

A numerical investigation on the added mass effect in the modal parameters of a liquid filled flexible tube

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Abstract— Vibration characteristics and the modal response of a liquid filled pipe system is affected by the added mass effect of the system. This in turn is going to influence the fluid structure interaction mechanism, when the fluid starts flowing. To have a deep understanding of the fluid structure interaction, it is essential to know how the modal parameters of pipe is affected by the addition of fluid mass. A computer program in ANSYS parametric design language (APDL) is developed to find out the effect of added mass in the dynamics of pipes conveying fluid. The code developed is validated by comparing the results obtained from the code to the experimental results from Zhang et al [10].

Keywords— *Modal analysis, added mass effect, flexible tube, vibration, fluid structure interaction*

I. INTRODUCTION

For the past sixty years immense attention has been received for the topic, flow through pipe and the fluid structure interaction caused by this. The change of pressure caused by the fluid structure interaction, generates vibration in the pipe. Fluid structure interaction effects the dynamics of the mechanism differently and it is in the designer's interest to study this phenomena in detail. This complex phenomena ranges from the simple garden hose to the complex flow through pipe in nuclear reactors, process pipe, penstocks etc. Another critical and very interesting, effect of fluid structure interaction is found in blood vessels carrying blood through it.

Analysis of the added mass effect of the liquid filled pipe without considering the flow is of great importance, as this will give an idea about the way, pipe is going to respond to the fluid structure interaction due to flow. Modal parameter study of pipe with and without added mass shed light on complex details regarding natural frequency and mode shape. Such a study will help in the dynamic analysis of pipe during flow. A lot of work has been going on in the area of the modal study of pipe and fluid structure interaction. These studies fall in the domain of experimental study, analytical study or both.

Tijsseling [1] gave a detailed guidance to published work (papers and books) in the area of modal analysis, fluid structure interaction and flow-induced vibration in liquid-

filled pipe systems. The effects of liquid on the modal properties of pipe structure was investigated experimentally by Hassan et al [2]. They conducted the experiment on aluminum pipe and the shaker force was applied at a single point. Zhang et al [3] conducted experimental studies on thick cylindrical tubes. But this experiment did not have the added mass effect included in the analysis. In this study no analytical methods have been discussed. Tijsseling et al [4] presented in detail the essential mechanisms that cause fluid structure interaction and presented relevant data that demonstrate the phenomenon. Reference [4] also briefed on the various numerical and analytical methods that have been developed and the recent contributions in the field. Gorman et al [5] conducted an analysis of flexible pipe under unsteady condition. The equations are fully coupled through equilibrium of contact forces, the normal compatibility of velocity at the fluid pipe interfaces, and the conservation of mass and momentum of the transient fluid. Zhang et al [6] conducted an experimental study on both pulsating and steady Newtonian fluid flow in an initially stretched rubber tube subjected to external vibration. Here also the shaker position was fixed. A flexible pipe conveying unsteadily flowing fluid is analysed in detail by Gorman et al [7]. The equations are fully coupled through equilibrium of contact forces, the normal compatibility of velocity at the fluid pipe interfaces, and the conservation of mass and momentum of the transient fluid. But, here no experimental work on the flexible pipe has been done. An overview of mechanics of pipes conveying fluid and related problems such as the fluid elastic instability under conditions of turbulence in pipe was examined by R. A. Ibrahim [8]. Different types of modeling, dynamic analysis, and stability regimes of pipes conveying fluid restrained by elastic or inelastic barriers are explained. Y L Zhang et al [10] has done extensive experimental analysis on modal analysis of pipe with and without fluid. They have conducted the experiment on rubber pipe.

The present literature survey gives a comprehensive idea about the works that has been done in the area of added mass effect and subsequently fluid structure interaction. The present paper tries to develop a computer program in Ansys parametric design language (APDL). The results obtained

from the analysis is validated using the experimental results from [10].

III FINITE ELEMENT FORMULATION

In the present APDL code elements for both structural analysis as well as fluid analysis will be used. The shell 181 element will be used in the structural analysis and fluid 30 will be used for fluid part. The details of the elements used are given below.

The SHELL181 element [9] has four nodes with six degrees of freedom at each node: translations in the x, y, and z axes, and rotations about the x, y, and z-axes. The SHELL181 element is suitable for analyzing thin to moderately-thick shell structures. Membrane option provides only translational degrees of freedom. The quadrilateral configuration is preferred over the degenerate triangular configuration. This element is suitable for linear, large rotation, and/or large strain nonlinear applications. Change in shell thickness is accounted for in nonlinear analyses. The element formulation is based on first order shear deformation theory (usually referred to as Mindlin-Reissner shell theory).

The isoparametric shape functions (N_i) for the element is given by:

For corner nodes:

$$\text{For } \xi_a = 0 ; \{N_a\} = \frac{1}{2}(1-\xi^2)(1+\eta_a\eta)$$

$$\text{For } \eta_a = 0 ; \{N_a\} = \frac{1}{2}(1-\eta^2)(1+\xi_a\xi) \quad (1)$$

For mid-side nodes:

$$\text{For } \eta_a = 0 ; \{N_a\} = \frac{1}{2}(1-\eta^2)(1+\xi_a\xi) \quad (2)$$

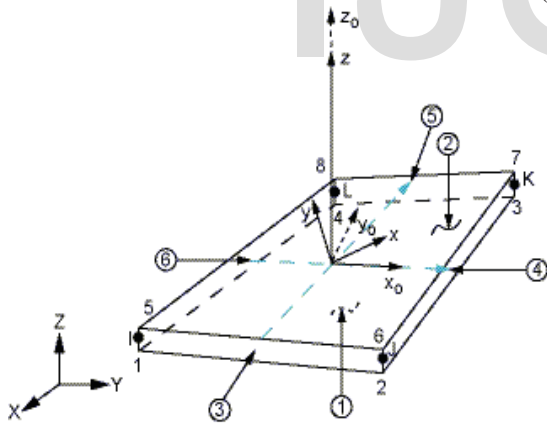


Figure 1 Shell 181 element

FLUID30 [9] is used for modeling the fluid medium and the interface in fluid/structure interaction problems. Typical applications include sound wave propagation and submerged structure dynamics. The governing equation for acoustics, namely the 3-D wave equation, has been discretized taking into account the coupling of acoustic pressure and structural motion at the interface. The element has eight corner nodes with four degrees of freedom per node: translations in the

nodal x, y and z directions and pressure. The translations, however, are applicable only at nodes that are on the interface. Acceleration effects, such as in sloshing problems, may be included. The complete finite element discretized equations for the fluid-structure interaction problem are written in assembled form as:

$$\begin{bmatrix} M_e & 0 \\ M^{fs} & M_e^p \end{bmatrix} \begin{Bmatrix} \ddot{u}_e \\ \ddot{p}_e \end{Bmatrix} + \begin{bmatrix} C_s & 0 \\ 0 & C_e^p \end{bmatrix} \begin{Bmatrix} \dot{u}_e \\ \dot{p}_e \end{Bmatrix} + \begin{bmatrix} K_e & K_e^{fs} \\ 0 & K_e^p \end{bmatrix} \begin{Bmatrix} u_e \\ p_e \end{Bmatrix} = \begin{Bmatrix} F_e \\ 0 \end{Bmatrix} \quad (3)$$

IV RESULTS AND ANALYSIS

The code developed using Ansys parametric design language (APDL) was used for the analysis of added mass effect. The code was developed for both modal analysis of pipe with and without fluid. The total number of elements for analysis with water as fluid had 210240 elements and 211546 nodes. The total number of elements for analysis without fluid were 18720 and nodes were 18772. The coupling between the shell element and fluid element was generated using the coupling equation of fluid and structure. The analysis gave the following results

The following are the data chosen from [10].The external diameter of the rubber pipe 9.7×10^{-3} m, internal diameter, 6.0×10^{-3} m and length 3.62×10^{-1} m. The Young's modulus of rubber 2.0924×10^6 Pa, Poisson's ratio=0.48, density of the rubber 1128.56 kg/m³ and water density 1000.00 kg/m³

The discretized structure and fluid is given below. Here the coupled analysis of fluid and structure is done

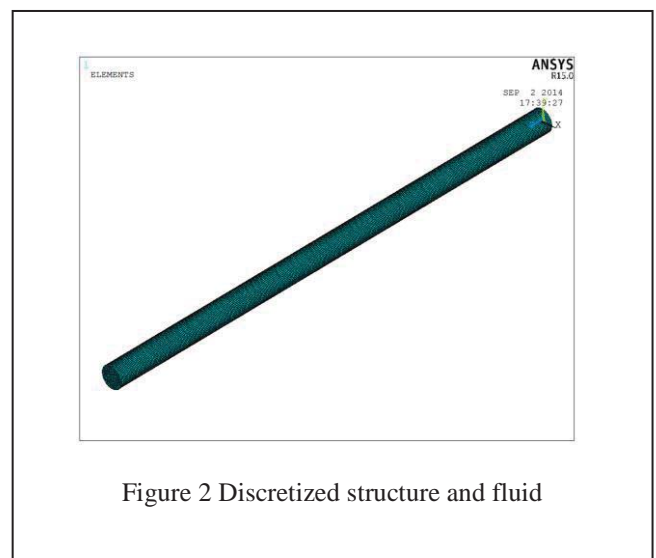


Figure 2 Discretized structure and fluid

Mode shapes from first to third mode, with and without fluid along with their natural frequency are given in the following plots

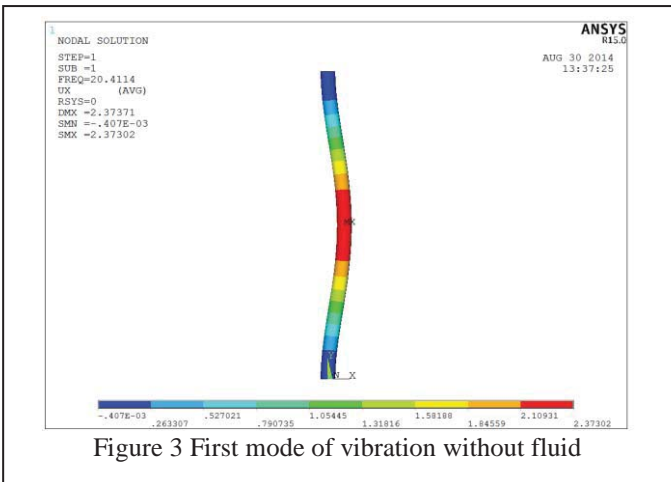


Figure 3 First mode of vibration without fluid

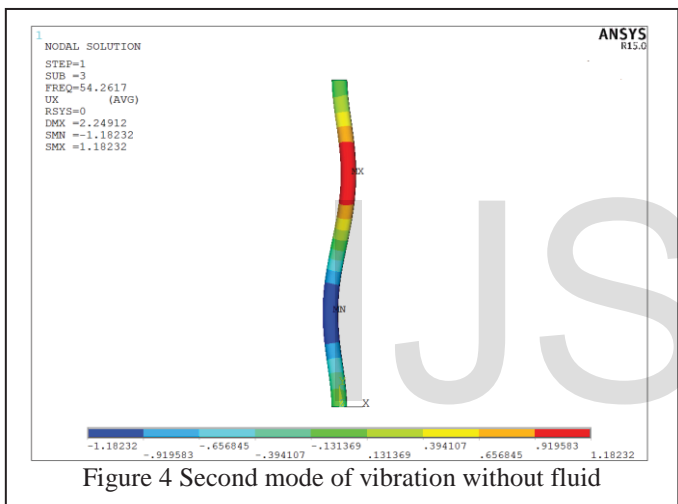


Figure 4 Second mode of vibration without fluid

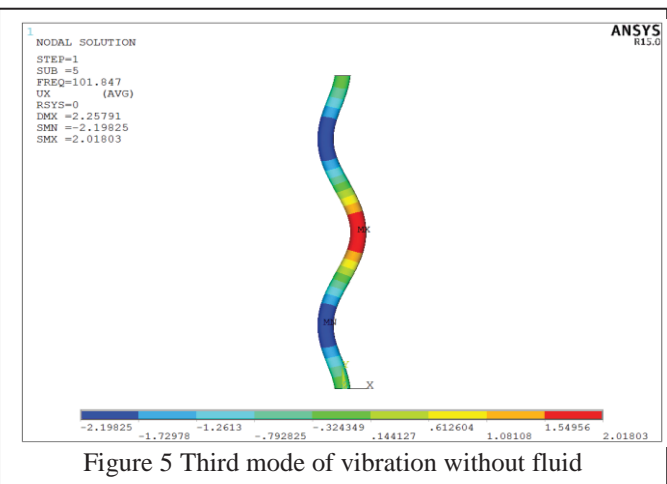


Figure 5 Third mode of vibration without fluid

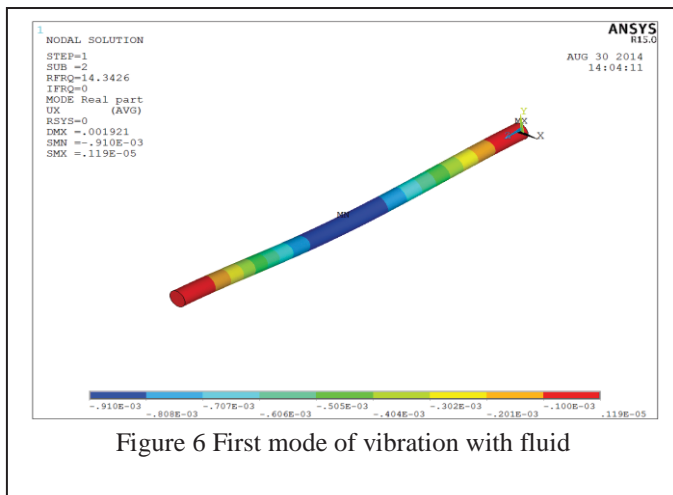


Figure 6 First mode of vibration with fluid

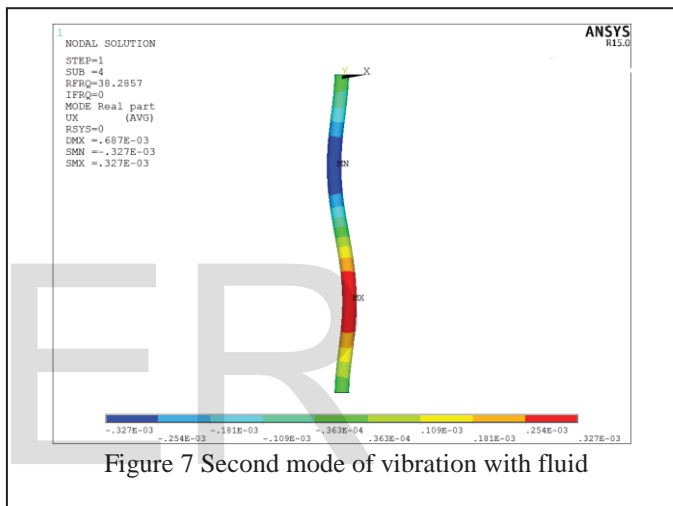


Figure 7 Second mode of vibration with fluid

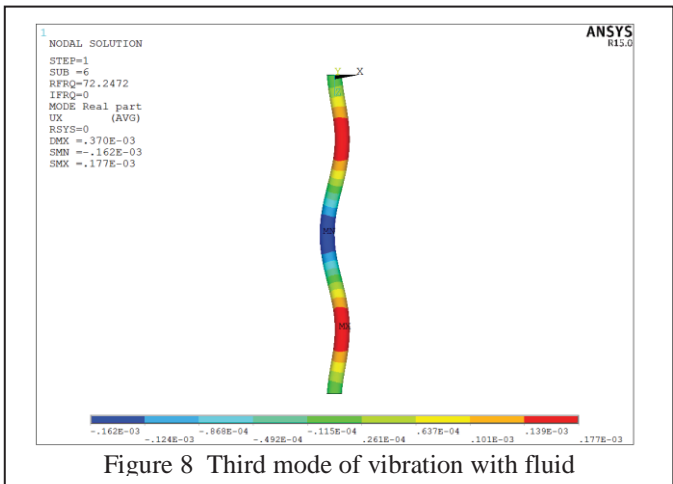


Figure 8 Third mode of vibration with fluid

The above figures are from the analysis of the pipe with fluid and without fluid condition. Figures 2 to 7 shows modes shapes of the pipe up to third mode with and without fluid. As it can be seen, the natural frequency of the fluid filled pipe at a particular mode is less than the natural frequency of the corresponding mode in the empty tube. For example, first mode of natural frequency of the pipe with fluid is 14.34 Hz, while the first mode of vibration for the empty tube is 20.41Hz. This difference happens because of the added mass effect of the fluid. The normally effect of the fluid will be to reduce the natural frequency. But for very thin pipes, if the fluid column frequency and the structure frequency come very close, the dynamics will depend upon the phase difference of the vibration of the fluid column to that of the structure.

A comparison of the result presented in Zhang et, al [10] obtained from the experimental analysis and numerical analysis [10] to the numerical analysis from APDL developed for the present model is given below in the following tables.

Table 1 Comparison of the natural frequency of pipe with fluid from Zhang et al [10] and numerical analysis using APDL

	Natural frequency of pipe with fluid		
	First mode	Second mode	Third mode
Present analysis using APDL	14.34	38.28	72.24
Reference [10] Experiment	14.56	45.41	83.15

Table 2 Comparison of the natural frequency of pipe without fluid from Zhang et al. [10] and numerical analysis using APDL

	Natural frequency of pipe without fluid		
	First mode	Second mode	Third mode
Present analysis using APDL	20.41	54.26	101.84
Reference [10] Experiment	18.65	59.38	106.74

As it can be seen from the table 1 and table 2, the results obtained from numerical analysis from the code developed using APDL and that from the experiment are in good agreement. The difference in the results are generally due to the end conditions. In experiment it is not possible to maintain the end condition properly, which is not the case with a computer program. This inaccuracy will affect the final result.

IV CONCLUSION

The aim of this work was to develop a code in APDL, which has been done successfully, since results from the experiment are matching closely with the result from numerical analysis. Further studies can be done for developing code for the flow.

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