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► **To cite this version:**

Imran Shaik, Shaik Riyaz Uddien, A Krishnaiah, Shankarachar Sutar. Numerical Analysis of Clamped Fluid Conveying Pipe. *Mechanics, Materials Science & Engineering Journal*, 2017, 10.2412/mmse.53.64.857 . hal-01966404

HAL Id: hal-01966404

<https://hal.science/hal-01966404>

Submitted on 28 Dec 2018

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Numerical Analysis of Clamped Fluid Conveying Pipe

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DOI 10.2412/mmse.53.64.857 provided by Seo4U.link

Keywords: clamped-clamped, Euler Bernoulli, fluid conveying pipe, weldment, ABAQUS.

ABSTRACT. This paper presents vibration analysis and mathematical model using Euler-Bernoulli and Hamilton's energy expressions for fluid conveying welded Galvanized Iron pipe with clamped-clamped boundary condition. A 3D CAD Model was developed in NX-ideas for empty pipe, pipe with fluid flow and welded pipe with fluid flow. Vibration analysis was performed on developed models for 3 mode shapes to generate frequency data using ABAQUS. The developed models were imported in to ABAQUS for generating frequency data. For the welded pipe, effects of weldment at girth welds on the vibration characteristics and stability of pipe was investigated. Results acquired from ABAQUS were compared with theoretical results of natural frequencies and observed the variation of 3% error.

Introduction. The fluid conveying pipes are widely used in many industrial applications such as chemical plants, fertilizer plants, nuclear plants and pharmaceutical industries etc. The pipes are subjected to different environmental conditions such as wind forces, earthquakes, and Coriolis forces of fluid flow. Over the last sixty years, extensive studies have been carried out on pipeline systems subject to different boundary conditions and loadings. These pipes however frequently transport fluids from initial point to destination. The subject of piping vibration has attracted a lot of attention from various researchers in recent times due to vast applications.

Avinash B. Kokare et.al [1], studied about vibrational characteristics of pipe conveying fluid and FE simulation to evaluate velocity and pressure distribution in a single phase fluid flow. Long Liu and Fuzhen Xuan [2], presented the flow induced vibration analysis of supported pipes conveying pulsating fluid using precise integration method. Gongfa Li et.al [3] investigated natural frequencies using Lagrangian interpolation function, the first order Hermite interpolation function and the Ritz method to obtain the element standard equation. Wentao Xiao et.al [4] studied finite element analysis of nonlinear vibration response using Lagrangian interpolation function, the first order Hermit interpolation function and the Ritz method to obtain the element standard equation, and then integrated a global matrix equation, obtained the response of conveying fluid pipe with the New mark method and Matlab. Muhsin J. Jweeg et al [5] dynamic Analysis of Pipes Conveying Fluid Using Analytical, Numerical and Experimental Verification with the Aid of Smart Materials and the results presented in this study compared with the results performed by using analytical solution for equation of motion and also, compared with the results performed by using ANSYS Software.

T.G. Ritto et.al [6] studied about dynamic stability of a pipe conveying fluid with an uncertain computational model. Ivan Grant [7] Presented on flow induced vibrations in pipes; a finite element approach methodology is used to determine the critical fluid flow velocity that induces the threshold of pipe instability. B. Mediano-Valiente et al. [8], discussed on stability analysis of a clamped-pinned pipeline conveying fluid by means of the eigenvalues of a Hamiltonian linear system associated. From this analysis, characteristic expressions dependent on material constants have been developed.

Nabeel. K. Abid et.al. [9] Investigated the stability of fluid conveying welded pipe is of practical importance because the welding induced residual stresses which effected on the vibration characteristic and stability of pipe. Singiresu S. Rao [10], Vibrations of Continuous Systems. Adekunle. O. Adelaja [11] investigated the nonlinear transverse vibration of a flexible pipe conveying hot pressurized fluid in pinned-pinned condition. M.P. Paidoussis and N.T. Issid [12] studied about dynamics and stability of flexible pipe containing flowing fluid, where flow velocity is entirely constant or with a small harmonic component superposed. L.G. Oslon and D. Janison [13] investigated motion of elastic pipes conveying fluid for various idealized cases.

Nomenclature.

| S No | Symbols | Description |
|------|----------------|--|
| 1 | ρ_p | Density of pipe in (kg/m ³) |
| 2 | ρ_f | Density of fluid in (kg/m ³) |
| 3 | U | Fluid velocity in (m/s) |
| 4 | E | Young's modulus in (N/m ²) |
| 5 | m_f | Fluid mass in (kg) |
| 6 | m_p | mass of the pipe in (kg) |
| 7 | W | Displacement component at any point in the cross section (m) |
| 8 | Dx | Small element of the pipe |
| 9 | $f(x,t)$ | External transverse force per unit area |
| 10 | $w(x, t)$ | Transverse deflection of pipe |
| 11 | $W_i(x, z, t)$ | I th normal mode shape of a pipe |
| 12 | Z | Axial strain in Z direction |
| 13 | U_i | I th mode of vibration |
| 14 | T | Weld Tension in N |
| 15 | K | Spring stiffness |

Modelling, Simulation and Analysis of fluid conveying pipe.

Firstly, mathematical model for clamped clamped boundary condition was developed and then fluid motion equation and natural frequency equations were also developed accordingly.

The model of fluid conveying pipe is done by using I-DEAS software and the analysis of the same is done by ABAQUS software which includes standard / CFD modules to analyze fluid structural interaction. Simulation of clamped-clamped pipe performed to get the frequencies of pipe without and with welding conditions.

The FE analysis was carried out to calculate vibration characteristics of a welded pipe conveying fluid with a velocity of 5m/s and boundary conditions using a general-purpose FE package ABAQUS/Standard V6.14. The approach is divided into five parts: thermal analysis, coupled field thermal-structure analysis, computational fluid dynamics (CFD), coupled field fluid-structure analysis, and modal analysis.

The coupled field fluid-structure analysis solved the equations for the fluid and solid domains independently of each other. It transfers fluid forces and solid displacements, velocities across the fluid-solid interface. The algorithm continues to loop through the solid and fluid analyses until

convergence is reached for the time step (or until the maximum number of stagger iterations is reached). Convergence in the stagger loop is based on the quantities being transferred at the fluid-solid interface.

The modal analysis was used to determine the vibration characteristics (natural frequencies and mode shapes) of a welded pipe conveying fluid. The natural frequencies and mode shapes are important parameters in the design of a structure for dynamic loading conditions. The procedure to do a pre-stressed modal analysis is essentially the same as a regular modal analysis, except that you first need to pre-stress the structure by doing a static analysis. Build the model and obtain a static solution with pre-stress effects turned on from thermal-structure and fluid-structure analyses

A non-linear transient thermal analysis was conducted first to obtain the global temperature history generated during and after welding process (at the weld region). The basis for thermal analysis is a heat balance equation obtained from the principle of conservation of energy. The FE thermal solution employed a nonlinear (material properties depend on temperature) transient thermal analysis using two modes of heat transfer: conduction, and convection, to determine temperatures distributions that vary over time. The applied loads at the region of weld are function of time which described by divided the load-versus-time curve into load steps. For each load step, its need to specify both load and time values, along with other load step options such as stepped or ramped loads, automatic time stepping, etc. It's then written each load step to a file and solves all load steps together.

Results and Discussion.

Mathematical model, simulation and different analyses were done for fluid conveying pipe. Different cases were also considered for analysis.

Mathematical model developed for fluid conveying pipe with fixed ends.

The Fig.1 shows the welded pipe conveying fluid, the welding is done at mid span of 1-inch Galvanized Iron pipe. Where E is young's modulus and I is moment of inertia of pipe and ρ is density of pipe material and L is length of the pipe.

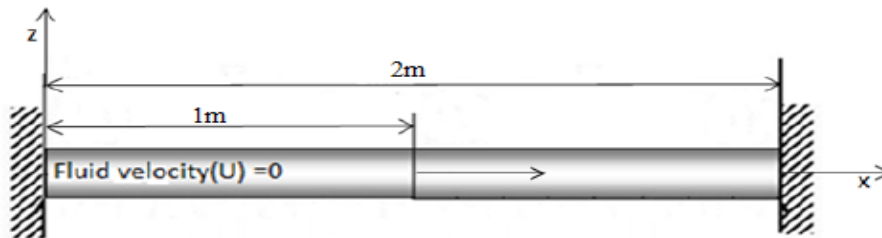


Fig. 1. Welded pipe conveying fluid with fixed ends.

The governing equation of motion of a fluid conveying welded pipe by using Euler-Bernoulli’s beam theory is given by:

$$EI \frac{\partial^4 w}{\partial x^4} + (m_p + m_f) \frac{\partial^2 w}{\partial t^2} + (m_f U^2 - T) \frac{\partial^2 w}{\partial x^2} + 2m_f u \frac{\partial^2 w}{\partial x \partial t} = 0 \tag{1}$$

Where the terms are as followed

$$EI \frac{\partial^4 w}{\partial x^4} = \text{Stiffness term}$$

$$\begin{aligned} (m_p + m_f) \frac{\partial^2 w}{\partial t^2} &= \text{Inertia term} \\ m_f U^2 \frac{\partial^2 w}{\partial x^2} &= \text{Curvature term} \\ 2m_f u \frac{\partial^2 w}{\partial x \partial t} &= \text{Coriolis force term} \\ T &= \text{Weld tension Term} \end{aligned}$$

The equation of fluid motion

The equation of motion of piping vibration is given below

$$EI \frac{\partial^4 w}{\partial x^4} + (m_p + m_f) \frac{\partial^2 w}{\partial t^2} + m_f U^2 \frac{\partial^2 w}{\partial x^2} = 0 \quad (2)$$

The Free vibration solution can be found using the method of separation of variables as

$$W = w(\xi) T(t) \quad (3)$$

Where $T(t)$ is a harmonic function $T(t) = e^{i\omega t}$

$$\frac{\partial^4 w}{\partial \xi^4} = T(t) \frac{\partial^4 w(\xi)}{\partial x^4}; \quad \frac{\partial^2 w}{\partial \xi^2} = T(t) \frac{\partial^2 w(\xi)}{\partial x^2}$$

Natural frequency equation for clamped-clamped pipe. In the present study, we use exact method to obtain the natural frequencies of fluid conveying pipe as given below:

$$W(x) = A \sinh(\alpha x) + B \cosh(\alpha x) + C \sin(\beta x) + D \cos(\beta x) \quad (4)$$

$$\frac{\partial w(x)}{\partial x} = A \alpha \cosh(\alpha x) + B \alpha \sinh(\alpha x) + C \beta \cos(\beta x) - D \beta \sin(\beta x) \quad (5)$$

$$\frac{\partial^2 w(x)}{\partial x^2} = A \alpha^2 \sinh(\alpha x) + B \alpha^2 \cosh(\alpha x) - C \beta^2 \sin(\beta x) - D \beta^2 \cos(\beta x) \quad (6)$$

$$\frac{\partial^3 w(x)}{\partial x^3} = A \alpha^3 \cosh(\alpha x) + B \alpha^3 \sinh(\alpha x) - C \beta^2 \cos(\beta x) + D \beta^2 \sin(\beta x) \quad (7)$$

Substituting in boundary condition, when $W=0$ at $x=0$

From equation (7)

$$W(x) = A\sinh(\alpha x) + B\cosh(\alpha x) + C\sin(\beta x) + D\cos(\beta x) \quad (8)$$

When $W=0$ at $x=0$

From equation (8)

$$W(x) = A\sinh(\alpha x) + B\cosh(\alpha x) + C\sin(\beta x) + D\cos(\beta x) \quad (9)$$

Substituting $x=0$

$$\alpha B + \beta D = 0$$

$$\frac{\partial W}{\partial x} = A\alpha\cosh(\alpha x) + B\alpha\sinh(\alpha x) + C\beta\cos(\beta x) - D\beta\sin(\beta x) \quad (10)$$

As $x=0$

$$\frac{\partial W}{\partial x} = A\alpha + \beta C \quad (11)$$

Now $W(x)=0$ at $x=1$

$$W(x) = A\sin(\alpha l) + B\cos(\alpha l) + C\sin(\beta l) + D\cos(\beta l)$$

Similarly,

$$\frac{\partial W}{\partial x} = \alpha A\cos(\alpha l) - \alpha B\sin(\alpha l) + \beta C\cos(\beta l) - \beta D\sin(\beta l)$$

From equations

We get

$$C_1 = \sin\alpha l, C_2 = \cos\alpha l, C_3 = \sin\beta l, C_4 = \cos\beta l$$

$$D_1 = \alpha\cos\alpha l, D_2 = -\alpha\sin\alpha l, D_3 = \beta\cos\beta l, D_4 = -\beta\sin\beta l$$

Stiffness matrix as follows

$$A = \begin{bmatrix} 0 & \alpha & 0 & \beta \\ \alpha & 0 & \beta & 0 \\ C_1 & C_2 & C_3 & C_4 \\ D_1 & D_2 & D_3 & D_4 \end{bmatrix}$$

By solving above stiffness matrix

$$A = \alpha^2 \beta \sin^2 \beta l + \alpha^2 \beta \cos^2 \beta l - \alpha \beta^2 \sinh \alpha l \sin \beta l - \alpha^2 \beta \cosh \alpha l \cos \beta l \quad (12)$$

Similarly,

$$B_1 = -\beta \begin{bmatrix} \alpha & 0 & \beta \\ C_1 & C_2 & C_3 \\ D_1 & D_2 & D_3 \end{bmatrix}$$

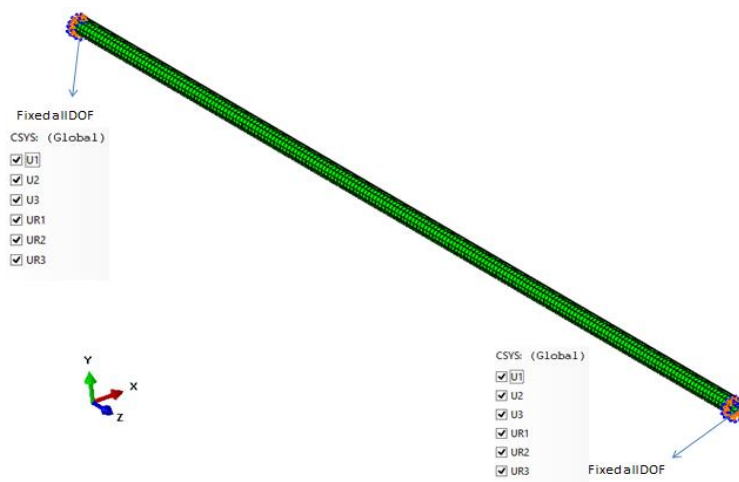
By solving above stiffness matrix

$$B_1 = -\alpha \beta^2 \cosh \alpha l \cos \beta l + \alpha^2 \beta \sin \beta l \sinh \alpha l - \alpha \beta^2 \sin^2 \alpha l + \alpha \beta^2 \cos^2 \alpha l \quad (13)$$

On combining and simplifying:

$$\cosh \alpha l \cos \alpha l = 1 \quad (14)$$

Simulation of clamped-clamped pipe. Fig. 2 (a) shows the finite element structural mesh model consists of 2266 elements and 2277 nodes with first order quadrilateral linear elements. Fig.2 (b) shows the finite element of fluid mesh model consists of 2400 elements and 3417 nodes with first order hexahedral fluid elements.



a)

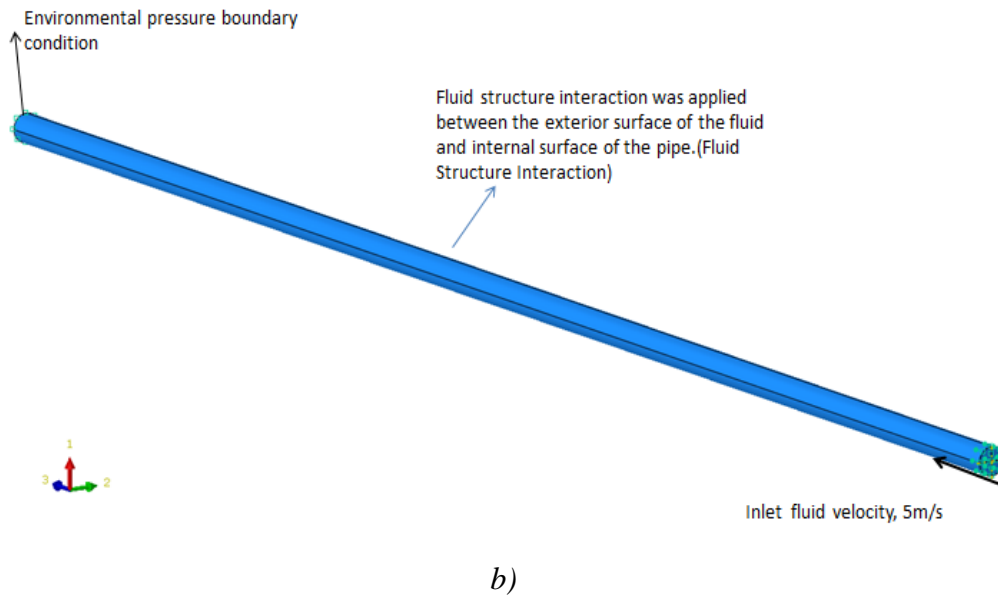


Fig. 2. (a) Finite element structural mesh model with boundary conditions, (b) finite element fluid mesh model with fixed ends.

Table 2. Material properties of GI pipe.

| | |
|----------------------------|-------------------------------|
| 1 Inch Pipe Span | 2 meters (welded at mid span) |
| Pipe Material | Galvanised Iron |
| Pipe Outer Diameter (OD) | 0.034m |
| Pipe Inner Diameter (ID) | 0.0304m |
| Pipe Wall Thickness (t) | 0.00178m |
| Density of Steel | 7850 kg/m ³ |
| Young's modulus (E) | 200 Gpa |
| Poisons Ratio | 0.28 |
| Fluid Density (ρ) | 1000 kg/m ³ |
| Mass of Pipe (mp) | 3.61 kg |
| Mass of Fluid (mf) | 1.76kg |
| Dynamic Viscosity of fluid | 0.001001 pa.s at 20° C |

Analysis of simulated model. Thermal analysis.

DC3D20 element type is used, which it is 3-D twenty nodes with a single degree of freedom, temperature, at each node. The 20-node elements have compatible temperature shapes and are well suited to model curved boundaries. It is applicable to a 3-D, steady-state or transient thermal analysis; it is applicable to a 3-D, steady-state or transient thermal analysis. Fig.3 & Fig.4 shows the preheating and cooling transformation during welding process.

Welding Process Cycle

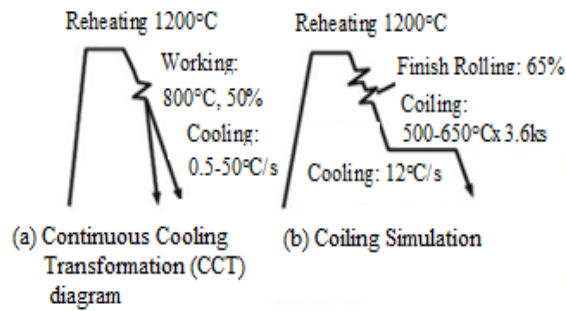


Fig. 3. Heat cycle.

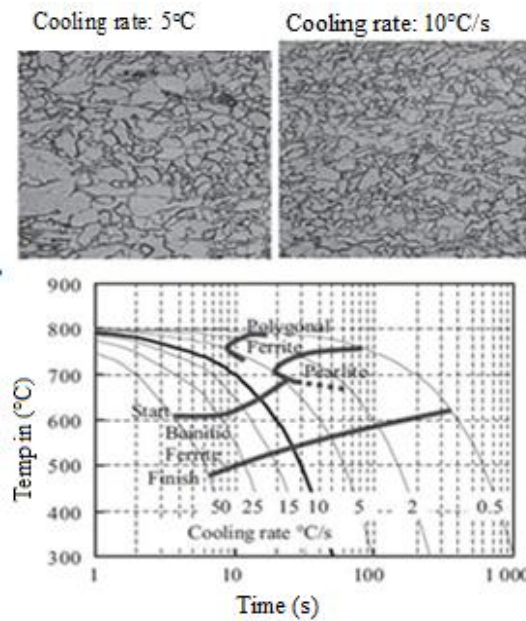


Fig. 4. Continuous cooling transformation diagram of Steel B.

Coupled field thermal structure. A stress analysis was then developed with the temperatures obtained from the thermal analysis used as loading to the stress model. C3D20 element type was used, which can mesh irregular shape without as much loss of accuracy. C3D20 element has compatible displacement shapes and is well suited to model curved boundaries. It is defined by 20 nodes having six degree of freedom per node. The element may have any spatial orientation. C3D20 has plasticity, creep, stress stiffening, large deflection, and large strain capabilities as shown in Fig. 5. Temperature plot in degree Celsius.

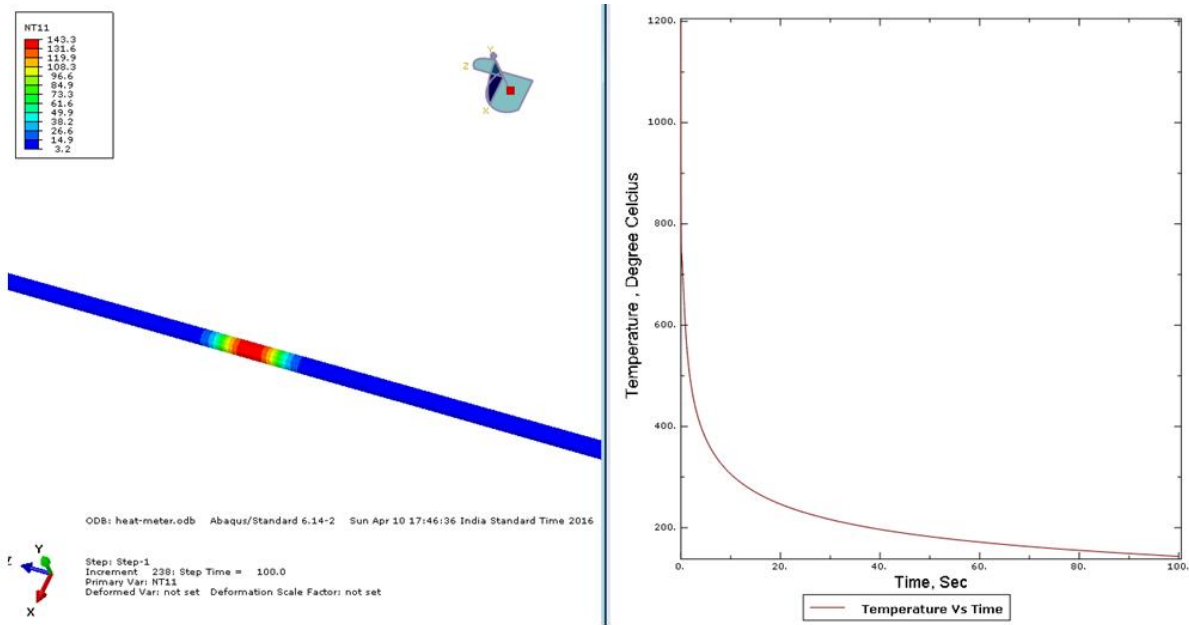


Fig. 5. FE analysis of clamped-clamped pipe with welding at mid span.

Cases Analysed. Fluid conveying pipe was analyzed by considering different cases and relevant analysis has been done.

- (1) Pipe acts as a beam when velocity, $(V) = 0$ and weldment effect, $(T) = 0$
- (2) Fluid flow velocity $(V) = 5.0$ m/sec, with weldment effect $(T) = 0$
- (3) Fluid flow velocity $(V) = 5.0$ m/sec, without weldment Effect, $(T) = 10$ N

Case 1 when there is no velocity and no weldment effect on a pipe it behaves as a beam. The results obtained are shown in table 3. Similarly, for case 2 analysis by considering a fluid velocity 5 m/sec and weldment effect $T=0$ the natural frequencies were found for 3 mode shapes.

Finally, in Case 3, $V=5$ m/sec and $T=10$. Newton is applied to piping system to obtain natural frequencies using FORTRAN program code. The natural frequencies of a clamped-clamped pipe with and without welding, with and without velocity for all 3 cases mentioned above are run by ABAQUS simulation software and results were generated and compared with analytical results.

Table 3. FE analysis of fluid conveying welded pipe with different conditions.

| Mode No. | Empty pipe $V=0, T=0$ | | Percent age of Error | Pipe without weld $V=5\text{m/sec}, T=0$ | | Percent tage of Error | Pipe with weld $V=5\text{m/sec}, T=10$ | | Perce ntage of Error |
|----------|--|---------------------------|----------------------|--|---------------------------|-----------------------|--|---------------------------|----------------------|
| | Natural Freq. by ABAQUS Software in Hz | Natural Freq. Theo. in Hz | | Natural Freq. by ABAQUS Software in Hz | Natural Freq. Theo. in Hz | | Natural Freq. by ABAQUS Software in Hz | Natural Freq. Theo. in Hz | |
| 1 | 50.82 | 49.58 | 2.43 | 36.35 | 35.76 | 1.6 | 31.36 | 30.71 | 2.07 |
| 2 | 139.36 | 137.52 | 1.32 | 99.54 | 98.15 | 1.39 | 85.75 | 83.92 | 2.13 |
| 3 | 271.31 | 265.37 | 2.18 | 192.66 | 187.13 | 2.87 | 166.22 | 163.97 | 1.35 |

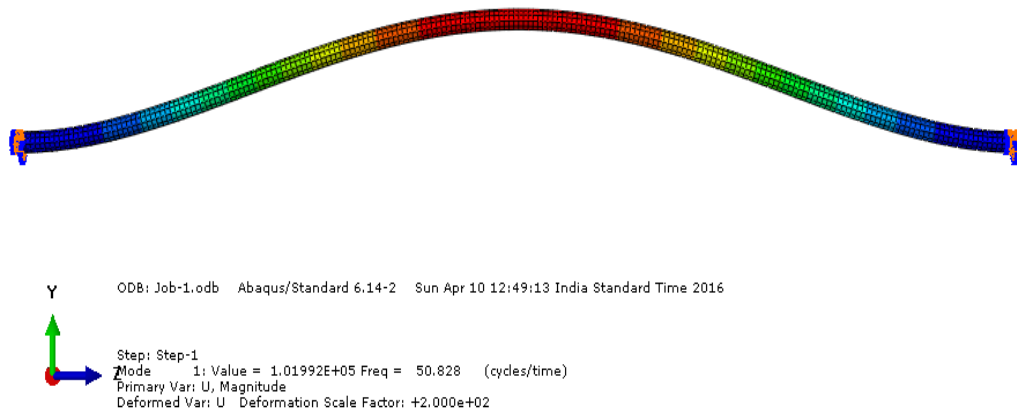


Fig. 6. Vibration analysis of clamped-clamped empty pipe ends without welding first mode shape.

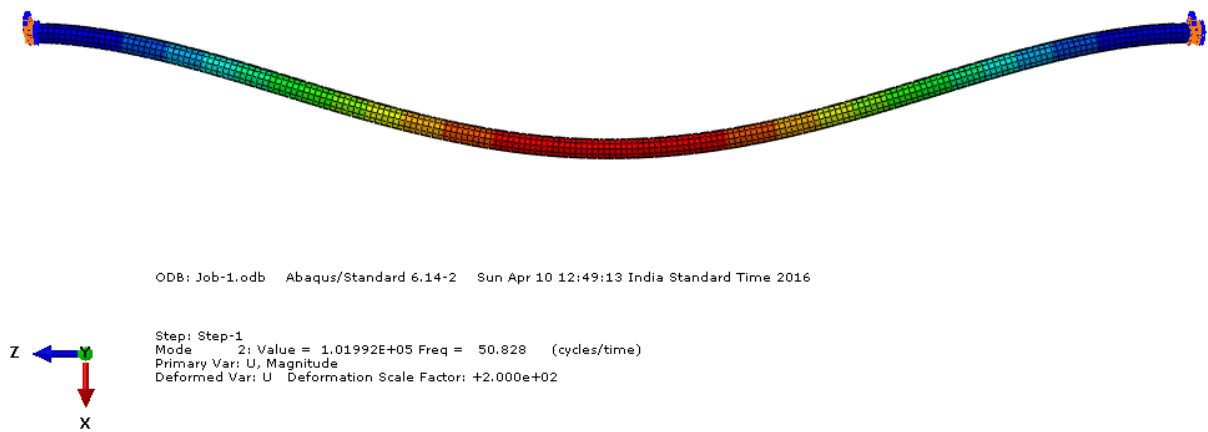


Fig .7. Vibration analysis of clamped-clamped empty pipe ends without welding second mode shape.

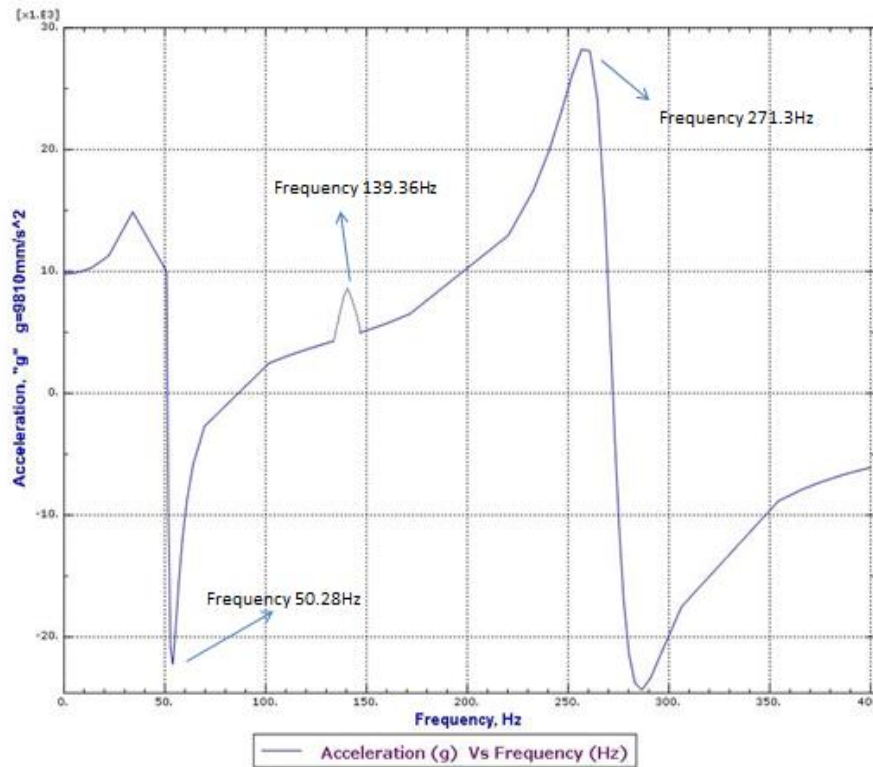


Fig. 8. Acceleration vs. Frequency of an empty pipe with clamped ends without welding.

The Fig. 6 and Fig. 7 show the finite element analysis of clamped ends for empty pipe with Abaqus simulation for first and second mode shapes. The first natural frequency of pipe is excited at 50.82 Hz, 2nd mode it is found to be 139.36 Hz and for 3rd mode shape 271.31Hz. For all the cases observed that the maximum deflection of the pipe is found approximately 2mm.

Similarly, harmonic analysis (sine sweep) was done on the structure by applying harmonic force of 1g acceleration to plot the Acceleration vs. Frequency. To find the frequency Peaks on the pipe as shown in Fig. 8.

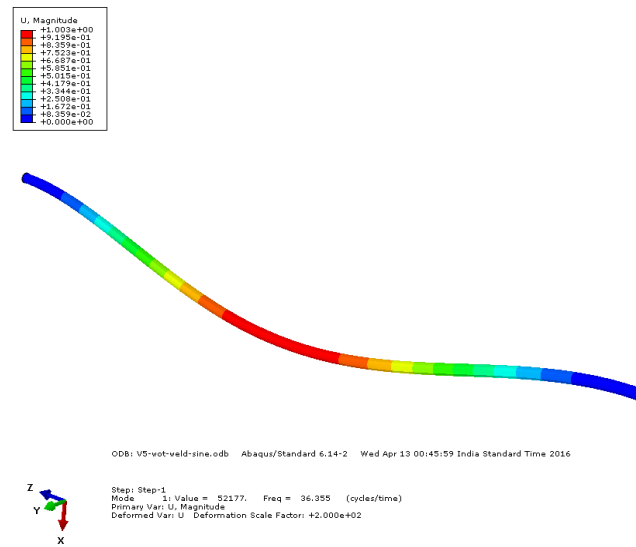


Fig. 9. Vibration analysis of clamped-clamped with velocity (V) =5m/sec without welding (T) =0.

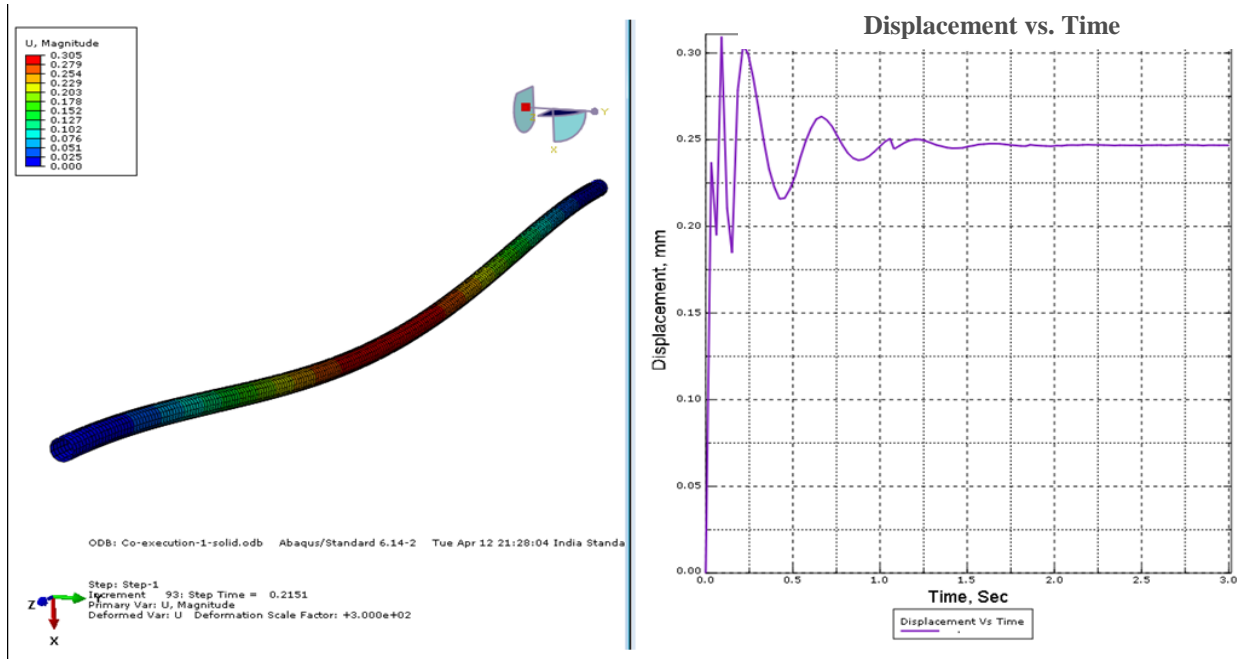


Fig. 10. FE analysis of clamped pipe with deflection plot at $V=5\text{m/sec}$ and $T=0$.

In case 2 fluid structure interaction is studied for clamped end pipe without welding and with fluid velocity $V=5\text{m/sec}$ and $T=0$ as shown in Fig. 9 and Fig. 10. The piping vibration natural frequencies are obtained for 3 mode shapes by ABAQUS simulation the 1st mode shape is found at frequency 36.355 Hz, 2nd 99.54 Hz and 3rd Mode 192.56 Hz for all the three cases the maximum displacement was found within 0.35mm from the displacement vs. time plot.

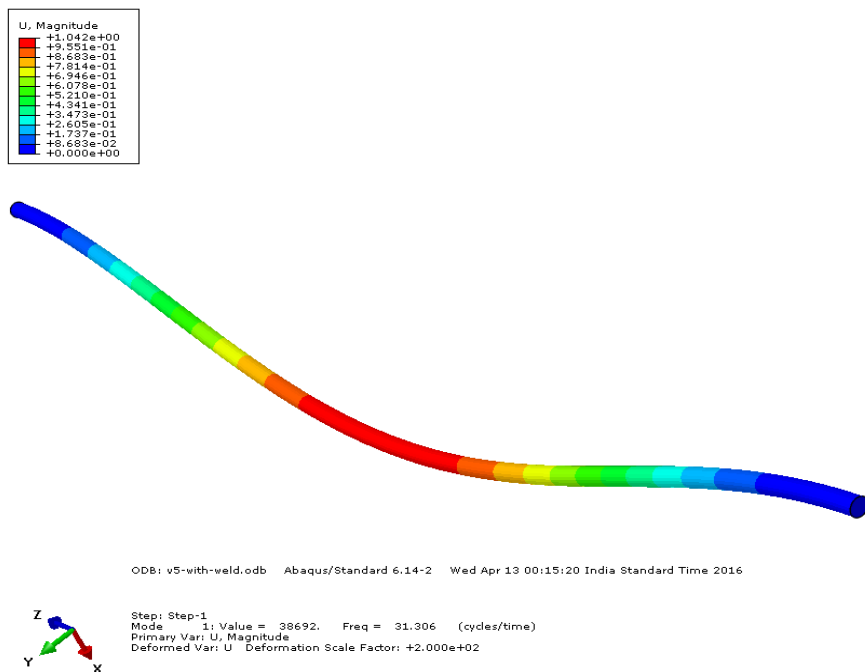


Fig. 11. Vibration analysis of clamped-clamped with velocity $V=5\text{m/sec}$ without welding $T=10\text{N}$

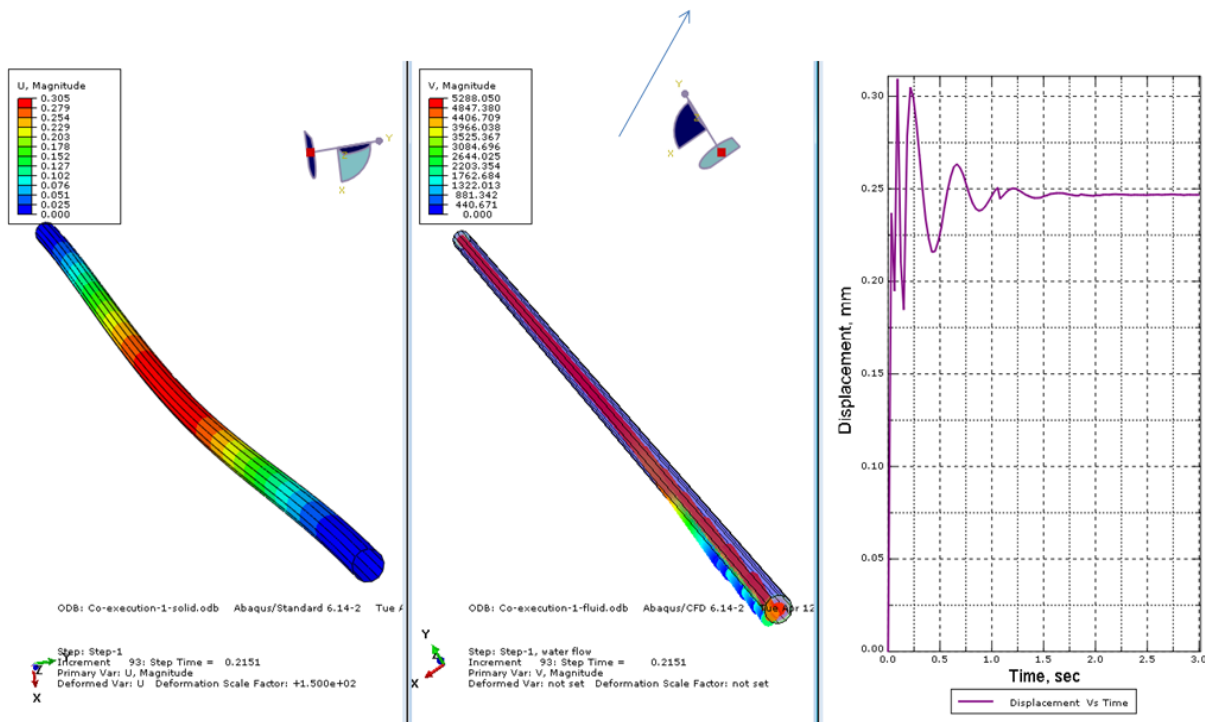


Fig. 12. Fluid Structure interaction of clamped pipe with $V=5\text{m/sec}$, $T=10\text{N}$.

The Fig. 11 and 12 shows the weldment effect for fluid velocity at (V) =5m/sec and $T=10\text{N}$. In this case the 1st mode of frequency is 31.36Hz, 2nd 85.75Hz and 3rd mode 166.22Hz the maximum displacement found for all 3 cases is 0.305 mm.

Summary. The fluid-conveying pipes considering c-c boundary condition are used to develop mathematical model.

The theoretical results of empty pipe and fluid flow in a pipe with applied velocities for three mode shapes are analyzed and compared with Abaqus software results of natural frequencies. The generated finite element data using Abaqus software are compared with analytical data.

- a) The natural frequency of the pipe increases with increase in fluid flow velocity for c-c ends.
- b) The weld deposit on a pipe with c-c ends also play a major role in reduction of natural frequencies with increase in weldment. The percentage error found to be less than 3% and it is in good agreement.
- c) The frequency of first mode of vibration is computed by varying the fluid flow velocity with and without welding effects, for which critical flow velocities are obtained.
- d) In the case of c-c condition the instability region lies in the range of 32.0 to 33.56 for magnitude of 10 weld tension.

Acknowledgement: Shaik Imran and Shaik Riyaz Uddien are students of Department of Mechanical Engineering, University College of Engineering, Osmania University, Hyderabad.

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