A comparison of the Lagrange multiplier and penalty formulations of the fictitious domain method for modelling fluid-structure interactions.

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1. Conclusions

In this article, a novel version of the DLM method was presented that has recently been incorporated into the open-source CFD code, Fluidity. This was followed by a comparison of the strengths and weaknesses of using a penalty formulation for the body force, in the fictious domain method, to those of adopting a Lagrange multiplier formulation. The specific penalty formulation selected was the IB method [1], which was already present in Fluidity prior to the addition of the DLM method. The new version of the DLM method was chosen as the Lagrange multiplier formulation. Despite the uniqueness of this version of the DLM method, both it and the immersed body method are representative of the majority Lagrange multiplier and penalty formulations from the literature, respectively. The findings from this comparative analysis are therefore also relevant for these other formulations.

Each method was used to solve three different benchmark problems and its performance was evaluated in terms of both accuracy and computation time. The first benchmark problem consisted of the pendulum motion of a cylinder that is attached to stationary pinned support. It therefore encompassed only rigid body dynamics, and the reaction force exerted by the pinned support was expressed in terms of penalty and Lagrange multiplier terms specifically derived for this problem. The second and third benchmark problems involved FSI originating from laminar flow through a channel and the harmonic motion of a cylinder immersed in a stationary fluid, respectively. The second and third benchmark problems were solved using both the IB method and the DLM method.

Despite differences in the physics encountered, the results from the benchmark problems all led to the same conclusions. For the penalty reaction force in the first problem and the IB method in the second and third problems, the outcome of the computation was strongly dependent on the value selected for the penalty factor. The value of this factor required for optimal results was not obvious and finding it required a trial and error approach. It was also observed that using a larger value for the penalty factor increases the noise present in the solution. Furthermore, even when using the optimal penalty factor value, the accuracy of the solutions produced was significantly lower than those from the Lagrange multiplier reaction force, for the first benchmark problem, and the DLM method, for the second and third benchmark problems. However, in all of the problems the computation times required by the Lagrange multiplier reaction force or the DLM method to complete the calculations were significantly longer than those needed by the penalty approach. The superior accuracy of the Lagrange multiplier reaction force and DLM methods therefore comes at the cost of a significantly higher computation time. Thus, if its accuracy is adequate for the problem being analysed, using a penalty method, such as the IB method, may actually be preferable as it could save an enormous amount of computation time.

All of the benchmark problems considered were two-dimensional. In the second and third benchmark problems, the solid bodies were modelled as rigid and their motions (one-way FSI) were prescribed, and the flows were entirely laminar. Nevertheless, the methods and findings discussed in this article should also be applicable to three-dimensional FSI problems. The work planned for the near-future will therefore focus on demonstrating the DLM method in Fluidity on problems that are three-dimensional and in which the motion of the solid body is calculated according to the forces exerted on it by the fluid (two-way FSI). The DLM method will also be extended so that it may be used to solve problems involving turbulence. A possible future direction is to also apply this method to FSI problems involving flexible structures.

References

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