Partitioned simulation of fluid-structure interaction

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I. Introduction

Simulations of fluid-structure interaction (FSI) are increasingly being used to calculate the mutual interaction between a fluid flow and a flexible structure. Mature, reliable and optimized codes are readily available to solve flow equations or structural equations separately but the handful of monolithic codes which are able to solve all equations in an FSI problem simultaneously have not yet reached this level of achievement. These monolithic codes are hard to manage and develop due to their vast size and complexity. Moreover, they cannot benefit from the fast solution techniques that have been developed for either flow equations or structural equations but they must settle for a compromise. Consequently, there is a strong need for partitioned solution techniques to couple an existing flow code with an existing structural code in a stable and efficient way.

II. Stability analysis

Before embarking on the development of new partitioned algorithms, a stability analysis [1] has been performed on an existing partitioned algorithm which iterates between the flow code and the structural code within a time step. In this analysis, the equations for the unsteady, incompressible and inviscid flow in a straight flexible tube are discretized on a one-dimensional grid and the error on the displacement of the fluid-structure interface is decomposed as a sum of Fourier modes. The outcome of the analysis is that only a fraction of these modes is unstable.

III. New coupling technique

Based on the insights from the stability analysis, a new coupling technique has been developed [2]. Coupling iterations between the flow solver and the structural solver will converge quickly as long as all unstable and badly damped Fourier modes are treated implicitly; conversely, all stable modes can be coupled in an explicit way. This desired partial implicitness at the fluid-structure interface has been obtained by performing quasi-Newton iterations with an approximation for the inverse of the residual's Jacobian matrix from a least-squares model (abbreviated as IQN-ILS).

The flow code and the structural code are treated as "black boxes", which means that no access to the source code of these programmes is required such that software modularity is preserved. A comparison with other partitioned and monolithic algorithms revealed that the IQN-ILS technique is at least as fast as the existing coupling techniques and easy to implement.

IV. Tango coupling code

The IQN-ILS algorithm and several other partitioned algorithms have been implemented in a C++ code named Tango, which is freely available to researchers. Tango can couple a flow code with a structural code but also, for example, a pyrolysis code with a combustion code. This means that Tango can be used for coupled problems in general and not only for FSI. The implementation of all techniques is "matrix-free", which signifies that matrix-

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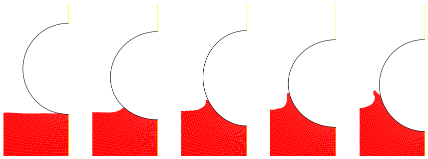

Figure 1. Snapshots (every 10 ms) of the impact of a composite cylinder on a water surface.

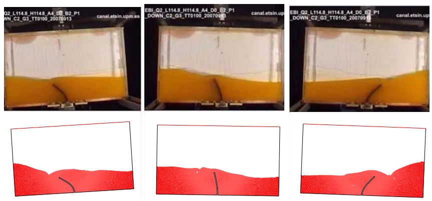

Figure 2. Snapshots (after 1.84 s, 2.12 s and 2.56 s) from experiments and simulations of the flexible baffle in a rolling tank.

vector products are calculated without storing the matrix in the computer's memory so problems with a large number of degrees-of-freedom can be solved. All codes communicate with each other by means of calls to an MPI 2.0 library.

V. Applications

One of the applications is the impact of a buoy from a wave-energy converter on a water surface (Figure 1). Such a buoy is made of a fiber reinforced composite material and the pressure at impact can damage this material. It has been verified that a composite cylinder can sustain an impact at 5 m/s.

Another application is related to the tanks of large LNG ships. A simplified test case with a flexible baffle in a partially filled rolling tank has been analyzed experimentally and numerically and the results show excellent agreement (Figure 2).

Many FSI applications also exist in the biomedical field, such as the simulation of large arteries. Figure 3 depicts the propagation of a pressure pulse in a straight artery and in the bifurcation of a carotid artery. The geometry of this bifurcation has been three-dimensionally reconstructed from CT-scans.

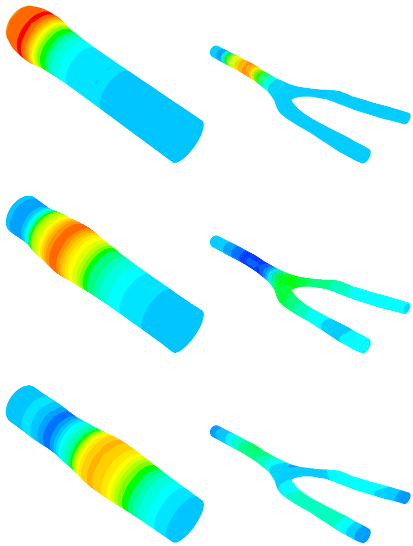

Figure 3. Snapshots (every 5 ms) of the pressure on the fluid-structure interface during the propagation of a pressure wave in a straight artery (left) and in an arterial bifurcation (right).

VI. Conclusions

A new coupling technique named IQN-ILS has been developed with the insights gained from an analytical stability analysis in mind. It has been implemented in a flexible C++ code such that complex fluid-structure interaction problems but also other coupled problems can be solved by coupling existing codes.

Acknowledgments

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References

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[2] J. Degroote, K.-J. Bathe, and J. Vierendeels, "Performance of a new partitioned procedure versus a monolithic procedure in fluid-structure interaction," *Computers & Structures*, vol. 87, no. 11–12, pp. 793–801, June 2009.