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Parallel partitioned coupling analysis system for large-scale incompressible viscous fluid–structure interaction problems

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ABSTRACT

Fluid–structure interaction (FSI) affects the dynamic characteristics and behaviors of the fluid and structure, and being able to understand and solve FSI problems is very important in engineering, science, medicine, and everyday life. Generally, FSI problems are simulated by either monolithic or partitioned methods. There are still many challenges in the development of better numerical methods for FSI problems in terms of accuracy, problem scale, stability, robustness, and efficiency. We have focused on partitioned methods because they allow the use of existing flow and structural analysis solvers without elaborate modification. This paper describes the development of a parallel partitioned coupling analysis system for large-scale FSI problems. In this study, we employed the existing flow and structural analysis solvers FrontFlow/blue (FFB) and ADVENTURE_Solid, respectively, both of which are general-purpose codes used to solve large-scale analysis models ranging from millions to billions of degrees of freedom (DOFs). In addition, we developed a parallel coupling tool called ADVENTURE_Coupler to efficiently handle the exchange of interface variables in various parallel computing environments. To achieve the robust and fast convergence of the fixed-point iteration, we employed Broyden's method, which is a quasi-Newton method, to update the interface variables. We verified the accuracy and fundamental performance of the developed FSI analysis system by using it to solve a FSI benchmark problem: the vortex-induced oscillation of a flexible plate in the wake of a square column. The results agreed quantitatively well with other researchers' results. Finally, we successfully applied the system to the analysis of the three-dimensional flapping motion of an elastic rectangular plate, with the objective of furthering the research and development of micro air vehicles (MAVs) with flapping wings.

1. Introduction

Fluid–structure interaction (FSI) is an interdependent phenomenon between a fluid and structural parts that affects the dynamic characteristics and behaviors of the fluid and structure. As there are many FSI problems in engineering, science, medicine, and everyday life, we recognize that it is very important to understand and solve FSI problems. Many researchers have attempted to develop numerical methods of solving FSI problems with improved accuracy, problem scale, stability, robustness, and efficiency (e.g., [1–32,33,34–56,57,58–66]). Although previous studies have made significant progress, there are still demands for further studies on how to decrease computational time and increase the degrees of freedom (DOFs) of models used to analyze real-world problems. For the above reasons, the development of an efficient and robust analysis system to solve large-scale FSI problems in parallel computing environments is considered a challenging task.

Generally, coupled phenomena can be simulated by either monolithic or partitioned methods. In monolithic methods, the equations describing the fluid and the structure are formed into a single system of equations, allowing the equations to be solved simultaneously. Conversely, the equations are solved separately in partitioned methods.

Monolithic approaches [34–39] are generally known to be accurate and robust and can be applied to solve strongly coupled problems, especially large added-mass effect problems. However, the DOFs of equations solved in the monolithic methods tend to be larger than those in the partitioned methods. Hence, algebraic splitting [40,42] or substructuring [36,41] has been proposed to avoid the larger DOFs of equations. Also, the monolithic methods require efficient iterative linear algebraic solvers rather than direct

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solvers. This necessitates the new development of effective preconditioners, such as the segregated equation solver for FSI (SESFSI) proposed by Tezduyar and Sathe [14,28,30], a nested iterative scheme proposed by Manguoglu et al. [43–45] for FSI problems, an extension of the balancing domain decomposition (BDD) method proposed by Minami et al. [46], and an extension of the finite element tearing interconnection (FETI) method proposed by Mandel [47] for acoustic FSI (AFSI) problems.

Conversely, the partitioned methods [48–56,57,58–66] use efficient techniques, such as fluid and structural equations, to solve each phenomenon, possibly without the elaborate modification of existing analysis solvers. Nowadays, iterative partitioned methods have attracted a great deal of attention because they can improve accuracy and robustness in comparison with simple partitioned methods. In iterative partitioned methods, fluid and structural problems are solved separately and iteratively by fixed-point iteration at each time step until the conditions of equilibrium and continuity are satisfied.

In our previous study [50], we developed a new parallel dynamic response analysis system of AFSI problems using iterative partitioned coupling methods, assuming incompressible inviscid flow. The system consists of independently developed acoustic flow and structural analysis solvers and a coupler. The coupler supports data exchange and the execution of several coupling algorithms. Through the analysis of a number of numerical examples, it was demonstrated that the system could be applied to large-scale AFSI problems with more than 10 million DOFs.

In this paper, we extend the above mentioned parallel-coupled analysis system to the analysis of incompressible viscous FSI problems with new developments. To solve problems with moving boundaries and the accompanying mesh distortion, we implemented the ALE method and mesh control into the parallel flow analysis solver FrontFlow/blue developed by Kato et al. [67,68]. The employed parallel structural analysis solver is the open-source software ADVENTURE_Solid developed by Yoshimura et al. [69,70]. We employed Broyden's method [72], which is a quasi-Newton method, as the iterative partitioned algorithm, together with a line-search technique.

To verify the performance of the developed FSI analysis system, we analyzed a benchmark FSI problem: the vortex-induced oscillation of a flexible plate in the wake of a square column. We then applied the system to the analysis of the three-dimensional flapping motion of an elastic rectangular plate with the objective of furthering the research and development of micro air vehicles (MAVs) with flapping wings.

The remainder of this paper is organized as follows. In Chapter 2, the governing equations of FSI problems are explained. The iterative partitioned coupling algorithm is described in Chapter 3. In Chapter 4, we present the parallel coupling system for large-scale FSI problems. In Chapter 5, we verify the accuracy and fundamental performance of the developed system by solving a benchmark problem. In Chapter 6, we describe the application of the system to a practical problem. Finally, we provide conclusions in Chapter 7.

2. Governing equations

Fig. 1 shows a typical FSI problem. The problem consists of two domains, a fluid domain Ω^F and a structure domain Ω^S. The two domains share an FSI interface Γ_{FSI}.

2.1. Fluid domain

The fluid domain is governed by the following Navier–Stokes equation in an arbitrary Lagrangian–Eulerian (ALE) frame of

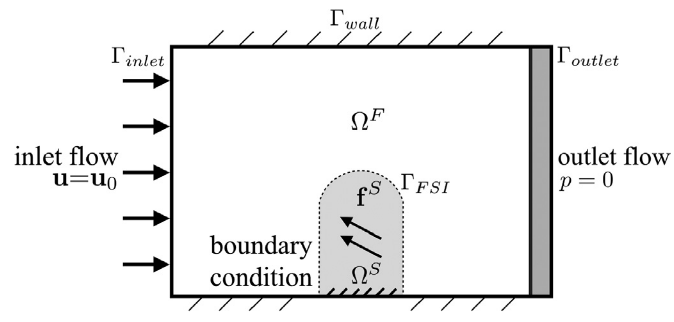

Fig. 1. Basic FSI problem.

reference

$$\rho^F\left(\frac{\partial \mathbf{u}}{\partial t} + \left(\mathbf{u} - \hat{\mathbf{u}}\right)\cdot\nabla\mathbf{u}\right) - \nabla\cdot\sigma^F = \mathbf{f}^F \quad (1)$$

and the continuity equation

$$\nabla\cdot\mathbf{u} = 0, \quad (2)$$

where ρ^F is the density of the fluid, $\mathbf{u}$ is the velocity of the fluid, $\hat{\mathbf{u}}$ is the mesh velocity, $\boldsymbol{\sigma}^F$ is the stress tensor of the fluid, and $\mathbf{f}^F$ is the external force applied to the fluid. Eq. (1) is derived by substituting the following stress tensor $\boldsymbol{\sigma}^F$ of the fluid into the Cauchy momentum equation:

$$\sigma^F = -p\mathbf{I} + 2\mu\mathbf{D}, \quad (3)$$

where p is the pressure of the fluid, $\mathbf{I}$ is the unit tensor, μ is the viscosity of the fluid, and $\mathbf{D}$ is the strain rate tensor given by

$$\mathbf{D} = \frac{1}{2}\left(\nabla\mathbf{u} + \nabla\mathbf{u}^{\mathrm{T}}\right). \quad (4)$$

2.2. Structure domain

The structure domain is governed by the Cauchy momentum equation of the Saint Venant–Kirchhoff model considering geometric nonlinearity:

$$\rho^S\frac{\partial^2\mathbf{d}}{\partial t^2} - \nabla\cdot\sigma^S = \mathbf{f}^S, \quad (5)$$

where ρ^S is the density of the structure, $\mathbf{d}$ is the displacement of the structure, $\boldsymbol{\sigma}^S$ is the stress tensor of the structure, and $\mathbf{f}^S$ is the external force applied to the structure. $\boldsymbol{\sigma}^S$ is given by

$$\sigma^S = \mathbf{E} : \epsilon^S, \quad (6)$$

where $\mathbf{E}$ is the elasticity tensor of the structure and $\boldsymbol{\epsilon}^S$ is the strain tensor of the structure.

2.3. Interface between fluid and structure domains

At the FSI interface Γ_{FSI}, the following conditions of continuity and stress equilibrium must be fulfilled:

$$\int \mathbf{u}dt = \mathbf{d} \qquad \text{on } \Gamma_{FSI} \quad (7)$$

$$\sigma^F\mathbf{n}^F + \sigma^S\mathbf{n}^S = 0 \qquad \text{on } \Gamma_{FSI}, \quad (8)$$

where $\mathbf{n}^F$ and $\mathbf{n}^S$ are the unit normal vectors of the fluid and the structure, respectively, at the FSI interface.

3. Iterative partitioned coupling method

The iterative partitioned coupling method divides an original FSI problem into three components: fluid analysis F, structure analysis S, and mesh control M. In the problem, the governing equations of the fluid, structure, and mesh control must satisfy the conditions of continuity and equilibrium at the FSI interface.

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