Experimental and computational investigation of fluid structure interaction of flexible tube’s dynamic properties

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Abstract. Flexible tubes are often used in hydraulic measurement, be it connection between pieces of hydraulic equipment or an extension from point of measurement to measuring sensor or as a substitute for a different material e.g. biological tissue. Such tube material allows for rather large deformation and therefore influences measured parameters. Laboratory set up consisting of pressure sensors and piston pulsator was used to gather experimental data. Frequency response and properties were obtained in a range of frequencies. Fluid structure interaction simulation using ANSYS FEM and Fluent CFD packages and simulation in ANSYS Mechanical with acoustic-capabilities were used to compare experimental and computational data. Results show correlation between different approaches. Suitability of flexible tubes is discussed regarding the obtained properties.

1. Introduction
This article is aimed on investigation of dynamic properties of flexible tubes and possible effect of these properties when they are used in an experimental measurement. Previous studies were conducted on a behaviour of flexible tubes and correlation between experiment and FSI modeling [1]. Other studies were concerned with a stress and response of flexible tube compared to a rigid one [2]. These studies are often motivated by a research focus on a biomechanics of arteries, cardiovascular system and related problems. This paper is investigating behaviour of flexible tubes commonly used for a hydraulic measurement for a purpose of connecting selected point from e.g. hydraulic pipe to a suitable position for a sensor.

2. Experiment
To investigate dynamic behaviour of a flexible tube following laboratory set up was prepared (Fig. 1). Chosen length $L$ of flexible tube was placed between two fixed mounted pressure sensors. Piston pulsator was connected to create a harmonic pressure changes. Tubes were filled with water. To avoid a pressure vacuum the whole system was pressurized and the pressurization also helps with bleeding trapped air bubbles. There are two valves to close off the hydraulic line after the pressure is at intended level and the air has been bled out of the system.

Since there is not an actual flow but effectively only fluctuations of a wave excited by a pulsator, therefore no pressure drop is considered.
Experimental measurement starts with setting pressure up to chosen value. After this step the piston pulsator is started and specific frequency is tuned. Data acquisition from pressure sensors follows for a specified time interval. Then the frequency of piston pulsator is changed and in this manner whole spectrum of frequencies is measured. Used piston pulsator device allows range from one and twelve hertz and the measured lengths were chosen appropriately to reflect this limitation.

| Table 1. PVC tubes measurement parameters |
|------------------------------------------|
| Parameter            | Value                        |
|----------------------|------------------------------|
| Lengths              | 3.5, 7, 10.5 meters          |
| Inner (outer) diameter | 7 (10) mm                   |
| Wall thickness        | 1.5 mm                       |
| Frequency            | 1 – 12 Hz (step ~1 Hz)       |

In the described way the tubes of different lengths (tab. 1) were measured and from data the frequency response was evaluated. Using fast Fourier transform the pressure data were transformed into spectral dependent form. In the Fig. 2. and 3. dependency of pressure ratio on a pressure in pipe is shown. From the trend it is clear that the response at a natural frequency
exhibits highest pressure difference between sensors on ends of tube. From data it can be seen that the influence of a pressurization is rather small. Inflection of a phase difference trend (Fig.5) agrees with a natural frequency in a pressure plot.

The data presented were all measured with a constant amplitude of movement of pressure pulsator which was $\sim$13 mm. This experimental measurement was part of a [3]. In cited work the structural properties were obtained by fitting mathematical model of harmonically excited water filled tube to measured data. Resulting parameters were constants of Kelvin representation of Standard linear solid model. Expectedly this method provides good fit with the experiment and the more complex simulations with fluid flow (CFD FSI) and acoustics elements (FEM) only use elasticity obtained in this manner.

3. Acoustic FEM simulation
To investigate this behaviour of tubes FEM (finite element method) acoustic simulation was used. Using acoustic capabilities of ANSYS mechanical package model of acoustic and solid elements was made. Harmonic analysis simulation was analogical to a experimental set-up, the system is being excited on a chosen frequency and then the data are collected. Contrary to experiment there is no need for a Fourier transform since the data are already in spectral space.

Simulated model was simplified to a tube without any other parts. Harmonic pressure oscillation from a pulsator was replaced by a boundary condition of acoustic pressure. This parameter was provided from a results of experiment — data of the pressure sensor on the end of tube connected to the oscillating device. This boundary condition is defined by a real and imaginary part of pressure amplitude on a selected surface, this values were obtained from pressure amplitude and phase in experiment. At the opposite end of tube was a rigid wall and there was FSI (fluid structure interaction) interface between solid and acoustic elements.

Parameters of solid domain in acoustic simulation were obtained as variables of material model fitted onto experimental data. Because of different approach to material and bulk viscosity of water, damping in acoustic computation was diminished. This is reason for a higher pressure ratio compared to experiment. Model was computed as a fully damped and compressible.

Figure 4. Pressure amplitude ratio, 10.5 m long tube

Figure 5. Phase difference 10.5 m tube
4. FSI simulation

FSI simulation was computed with use of coupled ANSYS structural solver and ANSYS Fluent for a fluid part. Connection between these two packages was performed using System coupling in ANSYS Workbench. Because of the nature of simulated phenomenon the simulation was transient computation with a time-step of one hundredth of a second. Fluid structure interaction is time and processing power hungry task so it was useful to simplify computed domain to one quarter of a tube.

Boundary conditions on ends of tube were pressure inlet and velocity inlet. Pressure was defined with experimental data in a similar method as in acoustics simulation but in this case with time dependent pressure amplitude with appropriate phase. Pressure change was defined using UDF (user defined function) in Fluent. Velocity on the other side of tube was zero. Surfaces splitting the tube in on quarter along the axis had symmetry boundary condition and on a fluid structure interface was wall.

Dynamic mesh with a smoothing method was chosen due to deformations of structural part. The diffusion was used in a smoothing with a diffusion function set cell volume and diffusion parameter equal to zero. Fluid zones were set as deforming and the wall was made a system coupling type. Both ends of tube had a fixed support meaning zero degrees of freedom for selected nodes of structural part. Surfaces of symmetry were set as a frictionless support. FSI interface was defined on a inner wall of structural part of tube.

Mesh consisted of hexahedral cells (in fluid part linear, in structure quadratic). Discretization in tangential direction was twenty elements in both domains, lengthwise mesh discretization consisted of elements with one centimetre length. Tube was split in two elements in radial direction and fluid part had a sixteen elements in this direction. With regards to simulated experimental harmonic analysis laminar model of fluid simulation was used, since the velocities are rather small and there is not any significant vortex development. Physical properties of solid and fluid domain were same as in acoustic simulation if applicable. Number of elements was in magnitude of tens of thousands for structural domain and hundreds of thousands for fluid one. Computational mesh for a seven meter long tube was twice as big to keep the same size of elements in all directions.

Compared to acoustic simulation the FSI computation used a certain level of pressure inside the tube so buckling could not develop a and the simulation would match the experimental process. Because of the nature of transient simulation it was necessary to compute enough timesteps so the pressure pulsation become harmonic in time. Long enough time of pressure pulsation can then be transformed into spectral space with reasonable resolution and analysis analogous to the experimental data evaluation performed. Another difference to FEM approach is incompressibility of fluid medium.

| Parameter            | Value         |
|----------------------|---------------|
| density (fluid)      | 998 kg·m⁻³    |
| density (solid)      | 1000 kg·m⁻³   |
| viscosity            | 1·10⁻³ Pa·s   |
| bulk viscosity       | 7 000 Pa·s    |
| sound speed (fluid)  | 1 500 m·s⁻¹   |
| Young modulus        | 85 MPa        |
| Poisson number       | 1.42          |
5. Results and Discussion

In Fig. 6 and 7 are results in graphs, there is an agreement of trends in experiment and both computational approaches. There is a difference which in case of acoustic data has been caused by a not incorporating enough structural damping. This was expected result and the low structural damping was used intentionally because of a method of evaluation of material parameters from experiment. For a FSI simulation main there are other differences like not incorporating compressibility and therefore the damping by a bulk viscosity in fluid. There is however damping brought into simulation from numerics and also from a stabilization of fluid structure interaction coupling.

Even though the numerical values differ, the trend and ability to match the pressure ratio peak on natural frequency suggest that both methods are applicable for determination and prediction this kind of phenomena. Acoustic simulation offers advantage in much lower computational needs while on the other hand is more sensitive on a boundary condition choice. Fluid structure interaction is vastly more computationally intensive task since it is transient simulation. There is also more problems with stability and convergence though it can provide more detailed insight into simulated problem. This was also limiting factor for a quantity of computed variants of tube length and frequency.

Figure 6. Pressure amplitude ratio, 3.5 m long tube, experiment and simulations comparison

Figure 7. Pressure amplitude ratio, 7 m long tube, experiment and simulations comparison

There are sources of these differences in numerical and experimental analysis. Concerning the FSI there is boundary condition of fixed support and simplification to one quarter of a domain, both of these differ from measured physical model. Then there are stabilization parameters of FSI computation that help with convergence by use of limiting transfer of mechanical energy between fluid and structural. Because of the computational costs there is limited amount of data for a FFT to obtain a final result. The acoustics simulation is also simplified model of reality and compared to a FSI model there is an assumption of harmonic pulsations only and material characteristics of damping were simplified. In an appended image (Fig. 8) directional deformations are shown and an expected mode shape of quarter length can be seen. Also the radial and tangential (twist) deformations are order of magnitude smaller than lengthwise change.
6. Conclusion
In this paper dynamic behaviour of a flexible tube excited by a low frequency pulsation is presented. It could be a considerable factor in a measurement of similar set-up. Possible analogical situation that could drawn same phenomenon is a flexible (e.g. plastic) tube connecting hydraulic systems. In a specific case it would be possible to measure higher pressures on a connected pressure sensor than there really is at point of tube connection due to dynamic pressure amplification. In the paper are also carried out FSI and acoustic FEM simulations as a means to predict this behaviour. These methods provide a way to model this phenomena and are capable of matching the trend of experimental measurement data.

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Figure 8. Deformation in cylindrical coordinate system axes (radial, tangential and longitudinal). Tube length 3.5 meter, 12 Hz, acoustic FEM simulation, only half of solid domain is shown for a better visibility. Scale is in millimeters.