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Large Eddy Simulation of the Vortex-Induced Vibration of a Circular Cylinder by using the Local Domain-Free Discretization Method

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Abstract. In this paper, the local domain-free discretization (DFD) method is extended to large eddy simulation (LES) of fluid-structure interaction and the vortex-induced vibration (VIV) of an elastically mounted rigid circular cylinder, which is held in the middle of a straight channel, is numerically investigated. The wall model based on the simplified turbulent boundary layer equations is employed to alleviate the requirement of mesh resolution in the near-wall region. The ability of the method for fluid-structure interaction is demonstrated by simulating flows over a circular cylinder undergoing VIV. The cylinder is neutrally buoyant with a reduced mass $m^*=11$ and has a low damping ratio $\zeta=0.001$. The numerical experiment of the VIV of a cylinder in an unbounded flow shows that the present LES-DFD method is more accurate and reliable than the referenced RANS and DES methods. For the cylinder in the middle of a straight channel, the effect of the channel height ($d^*=d/D$) is investigated. The variations of the response amplitude, vortex-shedding pattern and the length of the induced separation zone in the channel boundary layers with the channel height are presented.

AMS subject classifications: 74F10, 76F65

Key words: Immersed boundary method, domain-free discretization, large-eddy simulation, fluid-structure interaction, vortex-induced vibration.

1 Introduction

For the numerical investigation of fluid-structure interactions (FSI), transient re-meshing strategies, such as grid deformation/regeneration techniques, are usually required in

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boundary-conforming methods, which are time-consuming and increase the algorithmic complexity. Transient re-meshing strategies may work well in the framework of Reynolds-Averaged-Navier-Stokes (RANS), but typically lack accuracy when being coupled with eddy-resolved methodologies. The immersed boundary (IB) method, which can solve moving-boundary problems on a fixed mesh, is an alternative approach.

The IB method was firstly proposed by Peskin [1] to investigate FSI in the cardiovascular circulation. So far, many amendments have been proposed with the aim of improving the stability and the applicability of this method [2, 3]. The fundamentals and the recent applications to simulations of complex fluid-structure-interaction (FSI) problems are reviewed by Sotiropoulos and Yang [4] and Huang and Tian [5]. In [6, 7], Shu et al. proposed an IB method, named the domain-free discretization method (DFD), to solve partial differential equations (PDEs) on irregular domains. In the DFD method, the discrete form of a PDE at an interior node in the immediate vicinity of the IB may involve some exterior nodes. In the original DFD method, the functional values at an exterior dependent node are evaluated along the whole mesh line, so it is not applicable for complex domains. To make the method more general, a local DFD method was developed by Zhou et al. [8], in which the functional values at the exterior dependent nodes are obtained by using a proper local extrapolation along the direction normal to the wall and in conjunction with the boundary conditions. The local DFD method has been successfully applied to simulate various inviscid or laminar flows [8, 9]. Recently, it was extended to RANS simulation [10] and large eddy simulation (LES) [11] of turbulent flows by introducing the wall modeling techniques to alleviate the requirement of mesh resolution for the boundary layer.

Vortex-induced vibration (VIV) is a popular topic in the FSI field. This topic elicited the attention of researchers after the dramatic collapse of the Tacoma Narrows Bridge in 1940. The VIV phenomenon involves complicated physical mechanisms and cannot be despised in design of longer and slender structures, such as skyscrapers, bridges, and chimneys.

Most previous VIV studies are focused on the paradigm of a freely vibrating, elastically mounted rigid cylinder placed in a uniform and unbounded cross-flow. In the review of Williamson and Govardhan [12], the importance of several dimensionless variables are highlighted, including the mass ratio (m^*), the damping ratio (ζ), and the reduced velocity (U_r). Khalak and Williamson [13] reported that the amplitude response of a one-degree-of-freedom (one-DOF) VIV system can be categorized into two types, according to its mass-damping ratio ($m^*\zeta$). With a lower $m^*\zeta$, there are three distinct branches in the response curve with the variation of reduced velocity. The three branches are termed as the "initial", "upper" and "lower" branches. With a higher $m^*\zeta$, the upper branch does not exist.

To date, only a few studies have been dedicated to identifying the effect of a single plane wall in the vicinity of the elastically mounted cylinder. In this case, the cylinder is immersed in a semi-infinite flow and the dynamics of VIV is much more complex. The gap ratio, $S^* = S/D$, defined as the distance between the cylinder bottom and the