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Experimental and numerical investigation of flow field in flexible tube

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Abstract. The flexibility of walls influences the flow field in the cardiovascular system. The most of the existing experimental and numerical biomechanics work always tried to resolve this problem with rigid walls. In this work, an experimental simulation with the flexible wall will be carried out and the experimental data will be compared to the numerical solution. The aim of this work was to determine the influence of an elastic tube on final qualities of velocity profiles. Velocity profiles and deformations of the tube in the radial direction for any given time are the outcomes of this contribution. A high-speed camera was used in the experimental part of this work. The high-speed camera recordings enable to simultaneously detect the deformation of the flexible wall. The flexible tube was made of Tygon – a transparent material. Material parameters of Tygon were obtained from the uniaxial tensile test. The liquids used in the experimental measurement were air and water. The measurement was done for constant and pulsating volume flow. A pressure pulse generator was used to generate pulsatile flow. The computational simulation took advantage of the capability of commercial numerical solvers coupling between finite volume method CFD solution and finite element method mechanical solution. This approach is generally known as Fluid-structure interaction (FSI). Boundary conditions for numerical simulation were taken from measurement for reliable comparison of experimental and numerical results.

1. Introduction

Diseases of the cardiovascular system are common diseases caused by the type of lifestyle. To understand how cardiovascular diseases emerge and develop, plenty of experimental and numerical solutions have been performed. Originally blood flow was solved for a rigid material of blood vessels. However, the blood vessels material is highly elastic and therefore belongs to hyperelastic materials. Hyperelastic materials are matters, which evince elastic deformation larger than five percent. For that reason, the deformation of blood vessel walls has to be considered in solutions. This approach is called fluid-structure interaction (FSI). Experiment simulations with flexible tube were done in works [1, 2]. In these articles, the fully transparent elastic vessel was made from two-component polydimethylsiloxane. Determination of velocity profiles and wall deformation in radial direction were main purposes. Therefore particle image velocimetry (PIV) was used. Pulsating flow was generated by the pump in both cases. A mixture of water and glycerin was used as the liquid. Numerical solutions of this topic were made for many various models of material. Primal research of numerical FSI solution



was done with linear elastic material and Newtonian fluid [3, 8]. Nowadays constitutive models of blood vessels, which belong to hyperelastic materials, are used in the numerical solution of FSI. Majority representation has models like Money-Rivlin [5], Fung [6] and Neo-Hookean [7]. These constitutive models considered hyperelastic, isotropic, homogeneous and incompressible material in case of FSI. Any comparison between experiment and the numerical solution was done in works, which are the ones above mentioned. This comparison was done in the paper [8], but the material was just linear elastic. The main aim of this paper is a comparison between data from experiment and values from numerical solution of FSI with the hyperelastic material.

2. Methods

The purpose of this study was to compare data from the experimental and numerical calculation for physiological conditions (pressures ranging between 10 kPa and 16 kPa), but the material (Tygon), which was chosen for the flexible wall, is too stiff and has negligible deformation for physiological values of pressures. Therefore values of operating pressures were increased out of physiological range.

2.1. Experimental stand

New stand (see figure 1) was composed of steady flow inlet with a variable value of static pressure. Another part of the stand was pressure pulse generator which generated dynamic pulsation. Pressure sensors were placed on inlet and outlet of the flexible tube. Tygon was used as the material of the flexible tube. The inner diameter of pipe was 12.7 mm and outer diameter had value 15.9 mm. The tube had length 500 mm. Pressure sensor p_1 was placed higher than pressure sensor p_2 and the difference of altitudes was equal to tube's length. A high-speed camera was used for recording deformation of the outer tube diameter. The camera recorded displacements in the middle of the tube. Fixed support was used to attach Tygon tube on its inlet part. The outlet was attached by weight of pressure sensor and friction support.

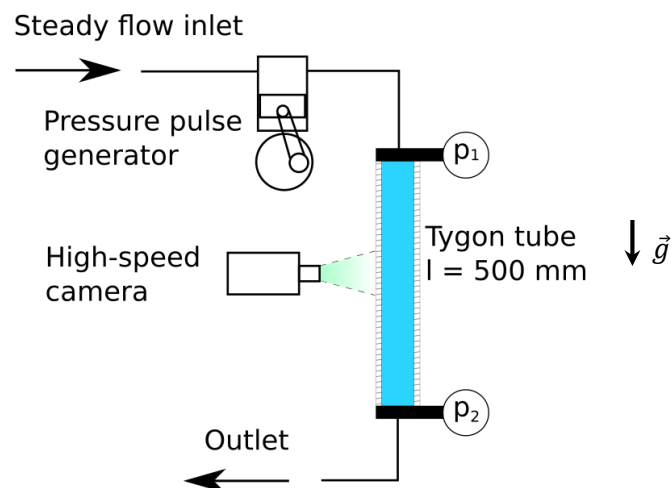


Figure 1. Scheme of experimental stand.

The experiment was done for two cases of loading. The first one was by only static pressure. The outlet of the whole stand was closed and the air was used as a medium for filling and pressurizing the tube. Pressure pulse generator was turned off for this experiment. The other type of loading was with dynamic pulsation. The stand had an open outlet in this case and therefore fluid could flow through the tube. Pressure pulse generator was turned on and water was used as a fluid medium.

Calibration of the camera was done for the steady state. The camera took a picture of pipe and number of pixels in the radial direction was determined by the contrast of pipe's edges at the interface of air and tygon. A thread was looped around the pipe to be sure, where is outer diameter directly (see

figure 2). The outer diameter was manually measured by caliper. Then was Pixels count per millimeter determined and it was equal to 13.83 pixels per millimeter.

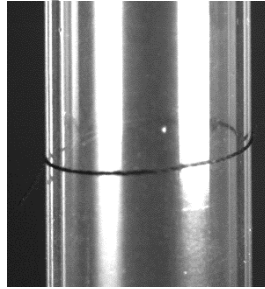


Figure 2. Detail of pipe.

2.2. Numerical solution

Commercial software (ANSYS) was used for numerical calculation of FSI. The transient structural was used as a solver of finite element method (FEM) and a fluid domain was solved by Fluent (software for computational fluid dynamics – CFD). Both software were connected with System coupling.

Numerical solution of FSI is a time-consuming process, and therefore whole domain was simplified. Cross-section of the domain was an only quarter circle (see figure 3).

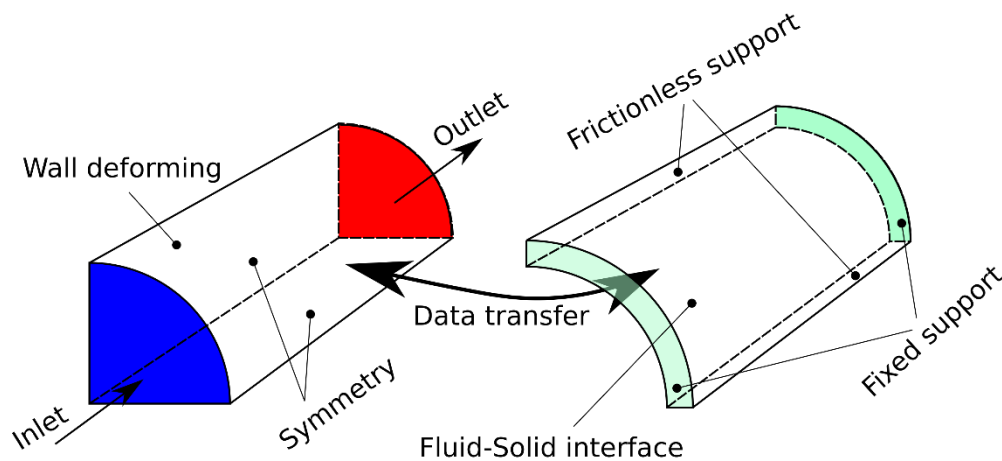


Figure 3. Geometry and boundary conditions.

Other parameters such as length and radius were the same as in experimental part. Symmetry boundary condition was used in fluid domain and Frictionless support boundary condition was applied to the structural domain. Boundary conditions for inlet and outlet were taken from experimental data. Velocity inlet and pressure outlet were used for simulation without dynamic pulsation. Velocity was equal to $0 \text{ m}\cdot\text{s}^{-1}$. Boundary conditions pressure inlet (total pressure) and pressure outlet (static pressure) were used for simulation with dynamic pulsations. Fluids were chosen the same as in experiments. The structural domain was attached by Fixed support on inlet and outlet. Material Tygon was considered as incompressible, homogeneous, isotropic and was defined by the neo-Hookean constitutive model. It was derived from the following hyperelastic strain energy function:

$$W = \frac{G}{2} (\bar{I}_1 - 3) \quad (1)$$

where W [Pa] is strain energy density,

G [Pa] is initial shear modulus,

$\bar{I}_1$ [-] is the first invariant of the right Cauchy-Green deformation tensor.

Material's parameters were found out from uniaxial tension test. Initial shear modulus had value 1.3 MPa. Stress-strain curves for Tygon are shown in figure 4.

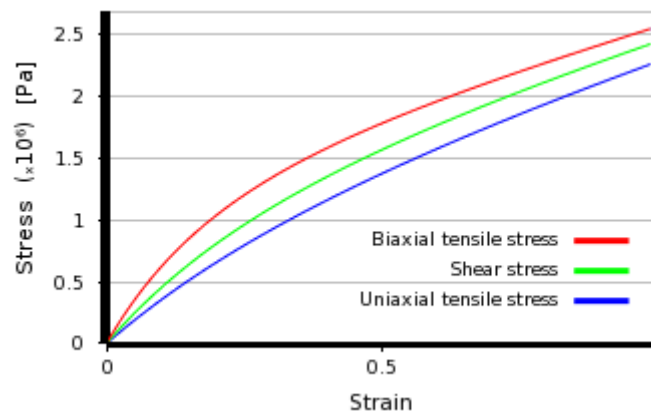


Figure 4. Tygon stress-strain curves.

Meshes of fluid and structural domains were made up of hexahedral elements. Mesh of the structural domain had 30 000 elements. 6 elements were defined in the radial direction, 20 elements were set in the tangential direction and 250 elements were used in the axial direction. Mesh of the fluid domain had 20 elements in radial and tangential direction. The fluid part was constituted by 75 000 elements. Maximal skewness of elements was 0.63 for the fluid domain and 0.03 for the structural domain. Maximum aspect ratio was 9.49 for the fluid domain and 7.52 for the structural domain.

Both solutions were calculated as transient. The size of time step was 0.005 s. Flow in the tube was considered as laminar. The geometry of both domains is changing during FSI calculation and therefore dynamic mesh was applied.

3. Results

Change of diameter with changing static pressure is shown in figure 5. The experiment was done for 9 different pressure loads. The smallest pressure was 24.4 kPa and the highest was 117.4 kPa. Numerical simulation was solved with continuous increasing pressure.

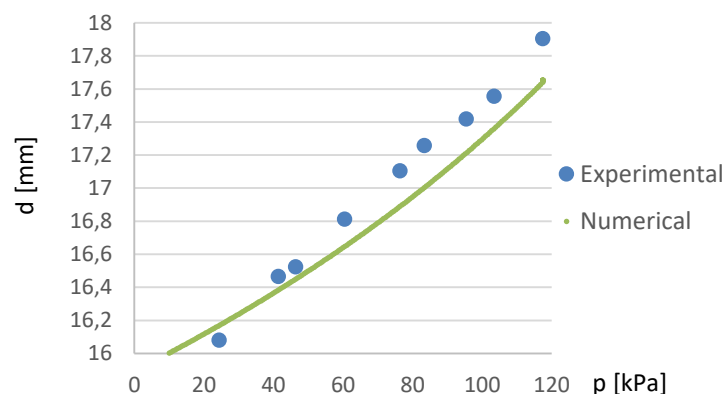


Figure 5. Diameter as a function of pressure.

Diameters from the experiment were except one measurement bigger than from calculation. The smallest differences were for values of pressure, which were close to 50 kPa. Inaccuracies of this solutions could be in both parts (experimental and numerical). Calibration of the High-speed camera was difficult. Cross section of real tube was not constant. Boundary conditions in experimental and

numerical part were a little bit different. Constitutive model, which was used to describe elasticity of the material, was not so correct as if direct data from the tensile test would be fitted.

In figure 6 are shown static pressures, which were recorded in a system with dynamic pulsations. The pressure differences between pressure sensors corresponded to experiment settings. Mean flow rate was $0.026 \text{ l}\cdot\text{s}^{-1}$. These data were used for boundary conditions in numerical solution.

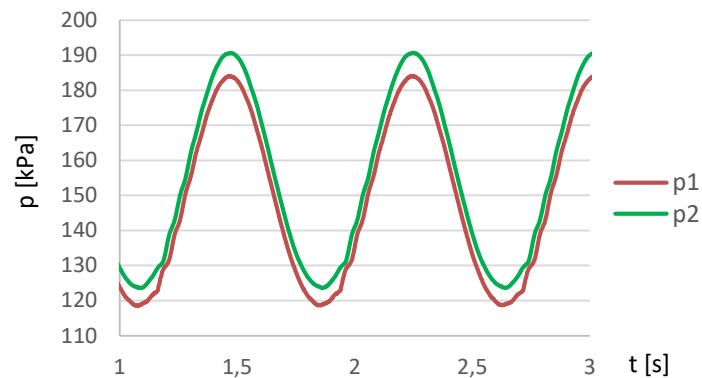


Figure 6. Pressure pulsations.

A comparison of experimental and numerical simulation for a system with dynamic pulsations is shown in figure 7.

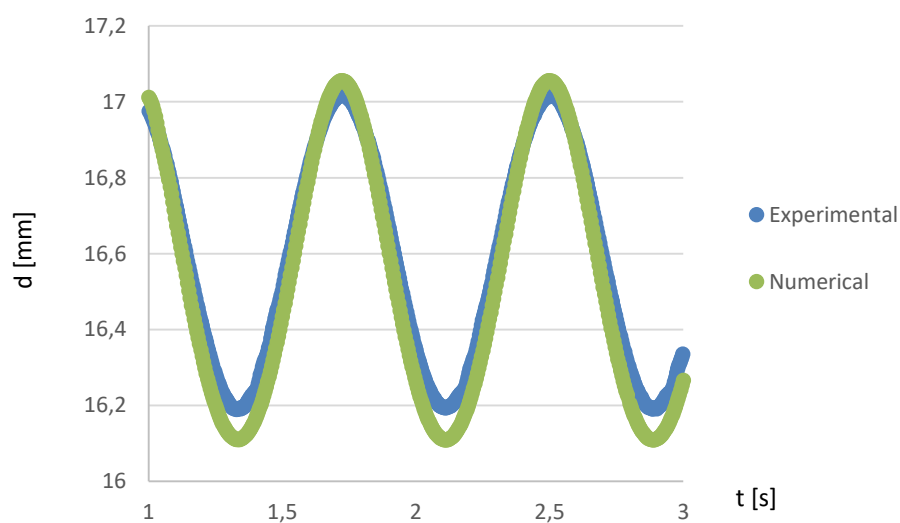


Figure 7. Comparison of external diameter from experimental and numerical part.

An interesting fact was that the data from simulation with dynamic pulsations fitted more than in a system without pulsations. Also, deformations were different. In figure 5 were diameters in case of small pressures smaller than from numerical solution. In figure 7 was it reversely. This could be caused by the flow of water inside the pipe or some inaccuracies, which one was this solution influenced for both cases (experimental and numerical). The biggest inaccuracy could be caused by the shape of a tube. The pipe's cross-section was not an ideal annulus (inner and outer diameter was not circular but elliptical and also wall thickness was not constant as it was considered in numerical simulations). This defect from manufacturing had an impact on deformations during experiments and the calibration of a high-speed camera. It is very complicated to define the right place of the outer diameter measuring by the caliper. Another problem in measuring by caliper was in compression of

the tube when the caliper gets in contact with pipe's wall. The calibration should be done with a steel pole because the manufacturing precision is much higher and it is not as pliable as tygon. The pole would be installed inside of the flexible pipe. This should guarantee annulus cross-section, better measuring by caliper and relatively constant contrast in the calibrating picture.

Velocity profiles for nine different times are shown in figure 8. These profiles were taken from the middle of the pipe (0.25 m behind inlet). It is obvious, that velocity profiles are time-dependent. Their magnitudes and radiuses were changed as it could be expected. The flow rate was never equal nor lower than $0 \text{ cm}^3 \cdot \text{s}^{-1}$, which corresponded to experiment. An interesting fact is a genesis of backward flow in the area, which was near to wall of the pipe. This negative velocity came into existence during pressure increases at boundary conditions. The wall's diameter was getting bigger but the flow rate was not changing so rapidly because of momentum conservation law (Navier-Stokes equations).

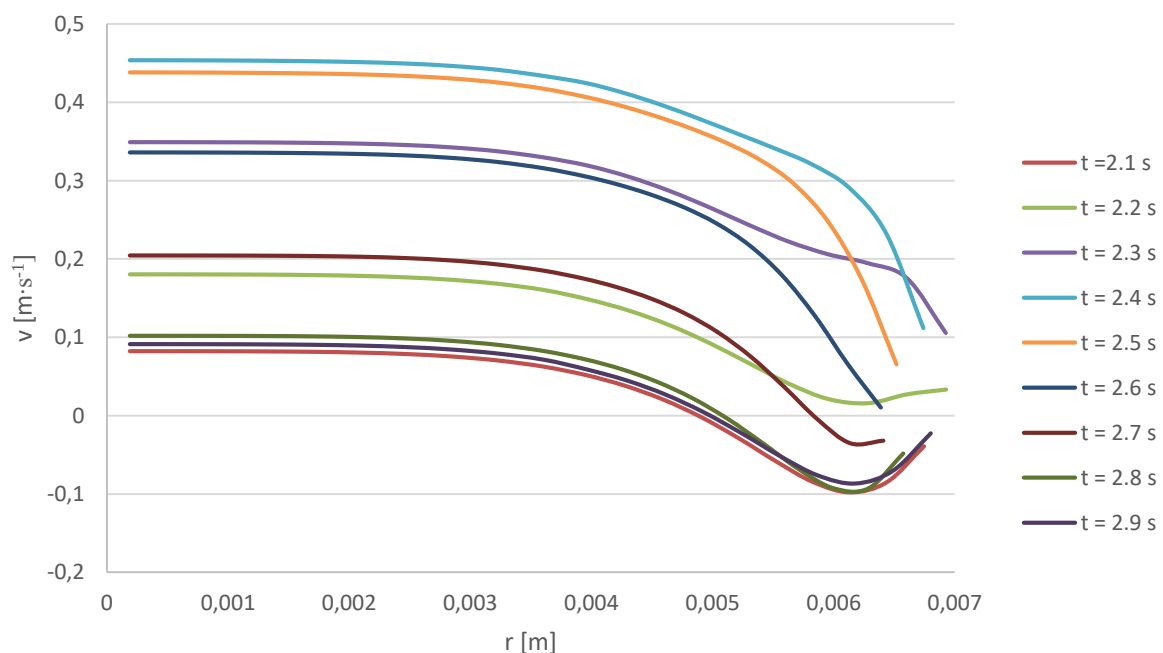


Figure 8. Axial velocity profiles.

4. Conclusion

Data from the experiment and the calculation were most precise for values of pressure around 50 kPa in the system without pulsations. Therefore measurement of the system with dynamic pulsations was done in an extent close to this value, because one of reason, why the data from experiment and simulation fitted the most, was a constitutive material model, which was used in numerical solutions. Comparison of external diameter from the experimental and numerical part for a system with dynamic pulsations came off relative good. Nevertheless, the amplitudes of deformations were different than in a system without pulsation. This could be caused by flowing liquid inside the pipe theoretically. The velocity profiles were greatly influenced by radial deformations of the wall, which also caused backward flow. The solutions showed the differences between the simplified numerical model and the real state of the experimental stand. Generally, solving this problem is very complex and complicated, because it is influenced by many inaccuracies.

In the future work will be done a better calibration of camera and mounting of the tube will be improved in the experimental part. PIV will be done in experimental part for a more precise description of flow in the tube, also these data could be in the future compared with velocity profiles from numerical solution.

Acknowledgment

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