Simulation on Vortex Induced Vibration of Circular Cylinder

T J Chang and K B Lua*

Department of Mechanical Engineering, National Chiao Tung University 1001 University Road, Hsinchu, Taiwan 300, ROC

*Email: engp4324@nctu.edu.tw

Abstract. In order to study the vortical flow field and the vibration caused by fluid-structure interaction (FSI), an efficient simulation setup was established. The simulation made use of the built-in Deforming Mesh function, Semi-Implicit Method for Pressure Linked Equations (SIMPLE) Algorithm and SST-kw Turbulence Model of Ansys Fluent to generate the flow field. A User Defined Function (UDF) was written to calculate the displacement of the cylinder based on the simulated flow field information. A range of Reduced Velocity was scanned through in order to find the “locked-in” region, which is the resonance occurring region. The present study focused on the forces acting on the cylinder and the resultant trajectory of different cylinder natural frequencies. The simulation needs further fine tuning to improve the accuracy.

1. Introduction

1.1. Motivation
Under the increasing demand on energy and the rapid consumption of non-renewable fossil fuels, researchers and engineers begin to focus on developing green energy. Some of the researchers start to develop Hydro energy harvester based on the vortex-induced vibration (VIV) and resonance phenomena. By matching the natural frequency of the Hydro energy harvester with the shedding frequency of the vortex, intensive power can be generated by resonance.

1.2. Vortex Induced Vibration (VIV) phenomenon.
The fluctuation of the force acting on the bluff body is caused by the alternative shedding of vortices from two sides of the body. The fluctuating force induces vibration, which in turn affects the flow pattern in the wake region. The type of flow pattern generated is associated with the ratio of the structure natural frequency \( f_n \) to vortex shedding frequency \( f_s \) (i.e. \( \omega_t = f_n/f_s \) [1]. By changing the ratio, the comprehensive study conducted by [2] revealed that the flow patterns appeared in the wake of an oscillating cylinder could be classified into the 2S mode, the 2P mode and the P+S mode. These modes are shown in figure 1. In the 2s mode, single vortex shed alternatively from each side of the cylinder, while in the 2p mode, a pair of vortices formed and shed from each side. And the p+s mode was the asymmetric combination of the two previous modes, a pair of vortices shed from one side while a single vortex shed from the other side alternatively. [3] provided a comprehensive discussion on the effects of dominant VIV parameters, including the mass damping ratio, natural frequency and reduced velocity, equipped the readers with a general understanding of VIV phenomenon. There are two “locked-in” regions which resonance appears. They are distinguished by
the maximum amplitude of the transverse oscillation. The higher amplitude region is called the upper branch, and the lower one called lower branch.

1.3. One degree of freedom (DOF) VIV simulation.
Several computational fluid dynamics studies focused on simplified two-dimensional (2D) VIV phenomenon. The works of [4] demonstrated that the application of RANS (Reynolds-averaged Navier–Stokes) code in the simulation of the VIV of a 2D cylinder is able to capture the flow accurately. [5] applied commercial CFD packages based on RANS code with shear–stress-transport (SST) k-ω model to conduct 2D simulation under fixed Re of 10000 with reduced velocity ranging from 3 to 14. Their results were compared with those obtained with three-dimensional (3D) simulation using a hybrid model of RANS and Large eddy simulations (LES) [6] as well as the experimental data. They claimed that the difference in pressure distributions were within acceptable range.

![Figure 1. Three kind of corresponding fluid patterns of different modes. (a) 2S mode. (b) 2P mode. (c) P+S mode.](image)

2. Method

2.1. The simulation domain
The relative sizes and geometry of the simulation domain is shown in figure 2. The settings were similar to those used in [5]. The working fluid was water. The properties of the water were imported from Fluent database. The density (ρ) was 998.2 kg/m³ and the viscosity (μ) was 0.001003 kg/m-s. Furthermore, the diameter of the cylinder (D) is set to be 0.03175mm and the Reynold number (Re = ρDV/μ) was fixed at 10000 as in [5] to facilitate comparison.

![Figure 2. The simulation domain.](image)

The boundary conditions are listed in table 1.

| Surface Type   | Symbol | Condition       |
|----------------|--------|-----------------|
| Velocity Inlet | V      | 0.3149 m/s      |
| Pressure Outlet| P_g   | 0 Pa Gauge Pressure |
| Side Wall      | -      | Symmetry        |
| Cylinder Wall  | -      | Wall            |
2.2. Mesh setting

In the deforming mesh technique, due to the need of deformation, unstructured mesh cells were created. As shown in figure 3, the domain can be split into three zones. In the cylinder zone surrounding the cylinder, the shape of the mesh cell was quadrilaterals and the dynamic mesh moved with the cylinder. The mesh remained unchanged since there was no relative motion between the mesh and cylinder. In the otter deforming zone, the meshes deformed and remeshed due to the cylinder motion. And the remeshing size was set to be within 0.001 to 0.0075 meters (0.03D to 0.2D).

![Figure 3. The mesh diagram. (a)The mesh zones (b) Mesh pattern.](image)

2.3. The details of the mesh setting of the cylinder zone

To ensure the accuracy of the simulation results, the first mesh layer above cylinder wall should be within the viscous sub-layer. As suggested by [8], when simulating with SST k-ω model, the first mesh layer above the cylinder wall should be located within $y^+ = 3$. The definition of $y^+$ is:

$$y^+ = \frac{\rho u_T y}{\mu}$$  \hspace{1cm} (1)

where friction velocity $u_T$ is defined as $\sqrt{\frac{\tau_w}{\rho}}$. $y$ is the distance from the cylinder wall and $\tau_w$ is the wall shear stress. In the preliminary run of simulation, the maximum value of wall shear stress ($\tau_{w,\text{max}}$) on the cylinder was found to be around 3 $\text{pa}$. The average wall shear stress $\tau_{w,\text{ave}}$ is assumed to be $\approx 0.5\tau_{w,\text{max}} \approx 1.5 \text{pa}$. To tested the sensitivity of the $y^+$ in three different mesh resolution in the radial direction. The mesh growth rate was fixed at 1.05. The mesh setups are shown in table 2. Correct vibration amplitude will be obtained only if the lift ($C_l = \frac{F_{\text{lift}}}{0.5 \rho D V^2}$) and drag ($C_d = \frac{F_{\text{drag}}}{0.5 \rho D V^2}$) coefficients are calculated correctly. The frequency of the vortices shedding should be validated in terms of Strouhal number ($S_t = f_s D/V$). Furthermore, the position of the separation point can be obtained by pressure coefficient distribution on the surface which is shown in figure 4.

![Figure 4.](image)

| Model         | Number of mesh on cylinder surface | Number of mesh in radial direction | Total number of mesh |
|---------------|------------------------------------|------------------------------------|----------------------|
| SST k-ω rough | 240                                | 60                                 | 35268                |
| SST k-ω medium| 320                                | 80                                 | 51428                |
| SST k-ω fine  | 400                                | 100                                | 70788                |
Table 3. The Comparison of the fix cylinder force report.

| Model              | $y^+$ | $C_{d,mean}$ | $C_{l,rms}$ | $S_T$ |
|--------------------|-------|--------------|-------------|-------|
| SST k-ω rough      | 8.7   | 1.328        | 0.923       | 0.208 |
| SST k-ω medium     | 3.2   | 1.439        | 1.149       | 0.202 |
| SST k-ω fine       | 1.2   | 1.290        | 0.978       | 0.202 |
| Dong et.al DNS [9] | -     | 1.143        | 0.448       | 0.203 |
| Norberg , Exp      | -     | -            | 0.25–0.46   | $\approx 0.2$ |

Figure 4. Pressure coefficient distribution in different mesh setup.

2.4. Turbulence model
To simulate with limited computational resources, RANS model was selected. In the RANS model, SST k-ω turbulence model is a hybrid model combining k-ε model and k-ω model. The k-ε model was applied in the free stream region to better estimate forces. The k-ω model was applied in the near-wall region to get accurate separation position and the viscous sublayer thickness. As the result (table 3), it is appropriate to use the SST k-ω model for the simulation of the VIV phenomenon.

2.5. Important parameters
The one degree of freedom (DOF) oscillation are governed by the equation

$$m \frac{d^2y}{dt^2} + c \frac{dy}{dt} + ky = Lift \ force$$

(2)

The schematic diagram of the system is shown in figure 5.

Expanding the damping coefficient (c) and spring constant (k) in terms of the natural frequency ($\omega_n$) and damping ratio ($\zeta$), the equation is transformed into

$$m \frac{d^2y}{dt^2} + 2\zeta \omega_n m \frac{dy}{dt} + \omega_n^2 m y = Lift \ force$$

(3)
Follow [5], the mass ratio ($m^*$) was set to be 11. The cylinder mass ($m$) was calculated with $m^* \rho \pi D^2 / 4$. In the search for resonant region that the vortices shedding frequency match with the body oscillating frequency, the simulation was conducted with changing reduced velocity ($U_r = \frac{V}{f_n D}$).

Due to the fixed Reynolds number, the velocity and cylinder diameter were fixed. The natural frequency of the cylinder could only be changed by changing the reduced velocity. From the definition of reduced frequency, $f_n = V / (U_r D)$. Next $\omega_n = 2\pi f_n$ was input into the motion equation (3).

2.6. Algorithm
Simulation was performed with time step size of 0.01 s. Navier-Stoke equations were solved by Semi-Implicit Method for Pressure Linked Equations (SIMPLE) algorithm. Pressure and momentum were discretized with second-order upwind scheme. The traverse velocity of the cylinder was calculated using the UDF code. The flow chart of the whole iteration is shown in figure 6.

![Flow chart](image_url)

**Figure 5.** The schematic diagram of 1 DOF VIV system.

**Figure 6.** Iteration process.
3. Results and Discussion

3.1. Force coefficient and the vibration amplitude

To obtain preliminary results rapidly, the rough mesh setup had been selected. The frequency test is shown is figure 7. The resonant region was found to be within $U_r = 8 - 16$. The experimental results of [10] showed that resonant appeared between $U_r = 4 - 12$. The resonant region of the present simulation shifted to higher $U_r$.

Figure 7. (a) $U_r = 24.30$, period $(T) = 0.55$s (b) $U_r = 16.20$, $T = 0.88$s (c) $U_r = 12.15$, $T = 0.67$s (d) $U_r = 9.72$, $T = 0.54$s (e) $U_r = 8.10$, $T = 0.47$ (f) $U_r = 6.94$, $T = 0.53$ (g) $U_r = 6.07$, $T = 0.52$ (h) $U_r = 5.40$, $T = 0.51$. 
3.2. The Pattern of vortex shedding

The vortex patterns are shown in figure 8 and figure 9, these patterns are very similar to those shown in [2]. In figure 8, for every stroke of cylinder motion, a pair of same sign vortices shed, formed the 2p mode wake pattern. In figure 9, a vortex shed from the upper side of the cylinder as it moves up and an opposite sign vortex shed from the bottom side as it moves down, therefore forming the 2s mode wake pattern. And the vorticity contour show that the vortices diffused in the wake region. The fast diffusion may be caused by the artificial diffusion setting in the simulation. To correct this problem, the mesh density should be increased in the wake region or higher order discretize scheme should be applied.

![Figure 8](image1)

**Figure 8.** The vorticity contour in a cycle of oscillation. \( U_r = 8.10, \xi = 0.001, m^* = 11 \). (a) T/6. (b) 2T/6. (c) 3T/6. (d) 4T/6. (e) 5T/6. (f) 6T/6.

![Figure 9](image2)

**Figure 9.** The vorticity contour in a cycle of oscillation. \( U_r = 6.07, \xi = 0.001, m^* = 11 \). (a) T/6. (b) 2T/6. (c) 3T/6. (d) 4T/6. (e) 5T/6. (f) 6T/6.
4. Concluding Remarks

The conclusion from the grid test results showed that the mesh density in the wake region should be increased, and the mesh resolution should also need to be increased to achieve lower y+.

As for the VIV simulation, the correct modes of wake patterns were observed, but the resonant region appeared at higher Ur when compared to experimental results. It might be the low resolution of the time step and the low-ordered discretization scheme. Fine tuning of the simulation will be carried out in the near future.

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