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Coupled delayed-detached-eddy simulation and structural vibration of a self-oscillating cylinder due to vortex-shedding

Abe H. Lee*, Robert L. Campbell, Stephen A. Hambric

Fluids and Structural Mechanics Office, Applied Research Laboratory, The Pennsylvania State University, PO BOX 30,
State College, PA 16804, USA

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ABSTRACT

The flow past a rigid-fixed cylinder and a self-oscillating cylinder is simulated at Re = 5000. The finite-volume based CFD package OpenFOAM is used for flow computations for a rigid-fixed cylinder. Extensive mesh convergence and time-step studies are conducted for a cylinder span of 2*D* (twice the diameter). Spanwise-pressure correlations and spectral calculations are conducted using longer cylinder span lengths: 4*D*, 8*D* and 16*D*. As the cylinder span size increases, better spanwise correlations are obtained. For a self-oscillating cylinder, the numerical approach that tightly couples DDES and FEA based on a fixed point iteration is used to predict the amplitude response and drag in a *lock-in* condition. The results of the rigid-fixed and self-oscillating cylinder computations compare favorably with experimental data.

1. Introduction

Vortex-induced vibration (VIV) has been an active research area in computational and experimental fluid dynamics over the past few decades. Fig. 1 shows visualization of the shedding vortices past a circular cylinder with aspect ratio of $L_z/D = 16D$. Flow over a bluff-body may cause oscillating forces on a structure within a narrow frequency band, and if the flow oscillating frequency coincides with the resonance frequencies of structure, it may induce large amplitude vibrations

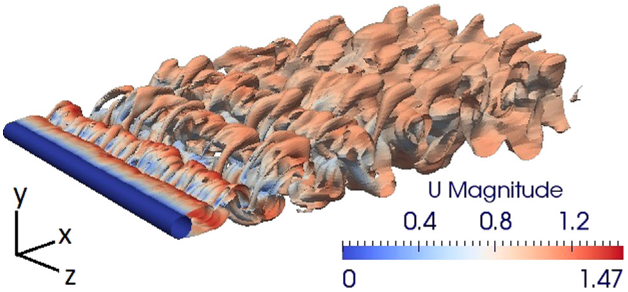

Fig. 1. Flow past a rigid-circular cylinder with a span-length of 16*D*. Instantaneous iso-surfaces of constant eddy-viscosity with velocity magnitude contours at Re = 5000.

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* Corresponding author.
E-mail addresses: ahl5084@psu.edu, abelee5084@gmail.com (A.H. Lee).

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and even structural failures. This is of great engineering importance, since many structures that are exposed to fluid flow may experience vortex-induced forces, e.g. offshore structures, bridge towers and cables, tall stacks and pipe lines. In particular, in flight vehicles, poor airfoil or rotor blade designs may cause undesirable noise and vibrations due to VIV. Another example where VIV might be problematic is sensor applications. Especially, for sensors used underwater, VIV might cause spurious noise in a signal. The above examples demonstrate the importance of understanding and preventing VIV in many engineering applications.

On the experimental side, a few decades of research efforts have yielded an extensive experimental database in a wide range of Reynolds numbers, e.g. two volumes of Zdravkovich (1997, 2003) contain comprehensive experimental results, and detailed discussions on the physics of the flow over a cylinder. Many reviews on the fluid-induced vibration (experiment and computation) can be found in the publications of Bearman (1984), Williamson and Govardhan (2008) and Sarpkaya (1979), and flow over cylinders in Niemann and Hölscher (1990) and Norberg (2003). In the past, in the VIV research much attention was given to the vibration of a structure transverse to the direction of freestream flow, in which the maximum vibration amplitude occurs. In recent studies, experimental work can be found that focuses on two-degree of freedom motion of cylinder vibration due to VIV in the transverse and parallel directions to the flow (Blevins and Coughran, 2009; Goncalves et al., 2013).

Along with experimental research activities, much work has been performed in the theoretical and numerical studies on VIV. Empirical and semi-empirical models have been developed and show good prediction results as in the works of Iwan and Blevins (1974), Blevins (1977), Facchinetti et al. (2004) and Farshidianfar and Zanganeh (2010), and also a good review on analytic models can be found in Gabbai and Benaroya (2005). On the computational research, with the advancement of computational resources and turbulence modeling strategies, bluff-body flow simulations at high Reynolds numbers of engineering interest have been extensively performed. The computational approaches include Large-Eddy Simulation (LES) (Breuer, 2000; Karabelas, 2010; Nishino et al., 2008; Krishnan et al., 2006), a hybrid scheme such as Detached-Eddy Simulation (DES) (Travin et al., 2000) and $k-\omega$ Scale-Adaptive Simulation (SAS) (Menter, 2003). Among many numerical approaches, a hybrid scheme such as Detached-Eddy Simulation has shown good predictions at much lower computational costs than LES. For fluid–structure interaction (FSI) of vibrating cylinders in VIV, however, computational cost is far more expensive than for stationary cylinders. Even with the improvement of computational resources, simulations that couple structural vibrations and unsteady bluff-body flows in VIV are quite challenging. Due to this, FSI computations have been limited to 2-dimensional fluid domains using Reynolds-Averaged Navier–Stokes (RANS) simulations (Wanderley et al., 2008; Zhao et al., 2012).

In this study, the flow past rigid-fixed and self-oscillating cylinders are studied extensively at $\mathrm{Re}=5000$, in which the flow is characterized by periodic turbulent shedding-vortices. Cylinder bluff-body flows have been used extensively to test numerical and turbulence modeling schemes, since the round shape of the cylinder causes a smooth flow separation, as opposed to rectangular geometry where flow separations are imposed by sharp corners (Travin et al., 2000). Especially, in bluff-body flows, the flow solutions such as drag, lift and shedding frequency strongly depend on how accurately turbulence models capture flow separations, transition in the boundary layer and unsteady behavior in the wake. Accurate predictions within a wide range of Reynolds numbers are indeed challenging. LES seems to be the best computational approach to capture unsteady physics at a reasonable computational cost, e.g. the unsteady flow in the wake of the cylinder. However, in the vicinity of the cylinder where flow separations occur, the cost of LES increases tremendously, because high grid resolution is required to capture small-scale eddies and flow separations accurately. Therefore, modeling strategies such as LES with wall-layer models (Piomelli and Balaras, 2002) have been developed to simulate wall-bounded turbulent flows at a lower computational cost. Also, hybrid RANS-LES schemes (Travin et al., 2000; Menter, 2003) have shown that the flows characterized by massive separations and unsteadiness can be tackled at much more manageable costs and yet perform accurate predictions. Among many modeling choices, Delayed-Detached-Eddy Simulation (DDES) is employed in this study for flow computations at $\mathrm{Re}=5000$. The trip-less approach introduced by Shur et al. (1999) is adapted to predict flow separation in a laminar boundary layer. In the trip-less approach, the inflow eddy viscosity is set to a value at least an order of magnitude smaller than the molecular viscosity. Thus, the turbulence model becomes dormant in the attached boundary layer. After the flow is separated (i.e. in the detached boundary layer), the vorticity causes quick production of eddy viscosity.

For rigid-fixed cylinders, the fluid domain is modeled as 3-dimensional where cyclic, or periodic, boundary conditions are used in the spanwise direction. As shown in Fig. 2, the diameter of the cylinder is $D=1$ m, and the velocity of the

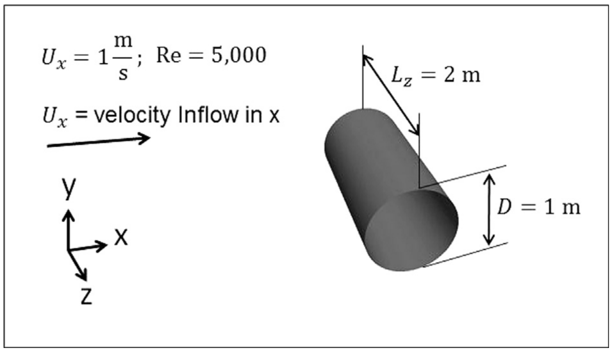

Fig. 2. Schematic of a rigid-fixed cylinder whose aspect ratio, L_z/D, is 2.