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Fluid-Structure Interaction Analysis of a Peristaltic Pump

Nagi Elabbasi*, Jorgen Bergstrom and Stuart Brown
Veryst Engineering, LLC
*Corresponding author: 47A Kearney Road, Needham, MA 02494. nelabbasi@veryst.com

Abstract: Peristaltic pumping is an inherently multiphysics problem where the deformation of the tube and the pumped fluid are strongly coupled. We used COMSOL Multiphysics to investigate the performance of a 180 degree rotary peristaltic pump with two metallic rollers, and an elastomeric tube pumping a viscous Newtonian fluid. The model captures the peristaltic flow, the flow fluctuations that result when the rollers engage and disengage the tube, and the contact interaction between the rollers and the tube. We are using the model to investigate the effect of pump design variations such as tube occlusion, tube diameter, and roller speed, on the flow rate, flow fluctuations, and stress state in the tube.

Keywords: Fluid-structure interaction, peristaltic pumping, multiphysics, nonlinear material, pump modeling

1. Introduction

A peristaltic pump is a type of positive displacement pump that moves fluid by squeezing a tube or hose causing the fluid inside to follow the motion of the roller. Peristaltic pumps are valuable for pumping abrasive or corrosive fluids that could damage or contaminate rotors or gears and for pumping delicate fluids such as blood. They are also useful for applications requiring rugged pumps with minimal maintenance. They are used in a wide range of industries including pharmaceutical, petrochemical, biomedical and food processing.

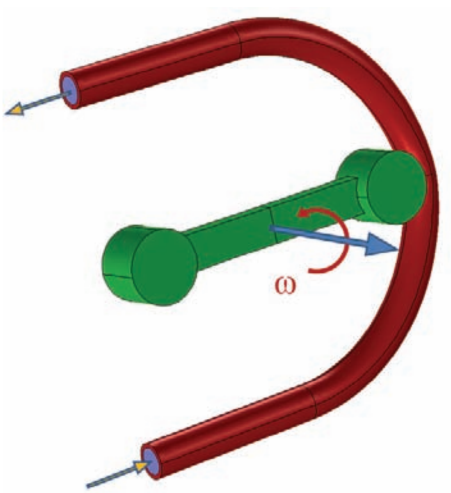

Figure 1. Peristaltic pump model

The optimal peristaltic pump design depends on the application, and most specifically on the nature of the fluid and the desired flow rate. The main design variables governing pump performance are the pump speed, inner tube diameter, tube material, degree of tube occlusion, and back pressure. In general, increasing pump speed, inner tube diameter, and occlusion increases the flow rate. Increasing fluid viscosity reduces the flow rate. Tube failure due to the high stress cyclic loading is one of the main constraints on pump performance.

2. Literature Review

Most analyses on peristaltic pumps are performed using empirical relations or analytical equations based on idealized flow and pump geometry, and are valid for a specific range of Reynolds numbers[1,2]. Numerical simulations have been performed based on lubrication theory[3], and CFD[4,5]. In most cases displacement of the fluid wall is explicitly assumed.

3. Model Setup in COMSOL Multiphysics

The peristaltic pumping process is a fluid-structure interaction problem with strong coupling between the solid and fluid domains. We developed a COMSOL model that captures the peristaltic flow, the flow fluctuations that result when the rollers engage and disengage the tube, and the contact interaction between the rollers and the tube.

In many pump applications, the rollers cause full or near-full tube occlusion. However, significant pumping also occurs with partial occlusion. In this work, we model a 180 degree rotary peristaltic pump (see Figure 1) with two metallic rollers, and an elastomeric tube pumping a viscous Newtonian fluid.

The pump tubes are typically made of elastomeric materials such as silicone, or thermoplastic elastomers such as Norprene® or Tygon®. These materials must withstand the high strain cyclic loads experienced by the tube. The behavior of these materials frequently exhibits strong strain rate dependence[6,7]. However, at this stage of analysis, we used a standard Mooney-Rivlin hyperelastic material model. The rollers are assumed to be elastic and rigidly connected to the rotating shaft. In some peristaltic pump configurations the rollers are spring-loaded to minimize impact forces and prolong tube life.

Contact pairs are created between the rollers and the tube. The roller surfaces are set as the contact "source" due to their significantly higher stiffness. Frictionless conditions are assumed since in practice the rollers can free to rotate about their own axis, leading to rolling contact that results in much lower frictional forces than sliding contact.

The fluid flow is described by the Navier-Stokes equations with laminar incompressible Newtonian flow and free boundaries at the inlet and outlet. Peristaltic pumps are commonly used to pump non-Newtonian fluids, such as mud, sludge or blood. The model can easily be modified to account for non-Newtonian fluid behavior. Integration coupling variables are used to track the discharged fluid and the volume of the fluid inside the tube.

A non-slip FSI boundary is automatically set up along the inner wall of the tube. COMSOL handles the fluid structure interaction using an Arbitrary Lagrangian-Eulerian (ALE) formulation. This involves a Lagrangian framework for the solid and an Eulerian framework for the fluid. A moving mesh model is used to track the deformation of the fluid mesh. The two-way coupling is captured along the FSI boundary by the fluid applying forces on the solid, and the solid displacement imposing a moving wall boundary condition on the fluid. These conditions can be expressed as[8]

$$\mathbf{v}_{\mathrm{Fluid}} = \mathbf{v}_{\mathrm{Solid}}$$

$$\mathbf{v}_{\mathrm{Solid}} = \frac{\partial \mathbf{u}_{\mathrm{Solid}}}{\partial t}$$

$$(\boldsymbol{\sigma} \cdot \mathbf{n})_{\mathrm{Fluid}} = (\boldsymbol{\sigma} \cdot \mathbf{n})_{\mathrm{Solid}}$$

where $\mathbf{v}$ is the velocity vector, $\mathbf{u}$ is the displacement vector, $\boldsymbol{\sigma}$ is the stress tensor, and $\mathbf{n}$ is the normal vector to the FSI boundary. COMSOL solves for the fluid velocity at the FSI boundary as an independent field.

4. Analysis in COMSOL Multiphysics

We split the peristaltic pump analysis into two stages. The first stage is a damped transient analysis that obtains the initial configuration of the pump shown in Figure 1. This is achieved by moving the rollers from a remote location where they are not impinging on the tube to their starting location. The second stage is a transient analysis that simulates the pump rotation by applying a constant angular velocity to the rollers. Since we are mainly interested in the steady state response, the results were only examined after the initial transients died out. For most pump configurations this occurred after one roller revolution. Figure 2 shows the deformed pump geometry at different times in the pump cycle.

We used two approaches to solve the fluid-structure interaction problem in COMSOL. The accurate approach is fully coupled and involves the simultaneous solution of solid and fluid fields. In the approximate approach we solve the solid mechanics problem first, followed by the fluid dynamics problem. This effectively leads to

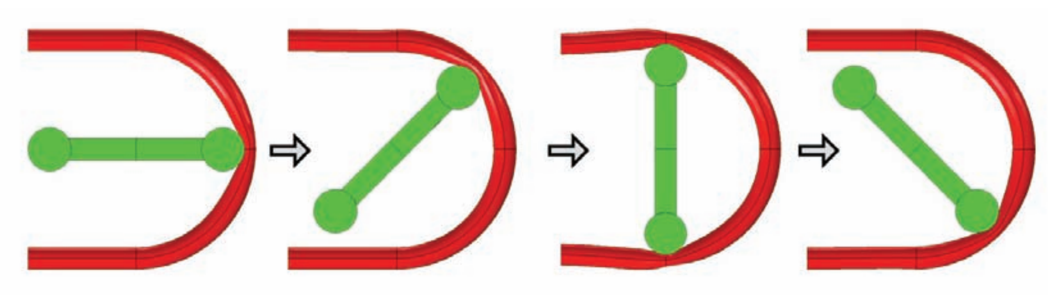

Figure 2. Pump configuration at four points in pump cycle

a one-way coupling where the fluid does not influence the tube deformation. The second approach requires less computational resources (memory and solution time), and for many pump configurations has little influence on the results. However, for cases where the fluid forces were high the predictions from the two approaches are different. The large fluid forces can be due to either high inertial or viscous fluid forces resulting from high fluid viscosity, high degree of occlusion and fast pump speeds.

A segregated solver was always used. One segregated solver step was used for the solid variables, a second solver step for the fluid and moving mesh variables, and a lumped solver step for the contact Lagrange multipliers.

5. Results

We used the model to investigate the effect of pump design variations such as tube occlusion, tube diameter, and roller speed, on the flow rate, flow fluctuations, and stress state in the tube.

Figure 3 shows the deformed geometry and fluid velocity contours for a pump speed of 60 Hz, 50% tube occlusion, and a fluid viscosity of 0.1 Pa·s. The highest fluid velocity is clearly at the compressed tube section. Figure 4 shows the Mises stresses in the tube for the same pump configuration. The stresses are highest at the region in contact with the rollers and specifically in the areas of the tube experiencing maximum

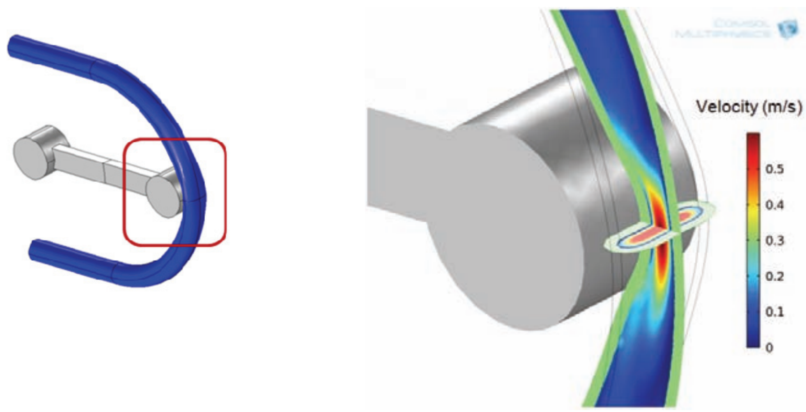

Figure 3. Velocity contours for one pump configuration

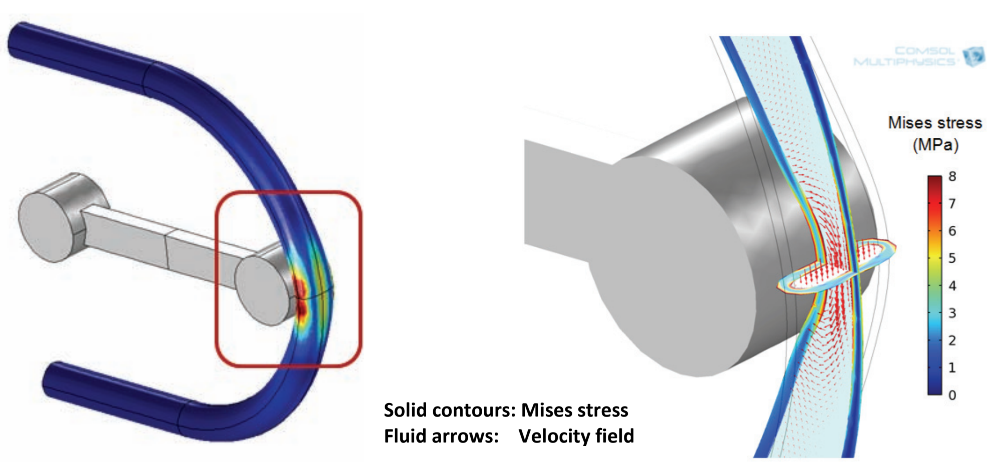

Figure 4. Mises stresses and velocity field in pump

change in curvature. The figure also shows an arrow plot of the velocity at two cross-sections. Note that at the compressed tube section the fluid velocity is opposite that of pump rotation indicating a local backflow.

The flow rate and total pump flow are shown in Figure 5. The figure shows that, for this pump configuration, a nearly constant flow rate is present for most of the pump cycle with brief periods of sharp drop in flow to the point of flow reversal. The drop in flow is at the time when the rollers contact and disengage the tube, which is at the vertical roller position. This severe change in velocity is commonly mitigated by modifying roller/housing geometry, or using spring loaded rollers.

We are currently using this model to further examine the effect of changes to the roller speed, the degree of occlusion and the fluid viscosity.

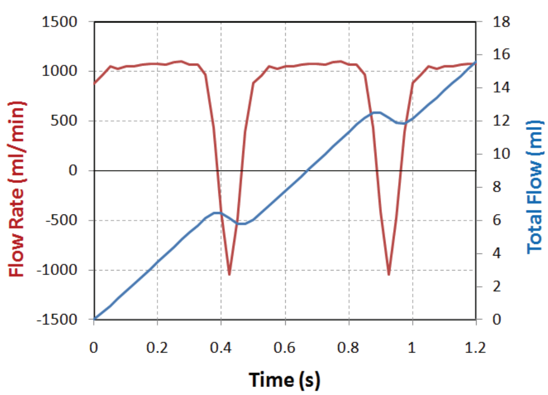

Figure 5. Flow rate and flow fluctuations

6. Conclusions

A parametric computational model of peristaltic pumps was developed, using COMSOL Multiphysics. The model captures the peristaltic pumping action, and the interaction between the rollers, tube and fluid. It was used to predict the stresses and strains in the tube, as well as the flow and flow fluctuations. We are working on enhancements to the model to account for the rate-dependent deformation of the tube, higher levels of tube occlusion, and effect of non-Newtonian fluids.

7. References

1. M.Y. Jaffrin and A.H. Shapiro, Peristaltic pumping, *Annual Reviews of Fluid Mechanics*, **3**, 13-37 (1971)
2. T.S. Chow, Peristaltic transport in a circular cylindrical pipe, *Journal of Applied Mechanics*, **37**, 901-905 (1970)
3. D. Takagi and N.J. Balmforth, Peristaltic pumping of viscous fluid in an elastic tube, *Journal of Fluid Mechanics*, **672**, 196-218 (2011)
4. S. Takabatake and K. Ayukawa, Numerical study of two-dimensional peristaltic flow, *Journal of Fluid Mechanics*, **122**, 439-465 (1982)
5. S. Takabatake, K. Ayukawa, and A. Mori, Peristaltic pumping in circular cylindrical tubes: A numerical study of fluid transport and its efficiency, *Journal of Fluid Mechanics*, **193**, 267-283, (1988)
6. J. Bergstrom and M.C. Boyce, Constitutive modeling of the large strain time-dependent behavior of elastomers, *Journal of Mechanics and Physics of Solids*, **46**, 931-954 (1998)
7. Veryst Engineering, PolyUMod user-material model library [online], www.veryst.com/PolyUModLibrary.html, 2011
8. COMSOL Documentation: Structural Mechanics Module, COMSOL 4.2 (2011)