ADDED MASS PARTITIONED FLUID-STRUCTURE INTERACTION SOLVER BASED ON ROBIN BOUNDARY CONDITION FOR PRESSURE

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Keywords: *fluid-structure interaction, added mass effect, finite volume method, pressure based flow solver, Robin boundary condition.*

An fluid-structure interaction (FSI) problem can be solved in a monolithic or partitioned way. Loosely or strongly coupled partitioned solution procedures solve the fluid problem separately from the structure problem what make this approach very popular due to its modularity and simplicity of implementation. In classical partitioned scheme known as the Dirichlet-Neumann (DN) scheme, the fluid problem is solved with a Dirichlet boundary condition (structure velocity) at the fluid-structure interface while the structure problem is solved with a Neumann boundary condition (fluid stress) at the interface. Loosely coupled partitioned DN schemes are stable only if the structure density is much larger than the fluid density. This requirement is easily achieved in some applications like aerodynamics, but not for example in hemodynamics where the density of blood is of the same order of magnitude as the density of arterial walls. In these cases, the energy of the discrete problem in the DN partitioned algorithm does not accurately approximate the energy of the continuous problem, introducing numerical instabilities known as the added mass effect. A possible solution to this problem is to sub-iterate the fluid and structure sub-problems at each time step until the energy at the fluid-structure interface is balanced. However, schemes that require sub-iterations, also known as strongly coupled partitioned scheme, may suffer from slow convergence issues which can be mitigate by using Aitkens dynamic relaxation method [1] or reduce order models [2].

Loosely coupled partitioned schemas which can efficiently cope with the added mass effect are very rare. One of such schemes with very good performance is the so called kinematically coupled β scheme [3, 4]. The scheme is based on the Lie operator splitting, where the fluid and the structure sub-problems are fully decoupled and communicate only via the initial conditions. The fluid and structure equations are split in a way such that the fluid problem is solved with a Robin-type boundary condition (BC) including the structure inertia what is the main ingredient of the scheme ensuring its unconditional stability. In the original implementation of this scheme, the second order accurate finite element method (FEM) is used for discretization of both fluid and structure model in space and overall temporal accuracy of the scheme is first order.

Main goal of this study is to implement the kinematically coupled β scheme in the changed computational framework where both fluid and structure sub-problems are discretized using second order accurate cell-centred finite volume method (FVM) and flow sub-problem is solved using pressure bases solver and SIMPLE-like solution procedure. In this work, first step in the fulfilment of the above mentioned goal will be presented, namely, the implementation of the Robin BC for the fluid sub-problem. In the context of the pressure based fluid flow solver, the proposed Robin BC is applied on the pressure field during the solution of pressure equation. Derivative of the pressure at the interface in the normal direction is defined by the simplified momentum equation and in the same time the value of the pressure is limited by the structure inertia. The Robin BC derived in such a way is very similar to the Robin BC proposed by Banks, Henshaw and Schwendeman [5]. Based on the Robin BC for pressure, the so called Robin-Neumann (RN) partitioned FSI scheme is proposed where the fluid sub-problem is solved with the Robin BC at the interface while the structure sub-problem is still solved with the Neumann BC. Although proposed FSI scheme does not consist of all ingredients of the kinematically coupled β scheme, it already shows very good performance in terms of stability and accuracy. New FSI scheme (see Algorithm 1) can be used as loosely coupled scheme (with one sub-iteration) for very low solid to fluid density ratio and if used as strongly coupled scheme it requires substantially less sub-iterations then IQN-ILS [2] or Aitkens scheme [1].

Algorithm 1: Loosely or strongly coupled Robin-Neumann partitioned FSI scheme.

1. Predict interface displacement by solving structure sub-problem using fluid force from the previous time step and move fluid mesh using calculated interface displacement
2. Solve fluid sub-problem using Robin BC for pressure at the interface
3. Solve solid sub-problem using Neumann BC at the interface
4. Move fluid mesh
5. Return to step 2 if the solution did not converge

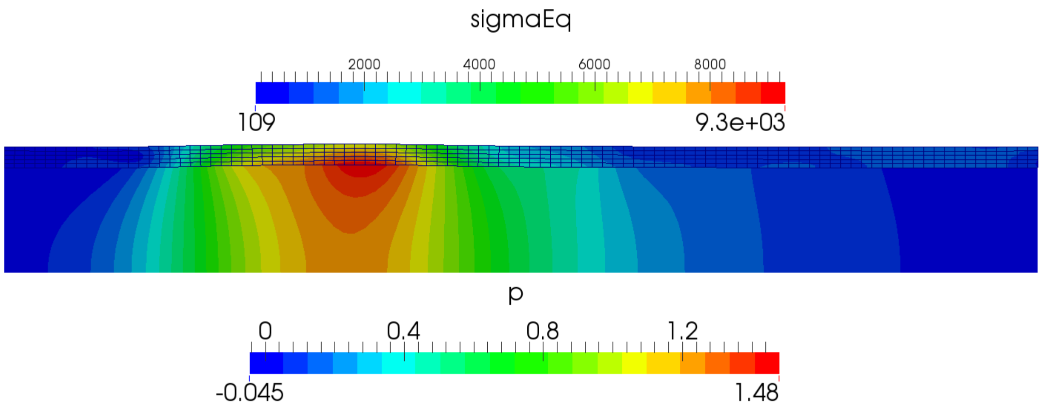

Figure 1: Pressure pulse propagation through thick elastic pipe: pressure field in the fluid sub-domain and equivalent stress in the structure sub-domain calculated using RN coupling scheme.

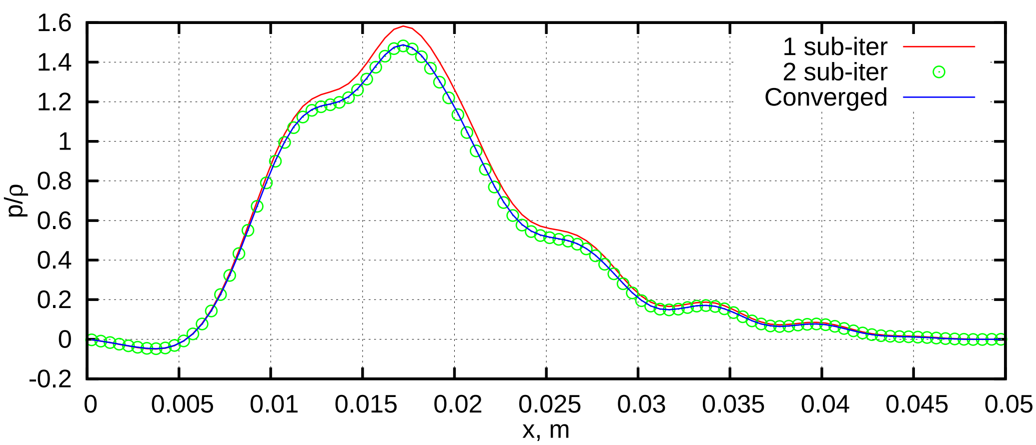

Figure 2: Pressure pulse propagation through thick elastic pipe: pressure field along the interface calculated using RN scheme. Fully converged solution is compared with the solutions obtained using 1 and 2 sub-iterations.

Table 1: Number of sub-iterations per time step and relative duration with respect to the RN scheme for the propagation of pressure pulse through thick elastic pipe.

Algorithm	Iterations	Duration
RN	3	1
DN/IQN-ILS	17	4.8
DN/Aitken	33	7.4

References

[1] U. Küttler and W. A. Wall, "Fixed-point fluid-structure interaction solvers with dynamic relaxation," *Computational mechanics*, vol. 43, no. 1, pp. 61–72, 2008.

[2] J. Degroote, K.-J. Bathe, and J. Vierendeels, "Performance of a new partitioned procedure versus a monolithic procedure in fluid–structure interaction," *Computers and structures*, vol. 87, pp. 793–801, 2009.

[3] G. Guidoboni, R. Glowinski, N. Cavallini, and S. Čanić, "Stable loosely-coupled-type algorithm for fluid-structure interaction in blood flow," *Journal of Computational Physics*, vol. 228, no. 18, pp. 6916–6937, 2009.

[4] M. Bukač, S. Čanić, R. Glowinski, J. Tambača, and A. Quaini, "Fluid-structure interaction in blood flow capturing non-zero longitudinal structure displacement," *Journal of Computational Physics*, vol. 235, pp. 515–541, 2013.

[5] J. Banks, W. Henshaw, and D. Schwendeman, "An analysis of a new stable partitioned algorithm for FSI problems. Part I: Incompressible flow and elastic solids," *Journal of Computational Physics*, vol. 269, pp. 108–137, 2014.