Numerical analysis on the vibrational characteristics of flexible tubes conveying fluids using two way fluid structure interaction.

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Abstract

Many complex mechanical engineering problems depend on numerical methods to get accurate results for analysis. Fluid-structure interaction is one such problem which results in the vibration of the structure due to the momentum transfer between the fluid and structure. Fluid-structure interaction problem can be solved using both coupled as well as uncoupled numerical techniques. The coupled technique is considered as a better option over uncoupled technique as it enables the simultaneous data transfer between the structure and fluid that result in a precise solution. The present study focuses on the fluid structure interaction due to the fluid flow inside a pre-stretched silicone tube, using coupled technique. ANSYS 18 software is used for investigating the problem by solving equations from different modules simultaneously. Two-way fluid-structure interaction coupling technique enables the parametric design of the ANSYS transient structural and ANSYS fluent separately and then combines the setup information using system coupling feature. The geometric features of the ANSYS static and ANSYS transient structural module are coupled together to obtain the pre-stretch conditions of silicone rubber tube. The energy transfer is visible in the form of local deformation of the silicone rubber tube or flow-induced vibration of the entire tube system. The numerical analysis is used to simulate the pressure variation along the silicone tube by coupling the solution file of transient structural with the results of the fluent part. The total deformation of the tube along the fluid flow is also presented. The natural frequency found out by coupling the data with ANSYS modal gives the values corresponding to 10% and 15 % pre-stretched conditions respectively of the tube and are compared with the experimental values for the above mentioned pre-stretched conditions.

Introduction

Fluid structure interaction is the term used to define the interaction between a solid structure and fluid flow. Fluid structure interaction has applications in many fields like marine engineering, underground water, oil or fluid conveying piping systems, internal fluid carrying applications in medical field such as blood transfusion device, tubes used to convey hot fluids in steam generator and the pipelines used to distribute fuel in rocket propelling engine. Depending on the complexity of the fluid structure interaction, different techniques can be employed. Simple fluid structure interaction problems involving rigid body motion such as an impeller rotating in a mixing tank can be solved completely using ANSYS CFD module. As the complexity increases one way fluid structure interaction technique can be used to solve the simulation involving the transfer of data from CFD module to structural and simulates the structural deformation. One way FSI technique solves the fluid and solid part one by one and the solution is obtained by using traditional solvers. The main drawback is the difficulty in the implementation of the bidirectional interaction between fluid part and solid structure. Two way fluid structure interaction technique is used to overcome this difficulty through a unified approach by formulating both fluid and solid equations together and solved synchronously with effective transfer of information from one module to another and vice versa.

The study on the flexible tube can be dated back to 1808 in which Young [2] conducted experiments using rubber hoses, flexible tubes and conducted experimental tests on flexible tube conveying incompressible fluid and obtained a relation to find propagation velocity of the pressure wave. Findings from this paper were mismatching with that of the experimental data because of the inability to formulate the coupling equation explicitly. But later in 1878 the work was rediscovered and analyzed properly by Korteweg et al. [3]. Reuderink et al. [4] formulated a method to identify the effect of pressure variation along the flow through the tube. The energy interaction between the tube surface and fluid is considered and accommodated the nonlinearity emerged in the flexible tube and compared with the experimental data. The linearity of mass and momentum conservation formula is found to be varying and nonlinearity is showing significant influence. Womersley et al. [5] did experiments using flexible tube conveying fluid and found out that viscous stress is directly proportional to the local strain rate. Experiments were conducted using tubes individually and tubes which were bundled together with axial binding force. Atabek et al. [6] did investigations analytically to analyze the fluid flow through a flexible tube and found that the fluid-structure interaction leads to the dilation of the tube at starting end and it leads to elastic deformation of the tube in repeated cycles. The obtained result was incorporated in the study of blood flow

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through arteries and was found out that the pulsatile flow-induced due to the pumping of blood from heart affect the flow through those arteries whose length is not long enough to damp out the pressure pulsation. This study inferred that the pressure wave propagation pattern can be analyzed at the inlet of the tube. Atabek et al. [7] worked on the theory proposed by Womersley [5] and considered flexible tubes of thin thickness in which the effect of flow is analyzed in both axial and radial direction. The existence of waves in two different planes was independently interpreted from Womersley [5] theory even though he did not highlight the inference himself. Governing equation for frequency was formulated by using momentum and continuity equation. The solution of these equations will give the value for velocity along two directions. The experimental setup was designed in such a way that a flexible pre-stretched tube conveying fluid with high viscosity to understand the flow characteristics of blood in blood vessels. The flexible tubes used for the experiment is having a very low thickness and is homogenous and isotropic. The wave propagation pattern is analyzed to reach at an inference that the propagating pressure waves are having wavelengths larger than the tube diameter. .

Though the development of preliminary governing equations and basic theories related to fluid-structure interaction were started from the early 1970's, the advanced analysis of fluid-structure interactions were possible only after the involvement of computer systems which could solve the governing equations within a short span of time. The development of simulation software which involves development and usage of user-defined functions paved the way to a new dimension in the analysis of fluid-structure interaction. For the analysis and modelling of pulsatile flow in stenotic arteries Bathe and Kamm [8] used the technique of coupling iteration using the prescribed value of time step and the obtained data were compared and validated with an existing analytical model and experimentally obtained data. The numerical analysis using two way fluid structure interaction has a major role in validating the experimental data because of its effectiveness in solving different set of equations together precisely and consuming lesser time than analytical method. Bak et al. [9] conducted investigations for the non-linear analysis of thin fabric made simple-shaped sail. Bak et al.[10] have conducted the fluid-structure interaction analysis by employing a partial two-way FSI method to calculate the 3-dimensional deformation of the main sail shape without the mast. The obtained results were comprising changes in the effective angle of attack, 3-dimensional flow separation, and stall. The study releved that it has the ability to change the thrust performance of a yacht according to changes in the lift and drag forces. Bak and Yoo [11] investigated the changes in lift and drag forces before and after deformation of the sail and rig for a sloop yacht with a masthead type rig. The shrouds and stays were not modeled with the fixed boundary conditions on each connecting points, so that the deformation of the rig simulated was not precise. Similar to these studies, Trimarchi et al. [12] used the Boundary Element Method to calculate the surrounding flow and the Finite Element Method (FEM) to calculate deformation of the sail without considering the mast and rig. The above literature review revealed that the numerical analysis of flexible tubes conveying fluid under pre-stretched condition has not yet been done. So this study employs the two way FSI technique using ANSYS 18 for the numerical analysis of the vibrational characteristics of pre-stretched silicone rubber tube conveying fluids.

Theory

Two way fluid structure interaction is a Multiphysics technique available in ANSYS 18 to simulate the interaction between the structure and fluid and vice versa. The stability of the structure can be get compromised because of the vibrations induced due to fluid structure interaction. ANSYS 18 is used to simulate the phenomenon of fluid structure interaction in order to ensure the safety and reliability of the system. Two way fluid structure interaction technique can be used for the analysis of complex problems. System coupling technique in ANSYS is used to solve both fluid and structural part simultaneously and the exchange of information happens in each step in to and fro direction. This method is used for the vibrational analysis of pre-stretched silicone rubber tube conveying fluid. The fully coupled fluid-structure interface to obtain the pressure variation along the tube surface, total deformation and the natural frequencies of the tube is shown in figure 1. The different ANSYS module involved in the two way FSI here are the static structural, transient structural, fluent and modal which are coupled using system coupling. The modal module is used to obtain the natural frequencies.

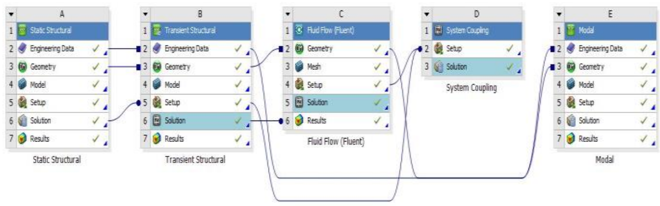

Figure 1- Two-way FSI coupled interface

Results and discussions

Two-way fluid-structure interaction technique is used in order to accommodate the effect of fluid pressure on the internal surface of the tube and the dilation effect of the tube on the fluid by coupling both ANSYS transient structural module and ANSYS fluent module by using system coupling.

The first step is the development of the pre-stretched condition using ANSYS static structure module by applying a force of 10 N and 14.5 N on one end of the tube while the other end held fixed and the data is coupled with transient structural module as shown in figure 1. The above mentioned values for force is selected by analyzing force-displacement curve corresponding to 10% and 15% pre-stretch. A pre-stretch of 2.5 cm and 3.75 cm is accommodated corresponding to 10% and 15% conditions respectively. The pre-stretch values 10% and 15% is selected in order to compare and validate the results obtained with experimental values[1]. In the next step selection of required modules in ANSYS

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workbench is done and then coupling is done between geometries in both transient structural and ANSYS fluent. The setup files from both transient and fluent is coupled using system coupling module. The further work in numerical analysis involves the selection of appropriate values for engineering data such as density of the flexible tube, young's modulus and poisons ratio. The material and geometric properties for static, transient and fluent part is assigned using the modelling and setup cells of the respective modules. Engineering data used for the design of silicone rubber tube is given in table 1. The experimental results for the silicone tube conveying fluid is obtained from [1].

Table 1- Engineering data for silicone rubber tube

PROPERTY	VALUE
Length	250 mm
Diameter	9 mm
Thickness	1.5 mm
Density	1150 kg/m^3
Young's modulus	30 MPa
Poison's ratio	0.47

The geometry of the silicone rubber tube is designed in such a way that the interaction between the fluid pressure and tube deformation at the fluid-tube interface and vice versa can be simulated precisely. The tube structure is designed as three separate elements such as line element, external tube surface and internal fluid element.

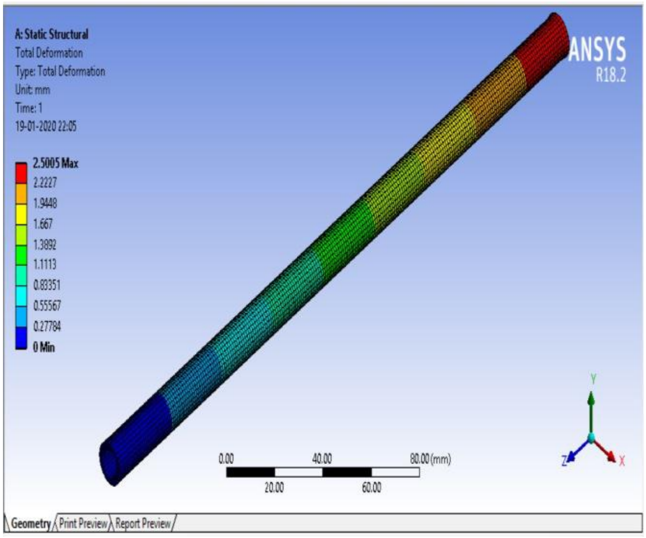

Figure 2- 10% pre-stretched silicone rubber tube

In the transient structural interface, the model cell is updated by keeping the line element and interior water element suppressed. The tube surface element is updated with a wall thickness of 1.5 mm. Both ends of the tube are fixed and the tube surface is made fluid interaction solid. Then the entire body has meshed finely with an element size of 1 mm.

In the next stage, we are dealing with the ANSYS fluent module. The line and the surface elements are being suppressed and the interior liquid element is made active and the liquid element is incorporated with a fine meshing of 1 mm. The element is incorporated with the inflation feature in which the scoping method is geometry selection and the side face selected with the corresponding circumferential edge as the limiting zone. In the inflation feature, the total thickness is specified with a number of layers 9, growth rate 1.2 and a maximum thickness of 2.5 mm. The algorithm used to incorporate inflation feature is pre-programmed in ANSYS. One of the two end faces is selected as velocity inlet profile and the other as pressure outlet face. The curved surface area is selected as the deforming wall and the entire body is made as a water element. The fluent body quality is checked and made sure the mesh quality is good enough to proceed with the analysis. The solver type is based on absolute velocity and transient time condition.

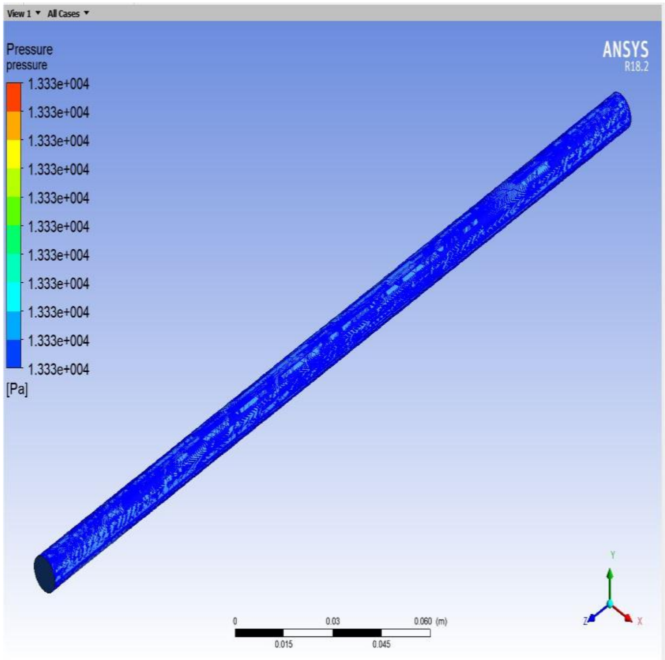

Figure 3 - Pressure variation along the tube surface

The minimum and maximum value of pressure is 12999.2 Pa and 13330 Pa. Therefore there is no significant variation observed in Figure 3.The material section under the solution setup tree is made active and fluent database is used to create the interior water element along with that material properties of water element such as density, shear viscosity etc. are selected. The cell zone condition for the interior fluid flow is updated as water-liquid from fluent database. The interior fluid flow element is loaded with user-defined function to control the flow velocity. The user-defined function written in C-language is used to give velocity boundary condition to the interior fluid flow. The system coupling module is now been updated with the data blocks in ANSYS transient and ANSYS fluent. The analysis settings in setup cell is updated with pre-programmed coupling initialization. The details of parameters assigned during the calculation and initialization step is shown in table 2.

Table 2- Parameters used in calculation and initialization procedure

Number of time steps	100
Time step size	0.01 sec
Maximum number of iteration	5
Reporting time interval	1 sec
End time	1 sec

Then the data transfer components for both the fluid-solid interface and deforming wall is created. The fluid-solid interface data transfer is done by selecting transient structural as source with incremental displacement and the target component is fluid flow (fluent) with displacement selected as variable for the deforming wall. The second data transfer is formulated by providing source as fluid flow and target as transient structural in order to obtain the fluid-structure interaction coupling correctly. After setting all the data required to couple both transient structural and fluent component, the convergence is tested with the system coupling solution cell. Once the convergence is attained, the solution cell of the transient structural component is coupled with the result of the fluent module. The results of the fluent element are again analyzed using CFD-post tool to obtain the pressure variation across the tube surface by inter linking wall deformation and the family component consisted of velocity inlet, pressure outlet and deforming wall. Further, the total deformation of the tube is obtained using transient structural and is shown in figure 4.

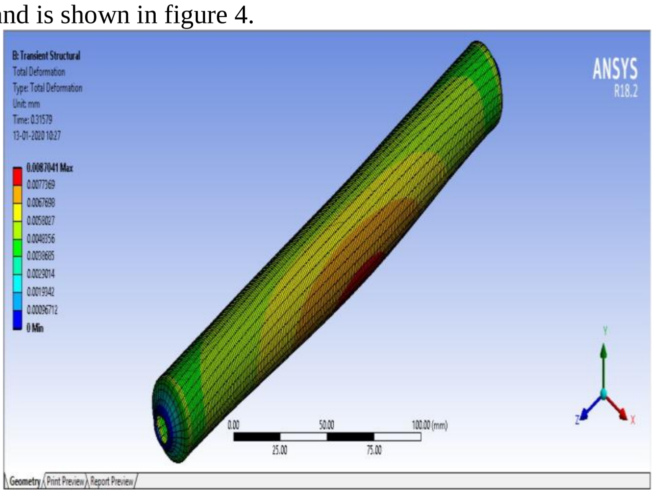

Figure 4- Total deformation of the silicone rubber tube

The obtained details are being coupled with the modal analysis module to obtain the natural frequencies of the tube conveying fluid. The result shows a first mode frequency of 24.342 Hz and 26.161 Hz for 10% and 15% pre-stretched conditions respectively. The first six frequencies are free-free condition frequencies and are neglected. The results obtained by using two-way fluid-structure interaction is validated by comparing with the experimental results [1]. The natural frequencies obtained experimentally for 10% and 15% pre-stretch are 24 Hz and 25.7 Hz for the first mode. The comparison of results obtained using two-way fluid-structure interaction coupling technique and experimental setup is given in table 3.

Table 3 - Numerical and experimental natural frequency of silicone tube.

SI No	Natural frequency (Hz)			Percentage variation in frequency (%)
	Pre-stretch	Two way FSI	Experimental	
1	10%	24.342	24	1.42
2	15%	26.161	25.7	1.76

The variation in natural frequencies may be due to the variation in boundary conditions of the tube in the experimental setup. The percentage variation of results obtained using numerical simulation and experimental setup is shown in table 3. The pre-stretching of the tube involves a major role in deciding the natural frequency of the tube as it reduces the sagging effect and natural frequency is being increased. The mode shape for the first fundamental frequency that is simple bending is shown in figure 5.

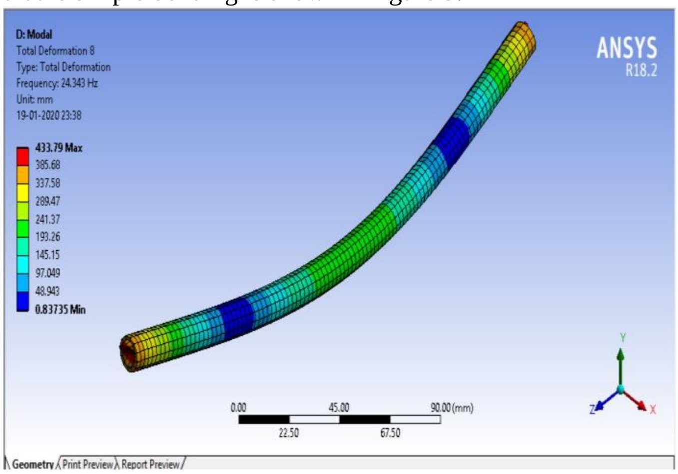

Figure 5- First mode shape of the silicone tube

Conclusions

The two-way fluid-structure interaction coupling technique simulates the interaction between the fluid flow and the tube surface and vice versa by means of momentum transfer. The pressure variation along the tube surface shows the change in energy interaction throughout the length of the tube. The deformation diagram indicates the correctness of the coupling technique as it shows the expansion and contraction of the silicone tube due to the fluid flow. The natural frequencies corresponding to 10% and 15% pre-stretched condition obtained using numerical technique is validated with the experimental results [1]. The variation of the experimental values of natural frequency with numerical values may be due to the variations in the boundary conditions of the experimental setup. The effect of pre-stretch will reduce the effect of sagging in the tube, which results in the increase of natural frequency. The further numerical analysis will be done in future with the pre-stretched condition for different lengths and thickness in order to find the optimum tube dimension for different applications.

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