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A numerical investigation of two-degree-of-freedom VIV of a circular cylinder using the modified turbulence model

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ABSTRACT

To simulate the fluctuating lift and resistance of the cylinder in vortex-induced vibration (VIV) accurately, the shear-stress transport (SST) turbulence model is modified in this paper. Then the correctness of the modified model is verified in the flow around a circular cylinder. After that, the numerical simulation of vortex-induced vibration of a cylinder with two degrees of freedom is carried out by using the embedded program of OpenFoam under three different initial conditions which are uniform acceleration, uniform deceleration and uniform velocity respectively. After the comparison and analyses of the vibration amplitude, frequency, fluid force, motion locus and vortex shedding, we find that there are some differences in the results obtained under three initial conditions. By contrast, the results of uniform acceleration condition are more accurate. Besides, the hysteresis mechanism can be analysed on the basis of the vortex shedding characteristics of uniform acceleration and deceleration. In general, the initial condition has a great influence on the numerical simulation of the vortex-induced vibration, and the validity of the modified turbulence model is further verified in the simulation.

1. Introduction

Vortex-induced vibration (VIV) is a fundamental phenomenon widely existing in many engineering fields, such as the risers in offshore oil and gas exploration, bridges, cables, antennas, etc. In the field of ocean engineering, the VIV of some cylindrical structures often appears under the effect of current. This is mainly due to the phenomenon that the vortex shedding occurs when the water flows around the cylinder, and the alternating vortex will produce periodic hydrodynamic loads. The structural periodic vibration is one of the important causes of the fatigue damage. In view of the practical significance of vortex-induced vibration, many scholars have been devoted to the study of the mechanism and characteristics of that (Lin and Wang, 2013; Wanderley and Soares, 2015; Kang et al., 2016; Cao et al., 2011).

Govardhan and Williamson (2000) investigated the amplitude response and frequency of the VIV of a cylinder at Reynolds number of 2000–12000. They found that there were two resonance regions of VIV in the condition of low mass damping ratio, and the vibration amplitude response would change with the mass ratio when the mass damping ratio is constant. Jauvtis and Williamson (2004) found that the VIV test results of single degree of freedom was similar to that of double degree of freedom when the mass ratio was 7. But when the mass ratio was 2.6, the cross flow amplitude of the two degrees of freedom produced “super upper branch”, and its amplitude arrived at 1.5D which had never been found before.

Pan et al. (2007) carried out the numerical simulation of the cylinder at low mass damping ratio using RANS code and attempted to simulate the “super upper branch” of VIV. But the final predicted vibration amplitude was smaller than the experimental value. Guilmineau and Queutey (2004) analysed the single degree of freedom VIV by numerical simulation on the basis of the low mass ratio VIV model test conducted by Williamson. In the simulation, the initial condition was set to be uniform acceleration. The calculated maximum vibration amplitude of the cylinder was found to be consistent with the experimental value, but the shape of the “upper branch” was not simulated accurately. He believed that the initial condition in the numerical simulation might have an effect on the vibration characteristics in the single-degree-of-freedom VIV. So it's necessary to investigate the effect of the initial condition on the characteristics of two-degree-of-freedom VIV while keeping the simulation accuracy higher.

One of the key points in the numerical simulation of vortex induced vibration is the selection of turbulence model. Celik and Shaffer (1995)

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analysed the problem of the flow around circular cylinder by using the standard $k-\varepsilon$ turbulence model and found that there were some obvious differences between the calculated results and the test results. Menter (1994) proposed the SST $k-\omega$ turbulence model by combining the standard $k-\varepsilon$ model and $k-\omega$ model. The accuracy of the SST $k-\omega$ turbulence model in the simulation of flow around cylinder has a certain improvement. However, considering that the SST $k-\omega$ turbulence model adopts the standard $k-\varepsilon$ model equations in the wake region and the standard $k-\varepsilon$ model has poor performance in the presence of abundant vortexes, the improvement in the application of SST turbulence model to the numerical simulation of cylinder VIV is still relatively necessary. Ünal et al. (2010) compared and discussed the computational results of several RANS turbulence models in the near-wake flow of a circular cylinder, pointed out that standard SST $k-\omega$ model seemed to be more advantageous for the simulation accuracy, but still not satisfying enough. Stringer et al. (2014) also hold that the accuracy of the numerical simulation for a circular cylinder remained to be improved when applying the standard SST $k-\omega$ turbulence model, especially for the VIV of the cylinder. Younis and Przulj (2006) improved the standard $k-\varepsilon$ turbulence model in the separation flow, which considered the effects of the interactions between the large-scale organized periodicity of the mean flow and the random, small scale high-frequency motions that characterize turbulence. So, according to the $k-\varepsilon$ turbulence model improved by Younis and Przulj (2006), the modification for the standard SST $k-\omega$ turbulence model, which can be applied in the flows dominated by vortex shedding, is a feasible idea.

In this paper, the standard SST $k-\omega$ turbulence model is improved to analyse the characteristics of the VIV of a cylinder in the CFD numerical simulation. In order to check the accuracy of the improved turbulence model for the simulation of fluctuating lift and drag, the calculation of the flow around the cylinder is carried out using an open source software named OpenFOAM. Then, based on the modified turbulence model and OpenFOAM, the numerical simulation of two-degree-of-freedom VIV of a circular cylinder with a mass ratio of 2.6 is conducted under three different initial conditions which involve uniform velocity, uniform acceleration and uniform deceleration. After that, the vibration amplitude, lock-in frequency, fluid force, trajectory and vortex shedding characteristics of the cylinder are analysed and compared under the three kinds of initial conditions. On this basis, the hysteresis mechanism of VIV is discussed, and the relationship between the vortex shedding mode and the hysteresis phenomenon under different initial conditions is studied.

2. Governing equations

2.1. Fluid modeling

In the Cartesian coordinate system, the fluid flow is controlled by the continuity equation and momentum equations (Navier–Stokes equations). By using Reynolds-Averaged Navier–Stokes (RANS) method, the continuity equation and Navier–Stokes equations can be described by (Celik and Shaffer, 1995)

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho \overline{u}_i)=0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho \overline{u}_i)+\frac{\partial}{\partial x_i}(\rho \overline{u}_i \overline{u}_j)=-\frac{\partial \overline{p}}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\mu \frac{\partial \overline{u}_i}{\partial x_j}-\rho \overline{u_i' u_j'}\right) \tag{2}$$

where ρ is fluid density, t is time, u_i and u_j are the velocity vectors, x_i and x_j are the position vectors of fluid unit, p is the pressure and μ is the dynamic viscosity. It should be noted that $\overline{\phi}$ represents the average value of the variable ϕ over time and ϕ' is the pulsating value.

The unknown turbulence variable $\overline{u_i' u_j'}$ in Eq. (2) are obtained here from Boussinesq's linear stress-strain relationship:

$$-\overline{u_i' u_j'}=\mu_t\left(\frac{\partial \overline{u}_i}{\partial x_j}+\frac{\partial \overline{u}_j}{\partial x_i}\right)-\frac{2}{3}\delta_{ij}k \tag{3}$$

where μ_t is the kinematic eddy viscosity and k is the turbulence kinetic energy both given by turbulence model, and δ_{ij} is the Kronecker symbol.

The additional equations, namely turbulence model need to be introduced for the continuity equation and Unsteady Reynolds-Averaged Navier–Stokes equations are not closed. One of the turbulence models commonly used in the problem of flow around a cylinder is the SST $k-\omega$ turbulence model. The characteristics of SST $k-\omega$ turbulence model is discussed in Section 2.2, and then it is modified by considering the expected change of the energy equilibrium due to vortex shedding.

2.2. The modified turbulence model

The SST $k-\omega$ turbulence model uses the standard $k-\omega$ model in near wall region, which can well simulate the laminar flow with reverse pressure gradient on the cylinder surface. However, it uses the standard $k-\varepsilon$ model to deal with the flow away from the wall, and it has already been mentioned that the standard $k-\varepsilon$ model fails in the prediction of flows dominated by vortex shedding in that it predicts a weaker vortex shedding intensity than that observed in measurements (Younis and Przulj, 2006). It has been widely verified by many investigations that the establishment of a vortex shedding field in a turbulent flow leads to direct energy input from the periodic mean-flow oscillations into the random turbulence motions (Jung and Park, 2005; Zhao, 2015; Zhu et al., 2016). This direct energy supply occurs at a frequency that corresponds exactly to the vortex-shedding frequency, but it haven't been considered in the SST $k-\omega$ turbulence model, which leads to some diffusion errors in the numerical simulation of the vortex shedding process in unsteady separated flows. The immediate implication is that, in unsteady separated flows, the dissipation-rate equation can be modified to reflect the expected change of the energy equilibrium due to vortex shedding. The specific derivation process is described below.

In the flow with vortex shedding, the form of energy spectrum function can be taken as (Reynolds, 1974)

$$E(\lambda,t)=\left(A^0+A^1(t)\right)\lambda^s \tag{4}$$

where A^0 is a constant and λ is the wavenumber vector. The index s is a matching index whose precise value is immaterial to the present discussion. $A^1(t)$ must vanish in the steady limit.

Thus the turbulence kinetic energy k and dissipation rate ε can be obtained by (Pope Cant, 2000)

$$k=\int_0^\infty E(\lambda,t)d\lambda \tag{5}$$

$$\frac{dk}{dt}=-\varepsilon \tag{6}$$

By postulating a shape for $E(\lambda,t)$ based on the measured spectrum given by Younis and Przulj (2006) and after integration of Eq. (5) there results

$$k=3s+\frac{5}{2}(s+1)A(t)\lambda_m^{s+1} \tag{7}$$

where λ_m^{s+1} is the wavenumber which corresponds to the location of the vortex-shedding frequency. Then we can take the two derivatives of kinetic energy k to get the rate of change of dissipation with time:

$$\frac{d\varepsilon}{dt}=-C_{\varepsilon 2}\frac{\varepsilon^2}{k}-\frac{1}{s+1}\frac{\varepsilon}{A^t}\frac{dA^t}{dt} \tag{8}$$

where $C_{\varepsilon 2}$ is the parameter in standard $k-\varepsilon$ model with the value of 1.92 (Younis and Przulj, 2006). We can compare the above derived dissipation