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Unsteady separation was computed using Lagrangian body fixed coordinates. The boundary layer equations retain the usual form except for a Coriolis term which is absent in the two dimensional body fixed coordinat case. Results of unsteady separation over a circular cylinder impulsively started are presented.

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Final Report for AFOSR 86-0368

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I. Introduction

This research spans from Oct. 1, 1986 through Apr. 30, 1988. The central theme has been to examine, and hence understand and possibly develop means to control, the phenomena of unsteady separation of the boundary layer of an arbitrarily moving body. If separation is important because of the penetration of the vorticity from the boundary layer into the mainstream, we clearly must go beyond the kinematic condition of reverse flow at the wall—which is synonymous with steady separation over a fixed wall in the original Prandtl concept, and ask what drives the fluid particles out of the boundary layer. For unsteady flows, the streamline pattern changes with the frame of reference and flow reversal as a criterion needs additional specification. In proposing the MRS-condition, for instance, Sears and Telionis (ref. 1) introduced a "suitable moving coordinate system". On the other hand, the physical development of separated flows around many unsteadily moving bodies have been described in the visualization experiments of Taneda (ref. 2). Taneda identified separation with the departure of "streak sheets" from the body, the streak sheets being formed by the tracer particles which he continuously created along the entire body surface. From the analytical viewpoint, Shen (ref. 3) proposed to focus on the pathlines to unify the treatments of steady and unsteady separation, by studying the boundary-layer equation in Lagrangian description. The idea was brought to fruition by a definitive study of the case of an impulsively-started circular cylinder (van Dommelen (ref. 4), van Dommelen and Shen (ref. 5)). The insights gained and the basic computational algorithm of the Lagrangian boundary-layer equations have served as the springboard of further ongoing research.

The boundary-layer approach has the advantage of exaggerating the particle traverse normal to the wall into a mathematical singularity at separation, thereby yielding a clear-cut "separation time" as well as a "separation location" along the wall. Meanwhile, however, the analysis must strictly speaking stop at the first occurrence of separation. Such questions as the progress toward a steady state, or the reattachment of the shear layer, require modifications beyond the classical boundary layer. In the long run, a Navier-Stokes solver particularly for high Reynolds numbers would be of key importance. For instance, the "diffusing vortex" method recently developed by Lu and Shen (ref. 6) for two-dimensional flows has demonstrated its efficacy in the case of the impulsively started circular cylinder at Re = 9500. The algorithm appears to be readily adaptable to the three-dimensional case and suitable for parallel computation.

During the 20-month period of this project, thc efforts have been mainly along the following directions:

(1) General formulation and considerations of unsteady viscous fluid dynamics referred to body-fixed arbitrarily moving axes;

(2) The boundary-layer theory for flow over arbitrarily moving bodies;

(3) Quantitative studies of the effects of variable body motion (in both translational and rotational degrees of freedom) on two-dimensional unsteady separation;

(4) Consolidation of the new "diffusing vortex" method for the computation of unsteady two-dimensional Navier-Stokes equations.

The achievements are summarized below, followed by a list of publications.

II. Achievements of the project

The main theme of this project is to describe the fluid dynamics around an arbitrarily moving body. The natural choice is to describe the fluid mechanics using the same set of rigid-body coordinates fixed to the moving aircraft. The Navier-Stokes equation referred to a set of coordinates fixed to an arbitrarily moving rigid body, differs from the usual one referred to an inertial frame only in the addition of extra body-force or acceleration terms. To an observer riding with the moving body, Fig. 1, the fluid behavior is described by, in customary notation,

$$\nabla \cdot \underline{u} = 0$$

$$\left(\frac{\partial}{\partial t} + \underline{u} \cdot \nabla\right)\underline{u} = -\frac{1}{\rho}\nabla p + \nu\nabla^2 u + \underline{F} + \underline{g} \qquad (1)$$

$$\underline{F} = -\left[\dot{\underline{U}}_A + 2\underline{\Omega} \times \underline{u} + (\underline{\Omega} \times \underline{r}) + \dot{\underline{\Omega}} \times \underline{r}\right]$$

Here $\underline{U}_A$ and $\underline{\Omega}$ are the translational and angular velocity of the body, respectively, and $\underline{g}$ is the gravity. Note that the moving-body effects, as represented by $\underline{F}$, consists of four vectors, each acting like a variable gravity. They are the familiar notions of the linear and angular accelerations, the centrifugal and the Corioli effects. As for the boundary conditions, if the moving body is rigid, then the surface acts as a fixed wall and the no-slip conditions prevail. Even in the simple case of an airfoil in oscillatory motion, the vague and intuitive "moving wall" effect, proposed by Ericsson (ref. 7), is already difficult to be made into a mathematical and quantitative statement. A general theory should be based on the moving body effects as summarized above. By analogy, there are now four generalized (vector) Froude numbers due to the rigid-body motion. (The reduced frequency $\Omega L/U$ and the acceleration parameter $\dot{\underline{\Omega}}L^2/U^2$ for a pitching airfoil are examples.) They may act alone or in any combination, depending on the circumstances. As the governing equations a re nonlinear, obviously we now have a vastly enlarged solution space, and must expect many new phenomena.

For the boundary layer approximation applicable to Eq. (1), our analysis shows that formally it reduces Eq. (1) to the form

$$\left.\begin{aligned} &\nabla \cdot \underline{u} = 0 \\ &\frac{D\underline{u}}{Dt} = \frac{D\underline{u}}{Dt}\bigg|_\delta + 2\underline{\Omega} \times (\underline{u}_\delta - \underline{u}) + \nu \frac{\partial^2 \underline{u}}{\partial z^2} \end{aligned}\right\} \qquad (2)$$

where z is normal to the body surface, and subscript δ refers to the edge of the boundary layer. Notably, Eq. (2) is of the same appearance as in the usual case referring to an inertial frame, with the exception of the Corioli's effect. The boundary layer still may be perceived as to provide a transition between the (relative) velocity at the edge of the boundary layer and the fixed wall, in the presence of the angular velocity of the moving body. All the other body-force terms are contained only in the relative velocity prevailing at the edge of the boundary layer. Equations (2) serves also to justify the practice of using the inertial-frame boundary-layer equations to analyze unsteady airfoil problems.

In particular, for two-dimensional plane motion, the pitching motion makes no contribution to the Coriolis force. Consequently the boundary-layer equations are just like those in an inertial frame, provided the local relative velocity is imposed as the free stream.

Most of the basic considerations, plus simplified calculations for an ellipse (as an idealized airfoil) to illustrate the quantitative nature of the theory to explain separation over moving bodies, were reported first in Shen (ref. 8). More accurate calculations are obviously indispensable. Thus, use was made of the existing Lagrangian program of van Dommelen (ref.4) for the circular cylinder, and that of Wu (ref. 9) for the ellipse. These were modified for the variable motions of interest, which include linear acceleration / deceleration effects. as well as pitching at different rates about arbitrary pivot locations along the chord (of the idealized airfoil). Some of the computed results and their discussion were presented in the First National Congress of Fluid Dynamics (Shen and Wu (ref. 10)).

While pinpointing the separation time and location is definitely of interest, more importantly the Lagrangian calculation actually identifies the fluid packet, which may be called the "seed packet", that is responsible for the eventual separation, manifested by the singularity resulting from its deformation history. It suggests that by influencing the evolution of the seed packet, control of unsteady separation seems a distinct possibility. More research in this direction is planned for the next phase. Conventional Eulerian calculations, of course, can yield no information on the seed packet, nor any clue on controlling unsteady separation.

The boundary layer approximation of course breaks down once massive separation sets in . In anticipation of such problems, the recent thesis of Lu (ref. 11) on a new vortex particle method for solving the incompressible Navier-Stokes equation seemed to us to be worthy of further development. To work toward an extension into the three-dimensional case, it was necessary first to put the two-dimensional case into better shape. In Lu and Shen (ref. 6), certain details were refined and the numerical example of an impulsively started circular cylinder at Re = 9500 was improved to show not only practical feasibility, but also excellent comparison with the experimental observations of Bouard and Coutenceau (ref. 12). Continued study and programming for the three-dimensional case was also initiated, but disrupted due to the departure of Dr. Lu, in October 1987, for an industrial position.

III. List of publications

1. Lu, A. Y.,*The Diffusion-Convection Vortex Method for Solving Two-Dimensional Incompressible Navier-Stokes Equation*, Ph.D. Thesis (Aerospace Engineering), Cornell University, 1986.

2. Lu, Z. Y., and Shen, S. F., *Solution of the Unsteady Viscous Incompressible Flow Past a Circular Cylinder by the Diffusing-Vortex Method*, presented at the 5th International Conference of Numerical Methods in Laminar and Turbulent flow, Montreal, July 6-10, 1987; to appear in **Numerical Methods in Laminar and Turbulent Flow**, editors C. Taylor, W. Habashi and M. Hafez, vol. 5, Pt. 1, Pineridge Press.

3. Shen, S. F., *Considerations for Analyzing Separated Flows over Arbitrarily Maneuvering Bodies,* revised version of a presentation at the Workshop on Unsteady Separated Flows, Colorado Springs, July 28-30, 1987, to appears in the Proceedings of the same.

4. Shen, S. F. and Tsuyin Wu, *Unsteady Separation over Maneuvering Bodies*, presented at 1st National Fluid Dynamics Congress, July 25-28, 1988, Cincinnati, OH, paper no. 88-3542-CP.

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7. Ericsson, L. E., *Dynamic Omnipresence of Moving Wall Effects, A Selective Review*, AIAA Paper No. 87-0241, 1987.

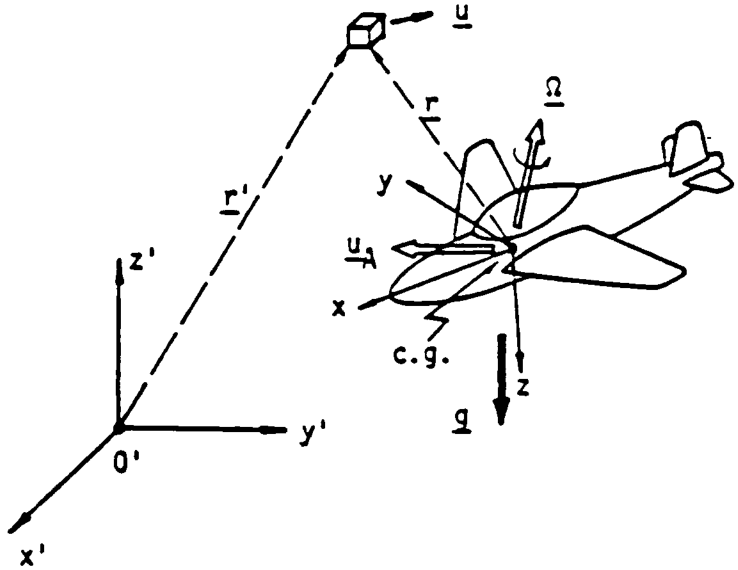
8. Shen, S. F., *Considerations for Analyzing Separated Flows over Arbitrarily Maneuvering Bodies*, revised version of a presentation at the Workshop on Unsteady Separated Flows, Colorado Springs, July 28-30, 1987, to appears in the Proceedings of the same.

9. Wu, T. Y., *Unsteady Incompressible Boundary-Layer Separation over a Two-Dimensional Impulsively-Started Cylinder Calculated by Lagrangian Method*, M.S. Thesis, Cornell University, 1985.

10. Shen, S. F. and Tsuyin Wu, *Unsteady Separation over Maneuvering Bodies*, presented at 1st National Fluid Dynamics Congress, July 25-28, 1988, Cincinnati, OH, paper no. 88-3542-CP.

11. Lu, Z. Y.,*The Diffusion-Convection Vortex Method for Solving Two-Dimensional Incompressible Navier-Stokes Equation*, Ph.D. Thesis (Aerospace Engineering), Cornell University, 1986.

12. Bouard, R. and Coutenceau, M., *The Early Stage of Development of the Wake Behind an Impulsively Started Cylinder for $40 < Re < 10^4$*, **J. Fluid Mech.** 101, 583-607, 1980.



General features of a body-fixed coordinates system

FIG. 1