

DISSERTATION

On

Numerical Analysis of Flow-induced Vibration of a Flexible Plate

Submitted in partial fulfillment of the requirement

for the award of degree of

**Master of Engineering
in
CAD/CAM Engineering**

Submitted by

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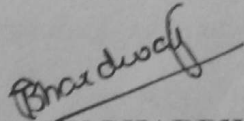
Declaration

I hereby declare that work done in this dissertation report entitled, "Numerical Analysis of flow induced vibration of flexible plate" submitted towards partial fulfillment of requirement for award of **Master of Engineering degree in CAD/CAM Engineering in Mechanical Engineering Department of Thapar University, Patiala**, is an authentic record of work carried out by me under the supervision and guidance of **Dr. Ashish Purohit, Assistant Professor of Mechanical Engineering Department, Thapar University, Patiala**.

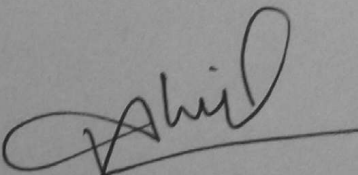
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This is to certify that above declaration made by the student concerned is correct to the best of my knowledge and belief.


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Abstract

Fluid-Structure interaction has gained importance since the natural calamities on foreign lands such as Tacoma bridge failure, and nuclear reactor failure due to unstable vibration. The study of these historical events highlights an important multi-physics phenomenon, which involves two-way fluid structure interaction. FIV has, now a day, employed to generate electric power using piezoelectric materials. This dissertation basically focused on numerical study of flow-induced vibration of a flexible structure behind the cylindrical body. When flow past over the bluff body, vortex-shedding takes place which causes perturbation in downstream structure. In the thesis, a systematic study of flow-induced vibration is carried out. In addition, influence of flow velocity and size of the bluff body on the level and frequency of the training flexible structure are investigated. It is observed the vortex shedding frequency locked with the structural frequency. For different flow velocity, different structural frequency synchronizes and results high amplitude vibration. The effect of variation in the size of the front bluff body gives high amplitude oscillation of structure for a range of sizes, beyond that arbitrary high amplitude vibration is noted.

Key words: Fluid-Structure interaction, Bluff-body, Membrane, Vortex-Shedding, Piezoelectric, Optimal, fluttering, and hydrofoils.

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Nomenclature

σ = Stress tensor,

ρ = Density,

f = Body force

d = Displacement (Structure)

$\bar{\epsilon}$ = virtual strain

\bar{d} = displacement of the structure

R_c^i = force acting on an element i

$()^B$ = denote the body of a solid structure

$()^{Sf}$ = denote the surface of a solid structure.

C= 19.7 for Reynolds number $250 < Re < 10^5$

D = Vector nodal- displacement

fr = Frequency of vibration,

L= Characteristics length

Re = Reynolds number

St = Strouhal Number

U= Flow velocity

ρ = Density

V =Velocity

d = Diameter of body

μ = Absolute viscosity

∇ = Gradient

$\int_V \bar{\epsilon}$ = volume integral of virtual strain

Note: This report uses S.I. units i.e., International system of units extended version of M.K.S.system.

Chapter 1

Introduction

1.1 Historical and Technological Background

Flow induced vibration is an important factor while analyzing the structure strength under dynamic consideration. Tacoma bridge destruction is one of the most significant incident happened due to non-periodic vortex-shedding and subsequent vortex-induced vibration [1]. The cause of failure of Tacoma Bridge was a puzzle in the minds of scientist, in terms of whether it failed due to unstable fluttering or vortex induced vibration. First theory given by scientist was the resonating vibration of bridge, which had increased too much consequently the structure damper cables failed. After the failure of suspension system, the vibration had been transferred to the bridge and no energy transfer mechanism was there to modulates or absorb that vibration energy [2]. It hinted researchers to understand that the bridge trusses and pillars system was unable to handle the structure instability and, hence, it collapsed. It may be interpreted that the vortex-shedding creates resonance in the bridge and that made it to collapse. This theory was later on discarded because when bridge collapsed the wind velocity was 60 miles per hour which is not matched with the natural frequency of the bridge. Then scientists concluded that unstable fluttering could be the main cause of collapsing of bridge. The disaster of Tacoma Bridge underlined the importance of flow-induced vibration in the design of structure operated under the flow conditions. The vortex induced vibration has great impact on engineering and construction work. The theory has given its existence and proof in modern world. The modern examples

include Burj Khalifa (United Arab Emirates), Empire State Building (Manhattan, U.S.A.), and Oresund Bridge (joining Sweden and Denmark) [3].

Unlike the undesirable effect of VIV, it is also utilized to generate energy. In University of Michigan, a research group has invented a hydrokinetic energy device, which is ideal for harnessing the energy of slow moving water which is known as VIVACE (Vortex Induced Vibrations Aquatic Clean Energy) [4]. As the experimental study of flow-induced vibration phenomenon needs sophisticated lab for testing, and thus, most of the engineers, have, now, started the use of computational methods to understand and explore the flow-induced vibration.

In nuclear power plants, the phenomenon of flow-induced vibration is common in the fuel rods. The rods are excited due to external parallel flow of deuterium over the rod [5], which causes in the rods. Experimental study of such bulky system is practically impossible, which underscores the need of computational study. The flow-induced vibration is not always unwelcomed, now days it is used to generate electrical energy by using patches of piezoelectric material on membrane that convert pressure created by flutter into electric energy.

Flow induced vibration has been a topic of research for a long time. Most of the research of the FSI is focused either on the unstable vibration of a thin plate/membrane or vibration of a cylindrical structural in flow. In case of a plate in flow, the system shows unstable flutter vibration beyond a critical flow velocity. The vibration of the plate is influenced by the motion of the plate itself and the excitation mechanism is defined as Movement-induced excitation. In case of a cylinder, the alternate vortex shedding from the cylinder causes oscillating lift force on the cylinder, which induced vibration in the cylinder. The excitation mechanism is defined as instability-induced excitation [6]. Many engineering problems are now solved using multi-

physics approach, where flow and structural domain are solved together, viz. include airplane in flow, submarine in sea water, sky-scraper in wind, and bridge pillars in sea water etc. When the flow interacts with the structure, it responds in terms of deformation and consequently affects the surrounding flow. A two-way fluid-structure interaction is involved. The fluid-structure interaction uses the coupling of computational fluid dynamics and computational structural dynamics equations of motion simultaneously and its impact on each other. The two methods for solving FSI are experimental or analytical method and numerical method. Considering the fact that experimental methods are not economical as numerical method for analyzing FSI problem. In FSI we have to use laser and sound sensor which are very expensive in nature and secondly the use of sophisticated labs to capture the interface interaction that made it impossible for early stage researcher to analyze the problem due to insufficient funds. Fluid Structure Interaction can be one-way where (interaction takes place in one direction due to weak Fluid-Structure coupling) and two-way (interaction takes place in two directions strong Fluid-Structure coupling). The past technological disasters in structures need the accurate study of FSI which give some logical information about the interpretation.

From the literature review, it has been noted that investigation of flow-induced vibration of flexible plate behind a bluff body is limited. In the present thesis, an investigation of flow-induced vibration of a flexible plate with a front obstacle is taken up. Present thesis work deals with the numerical analysis of vortex induced vibration using computational fluid dynamics, computational structural dynamics and computational mesh dynamics integration by considering mathematical model. FSI involves multi-physics concept to solve the major fluid and solid phenomenon due to its interaction. The numerical analysis would help us to predict the failure criteria of the structure due to flowing fluid properties. The results obtained in the computation

is further analyzed for theoretical behavior of the flexible splitter plate and provides a base for the future study on civil structures such as bridges and sky-scraper, airplane flutter mechanism and solution of energy harvesting problem. Thus, this thesis work deals with the better understanding of Vortex Induced vibration of a flexible structure in flow, which is expected to be helpful to optimize the energy harvesting using flow induced vibration.

1.2 Theoretical Aspects

Flow induced vibration

Flow induced vibration is divided in to controlled vibration i.e. vortex induced vibration and unstable vibration. The Figure 2 represents the vibration on the basis of type of flow.

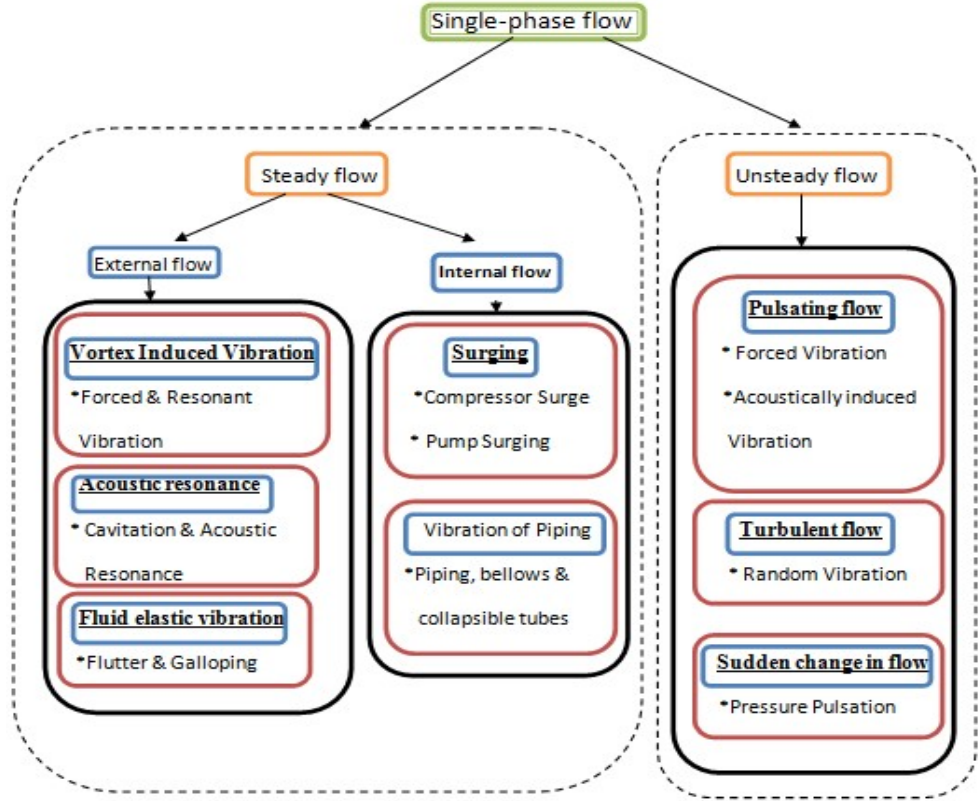


Figure 1: Flow-induced vibration [5]

Controlled Vibration: Vortex Induced Vibration

When fluid past a bluff body, alternating vortices on both sides is formed that create pressure difference on downside and upside of the cylinder. This alternating pressure difference made the vibration in the structure. In simple words vibration produced due to irregularities in the formation of vortices that cause the variation in transverse lift force but the average lift force is always zero. In other words, Vortex Shedding is responsible for vortex induced Vibration. When Vortex shedding frequency matches the natural frequency of the cylinder then the resonance has occurred that made the cause for structure failure.

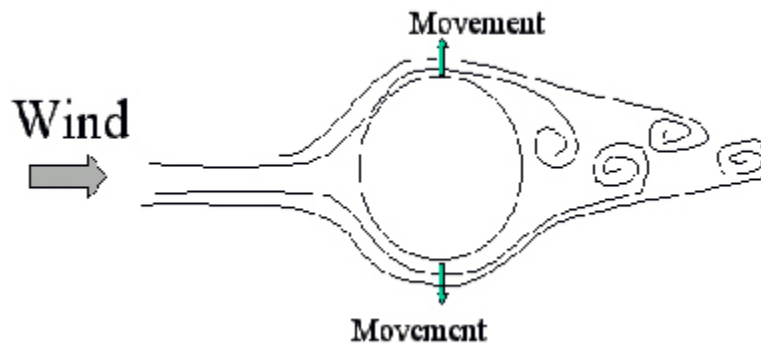


Figure 2: Lift force on the cylinder [8]

Von Karman Vortex Street named after Hungarian Physicist **Theodore von Kármán** .As shown in Figure 2 Von Karman street is the repeating pattern of swirling vortices caused due to unsteady boundary layer separation around bluff body.

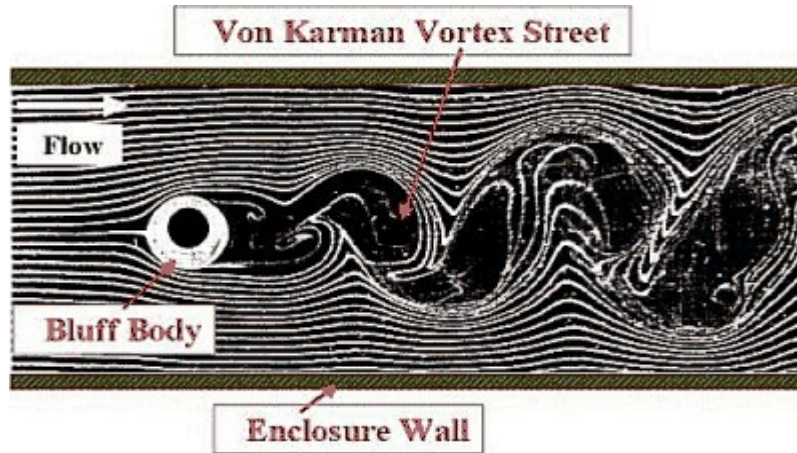


Figure 3: Von Karman Vortex Street [12]

Unstable Vibration: Flutter

The unstable vibration occurs due to boundary motion and flow disturbances and it grows with time and lead to failure of structure.

Fluttering in soft Palette (Snoring)

The common example of flutter is Snoring. When elastic structure come in contact with fluid flow it starts fluttering but if this fluttering cause instability in structure that causes its failure. The unstable fluttering is disaster but it could be used for harvesting of energy. When Human breath it causes the soft palette to flutter which creates noise and in simpler terms snoring. It is not a severe medical problem and solution for problem is that the length of soft palette is decreased with surgery [13]. The soft palette is showed in figure: 3 on next page.

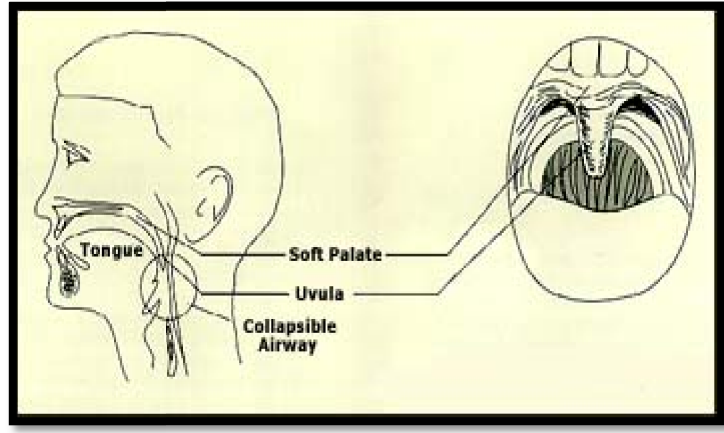


Figure 4: Human soft Palette [13]

Fluttering in Air-planes

It is the instability due to combination of both Lift and drag forces which develop fatigue in the structure and cause it failure. In past times aerial failure is considered due to snow deposition on the aerial but later on study provide the actual case where flutter and vortex induced vibration is the main cause of failure [14]. So it numerical study helped in understanding the phenomenon and their behavior in subcritical regime.

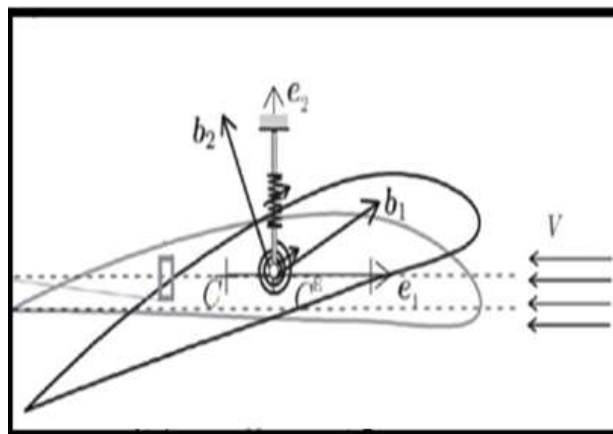


Figure 5: Flutter in Aerofoil [14]

Chapter 2

Literature Review

To understand the theory, various work carried out in the area of flow induced vibration. The literature review is categorized on the basis of flexible membrane, fixed membrane, hinged membrane and without membrane etcetera.

2.1 FSI of a cylinder with flexible support in flow

The devastating result of fluid- solid interaction in case of Tacoma Bridge made the researcher to think how a blowing wind can cause a collapse and there is a need for advancement in the multi physics phenomenon. The research has been made by A. Khalak and C.H.K. Williamson [24] to understand the behavior of rigid cylinder at very low mass and damping in flowing fluid by using Direct Numerical Simulation. The paper dealt with the understanding of mass-damping parameter, maximum amplitude attained by the cylinder, response of the cylinder and lock-in phenomenon. The observation showed that there is two distinct type of response for the elastically mounted rigid cylinder and mode transitions are discontinuous [7]. There is a deviation of Griffin plot that we used over the past 20 years from the experimental curve we obtained from the readings. It also explained that 2P (two pair of Vortex Shedding) mode is the most periodic of any wake patterns in the synchronization regime But the result is not clear about vortex mode for upper branch. P.W. Bearman [8] showed the dependency of Reynolds number on flexible cylinder having low product of mass ratio and damping. The experiment is carried out by using two cylinders in tandem arrangement and found that the in-line response is significantly greater than when cylinder in constrained to move in the inline [8]. Blackburn et al. have studied

the VIV of a cylinder through direct numerical simulation. They have compared the cylinder response observed for two-dimensional and three dimensional cases. A cylinder in a low Reynolds number flow is considered. Both experimental and numerical investigations are carried out.

2.2 FSI of plate/ membrane

Jimmo Lee and Donghun You [12] researched based on Computational methodology of vibration of splitter plate behind the cylinder or bluff-body. The splitter plate is not only used for modulation of vortex shedding but also for energy harvesting [9] by using piezoelectric material. To consider the above fact we should keep in mind what could affect the vibration in splitter plate behind the cylinder. The vibration is the result of Drag and lifts and for structures average lift force is zero but had some drag force. The presented work involves the application of CFD and CSD integration. Lee et. al. [14] found that when the splitter plate length, $l = d$ (diameter of the cylinder) it would vibrate with maximum amplitude. The forces produced due to vortex shedding are maximum at the tip and near the cylinder. There is a conclusion that splitter plate with length $l(=1d)$ and $l(=2D)$ are found to be first mode like and second mode like bending motions and if length of splitter plate ($\geq 3d$) then the deflection shape will appear to be the combination of first and second mode. It is very difficult to measure Strouhal number of vortex shedding and frequency of vibration of splitter using natural frequency but we can easily calculated by inducing free vibration due to non uniform distributed flow [10]. H.M. Blackburn [11] made comparison between the two-dimensional and three dimensional numerical simulations for water tunnel experiment by keeping Reynolds number and mechanical damping parameter identical. The observation showed that 2-dimensional and 3 dimensional simulations are nearly similar.

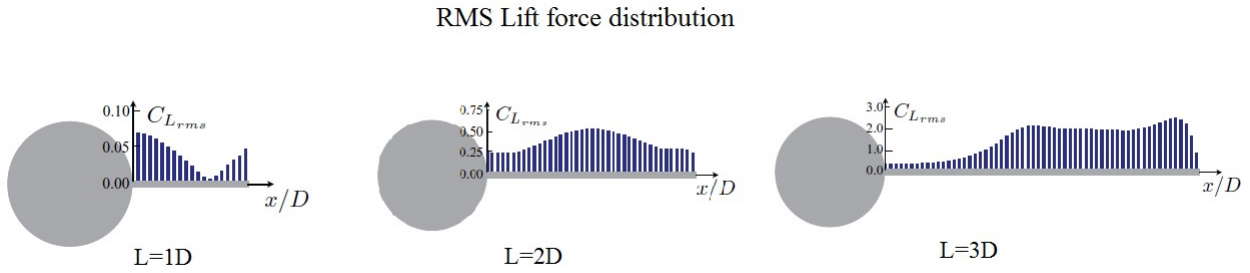


Figure 7: Lift force variation with Length

2.3 Hinged Splitter plate

So far the study has been carried out in the vibration of rigid splitter plate behind the bluff body but Assi and Bearman [15] used hinged splitter plate located at the centre of the cylinder with negligible stiffness and damping. It concluded that length to diameter ratio is helpful to determine the magnitude of oscillation. The amplitude of vibration is periodic at tip amplitude of about $0.45D$ and independent of L/D . The oscillation is a aperiodic if $L/D > 4$. The work is very much focused on the L/D to determine the nature and amplitude of oscillation.

2.4 Flexible Splitter Plate

In the past study made by researchers, it has been considered that the flexure rigidity of the splitter plate is constant. The rigid splitter plate suppresses the primary vortex shedding but these primary vortices played an important role in flexible splitter plate. The motion of hinged splitter plate is due to angular moment but in flexible splitter plate, the local pressure difference lead to local disturbances which made the dynamics of flexible splitter plate more complex. Shukla and Govardhan et. al. [21] studied the varying flexure rigidity gave it eel type motion [16] with the oscillation of amplitude of splitter plate increases linearly with the stream-wise distance [7]. The short splitter plate is non-periodic, the flap sometimes folding backwards on to itself and getting stuck in that position and then unfolding itself. The observation showed that frequency of

oscillation of plate lies in both modes i.e. close to conventional speed of vortices at Strouhal number of 0.2 but its non-periodic in nature.

2.5 Flexible splitter plate with Piezoelectric patches

The advancement has been made by using piezoelectric patches in flexible splitter plate laid the foundation for sustainable source of electric current. Sebastien Michelin and Olivier Doare [16] presented research on the use of piezoelectric pattern patches on flexible splitter plate and how the selection of modes varies its efficiency and robustness of energy harvesting process. The numerical study based on the variation of the parameters such as tuning ratio, flow velocity, mass ratio and piezoelectric coupling [23].The following observation has been made:

- The tuning means matching the frequency of solid, fluid and electric phases and the result of the study was that if the resistive element acts as short circuit or open circuit then the efficiency of harvested energy is maximum.
- The efficiency of energy harvesting is increased with increase in flow velocity.
- The variation in the mass ratio of the splitter plate showed that lighter flag (large mass-ratio) provide higher efficiency as compared to heavier flag (small mass ratio).
- The piezoelectric coupling has taken in to account the force coupling among fluid, splitter plate and electric system and observed that if we increased the coupling coefficient the electric potential is decreased and vice-versa.

2.6 Piezoelectric membrane behind the cylinder

In the latest study Yuelong Yu and Yingzheng Liu [13] made the use of piezoelectric membrane (PVDF) instead of patches. The experimental study made at subcritical and postcritical regimes.

The varying parameters are distance from cylindrical bluff body and length to diameter ratio. The result obtained is accordance with experiment performed using piezoelectric patches. It showed that both the terminal voltage and moving speed of the membrane segment if the ratio of the distance from the cylinder and length of the membrane is greater than 2 than the variation is sinusoidal [9]. The membrane showed hysteresis behavior of critical speed with a cyclic increase and decrease in flow speed was fully eliminated due to excitation of Karman Vortex Street on the membrane.

2.7 FSI of a flexible plate with an upstream bluff body

So far the study has been carried out in the vibration of rigid splitter plate behind the bluff body but Assi and Bearman [15] used hinged splitter plate located at the centre of the cylinder with negligible stiffness and damping. The experimental study showed that there is no oscillation in the splitter plate. The same methodology is used by Govardhan et. al. [22] but the location of the hinge is shifted to the base of the cylinder. The variable parameter in their work was Reynolds Number (Re), Splitter plate length to cylinder diameter ratio (L/D), and the relative mass of the plate. The result obtained show that the oscillation of the splitter plate is nearly periodic and its amplitude of oscillation is equal to the diameter of the cylinder [7]. The hinged splitter plate made the unsynchronized wake relative to the plate motion of larger splitter plate.

2.8 Conclusion of literature review

It is noted that significant work has been conducted on the FIV. Both numerical and experimental studies were carried out. One of the important areas of flow induced vibration is study of unstable vibration of a plate/membrane in the flow. A plate in flow exhibits unstable vibration beyond a critical flow velocity. Flag vibration, vibration of a paper in flow etc. are the

example of unstable flutter. Second important research area is FIV of flexible cylinders. Vibration bridges pillar, large buildings etc. Few studies are carried out on vibration of a flexible member behind a rigid bluff body. Now a day, these vibrations are used to generate energy using piezoelectric material.

Chapter 3

Objectives and Methodology

3.1 Objectives

From the literature review, it is identified that the investigation of FIV of a flexible splitter plate is limited. Investigation of a flexible plate is an important aspect to understand the dynamics of a plate like structure in the flow. Based on the literature review following objectives are considered.

- Numerical study of flow induced vibration of flexible plate in the air flow.
- Investigation of effect of flow velocity on the level of vibration of the plate.
- Investigation of size of upstream bluff body on the vibration of the plate.

3.2 Methodology

The methodology is to acquire the theoretical background and implementation of that knowledge to obtain the result in ANSYS-CFX coupling.

3.2.1 Mathematics of Computational Structure Dynamics

Momentum conservation equation for flexible structure is given by

$$\nabla \times \sigma + \rho(f - \ddot{d}) = 0 \quad [1]$$

From Principle of virtual displacement and Galerkin's method we get same set of equation for [1] and can be expressed as:

$$\frac{1}{\rho} \int_V \bar{\epsilon} \sigma dV = \int_V \bar{d} (f^B - \ddot{d}) dV + \int_{S_f} \bar{d}^{SfT} f^{Sf} dS + \sum_i \bar{d}^{iT} R_c^i \quad [2]$$

The vector has been introduced for Matrix conversion is as follow:

D = Vector nodal- displacement

$$d^{(m)} = Z^{(m)} D$$

$Z^{(m)}$ = Displacement interpolation matrix

$$\epsilon^{(m)} = U^{(m)} D$$

$U^{(m)}$ = Strain-Displacement matrix

Superscript I denotes initial stress and (m) denote element index.

Matrix form of equation [2] is expressed as:

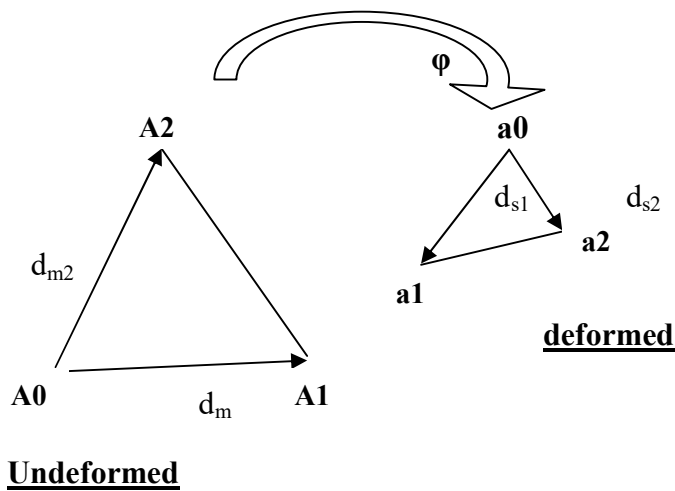
$$M\ddot{D} + KD = F \quad [3]$$

Where,

$$M = \sum_m \int_{V^{(m)}} \rho Z^{(m)T} Z^{(m)} dV^{(m)}$$

$$K = \sum_m \int_{V^{(m)}} U^{(m)T} C^m U^{(m)} dV^{(m)}$$

$$K = \sum_m \left[\int_{V^{(m)}} Z^{(m)T} f^{B(m)} dV^{(m)} + \int_{S^{(m)}} Z^{S(m)T} f^{S(m)} dS^{(m)} + \int_{V^{(m)}} U^{(m)T} \sigma^I dV^{(m)} \right] + R_C$$



Green Strain Tensor can be written as

$$E_{ij} = \frac{1}{2} \left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} + \frac{\partial u_k}{\partial x_i} \frac{\partial u_k}{\partial x_j} \right]$$

The strain tensor in matrix form can be expressed as

$$\begin{bmatrix} E_{XX} & E_{XY} & E_{XZ} \\ E_{XY} & E_{YY} & E_{YZ} \\ E_{XZ} & E_{YZ} & E_{ZZ} \end{bmatrix}$$

By neglecting second order terms we get linearization of strain tensor are as follow:

$$E = \epsilon = \frac{1}{2} (\nabla \cdot d + (\nabla \cdot d)^T) \quad [5]$$

Cauchy Stress- Strain relationship

If we standardize Hooke's law we get linear relationship between Cauchy stress and Cauchy strain and are expressed as:

$$\sigma_{ij} = \sum_{km} C_{ijkl} \epsilon_{km}$$

In the above relation there are 36 independent entries.

In special case of isotropic material we have two independent entries remaining and the relationship is described as

$$\sigma = 2\mu\epsilon + \lambda \text{tr}(\epsilon)I \quad [6]$$

Here $\text{tr}(\epsilon)$ = Sum of diagonal elements of ϵ

μ and λ are Lamé's constants.

Note: μ always positive where as λ can be negative.

3.2.2 Mathematics of Computational Fluid Dynamics

The incompressible Navier-Stokes equation is used is as follow:

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j} u_i u_j = -\frac{\partial p}{\partial x_i} + \frac{1}{\text{Re}} \frac{\partial}{\partial x_j} \frac{\partial u_i}{\partial x_j} \quad [7]$$

$$\frac{\partial u_i}{\partial x_i} - q = 0 \quad [8]$$

Where $i, j = 1, 2, \text{ and } 3$.

Strouhal Number: Strouhal number provides the basis of vortex shedding; it is an important measuring criterion in the calculation of flow induced vibration. It is dimensionless number used for oscillating flow mechanism proposed by Vincenc Strouhal to observe the Vortex shedding phenomenon.

$$St = \frac{fr L}{U} \quad [9]$$

It helps in deciding the frequency of vibration when bluff body placed in flowing field. Its value is 0.2 for low frequency.

Reynolds Number: It is Dimensionless number and defined as the ratio of inertial force and viscous force.

$$Re = \frac{\rho v d}{\mu} \quad [10]$$

Here ρ =Density, Velocity, d =Diameter of body and μ =Absolute viscosity

It is helpful in deciding the type of flow such as Laminar, Turbulent and Critical.

Crank-Nicolson Method is used for solving fluid physics problem. An iterative method such as Gauss-Seidel method is used for solving discretized non-linear momentum equation.

3.2.3 Algorithm for CSD-CFD

The Algorithm in FSI is two-way i.e. it take responses of structure and fluid domain and its interaction. The solver runs iteratively with time steps. The flow diagram showed ANSYS mechanical response is in the form of mesh displacement and CFX response is in the form of pressure in sructure. Algorithm procedure is continuous upgradation of the responses in one field due to other and vice-versa.

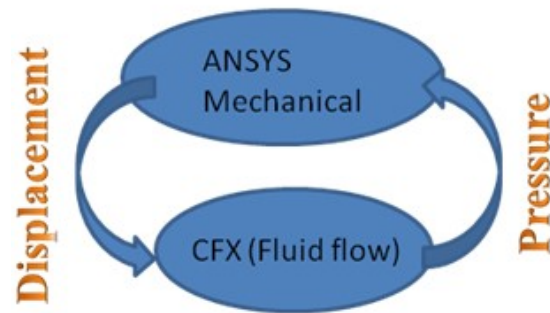


Figure 8: Methodology of FSI in ANSYS-CFX

The Two-way FSI involves the interaction between Structure and fluid or vice versa. In the FSI geometry there is a splitter plate of PVDF as a structural part and air at 25°C as the flowing fluid. The coupling of Transient structure and CFX has been performed to capture the interaction numerically and its response is taken as total mesh displacement. The FSI algorithm is iterative and transient that makes it impossible to solve analytically. Therefore, it is necessary to solve it numerically to obtain the phenomenon of vortex induced vibration.

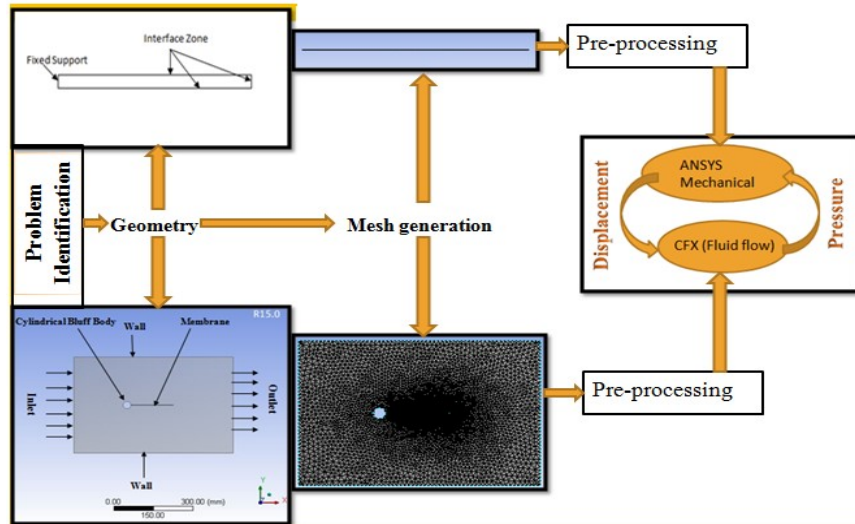


Figure 9: FSI Solving Procedure

Iterative Algorithm for CFD-CSD Coupling (Two-way)

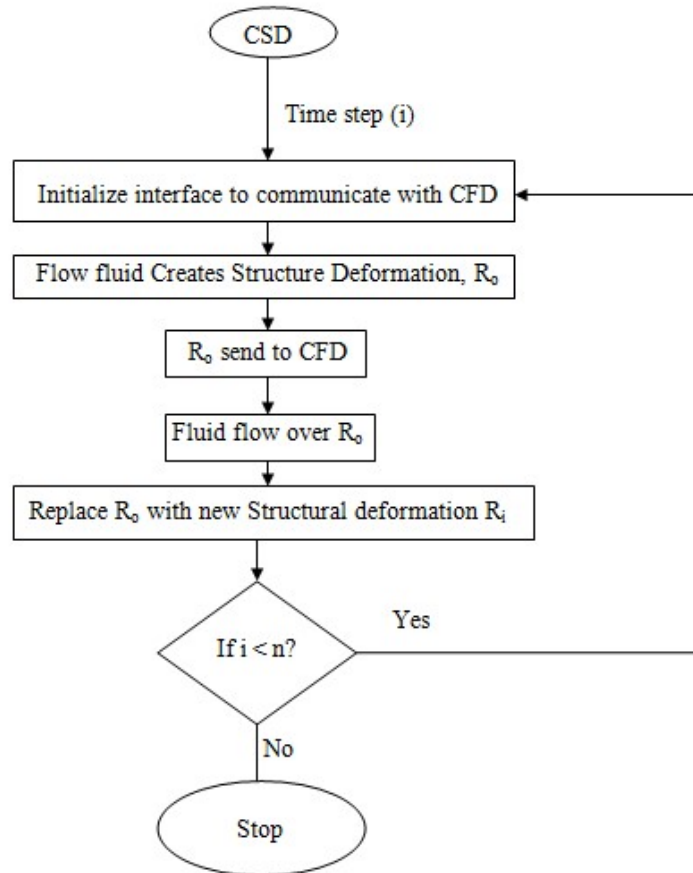


Figure 10: Algorithm for FSI

3.2.4 Boundary Conditions

Computational domain

The computational domain is considered with diameter=20mm where inlet fluid is flowing and outlet is at static pressure condition.

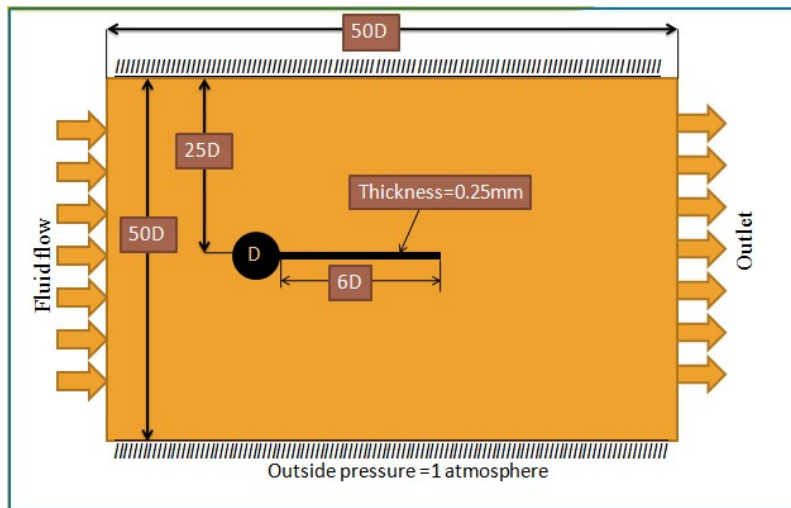


Figure 11: Computational Domain

Structure Domain

Figure Shown below depicts that the face of Splitter plate or flexible membrane is fixed supported and remaining three faces are the coupling zone between fluid and structure interaction.

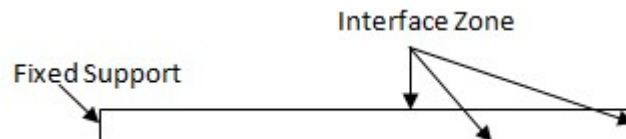


Figure 12: Two-dimensional view of Flexible Plate

Fluid Domain

Figure Shown depicts that the boundary conditions of fluid domain.

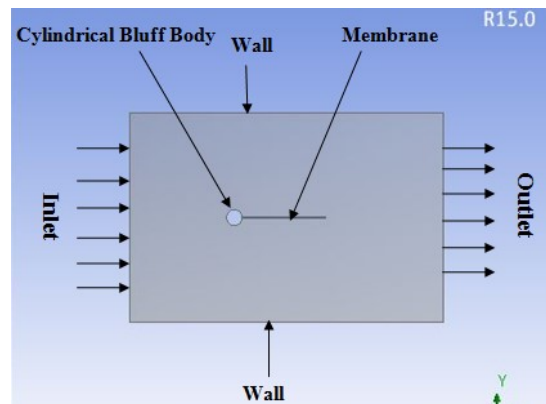


Figure 13: Fluid Domain

3.3 Validation of CFX code

Validation of CFX code depends upon the study of some researcher work numerically using CFD techniques and its accuracy in its implementation.

3.3.1 Mesh convergence study

Grid formaton is very critical in nature. It decides the computational timing and potential deficiency due to round off error. The finer Grid is time consuming but accuracy is high, so to keep the above facts in mind one should not neglect the interface zone where the interaction of two physics phenomenon take place. Now the limitation is not limited to accuracy however the optimisation of mesh at the interface zone. The proper mesh is important aspect of numerical analysis in this case we study the convergence of result on structured mesh (quadrilateral) and

unstructured mesh (tetrahedral). In structured mesh, the analysis should be perform to observe the transient steady state at high mesh density.

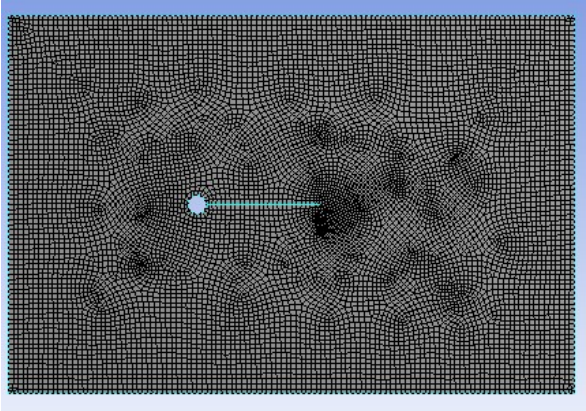
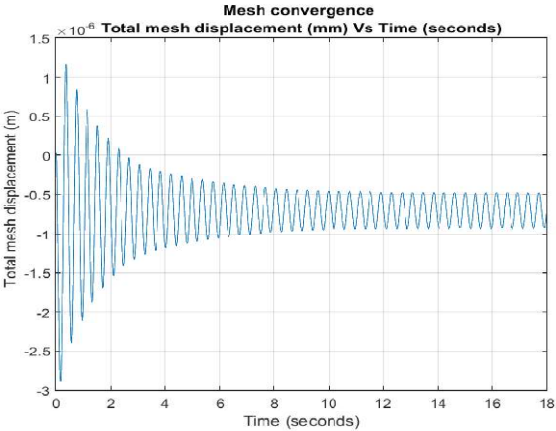


Figure14: Structured Mesh (Quadrilateral) average aspect ratio = 7.2

The FSI result of structured mesh is converged at 12 seconds whereas in unstructured mesh FSI results converge at 10 seconds. So we prefer unstructured mesh in terms of accuracy and ease of result.

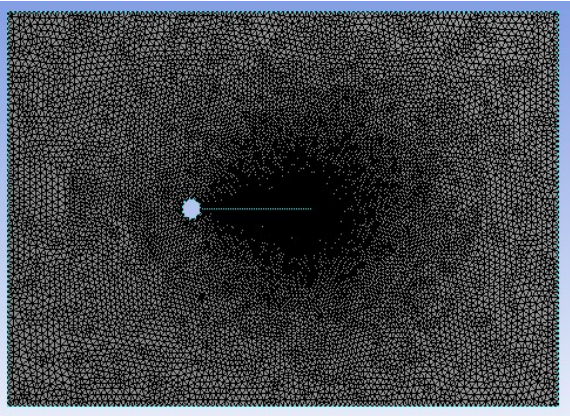
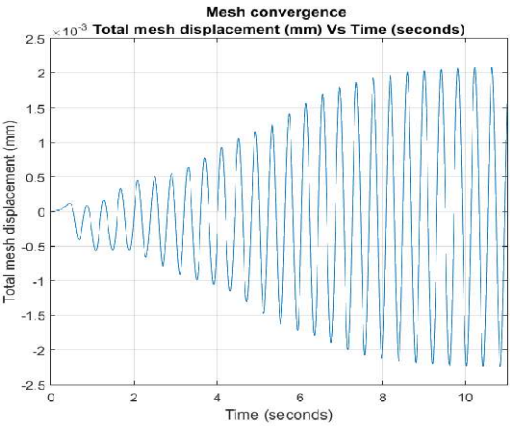


Figure 15: Unstructured Mesh (Tetrahedral) average aspect ratio = 5.00

3.3.2 Modal Analysis

Natural frequency of Splitter plate is very important in Data analysis and interpretation of fluid-induced vibration. Modal analysis is performed in ANSYS to obtain the various modes of splitter plate, and flexible membrane. The modal frequency also tells us about lock-in phenomenon when vortex-induced vibration matches the natural frequency of structural element. Therefore, modal analysis is our foremost step in the flow-induced vibration analysis.

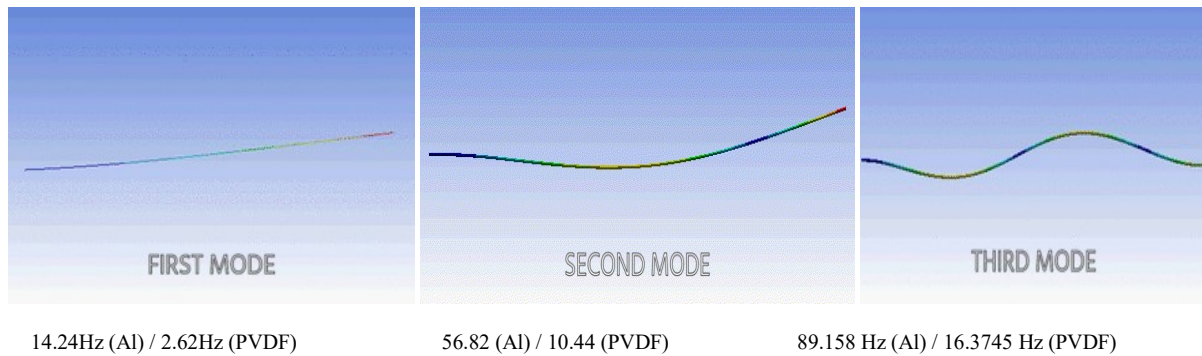


Figure 16: Modal Analysis (NTS)

Modes	Aluminum Plate Frequency(Hz)	PVDF Plate Frequency (Hz)
1	14.2128	2.613
2	56.8103	10.443
3	89.0700	16.374
4	249.393	45.8480
5	355.908	65.426
6	488.695	89.841

Figure 17: Eigen Frequency of flexible plate Table

Mechanical Properties:

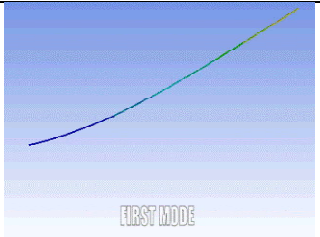
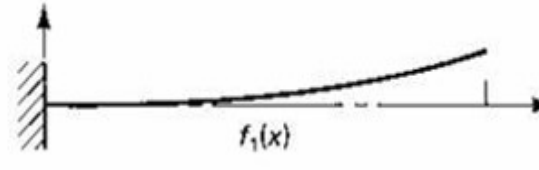
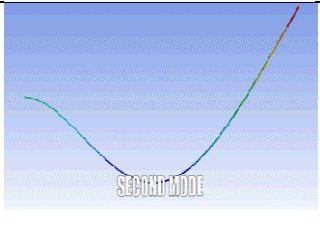
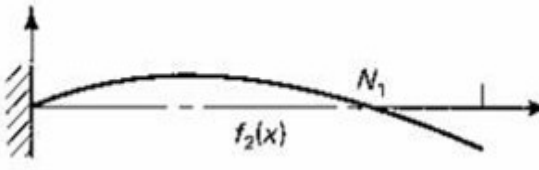
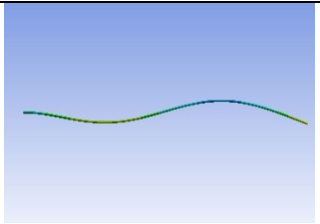
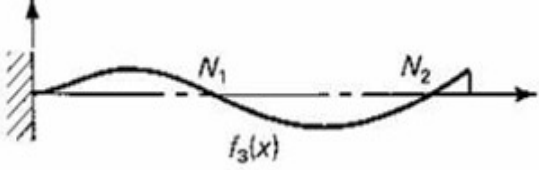
Properties	Aluminium	PVDF
Density	2770 kg/m ³	1270 kg/m ³
Young Modulus	71 E10 ⁹ Pa	1.1E10 ⁹ Pa
Poisson's Ratio	0.33	0.34
Bulk Modulus	6.9608E10 ¹⁰ Pa	1.1458 E10 ⁹ Pa
Shear Modulus	2.6692E10 ¹⁰ Pa	4.1045 E10 ⁸ Pa

Figure 18: Mechanical Properties

Conclusion from modal analysis

The membrane structure has many degrees of freedom but due to low computational facility we used two dimensional analyses neglecting the torsional factor which is responsible for galloping.

TABLE 1: EIGEN-FREQUENCY FORMULATION

Numerical Picture	Analytical Picture	Eigen frequency Formulation
		$f_1 = (1.875)^2 \sqrt{\frac{EI}{mL^4}}$
		$f_2 = (4.694)^2 \sqrt{\frac{EI}{mL^4}}$
		$f_3 = (7.855)^2 \sqrt{\frac{EI}{mL^4}}$

The results obtained from Computational Structural Dynamics (CSD) of aluminium and PVDF membrane gives the detailed picture of variation of its Eigen frequency with the density. If we made a comparison between analytical formulation and grid formulation the result of modal frequencies are similar.

3.3.3 Strouhal Number

When flow past a bluff body; it causes the lift and drag forces that results the cause of vibration in the bluff body the frequency of vibration is Strouhal frequency. The Strouhal number of cylindrical bluff body is determined numerically by varying the diameter from 5 mm to 30 mm and its frequencies have been plotted to find the Strouhal numbers at different radial dimensions. In order to calculate Strouhal number, Roshko gives the formula which is obtained as a result of large number of observation:

$$Sr = 0.212 \left(1 - \frac{C}{Re} \right)$$

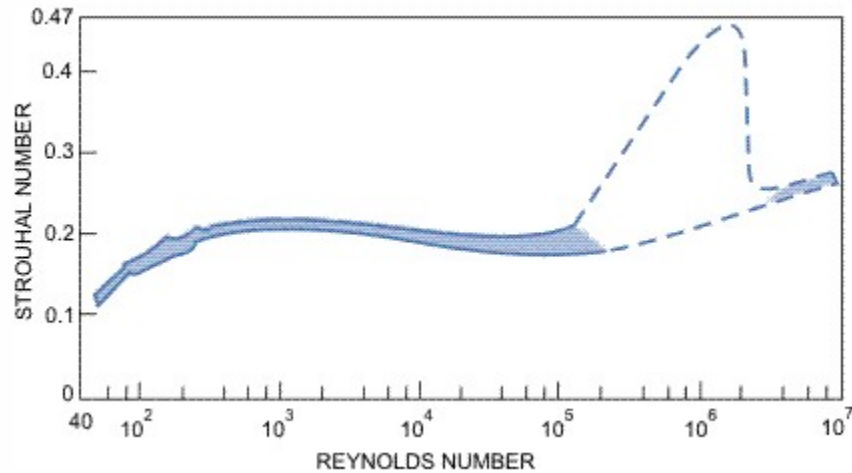


Figure 19: Strouhal number versus Reynolds number for circular cylinders (tubes). From Blevins R. D. (1990) Flow Induced Vibrations, Van Nostrand Reinhold Co.

Strouhal number of Rigid Cylinder

The Strouhal number of rigid cylinder has been numerically calculated at three diameters i.e. 18 mm, 19 mm, & 20 mm using unstructured mesh. The results are validated using Strouhal number for cylinder which is found to be 0.190.

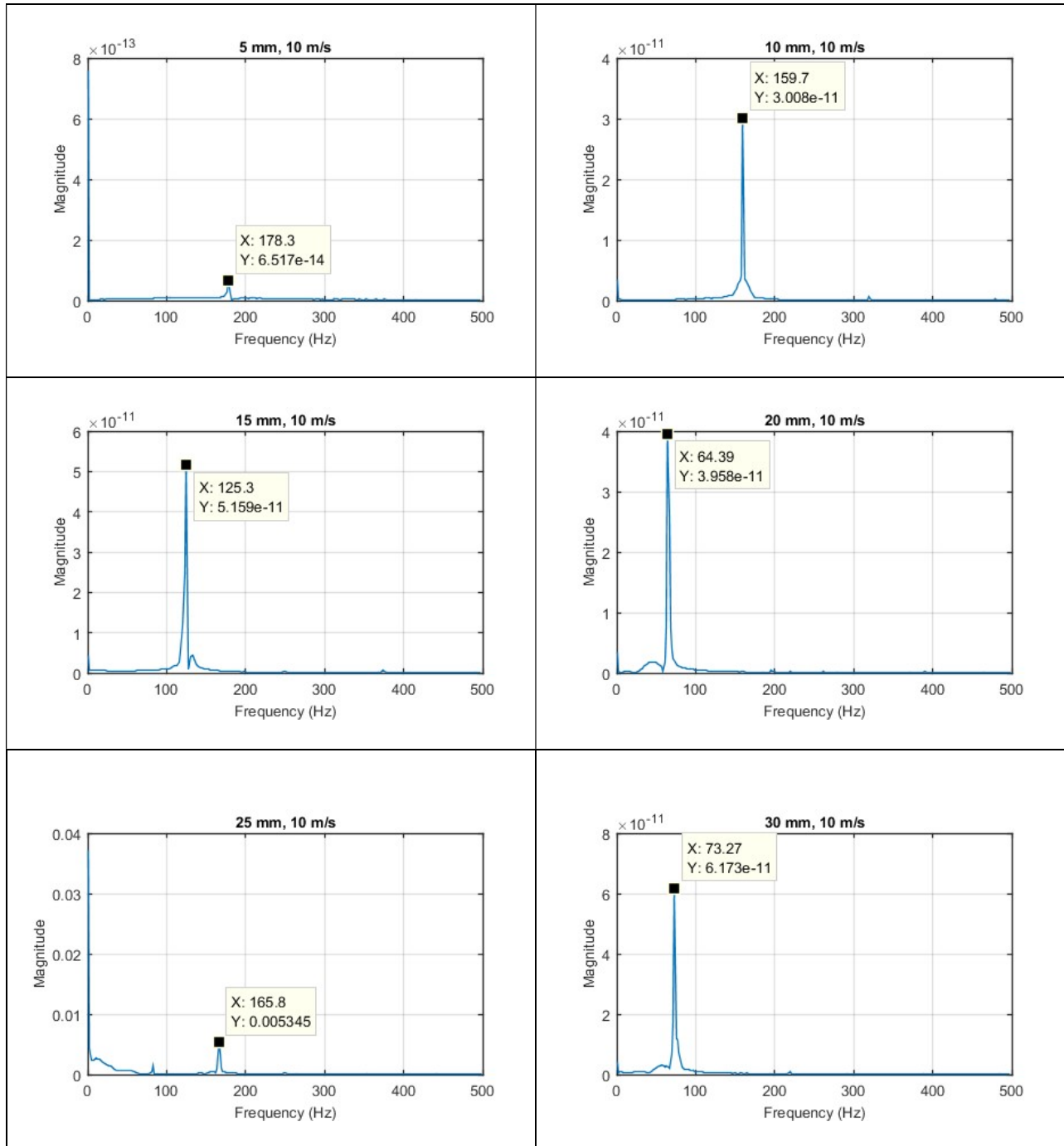
TABLE 2: STROUHAL FREQUENCY AND LIFT FORCE

Strouhal Frequency (Hz)	Lift Force (N)
Diameter 18 mm – Velocity 10 m/s	
<p>Strouhal Frequency (Hz)</p> <p>Magnitude</p> <p>X: 98.18 Y: 1.402</p>	<p>Lift Force (N)</p> <p>Time (seconds)</p>
Diameter 19 mm – Velocity 10 m/s	
<p>Strouhal Frequency (Hz)</p> <p>Magnitude</p> <p>X: 92.5 Y: 0.3248</p>	<p>Lift Force (N)</p> <p>Time (seconds)</p>
Diameter 20 mm – Velocity 10 m/s	
<p>Strouhal Frequency (Hz)</p> <p>Magnitude</p> <p>X: 102 Y: 1.112</p>	<p>Lift Force (N)</p> <p>Time (seconds)</p>

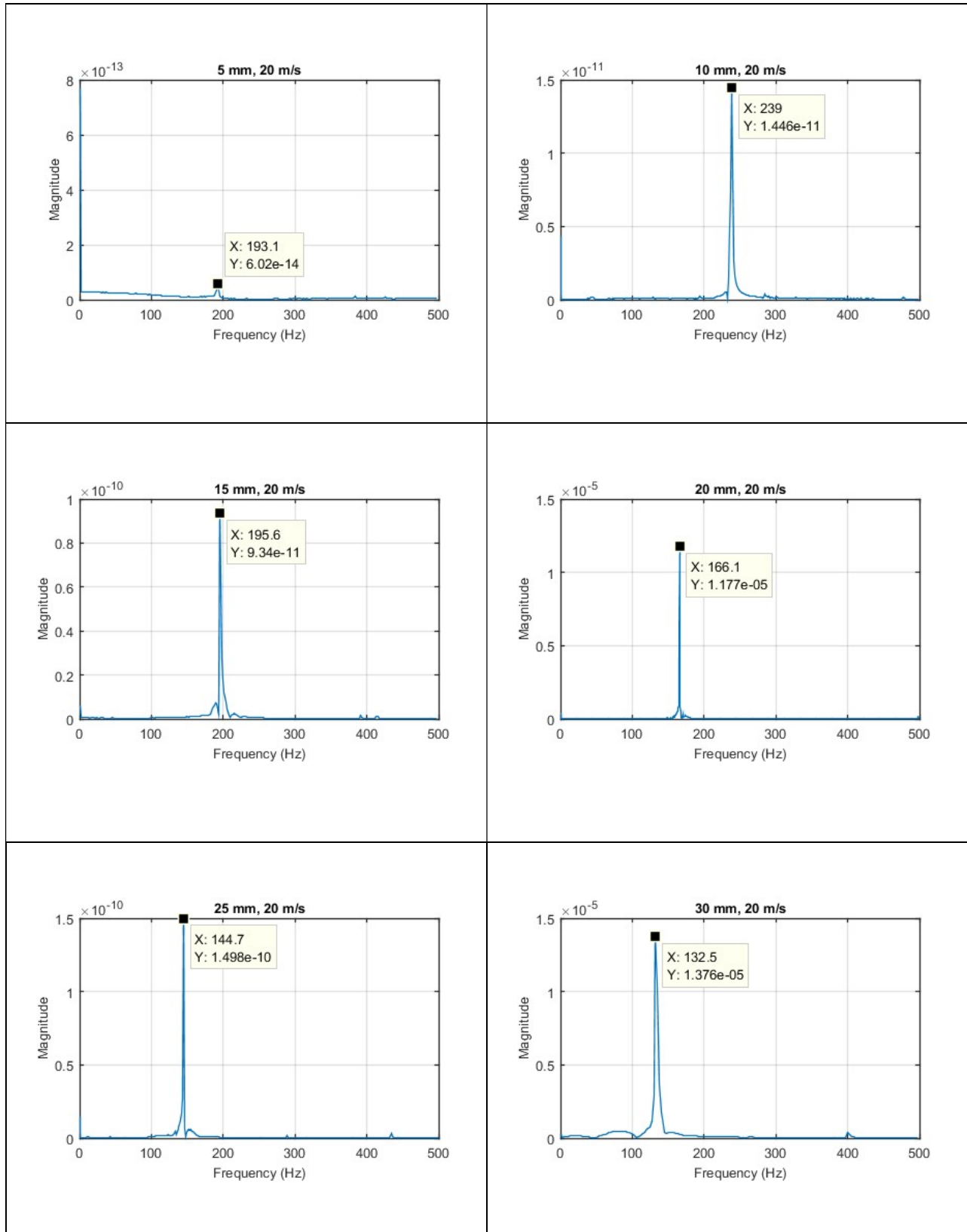
Strouhal number for Rigid Splitter Plate

The Strouhal number for rigid splitter plate has been calculated using variation in diameters. The frequency plots are shown as:

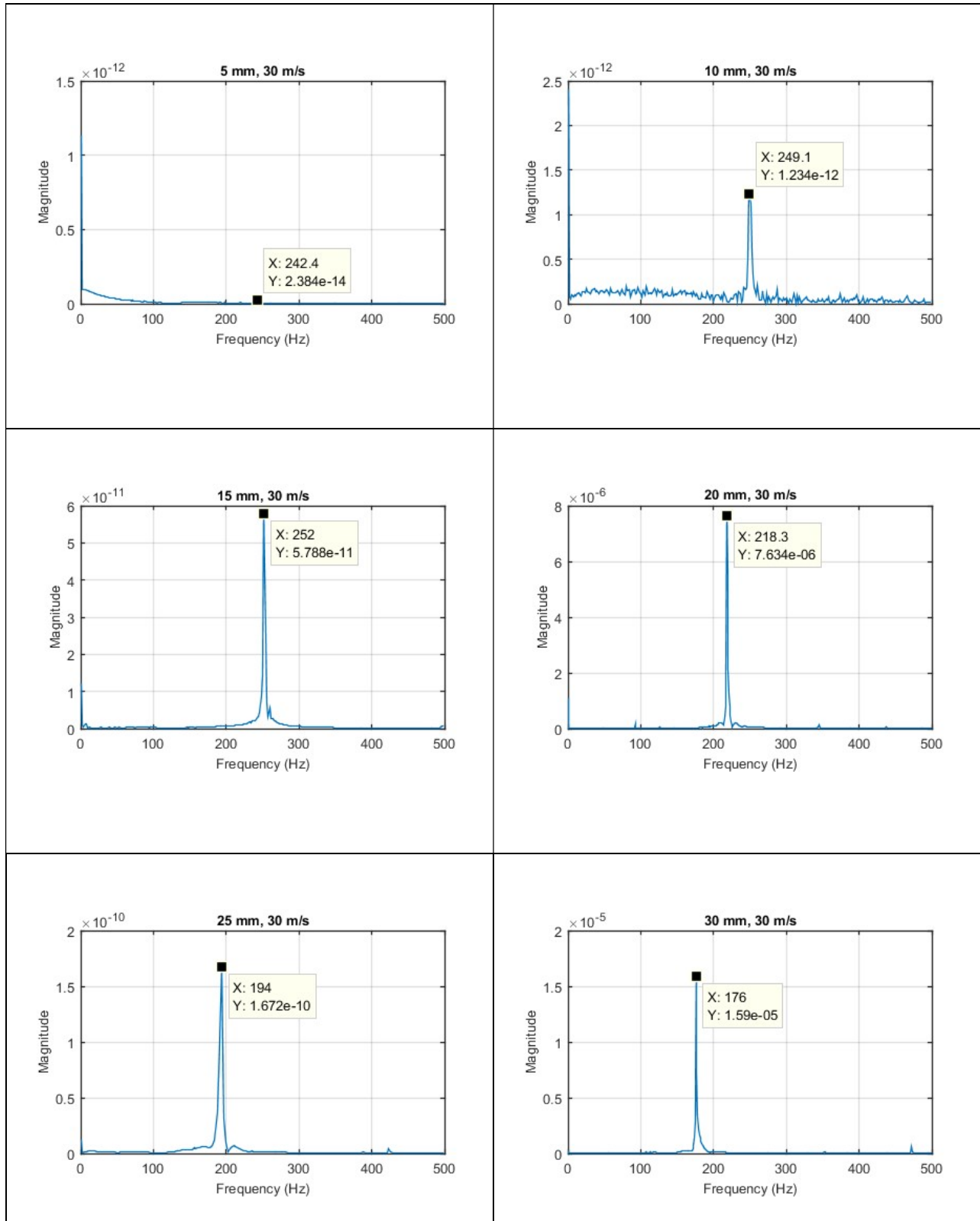
Strouhal Number Plot- Frequency Plots (10 m/s)



Frequency Plots (20 m/s):



Frequency Plots (30 m/s):



Observation of Rigid Splitter Plate

The data has been obtained from simulation of splitter plate is as follow:

Diameter (mm)	Velocity (m/s)	Frequency (Hz)	Strouhal Number
5	10	178.3	0.08915
5	20	193.1	0.04828
5	30	242.4	0.0404
Strouhal Number for dia. 5 mm			0.05928
10	10	159.7	0.1597
10	20	239	0.1195
10	30	249.1	0.08303
Strouhal Number for dia. 10 mm			0.12074
15	10	125.3	0.18795
15	20	195.6	0.1467
15	30	252	0.126
Strouhal Number for dia. 15 mm			0.15355
20	10	64.39	0.12878
20	20	166.1	0.1661
20	30	218.3	0.14553
Strouhal Number for dia. 20 mm			0.1468
23	10	86.96	0.20001
23	20	150	0.1725
23	30	200	0.15333
Strouhal Number for dia. 23 mm			0.175267
24	10	86.53	0.207672
24	20	148.148	0.1777776
24	30	200	0.16
Strouhal Number for dia. 24 mm			0.18182
24.5	10	86.02	0.210749
24.5	20	178.57	0.21874825
24.5	30	192.31	0.157053167
Strouhal Number for dia. 24.5 mm			0.19552
25	10	165.8	0.4145
25	20	144.7	0.18088
25	30	194	0.16167

Strouhal Number for dia. 25 mm			0.25235
25.5	10	81.1	0.206805
25.5	20	144.73	0.18453075
25.5	30	193.18	0.164203
Strouhal Number for dia. 25.5 mm			0.18518
26	10	81.3	0.21138
26	20	141.18	0.183534
26	30	170	0.147333
Strouhal Number for dia. 26 mm			0.180749
26.5	10	80	0.212
26.5	20	140.84	0.186613
26.5	30	188.68	0.1666673
Strouhal Number for dia. 26.5 mm			0.1884268
27	10	76.92	0.207684
27	20	140.845	0.19014075
27	30	186.05	0.167445
Strouhal Number for dia. 27 mm			0.18842325
30	10	73.27	0.21981
30	20	132.5	0.19875
30	30	176	0.176
Strouhal Number for dia. 30 mm			0.19819

Figure 20: Observation table of Strouhal number for rigid plate with variable velocity

The data has been interpreted using graphical representation and its trend is shown by using polyline because its r factor is nearly equal to 1. The polyline depicts parabolic nature of graph. The maximum Strouhal number is observed at 35 mm is 0.2096 and minimum Strouhal number is observed at 5 mm.

Strouhal Number of Rigid Plate

5 mm	0.0593
10 mm	0.1207
15 mm	0.1536
20 mm	0.1468
23 mm	0.1753
24 mm	0.1818
24.5 mm	0.19552
25 mm	0.1823
25.5 mm	0.1852
26 mm	0.1808
26.5 mm	0.1884
27 mm	0.1884
30 mm	0.1982
35 mm	0.2096

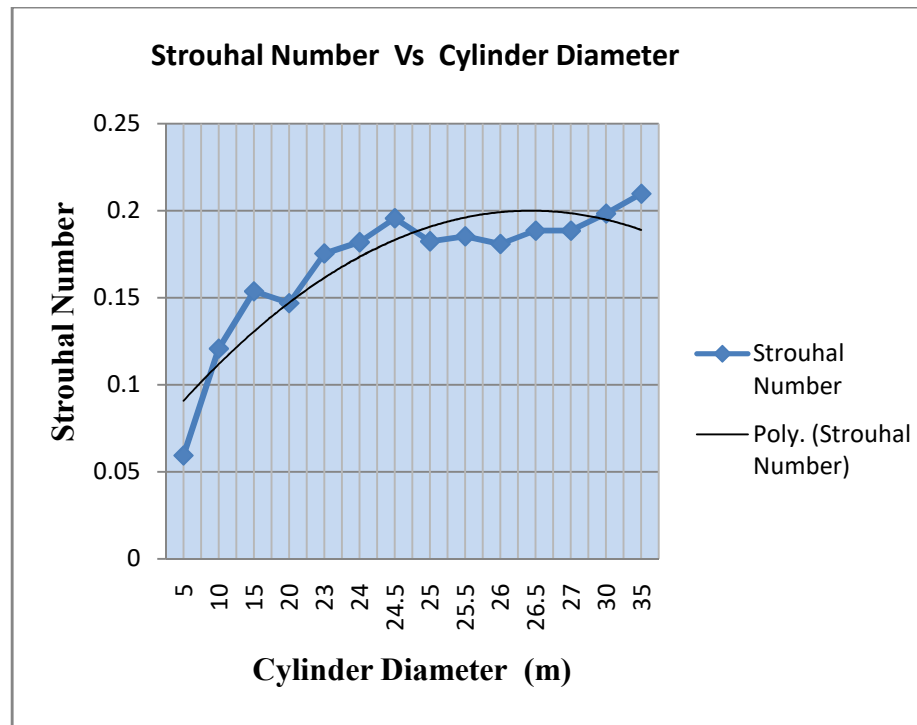


Figure 21: Strouhal Number for Rigid Cylinder

The graphical interpretation represents the variation of Strouhal number of rigid splitter plate and if we trended that data with quadratic polynomial line, the value of average Strouhal number is 0.2. The result from previous findings i.e. obtained from experimentation is accordance with the numerical data.

Strouhal Number for flexible splitter plate

The Strouhal number of flexible splitter plate is numerically calculated and the result is as follow:

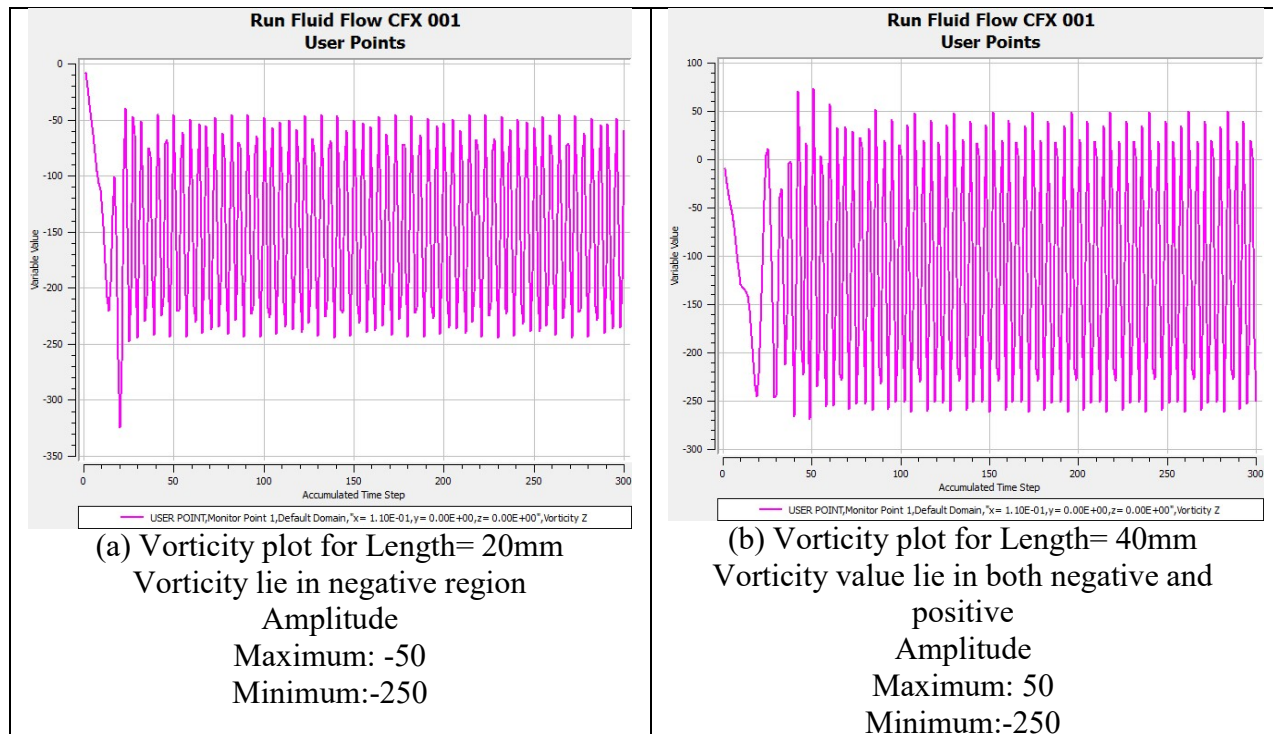
Velocity (m/s)	Frequency (Hz)	Strouhal Number
10	34.9	0.0698
20	69.44	0.0694
30	111.0699	0.074
Average		0.07

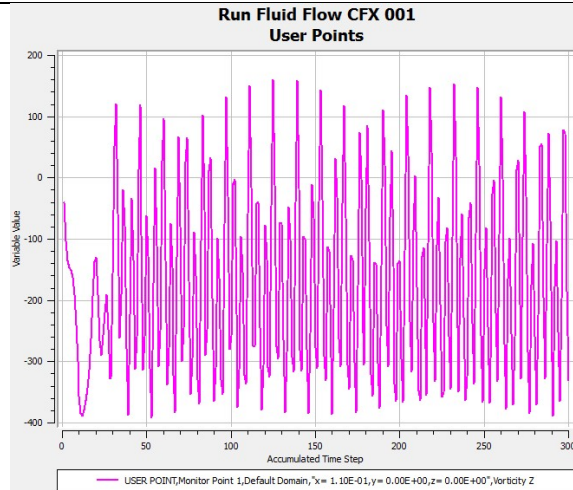
The Strouhal number of flexible splitter plate is 0.07 which provide the technical background of vortex shedding suppression technique.

3.3.4 Vortex shedding with length study

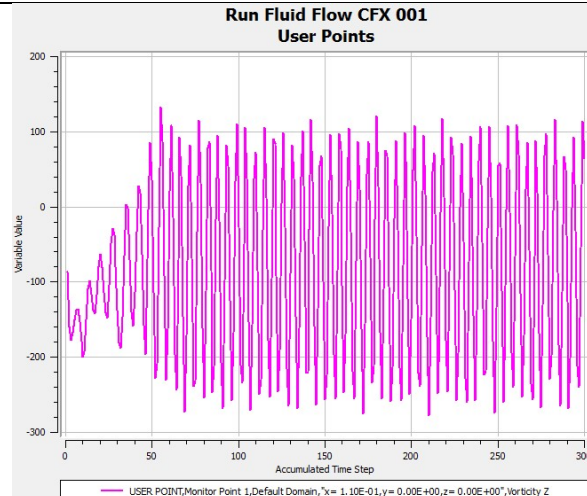
Vorticity plots is obtained at the tip of the splitter plate by varying the length of splitter plate keeping thickness constant.

Table 1: Vorticity plots

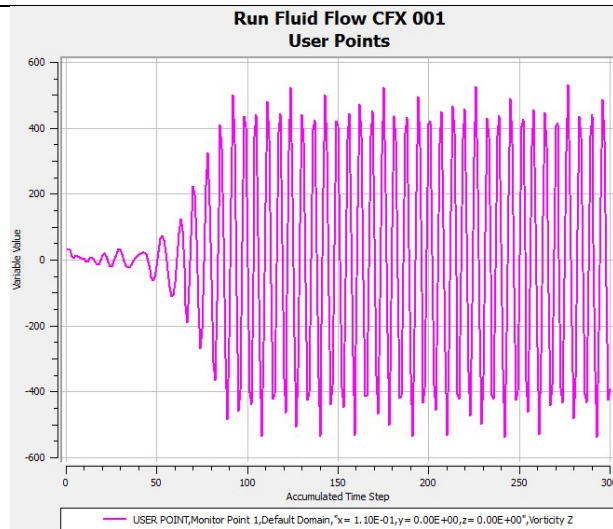




(c) Vorticity plot for Length= 60mm
 Vorticity lie in both negative and positive region
 Maximum: 100
 Minimum:-380



(d) Vorticity plot for Length= 80mm
 Vorticity lie in both negative and positive region
 Maximum: 100
 Minimum:-250



(e) Vorticity plot for Length= 80mm
 Vorticity lie in both negative and positive region
 Maximum: 400
 Minimum:-400

Interpretation:

As length increases symmetry of vorticity increases which results in negligible mesh displacement and we get an equilibrium state.

The pictures of simulated data depict that as length of splitter plate increases, the phenomenon of vortex shedding decreases and at certain length of splitter plate it suppressed completely.

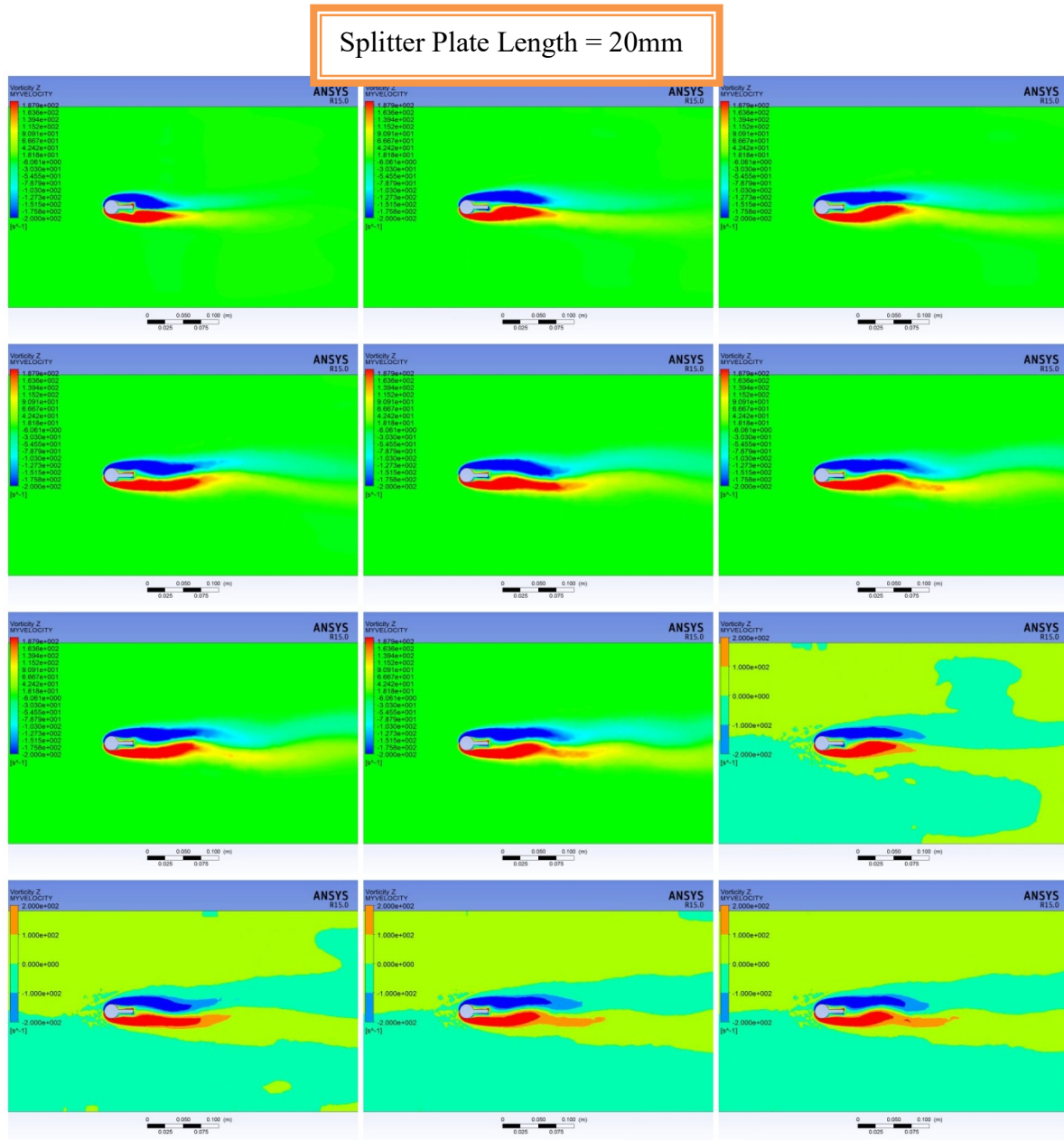


Figure 22: Splitter plate length=20mm

Splitter Plate Length = 40mm

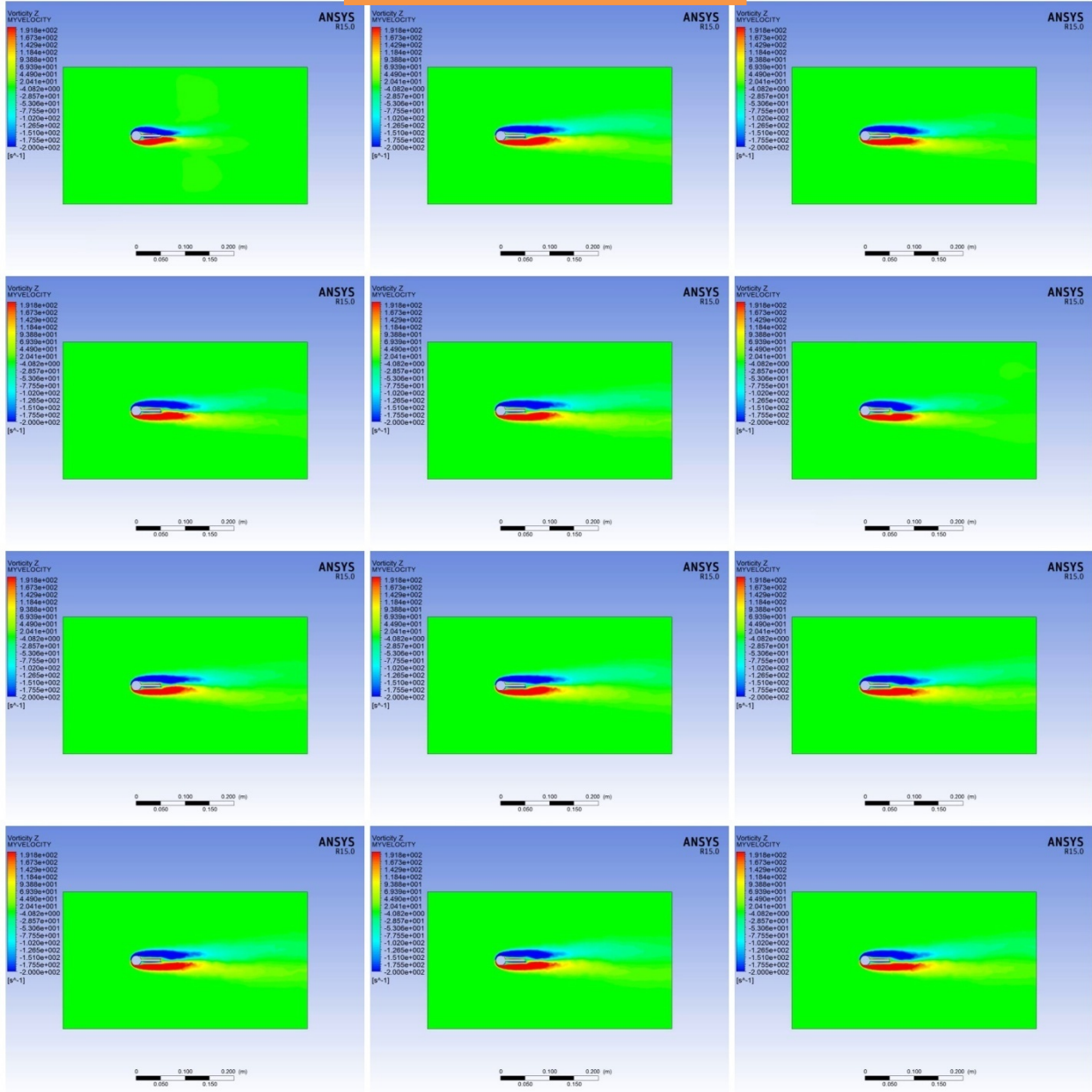


Figure 23: Splitter plate length=40 mm

Splitter Plate Length = 60mm

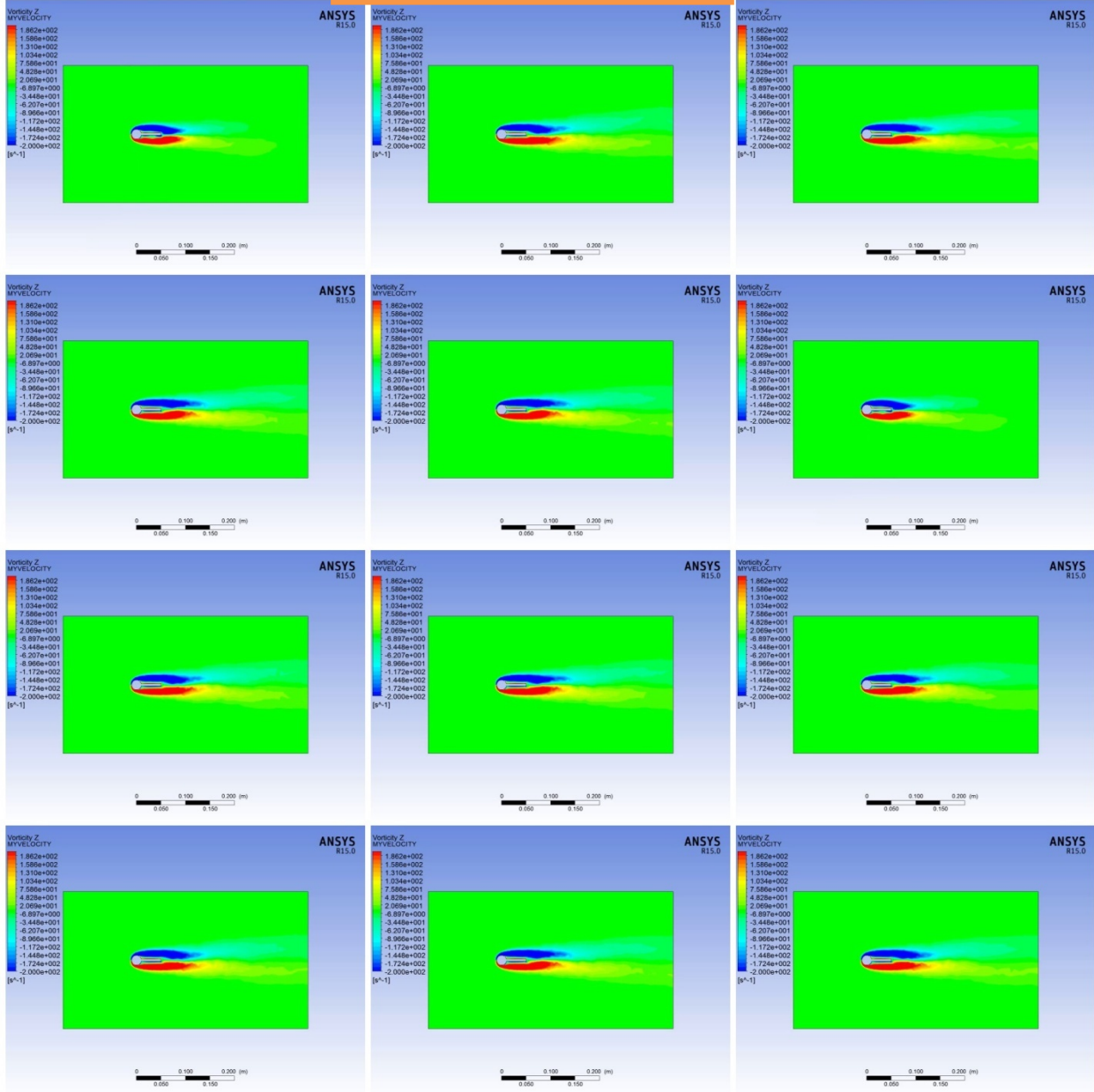


Figure 24: Splitter plate length= 60 mm

Splitter Plate Length = 80mm

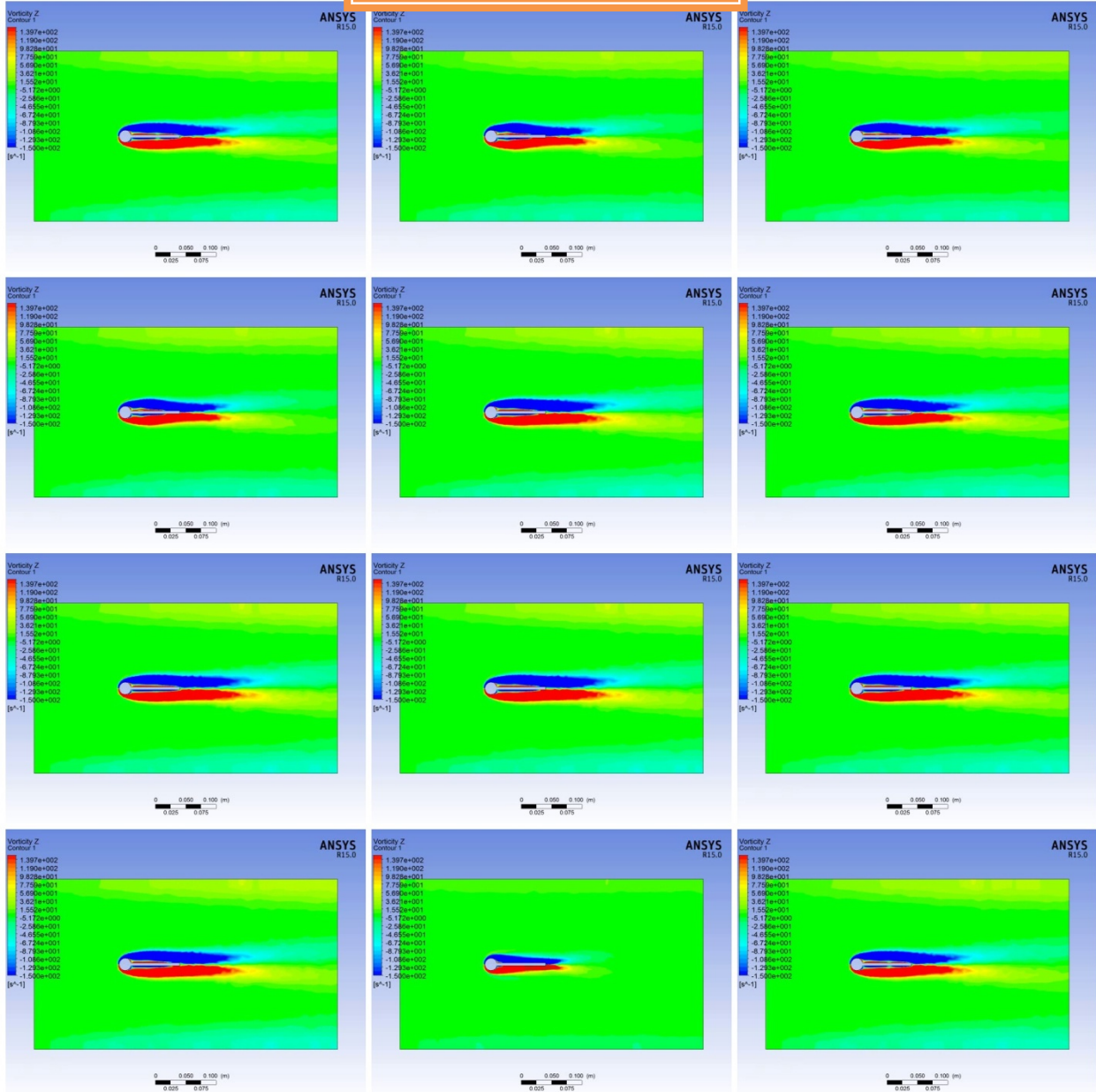


Figure 25: Splitter plate length= 80 mm

Splitter Plate Length = 100mm

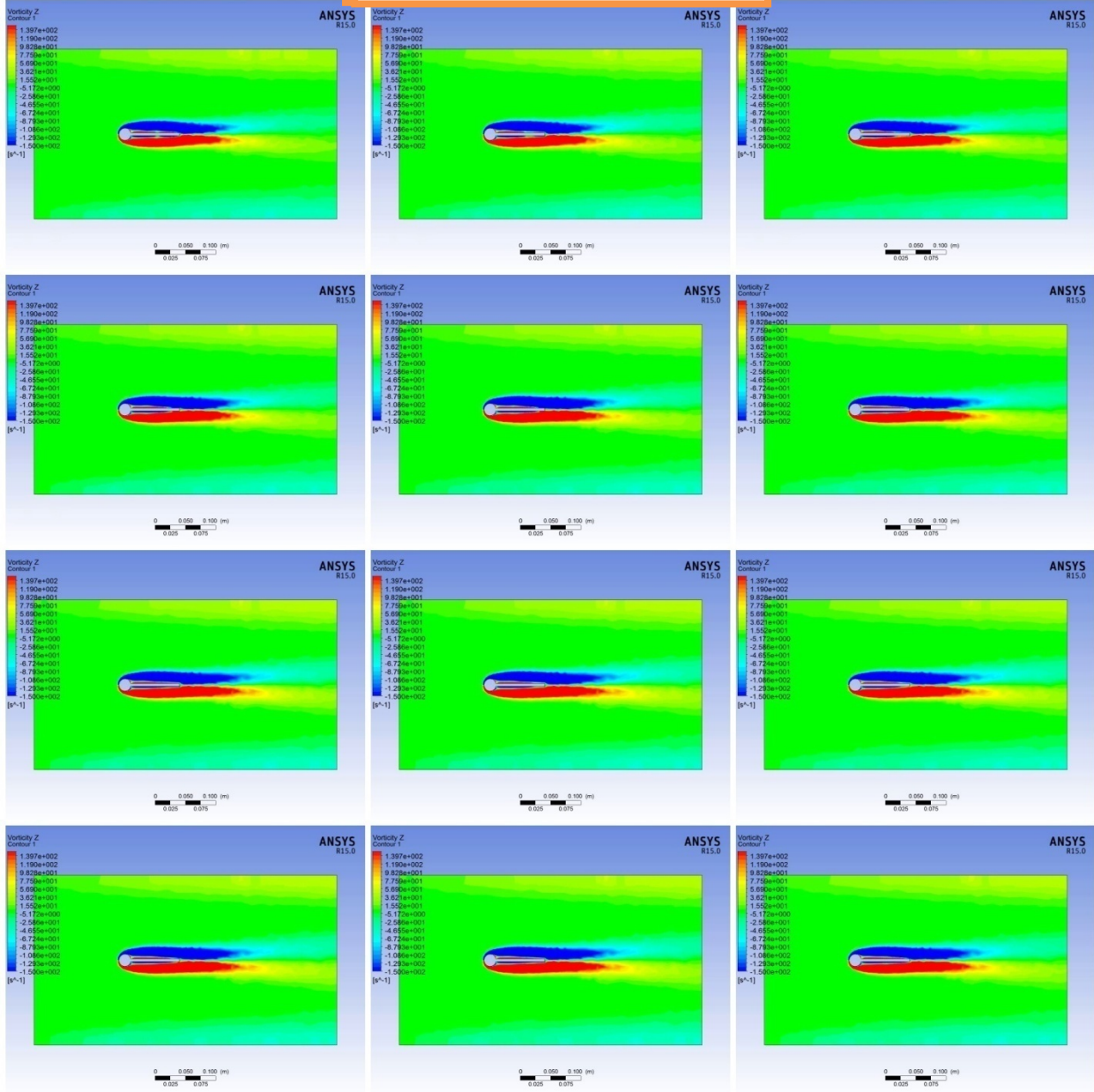


Figure26: Splitter plate length= 100 mm

Bluff-body without Splitter Plate

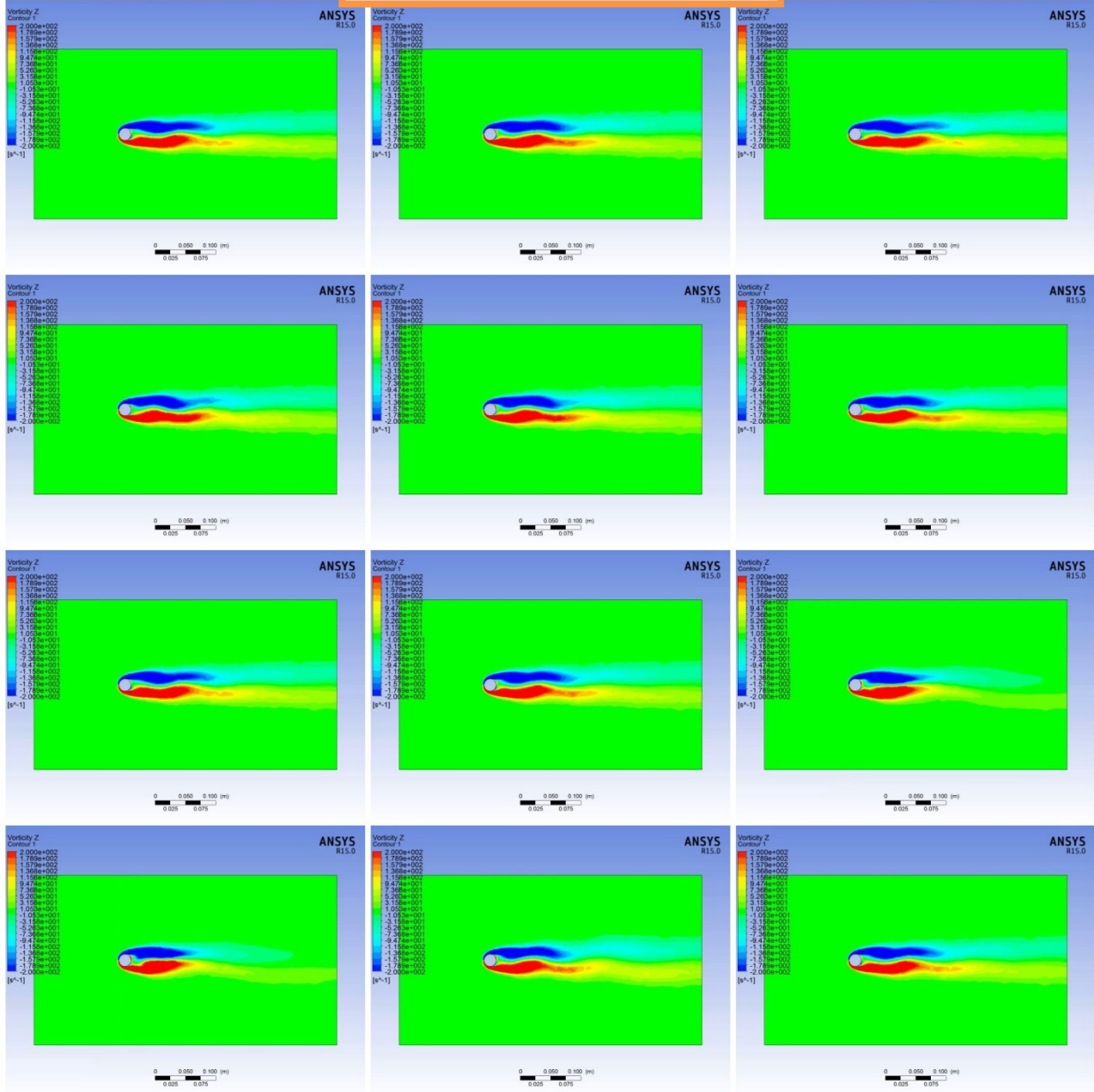


Figure 27: Simulated result of Cylindrical Bluff-body

The simulation is performed by varying the length of splitter plate. The simulated pictures show the vortex shedding phenomenon when flowing fluid past the cylindrical bluff-body.

Cases	Vortex-shedding
Flow over cylinder	Yes
Flow over splitter plate, length=20mm	Yes
Flow over splitter plate, length=40mm	Yes
Flow over splitter plate, length=60mm	Yes
Flow over splitter plate, length=80mm	No
Flow over splitter plate, length=100mm	No

Figure 28: Vortex Shedding with varying length of splitter plate

Chapter 4


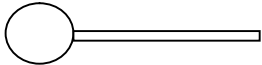
Numerical results and discussion


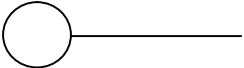
4.1 Test Cases

In the present study, Four different test cases has been consider to comprehensively understand the flow dynamics of a system of a rigid bluff body with a trailing plate.

The following test cases are studied by Computational Fluid and Solid Dynamics coupling on commercial software.

TABLE 2: DETAILS OF DIFFERENT CASES

Cases	Top View	Outline	Remarks
Rigid Cylinder		<u>Rigidly Fixed</u> Bluff-Body: Cylinder	Cylinder = ϕ 20 mm
Rigid Splitter plate behind cylinder		<u>Splitter Plate thickness</u> Length/Thickness= 1 to 8 (5)	Rigid plate: Thickness 2.5D Length = 120 mm Boundary Condition: No slip condition

Flexible Splitter Plate	 <p>Stiffness coefficient=0</p> <p>Mass Stiffness coefficient= 0 (Due to negligible mass)</p>	<p><u>Flexible Membrane:</u></p> <p>Length/Thickness ≥ 80 (5)</p> <p>Thickness range: 0.5-500 μm</p> <p>Lateral Dimension range: 100 μm and 10mm</p> <p>Thin membrane: Deflection \geq Thickness</p> <p>Thick membrane: Deflection \leq Thickness</p> <p>Material used: PVDF (Thin Membrane) Aluminium (Thick Membrane)</p>	<p>Length = 120 mm</p> <p>Thickness = 0.25 mm</p> <p>Boundary Condition: No slip condition</p>
Flexible membrane behind rigid cylinder		<p>Bluff-Body: Cylinder</p> <p>Rigidly Fixed</p> <p>Flexible Membrane placed behind splitter plate.</p>	<p>Cylinder = ϕ 20 mm</p> <p>Length = 120 mm</p> <p>Thickness = 0.25 mm</p> <p>Boundary Condition: No slip condition</p>

4.2 Flow over rigid Cylinder

Firstly, the basic of fluid dynamics is considered by using the rigid cylinder having negligible roughness coefficient is placed in flow field. This case does not require coupling because cylindrical bluff body is fixed in space.

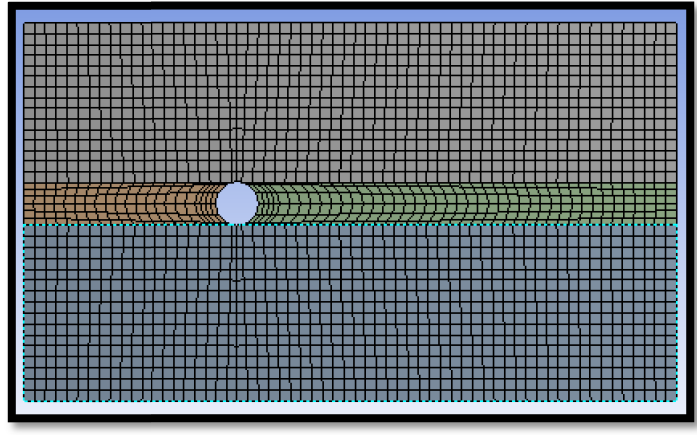


Figure 29: Mesh in case of rigid cylinder

4.3 Flow regime over Rigid Cylinder

When fluid past the cylindrical bluff-body Figure showed that vortex shedding take place in later stages starting with 2-single pair vortex (2S). The velocity is only 3.5 m/s is not enough to provide 2P, P+S, and 2P+2S.

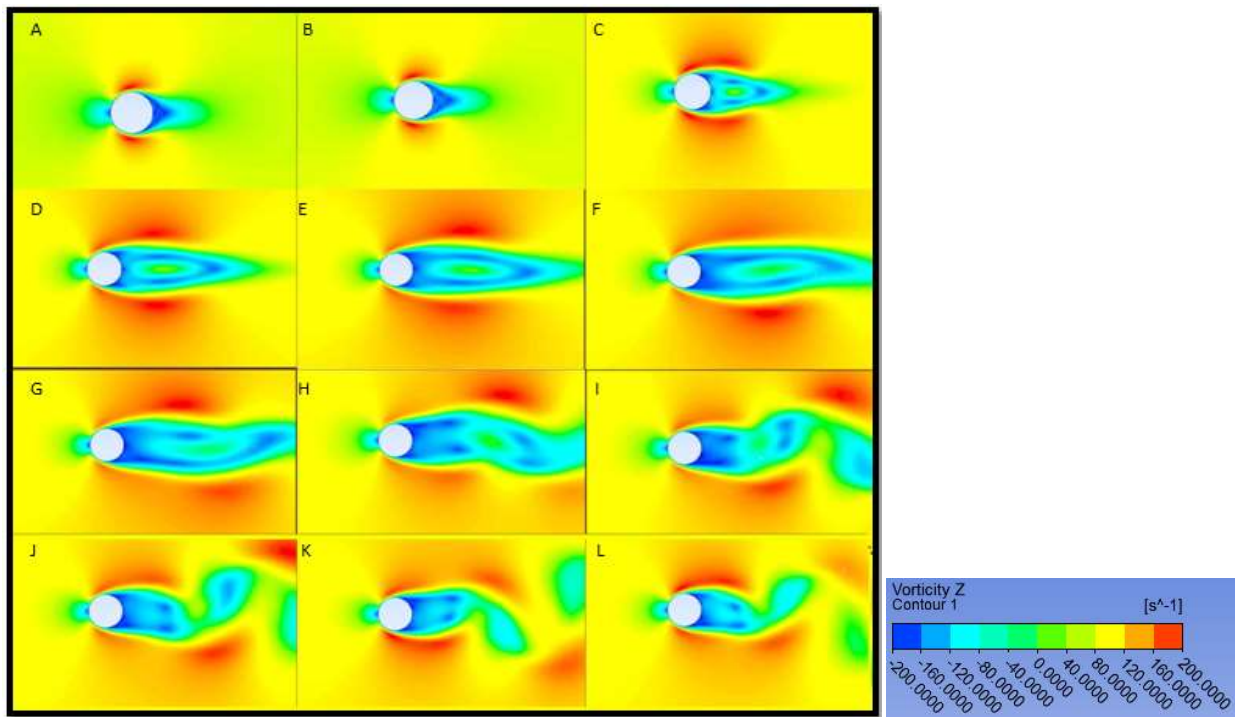


Figure 30: Flow behavior over rigid bluff-body

Two-degree-of-freedom vortex-induced vibration of a pivoted cylinder below critical mass ratio is shown in Griffin plot.

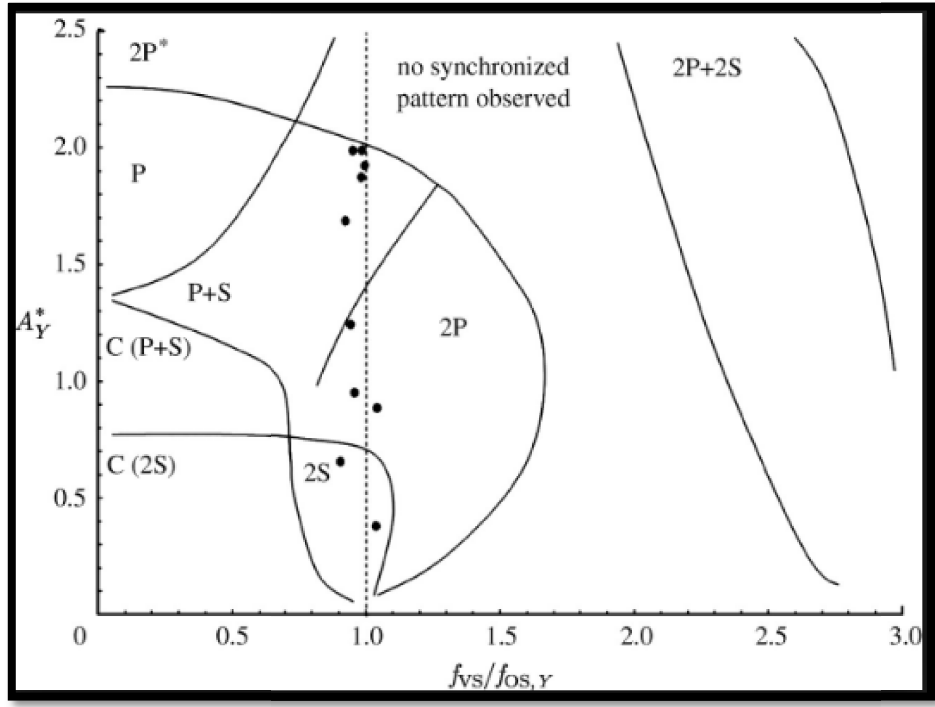


Figure 31: Griffin plot (C.M Leong, T Wei, 2008)

Here A_y is amplitude in y-axis, f_{vs} = frequency of vortex shedding ,and f_{os} = frequency of oscillating cylinder.

The results obtained from rigid cylindrical bluff body lie in 2S region that show the validity of the numerical study and research performed by C.M Leong and T Wei on cylindrical bluff body. (15)

4.4 Flexible membrane behind rigid cylinder

In this case, the membrane is taken under consideration i.e. aluminum and PVDF (piezoelectric material).The difference between Aluminum and PVDF is their bending stiffness coefficient

value which is zero in case of PVDF. The eigenvalues is necessary and calculated before fluid-structure interaction to understand the behavior of structure under the influence of flowing fluid.

4.5 Flow regimes of test cases

The regime of flow and their structural responses has been taken under consideration at fixed velocity i.e. 3.5 m/s. The prediction of velocity is due to presence of transition stage from first mode to second mode. This is necessary to study if we use splitter plate behind the cylinder its Eigen shape changes at 3.5 m/s but what happen for the other cases at same inlet velocity of flowing fluid.

The result has been carried out for aluminum membrane and PVDF membrane. The observation gives the visual representation of behavior of flow over bluff body and membrane. The flow regimes of bluff body had more pronounced vortex shedding as compared to flexible splitter plate.

The absence of obstruction gives first mode oscillation in flexible membrane whereas second mode oscillation in presence of bluff body.

Flow regime over flexible plate (Velocity = 3.5 m/s)

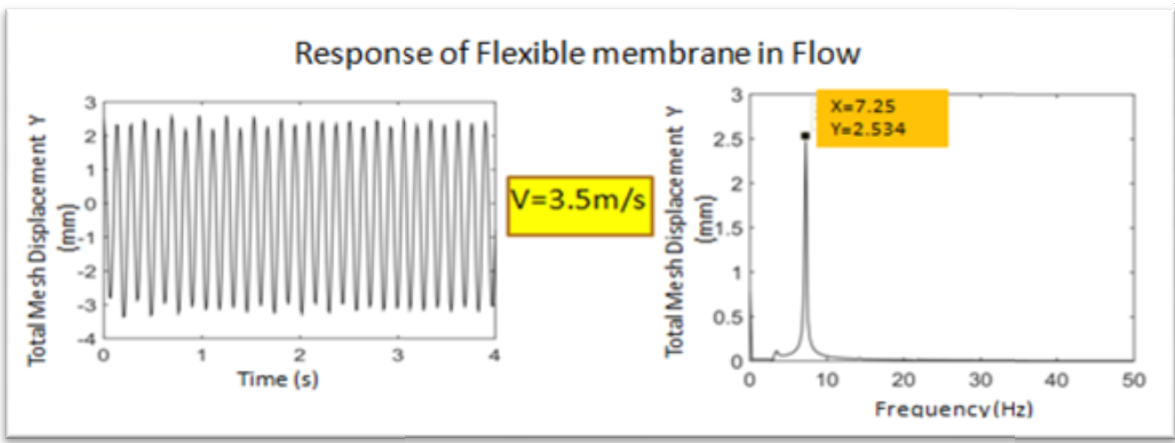
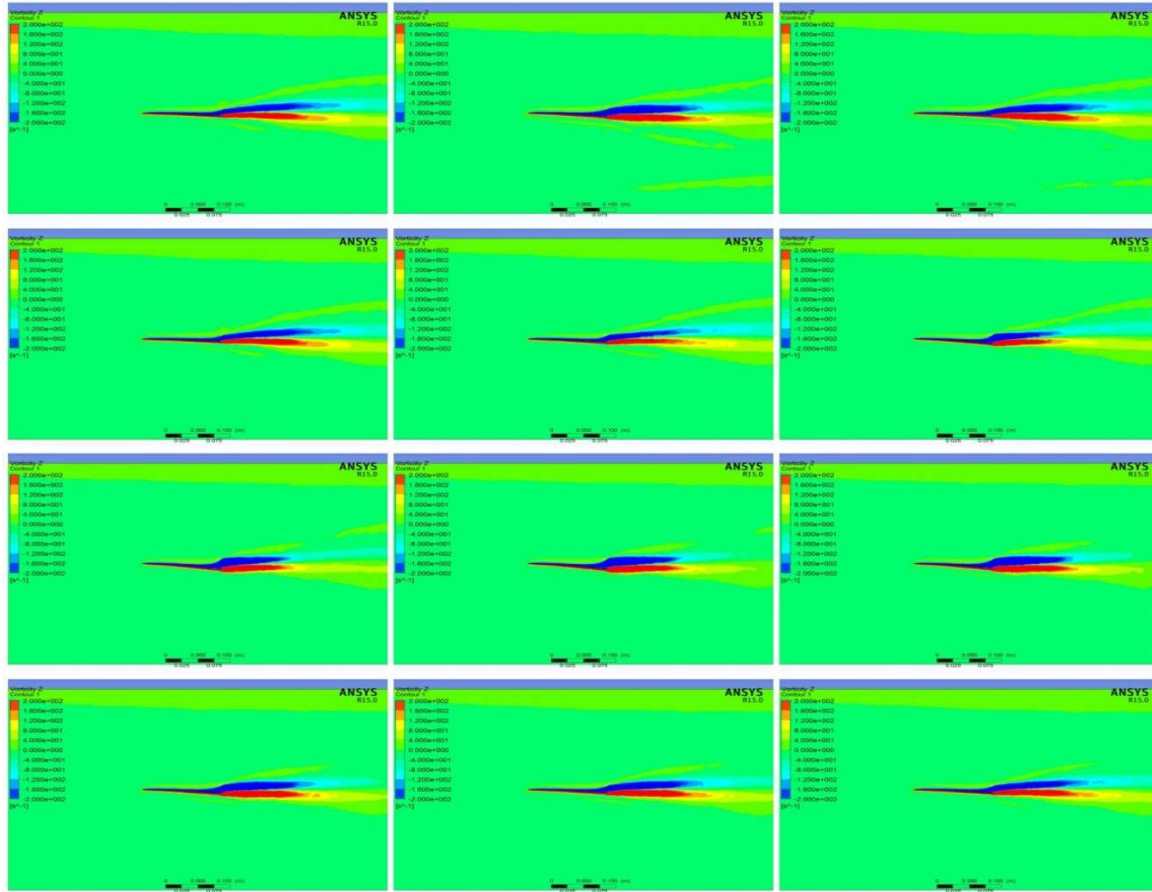


Figure 32: Flow regime and response of Flexible membrane

Flow regime over flexible membrane placed behind rigid cylindrical bluff-body (Velocity= 3.5 m/s)

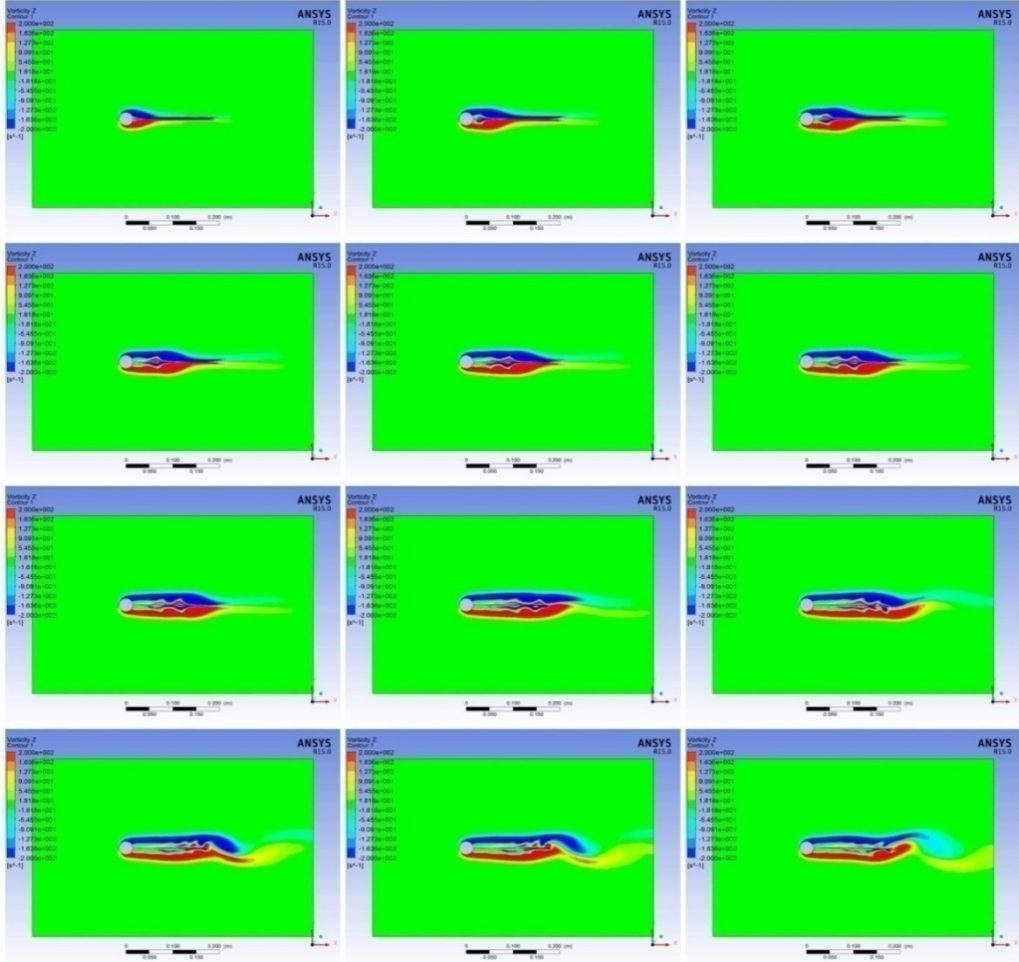


Figure 33: Flow regime and response of flexible splitter plate

4.6 Fourier Frequency Plots – MATLAB

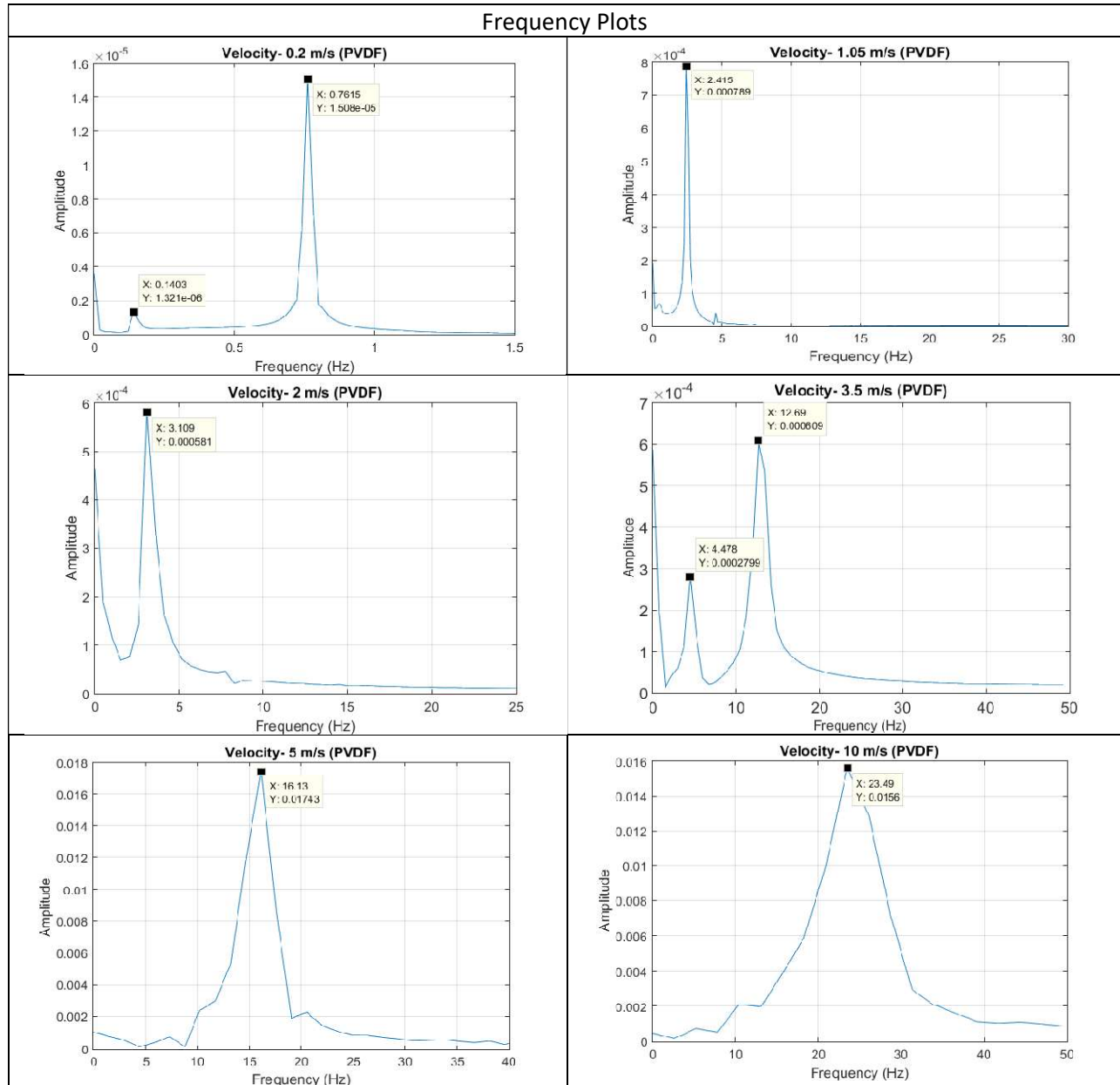


Figure 34: Frequency plots with variable velocity

TABLE 3: EIGEN FREQUENCY OBSERVATION

Velocity (m/s)	Frequency (Hz) at Strouhal Number = 0.07	Frequency (Hz) at Strouhal Number = 0.2	Oscillating Frequency (Hz)	Matched model Frequency (Hz)	Mode
0.2	0.7	2	0.765	2.61	First
1.05	3.675	10.5	2.415	2.61	First
2	7	20	3.109	2.61	First
3.5	12.25	35	12.69	10.44	Second
5	17.5	50	16.13	16.37	Third
10	35	100	23.48	16.37	Third

The Strouhal number calculated from the numerical analysis of splitter plate arrangement is 0.07. It is cleared from the below graphical interpretation that the oscillation of splitter plate is governed by Strouhal frequency.

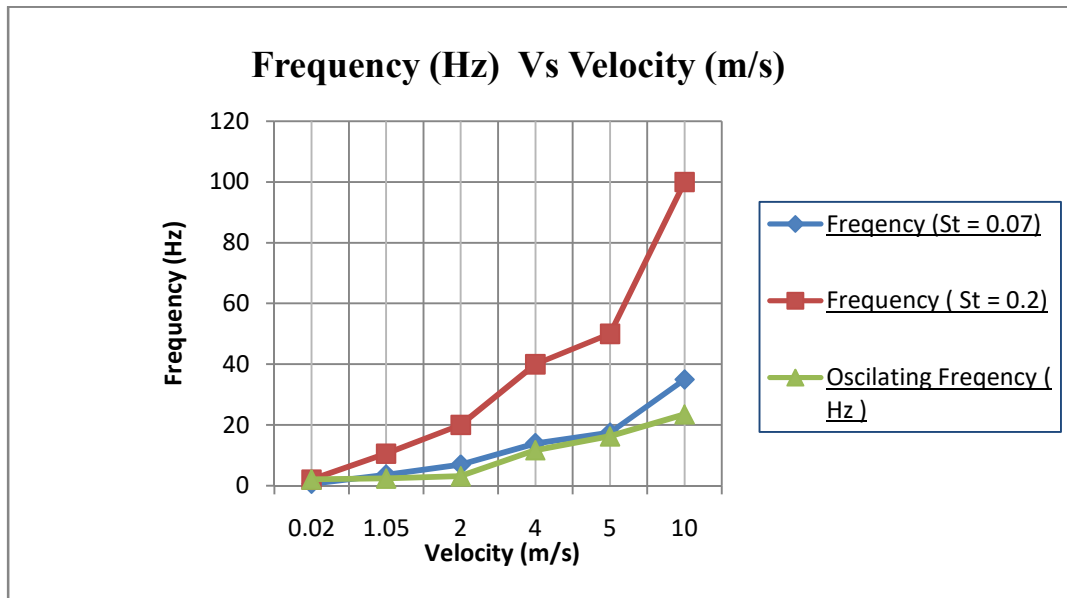


Figure 35: Frequency Vs Velocity Graph

Mesh Displacement Vs Time Plots - MATLAB

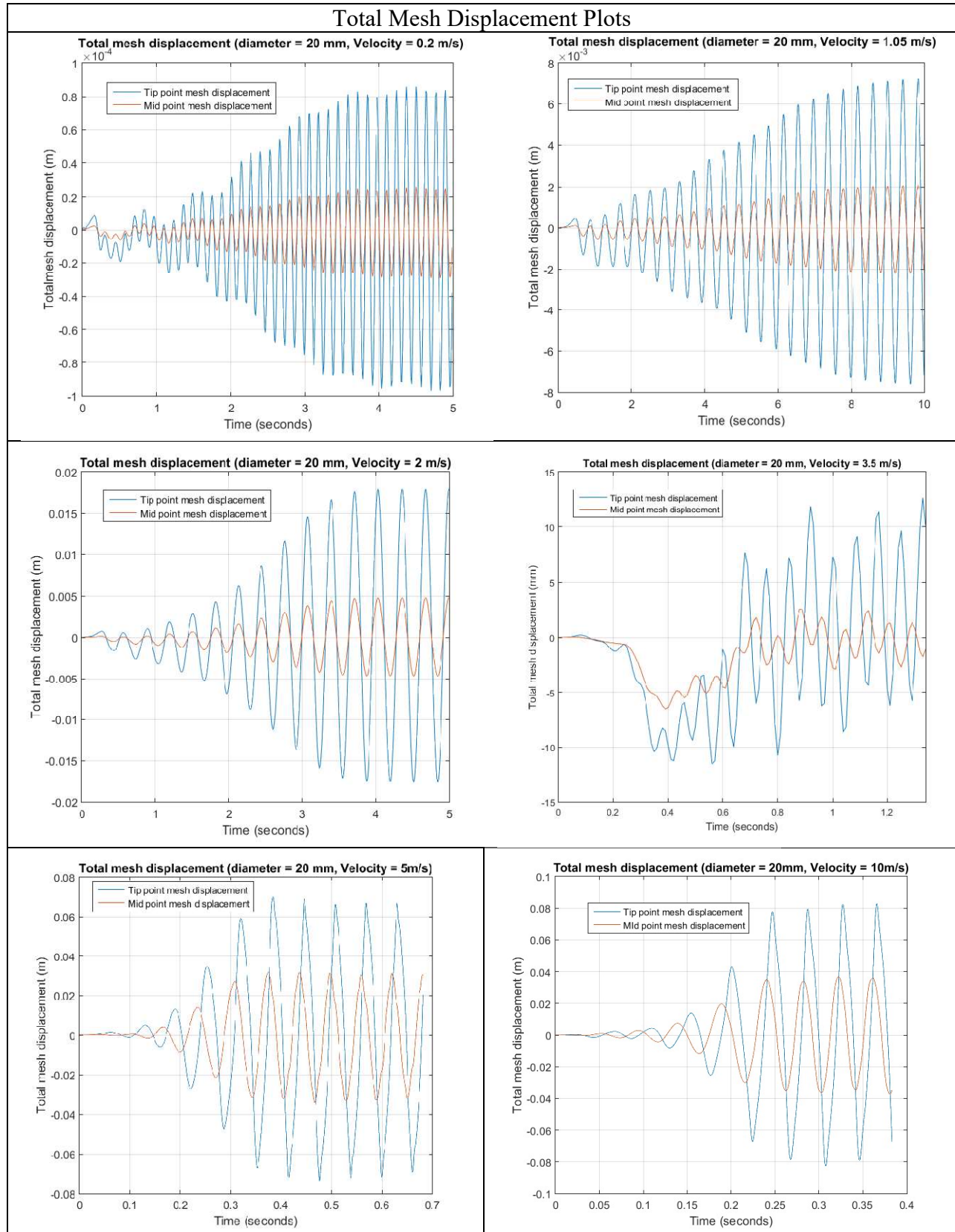
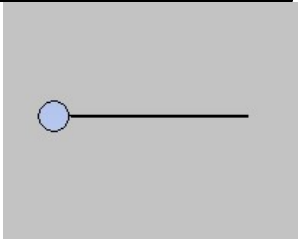
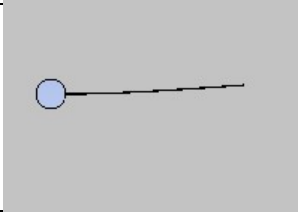
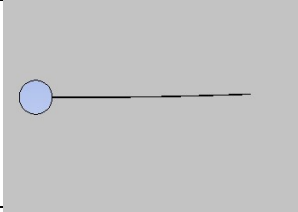
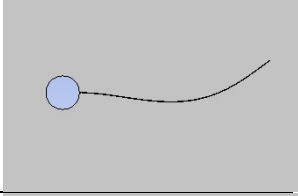
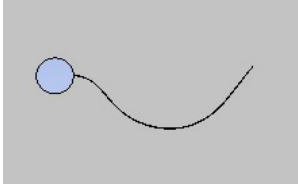


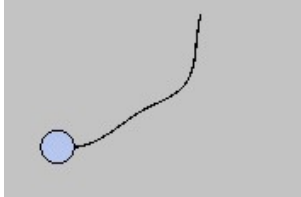
Figure 36: Total mesh displacement plots

Representation of splitter plate modal shape with velocity

Table 3: summarizes the results obtained for different flow velocities. The most important observation from that the modes of vibration are changing with change in the flow velocity.

TABLE 4 : TOTAL MESH DISPLACEMENT REPRESENTATION

Velocity (m/s)	Total mesh Displacement at a Point (Mid point) (mm)(instance)	Total mesh Displacement at a Point (Tip point) (mm)(instance)	Mode	Pictorial Representation
0.2	2.4851×10^{-5}	8.3906×10^{-5}	First	
1.05	0.0032715	0.0010473	First	
2	0.004436	0.0043326	First	
3.5	-0.0021369	0.0061577	Second	
5	0.066091	0.029906	Third	

10	0.082423	0.035725	Third	
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In the Graphical representation between splitter plate displacement and velocity it has been showed a little trough because of the sudden shift from first mode to second mode. The trend of the curve is ascending with velocity which showed that as velocity increases splitter plate displacement increases.

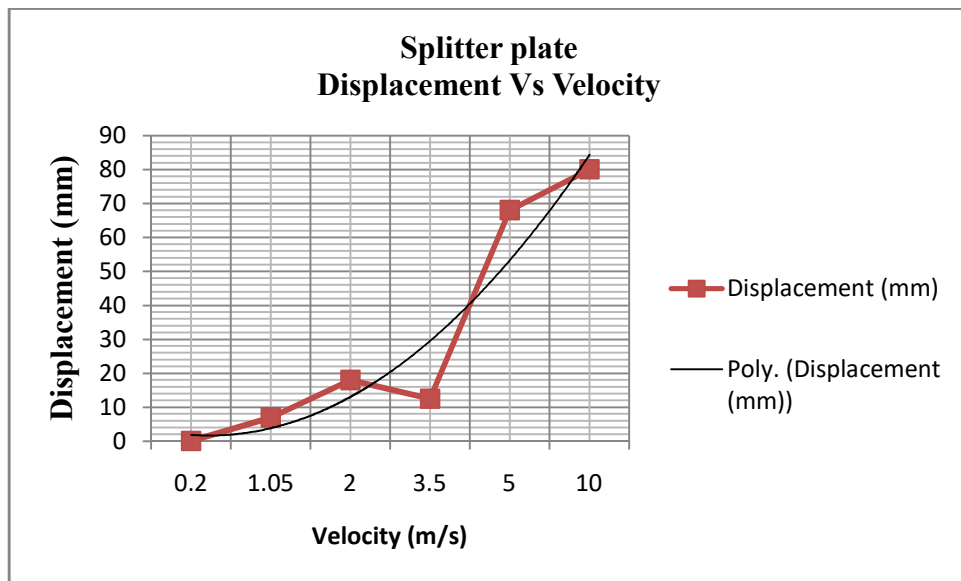
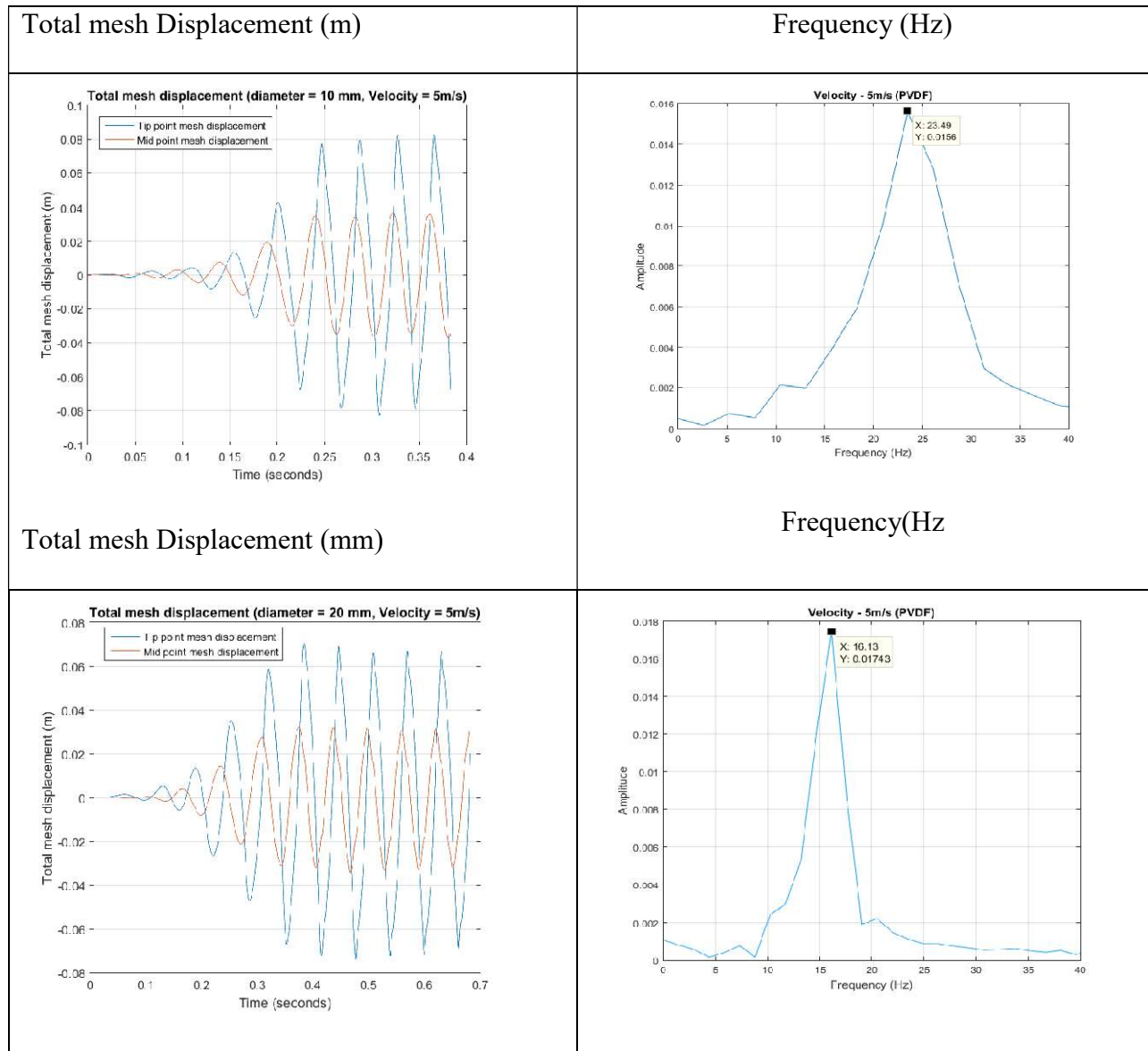


Figure 37: Displacement Vs Velocity Graph

4.7 Variation of frequency at different diameter

In this section the variation of frequency is measured by varying the diameter of the cylinder and the graphical interpretation depicts the slope is slanting downwards with increase in diameter of the cylinder.



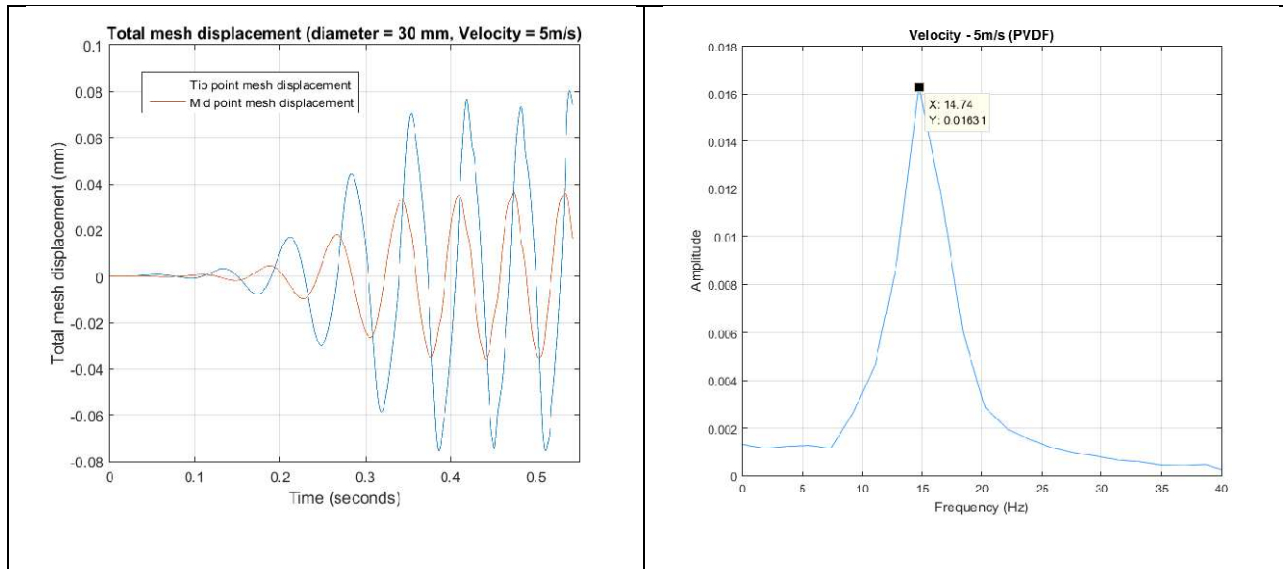


Figure 38: Total mesh displacement and Frequency Plots

Graphical representation of Frequency (Hz) Vs Diameter (mm)

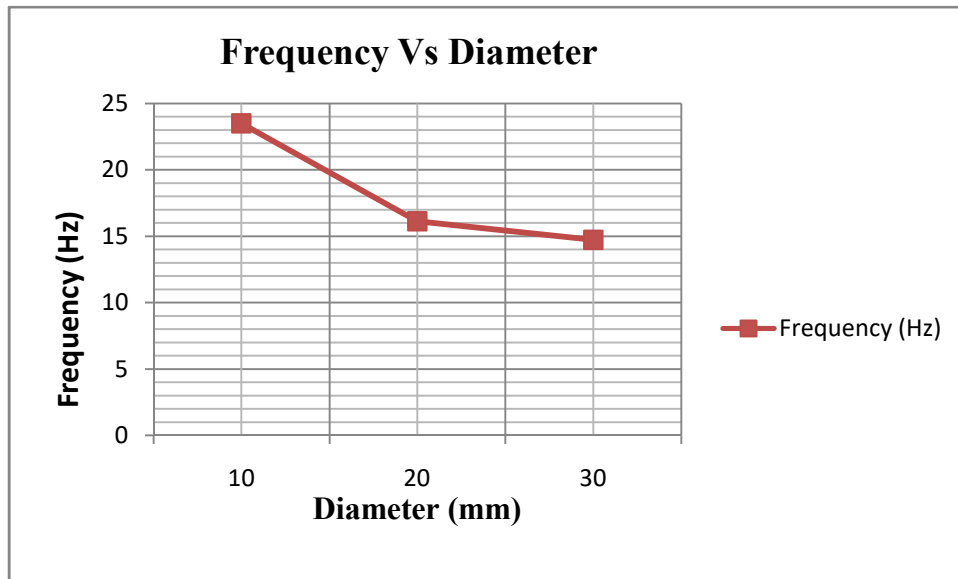


Figure 39: Graphical representation of frequency Vs Diameter

The above figure represents the relation between diameter and perturbation frequency. It gives the clear picture that frequency of oscillation is decreased with increase in diameter.

Chapter 5

Conclusions

5.1 Conclusion

Flow induced vibration (FIV) is a common phenomenon observed in many engineering applications. In most of the cases, it is undesirable and continuous research is underway to understand and control FIV. In few applications, like energy harvesting from FIV, it is utilized for the betterment of the society. In the present work, a problem of FIV of a flexible structure in flow is attempted. A test model of a plate with a front rigid cylinder is considered. It is noted that the flow is not smooth as it passes over the cylinder; there is a separation of boundary layer which creates pressure difference. The flowing fluid passing the cylinder causes the oscillation of fluid and the phenomenon is called Vortex Shedding. This vortex shedding is the result of vibration in the structure which is the scope of our work to analyze its impact with variation in velocity and its diameter. Numerical investigations are carried out in a commercial solver (ANSYS Workbench). In addition, the numerical solver is validated for a benchmark study.

Two different investigations are carried out to understand the complex phenomenon of flow induced vibration of plate. In the first study, effect of flow velocity is investigated, where it is noted that the change in the flow velocity excites the different modes of the plate. As the flow velocity increases, the vibration mode of the plate shifted from lower to higher modes. It is observed that the frequency of oscillation is no longer governed by the Strouhal criterion; however, the vortex shedding frequency synchronizes with the structural natural frequency. At different flow velocity, different natural frequency of structure locked-in. During the lock in

condition, high amplitude vibration is observed. Following are the important conclusions are made from the present investigations:

- ✓ **Strouhal Number:** The Strouhal number for flexible splitter plate is found to be 0.07. The Strouhal number calculated from numerical analysis is in accordance with the analytical and experiment value provided by Roshko i.e. 0.2 for rigid cylinder.
- ✓ **Splitter Plate:** At low flow velocity there is no deflection in flexible plate observed but as flow rate increase there is appreciable deflection that acquires steady state after certain time iterations. There is an increase in total mesh displacement with increase in velocity but there is a dump in slope due to transition of first mode to second mode.
- ✓ **Membrane:** The frequency of oscillation is governed by Strouhal number (0.07) and variation between Strouhal number (0.07) and oscillating frequency is small as compared to frequency of oscillation at Strouhal number 0.2. The membrane is oscillating in first mode at velocity range from 0.2 – 2 m/s. as velocity increases beyond 2m/s higher modes are observed.

In the second study, effect of size of bluff body on the level of vibration is computed and following observations are made are as follow:

- ✓ **Frequency:** As diameter increases the frequency of vibration decreases that validates the more wake area formation as radial dimension of cylinder increases.
- ✓ **Amplitude:** The amplitude of total mesh displacement is optimal at 20 mm diameter which shows that the computational work of fluid flow over rigid cylinder used 20 mm as a base reference for every computational work.

This work provides the vibration study of splitter plate and its modal behavior which in turn gives the basis for experimental study in energy harvesting solutions for optimal vibration.

5.2 Future Scope

Scientists and scholars used the Vortex induced vibration for power generation using Faraday Laws and piezoelectric membrane behavior in flowing fluid. This could be beneficial, if we numerically optimized the vibration behavior of flexible membrane to get maximum power generation. Secondly unstable vibration is never been solved in ANSYS, so it opened the gateway to the further implementation of ANSYS and CFX workbench. There is no question regarding the behavior of the flexible membrane in flowing fluid, whether it showed second mode or jump to flutter.

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Curriculum Vitae

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