A three dimensional method for modelling fluid-structure interaction of heart valves

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Introduction

Computational methods can be of great value in understanding heart valve (dis)functioning. However, the behaviour of the valves (mitral or aortic, mechanical or biological), which should cause no resistance to the flow during systole, but need to sustain transvalvular pressure gradients during diastole, is not easy to capture. A new approach for modelling the fluid-structure interaction of flexible heart valves is presented.

Objectives

Develop and validate an accurate and robust numerical tool for fluid-structure interaction in the cardiovascular system (emphasis on flexible heartvalves)

Methods

Using a finite element method, a Lagrangian description of a non-linear solid and an Eulerian description of a non-linear fluid are coupled by a Lagrange multiplier (Fig.1).

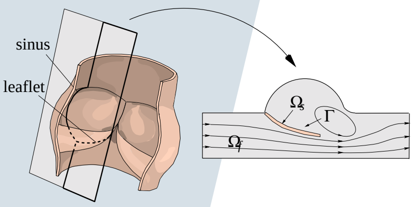

Figure 1 *Schematic view of the problem (picture: J. de Hart).*

This multiplier is defined along the solid boundary and allows the solid and fluid mesh to be non-conformal. The method is extended by an inexpensive adaptive meshing algorithm, which locally adapts the fluid mesh every time step to the position of the solid mesh [1]. Depending on the intersections of the solid with the fluid mesh, fluid elements are either reshaped or added (Fig.2).

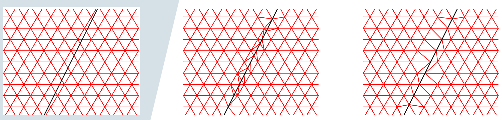

Figure 2 *Adaptive meshing of a fluid mesh intersected by a curve (left), by adding elements (middle) or shifting nodes (right).*

This minor adjustment of the fluid mesh provides for stronger coupling and higher accuracy, such that sharp transvalvular pressure gradients can be captured (Fig.5) and shear stresses at both sides of the valve can be computed (Fig.3). Additionally, the method is combined with a Lagrange multiplier based contact algorithm in order to capture the closure behaviour of the valve (Fig.4).

Results

First, a model problem is presented which shows large movement of a flexible solid slab through a pulsatile flow. As mentioned before, shear stresses can be computed at both sides of the solid (Fig.3).

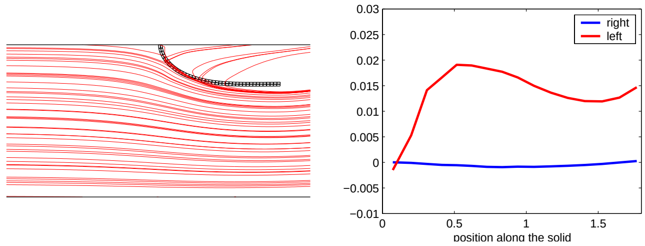

Figure 3 *Movement of a solid slab induced by a pulsatile flow and the corresponding shear stresses at both sides of the solid.*

Unlike Arbitrary Lagrangian Eulerian (ALE) methods, this method is easily extended with a contact algorithm without 'squeezing' fluid elements near the wall (Fig.4).

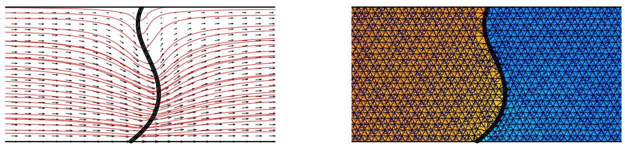

Figure 4 *Velocity and pressure field of solid slab sliding along fluid wall. Pressure is applied at the inlet (left wall)*

The method is extended to 3D and tested (Fig.5). Simulations with realistic leaflet geometry look promising (Fig.6).

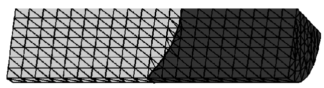

Figure 5 *Fluid pressure drop across a solid membrane. In the left and right part of the domain pressures are 5kPa and 0kPa, respectively*

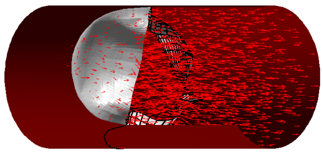

Figure 6 *Velocity vector field during opening of an aortic heart valve in a pulsatile flow.*

Conclusions

A fluid-structure interaction method is proposed in 2D and 3D, which is capable of describing large movements in a fluid domain. Furthermore, transvalvular pressure drops can be captured and shear stresses along both sides of the leaflets can be computed. The method will be validated by modelling realistic heart valve geometries and comparing the numerical results with experiments using MR.

References:

[1] R. Van Loon, P.D. Anderson, J. De Hart, and F.P.T Baaijens. A combined fictitious domain/adaptive meshing method for fluid-structure interaction in heart valves. *Int. J. Num. Meth. Fluids*, 46:533–544, 2004.

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