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Numerical Simulation of Phase Map Shift of Vibrating Cylinder at Low Reynolds Number

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Abstract

The circular cylinder under a cross flow experiences boundary layer separation. It is a classical problem of fluid dynamics found in applications such as tall building structures, pipes, tubes, cables etc. Based on the Reynolds number range, periodic flow develops in the wake. The pattern of vortex shedding from the sides of the structure causes pressure fluctuations which may lead to structural vibration. The motion of structure leads to influence the flow pattern especially in the wake. In this paper we compare results for two cylinders having similar mass ratios for Reynolds number range of 2500-6000 with different structural damping. Initial validation of coupled fluid structure interaction simulations is obtained using comparison of vortex shedding frequencies and RMS amplitudes of both cylinders with experimental data. At low damping cylinder follows a random trajectory different from the cylinder having high damping ratio. With turbulent flow conditions the phase map of the lightly damped cylinder shows significant shift compared to laminar flow. It is observed that for the lightly damped structure, the dominating frequency of structural vibration matches its natural frequency for the range where $S_t \sim 0.2$ with non-uniform flow conditions.

Keyword: Vortex-induced vibration, Strouhal number, Reynolds number, FFT.

1. Introduction

Vortex induced vibration of bluff bodies is of practical interest in many branches of engineering. Areas such as aero-elastic and hydro-elastic problems involve fluid-structure interaction with the interacting fluid are usually air and water. In many practical cases cylindrical structures are subjected to cross flows such as riser tubes, heat exchanger tubes, poles and round building structures. The cross flow often lead to generate vortex structure in the wake of the circular structure and at certain Reynolds number vortex are shed in a stream leading to fluctuation of force on the structure causing vortex-induced vibrations. The response of the cylinder and the broad physics of the neighbouring fluid in the problem of vortex-induced

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vibration have been well studied especially for 'lock-in' oscillation case, and several reviews discuss this problem (see [1-3] for example). When the frequency of the vortex shedding coincides with the natural frequency of the structure the response of the structure is enhanced. Feng [4] showed the resonance of a structure when the fluctuation frequency coincides with the vortex shedding frequency for a range of normalised velocity $U^{*} \sim 5$ to 8. Where $U^{*} = U/f_n D$ with f_n is the natural frequency and *D* is the diameter of the cylinder. It is also observed that the motion of the cylinder influences the flow field and in return the response of the structure is coupled. For very high mass ratio, (*m**, mass of oscillating structure / displaced fluid mass), and damping ratios such an effect has been studies [5]. Different wake structures are also reported at low mass and damping ratio [6] however these modes and responses are found for transverse vibration generally in a fluid flow. Moe & Wu [7] studied two dimensional motions with different mass ratios in the X and Y directions. Under these conditions a broader regime of velocity U^{*} was indentified over which resonant amplitudes are found. Also the comparison has shown that the stream-wise motion of the structure influences the motion in the transverse direction [JFM 1999].

The influence of free-stream turbulence on a single rigid cylinder in a cross flow has been studied extensively (for instance see [1-5]). In general free stream turbulence alters the vortex shedding frequency, pressure distribution and forces on the cylinder [5]. Experimental studies of circular cylinder subjected to non-uniform flow have also been carried out but generally limited to critical or sub-critical Reynolds number range [2].

In this research work we analyze two circular cylinders of similar mass ratios subjected to cross flow. The two cylinders are of same material however they are of different sizes and thus offer different structural damping. Both cylinders are subject to same Reynolds number varying from 2500-6000. Here we compare the response of both cylinders in x and y directions using numerical simulations. The results are also compared with the published experimental data [8]. The responses of both cylinders are also compared for uniform flow field (laminar) as well non-uniform flow field (turbulent).

2. Computational Model

The fluid flow is model using standard available modules of commercial CFD software Fluent. However in order to introduce structural coupling we use method of fully coupled interaction. A fully coupled interaction resolved the flow field using CFD solver (here Fluent) and the structural response of the rigid structural object is estimated using structural solver. The Fluent solver utilizes an implicit approach to the solution of the unsteady two-dimensional Navier-Stokes equations for computation of flow parameters. This is accomplished using constant physical time stepping in the calculations. In parallel calculations are performed using a domain re-meshing/deforming technique with efficient communication requirements, shown in Figure 1 a.

The flow field around the cylinder is simulated by solving the unsteady, compressible, laminar as well as turbulent (RANS) Navier Stokes equations using an implicit, up-wind, flux difference splitting, finite volume scheme. For turbulent model of flow the standard "*two equations Wilcox k-*μ *turbulence model*" is used [11]. This model shows best results as compared to other two equation and one equation models present in Fluent. This is due to better wake treatment of the turbulence model [11]. The solution is advanced using second-order time accurate scheme with fixed time step size; it was observed that approximately sixty iterations per physical time step produced the optimal convergence per iteration.

The frequency with which vortices are shed in the vortex street behind the stationary circular cylinder is measured from which dimensionless frequency or Strouhal number [12] is calculated and compared with experimental results [8]. The shedding frequencies are derived

from the fast Fourier transform of the lift coefficient, which is obtained via the time history of the coefficient of lift, 'C_L' for the solid wall obtained at each time step size of 10^{-5}.
The multi–block structured mesh is used for simulation. As convention the flow inlet is on the left side of the Figure 1 b. The right side and upper and lower boundaries are outlets. Three different mesh dimensions are used to conduct the mesh refinement study for the stationary cylinder consisting of 27504, 34832 and 35,742 cells respectfully. The mesh size of 34832 and 35742 find better approximation for the flow parameters with maximum difference less than 1%. The second mesh size of 34832 is used as the baseline mesh for all the computations involving flow past a cylinder. The 2D grid consisted of 34,832 cells and 6 blocks, and extended 50 diameters into the far-field (Figure 1 b).

The structural solver approximates the motion of the cylinder using a spring-damper mass model which permits translational motion along the stream (x) and transverse (y) directions. Under these simplifications the complete model represents the first bending mode in both coordinate directions. The cylinder is connected to two linear springs along each of the coordinate axes with structural dampers, a schematics is shown in Figure 1c. Since both L and D are functions of time, displacements in both coordinate directions will be excited by the unsteadiness in the flow.

$$m\ddot{x} + c\dot{x} + kx = D \qquad (1)$$

$$m\ddot{y} + c\dot{y} + ky = L \qquad (2)$$

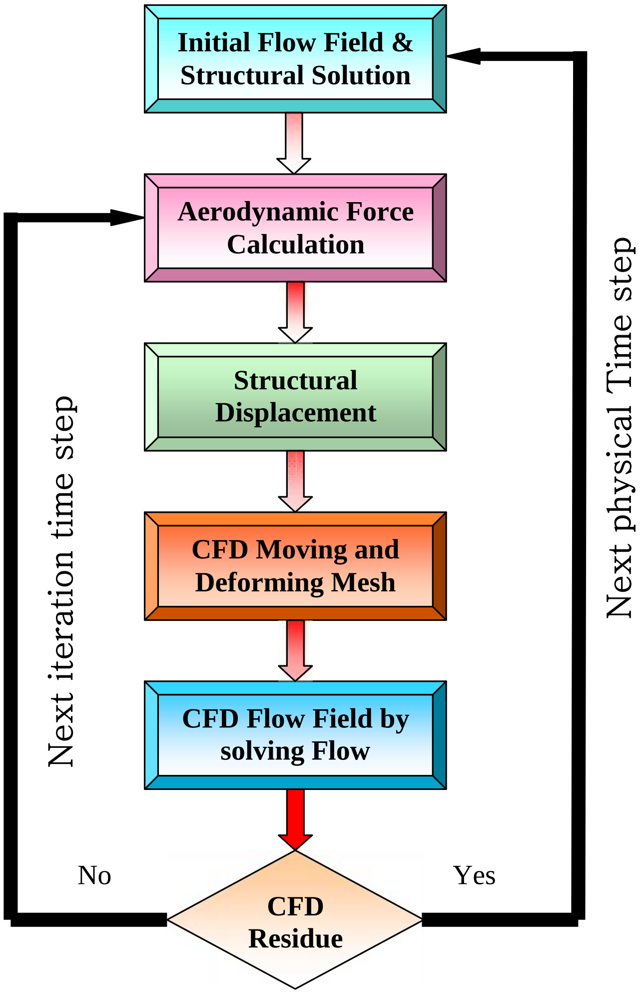

Figure 1(a). Overview of the fluid-structure interaction scheme.

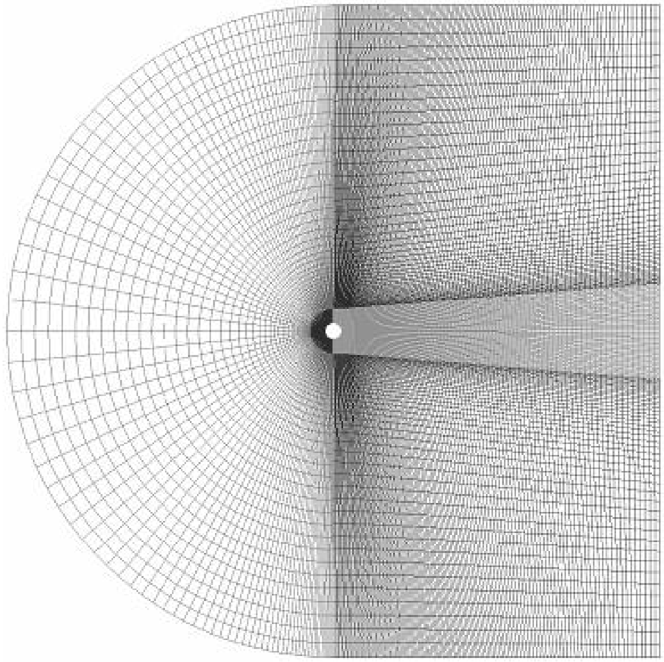

Figure 1 (b) 2D grid around Circular cylinder.

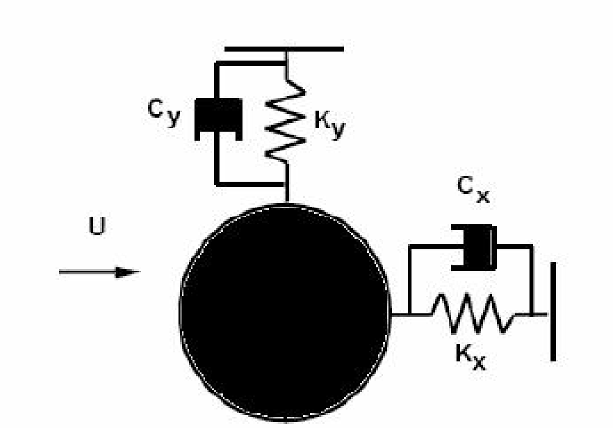

Figure 1 (c) Structural model of the Circular cylinder.

3. Results and Discussion

Initially validation of the numerical scheme is obtained by comparing results for the vortex shedding frequency for both cylinders with experimental data. The flow conditions are summarized in Table 1 and 2 for cylinder B1 and B2 respectively.

The RMS amplitude of the structural vibrations is also compared with the experimental results. Figure 2 and 3 shows the results for the case of both laminar and turbulent flow conditions. It can be seen from Figure 2a and b that S_t number for both cases is in good match with the experimental data. However turbulent flow simulations slightly better match compared to laminar flow conditions for both cases. This can also be observed in the RMS amplitude comparison for cylinders B1 and B2 in Figure 3a and 3b. The amplitudes predicted for the cylinder B1 are higher compared to the experimental results for both laminar as well as turbulent simulations. However results for cylinder B2 show better match with experimental results especially for turbulent flow simulations.

The amplitudes predicted for cylinder B1 are significantly higher compared to the experimental findings. This is can be linked with the structural damping of both cylinders as structural damping for cylinder B1 is 5 order of times lower than cylinder B2. The amplitudes predicted by turbulent flow simulations are higher than laminar flow model and matches well with the case for higher structural damping. While surprisingly for lightly damped case the experimentally observed amplitudes are lower while turbulent flow conditions still predict highest levels of amplitudes. The discrepancy between the amplitudes predicted by laminar and turbulent flow simulations is significant.

TABLE 1. FLOW PARAMETERS FOR CYLINDER B1

Reynolds number	Velocity (m/s)	Temperature (K)	Viscosity (kg/m-s)	Density (kg/m^3)	Pressure (Pa)
2500	9.93	288.15	1.79E-05	1.185536	98042.67
4600	18	288.15	1.79E-05	1.203398	99519.84
6000	23.7	288.15	1.79E-05	1.192139	98588.73

TABLE 2 FLOW PARAMETERS FOR CYLINDER B2

Reynolds number	Velocity (m/s)	Temperature (K)	Viscosity (kg/m-s)	Density (kg/m3)	Pressure (Pa)
2500	3.01	288.15	1.79E-05	1.170246	96778.25
4600	5.76	288.15	1.79E-05	1.125224	93054.97
6000	7.10	288.15	1.79E-05	1.190684	98468.46

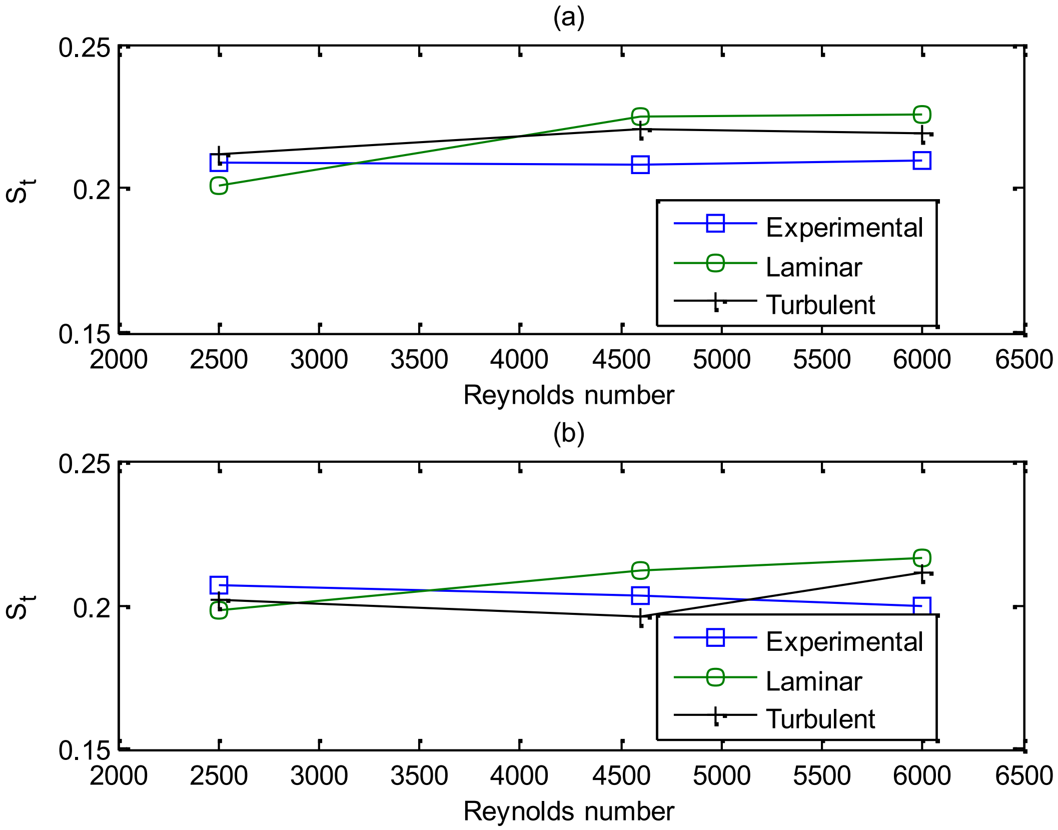

Figure 2. Comparison of Strouhal number for cylinder B1(a) and cylinder B2(b).

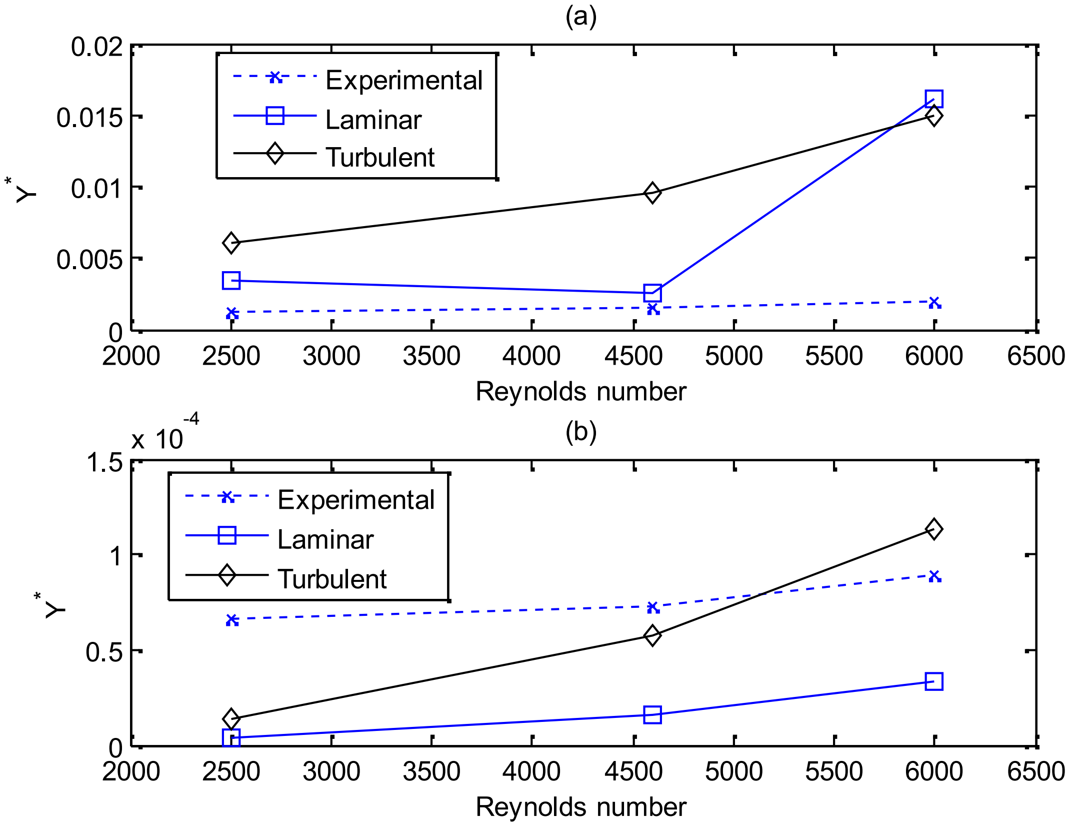

Figure 3. Comparison of rms amplitude for cylinder B1(a) and cylinder B2(b).

In order to investigate the difference between the two cases we show the trajectories of both cylinders in Figure 4. Figure 4 only shows trajectories of both cylinders for the case of Re 2500 where the match between experimental results is better. A significant difference between the trajectories of both cylinders can be seen. The trajectories of cylinder B2 for laminar and turbulent flow conditions resemble the typical trajectories seen previously [9], while cylinder B1 exhibits more chaotic trajectories. Importantly the trajectories of laminar and turbulent flow fields are also different for cylinder B1 (see Figure 4 (a) and (b)). For the turbulent flow conditions the cylinder B1 seems to have reached a saturated/limit cycle oscillations, while laminar flow trajectory shows non-uniform non-repeating pattern.

The difference between the laminar and turbulent flow trajectories can be linked with the fluidic damping mechanism of both. The phase maps of laminar as well as turbulent flow simulations are shown in Figure 5 and 6 for y-direction and x-direction respectively. Cylinder B2 in each case exhibit typical behavior irrespective of the flow approximations. Figure 5 (c and d) and Figure 6 (c and d) show that the cylinder B2 remains in a harmonic excitation pattern. While cylinder B1 shows a phase shift between laminar and turbulent flow simulations. Such a shift is also seen in some of the experimental for uniform and turbulent flows [4-5]. Both x and y direction phase maps indicate that in turbulent flow simulations the directional velocities are not in synchronization. Rather a lag of π/s is observed for laminar and turbulent flow in both directions. Also the amplitudes of directional velocities for both directions are similar, with lower displacement amplitudes for the laminar case. This suggests that the damping in laminar case is higher compared to turbulent flow. The findings are in consistence with the previous experiments [5-13] where separations angles are usually linked with the structural damping flow.

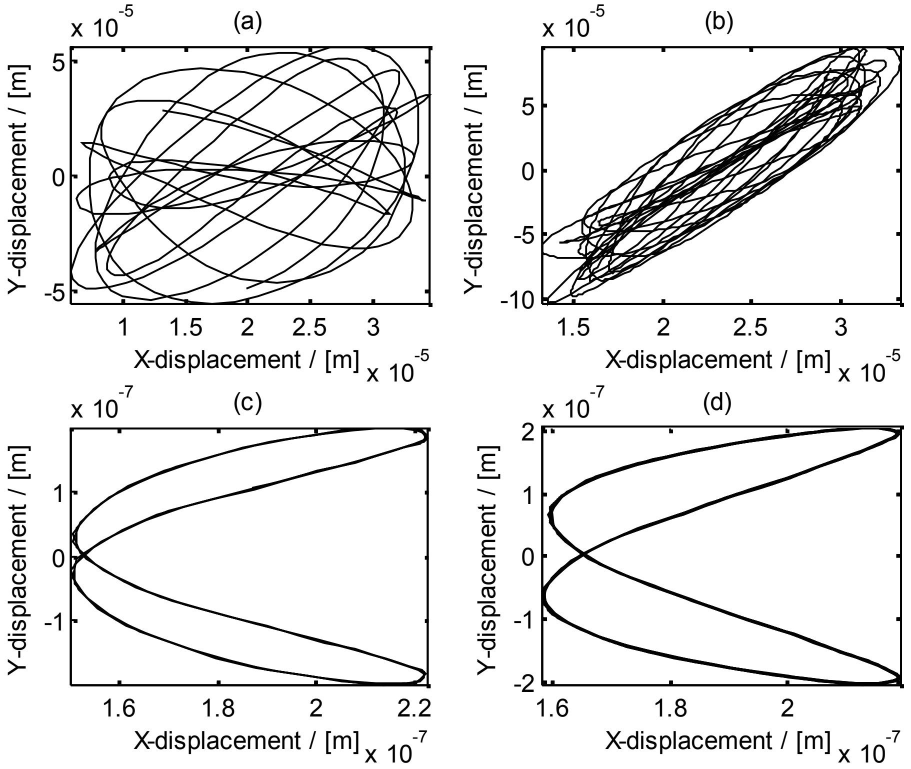

Figure 4. Trajectory plot for cylinder B1 (a) laminar (b) turbulent and cylinder B2(c) laminar (d) turbulent at Re = 2500.

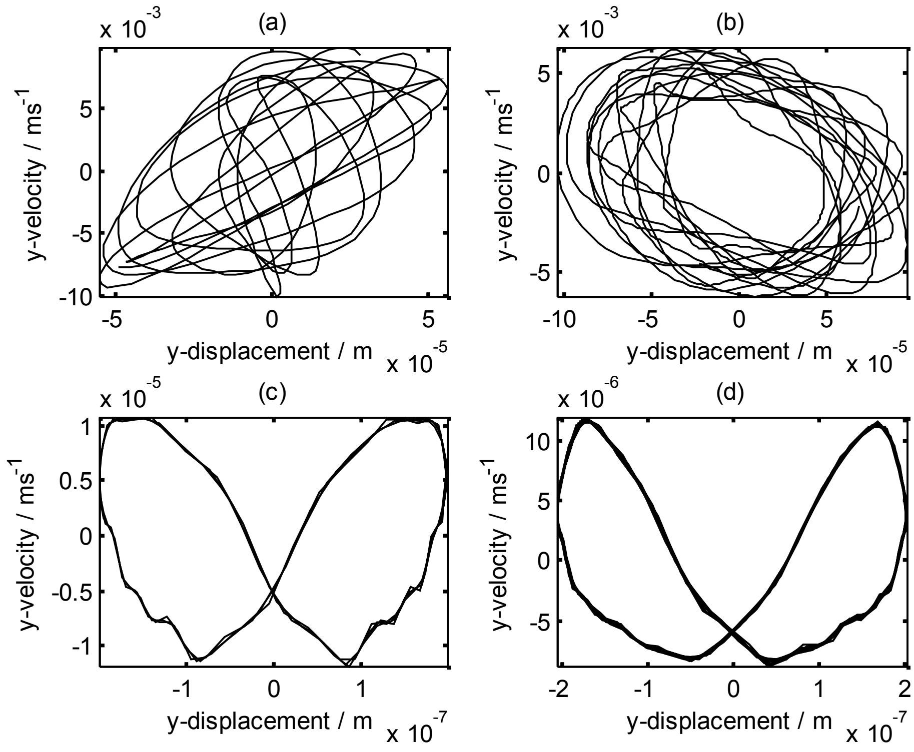

Figure 5. Phase map in y-direction for cylinder B1 (a) laminar (b) turbulent and cylinder B2(c) laminar (d) turbulent at Re = 2500.

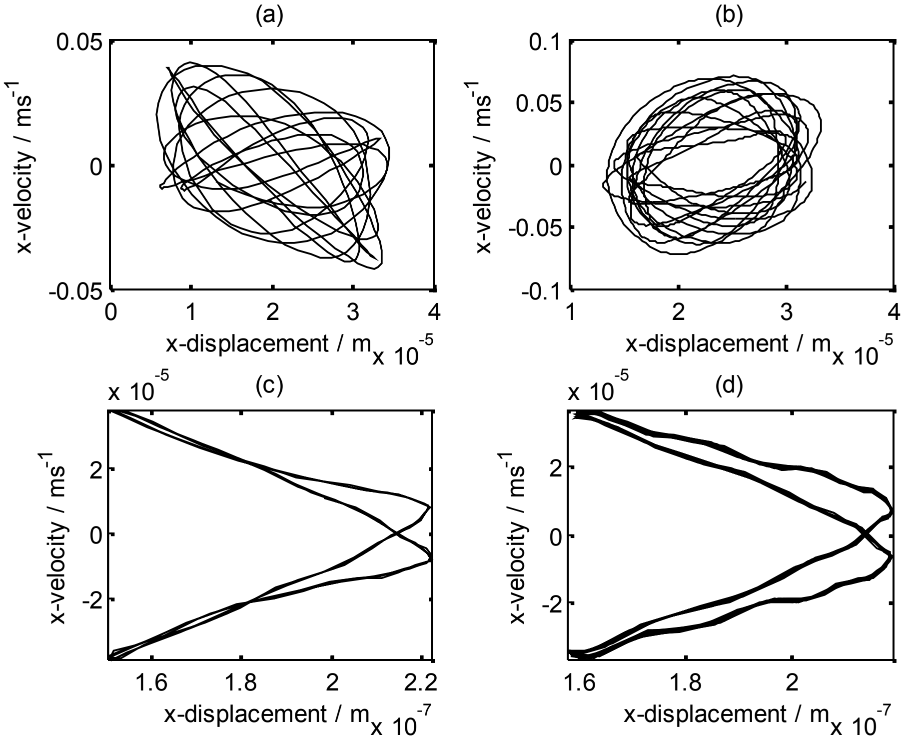

Figure 6. Phase map in x-direction for cylinder B1 (a) laminar (b) turbulent and cylinder B2(c) laminar (d) turbulent at Re = 2500.

The phase shift in the vibration of cylinder for laminar and turbulent flow fields at low Reynolds number can be related to the excitation frequencies the cylinder experiences. With the increase of flow velocity we expect changes in the excitation frequencies. The comparison of Fast Fourier transforms (FFT) of the y-direction amplitudes of both cylinders is shown in Figure 7 a and b. Figure 7a shows the normalized PSD at different incoming flow velocities for laminar case, and Figure 7b shows the same for the turbulent flow. The difference between the two is seen especially at higher velocities. For $U < 10$ m/s, the FFT results are similar with peaks for maximum amplitude appearing near the St ~ 0.2. For $U > 10$ m/s, the appearance of two peaks indicates a low frequency component is more dominant in the structural vibrations. A peak corresponding to vortex shedding frequency (St ~ 0.2) is still seen especially for laminar flow case. However lower frequency of oscillation is dominant especially for turbulent flow case.

The excitation frequency observed for the cylinder B1 is near the natural frequency of the cylinder and is significantly away and lower than vortex shedding frequency. It is also evident from FFT plots (Figure 7b) that in the turbulent flow cylinder's natural frequency is excited predominantly for the case when the vortex shedding frequency is higher compared to natural frequency of structure. A similar behavior is also seen in the laminar flow however the contribution from vortex shedding frequency is still significant. The shift of cylinder displacement frequency from the vortex shedding frequency has been observed in some of the recent experimental findings [5,8] especially for the turbulent/non-uniform flow conditions.

The dominating structural natural frequency of cylinder B1 is also observed in the experimental measured energy distribution. PSD plot of experimentally measured energy in the y-direction is shown in Figure 8(b). While for the case of cylinder B2, the natural frequency lies far from the vortex shedding frequency (see Figure 8(a)). The amplitudes observed for cylinder B2 are fairly low with high damping, thus no single dominating frequency appears in the spectra.

(a)

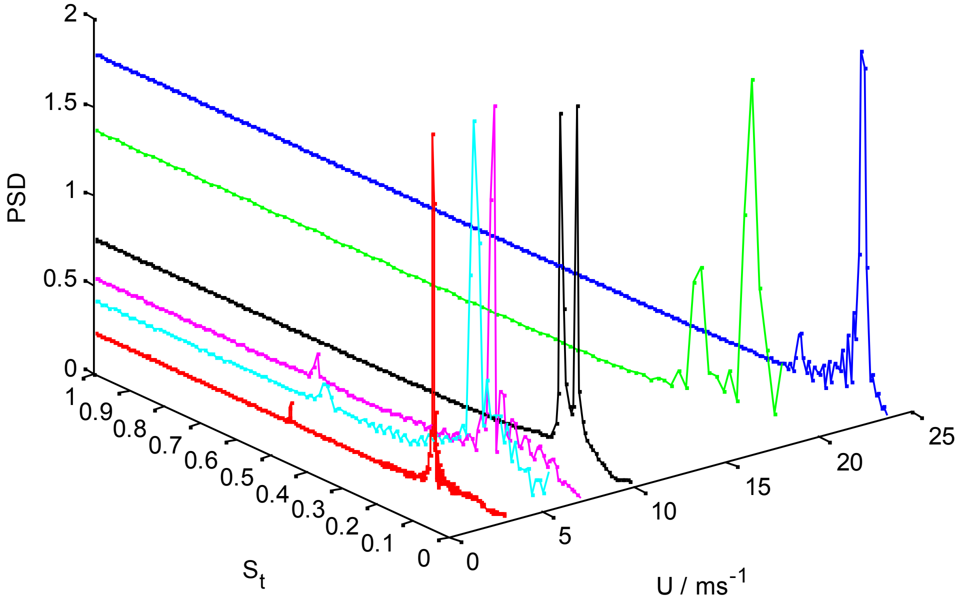

Figure 7a. FFT plot of y-direction displacement for cylinder B1 and cylinder B2 for laminar case.

(b)

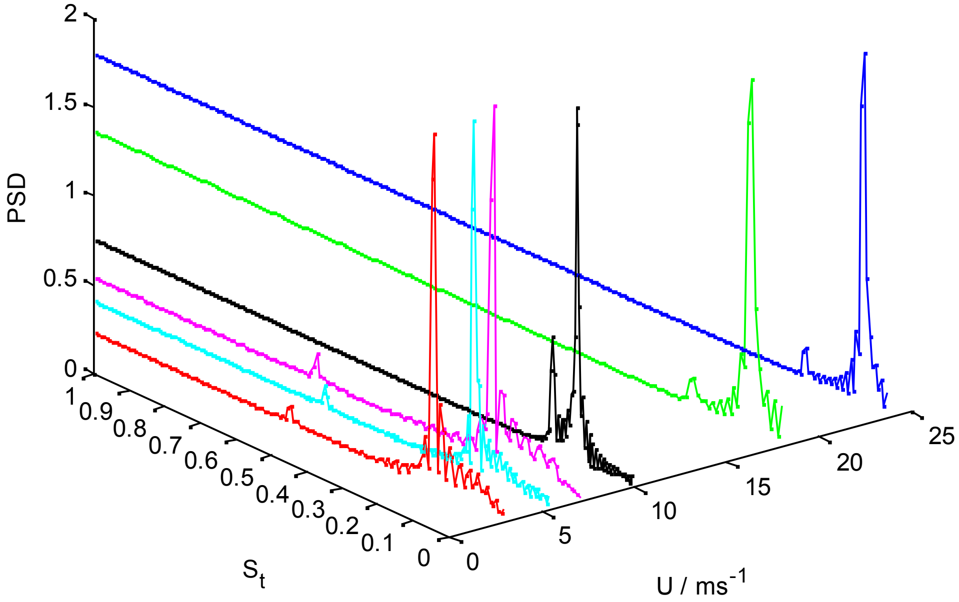

Figure 7b. FFT plot of y-direction displacement for cylinder B1 and cylinder B2 for turbulent case.

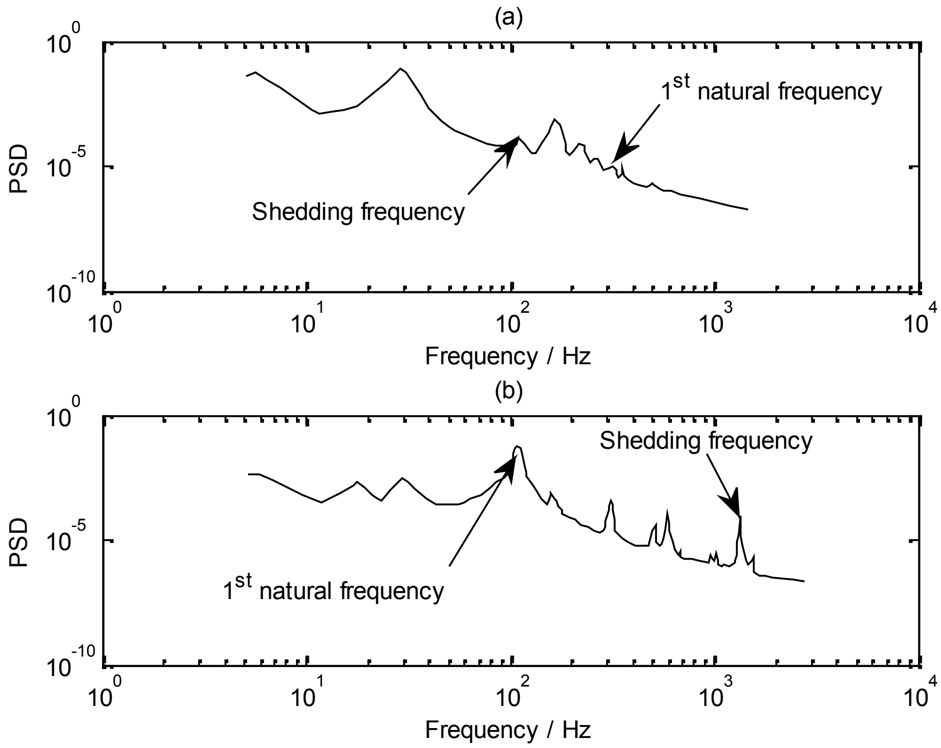

Figure 8. Experimental FFT plot of y-direction energy for cylinder B1 (b) and cylinder B2 (a).

4. Conclusion

A comprehensive analysis of two dimensional elastic cylinder using coupled fluid structure interaction has been carried out. Following important points can be concluded from above:

1. The simulations indicate that the lightly damped cylinder is susceptible to free-stream velocity which can lead to high amplitudes with random trajectory.
2. The influence of free stream turbulence on two dimensional cylinder is different from laminar flow. The cylinder seems to exhibit different trajectories.
3. The excitation frequency for lightly damped cylinder is found different from the heavily damped cylinder.
4. The synchronization is seen even away from vortex shedding frequency for lightly damped cylinder with low 1st natural frequency.

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