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Optimal stabilization of a flow past a partially hydrophobic circular cylinder

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ABSTRACT

Hydrophobic surfaces, enabling flow slip past a solid boundary, can be effective for passive flow control applications. In the present study, a computational investigation of flow past a circular cylinder with slip conditions is performed, at low values of Reynolds number, *Re*. Slip is modeled based on the Navier model. When slip conditions are applied on the entire cylinder surface, the present results demonstrate the stabilizing effect of increasing the non-dimensional slip length, $b^* = b/D$, b being the slip length and D the cylinder diameter, in agreement with recent studies. In particular, the Kármán vortex street is supressed at a critical value of b^*, which is an increasing function of *Re*. Further, it is shown that, for the same levels of b^*, the wake can be stabilized by implementing slip conditions only on a part of the cylinder surface. Guided by this observation, the problem of fully or partially suppressing the Kármán vortex street by means of a partially hydrophobic cylinder is addressed by formulating a multi-objective optimization problem, in which the product of slip length and hydrophobic area quantifies the control effort; a second objective function, characterizing flow unsteadiness, is thereby introduced. The optimization results demonstrate that, both for full and partial suppression of the Kármán vortex street, a proper use of partial hydrophobicity can lead to a significant reduction in passive control effort, in comparison to the case of the fully hydrophobic cylinder. Computed optimal solutions of the Pareto front are characterized by means of local stability calculations based on an Orr-Sommerfeld solver. It is shown that flow stabilization is attained when a global intensity of absolute instability, involving local absolute growth rates and the streamwise extent of absolute instability, is sufficiently reduced.

1. Introduction

Above a critical value of the Reynolds number, flows past bluff bodies, as a circular cylinder, are characterized by global instability, whose non-linear state is the Kármán vortex street. The Kármán street consists of the sequence of vortices shed, two per shedding cycle. The presence of the vortex street results in time-dependent drag and lift forces exerted on the body. This dynamic loading may lead to structural fatigue in engineering applications as cooling towers, oil risers and heat exchangers. Therefore, several methods have been applied in literature studies, in order to suppress vortex street, such as: (a) placement of a splitter plate [1], (b) suction/blowing on the cylinder surface [2–4] (c) cylinder rotation and/or rotary oscillation, including both experiments [5,6] and computations [7], (d) cylinder heating [8], (e) proper placement of a smaller cylinder in the wake [9–11], and (f) application of a Lorentz force [12]. All of the above control measures are characterized by either energy input or modification of the geometry setup.

Currently, hydrophobic and superhydrophobic surfaces, enabling fluid slip with respect to a solid surface, are considered as promising candidates for drag reduction and possibly heat transfer enhancement in engineering flow applications (see [13] and references therein). In flow past a circular cylinder, fluid slip at the cylinder surface leads to a delay of separation, and thus to the formation of a narrower wake. This reduces the intensity of lift and drag force oscillations [14], and may even lead to a complete suppression of the vortex street [15]. At increased levels of slip, the flow may be characterized by substantially higher values of Strouhal frequency [15,16]. These effects of slip on flow dynamics can be correlated to the modification of the near wake structure of the base flow, and mainly to the decreased extent of the two recirculation zones [17], which in turn affects the non-linear flow state.

In flow past a cylinder, a major advantage in implementing surface hydrophobicity is the lack of any other intervention in terms of either energy input or geometry modification. As the manufacturing of hydrophobic and superhydrophobic surfaces is still quite

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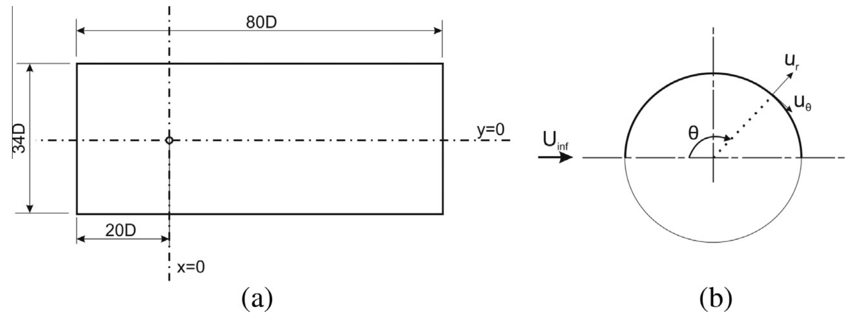

Fig. 1. (a) Flow domain. (b) Definition of local angle, measured from front stagnation point, and local velocity components on the cylinder surface, u_θ and u_r.

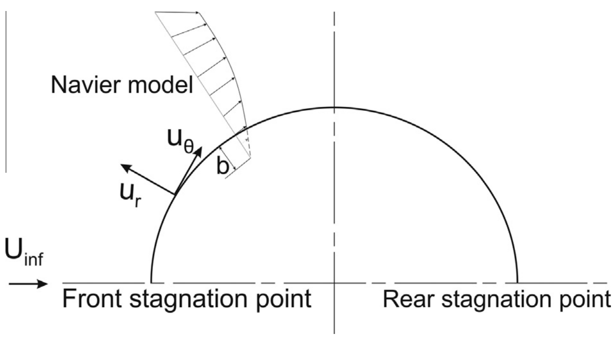

Fig. 2. Sketch of velocity profile near cylinder surface, for a slip length *b*.

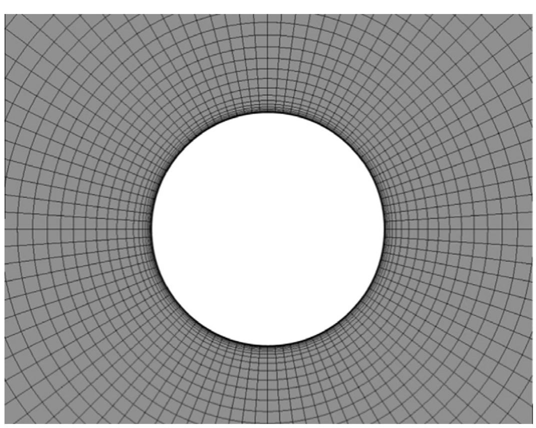

Fig. 3. Detail of a finite volume mesh close to the cylinder (the number of finite volumes osculating to cylinder surface is close to 100).

expensive, minimizing the associated cost (e.g. by minimizing the hydrophobic/superhydrophobic area and the material cost per unit area) should be a main consideration of a corresponding design.

The present study thus aims at the passive control of flow past a cylinder, aiming at a full or partial suppression of the Kármán vortex street. Here, a main consideration is to investigate whether optimization can lead to substantial reduction in control effort. Guided by CFD simulations in which hydrophobicity is applied only on part of the cylinder surface, a multi-objective optimization problem is formulated, aiming at arriving at desired levels of flow unsteadiness at a minimum control effort; the latter is quantified by the product of slip length and hydrophobic area. Optimal solutions are characterized by means of stability calculations.

An early analysis of the concepts of absolute and convective instability has been presented by Bers [18]. Huerre and Monkewitz [19] and Monkewitz et al. [20] considered further the relation between local theory and global dynamics, within the restrictions of linear and weakly non-parallel approximations, and the effects in open shear flows (mixing layers, jets and wakes). With the increase in computer resources, the linear or nonlinear analysis of strongly non-parallel flows could be realized. Relevant studies include [21] (non-modal stability analysis), [22] (bi-global stability analysis) and [23] (non-linear global modes and non-normality).

For wake flows, application of linear theory in characterizing local and global flow instability has been considered in the studies of Jackson [24], Zebib [25], Barkley and Henderson [26], and Mittal [27] (flow past a cylinder), as well as in Monkewitz and Nguyen [28], and in Monkewitz [29] (families of wake profiles). More recently, the dynamics of spatially developing wakes has been interpreted by Pier and Huerre [30] (family of wake profiles) and Pier [31] (cylinder wake). In the present study, a linear stability analysis approach is followed, aiming at a qualitative characterization of computed optimal flow solutions.

The paper is organized as follows. In Section 2, the problem setup is presented. In Section 3, results of numerical simulations of flow past a cylinder with slip on the entire or part of its surface (full/partial slip) are presented and analyzed. In Section 4, the optimization problem of the present study is defined, and the optimization results are presented and discussed, for two values of Reynolds number. In Section 5, stability calculations of the computed flow fields are presented, and used to interpret the optimization results. Finally, in Section 6, the main findings of the present study are summarized.

2. Problem definition

We consider a circular cylinder in uniform cross-flow. Flow fields are computed from the numerical solution of the non-dimensional Navier–Stokes equations for two-dimensional incompressible viscous flow:

$$\text{Continuity equation}: \quad \nabla \cdot \vec{u} = 0 \tag{1}$$

$$\text{Momentum equation}: \quad \frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} = -\nabla p + \frac{1}{\mathrm{Re}} \Delta \vec{u} \tag{2}$$

where $\vec{u} = (U, V)$ is the velocity vector and p the static pressure. Here, physical variables are non–dimensionalized with proper scales based on the cylinder diameter, D, the free stream velocity, U_{inf}, and the fluid density, ρ. Frequencies are non- dimensionalized as Strouhal numbers, $St = \frac{fD}{U_{\inf}}$. The Reynolds number is defined as $Re = \frac{U_{\inf} D}{\nu}$, where ν is the kinematic viscosity of the fluid.

The numerical solution of the governing equations utilizes the ANSYS CFX CFD code. Here, a second-order finite volume approach is adopted. The center of coordinates ($x = 0$, $y = 0$) is taken at the cylinder center. The following conditions are prescribed at the domain boundaries (see Fig. 1a).