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DEVELOPMENT OF A BLOOD FLOW MODEL INCLUDING HYPERGRAVITY AND VALIDATION AGAINST AN ANALYTICAL MODEL

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ABSTRACT

Fluid structure interaction (FSI) appears in many areas of engineering, e.g. biomechanics, aerospace, medicine and other areas and is often motivated by the need to understand arterial blood flow. FSI plays a crucial role and cannot be neglected when the deformation of a solid boundary affects the fluid behavior and vice versa. This interaction plays an important role in the wave propagation in liquid filled flexible vessels. Additionally, the effect of hyper gravity under certain circumstances should be taken into account, since such exposure can cause alterations in the wave propagation underexposed. Typical examples in which hyper gravity occurs are rollercoaster rides and aircraft or spacecraft flights.

This paper presents the development of an arterial blood flow model including hyper gravity. This model has been developed using the finite element method along with the ALE method. This method is used to couple the fluid and structure. In this paper straight and tapered aortic analogues are included. The obtained computational data for the pressure is compared with analytical data available.

INTRODUCTION

Long-term spaceflight causes the cardiovascular system of astronauts to adapt to microgravity. However, during a flight, in addition to microgravity, astronauts also face hypergravity up

to 3.2 g at launch, and about 1.4 g on re-entry [1]. Every human is subjected to whole-body accelerations in day to day life, e.g. traveling in road vehicles, sitting in a roller coaster or flying in an aircraft. When a human undergoes high accelerations for a longer period of time, for example astronauts or fighter pilots, the velocity changes may lead to many health problems, e.g. headache, loss of vision, loss of consciousness and even death. Due to these physiological effects it is desirable to understand the changes in the blood flow caused by whole body accelerations.

In order to understand the effect of hypergravity on the blood flow many studies have been performed. The studies found in the literature that take into consideration the effect of gravity can be categorized in experimental (*in-vivo* and *in-vitro*), analytical theories and computational models. In the literature there is a vast amount of *in-vivo* [2–9] experiments. Unfortunately there is a lack of well defined *in-vitro* wave propagation experiments in flexible aortic analogue vessels taking the effect of hypergravity into consideration as far as the author is aware of. However *in-vitro* experiments with centrifuges and hyperbolic flights have been performed [10].

Analytical models have been derived to theoretically investigate the influence of hypergravity on the blood flow. In the literature several analytical models can be found [11–17].

Computational models also play an important role in the understanding of the role of hypergravity on the human body. This may lead to the development of new tools and to a better design

of already existing protective pads or other countermeasure devices.

In experimental, analytical and computational models fluid-structure interaction (FSI) plays a crucial role since the deformation of the solid boundary cannot be neglected. When the heart beats a volume of blood is introduced into the vessel. The vessel has to accommodate to this change in volume and therefore the vessel wall expands. Due to this expansion of the vessel, the velocity and pressure of the fluid flow are affected since the fluid boundaries are altered. In the 1970s FSI equations were computationally solved for the first time due to the introduction of computers. Complicated two-dimensional and three-dimensional problems were solved using finite element or finite volume methods. In [18], an analytical method is presented that determines the pressure of a propagating wave in the aorta by using a multiple reflection and transmission theory.

Numerically solving FSI problems involves solving two distinct problems, a fluid and a solid problem. FSI can be solved in several ways. In the computational model presented in this paper, the *Iterative over each time step* method is used. Figure 1 assists the reader with the understanding of this FSI method.

Figure 1. Solution procedure of the *Iterative over each time step* method.

In a single time step in the *Iterative over each time step method* the fluid equations are solved and the pressure solution becomes the boundary condition for solving the solid equations. The solution obtained after solving the solid equations, is returned as a boundary condition for the fluid. The fluid equations are solved again. This process is repeated for the single time step until the system converges. When convergence is reached the process proceeds with the next time step [19, 20].

The computational model has been made in the program Comsol. Comsol is a finite element modeling package. The aim of this paper is to present a model developed in Comsol that is able to simulate wave propagation in the aorta subjected to hypergravity and to compare the numerical results with the results obtained from an analytical method.

MATHEMATICAL FORMULATION

By placing the vessels in vertical position, the fluid and the vessel wall will experience a pressure caused by gravity. The theory in [21] presents an analytical model for vessels undergoing hypergravity. The analytical results are compared in this paper

with the numerical results obtained by Comsol, for the case when $1g$ is applied. First, a short description is given of the analytical model, the geometry used, and the setup of the numerical model.

Wave Propagation in Flexible Vessels

Consider a vessel of length L , starting at $z = L_0 = 0$ and ending $z = L_N = L$; see Fig. 2. The vessel consists of N sub-

Figure 2. Schematic drawing of a vertically placed vessel undergoing hypergravity.

sequent sections represented by the intervals $[L_{n-1}, L_n]$, with $n = 1, 2, \dots, N$. The vessel is subdivided since every section can have different geometrical or material properties.

For each section n four different waves can arrive from two different directions, see Fig. 3.

Figure 3. Four waves arriving in section n .

These waves can be originated by

1. Forward traveling wave, $\hat{p}_f^{(a)}$, from section $n - 1$ which is transmitted into section n .
2. Forward traveling wave, $\hat{p}_f^{(b)}$, from section n which is reflected from section $n - 1$.
3. Backward traveling wave, $\hat{p}_b^{(c)}$, from section n which is reflected from section $n + 1$.
4. Backward traveling wave, $\hat{p}_b^{(d)}$, from section $n + 1$ which is transmitted into section n .

Here $\hat{p}_b$ represents the pressure of the backward traveling wave and $\hat{p}_f$ the pressure of the forward traveling wave.

Since gravity is included now, there is also gravity pressure present. The gravity pressure is caused by the volume of the fluid above position z_n . The total pressure at z_n is now given by

$$\hat{p}_t(\omega, z_n) = \hat{p}_f^{(a)}(\omega, z_n) + \hat{p}_f^{(b)}(\omega, z_n) + \hat{p}_b^{(c)}(\omega, z_n) + \hat{p}_b^{(d)}(\omega, z_n) + \hat{p}_g(\omega, z_n) \quad (1)$$

The analytical data, using Eqn. (1), will be used to verify the model made in Comsol.

Modeling Blood Flow using Comsol

The modeling package Comsol [22] can be used to model the behavior of blood flow through a blood vessel [20]. This modeling package is based on finite elements. The Arbitrary Lagrangian Eulerian (ALE), moving mesh, method is used for the coupling of the fluid and solid domain. The fluid flow application mode is defined on the ALE frame and the structural mechanics application mode is defined on a reference frame [22]. The interaction between the two domains is included by applying the *iterative over each time step* method.

The Fluid Flow The incompressible Navier-Stokes equations describes the fluid flow inside the vessel. The momentum and continuity equation, in the spatial moving coordinate system, are written as

$$\rho \frac{\partial \mathbf{u}}{\partial t} - \nabla \cdot [-p\mathbf{I} + \mu(\nabla \mathbf{u} + (\nabla \mathbf{u})^T)] + \rho((\mathbf{u} - \mathbf{u}_m) \cdot \nabla) \mathbf{u} = \mathbf{F} \quad (2)$$

$$\nabla \cdot \mathbf{u} = 0 \quad (3)$$

Here μ is the dynamic viscosity, ρ is the density, $\mathbf{u}$ is the velocity field, $\mathbf{u}_m$ the coordinate system velocity, p is the pressure, $\mathbf{I}$ the unit diagonal matrix and $\mathbf{F}$ is the volume force affecting the fluid. Since gravity alterations affect both the fluid and the solid, the applied gravity pulse has to be included in both domains. To include hypergravity in the fluid $\mathbf{F}$ has to be defined. The transition from 0g to 1g or 2g used is smooth. Therefore a gravity pulse similar to the pulse in Fig. 4 was applied. with

$$\frac{F_z}{\rho} = \sin^2 \left(\pi \frac{t}{2Dt_1} \right) (t < Dt_1) + 1(t > Dt_1)(t < (Dt_1 + Dt_2)) + (1 - \sin^2 \left(\pi \frac{t - (Dt_1 + Dt_2)}{2Dt_3} \right)) (t > (Dt_1 + Dt_2))(t > Dt_3) \quad (4)$$

Figure 4. Gravity pulse applied to the blood and blood vessel.

This gravity pulse is only applied in the z direction of the vessel. A normal inflow velocity pulse, starting at $t = t^*$, is defined at the entrance of the vessel. In this way the wave propagation with constant gravity can be determined. The velocity pulse satisfies the no-slip condition for the wall. The normal outflow velocity at the end of the vessel is set zero in order to close the vessel. On the solid wall the velocities are equal to the deformation rate.

The Solid Domain A standard linear solid model, the schematic representation of this model can be found in Fig. 5, is used to solve the structural deformations of the visco-elastic wall.

Figure 5. Standard linear solid model representing the viscous elastic model.

Here η is the dashpot's coefficient, E_e is the Young's modulus of the elastic part and E_v is the Young's modulus of the viscoelastic part. The stress, σ , and strain, ϵ , are related through

$$\sigma + \tau \dot{\sigma} = \frac{E_e}{2} \left(\epsilon + \tau \left(1 + \frac{E_v}{E_e} \right) \dot{\epsilon} \right) \quad (5)$$

where τ is called the relaxation time. To include the effect of hypergravity, a body load in the z direction is applied by using the same gravity pulse as was done in the fluid domain.

Moving Mesh To couple the fluid and the solid domain the moving mesh method ALE is used. ALE combines features

of the Lagrangian and Eulerian method. The Lagrangian method, often used in solid mechanics, follows the material during motion. However, without remeshing, this method cannot follow large distortions. The Eulerian method, often used in fluid mechanics can handle large distortions but it typically cannot take moving boundaries into account. Since ALE allows a flexible grid and a grid that allows for material to flow through it, this method is very helpful when the structure undergoes large deformations [23].

RESULTS AND DISCUSSION

The simulations have been performed for a straight (S) and tapered (T) vessel. In Fig. 6 the two vessels can be found. The

Figure 6. The polyurethane vessels

density of the vessel is 880 kg/m^3 . The parameters used for the fluid and the viscoelasticity of the vessel can be found in Table 1. In Fig. 4 the gravity pulse which has been applied can be found. At $t = t^*$ a velocity pulse is applied at the inlet of the vessel, that means that the wave propagation is measured when constant gravity is applied to both the fluid and the vessel.

Since only gravity is applied in the axial direction the problem is axi-symmetric and can therefore be solved in 2D. For both vessel S and T a structured grid of 12000 elements was used, 600×15 for the fluid domain and 600×5 for the solid domain. The parallel sparse direct linear solver, PARDISO, was used to solve the equations.

Table 1. Parameters used for the simulations

parameters	Vessel S	Vessel T
ρ [kg m^{-3}]	998	998
μ [$\text{kg m}^{-1} \text{s}^{-1}$]	1.04×10^{-3}	1.04×10^{-3}
K [$\text{kg m}^{-1} \text{s}^{-2}$]	337×10^6	337×10^6
E_e [$\text{kg m}^{-1} \text{s}^{-2}$]	7.5×10^6	7.5×10^6
E_v [$\text{kg m}^{-1} \text{s}^{-2}$]	3.7×10^6	3.8×10^6
τ [$\text{kg m}^{-1} \text{s}^{-1}$]	6.58×10^{-5}	1.97×10^{-3}

The obtained wave propagation is compared with analytical data available. In Fig. 7 the analytical results of J.M.B. Kroot and C.G. Giannopapa [21] can be found for vessel S and vessel T respectively, for the cases in which $0g$ and $1g$ are applied.

In Fig. 8 the computational results obtained with Comsol are shown. The results for both vessels S and T show that the wave propagations for the computational data are similar to those of Fig. 7. Furthermore in Fig. 8 the computational data when $0g$ is applied is used for the comparison. However, it appears that the numerical model can be used to predict the wave propagation of a pulse in a blood vessel undergoing hypergravity since the wave speed and the behavior of the waves is similar.

Since astronauts face hypergravity up to $3.2g$ in Fig. 9 the pressure for vessel S and in Fig. 10 the pressure for vessel T for $2g$ and $3g$ respectively can be found. It can be seen that hypergravity affects the damping of the wave.

CONCLUSION AND FUTURE WORK

A finite element model for modeling blood flow with hypergravity has been developed. This model has been compared with an analytical model. This model will provide a better understanding of the role of hypergravity in fluid structure interaction in flexible vessels and in particular of aortic relevance.

The computational model appears to be in good agreement with the analytical data when $1g$ is applied. Results are also presented for the case in which $2g$ and $3g$ are applied. Since the cause of the changes in the shape and damping of the pressure pulse cannot yet be explained, one has to be cautious when using the model to predict wave propagation in liquid filled flexible vessels when higher g-forces are applied.

In order to validate the numerical and analytical models further, experimental data is needed. However, no suitable experimental data is available in the literature as far as the authors are aware of. Therefore, the next step would be to perform experiments with a similar experimental set-up as in [19], but in a Large Diameter Centrifuge in order to generate g-forces.

(a) Pressure in vessel S

(b) Pressure in vessel T

(a) Pressure in vessel S

(b) Pressure in vessel T

Figure 7. The analytical results for the pressure evolution [21]; dashed line when $0g$ is applied, solid line when $1g$ is applied.

Figure 8. The computational results for the pressure evolution; dashed line data when $0g$ is applied, solid line data when $1g$ is applied.

(a) Pressure in vessel S when 2g is applied

(b) Pressure in vessel S when 3g is applied

Figure 9. The results for the pressure evolution using Comsol

(a) Pressure in vessel T when 2g is applied

(b) Pressure in vessel T when 3g is applied

Figure 10. The results for the pressure evolution using Comsol

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