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(Review Article)

Review on fluid-structure interaction problem modeling and recent developments

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Abstract

The fluid-structure interaction (FSI) problem plays significant roles in engineering simulations and design. This problem considers the interaction between the fluid domain and structural domain with one-way or two-way data transfer. There are several algorithms to solve the problem, mainly numerical duo to the complexity and nonlinearly. The numerical schemes focus on the modeling method of the coupling interface. However, there are several algorithms that merge the interface in the equations and deal with the domains as a unified set of equations. Future development could include artificial intelligence modeling and the inclusion of more physical domains into the systems.

Keywords: Fluid-structure interaction; Finite element modeling; Conforming mesh; Coupling interface

1. Introduction

The fluid-structure interaction (FSI) problem is one of the essential problems in engineering applications. It covers a class of problems that involve multidisciplinary interaction between a fluid domain and a structural domain. The importance emerges from the fact that there are many applications whose interacting domains should not be analyzed separately because that may cause accuracy issues or applicability, or both. The applications range from hydraulic analysis of ships and bridges, to blood pressure in blood vessels, to the aerodynamics of plane wings [1–6].

The FSI problem is of a practical advantage from engineering point of view because it ensures that the case under focus will have all the components necessary for a complete, realistic analysis. This, of course, comes at a cost; difficulty of solving such problems. The FSI problems are non-linear and complicated in nature. They are complicated in terms of formulation, structuring, and solving. Analytical solutions to model equations for most FSI problems are unattainable, and laboratory experiments have limited scope. Therefore, there are many methods and algorithms to solve the FSI problems, the majority of which are numerical. In the early analysis stages, the FSI problems were dealt with based on simple analytical analysis, such as the case of bridge vibration under the influence of wind, or more recently, the modeling of energy-harvesting devices and water hammering phenomenon [7,8]. Later, during the 1960s, when the finite element method (FEM) was developed, the analysis methods were strongly pushed forward in the direction of FEM [9–12]. The FEM allowed a wide range of numerical extermination of the techniques as well as the results schemes [13,14]. Later, the boundary layer was introduced, which offered features that expedite the calculations in way that are not available in the FEM [15].

Analytical techniques can be used to represent the FSI problem, however they are only applicable in specific circumstances with slender boundary conditions and domain characteristics. Therefore, the process uses numerical methods to get the desired results while maintaining application accuracy.

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Background information on each model will be provided in this review, followed by discussion of some key developments for the methodologies going forward.

2. Numerical Methods

As mentioned earlier, the FSI problem is an interaction combination of fluid and structural domains. Therefore, the numerical scheme has to take care of both domains' physical interactions. The influence of one domain on the other is accomplished via the interaction boundaries, typically the outer surface of the structural domain. Since the codes for both domains have already been developed over the course of years, it is advantageous to utilize that for the benefit of the FSI problem, which has been the case for the most part of numerical simulation. The modeling of the fluid domain dynamics is based on the Navier-Stokes equations, while the structural dynamics uses the dynamic constitutive equations of continuum mechanics. Since the fluid and structure are within the same domain, both systems have to be solved simultaneously for each time step of the problem period. Both solutions of the two domains as well as the time scheme constitute the main difference in the solutions schemes in FSI problems. All numerical techniques have to accurately model, first the boundary conditions of both domains, and, second, the interface dynamics between the fluid and the solid [2].

The fluid-structural interface is the most crucial part of the modeling of the FSI problem [16,17]. Since both domains can be analyzed independently once the information of the other domain is transmitted, an accurate representation of the interface is essential for precise modeling of an FSI problem. Most of the studies have dealt with various versions of the interface modeling and the goal for all of them is to move the interface and transmit the data across it in a representative way for the solid and fluid domains [18].

In general, the FSI problem is computationally intense and requires more computer resources than individual calculations for each domain alone [19]. The computational power is usually the driver for codes and schemes improvements, as computations could take long periods of time. The numerical schemes of the coupling interface of the two domains control most of the speed of the calculations; therefore, it has taken most of the studies. The studies focused mainly on ways and method to order-reduce the computational time as well as increasing the associated accuracies [20]. The classification of the solution algorithms is usually based on how the solution of the two domains is accomplished as well as the way the coupling interface is treated [21].

In the following sections, reviews of the available methods and algorithms of solutions will be presented, then some ideas on future developments will be discussed.

First: Monolithic numerical approach. In this approach, the domains of the fluid and structure are solved simultaneously within the same framework of mathematical formulation. Here, the problem of the structural domain is merged with the fluid domain to form a single problem that can be solved monolithically, then march in time to the next step [22,23]. The coupling interface in this kind of approach is dissolved within the formulation of the two domains. Clearly, this approach requires preparations on the modeling level on the problem in order to merge the two domains. As a result, the already established codes for numerical analysis (FEM and others) can not be utilized for the new problem. This means that the numerical code that will be developed for the problem cannot be used with other problems without significant modifications. Despite all of this, this approach can handle large time steps and can be more stable than the partitioned approach [24].

Second: Partitioned numerical approach. In contrast to the monolithic approach, the partitioning approach keeps every domain independent from one another and solves them separately; however, the interface surface between the two domains will be used in order to transmit the data across them[25,26]. This approach takes advantage of the already-available numerical codes and algorithms in order to solve complicated problems and cases. With this, comes the disadvantage of the need to keep an accurate track of the interface location coordinates on every time step, which makes this problem susceptible to cumulative errors and solution divergence [27,28].

Both of the aforementioned approaches' logic was based on the overall way the solution is handled. Moreover, there are other ways of classifying the available solution schemes.

Third: Conforming mesh methods. In this set of methods, the solution of the two domains is obtained independently, and the interface is considered a physical boundary [29,30]. The interface moves with the solid and fluid during the solution, and the location of the nodes will have to be updated in each iteration. The motion of the interface is resulted from the deformation of the solid due to the pressure of the liquid. Hence, the information set that has to be transmitted through the interface is pressure to the solid and movement to the fluid, hence the two-way interaction [31]. The solution in this scheme could start from the solid domain or the fluid domain, then the progress is made after a satisfactory convergence is reached. Thereafter, a method of deformation tracking is applied in order to update the coordinates of the interface's points and nodes [32].

Fourth: Non-conforming mesh methods. Another name for these methods is the immersed methods [33,34]. Here, the solid domain is immersed in the fluid domain, and the interface is dissolved and becomes a part of the solution of the two domains. The mathematical representation is accomplished by adding terms to the fluid dynamics equations to account for the solid interaction. Depending on the structure under analysis, the body can be a simple 1D boundary or a domain that occupies an area or a volume [35,36]. The modeling of the solid is done via a series of fiber-like structures that add force terms to the fluid domain equations. This, of course, comes at the cost of the accurate representation of the structural domain.

3. Recent development and future ideas

- FSI modeling can be pushed forward with new techniques that involve the involvement of several scales of modeling on the same problem. This can be utilized in order to avoid complex coupling interface mechanisms when there are parts of the interface that can be neglected without compromising the accuracy of the simulation. While at the same time modeling the larger scales according to the algorithms.
- Also, since the database of the simulation cases has been increasing in size, data from multiple modeling results can be used to train an Artificial Intelligence model for reliable to accurate prediction on the behavior of complex system modeling [37]. In order to properly train the AI models, the cases with high accurate results can be used for training and validation of the data. Then new cases can be introduced in order to test the resulting algorithm and model. Along the way, the AI model can be improved by introducing new datasets as well as correcting the established ones.
- The FSI modeling can be coupled with other physical characteristics of the domain, such as heat energy transfer. This would be helpful in terms of increasing the accuracy predictions of the two domains as well as the interface between them. Although this increases the problem's computational resources by several folds, this will be an essential step towards increasing the modeling realism.

4. Conclusion

The FSI problem has gained importance over the last few decades, mainly because of the increased computational power that is readily available on several levels. The utilization of the codes that were developed for the fluid and solid domains has pushed the researchers to take a route of monolithic approach and conforming mesh methods. The available methods basically differ in the approaches of the coupling interface modeling and how to predict its location with time. For future developments, more resources on computational power and AI methods can be used to investigate more problems with deeper issues.

Compliance with ethical standards

Disclosure of conflict of interest

We have no conflicts of interest to disclose.

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