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NUMERICAL SIMULATION OF LAMINAR FLOW PAST OSCILLATING CIRCULAR, SQUARE AND ELLIPTICAL CYLINDER

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Abstract — *Flow past circular cylinder is a fundamental fluid mechanics problem of practical importance. It has potential relevance to many practical applications such as submarines, off shore structures, bridge piers, pipelines etc. In scientific terms, the flow around circular cylinders exhibits various important physical phenomena, such as separation, vortex shedding and turbulence in the wake, at relatively low flow speed. Building on understanding of a single stationary cylinder, many researchers have focused on multiple stationary or oscillating cylinders.*

The present study numerically investigates the two-dimensional laminar flow past a circular, square and elliptical cylinder forced to oscillate transverse to the free-stream. The analysis are performed at a various range of cylinder oscillation frequency ranged between 0.8 and 1.2 of the natural vortex shedding frequency, and the oscillation amplitude is 50% of the cylinder diameter at fixed Reynolds number of 185 showing the typical two-dimensional vortex shedding. Numerical study carried out with CFD (Computational Fluid Dynamics) tools FLUENT with dynamic mesh. UDF (User Defined Function) are incorporated with FLUENT to give simple harmonic motion to cylinder.

Keywords*- Oscillating Cylinder, Vortex Frequency, UDF, Low Reynolds Number, Flow past body.*

I. INTRODUCTION

Generally flow past a structure has similar instabilities irrespective of its shape, whether it is rectangle or circle or any other shape but the boundary layer separation mechanism is significantly different. The flow dynamics is very much dependent on the geometry of the body. Neglecting the flow dynamics past bodies may result in poor performance of the system or in worst cases it may even lead to disasters like the Tacoma Narrows Bridge collapsed that happened in 1940. For example the vortex formation region is significantly broader and longer for a square cylinder as compared to a circular cylinder because of a larger effective surface area in the wake side of a square cylinder. Dong-Woo Park et al.[1] numerically investigates the two-dimensional laminar flow past a circular cylinder forced to oscillate transverse to the free-stream. The numerical simulations are performed at a various range of cylinder oscillation frequency ranged between 0.8 and 1.2 of the natural vortex shedding frequency, and the oscillation amplitude extended up to 50% of the cylinder diameter at one Reynolds number of 185 showing the typical two-dimensional vortex shedding. A. Roshko et al. [2] experimentally studied the existence of vortex synchronization in the wavelength-amplitude plane (which defines the shape of the body trajectory). Several new regions of synchronization occupying this plane have been identified up to amplitudes of five diameters and to wavelengths of 16 diameters. Rockwell et al.[3] experimentally showed that the switch of vortex formation position occurs according to the oscillation frequency. Koopmann et al.[4] conducted a flow visualization study for the investigation of the effect of the cylinder excitation in the transverse direction on the vortex street wake. He found that synchronization of the vortex-shedding frequency with the cylinder oscillation frequency (lock-in) occurred above a threshold amplitude of oscillation, which became larger as the deviation of the oscillation frequency from the natural shedding frequency was increased.

The objective of present study is to identify the effect of cylinder geometry, amplitude and frequency of oscillation on flow past cylinder. There are lot of research work going flow past oscillating cylinder. Specific Objective of present study. 1. Effect of cylinder geometry on flow past oscillating cylinder at fixed Reynold number. 2. Use of UDF in Fluent to give simple harmonic motion to cylinder.

II. NUMERICAL FORMULATION AND COMPUTATIONAL APPROACH

2.1. Modelling

The model geometry of laminar flow over oscillating cylinder is taken from numerical analysis of T.T.Do et al.[5]. The schematic dia. for circular cylinder is as shown in fig. 1. The cylinder is represented in two dimensions by a circle, and a flow domain is created surrounding the circle. The diameter of the cylinder can be specified, and the flow domain is adjusted based on these dimensions. In the present study cylinder geometry are varied to see effect on flow physics. Here we analyse three geometry Circular, Square and Elliptical cylinder(Fig. 2). Modelling is done using GAMBIT software. The dimension of square and ellipse are finding out from relation of equivalent hydraulic diameter.

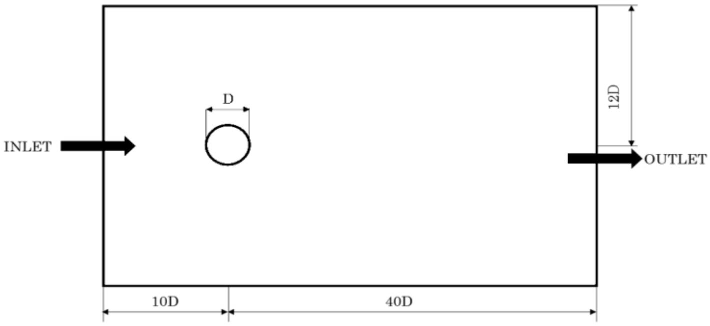
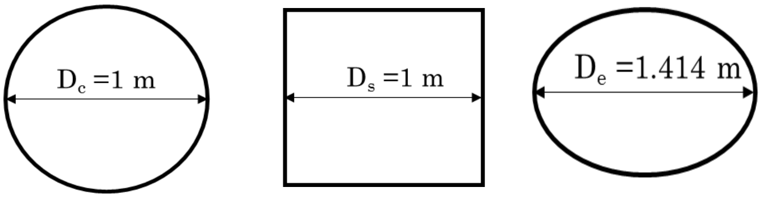


Fig. 1 Schematic diagram of Flow Domain



(a) (b) (c)

Fig. 2 Geometry of Cylinder (a) Circular, (b) Square and (c) Elliptical.

2.2. Meshing

Gambit pre-processing software are used for meshing. In present study cylinder subjected to oscillating motion so the total flow domain divided into two parts. First part near to oscillating cylinder which contain 6×6 m square domain surrounding to cylinder. Second part contains remaining all region. In order to make dynamic mesh the first part meshed with tri element. Meshing is shown in figure 3. Mesh is fine near to cylinder to extract the vortices (Fig. 4).

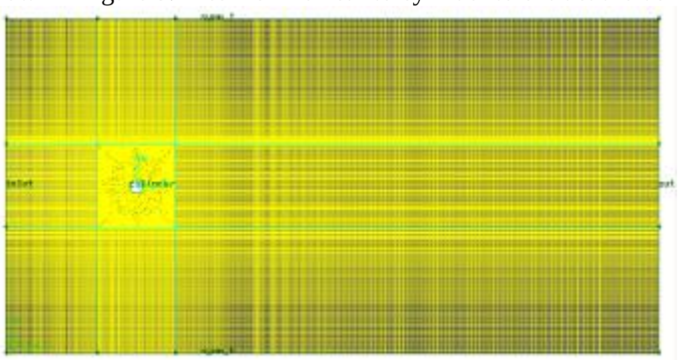


Fig. 3 Meshing of flow domain

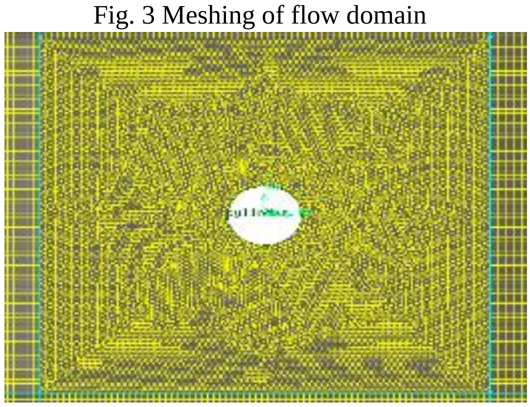


Fig. 4 Meshing near to cylinder

2.3. Solver Parameter and Boundary Condition

FLUENT commercial tool are used to define solver parameter. Mesh file generated by GAMBIT imported in FLUENT and necessary flow and solver parameter defined. Table I shows the value of boundary conditions. For present study 2-D transient pressure-based solver selected. Reynold number is fixed 185 so laminar model is selected for study.

Fluid properties are defined to set Reynold number 185. Density is taken 185 kg/m3 and dynamic viscosity 1 Pa·S. A variety of pressure based algorithms are available in fluent. For the present study, Pressure implicit and splitting of operator (PISO) algorithm is adopted for velocity and pressure coupling. PISO scheme more suitable for transient analysis with greater time steps. The simulation is stopped when a periodic condition for the vortex shedding process is established.

TABLE I
Boundary conditions

Zone name	Boundary Type	Specification
Inlet(U_∞)	Inlet	1 m/s
Outlet	Pressure-outlet	Zero Pascal (Gauge)
Cylinder	Wall	-
Top Edge	Symmetry	-
Bottom Edge	Symmetry	-

The oscillating motion of cylinder in FLUENT is defined using User defined function (UDF). The time step size is 0.05 sec and 30 iteration pre time step. The equation used to give harmonic motion is as follows:

$$V(y) = A\,\omega\cos(\omega t) \quad (1)$$

Where, V(y) is velocity of cylinder in y-direction. A is amplitude of oscillation. Amplitude ratio defined by,

$$A_r = A/D \quad (2)$$

Angular frequency of oscillation defined by,

$$\omega = 2\,\pi\,f_e \quad (3)$$

Where fe is frequency of oscillation is derived from frequency ratio (fr = fe/fo) and vortex shading frequency.

III. GRID INDEPENDENCE AND VALIDATION

3.1. Grid Independence

In present study, the grid independence study carried on three different mesh density grid. The details of number of elements are as given in table II. The grid independence study carried out by comparing Strouhal number for flow over circular cylinder as shown in fig. 5 at Reynold number 185. From fig. 5 we can see that Strouhal number same for medium and fine mesh which is less than the coarse mesh. It is cleared that medium mesh density is optimum and increasing mesh density beyond medium mesh density there is no any benefits in terms of accuracy but it only increases the computation time. The grid with medium grid density are taken on for further analysis.

are taken on for further analysis.

TABLE II
Details of Grids used for mesh sensitivity study

Grid Type	Number of elements
Coarse Mesh	29127
Medium Mesh	47153
Fine Mesh	62345

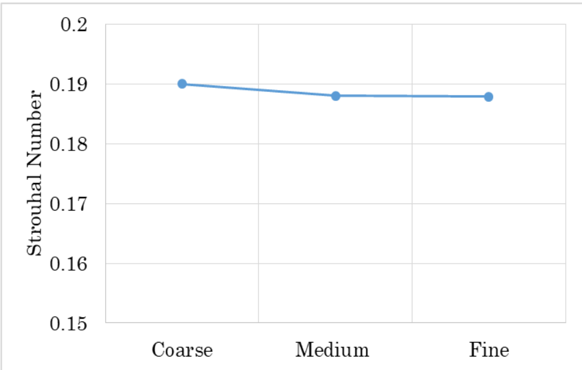


Fig. 5 Grid Independence Study

3.2. Validation of Numerical study

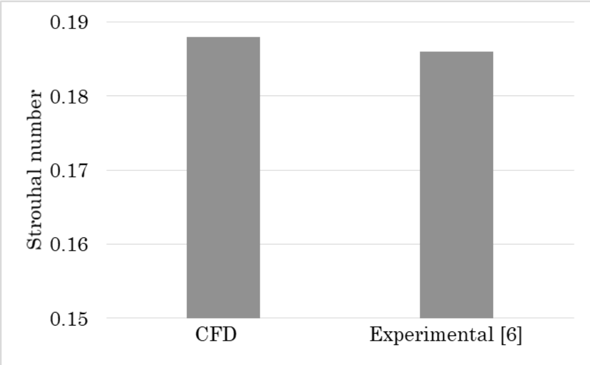


Fig. 6 Validation

The present study involves with numerical evolution of multiple cylinder geometries, hence the numerical methods/process followed here need to be calibrated against experimental data to ascertain and understand the predictability. For this purpose, present results are compared against test data of Williamson [6] for same Reynold number 185. Fig. 6 shows comparison of predicted Strouhal number against test data. The numerical results shows good quantitative agreement with test data. So the established numerical procedure can be used for further analysis.

IV. RESULTS AND DISCUSSION

Fluid flow characteristics of flow over a cylinder of different shape undergoing transversally oscillating motion at different frequency ratio are presented here. The considered oscillation frequency ratio are 0.8, 1.0 and 1.2. Oscillation frequency (f_e) calculate from the Strouhal number of the stationary cylinder at Reynold number 185. Table III shows the value of Strouhal number for all the shape of stationary cylinder. Predicted Strouhal number for the different shape shows good agreement with literature.[6] The effect of the motion of the cylinder on flow field can be explained by plotting flow streamlines.

TABLE III
Strouhal Number for stationary cylinder

Cylinder Shape	Strouhal Number
Circular	0.188
Square	0.149
Elliptical	0.210

Fig. 6 shows instantaneous streamlines during a complete vortex shedding cycle for circular cylinder at Re=185, fr = 0.8 and Ar = 0.8. For each one cycle the two vortex are continuously formed behind the cylinder. When circular cylinder at top extreme location anticlockwise vortex start shedding from bottom of the cylinder and then disappeared during cycle. Clockwise vortex formed when cylinder on extreme bottom position.

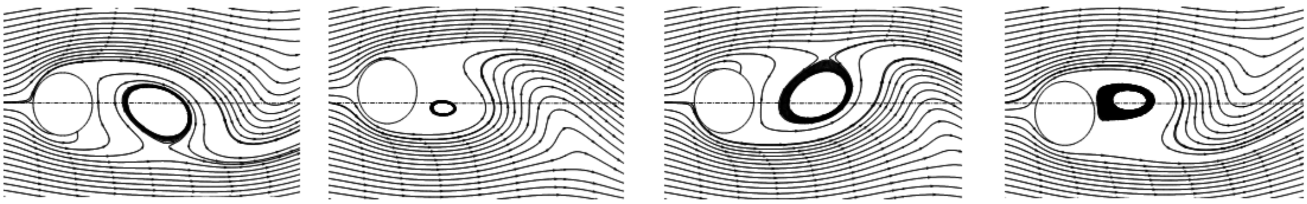


Fig. 6 Instantaneous streamlines during a complete vortex shedding cycle for circular cylinder at Re=185, fr=0.8, Ar=0.8 and t= (a) τ, (b) τ/4, (c) 2τ/4 and (d) 3τ/4.

Fig. 7 and 8 shows streamlines for circular cylinder for frequency ratio (fr) 1.0 and 1.1. When fr > 1 the clockwise vortex sheds from top of the circular cylinder on its extreme upper position. As the frequency increase the longitudinal and transverse distance between to vortices decreases. This flow behavior shows qualitative agreement with P. Anagnostopoulos [7] analysis. As the frequency of oscillation increases the vortex have not enough time to grow so that the vortex disappear near the cylinder.

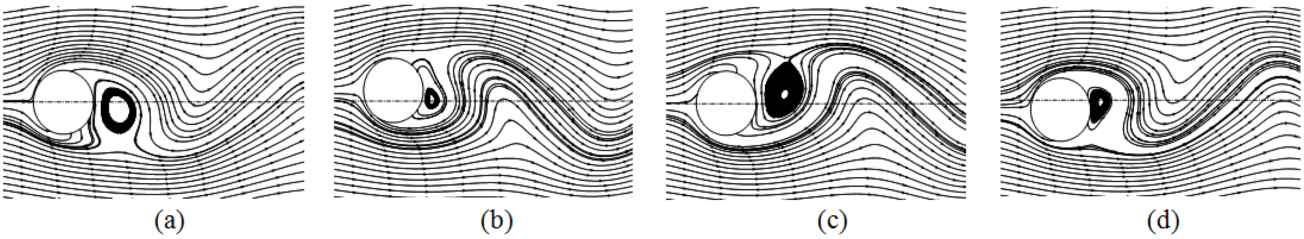


Fig. 7 Instantaneous streamlines during a complete vortex shedding cycle for circular cylinder at Re=185, fr=1.0, Ar=0.8 and t= (a) τ, (b) τ/4, (c) 2τ/4 and (d) 3τ/4.

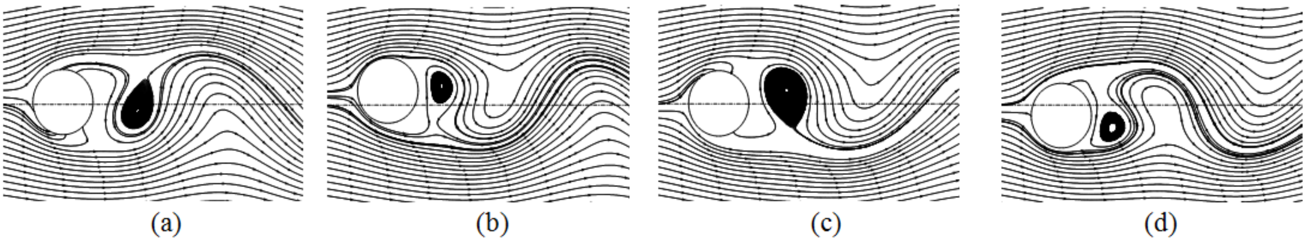


Fig. 8 Instantaneous streamlines during a complete vortex shedding cycle for circular cylinder at Re=185, fr=1.2, Ar=0.8 and t= (a) τ, (b) τ/4, (c) 2τ/4 and (d) 3τ/4.

Fig. 9, 10 and 11 shows the instantaneous streamlines during a complete vortex shedding cycle for square cylinder at Re=185, Ar = 0.8 and fr = 0.8, 1.0 and 1.2 respectively. The wake region behind the square cylinder is larger. The time taken by vortex to disappear is more compared to circular cylinder because of the vortex shedding frequency is smaller. At fr = 1.2, Fig. 11, the pattern exhibits a change; it shows two saddle points in the form of intersecting streamlines. This basic description persists up to the highest value of excitation frequency. Furthermore, the centers of the closed streamlines suggest the existence of vortices concentrations in those regions. For square cylinder obstruction to incoming flow is more so that the low pressure region behind square cylinder is more compared to circular cylinder. Remaining flow pattern same as the circular cylinder.

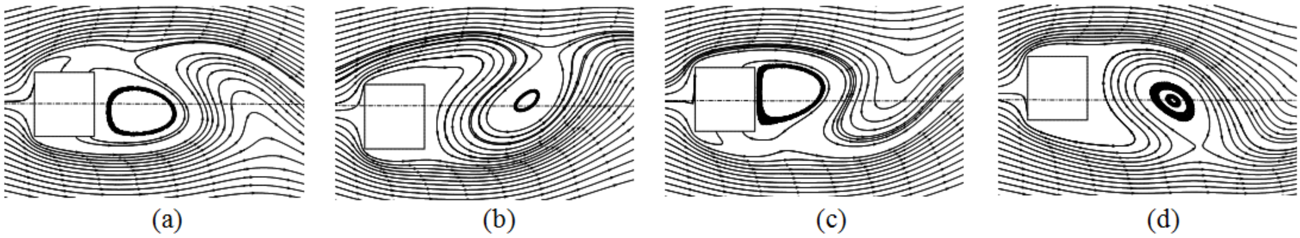


Fig. 9 Instantaneous streamlines during a complete vortex shedding cycle for square cylinder at Re=185, fr=0.8, Ar=0.8 and t= (a) τ, (b) τ/4, (c) 2τ/4 and (d) 3τ/4.

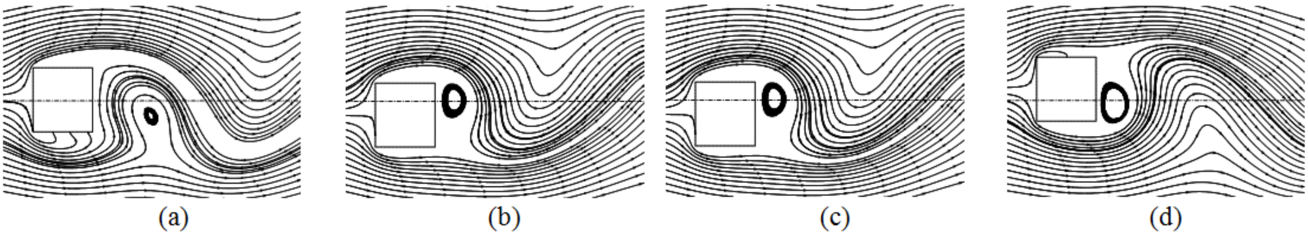


Fig. 10 Instantaneous streamlines during a complete vortex shedding cycle for square cylinder at Re=185, fr=1.0, Ar=0.8 and t= (a) τ, (b) τ/4, (c) 2τ/4 and (d) 3τ/4.

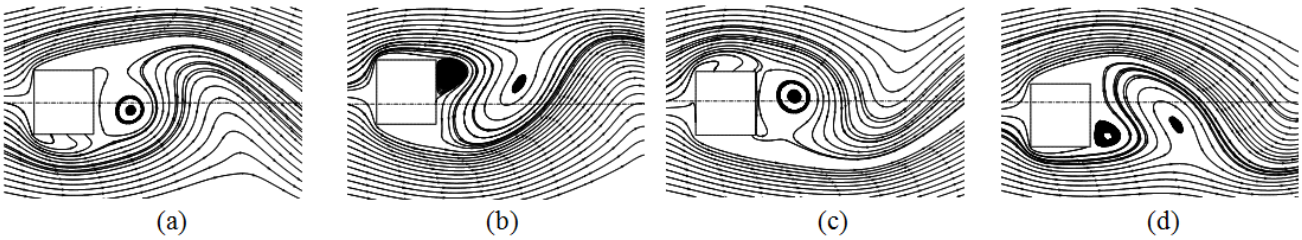


Fig. 11 Instantaneous streamlines during a complete vortex shedding cycle for square cylinder at Re=185, fr=1.2, Ar=0.8 and t= (a) τ, (b) τ/4, (c) 2τ/4 and (d) 3τ/4.

Fig. 12, 13 and 14 shows the instantaneous streamlines during a complete vortex shedding cycle for elliptical cylinder at Re=185, Ar = 0.8 and fr = 0.8, 1.0 and 1.2 respectively. Concentration of vortex is decreased for elliptical cylinder because for elliptical shape the obstruction to flow is less compared to circular and square so, the wake region behind cylinder have less area. The vortex shedding start from near to centerline. As the oscillating frequency increase the longitudinal and transverse distance between two vortices decreases and also the concentration of vortex decreases.

IV. CONCLUSION

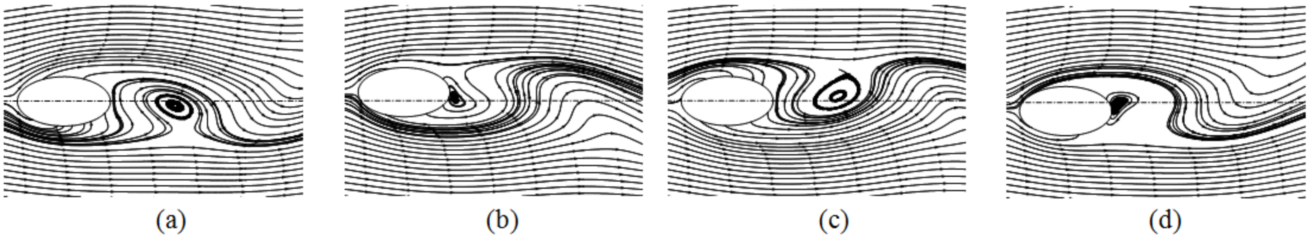


Fig. 12 Instantaneous streamlines during a complete vortex shedding cycle for elliptical cylinder at Re=185, fr=0.8, Ar=0.8 and t= (a) τ, (b) τ/4, (c) 2τ/4 and (d) 3τ/4.

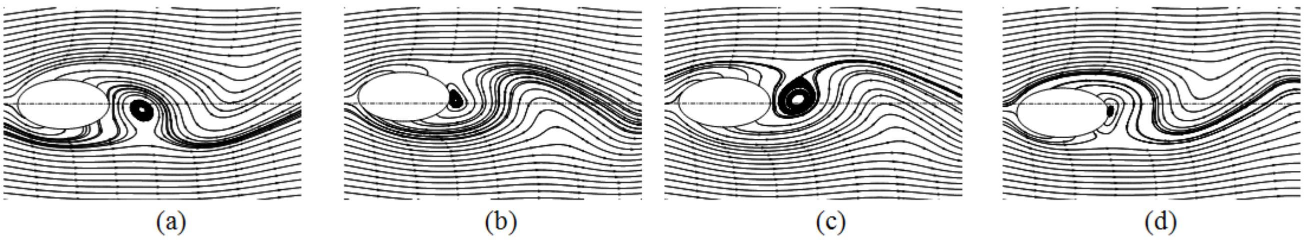


Fig. 13 Instantaneous streamlines during a complete vortex shedding cycle for elliptical cylinder at Re=185, fr=1.0, Ar=0.8 and t= (a) τ, (b) τ/4, (c) 2τ/4 and (d) 3τ/4.

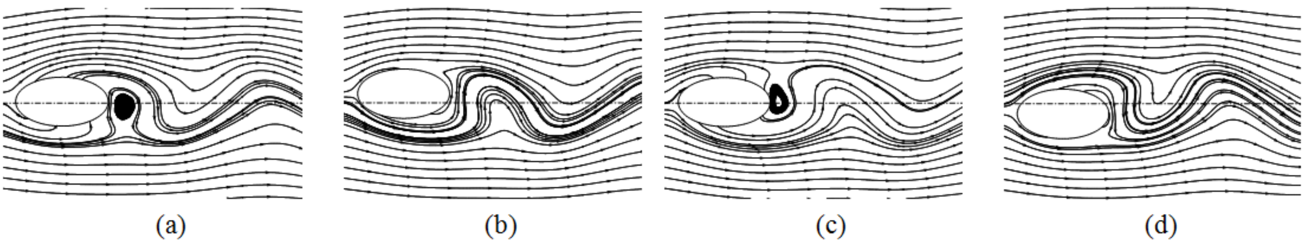


Fig. 14 Instantaneous streamlines during a complete vortex shedding cycle for elliptical cylinder at Re=185, fr=1.2, Ar=0.8 and t= (a) τ, (b) τ/4, (c) 2τ/4 and (d) 3τ/4.

In present numerical study, effect of frequency ratio on flow past oscillating cylinder of various shapes are carried out at fixed Reynolds number Re=185. UDF can be successfully used for numerical analysis of oscillating cylinder. Following Conclusion are made:

1. Regardless of shape as oscillating frequency increases the longitudinal and transverse distance between two vortices decreases.
2. When fr ≤ 1, the vortex shedding start from opposite side of body means when body on extreme top position vortex shed from bottom of the body.
3. When fr > 1 then the vortex sheds from same side of the body. 4. For elliptical cylinder the vortex concentration is less compared to circular and square cylinder due to stream line shape body. For elliptical cylinder vortex started near to center line.

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