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Experimental analysis of the fluid–structure interaction in finite-length straight elastic vessels

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ABSTRACT

Numerous bio-mechanical flow problems are characterized by fluid–structure interaction phenomena. To analyze in detail the impact of fluid–structure interaction on the overall flow structure and the wall motion the oscillating laminar flow in an elastic vessel is experimentally investigated by time-resolved particle image velocimetry and pressure measurements. The vessel deformation amplitude is varied between 0.5% and 6% of the vessel diameter at Reynolds number and Womersley number ranges of $300 \leq \text{Re} \leq 1000$ and $5 \leq \text{Wo} \leq 10$. Motivated by Womersley's fundamental results for rigid and elastic vessels it is the purpose of this study to extend the discussion to vessels of finite length undergoing high dilatation amplitudes and to provide benchmark data for numerical fluid–structure interaction methods. A detailed discussion of the results of the volume flux distribution, static pressure distribution, rate of change of the diameter, and wall-shear stress distribution is given and evidences a significant effect of vessel deformation on the distribution of the flow quantities. The inlet volume flux distribution excited by the piston pump generates an internal pressure distribution determining the vessel deformation which via the temporal derivative of the diameter change generates a delayed volume flux distribution that is superimposed onto the inlet volume flux. The comparison of the results with comparable rigid pipe flows shows variations in the velocity profile amplitude of up to 10% depending on the phase angle. The vessel elasticity leads to a wall-shear stress reduction during forward flow of up to 20%.

1. Introduction

Cardiovascular diseases cause the majority of deaths in Europe and the US [1]. To learn how cardiovascular diseases emerge and develop, numerous numerical simulations have been performed to analyze the highly intricate problem of the interaction of the flow and the elastic vessel wall. The wall-shear stress (WSS) mediates this interaction of the fluid with the vessel wall and thereby influences the endothelial cell function and phenotype [2–6].

Considering the mathematical relation between oscillating pressure and flow in rigid and elastic pipes, Womersley [7] made a comprehensive contribution to oscillating and pulsatile flow in elastic vessels. Based on his results the shape of the velocity profiles at oscillating flow in rigid pipes is characterized by the Womersley number

$$\text{Wo} = D_0/2\sqrt{\frac{\omega}{\nu}}, \tag{1}$$

which is defined by the pipe diameter D_0, the excitation angular frequency ω, and the kinematic viscosity ν. Womersley used a perturbation method based on the linearization of the governing equations of the fluid and the structure to analyze oscillatory and pulsatile flow through isotropic elastic vessels of infinite length at small dilatation amplitudes. His theoretical analysis was extended, e.g., by Whirlow and Rouleau [8], Atabek and Lew [9], Mirsky et al. [10], and Atabek [11] to account for anisotropy, thetering, and taper of the vessel wall. Compared to numerical analyses only a few experimental investigations on oscillating flows in elastic vessels are known. It is fair to state that the higher the flexibility of the structure, the less experimental data of the impact of the moving wall on the flow field are available.

The effect of vessel elasticity and pulsatile frequency on the WSS distribution was investigated by Duncan et al. [12] and Kuban and Friedman [13] by comparing rigid and compliant vessel models. The velocity distribution at various positions at the wall near the bifurcation was measured by laser-Doppler velocimetry and the wall displacement was determined by a linescan camera. The comparison of the rigid and the elastic vessel model showed a significant impact of the vessel elasticity on the WSS distribution, i.e., the WSS increased or decreased depending on the measurement

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location, while no significant effect of the pulsatile frequency on the mean WSS in the elastic model was observed. Mijovic and Liepsch [14] performed experimental studies at various flow conditions in an elastic bifurcation model using a laser-Doppler anemometer and showed the vessel elasticity to reduce flow separation. Time-resolved particle-image velocimetry (TRPIV) combined with a wall detection algorithm and non-invasive pressure measurements were applied by Pielhop et al. [15] to investigate the oscillating flow through a flexible, stenosed flow model. Flow fluctuations could be related to the motion of the flexible vessels walls via a frequency analysis. Compliant flow models were also investigated by two-dimensional particle-image velocimetry (2D-PIV) by Geoghegan et al. [16] and Eguchi et al. [17] but without a discussion on the effect of the vessel's elasticity on the flow.

Tang et al. [18] introduced an experiment-based 3D computational model with fluid–structure interaction (FSI) and simulated blood flow in stenotic collapsible carotid arteries using a generalized finite difference method. Based on experimental data for the pressure–area relationship the model provides a first-order approximation of the complex artery cyclic collapse process. Regarding a blood flow related large-displacement FSI problem, Gerbeau et al. [19] elaborated on the mesh generation from medical imaging data to implement realistic geometries. The nonlinear FSI coupling was tackled by a Jacobian-free Newton–Krylov method. Since the authors did not address the difficulties of FSI simulation like boundary conditions and constitutive laws their work is appropriate to only fit the coefficients of 1D structure models which allow a drastic reduction of computational complexity. Greenshields and Weller [20] proposed an alternative approach to solve the FSI problem in flexible tubes by solving both fluid and solid components within a single discretized continuum domain. Their results show good agreement with analytical solutions of wave propagation in elastic vessels. The idea of considering the fluid and the structure as a continuous medium was also proposed by Tallec and Mouro [21] and applied to a hydroelastic shock absorber without validation.

From the discussion of the experimental and numerical investigations it can be concluded that various phenomena have been analyzed in detail. Womersley's and the later mathematical analyses provide the fundamental understanding of oscillatory flow in straight elastic vessels of infinite length at small dilatation amplitudes. Since these models are based on a linearization of the governing equations they do not accurately reproduce large dilatation amplitudes and do not directly apply for finite vessel length. This is the reason for this study. In contrast to Womersley's results vessels of limited length and undergoing large dilatation amplitudes are experimentally investigated in detail. In this sense, the knowledge is extended to large dilatation and the data of this study serve as reference results to validate FSI solvers for elastic vessel flows. A data set of that kind requires the simultaneous measurement of the pressure and velocity distributions and the vessel deformation. Furthermore, the inflow and outflow conditions of the experiment are to be well defined. To provide such reference results consisting of noninvasive pressure measurements and time-resolved velocity distributions including the vessel wall response and the wall-shear stress is the first objective of this study. Second, the mechanism of the FSI in elastic pipes is to be analyzed and third, the impact of the elasticity of the vessel wall on the wall-shear stress distribution compared to a rigid pipe flow is to be investigated.

To achieve these objectives TRPIV measurements combined with synchronous measurements of the static pressure are performed in elastic, transparent vessel models at oscillating laminar flow of various dilatation amplitudes, i.e. for a range of Reynolds and Womersley numbers. The high spatial resolution of the velocity field allows to determine the WSS distribution. The pressure outside the elastic vessel and the velocity and the static pressure distributions in the inlet and outlet are recorded. The vessel models are manufactured at different wall thicknesses to analyze the effect of varying vessel compliance. The elastic vessel models are made from Polydimethylsiloxane (PDMS) with high accuracy. The optic, geometric, and structure-mechanic properties of each vessel model are measured in detail before the vessel is integrated in the refractive index matched test bench.

The paper possesses the following structure. The experimental facility, i.e., the elastic vessel model and the measurement technique, is discussed in Section 2. Subsequently, the data evaluation based on the TRPIV images is introduced. The vessel-wall detection and the wall-shear stress computation are described in detail. After the flow parameters are given in Section 4, the experimental results are discussed in Section 5 where first, the fluid–structure interaction in an elastic vessel is analyzed and then a comparison of flexible and rigid walls is presented. The results are presented very detailed to show the sensitivity of the measurement quantities with respect to the parameter variation, i.e., vessel geometry, dilatation amplitude and Reynolds and Womersley number. Finally, conclusions are drawn in Section 6.

2. Experimental setup

2.1. Elastic vessel model

The fully transparent, elastic vessels are made from the two component PDMS of the type RTV 615 by rotational casting. The casting mold defines an outer vessel diameter of $D_0 = 24$ mm at wall thicknesses of 0.90 mm (A), 1.02 mm (B), and 1.16 mm (C) to investigate the influence of the vessel wall thickness on the fluid–structure interaction. Due to the mismatch of the thermal expansion coefficients of the casting mold and the PDMS, the outer vessel diameter is approximately 2% smaller during the measurements which are performed at room temperature. The vessel length is 450 mm. When the vessels are inserted in the experimental facility they are stretched by 7.5% (A), 8.5% (B), and 7.5% (C) of the original vessel length. The geometric properties of the elastic vessels are measured optically. This allows a very high accuracy and contact-free determination of the initial wall thickness which is especially important when handling highly elastic material like PDMS. These measurements show the wall thickness variation over the whole vessel length to be less than 1% of the vessel wall thickness. To determine the structure-mechanical properties of each vessel model the Young's modulus and the vessel compliance are measured. The density of the vessel material is 1.019 kg/l. From every vessel model a sample to measure the refractive index is cast. The Poisson's number for hyperelastic materials like PDMS is 0.4999 [22].

The structure-mechanical properties are measured by conducting a tensile test using a probe cut from the investigated vessel. The probe is cut according to DIN standard 53 504 type S2 which ensures the correct application of the external force. The best fit of the strain–stress curves of vessel A is the 4th order polynomial

$$\sigma_{fit}(\epsilon) = 37.2654\,x^4 + -18.2032\,x^3 + 4.01815\,x^2 + 1.26225\,x \tag{2}$$

where the stress σ is in N/mm^2 and the strain ϵ defined by

$$\epsilon = \ln\left(\frac{l}{l_0}\right), \tag{3}$$

where l defines the tensile length and l_0 the initial tensile length. The Young's modulus $E = 1.4639$ N/mm^2 of vessel A is calculated at a standard deviation of 0.0163 N/mm^2 for a strain of up to 0.15, below which the material exhibits a linear behavior during the tensile test. The strain relevant for the measurements in this study