Numerical study on vortex induced vibration of three cylinders in equilateral–triangular arrangements

Feng Xu[1*], Yi-qing Xiao[1], Jin-ping Ou[2], Hai-tao Liu[1]

[1] ShenZhen Key Lab of Urban & Civil Engineering Disaster Prevention & Reduction, Shenzhen Graduate School of Harbin Institute of Technology, Shenzhen,518055, P.R.China

[2] School of Civil & Hydraulic Engineering, Dalian University, Dalian,116024, P.R.China

ABSTRACT

This paper presents a two-dimensional simulation of the vortex induced vibrations of three elastic cylinders in regular triangle arrangement at low Reynolds number. The motion of every single cylinder, which is free to oscillate in two degrees-of-freedom in a uniform flow and has the same mass and natural frequency in both X and Y directions, is modeled by a mass-spring-damping system. The displacement, mean and fluctuating aerodynamic forces, Strouhal number (St) and vortex shedding pattern in the wake for each cylinder are analyzed with eight spacing ratios L/D changing from 2.0 to 6.0. It is found that the simultaneous resonance in the x- and y- directions may occur for the downstream cylinder and the frequencies of the streamwise and transverse responses are same but with a phase shift. The cross-flow oscillation amplitude of three cylinders significantly increased compared with the flow-induced vibration of a single elastic cylinder and the streamwise oscillation of downstream cylinder is unneglectable for vortex-induced vibration of multi-cylinder system.

KEYWORDS: Three Cylinders, Vortex Induced Vibration, Spacing Ratio, Numerical Simulation

Introduction

Vortex induced vibrations (VIV) of cylinder group are a very common phenomenon in engineering, such as high-rise building groups, suspended cables of long-span bridges, marine cables and subsea pipelines in offshore platform, and so on. The resulting vibration has significant influence of the fatigue life of structures and could cause disastrous failure of industrial facilities with heavy financial losses. Therefore, engineers and researchers have spent much effort to investigate the VIV of cylindrical structures (Sarpkaya 2004, Govardhan 2001, Jauvtis 2003, Williamson 2004, et al). Nevertheless, the studying on VIV of the cross-flow past more than one or two cylinders is still relatively scarce, especially numerical simulation. Computational fluid dynamics (CFD) has become a powerful tool for solving complex fluid flow problems in the last decade and has been used to calculate the flow around single and multiple cylinders cover a wide range of Reynolds number (Re). In this paper, numerical simulations are presented for the VIV of three cylinders in equilateral–triangular arrangement at $Re=200$. The 2-D Navier-Stokes equations are solved by a finite volume method (FVM) with an industrial CFD code in which a coupling procedure has been implemented in order to obtain the cylinder response. The spacing ratio L/D is set as 2.0, 2.5, 3.0, 3.5, 4.0, 5.0 and 6.0 in turn. The main objective of this study is to examine the effect of L/D on the flow pattern, aerodynamic forces and response of the three elastically mounted cylinders.

Numerical method

Computational models and boundary conditions setting

The numbering and arrangement form of three equal diameter cylinders are shown in Figure 1. The L/D is defined as spacing ratio, here, L is the center-to-center distance, D is the cylinder diameter and equal to 0.01 m. The unstructured grids are employed to discretize the

[*] Corresponding Author, Post Doc, E-mail: xufenghit@hit.edu.cn

flow field as shown in Figure 2. The rectangle computational region is $45D\times30D$ with 15D upstream, 30D downstream and 15D on either side, respectively. The flow direction is from left to right, left side is set as velocity-inlet, right side is set pressure-outlet, the relative pressure is set as 0, the upper and lower free slip boundaries are set as symmetry and the model surface is set as wall.

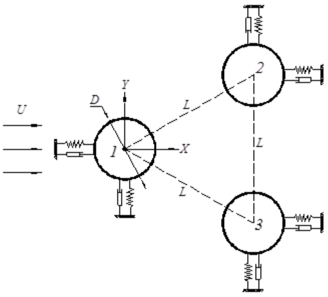

Fig.1 Calculation Model and arrangement form of three elastic cylinders

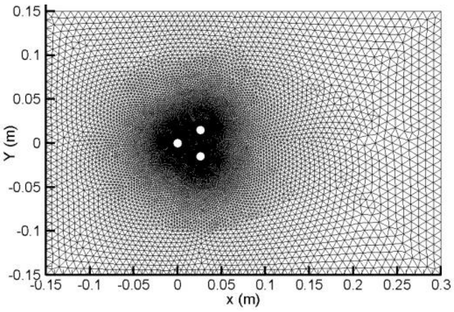

Fig.2 Computational region and Mesh division at L/D=3.0

Solution process of fluid-structure interactions

The fluid-structure interaction system was solved by loosely coupled method. The unsteady flow field is solved by CFD code (Fluent) based on a finite volume method (FVM) with a Pressure-Based algorithm. The Newmark-β method is manually written into the User-Defined-Function (UDF), during the calculation process, it is linked with solver to obtain the response of cylinders, the grid domain is updated by a dynamic mesh model. Utilizing rigid motion macro of Fluent to transfer cylinder's velocity to mesh, when the mesh iteration converged, the whole fluid domain is updated and the next time-step started. The loop continues until the stable solution is achieved.

Results analysis

Current studies confirm that the ratio between the natural frequency f_n of elastic cylinder and the vortex shedding frequency f_s^* of flow around rigid cylinder (hereinafter referred to as "frequency ratio f_n/f_s^*"), the dimensionless mass ratio $M^*=m/\rho D^2 l$ and reduced damping $S_g=8\pi^2 S_t^{*2} M^* \zeta$ are important parameters which have significant influence on the structural vibration. The parameters $S_g=0.01$, $M^*=1.0$ and $f_n/f_s^*=1.30$ are chosen for each of three cylinders, and a single cylinder with the same parameter subjected to VIV confined in the resonance band such as described by Zhou (1999).

Validation

Firstly, the flow around a rigid cylinder at Re=200 is carried out in order to ensure the reliability of numerical calculation.

Aerodynamic forces and Responses

This section shows the force coefficients vary as the spacing ratio for three cylinders in regular triangle arrangement, which include the mean and RMS value of lift coefficient $\bar{C}_l$ and C_l', the mean and RMS value of drag coefficient $\bar{C}_d$ and C_d', respectively.

The ratio of cross-flow and in-flow displacement mean and RMS values to diameter is shown in this section. The frequency analysis of the force and response of cylinders, the motion trajectories of each cylinder centroid for some of spacing ratio, the time histories of lift and drag coefficients, the ratio of the cross-flow and in-flow displacement to diameter D of every cylinder for different spacing ratios are also given.

Flow pattern

This section shows the instantaneous vorticity contours in the wake of three elastic cylinders in regular triangle arrangement.