Fluid structure interaction simulations and experimental validation of a pipeline immersed in liquid

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Abstract. In launch vehicles, there are number of fluid systems to cater to various requirements like propellant filling, draining to/from tanks, venting of ullage gases, pressurization of the tanks, feed systems to convey propellants to engine from tanks, lines to convey command gas to actuate various valves etc. These pipe lines are subjected to environmental loads i.e. vibration loads when the launch vehicle starts its course to place the satellite into its designated orbit. It is essential to study the dynamic characteristics of these pipe lines for the design of them for vibration loads. The response of these pipelines depends on fluid environment in which they are immersed. If a pipe line is immersed in liquid, its dynamic characteristics vary largely from that of a pipeline vibrating in ambient environment (air). If the pipe line immersed in fluid, natural frequency reduces and damping increases due to the added mass and fluid viscosity respectively. In order to study these effects, FSI studies are carried out on a pipe line immersed in water using ANSYS CFD and Mechanical software. Convergence studies with respect to time scale are carried out to benchmark the simulation procedure. This simulation procedure is validated by conducting the experiments.

1. Introduction

Launch vehicles generally consist of solid, liquid and cryogenic stages. Liquid and cryogenic stages use fuel and oxidizer for propulsion. Fuel and oxidizer are stored in two different propellant tanks. Gaseous medium required for actuation of valves and pressurization is stored in spherical gas bottles. There are number of fluid systems to cater to various requirements like propellant filling, draining to/from tanks,
venting of ullage gases, pressurization of the tanks, feed line to convey propellants to engine from tanks, lines to convey command gas to actuate various valves etc.

A fluid system consists of a set of pipelines of different diameters, their supporting brackets and other elements like valves. In stages, four surrounding environment conditions arise. They are: (i) pipeline carrying ambient gas immersed in ambient air (ii) pipeline carrying ambient gas immersed in liquid (iii) pipeline carrying fluids immersed in fluid (iv) pipelines carrying fluid in ambient air. These pipelines are subjected to different environmental loads i.e. vibration loads when the launch vehicle starts its course to place the satellite into its designated orbit. It is essential to study the dynamic characteristics of these pipelines with the surrounding environment conditions for the design of them. The dynamic characteristics vary with respect to the conditions in which they were immersed. The response of a pipeline immersed in fluid environment varies largely from that of a pipeline vibrating in ambient air. This paper focuses on quantifying the effects of added mass and viscosity of fluid on natural frequency and damping of a pipeline immersed in water subjected to vibration through fluid structure interaction simulations. Simulation studies are carried out by sequential coupling of fluid and structural domains. Convergence studies with respect to time scale are done in order to bench mark the simulation procedure. Experimental studies are also carried out to validate the simulation procedure.

2. Literature Survey
Amin Zare et al used Euler Bernoulli beam theory for mathematical formulation for dynamic characterisation of pipelines subjected to fluid flow induced effects\(^1\). H. S. Simha et all analyzed fluid conveying pipes with simply supported, cantilever and fixed boundary conditions were analyzed\(^2\). Fluid structure interaction can be studied by two ways, one way coupling and sequential coupling, where later gives the more accurate results\(^3\). When a structure is immersed in fluid environment, fluid structure interaction takes place which alters the response of the structure\(^4\). Vipin Kumar et al discussed different methods for solving the dynamic equations. Ritz method was used to obtain dynamic equations for pipelines under different boundary conditions\(^5\).

2.1. Added mass
Generally added mass is defined technically as a matrix which correlates the interaction of the mechanical structural elements through changes in fluid pressure. Expression for added mass for a perfect fluid at rest can be derived from the case of a simple harmonic oscillator. Added mass for a moving body inside an incompressible fluid does not depend on the viscosity\(^6\). Reduction in natural frequency of pipelines when immersed in an incompressible fluid is due to axial added mass coefficients caused by external fluid. Numerically the natural frequency can be obtained using Galerkin method\(^7\). The liquid layers surrounding a structure impose an asymmetry, which produces a difference in natural frequency in vertical and horizontal polarizations. The added mass coefficient is evaluated from the ratio between resultant force and acceleration acted on the wall\(^8\).

2.2. Damping
There are various factors which govern damping of pipe lines immersed in fluid. Fluid viscosity and flow velocity are main factors which cause increase in damping of the system. The solution for this system is solved using spectral element method in frequency domain\(^9\). When fluid is flowing around a structure, it induces an additional damping effect as a result of its viscosity. Depending on an initial condition, added stiffness matrix and external force is together modeled to obtain the viscous force\(^10\). Transfer matrix is a matrix that represents the motion of a single pipeline section. The matrix incorporating the boundary conditions is called a point matrix. Both these matrices are combined to form overall transfer matrix\(^11\). To
study the effects of added mass and viscosity, fluid structure interaction simulations of a pipeline made of polyimide immersed in water are carried out using ANSYS Mechanical and ANSYS CFD codes\textsuperscript{12}.

3. Numerical Methodology

Numerical simulations are done by CFD (computational fluid dynamics) simulations, which is the science of predicting fluid flow, heat transfer, mass transfer and chemical reactions. The pattern of fluid flow around a body immersed in liquid depends on the geometry of the body. For the FSI studies, fluid model and structure models are prepared. The interaction between the flow and the structure is based on sequential coupling of both.

3.1. Structural Domain

The structural domain represents the structure, its walls and boundary conditions. Basic equation of dynamic structural analysis for structural domain, static and transient analysis has to be carried out.

3.2. Fluid Domain

The fluid domain represents the fluid medium and its boundary conditions. Both the fluid and solid domain will have common boundaries where the fluid structure interaction takes place. Averaged Lagrangian Euler (ALE) method is used to study the dynamics of slowly varying waves in a moving medium. This method can be used for both linear and non-linear systems. Momentum and continuity equations are also solved.

4. Numerical Implementation and Mesh Statistics

FSI studies are carried out on a polyimide pipeline immersed in water. Figure 1 gives the schematic of the pipeline (a), structural domain (b) and fluid domain (c) used for FSI studies. Length and thickness normalized with the inner radius of the pipe line used for simulations are 16.95 and 0.034 respectively. Polyimide pipelines are fabricated by winding Fluorinated Ethylene Propylene (FEP) coated polyimide tape (Du Pont KAPTON film) and cured at 330°C. These polyimide pipe lines are used in cryogenic fluid systems as a flexible structural element to take care of thermal contraction requirements of propellant tanks. By virtue of their lower stiffness, it possesses flexibility to absorb differential contractions. Young's modulus and density of polyimide material are 2630 N/mm\textsuperscript{2} and 1750 kg/m\textsuperscript{3} respectively. Pipeline is discretized using three dimensional SOLID185 available in ANSYS Mechanical element library. Fluid domain is discretized as hexagonal grids with required boundaries.

![Figure 1. Schematic of the pipeline (a), structural domain (b) and fluid domain (c) used for FSI studies.](image-url)
5. Analysis Procedure

Water and air contained in the tank are idealized as incompressible viscous fluids. Initial volume fractions have been set using step function as specified by free surface modeling of Volume of Fraction (VOF) method. Liquid height of fluid is chosen as 0.6m from the tank bottom. Coupled solver with appropriate convergence control parameters and different time step sizes are used for carrying out convergence studies. Homogeneous Eulerian-Eulerian multiphase model available in ANSYS/CFD is used for obtaining numerical solution in which time dependent momentum (Reynolds Averaged Navier Stokes – RANS) equations along with continuity and volume fraction equations are solved.

Initial pressure condition is \( P_{\text{initial}} = P_{\text{air}} + \rho_{\text{water}} \times g \times (0.6 - z) \times \text{vf}_{\text{water}} \); set at opening boundary condition.

Coupled field analyses are those analyses in which the input of one analysis is dependent on the results obtained from another analysis. There are two ways of coupling the results. For the present FSI studies, sequential coupling is employed. For solving sequentially coupled problem, ANSYS Multifield Solver (MFX solver) is used to obtain robust and accurate solutions.

6. Results and Discussions

Convergence studies are carried out for different time scales (\( \Delta t \)) with structural damping (\( \zeta \)) = 0%. The analysis was carried out for time steps of 0.005, 0.002, 0.001, 0.0002 and 0.0001 sec. Figure 2 give the plot of damping obtained with respect to different pipe line tip displacements. From the figure it is observed that damping increases with tip displacement. As time step reduces damping reduces and converges to a similar result for two simultaneous time steps.

![Figure 2. Damping obtained from the FSI simulations for different tip displacements.](image)

From figure 2, it is observed that the result converges to a particular value for time steps of 0.0002 sec and 0.0001 sec. Damping of pipeline is estimated by using logarithmic decrement method. Experimental studies are also carried out for different tip displacements. Figure 3 gives the typical test data without and with filter (low pass band filter of 25 Hz) for a particular pipe line tip displacement.
Figure 3. Typical test data without and with filter.[13]

Experiments are also carried out for the same pipe line in air in order to determine structural damping. From experimental tests, a damping ratio of 1% is obtained. This structural damping is included and FSI simulations are repeated for the time scale of 0.0002 sec. Results obtained are compared with the experimental values and given in Figure 4. From Figure 4, it is concluded that both experimental and numerical damping values match fairly well. Thus simulation procedure is validated. This can be taken as a benchmark criterion for obtaining convergence for simulation procedure.

Figure 4. Comparison of experimental and FSI results.

7. Conclusion
Fluid structure interaction studies are carried out using ANSYS Multifield (MFX) solver for a polyimide pipe line immersed in water. It is found that damping ratio increases with increase in amplitude of test specimen. Convergence with respect to of time scale ($\Delta t$) is achieved for a time step of 0.0002 sec after several iterations without incorporating structural damping. FSI simulations are repeated for the converged time step after including the experimentally determined structural damping. Experiments are also carried out on similar pipe line immersed in water. Simulation results are compared with experimental results and
they match fairly well. Thus the simulation procedure with respect to convergence criterion is validated/benchmarked.

8. References
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