NUMERICAL SIMULATION OF THREE DIMENSIONAL FLOWS THROUGH A COLLAPSIBLE TUBE

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ABSTRACT

Three-dimensional numerical simulations of steady Newtonian viscous flow past an elastic tube are presented. The finite element package FIDAP was used to solve the equations governing the fluid mechanics and structural mechanics involved. Numerical solutions of the Navier-Stokes equations coupled with a large, non-linear deformation of brick elements are obtained for different Reynolds numbers in the range of 0 - 300. The computational results of the code are compared and validated with the computational predictions previously published in the literature.

INTRODUCTION

There are numerous physiological and clinical examples in which tubes are collapsed, for example: veins above the level of the heart and outside the skull collapse due to hydrostatic reduction of blood pressure; both veins and arteries are collapsed during sphygmomanometry; during micturition the uretra behaves like a passive collapsible tube; the ureter during peristaltic pumping collapses; lung airways collapse during forced expiration, etc.

The theoretical understanding and comprehension of the complex dynamics involved in phenomena related with the flow trough highly compliant vessels are therefore a key issue in biomechanical research. Given its importance and complexity, this subject has been a topic of great research for over 30 years. Many authors studied this physical phenomenon by using one-dimensional and two-dimensional models [1-6]. It goes without arguing that a complete understanding of the strongly non-linear behaviour of the structure ultimately requires a three-dimensional approach. However, due to the extensive computational resources required, to date there are relatively few investigations on flow in 3D collapsible tubes [7-9]. In this paper, we present some preliminary results of 3D numerical simulations for flow in collapsible tubes.

METHODS

When the external pressure of a compliant tube is increased up to a particular critical value, the structure buckles. To model this fluid-structure interaction problem involving large displacements, a mixed Arbitrary Eulerian-Lagrangian (ALE) method is used here, where the movable mesh is updated by employing a so called Computational Mesh Dynamics (CMD) method [10]. In other words, the mesh is modelled as a pseudo-elastic medium and therefore deforms smoothly governed by a set of elastic equations. This ensures the good mesh quality during the large deformation of the tube. An iterative scheme is used here: for a given mesh, the fluid flow equations are solved first. The pressure and the traction exerted by the fluid are successively applied to the structure and the structural and mesh equations are then solved. This gives us the structural displacement, and hence the updated mesh configuration. This process is repeated until the convergence is achieved.

RESULTS

In all the computations presented here the computational domain is a quarter of the deformable tube whose ends are both clamped to two rigid tubes. The material of the deformable tube is assumed to be elastic and linear, and the flow is laminar flow and Newtonian. The tube's radius is R=4 mm, the deformable tube length is L=10R and the wall thickness is h=R/20. The upstream and downstream lengths of the rigid tubes are respectively L_{up}=R and L_{down}=10R. The Young's module is $4.56x10^{-3}$ Pa, and the Possion's ratio is 0.49. These parameters are chosen to be the same as those used by Hazel & Heil (2002).

The deformed mesh is shown in figure 1 where the flow is directed as the z-axis. The grading is finer close to the area where large displacements were expected. The 27-noded brick elements were used to discretise both structural and fluid domain. The mesh convergence was validated by reapeating selected analyses using finer discretisations. Excellent agreements are also achieved with the computational results by Hazel & Heil [9 & private communication]. The flow and pressure fields for flow in the tube undergoes the external pressure of 1.63x10^{-6} Pa are shown in figures 2 & 3.

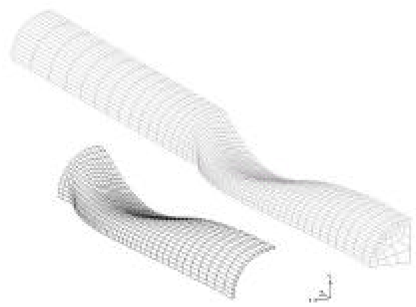


Figura 1. The finite element meshes created for the structure (bottom) and the fluid (top).

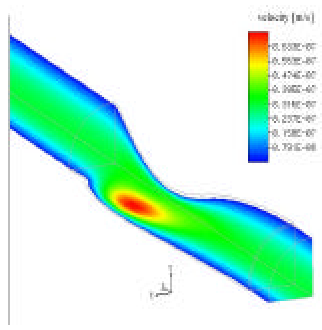
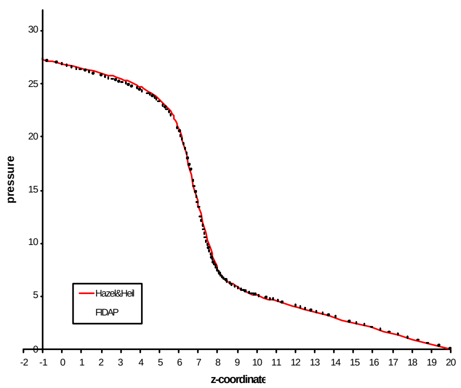


Figura 2. Contours of axial velocity on the x- and y- symmetry



planes of the computational domain.

Figure 3 The pressure distribution along the x-axis of the collapsible tube. The red line is the result from Hazel and Heil [9].

DISCUSSION AND CONCLUSIONS

Steady flows in a three dimensional collapsible tube are simulated using FIDAP. The results are successfully validated using the grid independence check, as well as using the computational results by Hazel & Heil [9] using thin shells. The finite thickness of the present model made it possible to simulate results that are more applicable with the experiments, which were usually conducted with relatively thick walled tubes [11]. Some preliminary comparison of steady flows in the thin and thick walled tubes will be presented.

To understand the self-excited oscillations in the collapsible tubes, it is necessary to investigate the time dependent behaviour of the system. This is currently underway.

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