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Time-Accurate Computation of Viscous Flow Around Deforming Bodies Using Overset Grids

P. Fast, W. D. Henshaw

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Time-Accurate Computation of Viscous Flow Around Deforming Bodies Using Overset Grids*

Petri Fast† William D. Henshaw‡

Center for Applied Scientific Computing
Lawrence Livermore National Laboratory

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Abstract

Dynamically evolving boundaries and deforming bodies interacting with a flow are commonly encountered in fluid dynamics. However, the numerical simulation of flows with dynamic boundaries is difficult with current methods.

We propose a new method for studying such problems. The key idea is to use the overset grid method with a thin, body-fitted grid near the deforming boundary, while using fixed Cartesian grids to cover most of the computational domain. Our approach combines the strengths of earlier moving overset grid methods for rigid body motion, and unstructured grid methods for flow-structure interactions. Large scale deformation of the flow boundaries can be handled without a global regridding, and in a computationally efficient way. In terms of computational cost, even a full overset grid regridding is significantly cheaper than a full regridding of an unstructured grid for the same domain, especially in three dimensions.

Numerical studies are used to verify accuracy and convergence of our flow solver. As a computational example, we consider two-dimensional incompressible flow past a flexible filament with prescribed dynamics.

1 Introduction

Flows where the fluid dynamics is coupled with the motion of the surrounding deformable boundaries are often studied experimentally. Yet, the numerical

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†E-mail: pfast@llnl.gov. Phone: (925) 424-2649.

‡E-mail: henshaw@llnl.gov. Phone: (925) 423-2697.

simulation of such flows is exceedingly difficult. Examples of fluid flows with dynamically evolving boundaries are given by insect flight (see, e.g., Wang & Childress [?], and the references therein), flow in collapsible tubes (Heil & Pedley [?]), and the recent experimental study on the dynamics of a silk thread in a quasi 2D soapfilm flow by Zhang, Childress, Libchaber & Shelley [?]. Flows with deforming bodies are ubiquitous in fluid dynamics, and so the work mentioned above is just a small sample of ongoing research in this field.

In this paper, we develop a new method for handling the geometric complexity arising from a dynamically deforming flow boundary. The key observation in our scheme is to use a thin, body-fitted grid near the deforming flow boundary, while using fixed Cartesian grids to cover most of the computational domain. See [?] for an application of this approach to computing free-surface dynamics in a thin gap (Hele-Shaw) flow. The grids are connected with interpolation equations to form an overset (Chimera) grid. Our implementation uses the Overture framework [?].

This approach is similar to the work of Löhner, Yang and Baum [?], who studied the separation of a flexible store using unstructured grids. Their grid generator was optimized to limit regridding to the neighbourhood of the deforming object. However, they were forced to regrid the whole computational domain periodically to obtain a high-quality finite element mesh. The advantage of using overset grids in this case is that regridding is localized, and is only needed near the moving boundaries. A global regridding is never needed after the initial grid has been generated.

The present work differs from the usual moving overset grid approach (see, e.g., the Proceedings of the First AFOSR Conference on Dynamic Motion CFD, 1996) where the moving objects are typically rigid. Our new approach is a significant step towards the full numerical simulation of fluid dynamics coupled to large scale deformations of the flow boundaries. We only consider deforming bodies with prescibed time-dependent shapes and trajectories in this work, and defer the study of more general flow-structure interactions to another publication.

2 Numerical method

We solve the incompressible Navier-Stokes equations using a velocity-pressure formulation

$$\mathbf{u}_t + (\mathbf{u}\cdot\nabla)\mathbf{u} + \nabla p - \nu\Delta\mathbf{u} = 0 \qquad (1)$$

$$\Delta p - (\nabla u\cdot\mathbf{u}_x + \nabla v\cdot\mathbf{u}_y + \nabla w\cdot\mathbf{u}_z) - C_d(\nu)\nabla\cdot\mathbf{u} = 0. \qquad (2)$$

The term $C_d(\nu)\nabla\cdot\mathbf{u}$ appearing in the equation for the pressure is used to damp the divergence [?]. For further details see also [?].

The Navier-Stokes equations are discretized on overset grids using second-order accurate finite-differences (see [?]). We use the Crank-Nicholson scheme for the viscous flux and an explicit predictor-corrector method for the other terms. This yields a second-order accurate time-stepping scheme.

The methods described here are implemented in the OverBlown flow solver [?] using the Overture framework[?]. In the following, we discuss briefly some of the relevant details. A more detailed description will be provided in the final version of this conference paper.

2.1 Overset grid generation for moving geometries

At each time step, the body-fitted grid or grids surrounding the deforming body must be regenerated. We use hyperbolic grid generation for this (see [?] and [?]).

The current interpolation weights become invalid after the body-fitted grids have been changed. If the changes are large enough, the current interpolation stencils cannot be used in the new grid. Hence the overset grid has to be regenerated everytime the flow geometry changes. Although this is not a significant expense in an incompressible flow calculation, less than 15%, we have optimized the Overture grid generator Ogen [?] also for moving grid computations.

The key idea is to try to use the existing overset grid as an initial guess for a grid where the components have moved slightly. First, we attempt to recompute the interpolation weights in the existing grid to account for the change in geometry. If some of the current interpolation points cannot be used in the new grid, then the grid algorithm looks for donor points near the previous ones. The full grid generation algorithm is invoked from scratch only if the moving grid algorithm fails.

This approach yields a good quality overset grid in most cases, and requires a full regridding only every 5-10 timesteps in our current experiments. In cases where the deformations during a timestep are small compared to the fluid velocity, a full regridding is performed even less frequently.

We remark that even the full overset grid generation algorithm is significantly cheaper computationally than a full regridding of an unstructured grid for the same domain. This is especially important in three dimensional problems.

2.2 Navier-Stokes equations on moving grids

The computational domain adjacent to a deforming body is discretized on a moving, body-fitted grid. Most of the computational domain is stationary in the applications of interest to us, and we use non-moving Cartesian grids on those parts of the computational domain.

A moving component grid is defined by a time-dependent mapping

$$\mathbf{x} = \mathbf{G}(\mathbf{r}, t)$$

where $\mathbf{r}$ denotes the coordinates on the unit-square (or unit-cube). The overset grid is formed from a collection of such mappings, one for each component grid, together with the interpolation conditions used to connect the components. On each grid we make the change of variables from $(\mathbf{x}, t)$ to $(\mathbf{r}, t)$ defined by $\mathbf{x} = \mathbf{G}(\mathbf{r}, t)$, $\mathbf{u}(\mathbf{x}, t) = \mathbf{u}(\mathbf{G}(\mathbf{r}, t), t) \equiv \mathbf{U}(\mathbf{r}, t)$, and $p(\mathbf{x}, t) = p(\mathbf{G}(\mathbf{r}, t), t) \equiv P(\mathbf{r}, t)$.

The Navier-Stokes equations (1)–(2) on a component grid are solved in a frame moving with the grid. Eqs. (1)–(2) on the component grid described by $\mathbf{x} = \mathbf{G}(\mathbf{r}, t)$ are written as

$$\begin{aligned} \mathbf{U}_t + [(\mathbf{U} - \dot{\mathbf{G}}) \cdot \tilde{\nabla}]\mathbf{U} + \tilde{\nabla} P &= \nu \tilde{\Delta} \mathbf{U}, \\ \tilde{\Delta} P + \sum_i \tilde{\nabla} U_i \cdot \partial_{x_i} \mathbf{U} &= 0, \end{aligned}$$

where $\tilde{\nabla}$ and $\tilde{\Delta}$ are the transform of ∇, Δ, respectively, to the $\mathbf{r}$ coordinates (see [?] for details).

2.3 Boundary Conditions

Suppose the position of a moving boundary is defined by $\mathbf{x} = \mathbf{g}(\mathbf{x}, t)$. The boundary condition on the velocity at a no-slip wall is

$$\mathbf{U}(\mathbf{r}, t) = \dot{\mathbf{G}}(\mathbf{r}, t).$$

On a moving no-slip wall the boundary condition for the pressure equation is obtained by dotting the normal $\mathbf{n}$ into the momentum equation:

$$\partial_n P = -\mathbf{n} \cdot \ddot{\mathbf{G}} + \nu \mathbf{n} \cdot \tilde{\Delta} \mathbf{U} \tag{3}$$

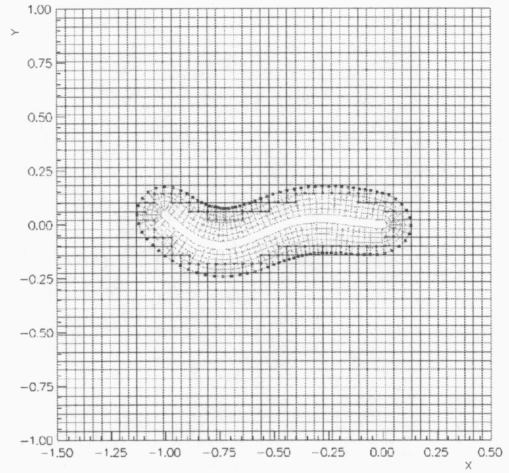
Note that the acceleration of the wall appears on the right hand side. The boundary condition $\nabla \cdot \mathbf{u} = 0$ is added, and can be used to reformulate the viscous term in Eq. (3) to enhance stability of semi-implicit time-evolution schemes (see [?], preprint).

3 Results

We study a 2D model problem where a flexible filament is placed in a viscous flow. The leading edge of the filament is fixed, and the filament motion is prescribed. Figure 1 shows the moving overset grids for this deforming body at two different configurations of the filament. The preliminary Fig. 2 shows flow past a rigid filament at a moderate Reynolds number (Re= 20) using non-moving overset grids.

The final version of this paper will contain several accuracy and convergence studies, as well as simulations of flow past deforming bodies at significantly higher Reynolds numbers, using moving overset grids.

Remark: The Overture technical reports mentioned here [?, ?] are available under `http://www.llnl.gov/casc/Overture`.



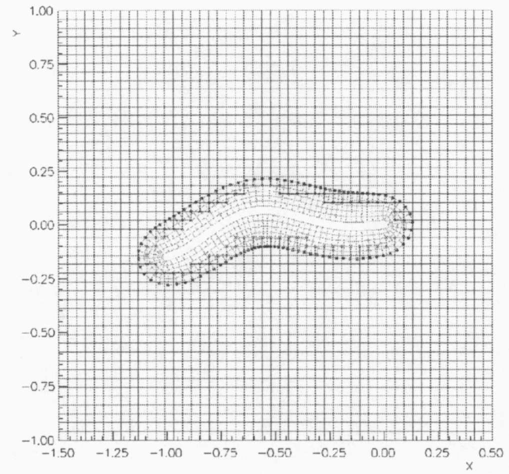


Figure 1: Overset grids for a geometry modeling a flexible filament in an incompressible 2D flow, similar to the experiments by Zhang *et al.*[**?**]. We show the overset grid at two different configurations of the filament.

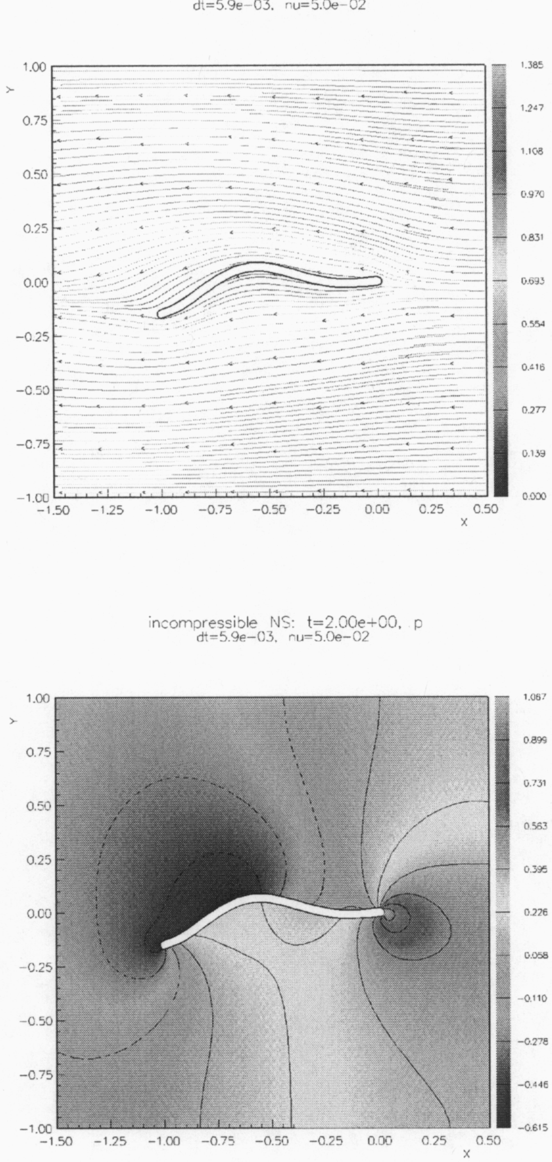


Figure 2: The streamlines(top) and pressure field(bottom) of an incompressible flow past a rigid (=non-flexible) filament. The flow is from right to left, with an inflow on the right-hand side of the box, and an outflow on the left-hand side of the box. The fluid satisfies a no-slip condition on the filament boundary, and a slip condition on the top and the bottom of the flow geometry. This is a preliminary figure where the grid is given by the bottom grid from Fig. 1, and the Reynolds number is moderate (Re≈ 20).