Bubble dynamics inside a compliant blood vessel

Strongly coupled FSI on a dynamic wedge mesh

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Abstract

In medical applications, ultrasound is no longer used exclusively for diagnostical purposes but also in a more intense and highly focused modification (HIFU) for interventional applications such as tumor treatment [1]. A newly devised application involving HIFU aims at imposing certain mechanical stress levels to the inner blood vessel wall (e.g. the blood brain barrier) in order to locally change its permeability with respect to certain pharmaceuticals. To this end, coated microbubbles dispersed in the blood are employed to increase the effect of the incident ultrasound field by forced oscillations. The method shows great potential in preliminary experiments [2], but a thorough investigation of the physical mechanism involved is still lacking. The key benefit of such an investigation would be the establishment of safety thresholds for the application of this technique in patients.

The goal of our present work is to develop a microscale model of the interaction between gas-filled microbubbles, blood and the respective blood vessel walls. A partitioned multi region black box interaction system that can accommodate the respective physical models for each region is envisaged (see Fig. 1). In order to achieve a consistent description of this complex system, we use OpenFOAM for its flexible and versatile numerical framework.

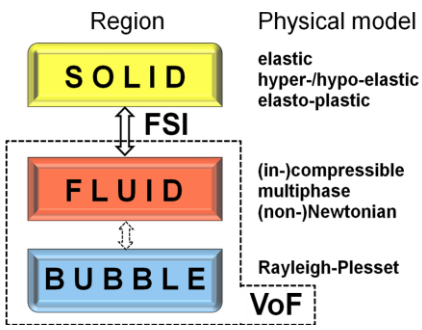

Fig. 1: Structure of the interaction model

The solver used for modeling the blood-wall interaction is based on icoFsiFoam (available in OF-1.5-dev) which provides interface coupling and dynamic mesh motion. Because the density ratio of blood and vessel wall is very close to unity, the components of the system show strong mutual influence and a strong coupling scheme has to be employed [3]. This is achieved by introducing an inner iteration loop into the time stepping scheme of icoFsiFoam in order to relax the system within each time step. Stable and efficient computation is improved by setting up an under-relaxation scheme.

The bubble is represented in our model by the respective boundary of the fluid region (see Fig. 2), which moves according to a prescribed pattern. Thus no third mesh region has to be introduced. This is a good choice for a first approach, as the Rayleigh-Plesset equation which describes the fluid-bubble interaction directly yields the bubble's radius given the inner pressure. The motion of the bubble boundary is set by directly accessing the motionU field.

Currently, we are running our calculations on a wedge mesh (see Fig. 2), which is designed to take advantage of the inherent symmetries of a simplified model, where one spherical bubble is placed at the center of a cylindrical tube. The wedge boundary condition allows computation of 3D axial symmetric problems on a mesh of just one cell layer thickness.

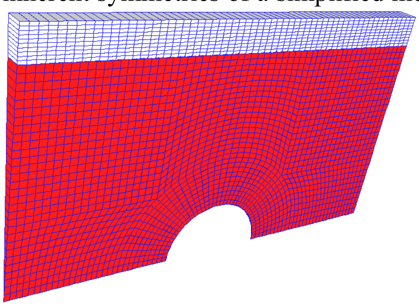

Fig. 2: Wedge mesh topology

While performing very well for the interaction of fluid and solid and at small oscillation amplitudes, dynamic mesh motion has limitations when dealing with extensive topology changes imposed by the oscillating bubble. Therefore, it may be advantageous to introduce topology changers to add/remove layers in order to account for large scale topological deformations at the bubble boundary.

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Key words: FSI, strong coupling, wedge mesh, dynamic mesh motion

References

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