Fluid-Structure Interaction (FSI) in Bioengineering

V. Kanyanta, N. Quinn, S. Kelly, A. Ivankovic, A. Karac

2nd OpenFOAM Workshop
Introduction

• Bioengineering mostly involves the study of the response of biological systems to mechanical loading or stimulus

• E.g Cardiovascular diseases where hemodynamic forces i.e. wall shear stress are known to play a key role in Atherosclerosis

• Numerical studies have become key to understanding the role of hemodynamic forces in cardiovascular diseases

• Most importantly – interaction between flowing blood and deforming vascular wall – FSI (critical)
• This presentation looks at 3 applications of FSI in Bioengineering – highlights the importance of FSI

2. Towards early diagnosis of Atherosclerosis - Role of WSS

3. Towards early diagnosis of Atherosclerosis - exploring a novel approach to detecting the development of Atherosclerosis plagues by focusing on the artery wall rather than the flow through it

4. Numerical study of an Abdominal Aortic Aneurysm (AAA)
Towards Early Diagnosis of Atherosclerosis: Role of Wall Shear Stress

A combined Experimental and Numerical Analysis

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Atherosclerosis is the leading cause of death in the developed world.

It involves local accumulation of lipids, calcium and proliferating cells within arterial walls.

Its development has been linked to the dysfunction of the endothelium - known to be caused by low & highly oscillatory WSS.
Objective:
Investigate the role of Wall Shear Stress (WSS) in Atherosclerosis while taking into account the flexibility/deformation of arteries.

Numerical Model:
- OpenFoam 1.2 - two-system FSI coupling scheme

Wave propagation through a fluid-filled straight flexible pipe
Wave propagation at speed \( c_f \)
Symmetry plane

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\[ \nu = 0.4995 \]
\[ E = 4.7 \text{MPa} \]
\[ \rho_s = 1000 \text{kg/m}^3 \]
\[ \eta = 0.004 \text{Ns/m}^2 \]
\[ \rho_f = 998 \text{kg/m}^3 \]
\[ K_f = 2.2 \text{GPa} \]
Numerical model validation - numerical predictions compared to analytical solutions

1. Pressure wave speed
   \[ C_f = \sqrt{\frac{K}{\rho_f} \left[ 1 + \left( \frac{D^2}{e(D - e)} - 2(1 - \nu) \right) \frac{K}{E} \right]^{-1}} \]

3. Radial deformation of pipe
   \[ d_y = \frac{D^2 p}{4Ee} \]

5. Fluid particle velocity
   \[ U_{axial} = \frac{\Delta p}{\rho_f C_f} \]

7. Axial stress wave speed
   \[ C_s = \left[ \frac{E}{\rho_s (1 - \nu^2)} \right]^{-1} \]

9. Poisson Coupling
   \[ \Delta \sigma_{axial} = -G_s \Delta p \quad \text{and} \quad \Delta p = -G_f \Delta \sigma_{axial} \]
   \[ G_s = \nu R e \left[ \left( \frac{C_s}{C_f} \right)^2 - 1 \right]^{-1}, \quad G_f = -2\nu \rho_f / \rho_s \left[ \left( \frac{C_s}{C_f} \right)^2 - 1 \right]^{-1} \]

13. Natural pipe oscillations (frequencies)
   \[ f = \frac{1}{2\pi R} \sqrt{\frac{4E}{\rho_s + \alpha R e \rho_f}} \]
   \[ \alpha = \frac{1}{2} \quad \text{for} \ M_{eq} = \text{total fluid mass}, \quad \frac{1}{3} \quad \text{or} \quad \frac{1}{4} \quad \text{for} \ M_{eq} < \text{total fluid mass} \]
<table>
<thead>
<tr>
<th></th>
<th>Formula</th>
<th>Numerical</th>
<th>Analytical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Wave Speed</td>
<td>$C_f$</td>
<td>13.125m/s</td>
<td>13.16m/s</td>
</tr>
<tr>
<td>Radial displacement</td>
<td>$D^2 p/4Ee$</td>
<td>0.051mm</td>
<td>0.053mm</td>
</tr>
<tr>
<td>Fluid particle velocity</td>
<td>$U_{axial} = \Delta p/\rho_f \ c_f$</td>
<td>0.325m/s</td>
<td>0.327m/s</td>
</tr>
<tr>
<td>Poisson Coupling</td>
<td>$\Delta p = -G_f \Delta \sigma_{axial}$</td>
<td>710 Pa</td>
<td>706 Pa</td>
</tr>
<tr>
<td></td>
<td>$\Delta \sigma_{axial} = -G_s \Delta p$</td>
<td>-1585 Pa</td>
<td>-1400 Pa</td>
</tr>
<tr>
<td>Axial Stress</td>
<td>$C_s = \left[ E/(\rho_s (1-\nu^2)) \right]^{-1}$</td>
<td>81.25m/s</td>
<td>79.14m/s</td>
</tr>
<tr>
<td>Natural Frequency</td>
<td>$f = \frac{1}{2\pi R} \sqrt{\frac{4E}{\rho_s + \alpha \frac{R}{e} \rho_f}}$</td>
<td>1084Hz</td>
<td><strong>1049Hz</strong></td>
</tr>
<tr>
<td></td>
<td>$\alpha = 1/2, 1/3 \ or \ 1/4$</td>
<td></td>
<td>1167Hz</td>
</tr>
</tbody>
</table>

- Very good agreement between analytical and numerical predictions
Investigated the effect of pipe flexibility on WSS transients by keeping the fluid particle velocity constant $V = \Delta p / \rho_f c_f$.

![Graph showing WSS at 60mm from inlet (Pressure BCs)]

- $U = 0.26\text{m/s}, \text{Hoop strain} = 0.8\%$
- $U = 0.26\text{m/s}, \text{Hoop strain} = 0.0064\%$
• To obtain a wider range of strains, used an axial flow velocity of 0.76m/s

WSS at 60mm from inlet (Pressure BCs)
Very significant differences between WSS transients in rigid and flexible geometries

This is independent of WSS magnitude

Meaningful WSS predictions only achieved in flexible geometries (p & V physiologically correct)
Rigid Geometry → No FSI → Wrong WSS analysis

- The interaction between flowing blood and deforming arterial wall critical to WSS analysis
- Hoop strain of as low as 0.2% result in significant changes in WSS transients
Towards Early Diagnosis of Atherosclerosis: A Combined Experimental and Numerical Approach

Niamh Quinn, Prof A. Ivankovic, A. Karac
Motivation For Research

- Traditional diagnostic techniques focus on blood flow and can only detect a plaque in the latter stages of the disease.
- This novel approach investigates the deformation of diseased arteries.
- Mechanical principles are applied to a medical problem in order to develop a diagnostic technique capable of identifying the disease in its early stages.
- Establish “Proof Of Principle”
Hypothesis

“An emerging plaque, causing a localised increase in arterial wall thickness, has a measurable effect on the deformation profile of the artery wall”
Static Testing: Numerical

• Finite Volume Solver: OpenFoam-1.2
• Simulation of experiments
• Linear elastic material
  – $E = 4.2\text{MPa}$, $\rho=1000\text{kg/m}^3$, $\nu=0.4995$
• Dimensions of geometry:
  – 400mm length, 8.8mm internal diameter, 0.7mm wall thickness
• Full convergence, tolerance $1\times10^{-6}$

Numerical predictions validated experimentally in polyurethane mock arteries
Experimental & Numerical Comparison: Deformation

- The experimental and numerical results show the effect of the thickened patch on the radial displacement.
- The decrease in displacement in the thickened section is 39-40%
Dynamic Testing: Numerical

- Fluid-Structure Interaction technique

- Models
  - Straight
  - Thickened patch
  - Thickened and stiffened patch

- Introduced a stiffened patch, $E_{stiff} = 12.2$MPa
  - Young’s modulus based on previous numerical study but agrees with values measured by Holzapfel et al.\(^1\)

- Fluid modelled as a Newtonian fluid

Pressure Waveforms

Arterial System

Fluid Inlet Pressure
Aortic Pressure

Fluid Inlet Pressure
Carotid Pressure

Fluid Inlet Pressure
Femoral Pressure

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Deformation Profiles: Straight & Thickened Models

Deformation Vs Time
Femoral Pressure

Deformation Vs Time
Aortic Pressure

Deformation Vs Time
Carotid Pressure
Straight, Thickened and Stiffened Model

![Graph showing Hoop Stress vs. Axial Position and Time with curves for Straight, Thickened, and Thickened & Stiffened models.]

- **Straight**
- **Thickened**
- **Thickened & Stiffened**

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Velocity Profiles under Carotid Waveform

T1 = 0

T2 = 0.192s

T3 = 0.504s

T4 = 0.624s

T5 = 1.2s

Straight

Thickened

Thickened & Stiffened
**Fluid-Structure Interaction Simulations on an Idealised Abdominal Aortic Aneurysm Model**

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Supported by the Irish Research Council for Science, Engineering and Technology (IRCSET)
V. Kanyanta, N. Quinn, S. Kelly, A. Ivankovic, A. Karac

Introduction

~90% mortality rate if rupture occurs
Geometry

• Fluid Diameter: 10mm

• Solid Inner Diameter: 10mm
  Wall thickness: 0.5mm
  Wall thickness in centre: 0.26mm
Fluid and solid properties

- Fluid properties – Water
  - $\sigma = 1000 \text{ kg/m}^3$
  - $\mu = 0.001 \text{ kg/ms}$

- Solid properties – Non-linear material, with the properties of polyurethane rubber

![Stress-strain curve for Wet Polyurethane Rubber](image-url)
Creation of aneurysm model
FSI in aneurysm model

- Physiologically realistic boundary conditions

- Fluid and solid meshes moving
- Arterial wall with non-linear material properties
Fluid Flow
Stress – Model 1
Stress – Model 2
Patient based geometry

- Female patient
- 68 years old
Fluid flow

Fluid flow
Fluid flow
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www.OpenFoam.co.uk