Flow Induced Vibration Analysis of Multi-Span Supported Tube

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Major Project

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By

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Declaration

This is to certify that

- The thesis comprises my original work towards the degree of Master of Technology in Mechanical Engineering(Design Engineering) at Nirma University and has not been submitted elsewhere for Degree.
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Abstract

Flow induced vibration around the tube is a critical phenomena in shell and tube heat exchanger. In present work, the flow induced vibration mechanisms have been studied to understand the behavior of flow induced vibration in multiple supported tube. Free vibration analysis has been carried out to find natural frequency for both single span as well as multi-span tube and for each of the natural frequency the corresponding mode shapes plotted.

Computational fluid dynamics approach has been used to study velocity distribution, pressure distribution, vorticity magnitude etc. The drag coefficient values at different Reynolds number obtained around the single tube. Strouhal frequency values are obtained from fast fourier transform analysis using extracted lift data. Harmonic force is calculated by incorporating the drag coefficient and Strouhal frequency values. Forced vibration analysis has been done to observe the vibration response of the tube by applying different harmonic forces. Vibration response of the multi span tube with varying span length is observed too.

Keywords: Flow induced vibration, Free vibration response, CFD analysis, Forced vibration response

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Nomenclatures

l	: Length of Tube
D	: Diameter of Tube (meter)
E	: Modulus of Elasticity (N/m^2)
I	: Moment of Inertia (m^4)
m	: Mass of System (kg/m)
D	: Diameter of Tube
U_∞	: Upstream Velocity
F	: Harmonic Force (N)
fs	: Vortex Shedding Frequency
f	: Exciting Frequency (Hz)
y	: Amplitude of Vibration (m)
ω	: Natural Frequency (rad/sec)
ω_e	: Exciting Frequency of Applied Harmonic Force (rad/sec)
β	: Dimensionless Frequency parameter
Re	: Reynolds Number
C_D	: Drag Coefficient
v	: Fluid Flow Velocity (m/sec)
ρ	: Fluid Density (kg/m^3)

Chapter 1

Introduction

1.1 Preliminary Remarks

In many structural elements, vibration is created due to flow of fluid like water, gas, air etc. Some example of this type of structures is tubes in shell and tube heat exchanger, wings of aero plane, tall standing chimney, long vertical columns and many more.

Flow induced vibration in tubes very often have been observed in operating heat exchanger. The vibration is so severe that tubes collide constantly with each other. There are chances of fatigue failure in structure due to dynamic loads. Flow induced vibration occur in many engineering situations, such as bridges, stacks, transmission lines, aircraft control surfaces, offshore structures, thermo wells, engines, heat exchangers, marine cables, towed cables, drilling and production risers in petroleum production, mooring cables, moored structures, tethered structures and spar hulls, pipelines, cable-laying, members of jacketed structures, and other hydrodynamic and hydro acoustic applications. [1]

1.2 Flow Induced Vibration

Flow induced vibration problem occurs under the influence of cross flow velocities. If the amplitude of vibration becomes large enough, tubes can be damaged by more of several mechanisms.
1). Thinning due to repeated mid-span collision.
2). Impact fretting wear at baffles & tube interface.
3). Fatigue & corrosion fatigue due to high wear rate.

Higher flow velocities & reduced structural supports can lead to severe flow-induced vibration problem. Tube failures due to excessive vibration must be avoided in heat exchangers and nuclear steam generators, preferably at the design stage. Thus, a comprehensive flow-induced vibration analysis is required before fabrication of shell and tube heat exchangers. It must be shown that tube vibration levels are below allowable levels so that unacceptable resonance and fluid elastic instabilities are avoided.[1]

1.3 Multi-span Tube

Most heat exchanger have multiple baffle supports.The length of individual span and shell side cross flow may vary widely. However,flow induced vibration prediction correlation are not sophisticated enough to treat the multi span tube vibration problem by single analysis. In most cases, natural frequency of an end span is obtained by treating as fixed-pinned beam. Similarly, for the intermediate supports consider it as a pinned-pinned beam.[1]

1.4 Aim of Present Work

The main objective of present study on "flow induce vibration analysis of multi span supported tube" is to find out the natural frequency of the multi-span tube and to study the vibration behavior of the multi-span tube under cross flow.

1.5 Methodology

a. Modal analysis is carried out for single and multi span tube by using Euler-Bernoulli beam theory. Mathematical code is prepared to find the natural frequencies and mode shapes.

b. CFD analysis of flow over pipe is carried out using GAMBIT & FLUENT softwares and various important data have been extracted like lift force data, drag coefficient values,drag force values etc.

c. The force vibration of the multi span tube is carried out using the force data extracted from the CFD analysis. Mathematical code is prepared to study the amplitude of vibration.

1.6 Outline of Thesis

Chapter 1 includes the basic introduction of flow induced vibration, objective of present work and methodology.
Chapter 2 includes the study of available literature on flow induced vibration.
Chapter 3 includes the free and forced vibration analysis of multi span tube.
Chapter 4 includes results and discussion.
Chapter 5 includes conclusion and future scope.

Chapter 2

Literature Survey

This section briefly discusses about the previous work carried out by the researchers in the various fields which are related to my topic and helped me to gain & build platform for my work.

2.1 Flow Induced Vibration

Flow induced vibration occurs mainly due to four mechanisms, which are fluid elastic instability, vortex shedding, turbulent buffeting and acoustic resonance. Basic flow induced vibration mechanism and procedure to carry out free vibration analysis of multi-span tube using Euler-Bernoulli theory is given in book by Singh and Solse.[1]

2.1.1 Excitation Mechanisms

In Reactor cross flow occurs at inlet and outlet of shell side flow, due to this cross flow force acts on tubes which causes vibration in tubes. Outer tubes of tube bundles are mainly susceptible for vibration, due to facing of cross flow.[1]

The excitation mechanisms generally regarded as responsible for flow induced vibration are under stated.

1) Vortex Shedding or flow periodicity

2) Turbulent Buffeting

3) Fluid Elastic Instability

4) Acoustic Resonance

a. Vortex shedding or flow periodicity:

As the fluid past the tube, the wake behind the tube no longer regular, but contains distinct vortices. The periodic shedding of vortices alternately gives rise to alternating lift and drag forces cause periodic movement of the tube.

Figure 2.1: Vortex sheding around tube[10]

Vibration due to vortex shedding will occurs when vortex shedding frequency matches with natural frequency of tube. The vortex shedding phenomenon can be characterized by non-dimensional parameter ' Strouhal number'.

$$S_u = \frac{f_v \times D}{U_\infty}$$

where;

S_u = Strouhal number

f_v= vortex shedding frequency

D = Tube outer diameter

U_∞ = Upstream velocity

b. Turbulent Buffeting:

Random velocity perturbation associated with turbulent eddies spread over wide range of frequencies distributed around a central dominant frequency. When the dominant frequency in the flow field coincides with the lowest natural frequency of the tube & considerable amount of energy transfer takes place. Which leads to high amplitude vibration and resonance. Turbulence present in flow fluid force acts on tube, which cause small amplitude of vibration in tube.[1]

c. Fluid Elastic Instability:

Fluid elastic vibration sets in at a critical flow velocity & become large amplitude if the flow is increased further A sudden change in vibration pattern within the tube array indicates instability. This mechanism will almost lead to tube failure in relatively short period of time. This phenomenon takes place when cross flow velocity is more than critical flow velocity. Due to this large amplitude of vibration occurs.[1]

d. Acoustic Resonance:

Flow across the tube bank has, in addition to its mean velocity in the flow direction, a fluctuating velocity transverse to the mean flow direction. This fluctuating velocity is associated with the standing waves surrounding the tubes. The resonant vibration of the standing waves is commonly called acoustic vibration. It occurs when acoustic natural frequency of fluid matches with natural frequency of tube.[1]

Fluid elastic instability mechanism is discussed and modal analysis undertaken for fluid force interacting between tubes where variation in tube amplitude controlled by tube support are given by Goyder. Equation for fluid elastic instability mechanism by considering three different areas are also discussed. Acoustic resonance takes place when the natural frequency of tube matches with natural acoustic frequency of fluid and produces large sound wave. Due to this vibration is created. This mechanism is mostly occurs in gaseous fluid flow as explained by Eisinger [4].

Fluid force acting on tube, due to that tube starts vibrating. Vibration of tube will change the flow pattern around tube, which causes change in force acting on tube and vibration amplitude of tube. This cycle repeats continuously. This mechanism takes place due to turbulence of flow, which imposes lift and drag force on tube. Due to these forces, vibration with small amplitude occurs. This causes long term wear of tube at baffle support region as explained by Taylor, Pettigrew and Currie [3]. Turbulence in flow is depends on Reynolds's number, tube pattern lay out, cross flow velocity. Flow velocity imparts fluid force on tube. When the flow velocity increased from certain velocity, fluid force acting on tube is more compare to the energy dissipated in damping mechanism. This leads to negative damping and large amplitude vibration takes place. This point is instability point and velocity at this point is called critical flow velocity. Beyond this point large amplitude of vibration occurs as explained by Pettigrew and Taylor [9].

Flow induced vibration in tubes causes wear of tube at baffle supported regions and tube thinning takes place. Pettigrew, Taylor, Fisher, Yetisir and Fisher [10] have explained importance of analysis of flow induced vibration in Heat Exchanger and also presented related damage components. Flow induced vibration causes savior damage in tube,so it necessary to carry out vibration analysis of tube bundle to prevent tube failures. Design guidelines and resulting damage assessment due to vibration for two phase heat exchangers such as nuclear steam generator, boilers and coolers are given by Pettigrew and Taylor [11]. Natural frequency of tube is governing parameter in vibration response calculation of tube and to find out natural frequency of tube modal analysis needs to be carried out.

Different type of damage patterns and region of failure are explained by Singh and Solse [1] are as follows.

Collision damage

Due to high amplitude of vibration tubes of bundle collides with each other. Tubes at periphery of bundle are mostly affected by this damage.

Baffle damage

There is clearance between tube hole in baffle and tube outer diameter. Hence due to vibration, wear of tubes takes place in supported small area and thickness reduces. Pressure distribution along the thickness of baffle is uniform, but at the edges sharp pressure pick takes place.

Tube sheet clamping effect

Tubes are clamped at tube sheet, so natural frequency increases. But due lateral deflection of tubes, high stresses produced in that region which is not desirable.

Material defect propagation

Every material has certain defects during its production, like small cracks etc. This leads to failure when vibration takes place.

Metallurgical failure

Tube material oxidation takes place during operation and oxide layers are formed on it. When alternating stress are acts on tube this layers will brakes and pits created on surface, this causes stress rising points.

Different regions of failures are as follows

a) Nozzle entrance and Exit region: In this region direct impinging of fluid on tubes takes place. Tubes are clamped in tube sheets so stress due small lateral deflection causes high stress in this portion.

b) Tube sheet region: Unsupported tube length is more in this region as compared to supported length span, so natural frequency of this region. Entrance and exit nozzles are generally placed in this region so direct cross flow impinge on tube bundle.

c) Tubes are under compressive stress. This occurs due to thermal expansion of tube.

2.2 Free & Forced Vibration Analysis of Tube

Lin and Tsai [6] presented free vibration analysis for multi span beam with concentrated spring mass system at different points. Formulation is done on base of Euler's beam theory. Firstly, the coefficient matrices for an intermediate pinned support, intermediate spring-mass system,left-end support and right-end support of a uniform beam derived. Then the numerical assembly technique for the conventional finite element method is used to establish the overall coefficient matrix for the whole vibrating system. Equating the last overall coefficient matrix to zero one determines the natural frequencies of the vibrating system and associate mode shape by putting the last integration constant into it. In this paper Finite element method is compared with numerical method and results are in good agreement.

Lin [7]presented Dynamic vibration analysis for multi span beam with concentrated spring mass system at different points. Formulation is done on base of Euler's beam theory. Firstly, the coefficient matrices for an intermediate pinned support, intermediate spring-mass system,applied force,left-end support and right-end support of a uniform beam derived. Then the numerical assembly technique for the conventional finite element method is used to establish the overall coefficient matrix for the whole vibrating system. Finally, the exact dynamic response amplitude of the forced vibrating system corresponding to each specified exciting frequency of the harmonic force is determined by solving thee simultaneous equation associated with last overall coefficient matrix. Finite element method is compared with numerical method and results are in good agreement. Wu and Shzh [8] presented dynamic analysis of multi-span fluid conveying pipe subjected to external load using transfer matrix method and dynamic stiffness matrix method.

2.3 Computational Fluid Dynamics(CFD)Analysis

Kumar and Mittal[15] presented stabilized space time finite element method with tandem arrangement for both inline and cross flow for one cylinder as well as two cylinder. Mittal and Kumar also presented the finite element formulation to study flow-induced oscillations of a pair of equal-sized cylinders in tandem and staggered arrangement placed in uniform incompressible flow.

Gerber and Hassan[16] presented computational fluid dynamic method to model the transient behavior of the fluid flow with explicit coupling to a structural model of the bluff body. The structural model represents the inertial, damping and spring characteristics of the bluff body presents preliminary validation of the model for laminar and turbulent flow in single tube arrangements. Chakraborty, Verma and Chhabra[17] presented study on the steady flow of an incompressible Newtonian fluid past a circular cylinder confined in a plane rectangular channel and flow parameters such as drag coefficient, length of the recirculation zone, and the angle of separation are presented as functions of the Reynolds number and blockage ratio. Pasto[18] presented experimental results on the behavior of a freely vibrating circular cylinder in laminar and turbulent flows. Wind tunnel tests have been performed by varying the cylinder roughness and the mass-damping parameter.

Chapter 3

Free & Forced Vibration Analysis

3.1 Free Vibration Analysis

Free Vibration Analysis of any structural element is required to find out fundamental natural frequency of system, which is lowest frequency from where structure starts vibrating. Modal analysis of tube is done in both way for single span as well as multi span configuration.

3.2 Modal Analysis of Tube

Single span and multi span tube modal analysis is done using Euler-Bernoulli's beam theory given in [1] and [14]. The classical governing equation of long slender tube is given by:

$$m\frac{\partial^2 w(x,t)}{\partial t^2} + EI\frac{\partial^4 w(x,t)}{\partial x^4} = 0 \tag{3.1}$$

Where, m is mass per unit length,

E is modulus of elasticity,

I is moment of inertia of tube.

The free vibration of a tube is harmonic in nature, than one has

$$y(x,t) = Y(x)e^{i\omega t}$$

and

$$z_p(t) = Z_p e^{i\omega t} \tag{3.2}$$

Where Y(x) and Z_p are the amplitudes of y(x,t) and $z_p(t)$,respectively. ω is natural frequency of the whole vibrating system

The substitution of Equation.(3.2) in Equation.(3.3) gives

$$Y'''' - \beta^4 \; Y \;\; = \;\; 0 \; , \tag{3.3}$$

where

$$\beta^4 = \frac{\omega^2 m}{EI} \tag{3.4}$$

or

$$\omega = (\beta l)^2 \left(\frac{EI}{ml^4}\right)^{1/2} \tag{3.5}$$

The solution of above equation takes the form

$$y(x) = c_1 \cos \beta x + c_2 \sin \beta x + c_3 \cos \beta x + c_4 \sinh \beta x \tag{3.6}$$

This equation is the displacement function for each tube segment will be

$$y\,(x) = An(Cos\beta x + Cosh\beta x) + Bn(Cos\beta x - Cosh\beta x)$$

$$+\, Cn(Sin\beta x + Sinh\beta x) + Dn(Sin\beta x - Sinh\beta x) \tag{3.7}$$

$$y^{'}\,(x) = \beta(An\,(-Sin\beta x + Sinh\beta x) + Bn\,(-Sin\beta x - Sinh\beta x)$$

$$+\, Cn(Cos\beta x + Cosh\beta x) + Dn(Cos\beta x - Cosh\beta x) \tag{3.8}$$

$$y^{''}(x) = \beta^2(An(-Cos\beta x + Cosh\beta x) + Bn(-Cos\beta x - Cosh\beta x))$$

$$+ Cn(-Sin\beta x + Sinh\beta x) + Dn(-Sin\beta x - Sinh\beta x) \quad (3.9)$$

$$y^{'''}(x) = \beta^3 An\,(Sin\beta x + Sinh\beta x) + Bn\,(Sin\beta x - Sinh\beta x)$$

$$+ Cn(-Cos\beta x + Cosh\beta x) + Dn(-Cos\beta x - Cosh\beta x) \quad (3.10)$$

3.2.1 Fixed-simply Supported Ends

This analysis of tube is considered as fixed at one end and simply supported on other end. It is the first span of multi-span tube. Figure (3.1) shows the first span of tube.

Figure 3.1: First span of tube(fixed-pinned)

Boundary condition:

At left end, $x = 0,\ Y(x) = 0\ \&\ Y'(x) = 0$

At right end, $x = l,\ Y(l) = 0\ \&\ Y''(l) = 0$

Utilizing Equation.(3.8) and Equation.(3.9) gives

$$\tan \beta_n l = \tanh \beta_n l \tag{3.11}$$

3.2.2 Simply Supported Ends

The intermediate spans are treated as simply supported tube as shown in Fig (3.2).

Figure 3.2: Intermediate span of tube(pinned-pinned)

Boundary condition:

At left end, $x = 0,\ Y(x) \ = \ 0,\ \ \& \ Y''(x) \ = \ 0$

At right end, $x = l,\ \ Y(l) \ = \ 0 \ \& \ Y''(l) \ = \ 0$

Utilizing Equation (3.9) gives

$$\sin \beta_n l = \sin \beta_n l = 0 \tag{3.12}$$

3.2.3 Free Vibration Analysis of Multi-span Tube

For modal analysis, Euler-Bernoullis beam theory given in [1] and [6] has been followed. Solution of Equation (3.3) is given by:

$$y(x) = An(\cos\beta x + \cosh\beta x) + Bn(\cos\beta x - \cosh\beta x) + Cn(\sin\beta x + \sinh\beta x) + Dn(\sin\beta x - \sinh\beta x) \quad (3.13)$$

It is considered that at the start of each span deflection is zero so, Above Equation (3.13) reduced to

$$y\,(x) = Bn(Cos\beta x - Cosh\beta x) + Cn(Sin\beta x + Sinh\beta x) + Dn(Sin\beta x - Sinh\beta x) \quad (3.14)$$

Boundary condition:

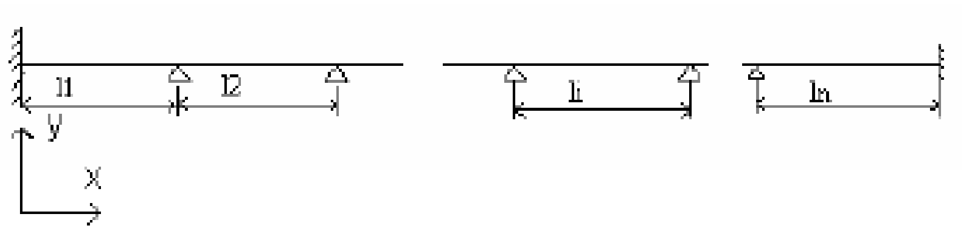

Figure 3.3: Multi span tube

At left end:

$$x_1=0\ ,\ y_1=0$$

At intermediate support points:

$$x_i = l_i; y = 0 \quad (3.15)$$

$$\frac{\partial^2 y_i}{\partial x_i^2}|x_i = l_i = \frac{\partial^2 y_{i+1}}{\partial x_{i+1}^2}|x_{i+1} = 0 \quad (3.16)$$

$$\frac{\partial y_i}{\partial x_i}|x_i = l_i = \frac{\partial y_{i+1}}{\partial x_{i+1}}|x_{i+1} \quad (3.17)$$

At right most end:

$$x_N = l_N$$

$$y_N = y_N^{'} = 0 \tag{3.18}$$

Thus three equations for each intermediate (N-1) supports and total three equations of two ends furnish 3N linear equations. For each dimensionless frequency parameter, one may obtained the corresponding integration constants and substitution of last constants into displacement functions of the associated tube segment will determine the corresponding mode shape of the tube.

3.3 Forced Vibration Analysis

Forced Vibration Analysis of any structural element is required to find out force vibration response of system, when concentrated harmonic force located at various position along the Tube length. Force vibration analysis of tube is done in multi span configuration.

3.3.1 Forced Vibration Analysis of Multi-span Tube

For forced vibration analysis, Euler-Bernoullis beam theory given in [1] and [7] has been followed. Solution of Equation (3.3) is given by:

$$y(x) = (An\ sin\ \beta x + Bn\ cos\ \beta x + Cn\ sinh\ \beta x + Dn\ cos\ \beta x) \tag{3.19}$$

$$y(x)^{'} = \beta(An\ cos\beta x - Bn\ sin\beta x + Cn\ cosh\beta x + Dn\ sinh\beta x) \tag{3.20}$$

$$y(x)^{''} = \beta(-An\ sin\beta x - Bn\ cos\beta x + Cn\ sinh\beta x + Dn\ cosh\beta x) \tag{3.21}$$

$$y(x)^{'''} = \beta(-An\ cos\beta x + Bn\ sin\beta x + Cn\ cosh\beta x + Dn\ sinh\beta x) \tag{3.22}$$

Figure (3.4) shows the Multi-span tube subjected to harmonic concentrated force.

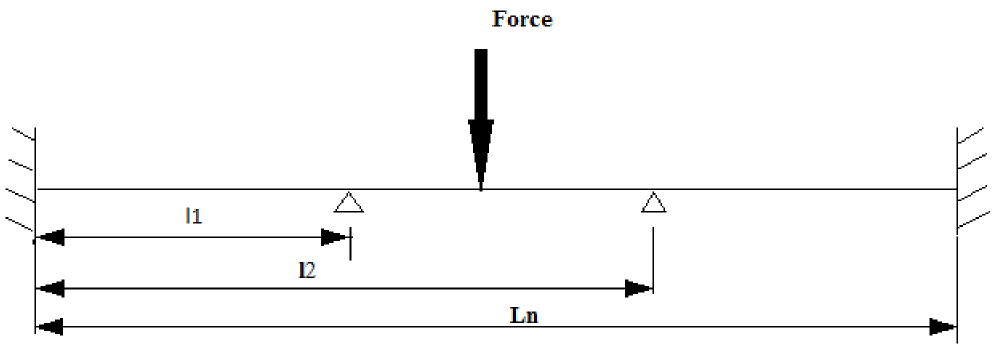

Figure 3.4: Multi-span tube with harmonic concentrated force

Boundary condition:

At left end:

If the left end support is fixed,then the boundary conditions are

$$x_1 = 0 \ , \ y(x) = 0$$
$$x_1 = 0 \ , \ y^{'}(l) = 0$$

At Intermediate Supports:

At all intermediate pinned supports continuity of deformations and equilibrium of moments require that

$$y_i = y_{i+1} \tag{3.23}$$

$$\frac{\partial^2 y_i}{\partial x_i^2} = \frac{\partial^2 y_{i+1}}{\partial x_{i+1}^2} \tag{3.24}$$

$$\frac{\partial y_i}{\partial x_i} = \frac{\partial y_{i+1}}{\partial x_{i+1}} \tag{3.25}$$

At Intermediate Applied Force:

If at mid span of tube harmonic concentrated force is applied then deformations and equilibrium of moments, forces require that

$$y_i = y_{i+1} \tag{3.26}$$

$$\frac{\partial^2 y_i}{\partial x_i^2} = \frac{\partial^2 y_{i+1}}{\partial x_{i+1}^2} \tag{3.27}$$

$$\frac{\partial y_i}{\partial x_i} = \frac{\partial y_{i+1}}{\partial x_{i+1}} \tag{3.28}$$

$$\frac{\partial^3 y_i}{\partial x_i^3} + \frac{F_v}{EI} = \frac{\partial^3 y_{i+1}}{\partial x_{i+1}^3} \tag{3.29}$$

At right most end:

If the right end support is fixed,then the boundary conditions are

$$x_N = l_N$$

$$y_N = y_N^{'} = 0 \tag{3.30}$$

If the exciting frequency or the dimensionless frequency parameter of the harmonic force is known, then one may obtain the corresponding integration constants. Substituting the integration constants into the corresponding displacement function Equation (3.19) of associated tube segments will give vibration amplitude of the tube.

Chapter 4

Result & Discussion

4.1 Preliminary Remarks

In this chapter, dimensionless frequency parameters and natural frequency data for single span as well as for multi span tubes are tabulated and corresponding mode shape results are displayed too. Computational fluid dynamics(CFD) analysis results obtained at different Reynolds no are displayed. Exciting Frequency of the applied harmonic force obtained using the Fast Fourier Transform code. And at last forced vibration analysis plots at different span lengths are plotted. All numerical results of this thesis are obtained based on a uniform Euler-Bernoulli beam theory with given data: length of tube l=1 meter, Diameter of tube D=1 meter, Young's modulus $E = 2.068e11N/m^2$

4.2 Free Vibration Analysis of Tube

In Free vibration analysis of tube, two different spans are considered with different boundary condition.One is with fixed-fixed condition and another one with fixed-pinned condition. Four set of dimensionless frequency parameters and natural frequency values are tabulated and the corresponding mode shapes plotted using the Equation (3.7) to (3.10).

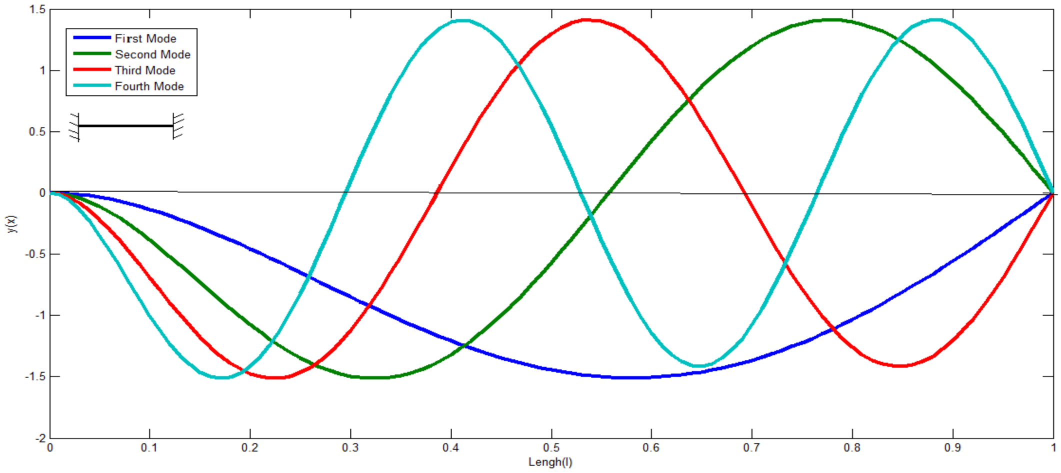

Figure 4.1: Mode shapes for Single span tube with fixed-pinned supports

Table 4.1: Single span tube with fixed-pinned supports

Mode	Dimensionless Parameter β	f_1(Hz)	ω_1(rad/sec)
1	3.9266	31.5274	198.098
2	7.0686	102.1695	641.950
3	10.2102	213.1685	1339.40
4	13.3518	364.5307	2290.40

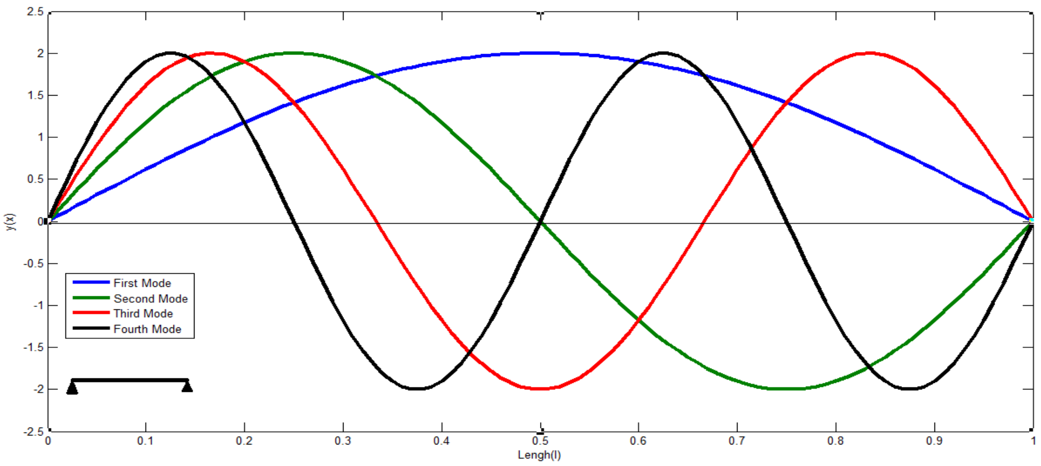

Figure 4.2: Mode shapes for single span tube with pinned supports

Table 4.2: Single span tube with pinned-pinned supports

Mode	Dimensionless Parameter β	f_1(Hz)	ω_1(rad/sec)
1	3.1416	20.1816	126.8049
2	6.2832	80.7265	507.2198
3	9.4248	181.6347	1141.206
4	12.5664	322.9061	2028.980

For tube with fixed supports at both ends and one intermediate pinned support, four set of dimensionless frequency parameters and natural frequency values are tabulated and the corresponding mode shapes plotted using the Equation (3.19) to (3.30). Span length: $l1$=0.5 meter, $l2$=0.5 meter

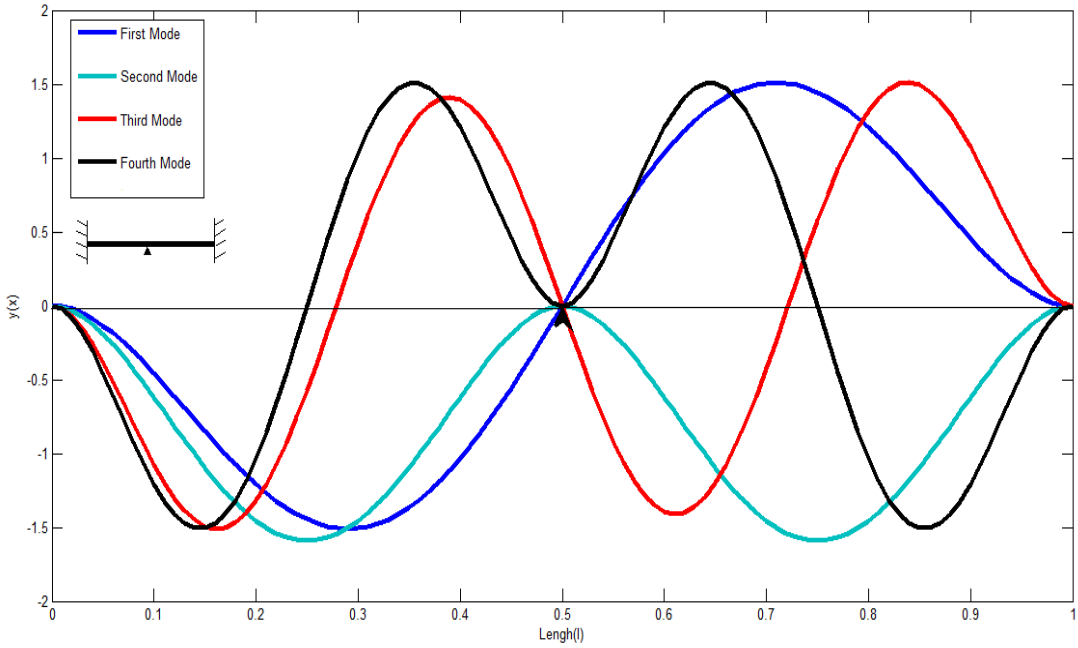

Figure 4.3: Mode shapes of tube with one intermediate pinned supports

Table 4.3: Tube with one intermediate pinned support

Mode	Dimensionless Parameter β	f_1(Hz)	ω_1(rad/sec)
1	7.8532	126.1095	792.369
2	9.4601	182.9978	1149.80
3	14.1372	408.6781	2567.80
4	15.7062	504.4380	3169.50

For tube with fixed supports at both ends and two intermediate pinned support, four set of dimensionless frequency parameters and natural frequency values are tabulated and the corresponding mode shapes plotted using the Equation (3.19) to (3.30). Span length: $l1$=0.3 meter, $l2$=0.4 meter, $l3$=0.3 meter.

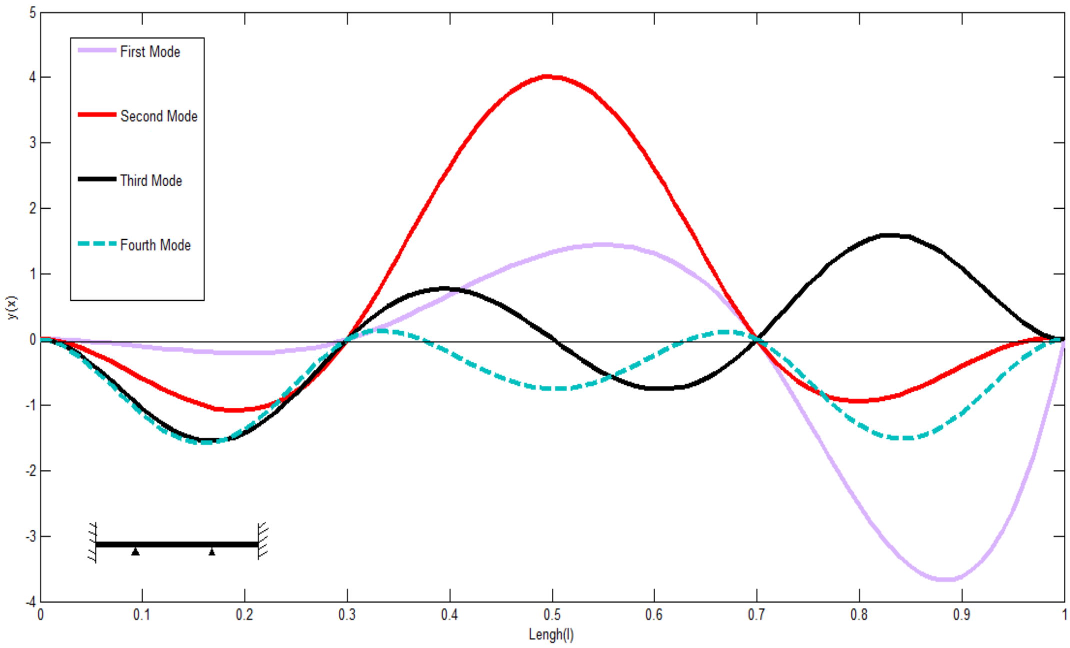

Figure 4.4: Mode shapes of tube with two intermediate pinned supports

Table 4.4: Tube with two intermediate pinned supports

Mode	Dimensionless Parameter β	f_1(Hz)	ω_1(rad/sec)
1	4.0003	32.7220	205.5983
2	9.6559	190.6514	1197.90
3	13.8279	390.9912	2456.70
4	14.7987	447.8181	2813.70

For tube with fixed supports at both ends and three intermediate pinned support, four set of dimensionless frequency parameters and natural frequency values are tabulated and the corresponding mode shapes plotted using the Equation (3.19) to (3.30). Span length: $l1$=0.3 meter, $l2$=0.2 meter, $l3$=0.2 meter, $l4$=0.3 meter.

Table 4.5: Tube with three intermediate pinned supports

Mode	Dimensionless Parameter β	f_1(Hz)	ω_1(rad/sec)
1	4.2664	37.2201	233.2201
2	13.8277	390.9799	2456.6
3	14.2793	416.9350	2619.7
4	18.1008	669.9618	4209.5

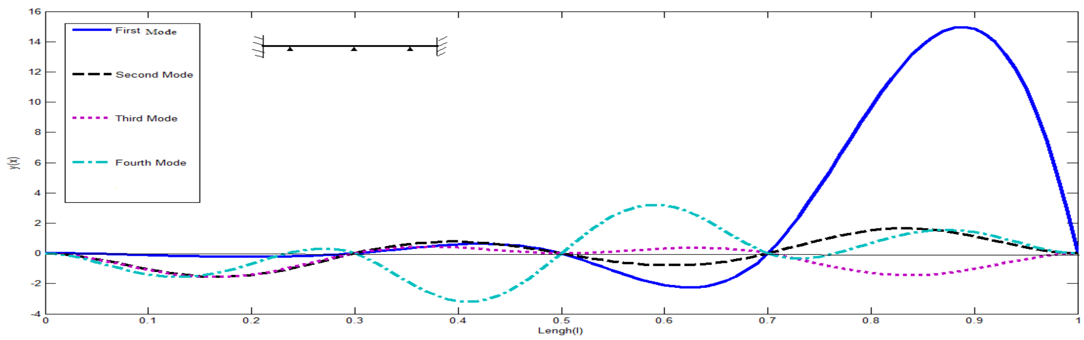

Figure 4.5: Mode shapes of tube with three intermediate pinned supports

4.3 Computational Fluid Dynamic Analysis

Computational fluid dynamics (CFD) is available tool to simulate the complex flow problems. In solution of fluid problems complex differential equations are involved, which requires higher end computational tool to solve them. CFD produces virtual flow domain according to boundary condition given by user, and gives the flow behavior.

Circular tube is modeled and meshed with the help of GAMBIT tool. The meshed geometry exported to FLUENT for further analysis where the virtual flow of fluid is given from one side of domain at two different Reynolds no. First analysis done at *Re*=10,000 and Second one at *Re*=100000. Fluid material is H_2O*(liquid)* and the total time of the simulation is 20 seconds. Drag coefficient and drag force values at both Reynolds number obtained and velocity distribution, pressure distribution, vorticity magnitude studied as well. For every time steps lift coefficient values extracted to further plot the FFT frequency spectrum.

Below figures show the contour of velocity magnitude, static pressure, vorticity magnitude and stream function at *Re*=10,000 & *Re*=100000 respectively.

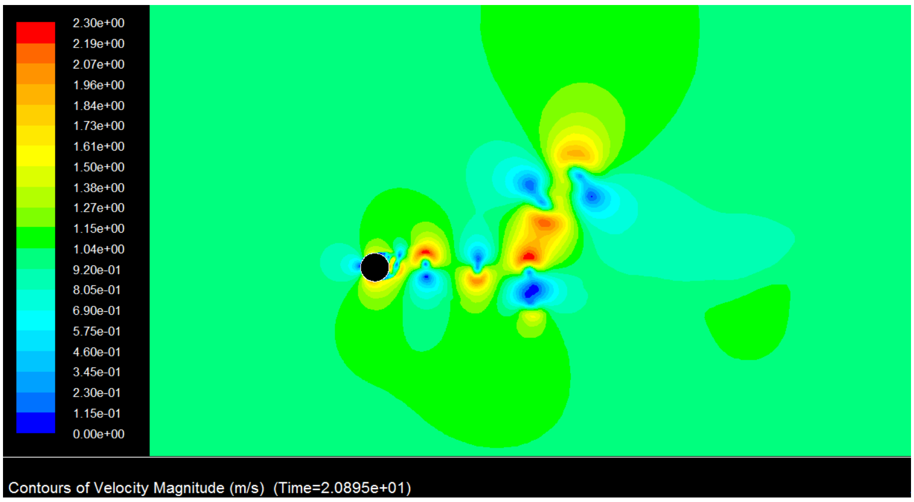

Figure 4.6: Contour of velocity magnitude at *Re*=10,000

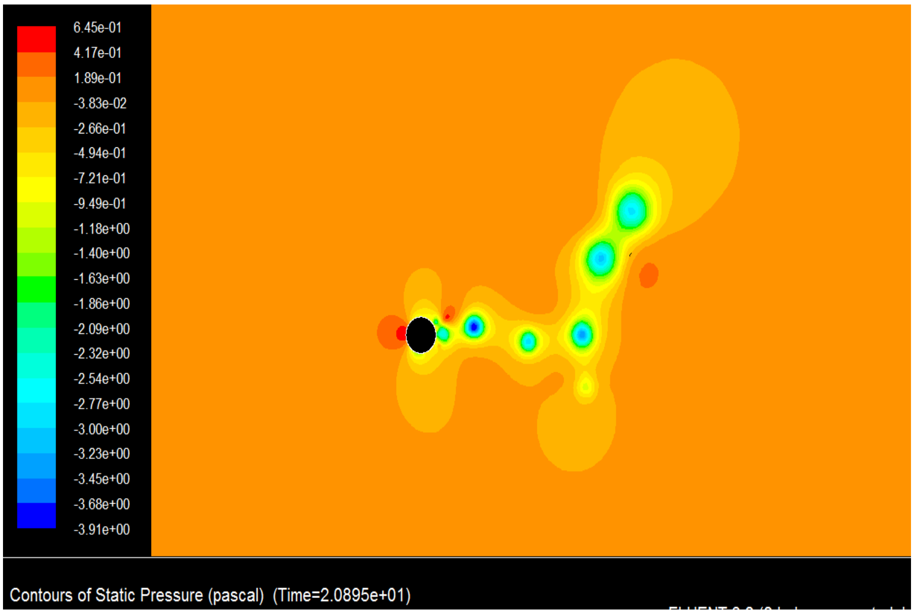

Figure 4.7: Contour of static pressure at Re=10,000

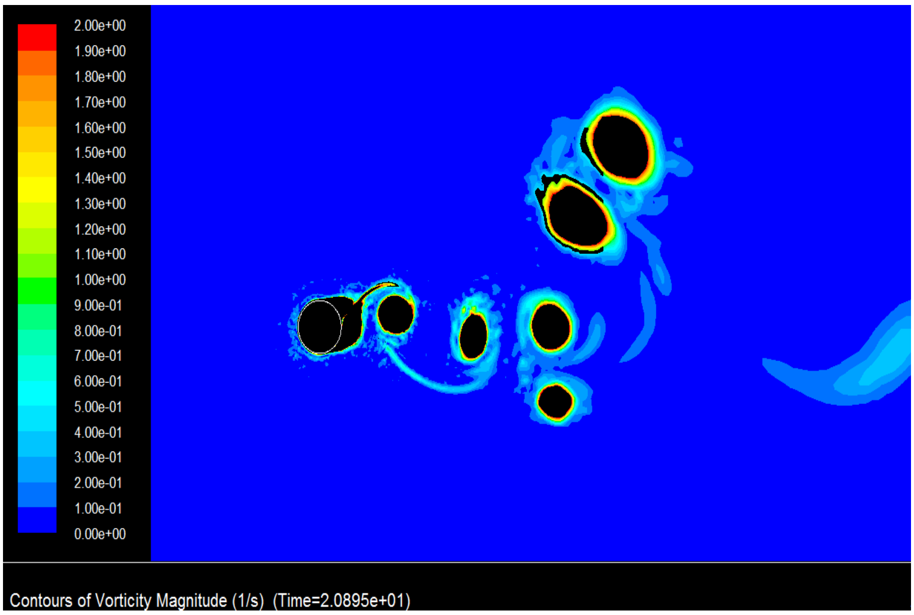

Figure 4.8: Contour of vorticity magnitude at Re=10,000

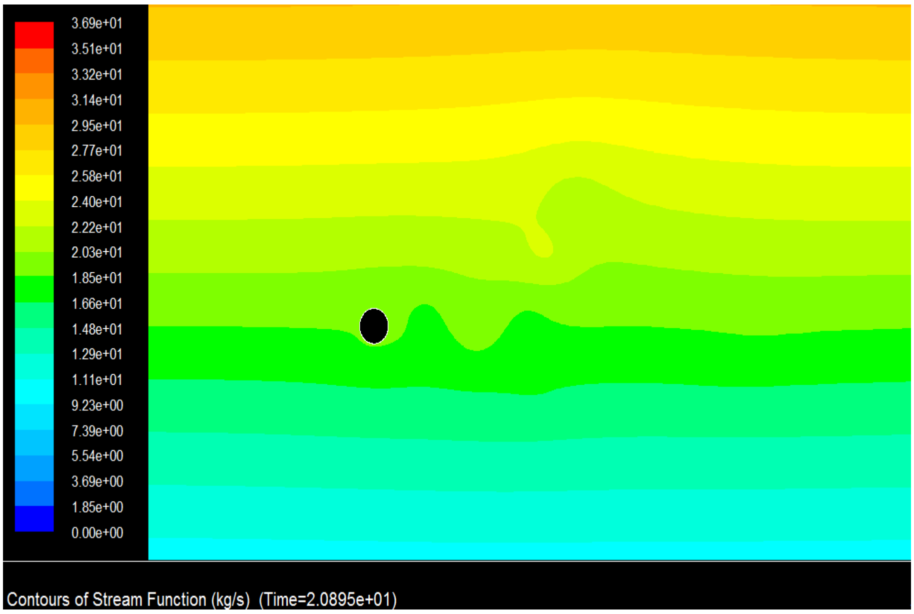

Figure 4.9: Contour of stream function at Re=10,000

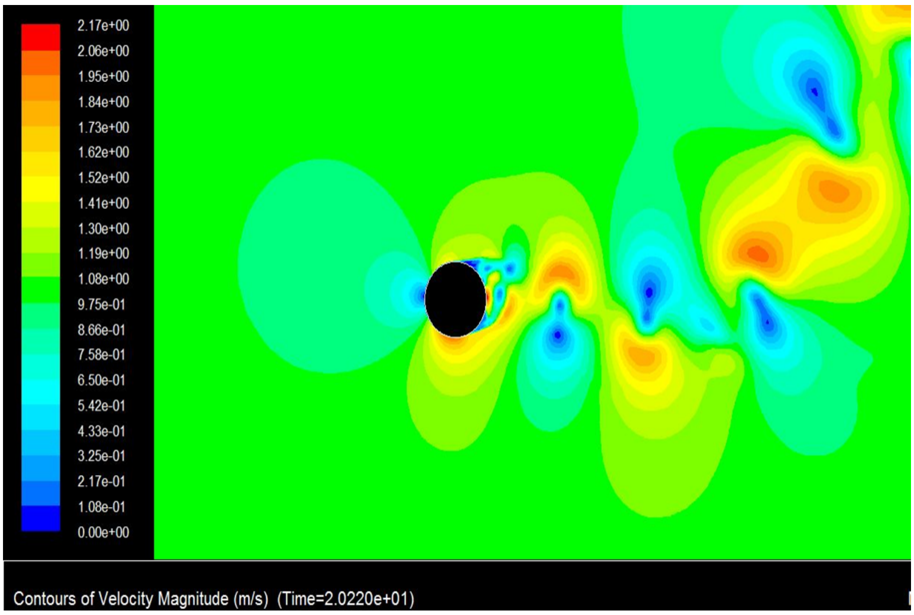

Figure 4.10: Contour of velocity magnitude at Re=100000

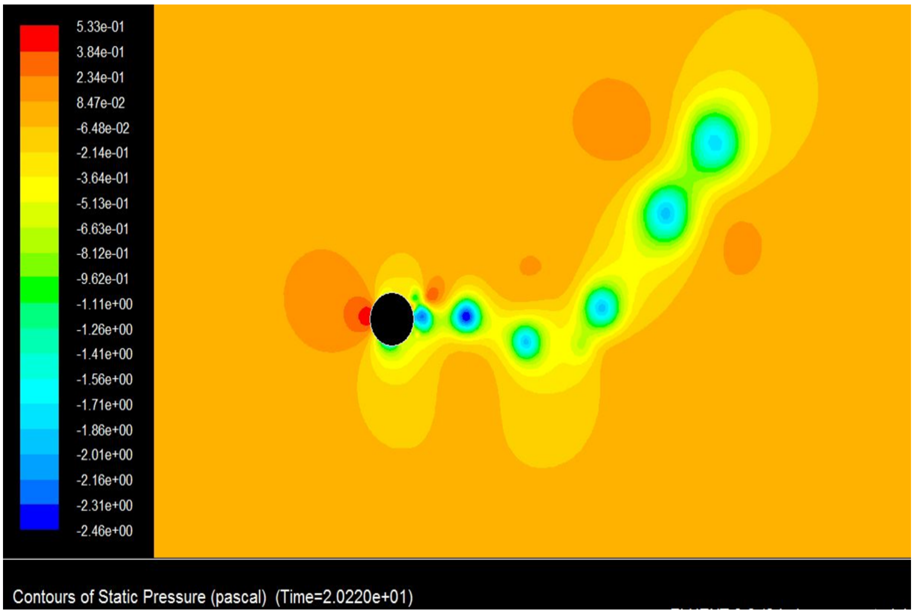

Figure 4.11: Contour of static pressure at Re=100000

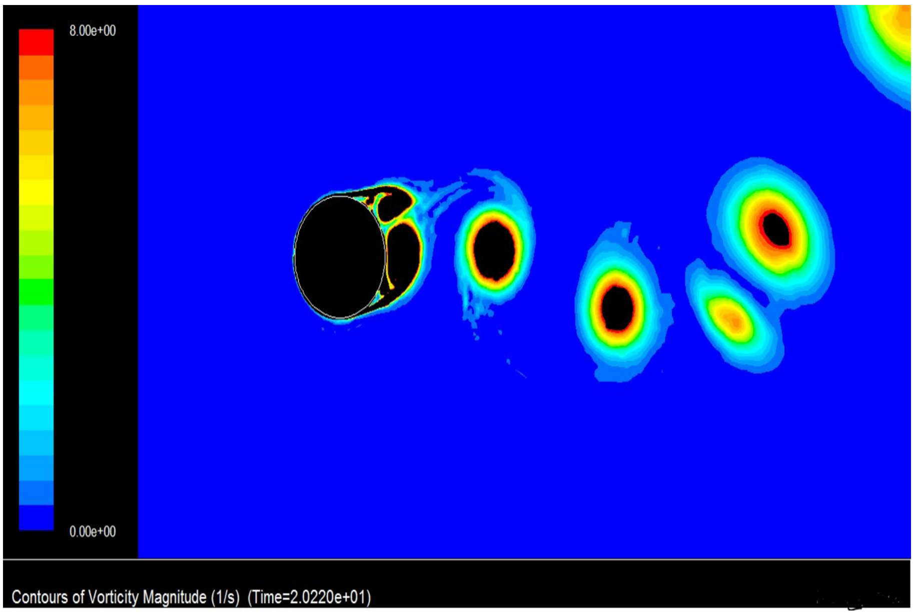

Figure 4.12: Contour of vorticity magnitude at Re=100000

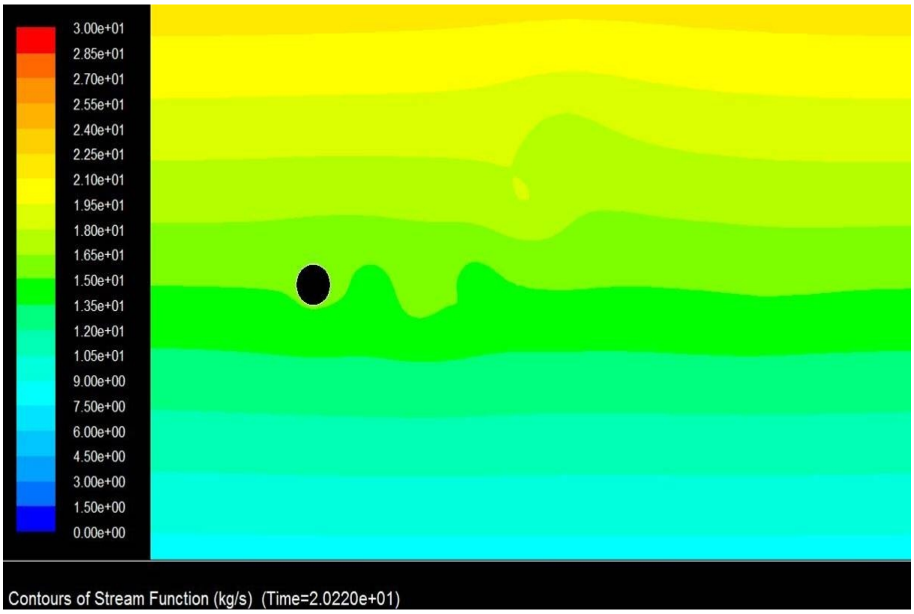

Figure 4.13: Contour of stream function at Re=100000

Below table (4.6) shows the drag coefficient values obtained from CFD analysis on FLUENT at Re=10,000 and Re=100000.

Table 4.6: Drag coefficient at Re=10,000 and Re=100000.

Zone name	Reynolds no Re	Total Drag Coefficient C_D
Tube	10,000	1.1709249
Tube	100000	1.4705883

4.4 Forced Vibration Analysis of Tube

In forced vibration of tube, drag force is calculated with the help of equation (4.1) by considering water fluid properties, forcing frequency obtained from FFT frequency plot, total time t=20 seconds, drag coefficient value obtained from CFD analysis. Forced vibration responses are plotted by incorporating all above data and responses with varying span lengths at constant applied force plotted as well.

When fluid flow past a circular pipe with sufficient velocity. Vortices are formed in the wake region, such vortices are referred as kármán vortices and shed in a regular pattern over a wide range of Reynolds numbers. The vortices shed alternately from opposite sides of the tube with a frequency *f*. This causes an alternating pressure on each side of the pipe, which acts as a ṡinusoidally varying force F perpendicular to the velocity of fluid before its flow is distributed. This force is given by [19]

$$F = \frac{C_D \, \rho \, v^2 \, A}{2} \times \sin(2\pi f t) \tag{4.1}$$

where;

C_D= Drag coefficient(dimensionless)

v = Fluid velocity (m/sec)

A = Projected area of pipe perpendicular to v (m^2)

ρ = Mass density of fluid (kg/m^3)

Below fig (4.14) & (4.15) depicts the FFT frequency spectrum using the lift data extracted from the CFD analysis. The frequency value highlighted in this spectrum is called Strouhal frequency(*f*).[20]

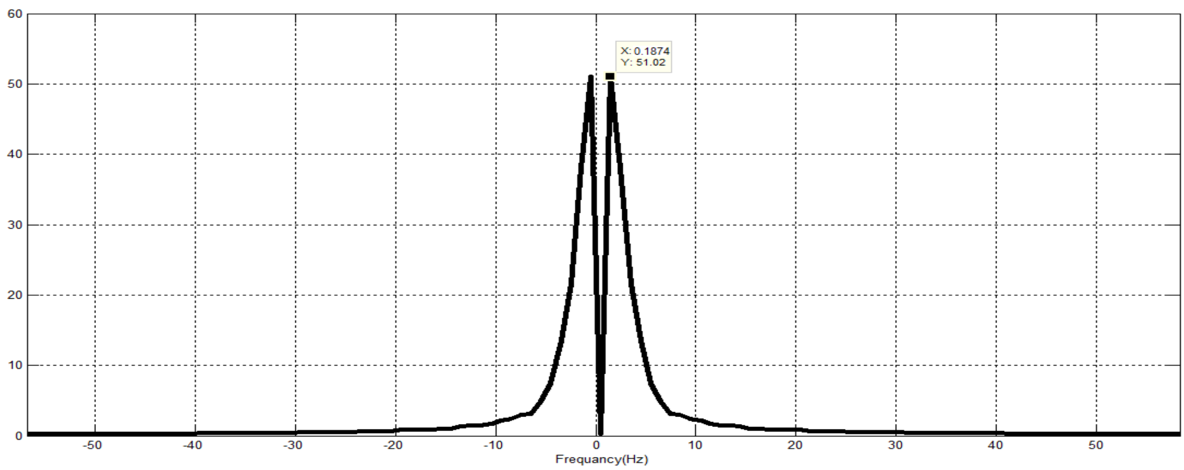

Figure 4.14: Frequency spectrum (Re=10000)

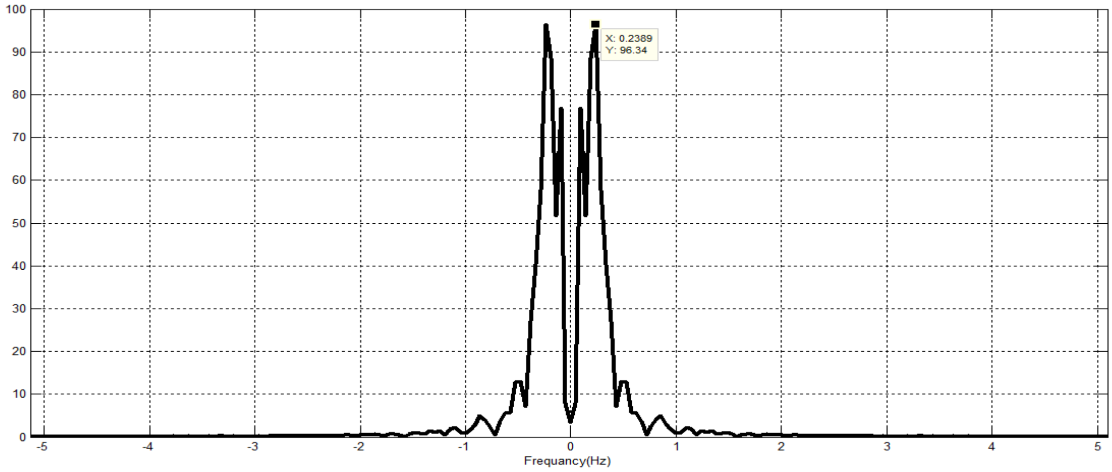

Figure 4.15: Frequency spectrum (Re=100000)

Force is calculated using the equation (4.1).Table (4.7) indicates the calculated values of force at different Reynolds number and time t=20 seconds.

Table 4.7: Harmonic force values at Re=10000 and Re=100000.

Reynolds no Re	Alternating Force (N)	Forcing Frequency ω_e(rad/sec)
10,000	5.8891	1.1768
100000	9.4258	1.5003

Figures below depicts the forced vibration response at constant Force value without varying span length as well as varying span length. Total length of the entire pipe is 1 meter with two intermediate supports. Here, there are three sets of span lengths considered:

First one: ℓ_1=0.3 meter, ℓ_2=0.4 meter, ℓ_3=0.3 meter,

Second one: ℓ_1=0.2 meter, ℓ_2=0.6 meter, ℓ_3=0.2 meter,

Third one: ℓ_1=0.4 meter, ℓ_2=0.2 meter, ℓ_3=0.4 meter.

Figures (4.16) & (4.17) shows the forced vibration response of tube with two intermediate supports and subjected to harmonic force at Re=10000 and Re=100000 using Equation (3.19) to (3.30).

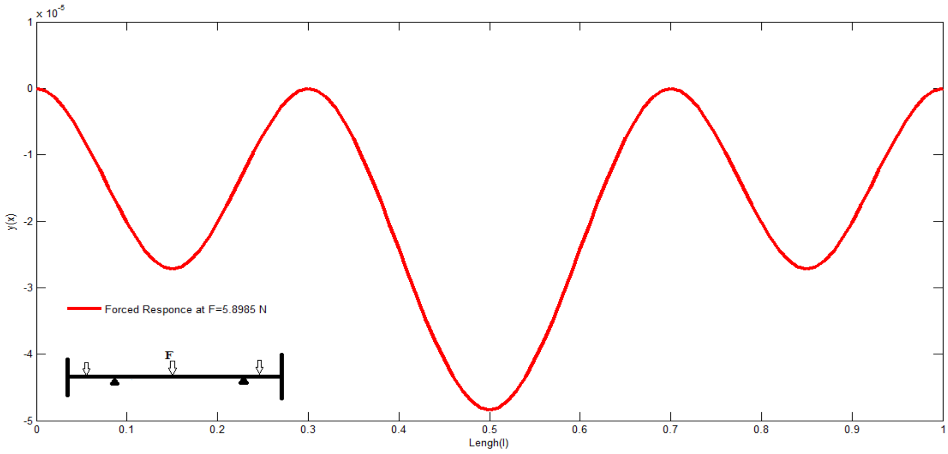

Figure 4.16: Forced vibration response of multi span tube (Re=10000)

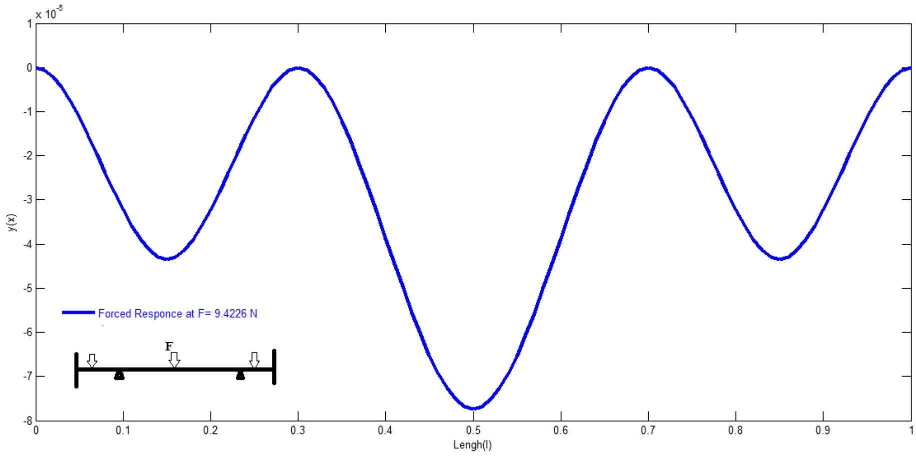

Figure 4.17: Forced vibration response of multi span tube (Re=100000)

Figures (4.18) & (4.19) shows the forced vibration response of tube with two intermediate supports and subjected to harmonic force with varying span length at Re=10000 and Re=100000.

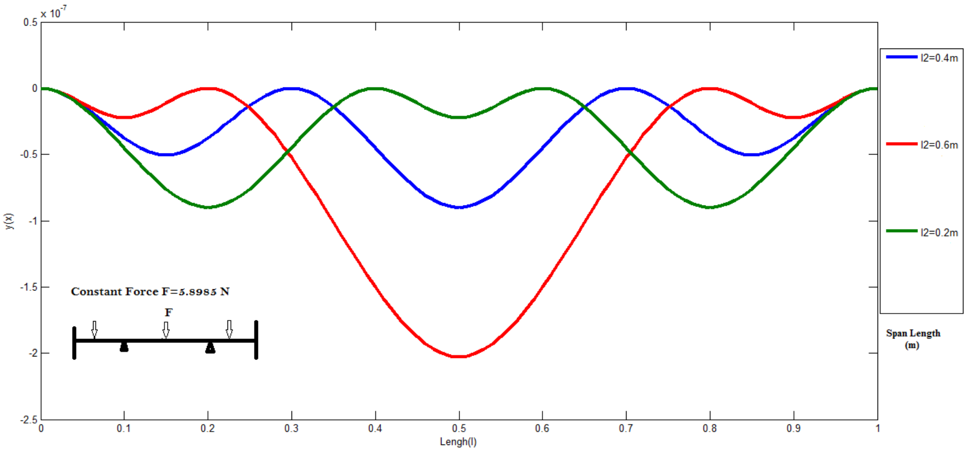

Figure 4.18: Forced vibration response of multi-span tube with varying span

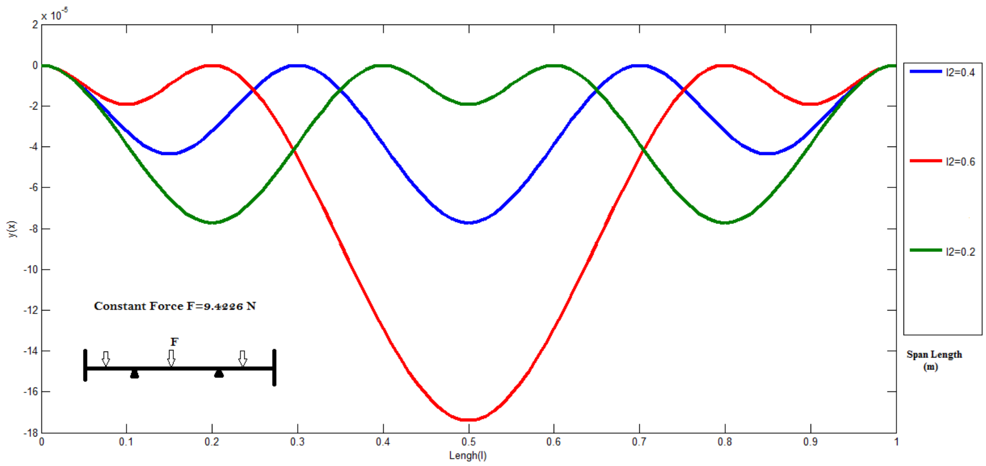

Figure 4.19: Forced vibration response of multi-span tube with varying span

Figures (4.20) & (4.21) shows the time dependent vibration behavior at predefined value of the displacement $w(x)$, which is obtained from the forced vibration analysis of multi span tube. Vibration pattern is studied for both values of applied forces by incorporating first natural frequency of tube.

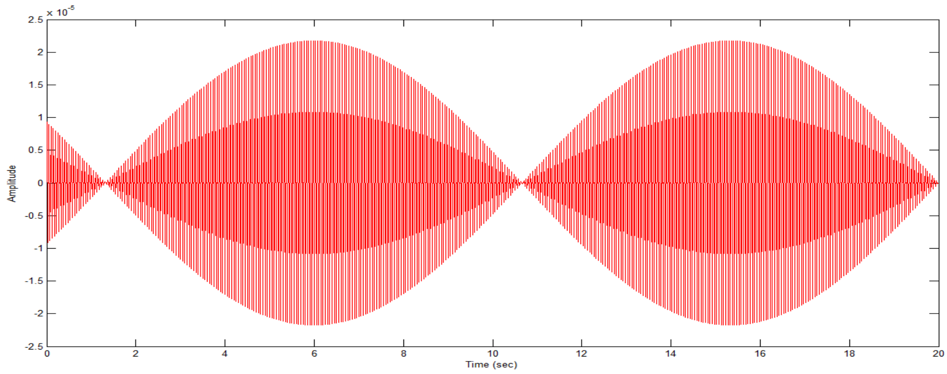

Figure 4.20: Time dependent vibration behavior at Re=10000

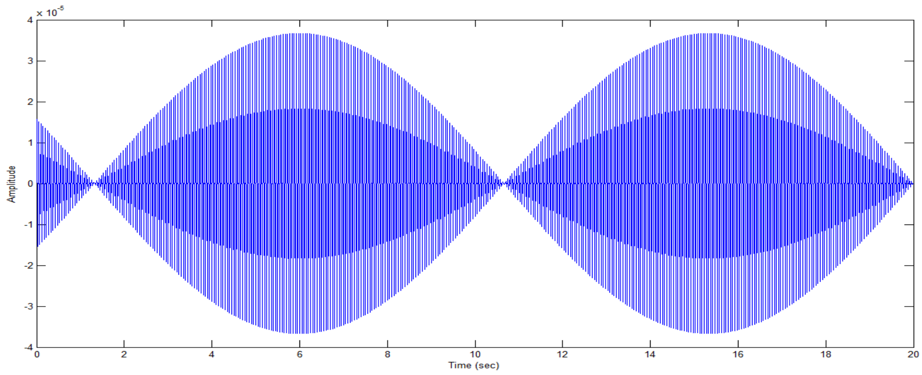

Figure 4.21: Time dependent vibration behavior at Re=100000

Chapter 5

Conclusion & Future Scope

Free vibration analysis of single span as well as for multi span tube is studied. Drag coefficient values obtained from the CFD analysis are very nearer to the standard values of drag coefficient. FFT frequency spectrum gives very adequate Strouhal frequency values for each of the considered Reynolds numbers.

In forced vibration analysis of multi-span tube, vibration pattern observed gives good idea about the vibration occurs due to the cross flow. It is also observed that the vibration response varies with varying span length. Time dependent response of the tube is studied at selected point.

Future Scope

- Experimental analysis approach can be used to validate the obtained results.
- Analysis of vibration due to two-phase flow can be done. Two phase flow is more complex phenomena.
- Tube vibration effects on other tubes in the tube bundle can be study.

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