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Unsteady Flow About Bluff Cylinders

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ABSTRACT

A general method is presented for solving the Navier-Stokes equations in two dimensions using the Random Vortex Method (RVM), which is particularly attractive for modeling highly separated flows. New techniques are developed for the RVM to handle unsteady flows about arbitrarily shaped cylinders, which are allowed to undergo any prescribed motion. Computations of the convective interaction of vortex blobs are achieved by a fast order N algorithm. New expressions for such computational methods to calculate the forces on moving bodies are also given. Various problems of engineering significance are studied by this methodology, including the unsteady accelerating motion of a cylinder, an oscillating current about a fixed cylinder and about a transversely-oscillating cylinder. Numerical results are found to agree well with experimental ones and certain existing computations.

INTRODUCTION

Since its introduction, the Random Vortex Method (RVM) (Chorin, 1973) and its several variants have become increasingly popular as methods for simulating viscous flows at high Reynolds numbers. Being a Lagrangian method, it is free of some of the difficulties associated with Eulerian methods, e.g., numerical diffusion and open boundary conditions. Another advantage of the method is that computational elements are concentrated automatically in the regions of the flow that are of most interest. The stream function-vorticity formulation is normally used, i.e., the vorticity transport equation and the Poisson equation for the stream function are solved rather than the Navier-Stokes equations in primitive variables. This is perhaps the best available method for studying separated flow around bluff bodies at high Reynolds numbers — the type of flow one often encounters in maritime engineering.

Several variants of this method are now available. In the original method, Chorin (1973) used the idea that vortex blobs can be generated on the boundary of the body to satisfy the no-slip condition. They are then convected and diffused according to the vorticity transport equation. Since the velocity field is an integral of the vorticity field, the latter is smooth despite the fact that vorticity is represented by "concentrated" vortices. Hence away from the bodies, the smoothness of the solution is not of concern. Appealing though this method was, it had three major shortcomings:

1. The velocity field close to the body was not well-represented.
2. As the number of computational elements (say, N) grew with time, the computational effort increased as N^2 per time step.
3. Because diffusion was simulated using a random-walk algorithm, the results had only a statistical interpretation.

Several ideas have been put forward to overcome these problems. An extensive review of the theoretical and numerical developments may be found in Sarpkaya (1989) and Sethian (1990). In particular, one of the more popular versions is the vortex-in-cell (VIC) algorithm (Christiansen, 1973), in which a finite-difference method is used to solve the Poisson equation for the stream function. This procedure alleviates the first two shortcomings, as the flow near the boundary is numerically smoothed by the grids and the computational effort is reduced to $O(m \log m + N)$, where m is the number of grid points.

However, the necessity of using grids somewhat restricts the type of body geometry that can be studied, unless an additional mapping procedure is utilized. Thus, to avoid using grids, we retain the original grid-free formulation, but the Poisson equation is solved by using a boundary-integral equation method, which can handle arbitrary body shape effectively. To improve the representation of flow close to the body, we rely on a vortex-sheet algorithm proposed by Chorin (1978), which mimics boundary-layer flows. To reduce the intensiveness of $O(N^2)$ computations, we adopt a recent algorithm of Carrier et al. (1988), which reduces the effort to $O(N)$. In light of the ease of computation and simplicity of the random-walk algorithm, we have not eliminated the third shortcoming mentioned above and rely instead on spatial or time filtering, should detailed flow features be desired.

In this paper, we will report some of the successes of our improved RVM method by comparing our results with existing ones and by presenting new results for physical problems not previously considered. First, we consider the case of a uniform flow past a fixed circular cylinder, carried out primarily to validate our method. This had also served as a test case for checking the effects of various numerical parameters. In previous works where

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KEY WORDS: Vorticity, separated flows, wave forces, Navier-Stokes equations, computational fluid dynamics.