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Numerical investigation of flow around one finite circular cylinder with two free ends

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ABSTRACT

Flow around one finite circular cylinder with two free ends is of both fundamental and practical importance, without a detailed discussion yet. In this study a numerical investigation is performed to demonstrate its flow pattern and turbulent structure varying with the aspect ratio and Reynolds number. The results show that the drag coefficient decreases dramatically in comparison with the two-dimensional model and the horseshoe vortex around the mounted cylinder with one free end disappears. Instead, a pair of stationary recirculating eddies behind the cylinder is found in the axis direction at low Reynolds number. With the increasing of Reynolds number, four spiral vortices are formed by the interaction of the two three-dimensional separated flows from two free ends and the wake formed by the cylindrical surface. The separated flow recirculates to the backside of the cylinder and increases its local pressure. Additionally, an intersection zone and a backflow is found close to the end surface, caused by the up-wash flow from the sharp leading edge of the cylinder. Finally, a new relationship between the drag coefficient and the Reynolds number for one finite circular cylinder with two free ends is proposed.

1. Introduction

Flow around one circular cylinder in a disturbance-free stream has attracted a great attention over the years (Akoz, 2012). While the two-dimensional 'infinite' circular cylinder in a steady cross-flow has been one of the classical problems in fluid mechanics, and the model of one finite circular cylinder with one free end has attracted a great deal of attention, the flow around short circular cylinder with two free ends remains relatively unexplored (Escobar et al., 2013). It has been demonstrated that the presence of free ends makes the problem complicated, with highly turbulent vertical structures in the flow field around the cylinder (Stone, 2017). Despite a quite simple geometry, the flow structure near the free ends is not well understood. Most important, such a flow configuration can be found in many engineering applications. In most practical applications there is at least one free end and sometimes two free ends, such as ship radar aerials, submerged vehicles, cylinder elements in roller bearings, etc (Sumner, 2013). Using results of two-dimensional infinite model cannot truly capture phenomena such as alternating vortex shedding, and may cause large fluctuating pressure forces, noise, vibrations and even structural failure when the vortex shedding frequency coincides with the body's own natural frequency (Kiani and Javadi, 2016; Park et al., 2016). Therefore, understanding the dynamics of three dimensional flow around one circular cylinder with two free ends can provide valuable knowledge with both fundamental and practical importance.

For flow around one finite circular cylinder with one free end (mounted on the flat wall), remarkable research has been devoted to understand its characteristics (Cakir et al., 2015). A horseshoe vortex system is found at the body-plate junction, with a Karman-type vortex shedding in the main wake and a three-dimensional separated shear flow structure around the free end surface. It is found that the three-dimensional flow around the top surface developing into the wake considerably influences the wake flow pattern of the finite circular cylinder, as shown in Fig. 1. The shedding frequency in the wake changes along the cylinder span and it is caused by the existence of a cellular wake oscillating up and down in the tip region. The fluctuating force acting on the cylinder in the traverse direction is also found to vary along the cylinder axis, as a result of the unsteady separated flow emanating from the top edge of the cylinder (Baban and So, 1991). It has been validated that the three-dimensional separated shear flow around the free end surface is a key element which determines the wake behavior of the finite cylinder.

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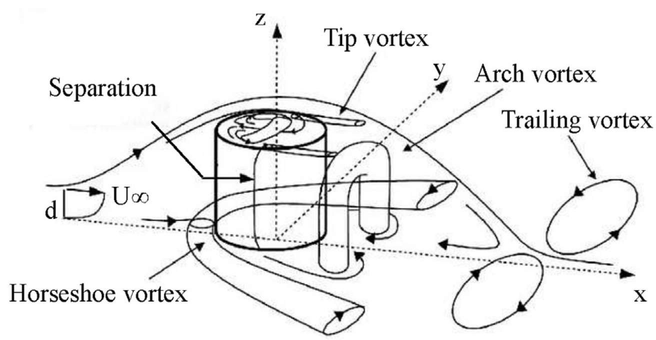

Fig. 1. Sketch of flow around one finite circular cylinder with one free end (Sumner, 2013).

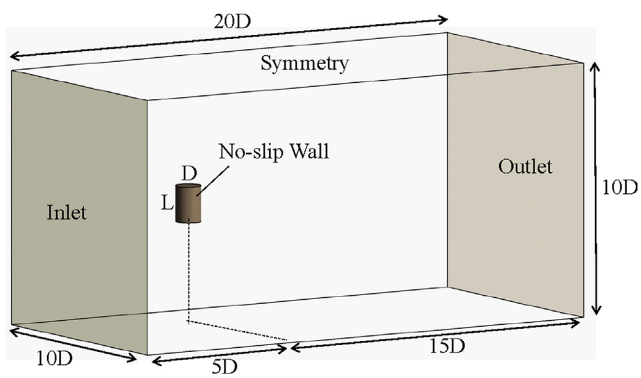

Fig. 2. Geometry and boundary condition of the calculation domain.

Regarding to the flow around one circular cylinder with two free ends, three-dimensional separated shear flow around two free ends makes the flow pattern more complex unquestionably, while relatively scant attention has been attracted so far. Okamoto & Yagita (Okamoto and Sunabashiri, 1992) assumed that an equivalent cylinder with two free ends is twice a cantilevered cylinder with one free end and is symmetric about the plane boundary. But they ignored the combined effect of two shear flows from two free ends. Without the boundary layer effect on the plate wall, the horseshoe vortex and arch-shaped vortex may disappear. Wieselsberger and Zdravkovich (Zdravkovich et al., 1989) experimentally measured drag coefficient and pressure distribution of one finite circular cylinder in the range $400<Re<8\times 10^5$. Sheard (Sheard et al., 2005) employed numerical methods to study the flow around a cylinder with free hemispherical ends and found that the quasi-two-dimensional wake behind the cylinder is deformed by the three-dimensional effects induced by the flow around the hemispherical ends. Vakil (Vakil and Green, 2009) investigated the flow over yawed cylinders in the Reynolds number range $160 < Re < 10^3$. The sensitivity of the results to the cylinder end conditions is highlighted.

Although there is abundant previous work on finite and/or infinite cylinders either with on free end or one free end, the authors could find few previous research on the flow around one finite circular cylinder with two free ends. This is of particular interest because, as stated previously, it is valuable for practical applications.

In this article, a numerical simulation method is proposed to explore the flow pattern and turbulent structure around one finite circular cylinder with two free ends. Flow characteristics around the free end is investigated, to illustrate the overall flow past the finite circular cylinder. Its influence to the shedding wake from the cylindrical surface is presented. Pressure distribution and drag coefficient on the cylinder are studied for different aspect ratios and Reynolds numbers and finally, a relationship between drag coefficient and Reynolds number suitable for short circular cylinder with two free ends is summarized.

2. Numerical approach

2.1. Numerical computation domain

To simulate flow structure around the finite circular cylinder with two free ends, the classical Navier-Stokes equations are solved to discribe the fluid behavior (Udoewa and Kumar, 2012; Liu et al., 2017). The finite volume discretization method is used to approximate the N-S equations by a system of algebraic equations for the variables at some set of discrete locations in space. The geometry of calculation fluid domain and the boundary condition are shown in Fig. 2. The cylinder center is placed 5 times diameter of the cylinder (5D) downstream of the inlet and 15D upstream of the outlet. The other four sides are 5D far from the center of the cylinder. The aspect ratio is defined as the length to diameter ratio L/D. The fluid domain is dispersed with structured hexahedron grid using the software ANSYS ICEM 16.9.

2.2. Governing equations

To catch the detail of vortices in the fluid field in acceptable calculation time, the Shear-Stress Transport (SST) Scale-Adaptive Simulation (SAS) model is used (Menter and Egorov, 2010), which is different from the conventional RANS formulations. As a measure of the local flow length scale, a classic boundary layer length scale introduced by von Karman is generalised for arbitrary three-dimensional flows. The von Karman length scale explicitly enters the transport equations of the turbulence model. The resulting model remains a RANS model, as it delivers proper RANS solutions for stationary flows and maintains these solutions through grid refinement. On the other hand, for flows with transient instabilities like those in the massive separation zones, the model reduces its eddy viscosity according to the locally resolved vortex size represented by the von Karman length scale. The SAS model can under those conditions resolve the turbulent spectrum down to the grid limit and avoids RANS-typical single-mode vortex structure (Hanjalić et al., 2015).

The governing equations of the SST-SAS model differ from those of the SST RANS model by the additional SAS source term Q_{SAS} in the transport equation for the turbulence eddy frequency ω.

$$\frac{\partial \rho k}{\partial t} + \nabla\cdot(\rho U k) = P_k - \rho c_\mu k\omega + \nabla\cdot\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\nabla k\right] \tag{1}$$

$$\frac{\partial \rho \omega}{\partial t} + \nabla\cdot(\rho U \omega) = \alpha\frac{\omega}{k}P_k - \rho\beta\omega^2 + Q_{SAS} + \nabla\cdot\left[\left(\mu + \frac{\mu_t}{\sigma_\omega}\right)\nabla \omega\right] + (1-F_1)\frac{2\rho}{\sigma_{\omega 2}}\frac{1}{\omega}\nabla k\nabla\omega \tag{2}$$

where $\sigma_{\omega 2}$ is the σ_ω value for the $k-\xi$ regime of the SST model.

$$Q_{SAS} = max\left[\rho\zeta_2\kappa S^2\left(\frac{L}{L_{\nu k}}\right)^2 - C\cdot\frac{2\rho k}{\sigma_\Phi}max\left(\frac{|\nabla\omega|^2}{\omega^2},\frac{|\nabla k|^2}{k^2}\right),0\right] \tag{3}$$

The additional source term Q_{SAS} originates from a term in Rotta's transport equation for the correlation-based length scale (Menter and Egorov, 2010). Since the integral is zero in homogeneous turbulence, it should in general be proportional to a measure related to inhomogeneity. The model parameters in the SAS source term are:

$$\zeta_2 = 3.51, \sigma_\Phi = 2/3, C = 2 \tag{4}$$

The value L in the SAS source term is the length scale of the modelled turbulence, and the Von Karman length scale $L_{\nu k}$ is a three-dimensional generalization of the classic boundary, which imposes the limiter to prevent the SAS equilibrium eddy viscosity from decreasing below the LES subgrid-scale eddy viscosity.

$$\mu_t^{eq} \geq \mu_t^{LES} \tag{5}$$