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Computing the artificial compressibility field for partitioned fluid-structure interaction simulations

*** Peter Råback, Esko Järvinen and Juha Ruokolainen**

CSC – Finnish IT Center for Science
P.O.Box 405, FIN-02101 Espoo
{raback,ejarvine,jpr}@csc.fi

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ABSTRACT

When fluid-structure interaction (FSI) problems are solved using a partitioned iteration strategy convergence may be difficult to obtain. This is particularly true for interior problems dealing with incompressible fluid – a canonical case of this is the blood flow in elastic arteries. One main reason for the convergence problems lie in the velocity boundary conditions that may be incompatible with the continuity equation during the iteration process and thereby give rise to spurious pressure pulses.

To overcome the convergence problems a method of artificial compressibility has been introduced [1,2]. The method uses artificial compressibility to mimic the elastic behavior of the walls. The modified continuity equation yields

$$\frac{c}{\Delta t}\left(p^{(m)} - p^{(m-1)}\right) + \nabla \cdot \vec{v}^{(m)} = 0, \tag{1}$$

where m is the current iteration step related to fluid-structure coupling. When the iteration converges $p^{(m)} \rightarrow p^{(m-1)}$ and incompressible nature of the fluid is retained. As a result of the modification the inconsistency between velocity boundary conditions and incompressibility constraint is overcome. When the intertial forces of the elastic structure are small the equation gives good estimates for the pressure fields of the coupled system.

The success of the artificial compressibility method in FSI relies on an nearly optimal selection of the artificial compressibility parameter c. For simple geometries the value of c may be computed from analytical formulas [1]. Also the known compressibility value may be scaled to account for nonlinear elastic response [2]. However, for fully generic geometries predefined forms of the compressibility field are hard to derive. This shortcoming of the method was also pointed out by Küttler et al. [3].

In this paper we concentrate on the application of a test load method where the compressibility field is determined from the elementwise volume change dV_e caused by a pressure load P_0,

$$c = \frac{1}{P_0}\frac{dV_e}{V_e}. \tag{2}$$

This method of defining the compressibility uses the properties of the mesh extension method that is used to map the deformed mesh in the fluid domain [4]. Typically the extension method involves the

solution of Laplace's or Navier's equation for the fluid domain. We discuss the different alternatives for the extension method and show that the successful determination of the compressibility parameter is quite insensitive to the mesh extension method.

The test load method for computing the compressibility field, and the partitioned fluid-structure interaction scheme have been implemented in Elmer finite element open source software [5]. In this paper we give a number of examples ranging from simple 2D to complicated 3D geometries. It is shown that the test load method reproduces the analytical results in simple geometries and is able to deliver a nearly optimal results even for the most complicated cases. Monotonic and relatively fast convergence behavior is demonstrated for all test problems.

We believe that the presented methodology completely eliminates the convergence problems for those incompressible internal flows cases where inertial forces play a minor role. The methods are mathematically simple and are easy to implement even to existing codes.

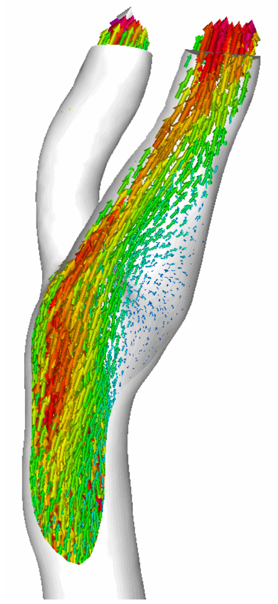

Figure 1: A snapshot from fluid-structure interaction simulation of an elastic carotid artery.

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