder (not shown here). The overall effect of the slits can be summed up by the more firm attachment of the shed fluid to the downstream face of the cylinder. The presence of the slit prevents the shear stress from building up sufficiently on any given side of the cylinder. As a result, and due to the premature release of the shear built up naturally, the intensity of shedding is modulated, albeit with no dynamic control of the structure nor the flow.

Examination of the flow properties reveals the extent of the reduction of flow properties such as the drag coefficient. Compared to the un-slit cylinder, the coefficient of drag, C_d, was reduced from 1.353 to 1.162, a reduction of more than 14%. Due to the reduced fluctuation of the flow around the cylinder, a corresponding decrease in Nusselt number (15.5%) and total heat transfer (4.44%) from the cylinder is also observed when slits are introduced.

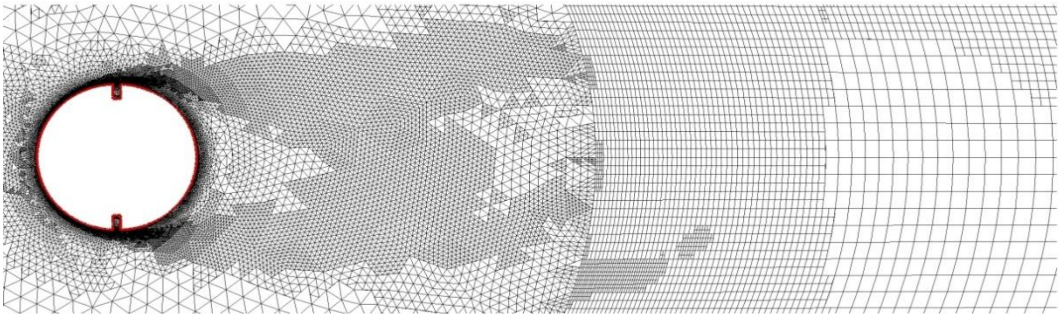

Fig. 1. Sample mesh of the computational domain.

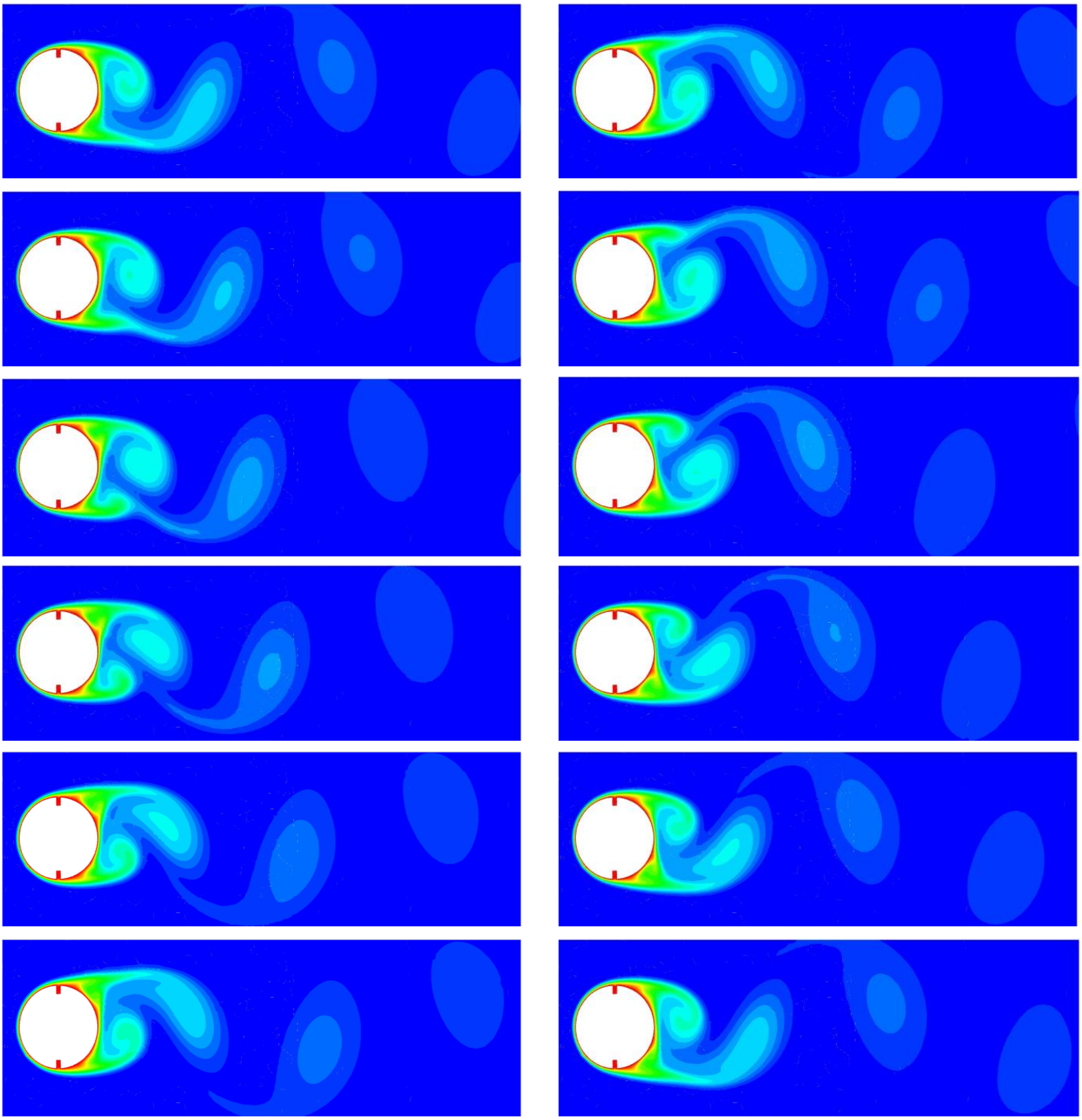

Fig. 2. Temperature contours around the cylinder with slits at Re=1000. The twelve figures show contours through one complete cycle of vortex shedding. These are recorded after cyclic behavior was established. Figures on the left column constitute half of the cycle (top to bottom), while those on the right constitute the second half. A video of the simulation can be found at http://db.tt/ujkHhUxu.

IV. PRELIMINARY CONCLUSIONS

In this study, finite-width and -length slits are used in a cylinder in uniform flow and the associated reduction in drag is quantified at a Reynolds number of 1000. It is shown that this passive technique can lead to good reductions in drag from a cylinder in steady, uniform flow. Reductions in the Nusselt number and total heat transfer rate from the surface of the cylinder also resulted.

Ongoing work on the problem includes testing the phenomenon at different slits count, locations, and aspect ratios, in order to come up with a truly optimum configuration. Results at different Reynolds numbers are also being sought in order to quantify its effect on reductions.

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Raed I. Bourisli received his B.S. degree from Seattle University, Seattle, WA in 1997, M.S. degree from the University of Washington, Seattle in 2000, and his Ph.D. degree from Rensselaer Polytechnic Institute, Troy, NY in 2005 all in mechanical engineering. He is an associate professor with the Mechanical Engineering Department, College of Engineering and Petroleum, Kuwait University, Safat, Kuwait. His current research interests include heat transfer, computational fluid dynamics, and optimization.