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FINITE VOLUME FLUID/STRUCTURE INTERACTION APPLIED TO PATIENT-SPECIFIC ARTERIAL FLOW

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ABSTRACT

There are two possible approaches to solving Fluid-Structure Interaction (FSI) problems computationally. One approach is to link together preexisting (often commercial) solvers, usually with a finite-volume (FV) solver for the fluid flow, a finite-element (FE) solver for the structural analysis and a third, bridging code performing the tasks of coupling the solvers, data interpolation and simulation management. This has the benefit of utilising existing and well validated solver code. However it also imposes limitations on the mode of coupling and creates problems with the model setup. For example, it is quite difficult to achieve converged coupled solution due to difficulties with creating a coupled iteration loop across a fluid and a structural solver within a single time-step.

The alternative approach is to undertake the whole solution problem entirely within a single code, which involves implementing the fluid computation in FE software or the structural computation in FV software [1, 2]. Within the Open Source OpenFOAM toolkit, this methodology has been implemented and tested on simple geometries such as flow past a cantilevered elastic square beam [3]. The fluid flow is modelled using the Navier-Stokes equations for incompressible Newtonian fluid, modelled using the Arbitrary Lagrangian-Eulerian formulation (ALE), whilst the solid deformation is described using the geometrically nonlinear momentum equation in Lagrangian formulation. Spatial discretisation of both models is performed using second-order accurate unstructured FV method, with automatic mesh motion used to accommodate fluid-solid interface deformation. Coupling between the two models is performed using a loosely-coupled staggered solution algorithm, with the force transfered in one direction and the displacement in the other.

One area in which FSI is important is biomedical simulation, particularly of flow in arteries. The compliance of arterial walls is an important aspect of the flow through the cardiac cycle, and can be of crucial importance in a number of medical conditions such as the development of aneurysms. Simulation of the flow in such cases is complicated by the geometry of the problem, which is complex across a range of length scales, with the artery changing direction and cross-section continuously, and also branching. Not only is this geometry complex to characterise and specify, but it also varies from individual to individual in ways which may be of interest; simulation on idealised geometry can be shown

to generate results which are qualitatively as well as quantitatively in error [4]. Thus there has been a great deal of research into techniques for generating computational meshes from medical scans (MRI or CT scans), which enable the generation of patient-specific geometries and meshes. One approach to this task is the Voxel method, in which the scan pixels representing the volumes of interest are segmented out into separate masks; these segmented regions are then meshed using the Marching Cubes algorithm, and truncated at the boundaries of each mask [5]. This approach is implemented in the ScanIP/ScanFE package (Simpleware Ltd), which also includes image manipulation tools to preprocess the raw data, automatic and manual tools for segmentation, and subsequent mesh manipulation to smooth surfaces or improve mesh quality are also available. The output from this is a high quality tet or mixed tet/hex mesh for each segmented region, with guaranteed matching between the interface boundaries.

In this work we present the results of a demonstration study involving FSI on arterial flow. Meshes have been generated for the flow domain and the artery wall using MRI scans of a femoral artery, and converted to OpenFOAM mesh format. Calculations have then been performed assuming the blood flow to be Newtonian and laminar, for a simple sinusoidal inlet flow variation and compliant walls, using the coupled FSI solver in OpenFOAM. Further calculations have also included non-Newtonian effects as well. Results are presented for wall shear stress and wall internal stress.

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