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Numerical simulation of super upper branch of a cylindrical structure with a low mass ratio

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ABSTRACT

SST (shear stress transport) k-ω and Newmark-β methods are used to comprehensively understand vortex-induced vibration (VIV) characteristics of a cylindrical structure with a mass ratio of 2.6 in a range of reduced velocity from 2.0 to 14.0. The details of drag and lift forces, cross-flow and streamwise displacements, vortex pattern, trajectory, and frequency of VIV are presented and compared systematically with the experimental work of Jauvtis and Williamson that first captured the super upper branch in VIV with the maximum value of 1.5 D (diameter). In this study, the numerical simulation results successfully captured the initial branch, the lower branch, and the super upper branch. Very few research studies have successfully simulated the super upper branch by numerical methods. The vibration amplitude corresponding to the super upper branch is stable and the maximum value of the super upper branch is 1.46 D, which is fairly consistent with the results of the Jauvtis and Williamson experiment. This research also successfully captured the law of trajectory under different reduced velocities. With the reduced velocity increasing, the trajectories switch from an irregular shape to a regular "Figure 8″ shape and then enter into an irregular movement, finally again into a regular movement of a Figure 8 shape or crescent. In the range of the super upper branch, the vibration trajectories gradually change from a Figure 8 shape to a crescent shape with the increase of the transverse vibration amplitude. This work has successfully captured the different vortex patterns corresponding to each branch under different reduced velocities, and found the transitional forms of 2S to 2T, 2T to 2P, and 2P to 2S, respectively.

1. Introduction

Vortex-induced vibration (VIV) is a widespread natural phenomenon, especially in the field of ocean engineering where the VIV of a riser is a common phenomenon. Much research on the VIV of marine risers has been conducted, with Bearman (2012), Williamson (1996), Williamson (2004, 2008), Sarpkaya (2004), Gabbai and Benaroya (2005), Wu et al. (2012) summarizing the research results of a cylindrical structure or a riser VIV in recent decades.

Early research was mainly focused on the study of a cylindrical structure VIV, especially the study of one degree of freedom (1 DOF) VIV, which considers only transverse vibration. Feng (1968), Khalak and Williamson (1996, 1999), Govarhan and Williamson (2000), Brika and Laneville (1993, 1997), and Anagnostopoulos (1994) published representative results for 1 DOF VIV of a cylindrical structure. However, the vortex shedding produced not only lift that caused transverse vibration of a cylindrical structure, but also pulsating resistance that caused streamwise vibration of a cylindrical structure. The streamwise vibrations affected the transverse amplitude, which became a matter of concern for research. As the research progressed, Moe and Wu (1990) for the first time experimented with two degrees of freedom (2 DOF) VIV of a cylindrical structure. Compared with the 1 DOF system that restricts the streamwise movement of a cylindrical structure, the 2 DOF system stimulated a larger transverse amplitude, but the increment was

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smaller. Subsequently, Sarpkaya (1995) studied the VIV of a cylindrical structure with different natural frequency ratios f_x/f_y, and found that when $f_x/f_y = 1.0$, the maximum transverse amplitude of the 2 DOF system was 19% higher than that of the 1 DOF system, with the maximum transverse amplitude reaching 1.1 D (diameter). Jauvtis and Williamson (2003, 2004) studied the VIV characteristics of a cylindrical structure at low mass and damping with 1 DOF and 2 DOF and found that when the mass ratio m^* was equal to 7.0, the maximum amplitude of the 2 DOF system was similar to that of the 1 DOF system that restricted the streamwise movement of a cylindrical structure. When the mass ratio m^* dropped to 2.6, the 2 DOF system developed a super upper branch of transverse response amplitude, the largest response amplitude reaching 1.5 D, a result that all previous experiments had failed to obtain, and the “2T” vortex mode corresponding to the maximum transverse amplitude was observed. Blevins and Coughran (2009) adopted a physical experiment method to comprehensively study the VIV of a cylindrical structure with 1 DOF and 2 DOF with variable mass ratios and found that the measured maximum amplitude was 1.75 D for a smooth 2 DOF cylinder at a Reynolds number (Re) of 139000.

Much research based on experimental study has been performed to study VIV numerically. Most scholars have used two-dimensional (2D) numerical simulation to study the VIV of a cylindrical structure with low mass-damping (Brika and Laneville, 1993; Newman and Karniadakis, 1997; Zhou et al., 1999; Blackburn et al., 2001). For Re = 100–200, numerical simulations (Brika and Laneville, 1993; Newman and Karniadakis, 1997; Zhou et al., 1999; Blackburn et al., 2001), including our previous research (Han et al., 2015, 2016, 2017), gave similar amplitude results (A/D = 0.6) that were lower than the expected values. Subsequently, some scholars simulated the VIV of a cylindrical structure with Re = 1000, with the amplitude of transverse vibration reaching a value of A/D = 0.7. All these numerical simulations were carried out at low Reynolds numbers, well below the Reynolds numbers used in the classic experiment (Jauvtis and Williamson, 2004). For this reason, numerical simulation seemed to capture only the initial and lower branches, whereas the upper and super upper branches were absent. Recently, some scholars began to use numerical simulation methods to study the VIV of a cylindrical structure at Reynolds numbers matched with the classic experimental values. Guilmineau and Queutey (2004) used a RANS numerical scheme to simulate the VIV of a cylindrical structure for 1 DOF and compared their results with the experimental data reported by Khalak and Williamson (1996). The numerical scheme acquired the vortex shedding pattern of the initial branch, the lower branch, and the maximum vibration amplitude corresponded to the experimental data, but the super upper branch data were not consistent with the experimental results. Wanderley et al. (2008) used an upwind TVD 2D numerical scheme to solve the RANS equations and used the k-ε turbulence model to simulate the VIV of a cylindrical structure for 1 DOF with the mass ratio being equal to 1.8. The numerical simulation results were compared with the benchmarking experimental results when the mass ratio was equal to 2.4 (Khalak and Williamson, 1996). The numerical results were in a good agreement with the experimental data and captured the corresponding response branch and vortex patterns. Pan et al. (2007) adopted RANS codes and the SST k-ω turbulence model to simulate the VIV of a cylindrical structure for 1 DOF, and the result was compared with the experimental data reported by Khalak and Williamson (1996). That numerical simulation also failed to capture the super upper branch and the authors explained the possible reasons. Srinil et al. (2013) studied a flexibly mounted circular cylinder for 2 DOF with variable nature frequency ratios f_x/f_y using experimental and numerical methods and reported that when $f_x/f_y = 1.0$ and mass ratio $m^* = 3.5$, the transverse amplitude of the numerical simulation was much smaller than that of the experimental value. The super upper branch predicted by Gsell et al. (2016) using a direct numerical simulation method was lower than that obtained by Jauvtis and Williamson (2004). It was necessary to show that Re = 3900 in the numerical simulation, whereas Re was in the 1000–15000 range in experiment (Jauvtis and Williamson, 2004). By using the 2D RANS code and the SST k-omega method, Zhao and Cheng (2010, 2011) obtained the super upper branch and 2T vortex shedding pattern with initial conditions of velocity increasing constantly, which was in a good agreement with the experimental results (Jauvtis and Williamson, 2004). However, the numerical results did not detail the time history of the drag and lift forces, cross-flow and streamwise displacements, vortex pattern, trajectory, frequency of VIV compared with the reported experiment (Jauvtis and Williamson, 2004). Li et al. (2014) adopted two typical turbulent models to simulate the VIV of a cylindrical structure for 1 DOF, and the predicted maximum amplitude was lower than that obtained by Khalak and Williamson (1996). Kang et al. (2017) applied a modified SST model based on OpenFOAM to simulate experimental results (Jauvtis and Williamson, 2004) and it captured the maximum amplitude reaching values of 1.4 D when the entrance velocity was made to increase constantly in the process of numerical simulation. Although the results obtained by Kang et al. (2017) were consistent in trend with experimental results, representing considerable progress, the result still left room for improvement, i.e., (1) the reduced velocity corresponding to the maximum amplitude was lower than that of experimental results (Jauvtis and Williamson, 2004); (2) the amplitude of time histories of transverse displacement y/D was not stable in the simulation, especially in the later stages of numerical simulation, when the transverse vibration amplitude fell into the lower branch, which was not consistent with the reported experiment (Jauvtis and Williamson, 2004). Overall, within the scope of the low Reynolds numbers, numerical simulation of the VIV of a cylindrical structure has been performed systematically and successfully, but at higher Reynolds numbers, the numerical simulation of that VIV still encounters some problems, for example, in the simulation of the super upper branch, the stability of the vibration amplitude corresponding to the super upper branch, the details of the drag and lift forces, the cross-flow and streamwise displacements, vortex pattern, trajectory, and frequency of VIV under varied reduced velocities.

Compared with previous studies, this study grabs the missing details of previous studies, which are essential to successfully simulate the super upper branch of VIV. The initialization of numerical simulation started from a cylinder with a specified reduced velocity case, i. e., the inflow velocity is kept constant, the dynamic viscosity $\mu = 0.000784\ N{\cdot}s{\cdot}m^{-2}$ and the density of the fluid $\rho = 995.3\ kg/m^3$(Jauvtis and Williamson, 2004). At the freestream boundary, the turbulence intensity was 0.9% (Govardhan and Williamson, 2006), the turbulence length scale was 0.04 D (Wanderley and Soares, 2015). In addition, in this study, the RANS code, the SST k-ω and the Newmark-β methods are adopted to simulate the VIV of a cylindrical structure, and the numerical results are compared systematically with the experiment data reported by Jauvtis and Williamson (2004). The details of drag and lift forces, cross-flow, and streamwise displacements, vortex pattern, trajectory, and frequency of VIV are presented. The simulation results obtained for the super upper branch, initial branch and lower branch are more accurate than those from previous reports. The vibration amplitude corresponding to the super upper branch is stable and more consistent with the experimental results (Jauvtis and Williamson, 2004).

2. Numerical method

2.1. Fluid governing equations

The flow field of the VIV of a cylindrical structure can be considered as an unsteady, incompressible, two-dimensional turbulent flow field. Therefore, the fluid governing equation used in this study is the unsteady and incompressible RANS equation written as follows: