STUDY OF VORTEX INDUCED VIBRATION OF A FLEXIBLE CYLINDER WITH RIGID SPLITTER PLATE

Thesis
Submitted in partial fulfilment of
Requirement for the degree of

MASTER OF ENGINEERING

in
CAD/CAM Engineering

by

Jai deep Sachan

801784007

Under the Supervision of

Dr. Ashish Purohit

(Assistant professor in MED, TIET)

THAPAR INSTITUTE
OF ENGINEERING & TECHNOLOGY
(Deemed to be University)

MECHANICAL ENGINEERING DEPARTMENT

THAPAR INSTITUTE OF ENGINEERING AND TECHNOLOGY, PATIALA

July 2019

CERTIFICATE

This is to certify that the work done in this thesis title “**Study of vortex induced vibration of a flexible cylinder with rigid splitter plate**” submitted in the partial fulfilment of requirement for the award of master of engineering degree in CAD/CAM in the mechanical engineering department of Thapar Institute of Engineering and Technology, Patiala, is an Authentic record of the work carried out by me under the guidance of Dr. Ashish Purohit , Mechanical Engineering Department, Thapar Institute of Engineering and Technology, Patiala. The embodied in this report has not been submitted in any part or full to any other university or institute for the award of any degree.

Jaideep

Jaideep Sachan
Roll no. 801784007

This is to certify that above declaration made by the student concerned is corrected to the best of my knowledge and belief.

Ashish

Dr. Ashish Purohit
Assistant Professor,
MED
Dated 09/08/2019

AKONOWLEDMENT

Foremost, I would like to express my sincere gratitude to my Adviser Asst. Prof. Dr. Ashish Purohit for the continuous support of ME study and research, for his motivation, enthusiasm, and immense knowledge. The door to Prof. Purohit office was always open whenever I ran into the trouble spot a question about my research. His guidance helped me in all the time of research and writing of this thesis. I have learned so much from them and look forward to their continuous support future endeavours in life.

Finally, I must express my very profound gratitude to my parents for providing me with unfailing support and continuous encouragement throughout year of my study and through the process of researching and writing the thesis. This accomplishment would not have been possible without them.

Jaideep

Jaideep Sachan

Roll no. 801784007

ABSTRACT

Flow induced vibration in large chimney or marine riser is always been a matter of concern and continuous efforts are being made to control it. In the present work, a problem of vibration control of a cylindrical body placed in flow is attempted. A two-dimensional numerical study of vortex induced vibration of a flexible cylinder with a rigid splitter plate is carried out at low Reynolds number flow condition. A parametric study to know the effect of length of splitter plate on the level of vortex induced vibration is also done. Four cases of different splitter plate's length are considered (0.25D, 0.5D, 0.75D and 1D) and vibration response of the cylinder is monitored. In addition, some pre simulations to identify lock-in vibration of the system are also conduced. The results obtained indicate that by adding a splitter plate, vibration level reduces drastically. For a splitter plate of length 0.25D, the vortex induced vibration amplitude reduces up-to 87.50% compared to the case of vibration of cylinder without the splitter plate. The maximum reduction in vibration amplitude is achieved for the length of 0.75D which is 97.50%. Based on the implications in the implementation of such plate on the real structures, a plate of smaller length is finally suggested to use to reduce vibration of circular section structures. It is also found that beyond the length of 0.75D, vibration level increases that may be due to occurrence of galloping instability.

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURES AND ABBREVIATIONS

D	Diameter of cylinder
f	Vortex shedding frequency
L	Length of the splitter plate
M	Mass of the cylinder
C	Damping of the system
K	Stiffness of the assembly
$\mathrm{Y(t)}$	Vertical displacement
$\dot{\mathrm{Y}}\mathrm{(t)}$	Velocity component in vertical direction
St	Strouhal Number
Hz	Hertz

Abbreviations

BC’s	Boundary conditions
FSI	Fluid structure interaction
VIV	Vortex induced vibration
DNS	Direct numerical simulation
Re	Reynold Number
CFD	Computational fluid dynamics
LES	Large eddy simulation

CONTENTS

1. INTRODUCTION

2. LITERATURE REVIEW

3. NUMERICAL METHODOLOGY

4.RESULT AND DISSCUSSION

6. REFERENCES

CHAPTER 1

INTRODUCTION

Fatigue failure of large marine risers due to low speed water current or failure of tall chimney by the light wind have always been a matter of concern for the engineers. When a moving fluid interacts with solid structure(s), both solid and liquid mediums experience unsteady forces that may also lead to oscillation of both the mediums. Such interactions are known as Fluid structure interaction (FSI) which is a commonly observed phenomenon in many industrial applications. Interaction of moving fluid with cylindrical pipes in marine application, hollow tubes in heat exchanger, tapered cylinder in tall chimney, high tension electricity cable lines, hull of submarine, aerofoil shaped wings in aviation industry are some of the examples of FSI. Sometime, the frequency of dynamic force coincided with the natural frequency of the system and thus the system exhibits large amplitude oscillation. In particular, off shore marine risers get damaged by low velocity ocean current and gains importance. To circumvent this flow driven vibration, efforts are being made to overcome the design prospective of marine structure, with the objective of finding path to control structure response without increasing hydrodynamic forces.

1.1 Vortex-Induced Vibration:

When flow passes over a cylinder, the flow separates into two layers and these layers form an unsteady region in which vortex shedding is formed. Vortex shedding applies fluctuating lift and drag force on the structure, if structure is rigid then it fails due to the fatigue failure, or if it is flexible, it will exhibit vibration. These undesirable vibrations affect the functionality of structure and also its life span. Such flow driven vibration can be expresses using a simple single degree of freedom expression given in equation 1.1 and the single degree of system is shown in the figure 1.

$$M\ddot{Y}+C\dot{Y}+KY = F_1(t)+F_2(t) \qquad 1.1$$

where M represents mass of the system, C is total damping and K is stiffness of the structure. RHS defines forces on the system.

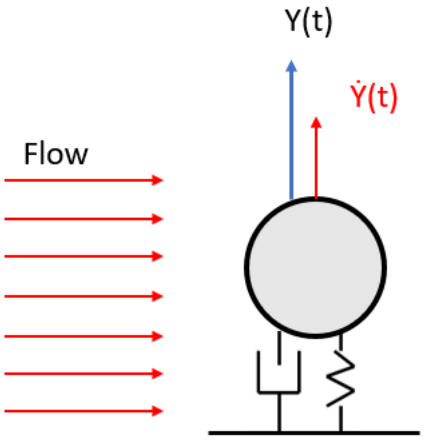


Fig.1 Single degree of freedom model of mass spring damper system

The unsteady forces due to the fluid structure interaction can be divided into two parts as $F_1(t)$ and $F_2(t)$ shown in Equation 1.1. One is corresponding to a mechanical external excitation, another can be flow induced excitation. In case of a flexible cylinder in flow, without any other excitation, the force terms will be $F_1(t)\neq0$, $F_2(\mathrm{t})=0$, the vibration of system depends on flow pattern of fluid in wake region. As in the case of cylinder, its own vortex shedding becomes an excitation mechanism. The frequency of vortex induced vibration can be expresses by a non-dimensional Strouhal number ($St = fD/u$), where f is vortex shedding frequency, D is diameter of the cylinder and u is the flow velocity. Strouhal number defined as the ratio of local velocity of the fluid to the mean flow velocity of the fluid. In case of flow over a stationary cylinder, Strouhal value lies between 0.18-0.22, which is an indication of formation of vortices.

When flow passes over the cylinder with flexible support, vortex field forces it to produce vortex induced vibration. In VIV, as the flow velocity increases, vortex shedding frequency increases and so the excitation frequency. When this excitation frequency becomes close to the natural frequency of the flexible cylinder, interesting lock-in phenomena is observed. For a particular narrow range of flow velocity, the vortex shedding frequency synchronise with the natural frequency of the structure, which results high amplitudes vibration.

1.2 Suppression of vortex induced vibration (VIV)

A significant amount of work has been published in open literature with various methods to passively supress the Vortex Induced Vibration (VIV). One of the methods to reduce VIV is implementation of helical strakes on the surface of the cylindrical body [6-9]. The strake suppresses the vortex formation.

Other passive control method has been investigated to control the drag forces induced by helical strakes. Splitter plate and fairing tail have been used for the suppression of VIV with drag reduction Assi et al. [12]. Among the passive control method, the splitter plate has been one of the best methods to control the VIV. Apelt et al. [14] noted that the drag force was considerably reduced when splitter plate is attached to the base of cylinder. Kwon and Choi [15] performed a numerical study to control the vortex shedding in laminar flow, with splitter plate attached on the base of cylinder. Shukla et al. [19, 20] performed an experimental work to study the dynamics of flexible splitter plate in downstream of a circular cylinder.

It has been observed that the flow over cylinder is a canonical problem of many industrial applications in which problem of vortex induced vibration is observed, and this problem opens the door for researcher to contribute their efforts. The problem considered in this thesis is related to study control techniques of VIV of cylinder using rigid splitter plate. In addition to control the VIV, a complete understanding of this phenomena is also required.

1.3 Scope of the work

From the literature review it has been observed that a significant amount of experimental and numerical study has been performed to study the flow over cylindrical and other shaped bluff body. Numbers of researches are dedicated to investigate effect of a rigid or a flexible plate on the flow dynamics. In case of a rigid plate, presence of plate significantly alters the unsteady lift and drag forces on the body. Contrary to this, a flexible plate shows oscillations and also, sometime instable flutter. In most of the studies of a cylinder with a rigid trailing plate, instead of actually simulating mechanical vibration of the system, a rigid geometry is assumed and fluctuation in the lift force is mainly measured, which are later correlated with the suppression of the vibration of the system.

A detailed investigation, of flow induced vibration of a flexible cylinder with a rigid splitter plate, including FSI is rare in the literature. In fact, such investigations would be closer to the actual real-life problem e.g. oscillation of a long flexible marine riser, where in the cylindrical body remains flexible and addition of an aft body will affect its vortex induced vibration. Thus, there is a need to explore the area in which vibration amplitude of flow over flexible cylinder control through rigid splitter plate. Based on the need analysis from the literature review and from the author's current understanding, following objectives are formed for the present thesis.

- Numerical modelling and simulation of a problem of flow over a flexible cylinder. Investigation of effect of a splitter plate on the variation in the lift force of a rigid cylinder.
- Estimation of VIV of a cylinder with a splitter plate.
- Study of suppression of flow induced vibration of a cylinder by adding different splitter plate.

1.3 Thesis organization

Detail of the thesis given with chronological order of different chapter is given below

Chapter 1: Introduction Significance of investigations on the flow induced vibration is discussed. A detail of Vortex Induced Vibration (VIV), a brief discussion of vortex induced vibration suppression technic scope of the work and present work study is weighed up.

Chapter 2: Literature Review

Flow over cylinder, flow over fixed cylinder with rigid splitter plate, flow over rotatable splitter plate and flow over fixed cylinder with hinge/flexible splitter plate are reviewed. In addition, review of recent work of flow over cylinder with rigid splitter plate with DNS.

Chapter 3: Numerical Methodology

Problem description, numerical scheme, method of solver, and flow computational domain are briefly discussed. The grid convergent study and boundary condition are described in detail. A short discussion about the multi-field solver and coupling of fluid and structure domain.

Chapter 4: Result and Discussion

Flow field characteristic in wake region and response of the flow over fixed cylinder are described in detail. The results of flow over cylinder with rigid splitter plate are discussed in detail. Lock-in range study of flow over flexible cylinder is carried out. Vibration amplitude response and frequency spectrum of the flow over flexible cylinder with varying splitter plate length (0.25D, 0.5D, 0.75D, 1D)

Chapter 5: Conclusion and future Scope

In this section concluding remark of the research and future scope of investigation are discussed

CHAPTER 2

LITERATURE REVIEW

Based on the need of the development of a system to reduce the flow induced vibration in a large chimney or marine riser like structure, a comprehensive literature has been surveyed.

2.1 Flow Over Cylinder

Bearman [1] gives a review paper in which they compare flow behaviour after the bluff body, suggested that for the complete understanding of fluid behaviour in wake region, the research is performed with different shape bluff. A clear prospective is required for the modelling of free and forced vibration VIV. A continuous development is required for the mathematical modelling of vortex induced vibration.

Sarpakya [2] has presented a review paper in which a comprehensive study of vortex induced vibration of circular cylinder is carried out. In this review paper a detail analysis of theoretical insight, experimental work and numerical models are traced. And some useful suggestion is given for the further study. A proper dedicated numerical investigation is required for to study the behaviour of flow filed in the wake region, modelling of small eddy required in turbulent flow.

Williamson and Govardhan [3] have performed an experiment to study the behaviour of transvers vibration of elastically mounted rigid cylinder. In this study two cases are investigated in the first case low mass damping ratio is considered in which three branches of amplitude response are found, initial branch, upper branch and lower branch. At the high mass damping ratio only two branches were present and upper branch is absent.

Yamamoto [8] has performed a numerical simulation to study the vortex induced vibration of marine riser with real life condition. Investigation involves a cantilevered flexible cylinder in with free and fixed end. The finite element method is used which solved by the Euler Bernoulli beam theory and the integration of equation gives the hydrodynamic forces and the response of the cylinder. Discreet vortex method is used to calculate the hydrodynamic forces. Two cases of investigation were used in which the shear flow field are considered and velocity linearly varies along the length. In the first a trapezoidal flow field was used and in the second case triangular flow field adopted. Results obtained were compared with Quasi-Steady theory; the vibration amplitude is more in this case the possible region of behaviour is solving the governing equation.

Gabbai and Benaroya [5] present a review paper in which a comparison of different mathematical model used to solve the Vortex induced vibration of flow over circular cylinder are discussed in detail. From the comparison author concluded that the VIV is a nonlinear self-regulating multi degree of freedom phenomenon.

Bourguet et al. [7] have performed a numerical simulation employed with three Re 110 to 1100. In this investigation laminar, transition and turbulent flow field considered. The main focus of this study is to investigate the lock-in phenomena in whole length of the pipe with different shear velocity and effect of mass on the lock-in are study. Mono and multi frequency response of the structure is same in all the cases. Response of the structure is a combination of standing and traveling wave pattern. The ratio of in-line frequency and cross frequency ratio is 2. Due to the long cylinder length lock-in defined locally, when cross flow vibration frequency matches with the local vortex shedding frequency. And rest of length is at non lock-in region. The lock-in zones are present at high velocity region.30% of the structure length cover in cases of study and rest of the fall in category of no-lock-in range.

Huang [11] proposed an experiment with fixed and flexible cylinder in which triple helical grooves are formed at the surface of the cylinder. In the case fixed cylinder strut is used in towing tank and the effect of grooves on the drag force of cylinder is study. In the case of flexible cylinder, a cantilevered flexible cylinder of attached and the effects of helical grooves on the vibration amplitude are investigated. For the fixed cylinder case Re varies $3.1\text{x}10^4$ to $3.75\text{x}10^5$ and in case flexible cylinder $1.3\text{x}10^4$ to $4.6\text{x}10^4$. Results of the investigation show the peak amplitude of vibration reduces up-to 65% and the drag force reduction of fixed cylinder up-to 25% was achieved.

Yin et al. [9] deduce a test on the prototype model with the different surface roughness ratio in towing tank MARINTEK model. Test is performed with free oscillation and force-controlled motion. In both the cases $Re=4 \text{ x } 10^5$ is considered.

Figure 2 represent the model of test rig with smooth riser model. And results of the test show the dependency of the Re with surface roughness. Two excitation regions for the smooth riser and one excitation region for the rough riser were found. In the critical and supercritical region, the vibration amplitude is less sensitive to the Re than that at lower Re. Vibration amplitude is larger at low Re and smaller at high Re.

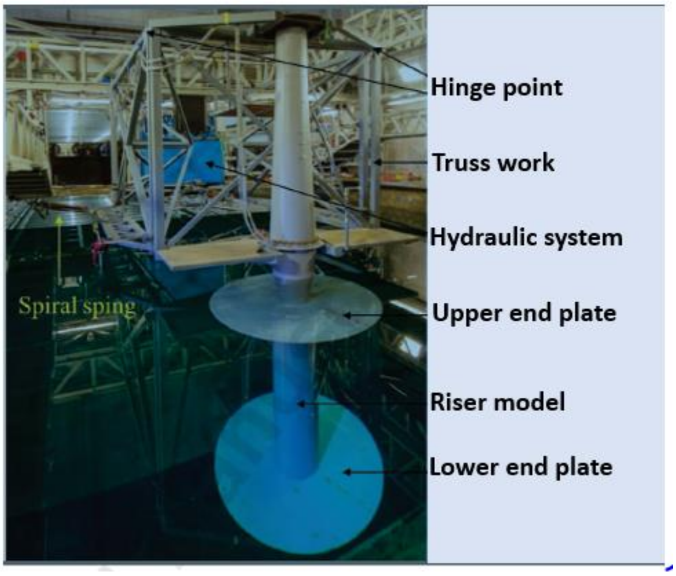


Fig. 2 Prototype model of rig [9]

2.2 Flow Over Fixed Cylinder with Rigid Splitter Plate

Akili et al. [17] have proposed experiments in the shallow water to investigate the passive control of vortex shedding through the splitter plate. A test model of a fixed cylinder with a splitter plate is used. Tests are performed at a fixed Reynolds number Re=6300 with variation 0.2-2.4 in the length of the trailing splitter plate was considered. They found that the flow property considerably changes up-to plate length L/D=1, after that any significant changes are not observed, large scale vortex shedding completely is disappears at plate length 1.2D. And they also found that the width of the splitter plate not play any critical role for the attenuation of the vortex shedding.

An experimental work has been carried out by the Apelt et al. [14] in which the study is performed with very high Re=$1.45\text{x}10^4$ and effect of splitter plate length at turbulent flow are found. The main motive of this study is to investigate the effect of splitter on pressure distribution and vortex shedding characteristics in wake region. When they added a short length (L=1/16D) splitter plate 9% reduction in drag force is observed, at the plate length L=D drag reduces up-to the 35%. Vortex shedding frequency varies with ±10%over the range of L/D≤2. The short plates stabilised the flow and reduces the wake length and provide a fixed formation point of the vortices, and long splitter plate make a hindrance between the shear layers due to which irregular vortex are form.

Kwon and Choi [15] performed a numerical simulation to investigate the effect of splitter plate of flow over fixed cylinder in laminar flow region in which the Re varies 80-160. They observed that at every Re a critical plate length, after which vortex shedding completely suppress. The finding of the simulation, critical length of the splitter plate is directly proportional to the Re. Drag force significantly reduced at the insertion of splitter plate. An optimum plate length for minimum drag at given Re.

Wang et al. [16] uses CFD technic with renormalization group (RNG) turbulence model to solve the problem of flow over cylinder with different splitter plate. They have considered a Re 1000 and 30000 with varying splitter plate length between 0.5D-2D. The result of Numerical simulation shows that amplitude of drag force reduces 20-35% and amplitude of lift force reduction is 94-97% at plate length 1.2D

Direct Numerical Simulation technic has been used by the L. A. Araudo et al. [18] in which 2-D and 3-D numerical simulation of flow over fixed cylinder with splitter plate is deduce. In this investigation they use different flow field of Re (100, 160, 300 and 1250). Aim of this study to determine the optimum plate length with in the Re range studies, at which minimum lift and drag force co-efficient. The length of the splitter plate is varied up-to 12D. In all the cases only attenuation of vortex shedding is observed but complete suppression is not observed. At the 3-D numerical simulation with Re=1250, the vortex shedding is attenuated, only turbulent kinetic energy along with Reynolds stress reduces.

2.3 Flow over fixed Cylinder with Flexible Splitter Plate

Shukla et al. [19] performed an experiment to predict the flow behaviour of fixed cylinder with a hinge splitter plate. Experimental results show that amplitude of oscillation of splitter plate increases with the Reynolds number at low value of Re, the amplitude saturates at higher Re. For smaller splitter plate length (L/D<3), the amplitude of tip oscillation was nearly 0.45D with periodic in nature, when (L/D>4) the nature of oscillation was aperiodic.

Wu et al. [24] have deduce a numerical investigation, the effect of reduced velocity ratio of flexible cylinder with hinge splitter plate at Re=150 are observed. From the result of this investigation following results are obtained. The lock-in range of velocity shift when splitter plate is attached to the cylinder. When an external excitation was imposed on the splitter plate, vibration amplitude of the cylinder reduces. Stiffness of the plate plays a role for the attenuation of the vortex shedding.

Shukla et al. [20] study the dynamics of flexible splitter plate in the wake of a circular cylinder with experimental setup, and observed that the flexural rigidity of plate plays an important role for the suppression of vortex shedding, if value of flexural rigidity increases the amplitude of response shifted to higher flow velocity.

Shengiping et al. [23] have deduce an experiment to predict the structure instability for a circular cylinder with flexible splitter plates. The finding of the experiment indicate that the lock-in range of the velocity generally shifted to higher velocity range, lock-in range is depending on the Re. By adding the flexible splitter plate the vibration amplitude reduces up-to 34 %.

Sudhakar and Ven Ganesan [21] numerically investigate vortex shedding characteristics of a circular cylinder with an oscillating splitter plate by solving the Two dimensional Naiver - Stroke equations with in house code at Re=100 and observed that oscillating plate of length 1D supress the vortex shedding which is equivalent to the vortex shedding of fixed plate length of 5D. Oscillation of the plate significantly affects the shedding frequency of flow field in the wake region.

Kundu et al. [22] have been investigated the flow induced vibration of flow over flexible cylinder in pulsating laminar flow through in-house code. The result of this investigation shows that the oscillation frequency at particular mode is twice the natural frequency of the plate and the mode of oscillation of the cylinder depends on the plate length. At the lock-in range displacement of the plate and drag coefficient increases.

2.4 Summary of Literature review

Form the literature review it has been observed that significant amount of numerical and experimental work has been performed to study the flow over fixed cylinder in which flow characteristics in wake region are investigated. So many experimental researches are devoted to find out effect of flow characteristic on the structure parameter and effect of structure parameter dependency on the flow. Many research works performed to develop various techniques to reduce vortex induced vibration of cylindrical object. It is investigated that implementation of a rigid plate in the downstream side influences the vortex shedding pattern of the system. Ample of investigations are dedicated to find out the effect of fixed/flexible splitter plate on the flow field and which parameter of the plate is play a critical role. In most of the related researches, the focus of the research was to understand effect of structure dynamics on the flow field over cylinder, as well as how the pressure distribution, lift and drag force affected by the plate dynamics. In case of turbulent flow wall shear stress are also investigated.

Study of vortex induced vibration of flexible cylinder are plenty, nevertheless, VIV of a flexible cylinder with a rigid splitter plate is considerably less investigated. These investigations are playing an important role to relate the practical application and must be investigated in detail.

CHAPTER 3

OBJECTIVE OF THE WORK AND METHODOLOGY

From the literature review, it is note that there is a required to explore the influence of a rigid aft structure on the VIV of a flexible cylinder. Based on the need analysis from the literature review and from the author’s current understanding, following objectives are formed for the present thesis.

- Numerical modelling and simulation of a problem of flow over a flexible cylinder. Investigation of effect of a splitter plate on the variation in the lift force of a rigid cylinder.
- Estimation of VIV of a cylinder with a splitter plate.
- Study of suppression of flow induced vibration of a cylinder by adding different splitter plate.

3.1 Problem description

In the present investigation, a numerical simulation of flow over flexible cylinder with rigid splitter plate is considered. The objective of the present work is to investigate the effect of rigid splitter plate on the vibration amplitude of flow over flexible cylinder. To perform this type of study a uniform flow field is require. Two-dimensional flow field is used for this type of study with lower Reynold number (control by the diameter of cylinder and velocity of flow field) conditions. In the present work two-dimensional flow fields is considered because it is computationally simple, economical and less time consuming. Assembly of the test model placed on low Reynold number 160. In addition to study the flow over flexible cylinder with rigid splitter plate, a reference case of flow over fixed cylinder with same Reynolds number is carried out section 2.1.

3.2 Numerical Scheme

Flow over flexible cylinder with rigid splitter plate involved multi-domain physics of fluid structure interaction (FSI). In fluid structure interaction problem, two different physical domains interact with each other. In which the fluid particle interact with solid surface of the flexible cylinder and cylinder responds through the deflection. The motion of the cylinder disturbs the surrounding flow field properties. Hence a feedback mechanism is developed between the solid and fluid and structure respond through the oscillatory motion. DNS and LES methods are used to solve this type of multi-domain physics problem but these methods are time consuming and costlier therefore a hybrid method is implemented in this present work. The flow characteristics are computed with Ansys multifield solver, which solve the fluid structure interaction problem.

3.2.1. Multi-Field Solver

In ANSYS multifield solver the structure dynamics is solved in transient structure solver and flow characteristic is computed in the CFX solver. CFX solver uses the Navier-Stroke equation for solving the instantaneous fluid flow property. In the Navier-Stroke equation mass, momentum and energy conservation equation are used. The equations are unsteady and compressible in the nature. CFX module based on the finite volume method where the solution variables are stored at the nodes of discretized volume. Control volume is formed around each node using a median dual approach (Ansys Inc,2010). Solution have second order accuracy and governing equations are integrated over each control volume. A linear shape function is used between the nodes. For the transient structure second order Euler backward method is used (Ansys Inc, 2010b). All the simulations are performed in a uniform flow field of Reynold number 160. At the low Reynolds number flow is laminar, therefore turbulent modelling is not required. Table 1 shows the property of the flow solver.

Table 1 Summary of the flow solver

Flow type	Laminar, unsteady and incompressible
Advection scheme	High Resolution
Transient scheme	Second order backward
Solver precision	Double precision
Mechanical solver variable	Displacement
Flow solver variable	Pressure/Force
Coupling time	.002s

CFX module is design to solve the three-dimensional flow problems. For the solution of the two-dimensional problem we used only one element in the third dimension of the computational domain. The transient structure solver involves basic equation of mass, spring and damper system. Governing equation involves to calculates the response for any arbitrary time-dependent loading (Ansys Inc, 2010a).

$$[M]\{\ddot{y}\} + [C]\{\dot{y}\} + [K]\dot{} = \{F(t)\} \qquad (1)$$

FSI problem is transient problem in which two solvers are coupled and structure displacement and fluid flow characteristics transfer in each cycle of time. The coupling requires a common surface between the fluid and structure domain. Meshing at the interface may be different. In multi-field solver displacement data is transfer from the transient structure and flow property send to the flow solver. Data transfer flow diagram is given in figure 2.

Table 2 Property of the fluid and structure domain

Sr.no.	Properties	Values
1	Density of the fluid(kg/m^3)	100
2	Dynamic viscosity of the fluid (N s/m^2)	0.4
3	Density of the fluid solid	7700

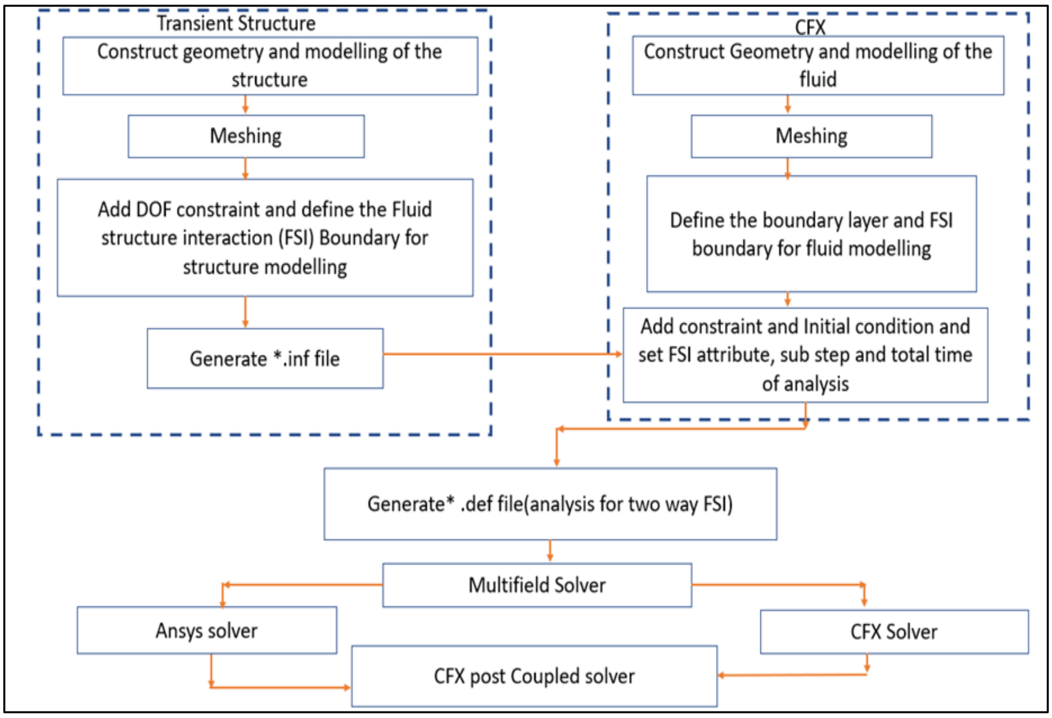


Fig 3.1 Schematic of the data flow in Ansys multi field solver

The different extension file share data between the solver and result are saved in form of transition file, with the help of these transition file time history of each cycle is easily analyse.

3.3 Flow computational domain

Figure 1 shows the flow of the fluid domain. To neglect the boundary properties of the flow domain, a flow domain size of 3m x 2m is considered. Cylinder is placed at the 3D distance from the inlet and 5D (D is the cylinder block diameter) distance from the top and bottom of the boundary. Outlet boundary is considered at a distance of 15D from the inlet boundary. This domain size is sufficient to avoid the boundary layer effects and the vortices are convicted without affecting the flow inside the domain. At the inlet a uniform flow velocity is provided. At the outlet of the domain average static pressure boundary conditions are used which gives the variation of local pressure with constant average pressure. The use of symmetrical boundary is employed for the top and bottom wall of the computational domain. A symmetrical boundary gives the similar effects on the flow distribution. No slip boundary state is used at the cylinder surface to fulfil the condition of continuum.

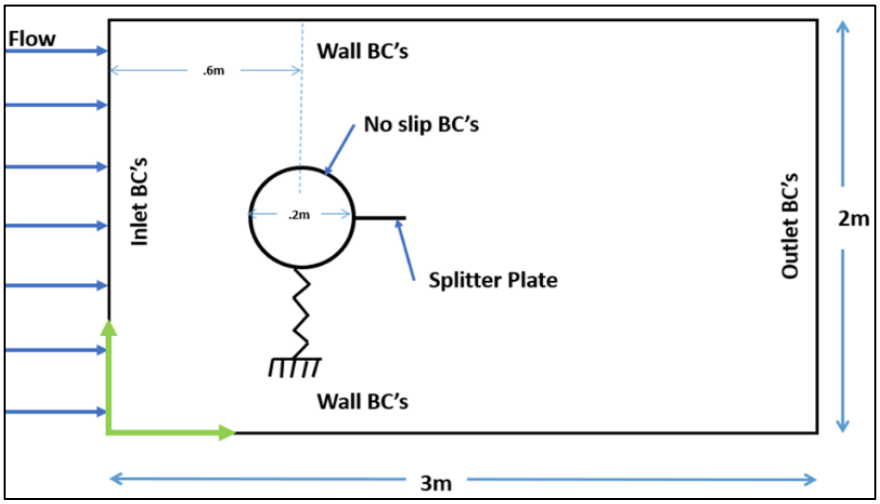


Fig. 3.2 Schematic of flow domain with boundary condition

Uniform mesh is used to discretise the cylinder. A triangular element size of 0.05D is used at the surface of a cylinder which avoids the curvature effects of the domain. At the plate surface rectangular type of element is used and the number of elements is varying according to the plate length. To the discretization of the flow domain higher density mesh is used at the surface of cylinder and plate. A uniform gird points are used in peripheral direction and exponential stretched grid points are used in radial direction. For the optimization of the grid structure, grid convergence study is carried out. Eight different grid density structure of different compactness are used which is based on the convergence of lift force and frequency of the lift. For the numerical simulation, a highly-resolve advection pattern is employed for second order backward Euler transient scheme. For the simulation, time step considered is .01. Convergence of the grid has been achieved at 59190 elements the value of lift and frequency obtained is same.

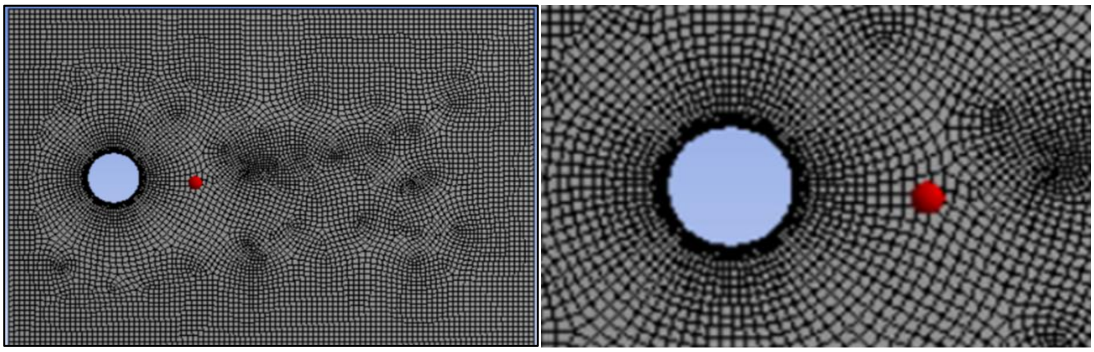


Fig3.3 (a) Grid configuration around the cylinder **(b)** Zoomed view of grid close to cylinder

Table 3Summary of the grid convergence study

Serial no.	Number of elements	Lift Force(N)	Frequency
1	19340	2.219	3.068
2	26047	1.731	3.201
3	30872	1.927	3.301
4	36474	2.827	3.344
5	45854	2.567	3.339
6	49530	2.827	3.347
7	59190	2.405	3.346
8	72082	2.407	3.334

CHAPTER 4

RESULT AND DISCUSSION

Two dimensional numerical simulations are performed for different test cases of flow over a fixed cylinder, flexible cylinder, cylinder with splitter plate etc. All the simulations in present work are performed for same Reynolds number of 160.

4.1 Flow over Fixed Cylinder:

To study flow while flow passes over a fixed cylinder, two-dimensional simulation for a case of flow over fixed cylinder is carried out. A cylinder of 20 cm diameter is considered and same computational domain as discussed in Section 3.3 is used. It is observed that in the beginning of flow, the fluid passes over the cylinder and forms two shear layers. The layers then extended in the wake region and with the course of the time, alternate vortex shedding formed, shows in figure 4.1(a-d).

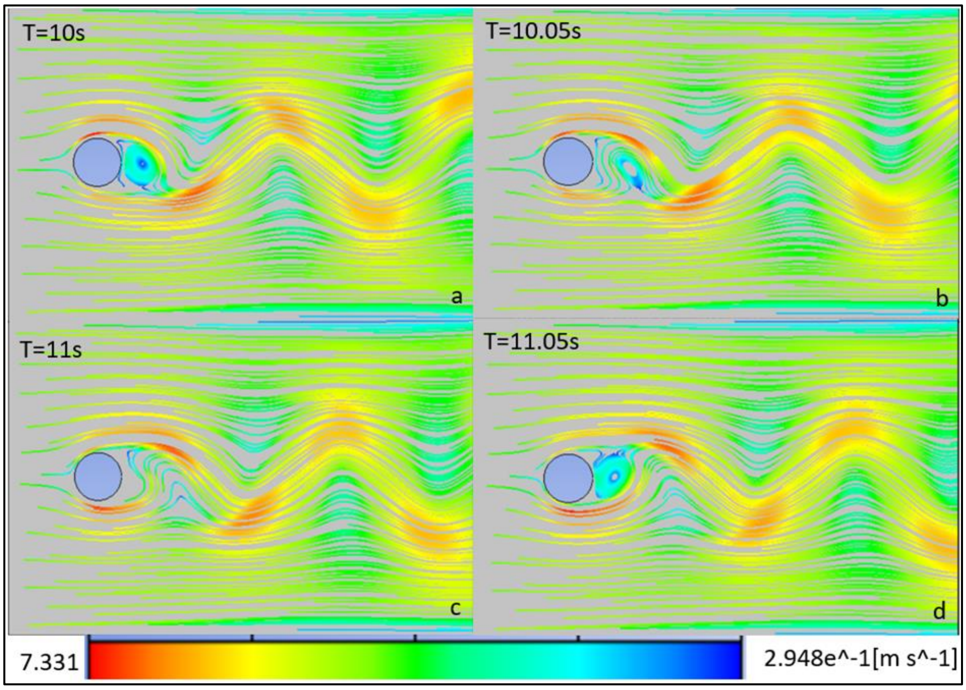


Fig. 4.1 Stream lines flow pattern of flow over cylinder at time instant 10s,10.05s, 11s and 11.05s (a, b, c and d)

From the figure, it is observed that the top shear layer creates a clockwise circulation, noted at time instant T=10s. With the course of time, the circulation diminishes, shown in Figure 4.1 b at instance 10.5 s. After the top layer circulation, bottom shear layer forms an anticlockwise circulation which weakens with time, Figure 4.1 (c-d) The alternate shedding from the cylinder creates an alternate lift force and drag force on the cylinder. The figure 4.1(a-d) indicates an alternate vortex shedding in the wake region, denoted as the Von Karman effect.

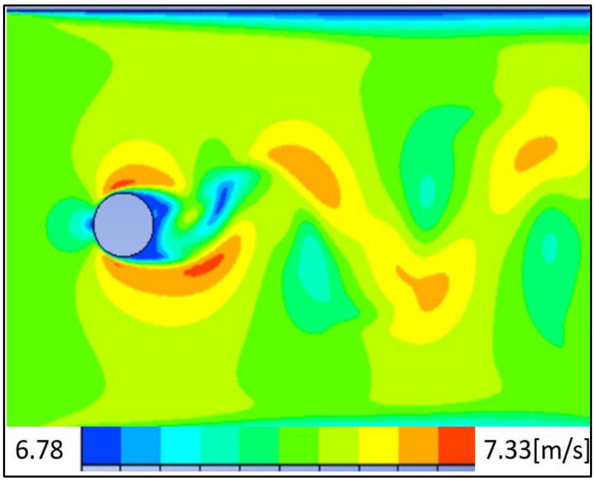


Fig. 4.2 Velocity contour at t=10s

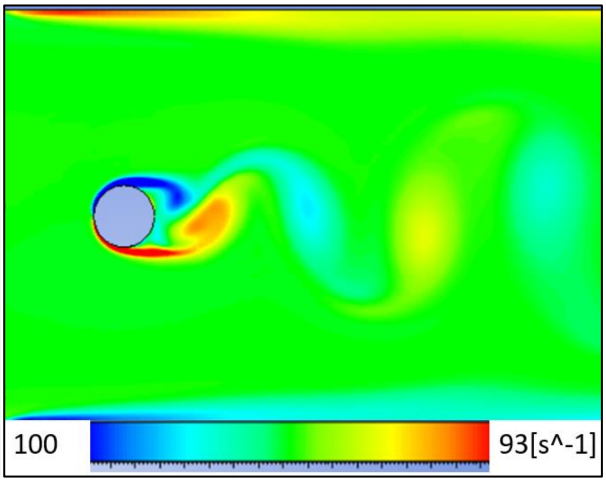


Fig. 4.3 Vorticity contour at t=10s

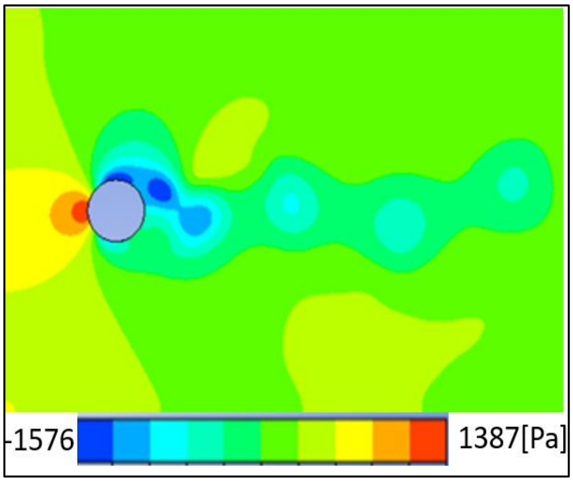


Fig. 4.4 Pressure contour at t=10s

Figure 4.2- 4.4 represent velocity, vorticity and pressure contours at flow domain for the event of fluid flow over cylinder when cylinder is taken as rigid. The mapping of colours for different contours is plotted for a time instance of 10 second after the flow begins. A vortex street pattern is indicated in all the figures for the cylinder wake. Figure 4.5 and 4.6 show

time history of fluctuating lift force over the cylinder and corresponding frequency spectrum. The frequency spectrum indicates that the oscillating frequency of the lift force is 3.33 Hz. The observed frequency results a Strouhal number 0.18 is 3.6 Hz which is matching with the standards.

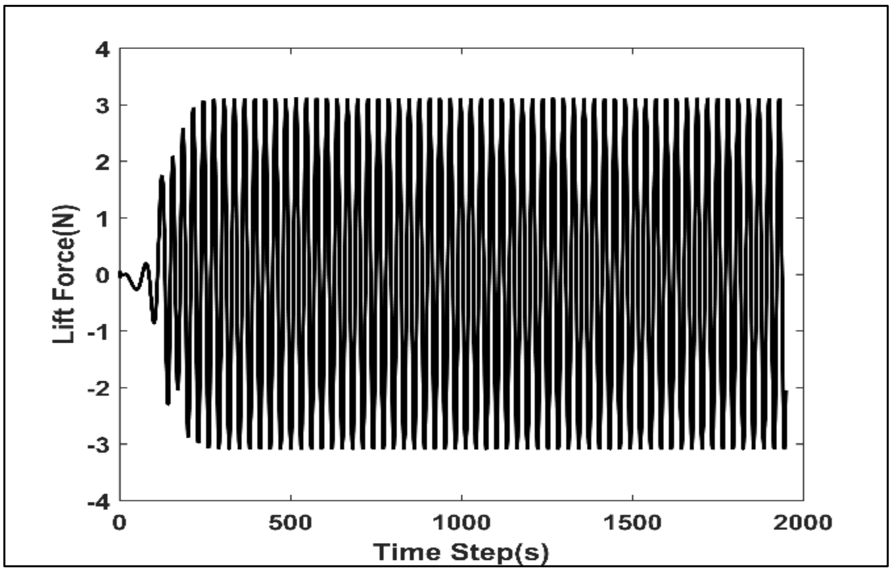


Fig. 4.5 Time history of lift force variation of flow over cylinder

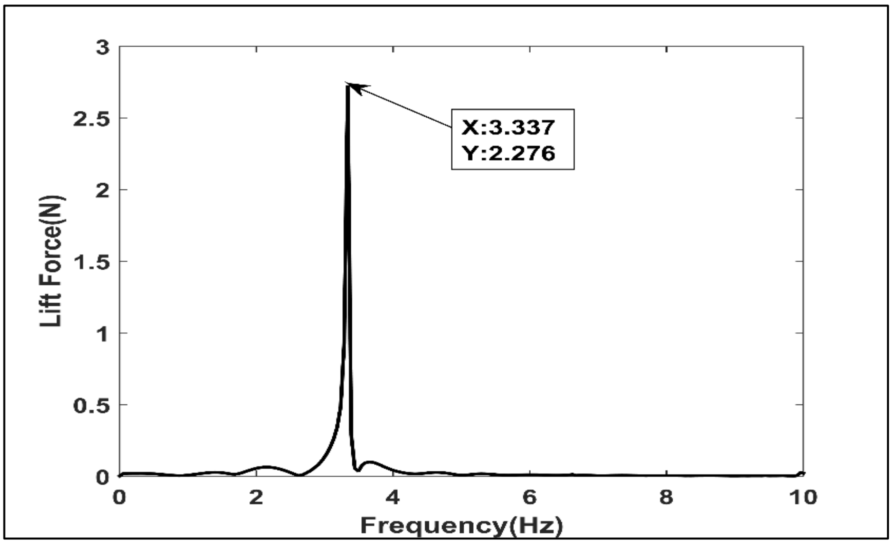


Fig. 4.6 Frequency spectrum of lift force fluctuation of flow over cylinder

4.2 Flow over fixed cylinder with rigid splitter plate

In this investigation, the test geometry is modified when a rigid splitter plate is added at the trailing cylinder side. The flow domain and a cylinder are considered same as used in the previous case (Section 4.1). The main focus of this analysis is to find out the variation in the lift force with respect to the presence of a trailing plate and how it changes when the length of splitter plate is changed. The instantaneous streamline flow field pattern of flow over cylinder with splitter plate of length0.25D is shown in figure 4.7. Since the splitter plate made obstruction between upper shear layer and lower shear layer, the wake region remarkably extends in the direction of streamwise with the plate length. Elongation of the shear layers can be observed from Figure 4.7(a-d). Due to the shifting of wake region, magnitude of lift force fluctuation over the surface of cylinder decreases.

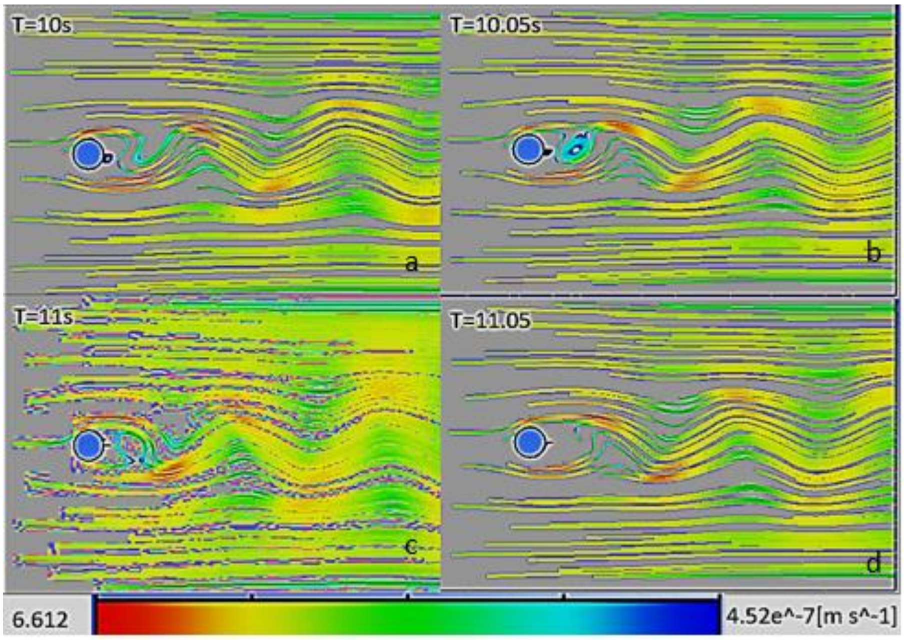


Fig. 4.7 Streamline pattern of flow field of flow cylinder with splitter plate length at different time instant (t=10s, 10.05s, 11s and 11.05s)

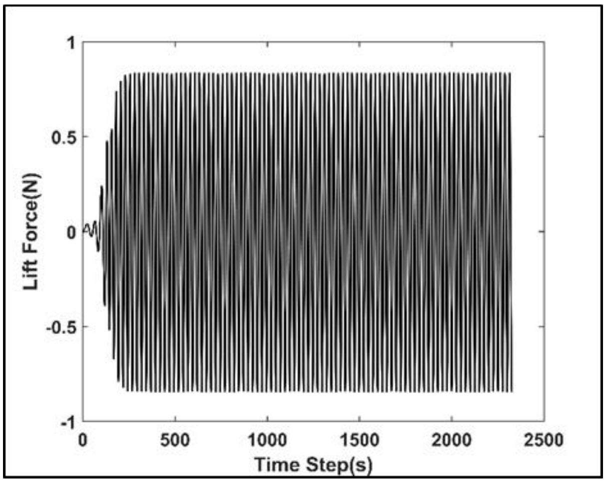


Fig. 4.8 Lift force variation on the cylinder with splitter plate length of 0.25D

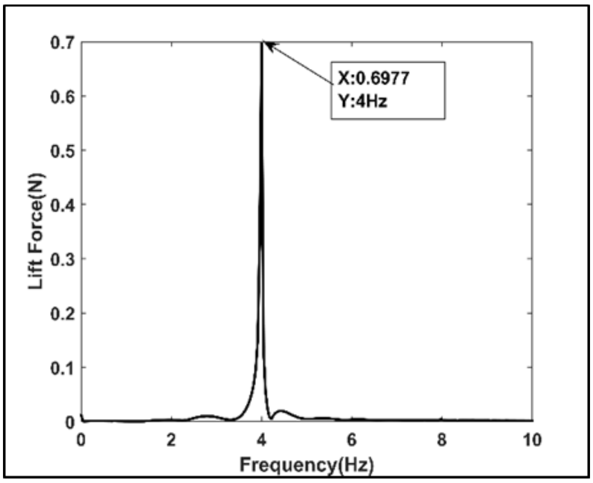


Fig. 4.9 Frequency spectrum of lift force with splitter plate length of 0.25D

Time history of the lift force over the cylinder and its frequency spectrum are shown in figure 4.8 and 4.9. The figure shows a dominating frequency of 4 Hz is observed, which was lower when the flow over a cylinder is considered without a section of trailing plate. In case of increased length of splitter plate, the further extension of shear layer in the downstream side is observed and then noted for a shorter splitter plate. It is evident that extended shear layer will cause lower fluctuating forces over the surface of the cylinder. The instantaneous streamline flow field pattern of flow over cylinder with 0.5D splitter plate length is show in figure 4.10. Since the splitter plate made obstruction between upper shear layer and lower shear layer, the wake region remarkably elongates in the direction of stream with the plate length. Elongation of the shear layers can be observed from Figure 4.10 (a-d). To find out the role of a plate on the dynamics of the flow, three more cases of plate length 0.5D, 0.75D and 1D have performed. Due to the shifting of wake region, magnitude of lift force fluctuation over the surface of cylinder decreases.

Figure 4.10-4.13 show the streamline pattern of flow field with splitter plate length 0.5, 0.75 and 1D. Time history of lift force fluctuation all the three cases shown in figure 4.13-4.18.

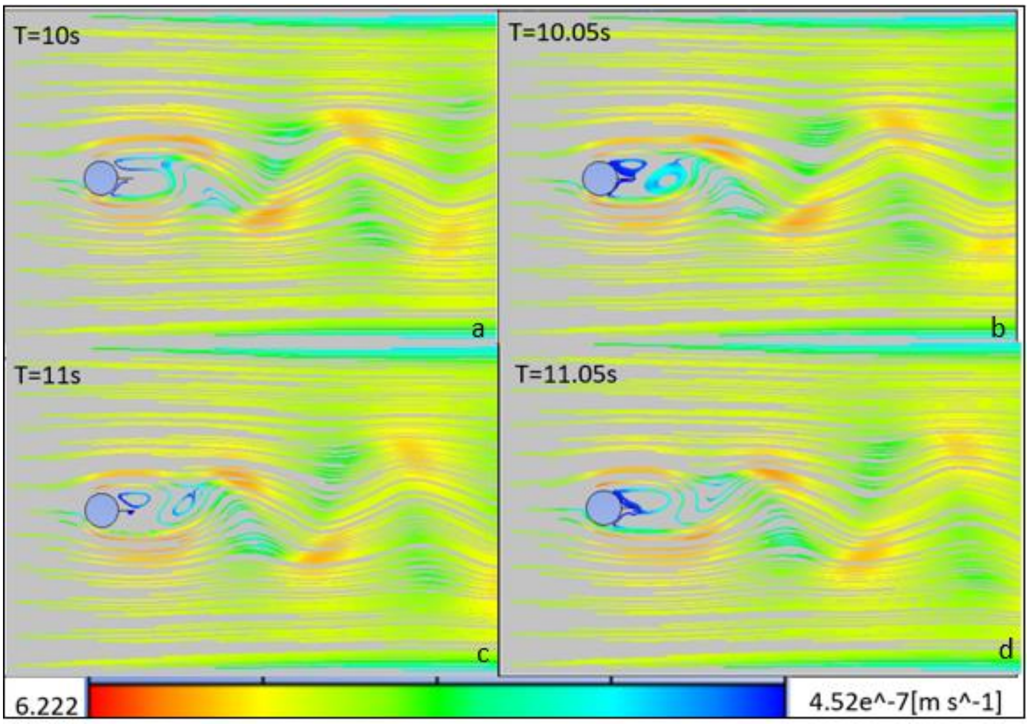


Fig. 4.10 Streamline pattern of the flow field of flow over cylinder with splitter plate length 0.5D at instant of time t=10s, 10.05s, 11s and 11.05s

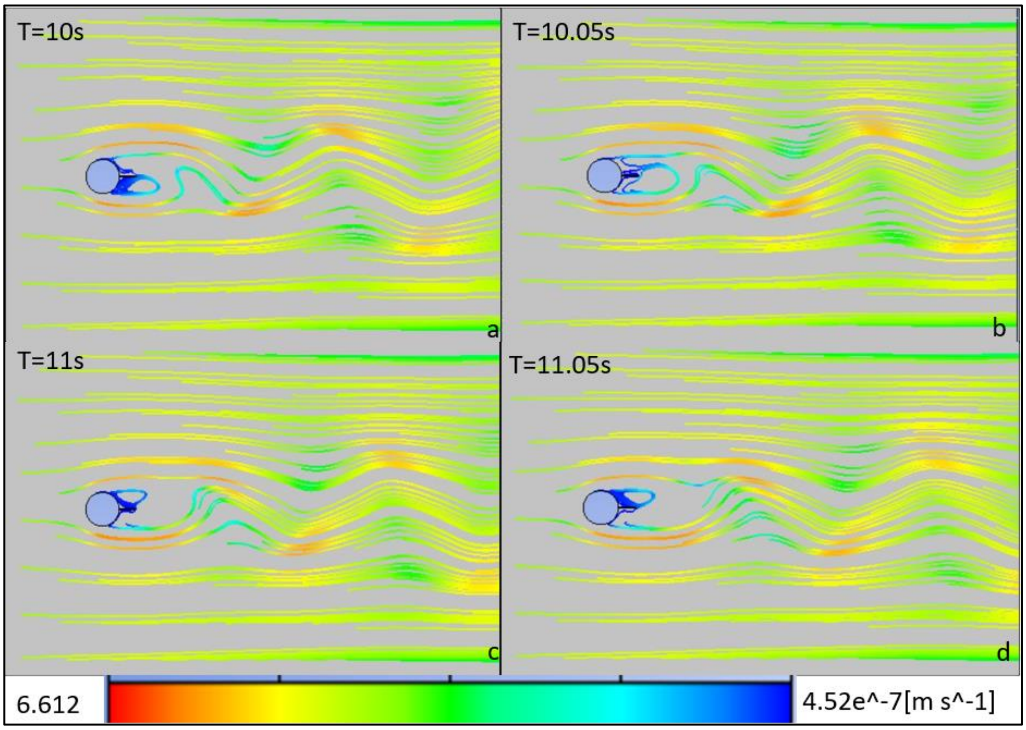


Fig. 4.11 Streamline pattern of flow field with splitter plate length 0.75D at instant of time t=10s, 10.05s, 11s and 11.05s

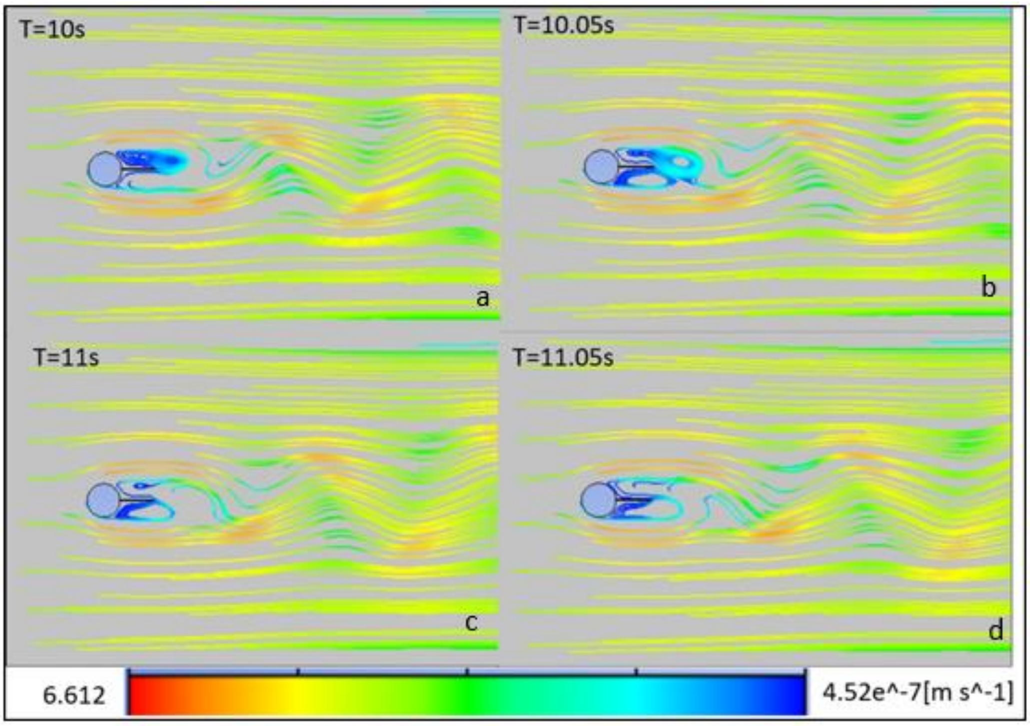
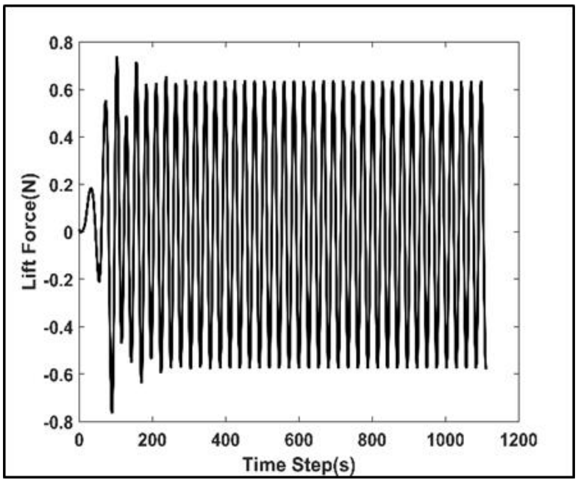


Fig. 4.12 Stream line pattern of flow field of flow over flexible cylinder with splitter plate length 1D at time instant 10s, 10.05s, 11s and 11.05s



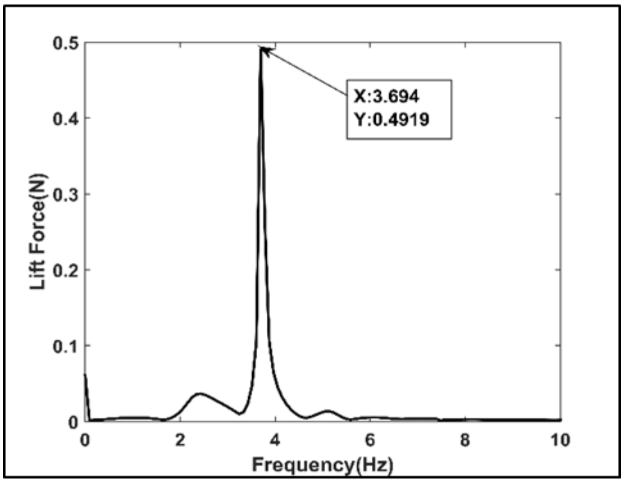
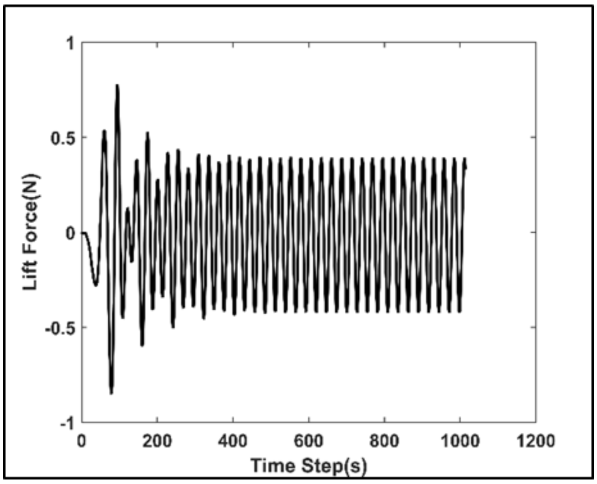


Fig. 4.13 Lift force variation on the cylinder with splitter plate length of 0.5D

Fig. 4.14 Frequency spectrum of lift force variation with splitter plate length 0.5D



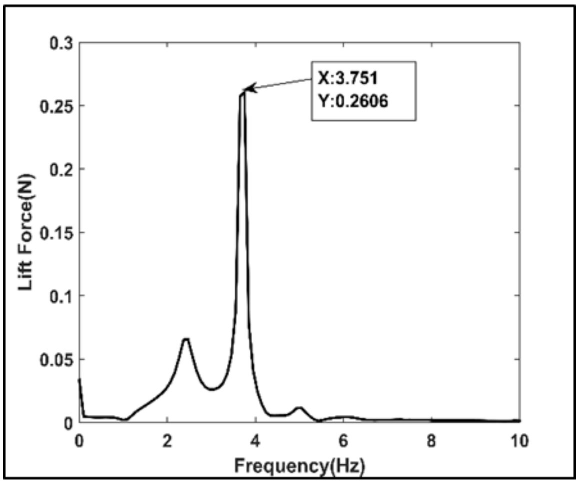
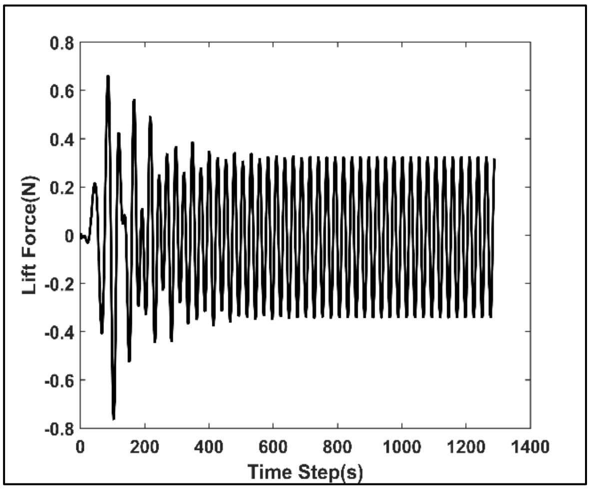


Fig. 4.15 Lift force variation on the cylinder with splitter plate length of 0.75D

Fig. 4.16 Frequency spectrum of lift force variation with splitter plate length 0.75

Table 4 reviews variation in the results found for the different plate lengths. A comparatively study of lift variation with the flow over a fixed cylinder is carried out. With the insertion of 0.25D splitter plate length 73.63 % reduction in lift force amplitude at saturation state is observed. 78.38% reduction in case of 0.5D splitter plate length is observed. Maximum reduction 88.46 % lift force is achieved at 0.75D. In case of plate length 1D splitter plate length negligible amount of the lift force reduces as compare to the 0.75D. When lift force variation is compare with the bare cylinder 88.88 % reduction is achieved.



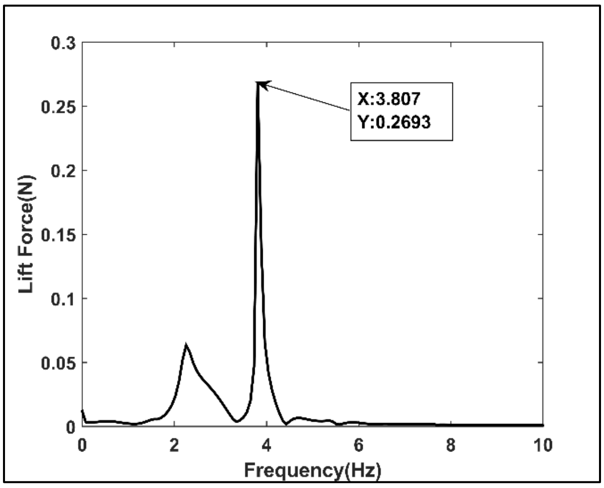


Fig. 4.17 Lift force variation on the cylinder with splitter plate length of 1D

Fig. 4.18 Frequency spectrum of lift force variation with splitter plate length 1D

Table4 Comparison of lift force variation of flow over a fixed cylinder with flow over a fixed cylinder with rigid splitter plate length L=0.25D, 0.50D, 0.75D and 1D

I. No	Splitter plate length	Lift force variation(N)	Frequency of the lift force(Hz)	% Reduction in lift force as compare to bare cylinder
1	0	2.276	3.3	0
2	0.25D	0.600	4	73.63
3	0.50D	0.4919	3.6	78.38
4	0.75D	0.2626	3.7	88.46
5	1D	0.2606	3.8	88.55

When we compare the result of lift force is continuously decreases and corresponding frequency of lift force also decreases. A complete attenuation of the vortex shedding at plate length more than 5D is observed for this simulation. The results of the simulation have good agreement with the standard results obtained in previous investigations. Kwon and Choi [7] reported that the critical length, when the shedding supresses, of the splitter plate at 160 Reynolds number is more than the 5 times the diameter (D) of the cylinder. Roshko [25] reported from the experimental result that critical length of the plate is L=5D at relatively higher Reynolds number of 1.45×10^4. Apelt and West [6] also showed that a complete suppression of the vortex shedding at L=5D at $10^4 < Re < 5 \times 10^4$. It is fascinating to note that the splitter plate length plays a similar role for attenuation of the vortex shedding with very low and high Reynolds number.

4.3 Flow over flexible cylinder

It is known that a flexible cylinder in flow exhibits lock-in. The Lock-in condition depends on the structure property e.g., mass, damping and the stiffness of the body and on the flow field in terms of vortex shedding frequency. [3]. As the main focus of the present study is check role of an aft body (splitter plate) of the VIV of a cylindrical object while it is vibrating on its peak level at locked in condition. Therefore, first, it is desirable to identify a condition where the system exhibits locked-in behaviour. In the present work, preliminary tests are conducted to achieve lock-in for the given set of flexible cylinders. There may be two approaches to achieve lock-in condition either by altering the flow velocity and noting vibration response or by changing the structure property and keeping flow constant. In the present work, second approach has been followed. Number of simulations are carried out for different Structural stiffness value and based on the response observed; a lock-in state is identified. Three cases of test simulation are performed in which the stiffness 1364N/m, 1984N/m and 2364N/s are considered. To monitor the displacement of the cylinder structure a monitor point is kept at the surface of the structure.

Figure 4.19-4.24 show time history and frequency spectrum of the vibration amplitude of flexible cylinder measured at the fixed monitor point.

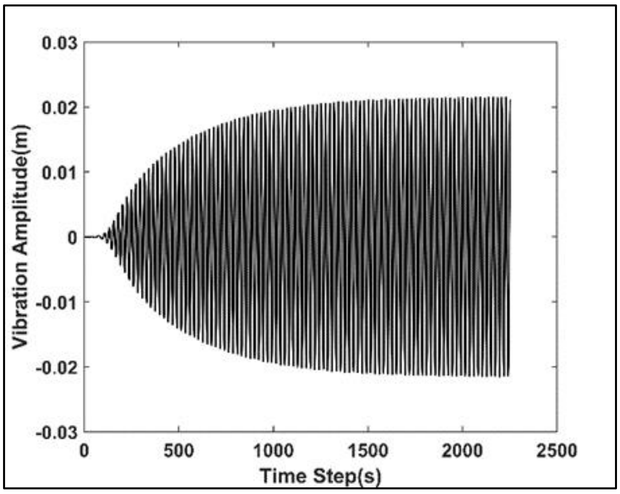


Fig. 4.19 Vibration amplitude of the flexible cylinder with stiffness 1984N/m

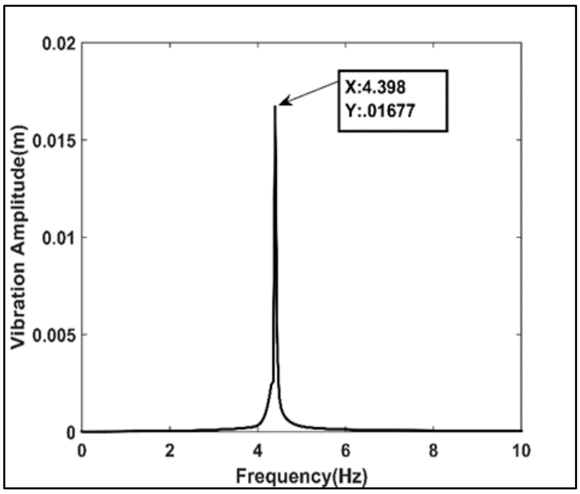


Fig. 4.20 Frequency spectrum of the Vibration amplitude 1984N/m

From the figures 4.20, it is observed that the maximum amplitude of the vibration is achieved in the case of stiffness 1984N/m, which shows the locked-in condition of coupled fluid-structure system. It indicates that the structural natural frequency synchronises with vortex shedding frequency and system vibrate with the high amplitude of vibration [3].

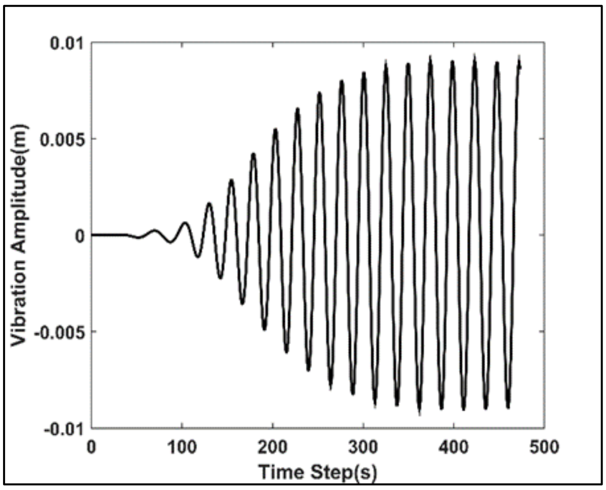


Fig. 4.21 Vibration amplitude of the flexible cylinder with stiffness 1364N/m

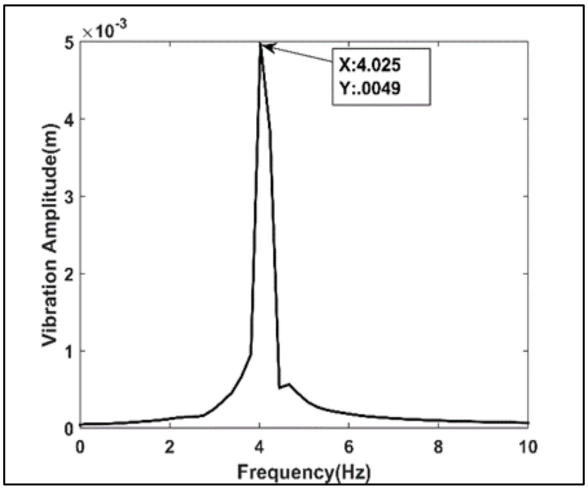


Fig. 4.22 Frequency spectrum of the Vibration amplitude with stiffness1364N/m

For the next simulations to identify role of a splitter plate on the VIV of flexible cylinder, current set of structural (stiffness 1984N/m and mass 2.512 kg) and flow properties (flow velocity 4 m/s at Re 160) that exhibited lock-in are used.

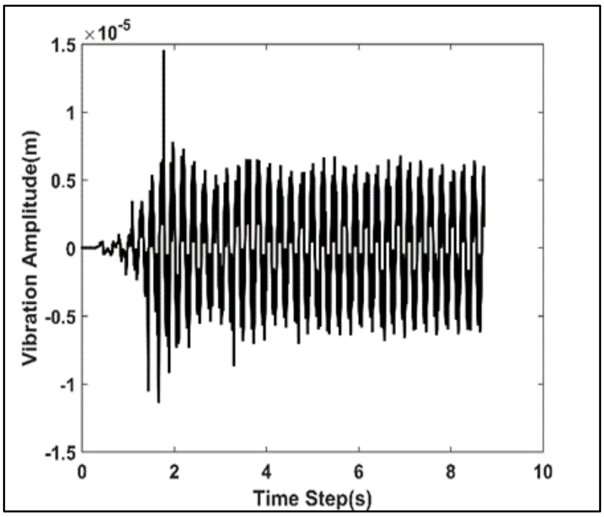


Fig. 4.23 Vibration amplitude of the flexible cylinder with stiffness 2386N/m

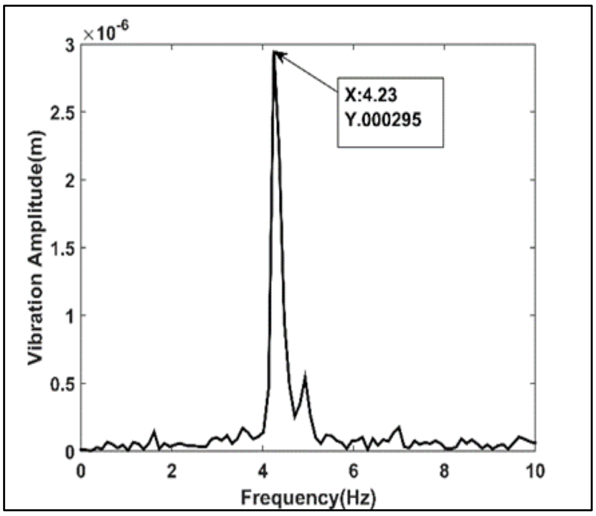


Fig. 4.24 Frequency spectrum of the Vibration amplitude 2386N/m

4.4 Flow over a flexible cylinder with different splitter plate length

Effect of splitter plate on the flow induced vibration of cylinder is now investigated. In section 4.2, it is noted that due to the implementation of a trailing pate, amplitude of the lift force on the cylindrical surfaces reduced significantly. As the primary goal of the present study is to develop a scheme to control flow induced vibration in large chimney or marine risers like structure, here also, it is expected that a trailing plate will reduce the flow induced vibration of a vibrating cylinder. Considering this advantage of a trailing plate, different cases of different plate length attached on a flexible cylinder are now investigated.

As we want to control flow induced vibration in large chimney or marine risers like structure by adding an aft end plate structure, selection of the length of the splitter plate is an important aspect. These structures are quite large and withstand in dynamic environment, it is always cautionary to add an aft body to the structure, which may cause other difficulties in the regular operation of the system. A longer aft structure may cause instability in the structure. and thus, the shorter length of the trailing plate will always be beneficial. In this study, investigations are carried out for four different lengths (0.25D, 0.5D, 0.75D and 1D) of trailing plate. All the simulations are performed for a constant flow velocity of 4m/s and Reynolds number 160 and the same computational domain as considered in the previous investigations (Section 4.3) is used.

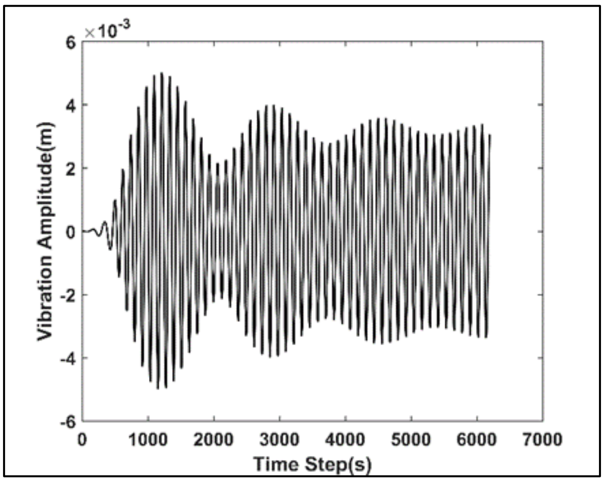


Fig. 4.25 Vibration amplitude of flow over flexible cylinder with splitter plate length of 0.25D

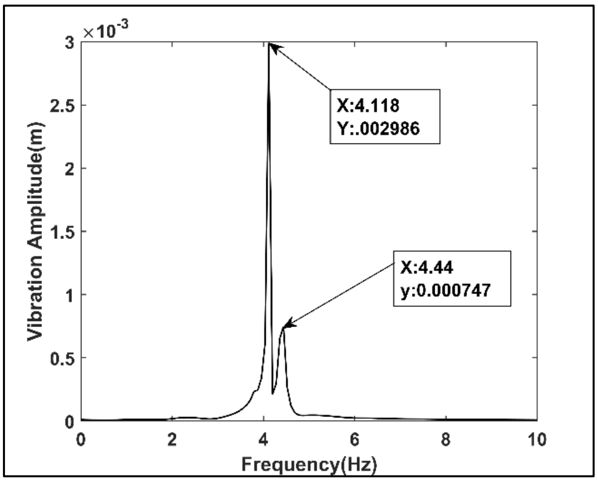


Fig. 4.26 Frequency spectrum of flow over flexible cylinder with splitter plate length of 0.25D

It may be inferring that two peaks in the frequency spectrum are corresponding to the natural frequency of the system (Section 3.3) 4.11Hz at which system vibrates, and the vortex shedding frequency 4.4 Hz. As the two frequencies are closed, the observed result shows that the vortex shedding frequency synchronising with the natural frequency and causing high amplitude vibration. In addition, a beating kind of time response is also an indication of present of two slightly close frequencies in the system.

When plate length changes to L= 0.5D, Response changes. The time history and frequency spectrum of the vibration amplitude for the present case are shown in figure 4.27-4.28. Vibration amplitude and oscillation frequency of the cylinder decreases as compare to the previous case but trend of oscillations is similar. As plate length is increases, oscillation frequency of the system changes from 4.11Hz to 3.709Hz with amplitude 0.002 to 0.001. Due to the plate length, shear layers are more extended in the wake region, and vortices are formed for away from the cylinder base.

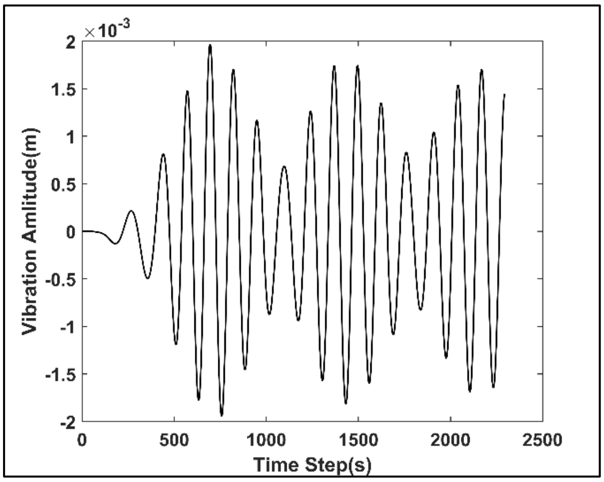


Fig. 4.27 Vibration amplitude of flow over the flexible cylinder with splitter plate length of 0.5D

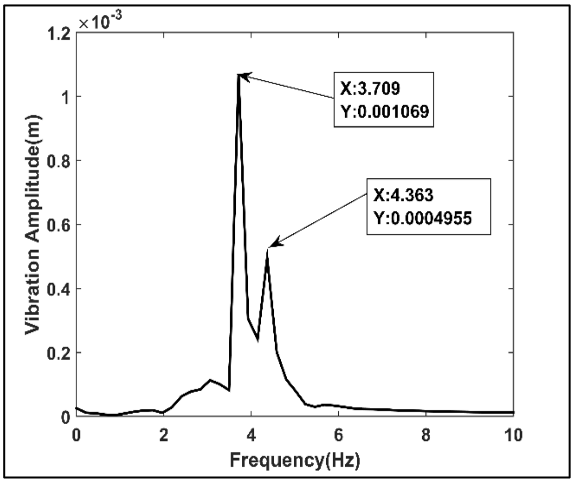
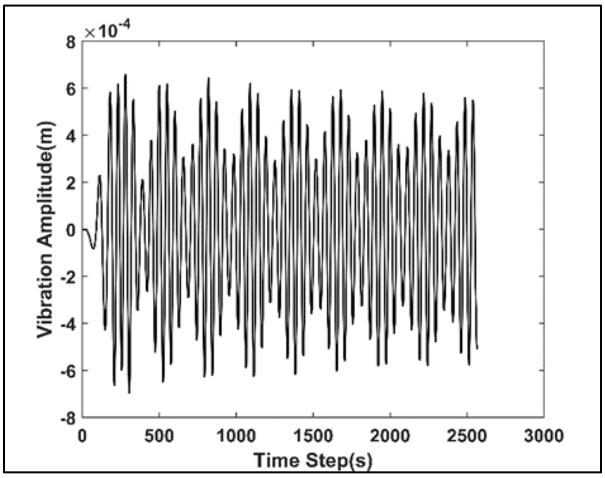


Fig. 4.28 Frequency spectrum of flow over flexible cylinder with splitter plate length of 0.5D

Figure4.27 show fluctuation of displacement of the cylinder for plate of 0.75D and 1D respectively. As plate length 0.75D is considered the amplitude of vibration decreases up-to 66.66% with respect to plate length 0.5D. When splitter plate of length 1D is considered, the amplitude of the vibration is continuously increases, shown in the figure 4. (3-32). Observed increasing nature of the vibration amplitude indicates the reattachment of the vortices with splitter plate.



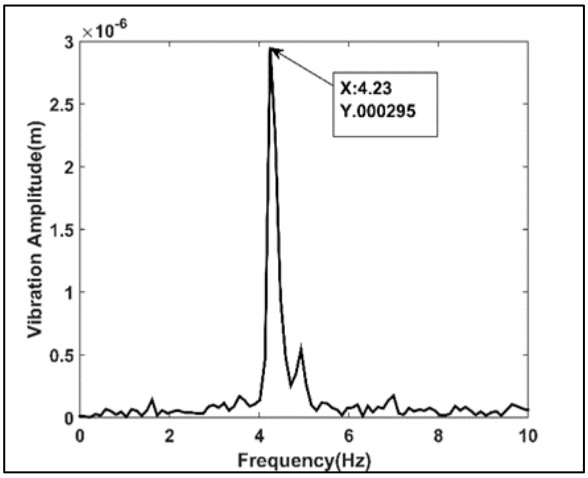
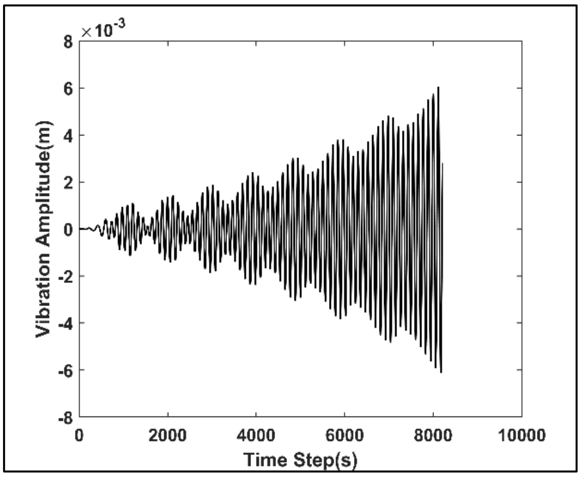


Fig. 4.29 Vibration amplitude of flow over the flexible cylinder with splitter plate length of 0.75D

Fig. 4.30 Frequency spectrum of flow over flexible cylinder with splitter plate length of 0.75D

Table 4 summarizes the vibration response of different splitter plate length. For the comparison, vibration amplitude for the case of a cylinder without the splitter plate (base cylinder) is also added in the table. The table indicates that for a plate length of 0.75D, a maximum reduction of 97.50% is achieved.



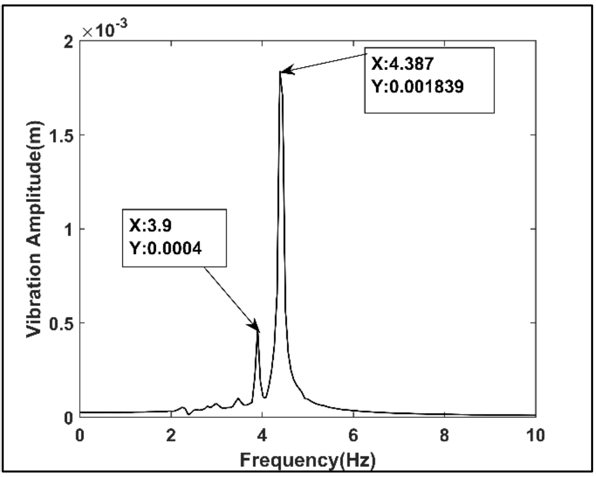


Fig. 4.31 Vibration amplitude of flow over the flexible cylinder with splitter plate length of 1D

Fig. 4.32 Frequency spectrum of flow over flexible cylinder with splitter plate length of 1D

In case of plate length L= 1D, the magnitude of vibration continuously increasing, the possible reason for this behaviour is the reattachment of vortices on the plate, that may causes increase in the vibration amplitude.

Table 5 Comparison of vibration amplitude of flow over a flexible cylinder with a flexible cylinder with rigid splitter plate length of L=0.25D, 0.5D, 0.75D and 1D

Sr.n	**Test case**	**Vibration amplitude(m)**	**% Decrease of vibration amplitude as compare to bare cylinder**
1	Bare cylinder	0.016	0
2	Cylinder with 0.25Dsplitter plate length	0.0029	87.50
3	Cylinder with 0.5D splitter plate length	0.0010	93.75
4	Cylinder with 0.75D splitter plate length	0.0004	97.50
5	Cylinder with 1D splitter plate length	-	-

CHAPTER 5

CONCLUSIONS

The motivation of this work is that this problem is closely related to marine riser type structure, which fails due to fatigue failure. In this study, a numerical investigation of vortex induced vibration of flow over flexible cylinder with rigid splitter plate is carried out. Different numerical studies of flow over a fixed cylinder, flow over a flexible cylinder, flow over a cylinder with a rigid plate and eventually flow over a flexible cylinder with rigid splitter plate is performed. The effect of length of the plate on the overall VIV of the flexible cylinder is also investigated. The results obtained indicated that with the insertion of 0.25D splitter plate a considerable amount of vibration amplitude is reduced without affecting the structure dynamics. Maximum reduction of vibration amplitude is achieved for the in case of 0.75D plate. For a plate of 0.25D length, an overall 87.50% reduction in the vibration when compared with a case of cylinder without a plate is noted. This reduction percentage increases to 97.50 % for a plate of length 0.75D. However, it is suggested that a long trailing structure may influence the dynamics of the structure. Additionally, a long splitter plate is not justifiable from the practical point of view and may induced instability. Therefore, from the present investigations, it is suggested to apply a trailing plate of length 0.25D to get a reasonable reduction in the vibration of the cylindrical body.

Future Scope of the work

The future scope of this work may be a three-dimensional numerical simulation of vortex induced vibration of flexible cylinder with rigid splitter plate. The three-dimensional characteristics of the flow may result more detail, however, the authors strongly believe, that the two-dimensional simulations are justifiable and an experimental validation should be performed in the future. Another extension of the present work is to identify the effect of a flexible splitter plate on the flow induced vibration of flexible cylinder.

References

1. Bearman, P.W., 1984. Vortex shedding from oscillating bluff bodies. *Annual review of fluid mechanics*, *16*(1), pp.195-222.
2. Sarpkaya, T., 2004. A critical review of the intrinsic nature of vortex-induced vibrations. *Journal of fluids and structures*, *19*(4), pp.389-447.
3. Govardhan, R. and Williamson, C.H.K., 2000. Modes of vortex formation and frequency response of a freely vibrating cylinder. *Journal of Fluid Mechanics*, *420*, pp.85-130.
4. Bearman, P.W., 1984. Vortex shedding from oscillating bluff bodies. *Annual review of fluid mechanics*, *16*(1), pp.195-222.
5. Gabbai, R.D. and Benaroya, H., 2005. An overview of modeling and experiments of vortex-induced vibration of circular cylinders. *Journal of Sound and Vibration*, *282*(3-5), pp.575-616.
6. Bruno, L., Fransos, D., Coste, N. and Bosco, A., 2010. 3D flow around a rectangular cylinder: a computational study. *Journal of Wind Engineering and Industrial Aerodynamics*, *98*(6-7), pp.263-276
7. Bourguet, R., Karniadakis, G.E. and Triantafyllou, M.S., 2011. Lock-in of the vortex-induced vibrations of a long tensioned beam in shear flow. *Journal of Fluids and Structures*, *27*(5-6), pp.838-847.
8. Yamamoto, C.T., Meneghini, J.R., Saltara, F., Fregonesi, R.A. and Ferrari Jr, J.A., 2004. Numerical simulations of vortex-induced vibration on flexible cylinders. *Journal of fluids and structures*, *19*(4), pp.467-489.
9. Yin, D., Lie, H. and Baarholm, R.J., 2017, June. Prototype Reynolds number VIV tests on a full-scale rigid riser. In *ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering* (pp. V002T08A033-V002T08A033). American Society of Mechanical Engineers.
10. Quen, L.K., Abu, A., Kato, N., Muhamad, P., Sahekhaini, A. and Abdullah, H., 2014. Investigation on the effectiveness of helical strakes in suppressing VIV of flexible riser. *Applied Ocean Research*, *44*, pp.82-91.
11. Huang, S., 2011. VIV suppression of a two-degree-of-freedom circular cylinder and drag reduction of a fixed circular cylinder by the use of helical grooves. *Journal of Fluids and Structures*, *27*(7), pp.1124-1133
12. Assi, G.R., Bearman, P.W. and Kitney, N., 2009. Low drag solutions for suppressing vortex-induced vibration of circular cylinders. *Journal of Fluids and Structures*, *25*(4), pp.666-675
13. Gharib, M.R., 1999. *Vortex-induced vibration, absence of lock-in and fluid force deduction* (Doctoral dissertation, California Institute of Technology).
14. Apelt, C.J., West, G.S. and Szewczyk, A.A., 1973. The effects of wake splitter plates on the flow past a circular cylinder in the range 10 4< R< 5× 10 4. *Journal of Fluid Mechanics*, *61*(1), pp.187-198.
15. Kwon, K. and Choi, H., 1996. Control of laminar vortex shedding behind a circular cylinder using splitter plates. *Physics of Fluids*, *8*(2), pp.479-486.
16. Wang, J., Liu, H., Gu, F. and Zhao, P., 2010, January. Numerical simulation of flow control on marine riser with attached splitter plate. In *ASME 2010 29th International Conference on Ocean, Offshore and Arctic Engineering* (pp. 489-498). American Society of Mechanical Engineers.
17. Akilli, H., Karakus, C., Akar, A., Sahin, B. and Tumen, N.F., 2008. Control of vortex shedding of circular cylinder in shallow water flow using an attached splitter plate. *Journal of Fluids Engineering*, *130*(4), pp.041401.

18. de Araujo, L.A., Schettini, E.B.C. and Silvestrini, J.H., 2018. Direct numerical simulation of the flow around a cylinder with splitter plate: analysis for moderated Reynolds numbers. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *40*(6), pp.276.

19. Shukla, S., Govardhan, R.N. and Arakeri, J.H., 2009. Flow over a cylinder with a hinged-splitter plate. *Journal of Fluids and Structures*, *25*(4), pp.713-720.

20. Shukla, S., Govardhan, R.N. and Arakeri, J.H., 2013. Dynamics of a flexible splitter plate in the wake of a circular cylinder. *Journal of Fluids and Structures*, *41*, pp.127-134.

21. Sudhakar, Y. and Vengadesan, S., 2012. Vortex shedding characteristics of a circular cylinder with an oscillating wake splitter plate. *Computers & Fluids*, *53*, pp.40-52.

22. Kundu, A., Soti, A.K., Bhardwaj, R. and Thompson, M.C., 2017. The response of an elastic splitter plate attached to a cylinder to laminar pulsatile flow. *Journal of Fluids and Structures*, *68*, pp.423-443.

23. Liang, S., Wang, J., Xu, B., Wu, W. and Lin, K., 2018. Vortex-induced vibration and structure instability for a circular cylinder with flexible splitter plates. *Journal of Wind Engineering and Industrial Aerodynamics*, *174*, pp.200-209.

24. Wu, J., Shu, C. and Zhao, N., 2014. Numerical investigation of vortex-induced vibration of a circular cylinder with a hinged flat plate. *Physics of Fluids*, *26*(6), p.063601.

25. Roshko, A., 1961. Experiments on the flow past a circular cylinder at very high Reynolds number. *Journal of Fluid Mechanics*, *10*(3), pp.345-356.