Study of Fluid Induced Vibrations using Simulation Means and their Effects during Internal Flows

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Abstract - *The discharge pipe line is one of the important devices for cutter suction dredgers, while the pipes connecting to cutter, pump and valves guarantee the high dredging and transportation efficiency. The flow mixed with water and soil with different density is highly turbulent and unsteady, which induces vibrations along the pipe and also cause abrasion inside the pipe especially at bends and T branches. The flow exciting force induce the pipe stress and deformation while the pipe deformation will influence the flow pattern. Due to the large diameter of discharge pipe and lots of bends and T branches, the fluid structure interaction (FSI) should be introduced for pipe dynamic analysis and supporter design. The uncertainty of the mixed flow makes it not possible to design or test all the working conditions. Therefore, the CFD technique has been employed for numerical analysis. The typical pipe lines and their supporters with specified exciting source are investigated. Modal analysis and stress results give proof for optimal supporter design and pipe line. [3]*

The study presents methodology for analysis of piping vibration state. The acoustic resonance of medium (steam or water) is considered as most probable source of flow-induced vibration. The amplitude-frequency and phase-frequency characteristics of the gas-dynamic forces acting upon the piping discontinuities (bends, tees, branches etc.) are defined. [12]

1. INTRODUCTION

In recent years, two-phase flow induced vibration (FIV) has been given increasing attention in various engineering fields including petroleum pipelines, power and processing plants, heat exchangers, as well as in the nuclear power plant components. In these applications, knowledge of gas liquid two-phase flow induced force fluctuation magnitudes and its predominant frequency is paramount for designing the safely operable engineering systems and avoiding structural damage that may be caused by fluid solid interaction.

Transmission pipelines are the key arteries of the oil and gas business. They operate continuously on 24/7 bases to deliver the product. Industrial pipe systems are generally used in many arenas like hydropower power plants, transportation of the gas and oil, urban water supply and nuclear industry. Pipe systems facing the dynamic forces during coupling impact in between internal fluids and structure caused the pipe vibration and in certain cases rupture. internal two-phase flow through the production pipes is an example of the FSI in which; the fluid pressures are transferred to the pipe wall and inversely the structural deformation represented by the displacement is transferred back to the fluid domain Overall, the most complicated phenomenon among all the internal two-phase flows in a pipeline is the slug flow. The major reason being it's associated local fluctuations of phase, i.e. intrinsically unstable. Apart from phase, there are other parameters such as: pressure, density, velocity, momentum flux as well as other hydrodynamic parameters. With such fluctuations, resonance could be generated as a result of the closeness between piping natural frequency, and the excitation force frequency. As a result of such observation, performance of a designed system could be greatly hampered or in most cases destroy the system structure. To design safe and reliable piping systems free from excessive vibrations, piping designer needs to know the frequencies of excitation forces in the piping and must be able to calculate the natural frequencies of the pipeline system. Operating such pipelines at comparatively low flow rates and pressure could lead to the occurrence of long slugs. With the advent of such long slugs, serious operational problems could be encountered as a result of strong fluctuations in pressure or the flow supply. Vibration in a piping system is a complex phenomenon not well understood by many pipework designers. Currently, there are no standards and just a few guidelines to assist in determining which systems might be at risk. However, there are limited studies on the vibration characteristics which are induced by unsteady two-phase flow. [16]

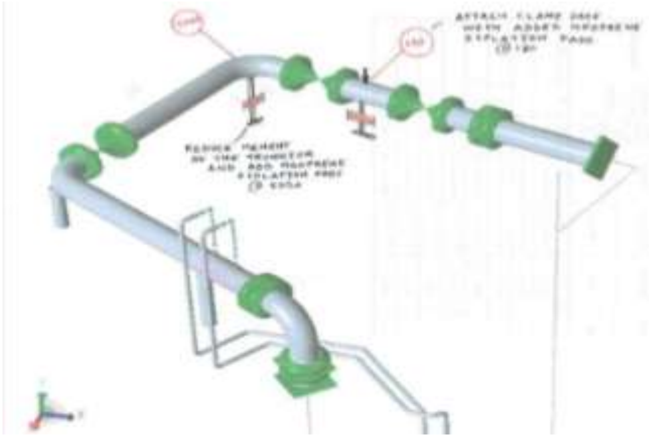


Figure 1.1 shows a typical piping system with supports. [15]

The terminology, "FIV", was first introduced by Robert Blevins in 1977. He was the first to classify the phenomena according to hydrodynamic and structural dynamics, and has developed a fundamental road map to analyze the problem. Based on his classification, fluid dynamic mechanisms responsible for FIVs are categorized according to steady and unsteady conditions. The categories of FIV phenomena are coupled with structural dynamics through hydrodynamic force acting on the structure. When the hydrodynamic force is acted on the structure surface, it will undergo deformation. The deformed structure will then react and apply the opposite force against fluid based on its material properties, such as elasticity, natural frequency, damping parameters, and so on. During the process, flow is disturbed and direction and magnitude of the hydrodynamic force may change considerably. Consequently, FIV is generated due to the linkage of force fluctuations between these two dynamic forces. In order to predict FIV phenomena, separate models for fluid and structural dynamics can be developed, and they are coupled with hydrodynamic and structural force terms. Models available for structural dynamics are near-linear for most cases and can be modeled as linear-oscillator. [23]

In chemical and oil industries, pipe is very important for the flow of gas or oil through the pipe line if u observed in any home or office, water connection of the pipe line of motor to water tank. We can see easily the pipe joints with different joints type. The vibration is the most important for the design of the pipe line joints in every industry. In this study we design the pipes using the solid works software and analysis in the Ansys software for the study of the vibration behavior. [14]

Hydraulic induced vibration starts with a continuous flow disturbance that creates a periodic pressure pulse and changes in direction (elbow, tee, bend) or changes in flow cross section (valve, orifice, reducer) this pressure pulse causes pulsating forces on the pipe and makes it vibrate the complexity of the vibro-acoustic behavior of flexible, fluid-filled pipe systems is predominantly determined by two parameters, the frequency and the ratio of the masses per unit pipe length of fluid and pipe wall. The number of simultaneously propagating waves in the pipes increases with frequency. The mass ratio determines whether fluid borne and structure-borne waves may be treated separately. If this ratio is close to one, fluid pulsations and mechanical vibrations will be strongly coupled, so that it becomes necessary to consider their interaction when analyzing the dynamic behavior therefore, it is vitally important that the evaluation of natural frequency of a pipe be accurately to prevent any resonance condition. There have been extensive studies on the modeling and analysis of fluid conveying pipes over the past half-century, as the pipe conveying fluid has established itself as a generic paradigm of a kaleidoscope of interesting dynamical behavior. The effect of internal flow on transverse vibration of a pipe was studied. Coriolis acceleration of the internal fluid was taken into account, the geometry of fluid conveying pipe systems is generally complicated. For these problems, analytical methods are not sufficient for the vibration analysis of real pipeline systems. Therefore, it is desirable to utilize numerical or approximately analytical methods such as finite element method. (FEM). [4]

Vibrations in hydraulic systems may be induced by fluid flows as well as mechanical sources of vibration. Components of hydraulic systems such as pumps, hydraulic engines and valves generate pulsation of fluid flow. On the other hand, vibrations in the system can be induced by unbalanced and misaligned rotating parts of the drive system as well as time variable forces and moments acting upon the hydraulic system components. Vibrations of hydraulic pipes can be caused by factors associated with fluid flow or due to mechanical excitations. Vibrating elements such as hydraulic pumps as well as vibration of the supporting structure can become the source of kinematic excitations. Vibration propagation is facilitated by a rigid connection between the frame, system components and interconnecting pipes and hoses. Furthermore, hydraulic lines are subjected to loads and vibrations caused by fluid flow. These include pulse loads resulting from valve operation (e.g. water hammer effect) as well as time varying forces resulting from pressure pulsation. [7]

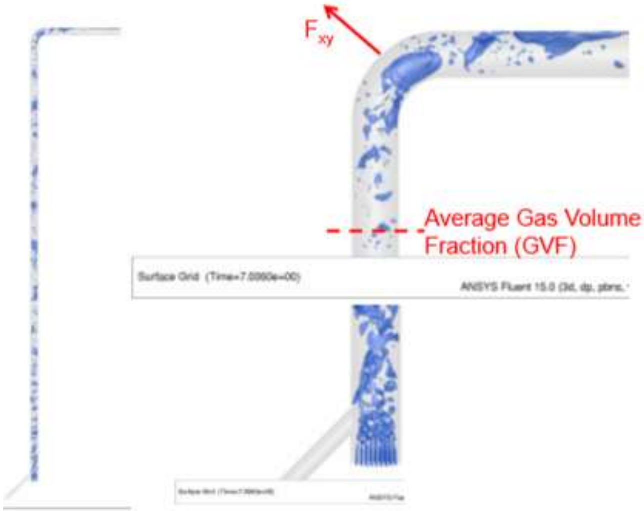


Figure 1.2 shows the multiphase flow pattern. [22]

Solid structures are often in contact with at least one fluid. Therefore, the motion of the fluid and that of the solid are not independent from each other but constrained by a few kinematical and dynamical conditions which model the contact. As a corollary, the fluid and the structure, considered as a whole, behave as a dynamically coupled system. The system could be splitted into fluctuating and permanent motion components, when there is no permanent motion or absence of any permanent flow, the fluid-structure coupled system is always dynamically stable and called fluid-structure interaction (FSI). Whereas incase permanent flow exists and various dynamical instabilities can occur which may have disastrous consequences on the mechanical integrity of the vibrating structures and referred as flow induced vibration problems. This distinction is extremely useful, as it has profound implications concerning the physical behavior and mathematical modeling of the coupled system. Practical relevance of fluid-structure interaction to engineering is nowadays asserted by a host of problems which are currently addressed to design structural components against excessive vibrations and noise in most industrial fields. It is also convincing that fluid structure interaction problems are fascinating and challenging which makes the study very appealing. [20]

3. Literature survey

Shaik Imran Behmad, Ashwani Kumar, Pravin P. Patil on "Vibration characterization of different pipe joint using finite element method (Ansys)" [1] has considered Finite element analysis as a computer modelling approach has provided engineers with a versatile design tool, especially when dynamic properties need to be perused. Modal analysis has become a major technology in the quest for determining, improving and optimizing dynamic characteristics of engineering structures. Not only has it been recognized in mechanical and chemical engineering but other engineering fields also. Study of the dynamic behavior of engineering structures is better appreciated, it becomes important to design them with proper consideration. The pipes design in solid edge software and imported into the Ansys software in the form of IGS file format and converting into discretization model (mesh). The meshing of the pipe contents the element and nodes.

K. Hirota, Vibrations induced by internal flow [2] have investigated studied two-phase flow regimes gas liquid two-phase flow in piping has various flow patterns, corresponding to different conditions, different flow rates, physical properties, etc. Piping vibration due to gas liquid two-phase flow has characteristic excitation forces corresponding to these flow patterns. The flow patterns are classified as follows:

A) Bubbly flow: mainly liquid flow with dispersed bubbles; the gas flow rate is very low and the flow-induced forces are small.

B) Plug flow and slug flow: large bubbles move in the piping intermittently in the case of plug flow. For slug flow, large bubbles, having the shape of artillery shells that almost fill the pipe, and liquid slugs flow alternately. Two-phase flow turbulence is low for both flow patterns. When a liquid slug, which has a high density, passes through the elbow portion of the piping, excitation forces are generated. These forces can cause piping vibration.

C) Froth flow: liquid slugs contain many bubbles in the case of froth flow. The shape of the gas bubble is distorted and the flow is highly turbulent. Flow-induced forces are also large because of the high turbulence.

D) Mist flow: the main flow is gas flow. Liquid droplets flow in the piping like mist. This flow is basically the opposite of bubbly flow. Flow-induced forces are therefore small.

E) Annular flow: this flow consists of liquid film flow adhering to the inner wall of the piping, and gas flow in the center of the piping. The liquid film flow is not completely stable. Piping vibration sometimes occurs due to turbulence in the liquid film flow.

F) Stratified flow and wavy flow: gas liquid two-phase flow is stratified into the upper side gas and the lower side liquid in the case of horizontal piping. If the interfacial surface of gas and liquid is not wavy, the flow is called a stratified flow. If the interfacial surface is wavy, it's called a wavy flow.

J.j. Liu, ding yu, and long yu, [3] research on pipe vibration analysis and optimal supporter arrangement have the followings results as per support systems provided at different areas

1. When the angle of the bend increases, the max stress and strain of the structure will also increase. The stress and strain will be more sensitive to the angle change. Large angle of the corner should be avoided so that the structure would not be damaged.

2. When the distance between the guide brackets and the fixed ends increases (the guides bracket become closer to the corner), the max stress and strain of the structure decreases. As a result, it would be safer for the pipeline structure. So, it's a good choice to shorten the distance between the guide brackets and the corners to decrease the stress and strain to ensure the safety of the pipeline structure.

3. When the distance between the guide brackets and the fixed ends increases (the guides brackets become closer to the corner), the vibration frequency of each modal also increases. When the frequency of external excitation is close to the resonance area, it's a good idea to adjust the position of the brackets to change the natural frequency to avoid resonance.

M. Dahmane, D. Boutchicha, L. Adjlout, one-way fluid structure interaction of pipe under flow with different boundary conditions [4] have presented study of pipes vibration, hydrodynamic structures, through analytical and numerical approaches. A tool is used to intend the calculation of natural frequencies and visualize the flow in the pipe system filled on fluid. At first time, the hydrodynamic problem is treated by analyzing the first two natural modes of particular cases. Several examples were processed to determine the influence of the fluid velocity and different geometrical and physical parameters on the phenomenon of fluid-structure interaction. The main findings can be summarized as follows:

1. The first conclusion which one can draw from this study is that the frequencies of the system fluid-structure depend on the geometrical and physical properties.

2. The natural frequencies of the pipe conveying fluid depend on the velocity of the fluid. At a certain critical velocity, the first natural frequency decreases until vanishes, the natural frequencies of this case can be obtained analytically.

3. The increase in the β (mass ratios) increased the value of the added mass to the system and therefore decreases the frequency parameter.

4. The results obtained numerically are similar to those obtained by the analytical approach for the determination of the natural frequencies. A global error on the first frequency of the order 1.15% is very satisfactory.

5. After the numerical validation, we can study the one-way fluid solid interaction of pipe under flow with different physical and geometrical parameters.

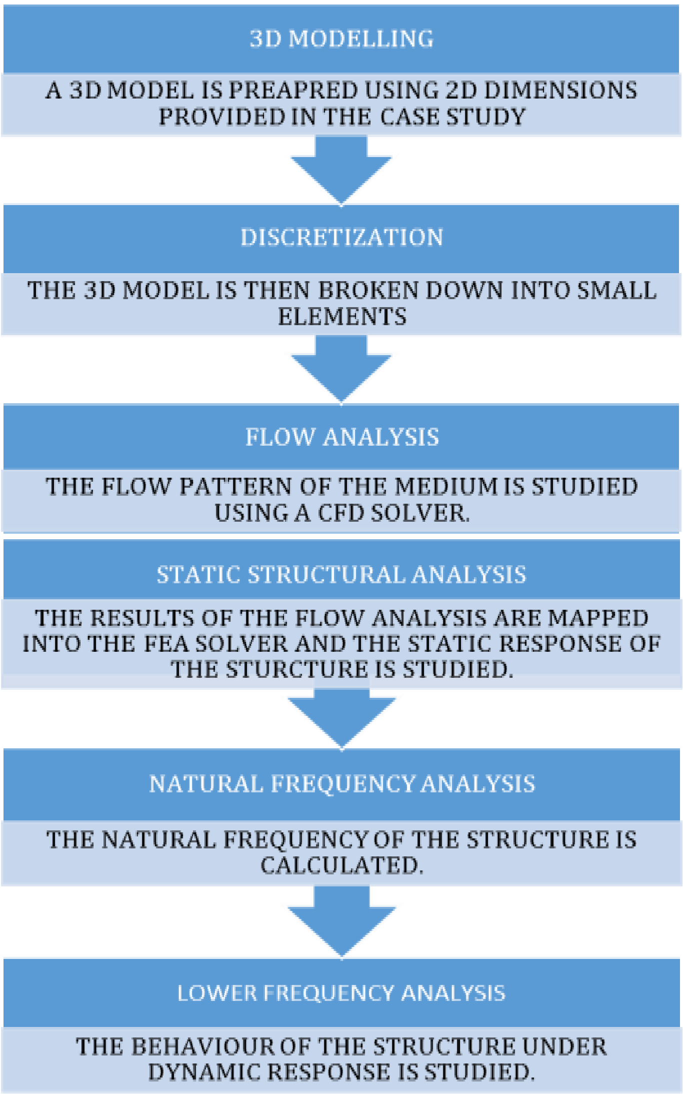
Zahid I. Al-hashimy, Hussain h. Al-kayiem and rune w. Time [16], “experimental investigation on the vibration induced by slug flow in horizontal pipe”, have conducted experiment on the effect of slug flow on vibration characteristics in horizontal circular transparent pipe The vibration response of the pipe appears highly dependent on water superficial velocities. For a given air superficial velocity, the vibration displacement increases when water superficial velocity increases. On the other hand, the average of maximum displacements increased by 64% when the water superficial velocity increased from 0.65 m/s to 1.0 m/s. The vibration frequencies generally decreased with increasing water superficial velocities. Where, the average of the maximum frequencies decreases by 9% when the water superficial velocity increased from 0.65 m/s to 1.0 m/s.

Kamalakar G. wagh, Prof. Dr. M. Saha,[17] Design and analysis of piping system for optimization of pipe wall thickness’, has investigated stresses in pipe or piping systems generated due to various loads experienced by the system. These loads are generated in pipe system which is sustained by pipes are supported, piping systems static properties such as own weight or simple transmitted loads. From this research it is concluded that standard pipe thickness & allowable pressure for the piping system is much greater than the required fluid pressure & fluid flow for given piping system. Therefore, for the larger project piping system it should beneficial to manufacture pipe spool with such reduced thickness. Also, it is observed that finite element analysis gives better results than manual calculation so it is better to do pipe stress analysis for given piping system for the larger project with reduced thickness.

A.sivanagaraju, S Krugon, Dr M Venhateswarrarao, Stress analysis of process pipe line systems, [18] have presented the experimental results. These results confirm the prior design and analysis of a Process Plant Piping System using CAESER. This CAD package provides a systematic and efficient methodology for designing and analysis with far less effort. Compare the SIF results against the results obtained with CAESER which are documented in table 2, by using some observations on SIF equations are found to be same. The colour coded SIF distributions are displayed in figure5 and the results are plotted in graph3. So, the analysis of a piping system using CAESER gives more accurate and precise results.

Ms. Prachi N. Tambe, Prof. Dr. K. K. Dhande, Flexibility and stress Analysis of piping system using CAESAR- ll – case study,[19] have focused on the analytical study of piping systems is done using the process piping code ASME B 31.3 and 3D software tool CAESAR II is used for piping system modeling and stress analysis purpose. The analytical and software output is observed. The flexibility analysis requirement for the piping system is checked analytically using the design code ASME B 31.3 and also the system is stress analyzed using CAESAR II software.

4. Methodology



3D MODELLING

A 3D MODEL IS PREAPRED USING 2D DIMENSIONS PROVIDED IN THE CASE STUDY

DISCRETIZATION

THE 3D MODEL IS THEN BROKEN DOWN INTO SMALL ELEMENTS

FLOW ANALYSIS

THE FLOW PATTERN OF THE MEDIUM IS STUDIED USING A CFD SOLVER.

STATIC STRUCTURAL ANALYSIS

THE RESULTS OF THE FLOW ANALYSIS ARE MAPPED INTO THE FEA SOLVER AND THE STATIC RESPONSE OF THE STURCTURE IS STUDIED.

NATURAL FREQUENCY ANALYSIS

THE NATURAL FREQUENCY OF THE STRUCTURE IS CALCULATED.

LOWER FREQUENCY ANALYSIS

THE BEHAVIOUR OF THE STRUCTURE UNDER DYNAMIC RESPONSE IS STUDIED.

The geometry is prepared in solid works. Geometry is made up of two different parts. The first part being the fluid domain and the later part is the solid pipe material. The geometry is meshed using tetrahedral elements as they are most suitable for flow analysis due to the element structure. The model is first solved in Fluent solver and the results are then mapped into the FEA solver. The CFD solver uses naviers stroke equation to solver the pressure induced on the pipe walls.

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right]$$

Figure 4.1 shows the Naviers stoke equation [13]

Where, ui, uj are velocity components, ρ is air density, P is air pressure, μ is dynamic viscosity, and t is time. In this equation.

The FEA solver is based on FEM method and uses the following stiffness matrix formulation to calculate the displacements.

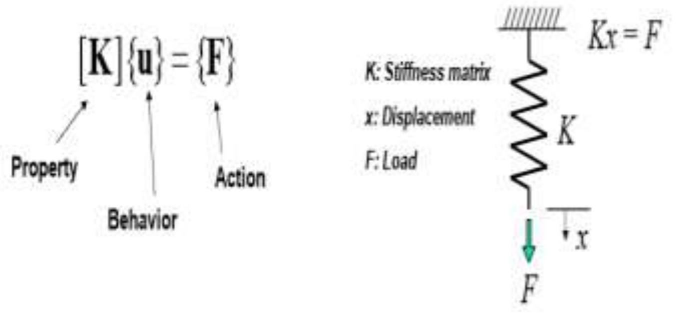


Figure 4.2 shows the Stiffness matrix equation [13]

Table 4.1 shows the material properties of fluid.

Material	Stainless steel
Density	7850 Kg/m3
Poisson's ratio	0.3
Youngs modulus	200 Mpa
Tensile yield strength	250Mpa
Tensile ultimate yield	460 Mpa
Material	Water
Density	997 Kg/m3
Viscosity	0.001 Kg/ m-s
Material	Air
Density	1.225 Kg/m3
Viscosity	1.79 x 10-5 Kg/ m-s

4.1 Comparing mechanical calculations versus simulation results

Calculations

Let us consider a hollow pipe with water inside for comparing mathematical calculations and simulation results. Following are the dimensions and calculations.

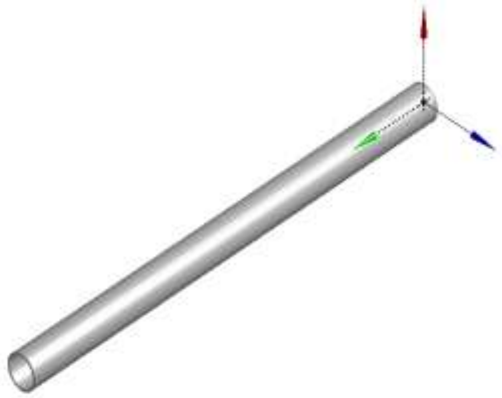


Figure 4.1.1 shows sample geometry

Outer diameter of pipe D = 200 mm
Inner diameter of pipe d = 180 mm
Length of pipe L = 3000mm
Total weight acting P = Total weight of pipe and water
Weight of pipe = volume X density [16]
Volume of pipe (V) = V1 – V2
V1 = π/4 d^2 X L
= 0.094 m^3
V2 = π/4 d^2 X L
= 0.076 m^3
V = 0.018m^3

Density of Pipe = 7850 kg/m^3
Weight of pipe = 7850 x 0.018
= 140.5 Kg
Weight of water = volume X density
Volume of water V3 = π/4 d^2 x L
= π/4 x 0.18 x 3
= 0.076m^3
Density of water = 997 Kg/m^3
Weight of water = 0.076 X 997
= 746.65 N
= 0.25N/mm^2
Total weight = wt. of pipe + wt. of water
= 140.5 + 75
= 215.5 Kg.
= 2114.055 N
= 0.7 N/mm^2

Young's modules E = 2 X 105 MPA (N/mm^2)
Center distance C = 100
Moment of inertia I = (π/64) X (OD^4 – ID^4)
= 2.7 X 10 ^7 mm4

Section modulus $Z = (\pi/32\ OD) \times (OD^4 - ID^4)$
$= 2.7 \times 10^5\ mm^3$

Stresses at center of pipe $= PL2/8Z$ [17]
$= 0.25 \times 3000^2 / 8 \times 2.7 \times 10^5$
$= 1.02$ Mpa

Natural frequency
$Wn = \sqrt{k/m}$
$Wn = K2\ \sqrt{EI/pAL^4}$
$W1 = k^2\ \sqrt{E1/pAL^4}$

Where,
K = constant = βL = 4.7 for fixed on both sides
E = 200 MPA
$I = \ = 2.7 \times 10^7$ mm4
p = 7850 Kg/m3
$A = (\pi/4) \times (OD2 - ID2)$
$= 5.97 \times 103\ m^2$
L = 0.3 m

$W_1 = 822$ rad/s
Frequency (Hz) = $W1/2\pi$
= 130Hz

Simulation-
Mesh

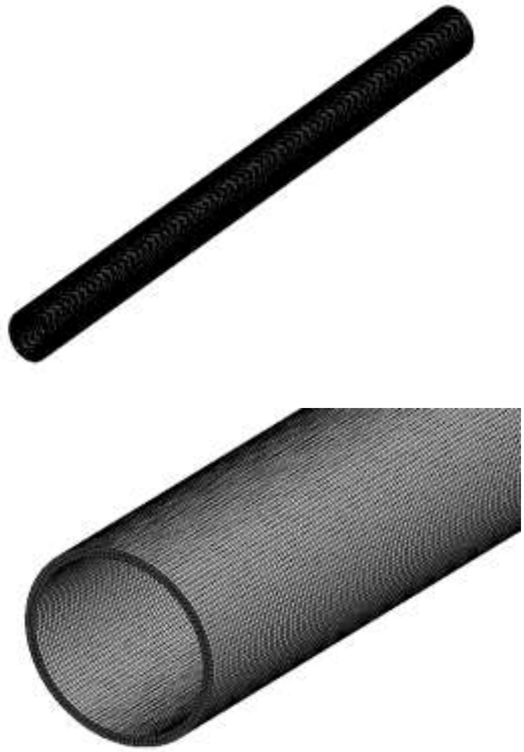


Figure 4.1.2. Shows mesh image of pipe

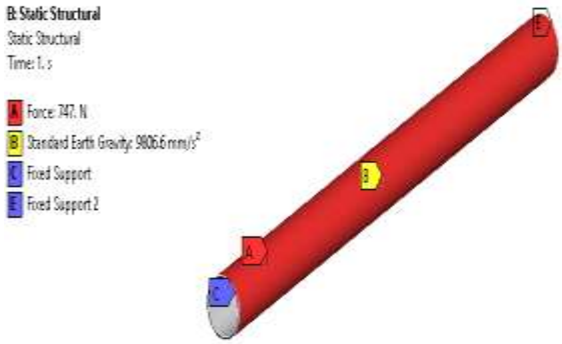


Figure 4.1.3. Shows boundary conditions applied to pipe

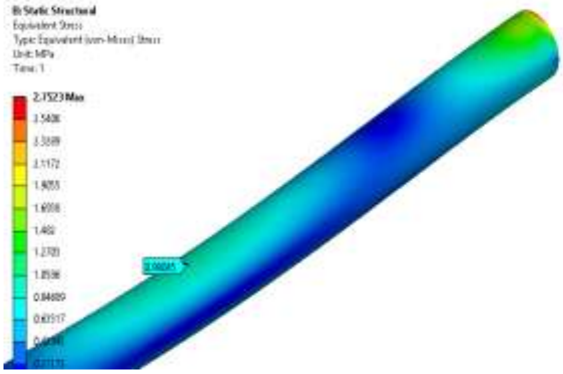


Figure 4.1.4 shows stress plot in pipe

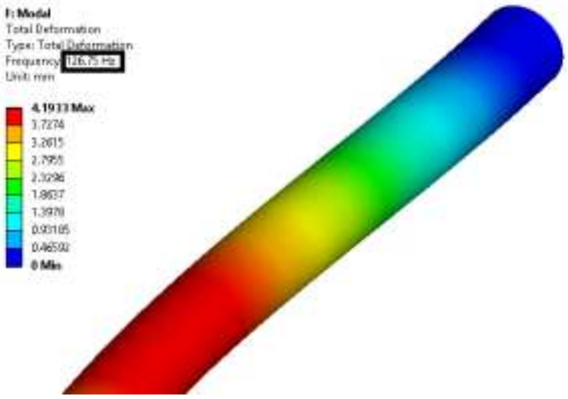


Figure 4.1.5 shows first natural frequency of sample case

Comparison table

	Hand calculations In MPA	Simulation Results in MPA	Percentage error (%)
Stress at center	1.02	0.985	3.5
First natural frequency	130	126.75	3.25

5. Analysis

In the above study, we have taken a small component and compared hand calculations and simulation results. The results match with 3.5 % marginal error and thus we can use simulation techniques to solve such type of problem statements. Mechanical calculations are easy when the geometry is small dimensionally but when the component is huge or complex such simulation methods ease the work.

Piping systems can be lengthy. It can be of different cross-section also. In such cases, the system is broken down into small units and considered as beam elements. Also if the system has bends within its length, lagrangian formulation is applied to calculate the reaction forces due to flow. Thus in such complex system simulation techniques can be used to formulate the results. The simulation matrix uses a finite element method to calculate the result. The domain is divided into small elements and all together they form a stiffness matrix which helps to compute the problem. Also ansys also provides the ease of mapping the results from cfd solver to fea solver.

In further study we have taken a pipe system, 4.5 m in length with four bends. We have assumed two cases for the problem. In first case we have assumed a single phase flow of water and in the second case we have two phases, water and air. Thus introduction of air leads to unbalanced internal forces which induced vibrations in the system.

5.1 Geometry

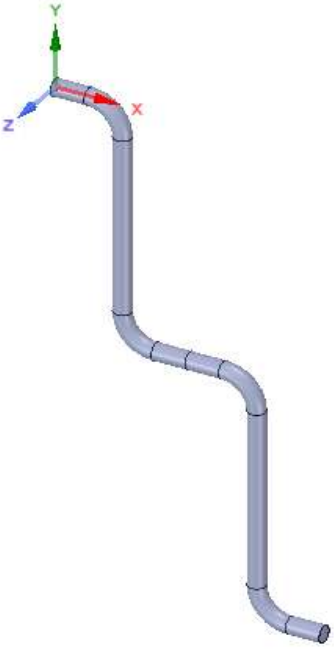


Figure 5.1 shows the 3D model of component

5.2 Mesh

Figure 5.2 shows mesh model of componet

Tetrahedral Mesh

Almost all geometries of industrial applications contain one or several domains that are just not practical to sweep. These domains must then be covered by a tetrahedral mesh. The Free Tetrahedral operation builds surface meshes on unmeshed faces before it builds volume meshes. The surface mesh must conform to geometry boundaries, but the Surface Mesh nodes can be moved around within the faces during element quality optimization. Faces that are already meshed, however, remain frozen and can therefore result in a lower element quality.

A tetrahedron only has triangular sides, so something is needed to transition from faces with quadrilateral elements. This "something" is the pyramid. A pyramid element is formally a hexahedral element where one of the element faces is collapsed into a point, leaving an element with one quadrilateral face and four triangular faces. The domain has 99810 elements and 21435 nodes.

5.3 Case one- Turbulent single phase

For the first case we have water as single phase flow medium. Gravitational effects are taken into consideration. The flow is assumed to be turbulent as per the shape of the component and a basic K- epsilon turbulent model is considered.

The fluid domain as one inlet and one outlet and inlet velocity of water is considered as 1m/s. The component is fixed for the inlet and outlet sides. Pressure load for CFD solver is taken as imported load

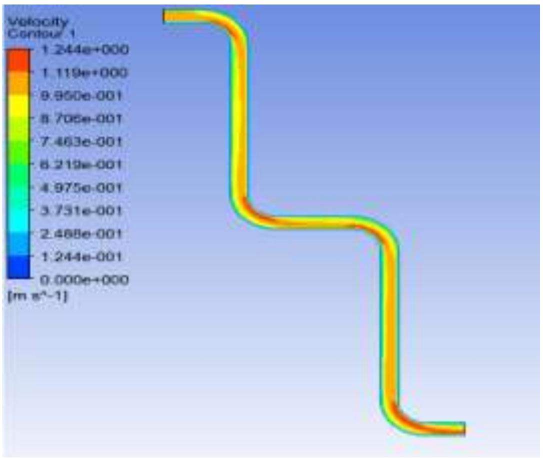


Figure 5.3.1 shows velocity profile of single phase turbulent flow

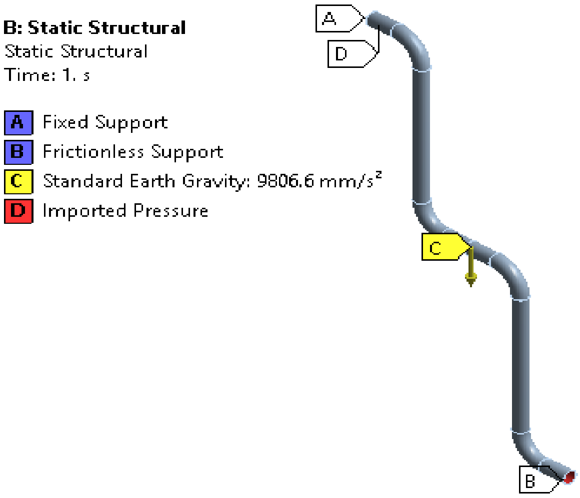


Figure 5.3.2 shows the boundary condition of FEA solver

5.3.1 Stress & deflection due to turbulent flow

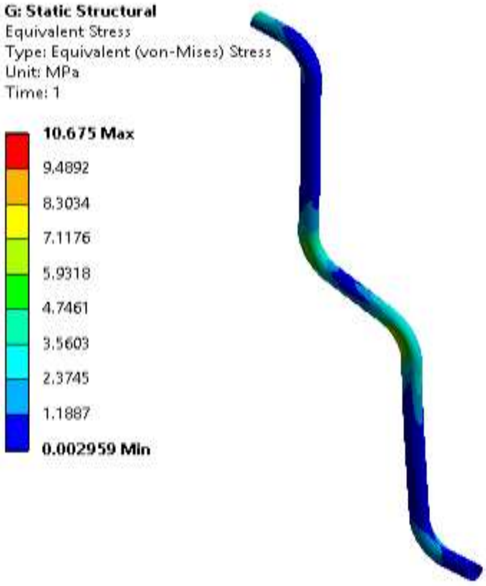


Figure 5.3.3 shows stress plot in single phase

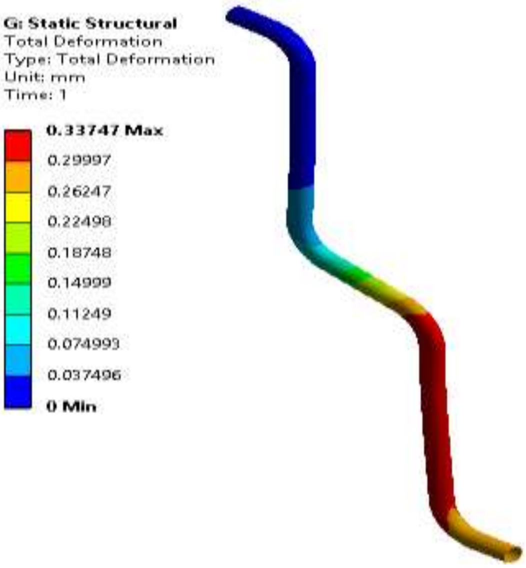
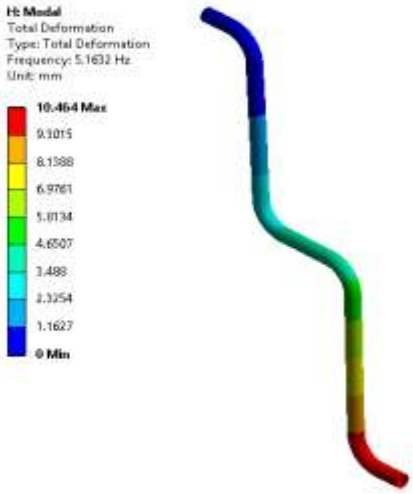
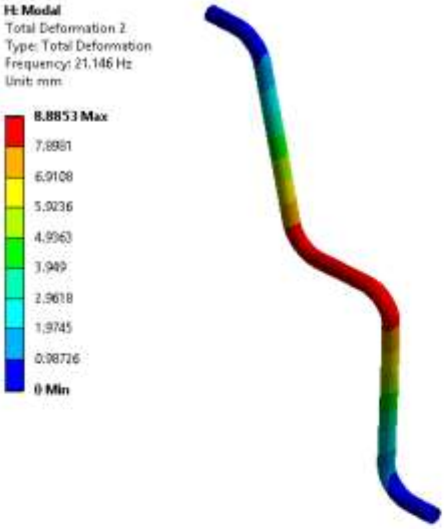


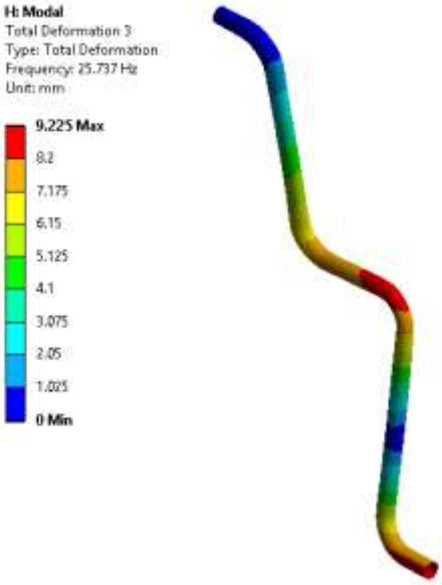
Figure 5.3.4 shows deflection plot in single

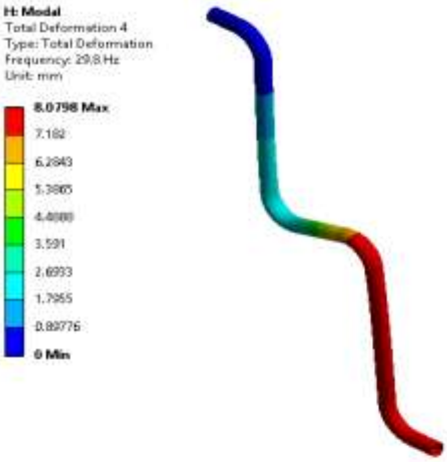
5.3.2 Mode shape results

Mode	Frequency in Hz		Deflection in mm
Mode 1	5.16		10
Mode 2	21.14		8.88
Mode 3	25.73		9.22
Mode 4	29.8		8
Mode 5	60.3		11









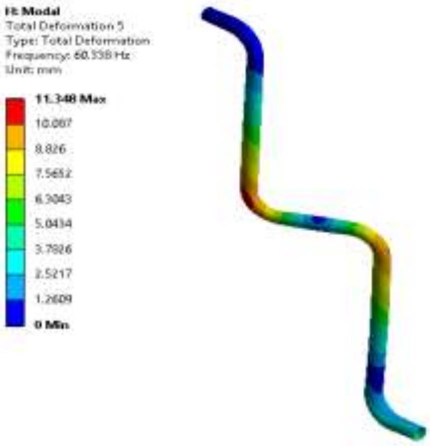


Figure 5.3.5 shows the modal values of the component

5.3.3 Harmonic analysis 0 – 30 Hz

Stress and deflection plot

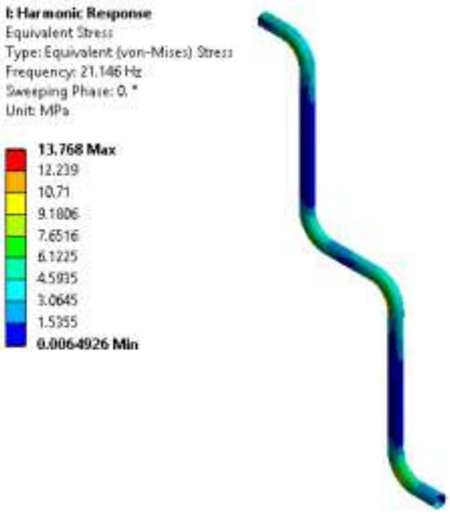


Figure 5.3.6 shows stress plot of harmonic single phase

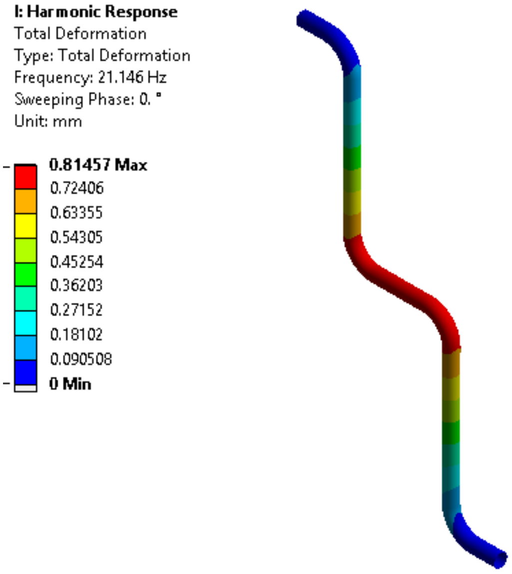


Figure 5.3.7 shows deflection plot of harmonic single phase

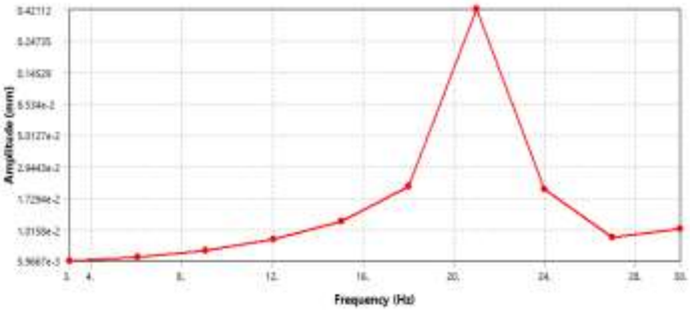
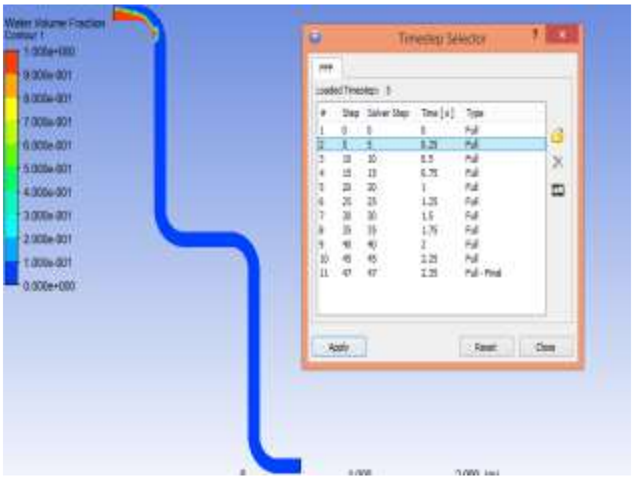
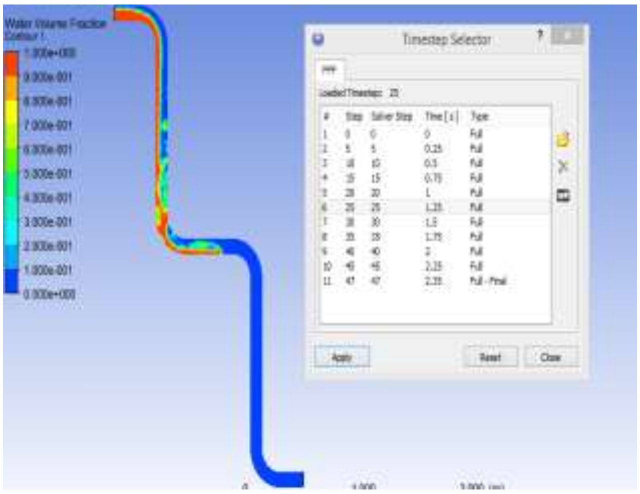


Figure 5.3.8 shows deflection of component in single phase

5.4 Case two - Multiphase analysis





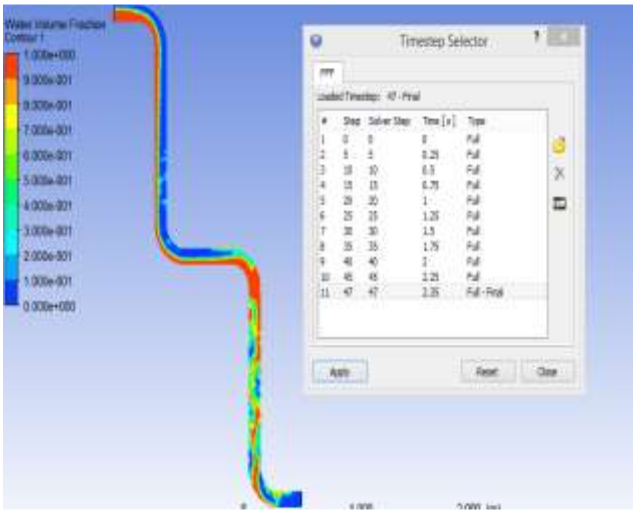


Figure5.4.1 shows different stages of multiphase flow.

5.4.1 Static stress and deflection plot of multiphase

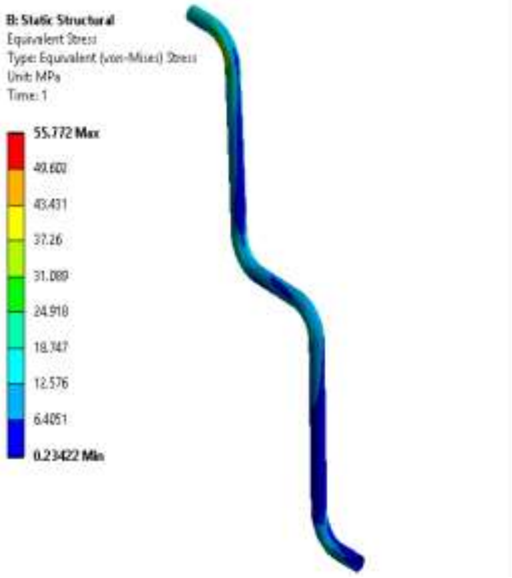


Figure 5.4.2 shows static stress plot for multiphase

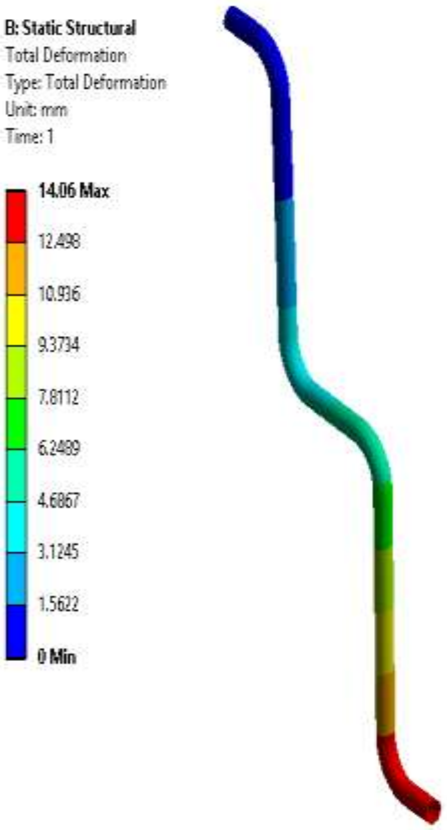


Figure 5.4.3 shows static deflection plot of multiphase

5.4.2 Harmonic analysis 0 – 30 Hz

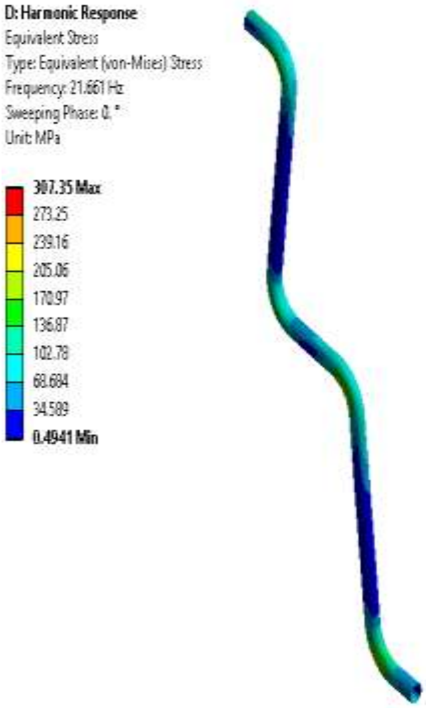


Figure 5.4.4 shows stress plot of harmonic multiphase phase

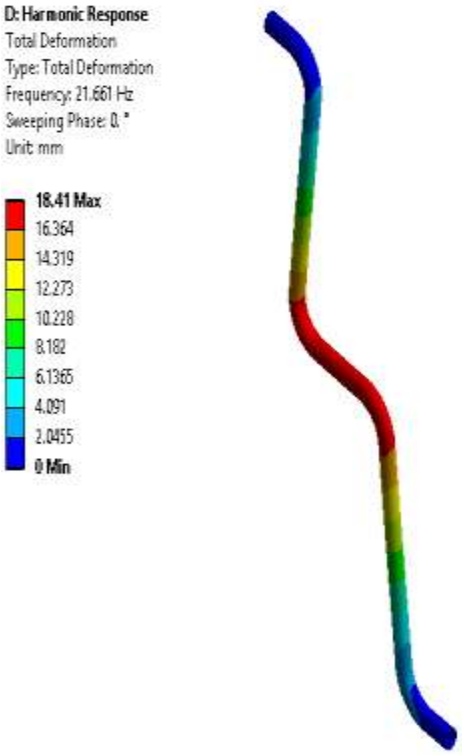


Figure 5.4.5 shows deflection plot of harmonic multiphase

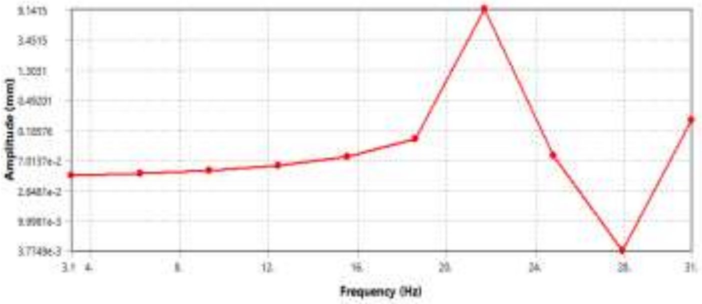


Figure 5.4.6 shows the deflection of component in multiphase

6. Conclusions

For this study, two different cases have been taken. One with turbulent flow and the other one is multiphase flow

Case 1 Turbulent flow single phase	Stress in Mpa	Deflection in mm
Static plot	10.67	0.33
Harmonic plot	13.7	0.81
Case 2 Multiphase flow		
Static plot	55	14.5
Harmonic plot	307.4	18.4

From the above study we can conclude that multiphase flow can produce huge deflection due to uneven pressure induced on the pipe wall. The stress in the pipe wall region are beyond the yield point region and may cause permanent deformation. This study concludes that air entering the system can damage it and proper support systems should be provided to reduce the vibrations.

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