

Development of a blood flow model including hypergravity and validation against an analytical model

Citation for published version (APA):

Geel, van, M. H. A., Giannopapa, C. G., Linden, van der, B. J., & Kroot, J. M. B. (2011). *Development of a blood flow model including hypergravity and validation against an analytical model*. (CASA-report; Vol. 1147). Technische Universiteit Eindhoven.

Document status and date:

Published: 01/01/2011

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

EINDHOVEN UNIVERSITY OF TECHNOLOGY
Department of Mathematics and Computer Science

CASA-Report II-47
September 2011

Development of a blood flow model including hypergravity
and validation against an analytical model

by

M.H.A. van Geel, C.G. Giannopapa, B.J. van der Linden, J.M.B. Kroot



Centre for Analysis, Scientific computing and Applications
Department of Mathematics and Computer Science
Eindhoven University of Technology
P.O. Box 513
5600 MB Eindhoven, The Netherlands
ISSN: 0926-4507

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

M.H.A. van Geel* C.G. Giannopapa† B.J. van der Linden‡ J.M.B. Kroot

Dept. of Mathematics and Computer Science

Eindhoven University of Technology

PO Box 513, 5600 MB Eindhoven

The Netherlands

Email*: m.h.a.v.geel@student.tue.nl

Email†: c.g.giannopapa@TUE.nl

Email‡: B.J.v.d.Linden@TUE.nl

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.

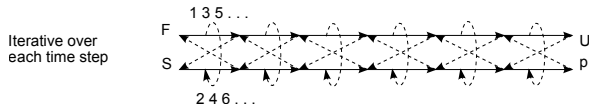


Figure 1. Solution procedure of the *Iterative over each time step* method.

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-

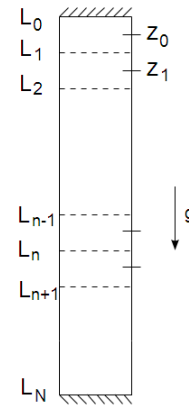


Figure 2. Schematic drawing of a vertically placed vessel undergoing hypergravity.

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.

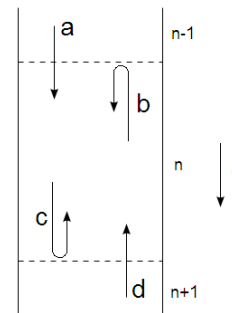


Figure 3. Four waves arriving in section n .

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

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

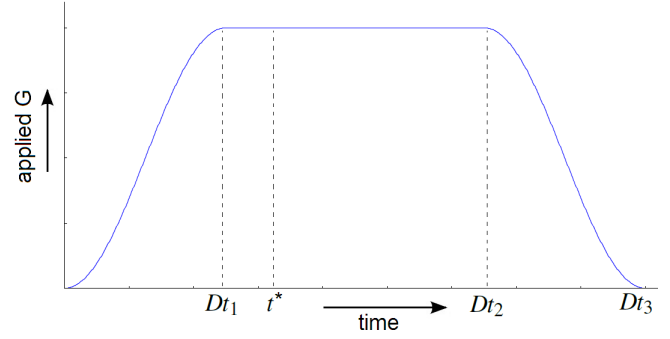


Figure 4. Gravity pulse applied to the blood and blood vessel.

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.

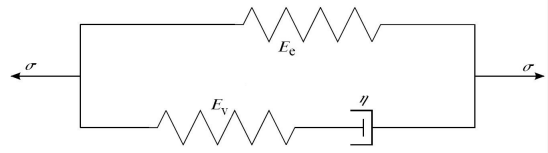


Figure 5. Standard linear solid model representing the viscous elastic model.

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

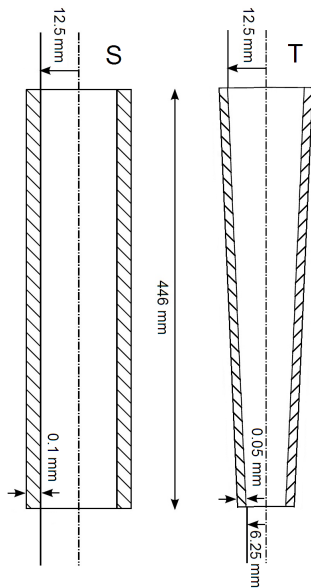


Figure 6. The polyurethane vessels

density of the vessel is $880\text{kg}/\text{m}^3$. 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.

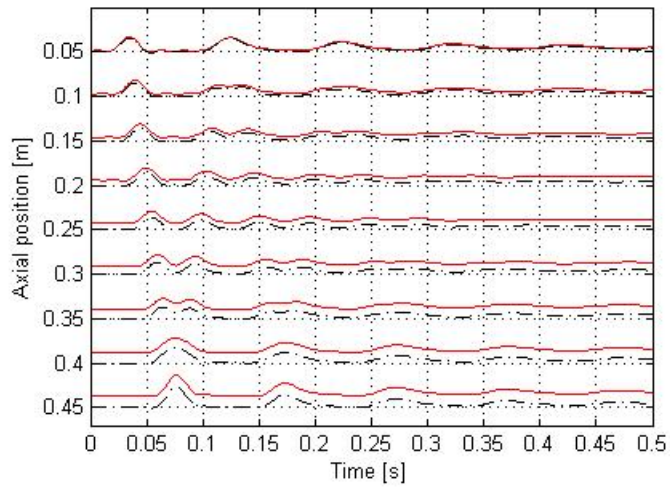
Since astronauts face hypergravity up to $3.2g$ in Fig. 9 the pressure for vessel S and in Fig. 10 the pressure for vessel T for $2g$ and $3g$ respectively can be found. It can be seen that hypergravity affects the damping of the wave.

CONCLUSION AND FUTURE WORK

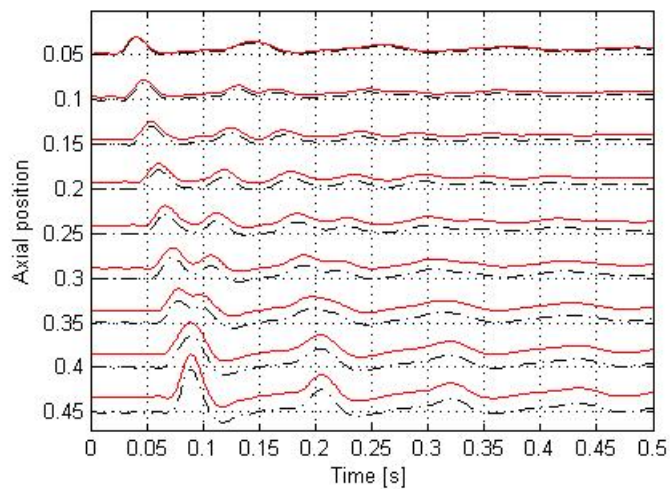
A finite element model for modeling blood flow with hypergravity has been developed. This model has been compared with an analytical model. This model will provide a better understanding of the role of hypergravity in fluid structure interaction in flexible vessels and in particular of aortic relevance.

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.

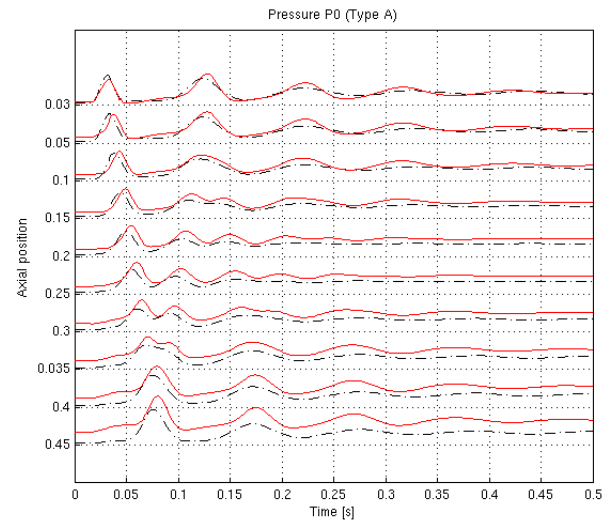
In order to validate the numerical and analytical models further, experimental data is needed. However, no suitable experimental data is available in the literature as far as the authors are aware of. Therefore, the next step would be to perform experiments with a similar experimental set-up as in [19],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



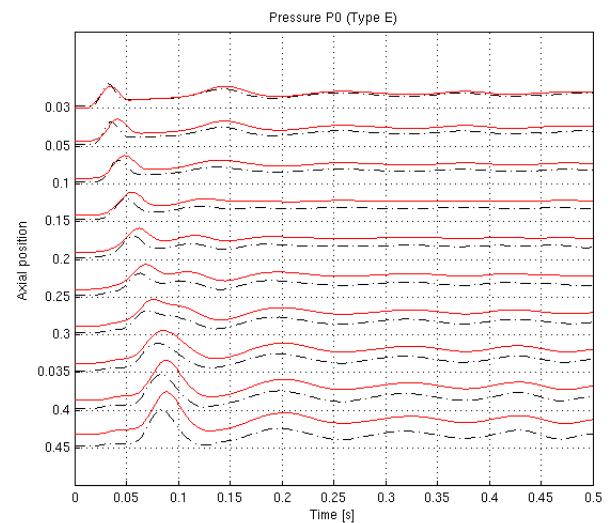
(a) Pressure in vessel S



(b) Pressure in vessel T



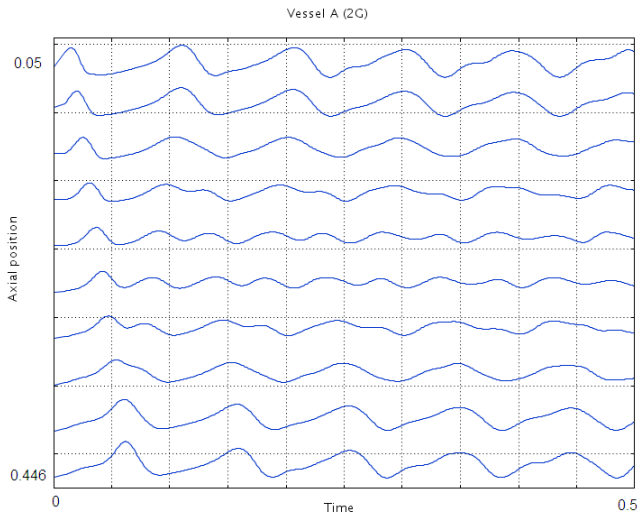
(a) Pressure in vessel S



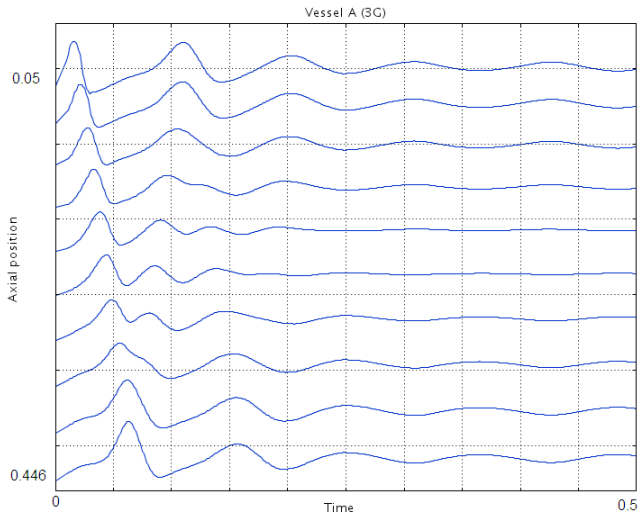
(b) Pressure in vessel T

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.

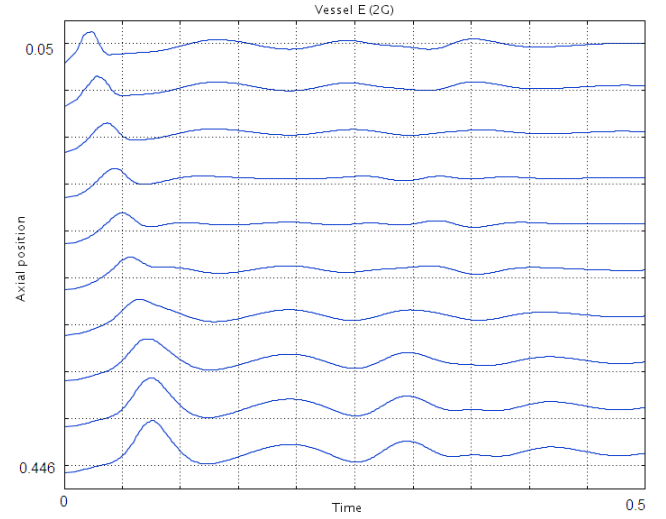


(a) Pressure in vessel S when 2g is applied

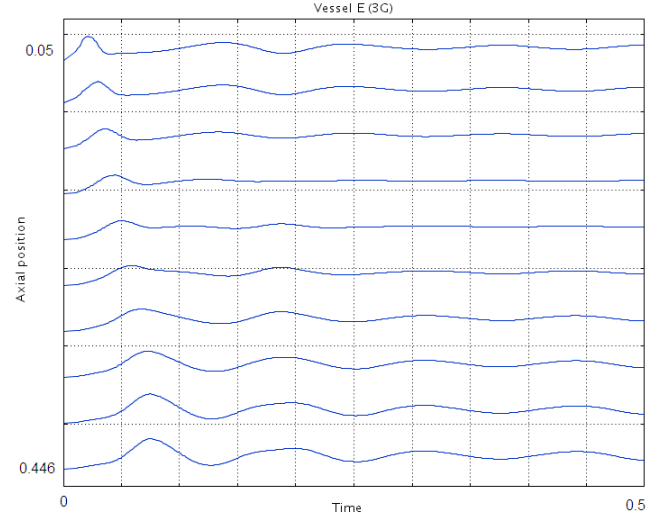


(b) Pressure in vessel S when 3g is applied

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

REFERENCES

- [1] Miller, K., 2003. "The pull of hypergravity: A nasa researcher is studying the strange effects of artificial gravity on humans". *Science@NASA*, pp. 1 – 9.
- [2] Watenpaugh, D., Breit, G., Buckley, T., Ballard, R., Murthy, G., and Hargens, A., 2004. "Human cutaneous vaascular responses to whole-body tilting, g_z centrifugation, and lbnp". *Journal of Applied Physiology*, **96**, pp. 2153 – 2160.
- [3] Ossard, G., J.M.Clère, Kerguélen, M., Melchior, F., and Seylaz, J., 1996. "Cerebral blood flow velocity responses induced by a 70-hpa vasalva manoeuvre associated with normo- and hypergravity in humans". *Journal of Applied Physiology*, **72**, pp. 502 – 508.
- [4] McKinley, R., Tripp, L., Bolia, S., and Roark, M., 2005. "Computer modeling of acceleration effects on cerebral oxygen saturation". *Aviation, Space and Environmental Medicine*, **76**, pp. 733 – 738.
- [5] Rohdin, M., and Linnarsson, D., 2002. "Differential changes of long diffusing capacity and volume in hypergravity". *Journal of Applied Physiology*, **93**, pp. 931 – 935.
- [6] Petrak, J., Mravec, B., Jurani, M., Baranovska, M., Tillinger, A., Hapala, I., Frollo, I., and Kvetňanský, R., 2008. "Hypergravity-induced increase in plasma catecholamine and corticosterone levels in telemetrically collected blood of rats during centrifugation". *Annals of the New York Academy of Sciences*, pp. 201 – 208.
- [7] Goldstein, O., and Ishay, J., 1998. "The white blood cell line: changes induced in mice by hypergravity". *Advances in Space Research*, **21**, pp. 1333 – 1343.
- [8] Eichler, W., Frank, I., Nehring, M., Welsch, H., and Klotz, K., 2004. "Hypergravity and dehydration-induced shifts of interstitial fluid in the skin monitored by ultrasound". *Aviation, Space and Environmental Medicine*, **75**, pp. 760 – 763.
- [9] Florence, G., Roucher, P., Vallet, R., Lemenn, M., Charbonne, R., and Seylaz, J., 1994. "Cortical blood flow and $+g_z$ acceleration in conscious rabbits". *The American Physiological Society*, pp. 2527 – 2534.
- [10] Russomano, T., Rizzatti, M., Coelho, R., nd D. de Souza, D. S., and Prá-Veveda, P., 2007. "Effects of simulated hypergravity on biomedical experiments". *IEEE Engineering in medicine and biology manazine*, May/June, pp. 66 – 71.
- [11] Sud, V., and Sekhon, G., 1984. "Blood flow subject to a single cycle of body acceleration". *Bulletin of Mathematical Biology*, **46**, pp. 937 – 949.
- [12] Sud, V., and Sekhon, G., 1985. "Arterial flow under periodic body acceleration". *Bulletin of Mathematical Biology*, **47**, pp. 35 – 52.
- [13] Misra, J., and Sahu, B., 1988. "Flow through blood vessles under the action of a periodic acceleration field". *Computers & Mathematics with Applications*, **16**, pp. 993 – 1016.
- [14] Chaturani, P., and Palanisamy, V., 1991. "Pulsatile flow of blood with periodic body acceleration". *International Journal of Engineering Science*, **29**, pp. 113 – 121.
- [15] Sivastava, L., Edemeka, U., and Srivastava, V., 1994. "Effects of external body accelerations on blood flow". *Japanese Journal of Applied Physics*, **33**, pp. 3648 – 3655.
- [16] Chaturani, P., and Isaac, A., 1995. "Blood flow with body acceleration forces". *International Journal of Engineering Science*, **33**, pp. 1807 – 1820.
- [17] Misra, J., and Pal, B., 1999. "A mathematical model for the study of the pulsatile flow of blood under an externally imposed body acceleration". *Mathematical and Computer Modelling*, **29**, pp. 89 – 106.
- [18] Giannopapa, C., and Kroot, J., 2009. "Multiple reflection and transmission theory for wave propagation in the aorta". *Proceedings of PVP2009*, pp. 1 – 9.
- [19] Giannopapa, C., 2004. "Fluid structure interaction in flexible vessels". PhD thesis, King's college London.
- [20] van Geel, M., Giannopapa, C., and van der Linden, B., 2010. "Development of a blood flow model and validation against experiments and analytical models". *Proceedings of PVP2010(26150)*, pp. 1 – 9.
- [21] Kroot, J., and Giannopapa, C., 2010. "Hyper-gravity and multiple reflections in wave propagation in the aorta". *Proceedings of PVP2010(26151)*, pp. 1 – 7.
- [22] *COMSOL Multiphysics Quick Start and Quick Reference*, November 2008.
- [23] Donea, J., Huerta, A., Ponthot, J.-P., and A.Rodríguez-Ferran, 2004. *Encyclopedia of Computational Mechanics: Arbitrary Lagrangian-Eulerian Methods*, Vol. 1: Fundamentals. John Wiley & Sons.

PREVIOUS PUBLICATIONS IN THIS SERIES:

Number	Author(s)	Title	Month
II-43	M.V. Shenoy R.M.M. Mattheij A.A.F. v.d. Ven E. Wolterink	A mathematical model for polymer lens shrinkage	Sept. '11
II-44	P.I. Rosen Esquivel J.H.M. ten Thijsse Boonkamp J.A.M. Dam R.M.M. Mattheij	Wall shape optimization for a thermosyphon loop featuring corrugated pipes	Sept. '11
II-45	J. de Graaf	A complex-like calculus for spherical vectorfields	Sept. '11
II-46	C. Cancès I.S. Pop M. Vohralík	An a posteriori error estimate for vertex- centered finite volume discretizations of immiscible incompressible two-phase flow	Sept. '11
II-47	M.H.A. van Geel C.G. Giannopapa B.J. van der Linden J.M.B. Kroot	Development of a blood flow model including hypergravity and validation against an analytical model	Sept. '11