N94- 34973

INVESTIGATION OF MECHANISMS FOR VORTICITY GENERATION AND FLOW SEPARATION ON BODIES IN UNSTEADY MOTION

Chuen-Yen Chow and Kai-Hsiung Kao
Department of Aerospace Engineering Sciences
University of Colorado, Boulder, CO 80309-0429

ABSTRACT

Described in this work is an attempt to identify and examine the mechanisms responsible for the generation/shedding of vorticities and the separation of flow from bodies in forced unsteady motions through a viscous fluid. To gain insight into the basic physics of unsteady fluid dynamics, possible mechanisms are isolated and examined separately by assuming different simplified flow arrangements. Even without depending on the availability of the supercomputers, it might be possible to explain or predict some complex unsteady flow phenomena based on the fundamental understanding of the individual mechanisms.

OBSERVED UNSTEADY FLOW PHENOMENA

A numerical study has been made of the flow around an abruptly started elliptic cylinder through an incompressible viscous fluid at a constant angle of attack. The following special features have been observed in the results of that study:

- The zero streamline on the upper surface moves quickly to the trailing edge so that the Kutta condition is automatically satisfied on a body whose trailing edge is not sharp. See Fig. 1. The same phenomenon is also found even on an ellipse of a very small eccentricity as shown in Fig. 2.

- Vorticities are generated from the leading edge and are convected downstream along body surfaces while being diffused sideways. Parts of the vorticities are shed from the trailing edge. See vorticity contour plots in Figs. 1 and 2.

- At a high angle of attack, leading edge separation may occur as shown in later stages of Fig. 1.

• In contradiction to the inviscid analysis, a body without a sharp trailing edge, such as the elliptic cylinder considered here, can generate a lift in a viscous fluid. Figure 3 reveals that the computed steady-state lift increases with increasing slenderness of the ellipse.

QUESTIONS AND APPROACHES TO FIND ANSWERS

Based on the aforementioned observations, some questions arise concerning the fundamental physics of the unsteady fluid dynamics. In most experimental and numerical studies of unsteady flows, a large number of parameters are involved, such as the body geometry, time dependent body motion, viscous and inertial forces of the fluid, etc. The nonlinear coupling of those parameters makes the flow phenomena too complex to fully comprehend. In searching for answers to those questions, an approach is followed in which the influential parameters are separated and examined individually by choosing various appropriate simplified flow configurations. After the effect of each parameter is throughly understood, even without intensive numerical computations, the overall behavior of a given unsteady flow might become predictable based on a synthesis of the influences from all parameters involved in that particular problem.

Question I. What are the mechanisms that cause the production of vorticity on a body in forced unsteady motion?

To answer this question several classical unsteady flow problems with exact solutions are reviewed. For a flat plate of infinite extension started impulsively into a constant motion U in its own plane, vorticity is generated instantaneously at the surface and diffuses away into the fluid in the normal direction. At a later time the shear stress at the plate is finite, but it cannot generate additional vorticity. The total vorticity contained in the fluid per unit projected area of the plate is a constant, which is proportional to U but independent of the viscosity of the fluid. Examined also are the unsteady plane and cylindrical Couette flows. The conclusion is that vorticity is generated by tangential acceleration of a solid surface, but not by the shear force exerted by the surface on the fluid.

In the case of the Blasius boundary layer flow, all vorticity is generated at the leading edge. The total amount of vorticity, which is proportional to the relative velocity of the plate through the fluid, is convected downstream without changing its total magnitude despite the presence of wall shear forces along the boundary layer.

The generation of vorticity by tangential pressure gradients along a surface and the consideration for bodies of finite dimensions are omitted in this abstract.

Question II. What are the mechanisms that cause the zero streamline to move toward the rounded trailing edge of a body, and what are those that cause leading edge separation?

The possible influential parameters are many, including for example the body curvature, local vorticity distribution, pressure gradient, and the surface velocity relative to the external flow. The flow structure near the trailing edge of an impulsively started elliptic cylinder was studied previously by us using the method of matched asymptotic expansions. The representative result shown in Fig. 4 describes the process by which a region of concentrated vorticity is lifted off the trailing edge and shed into the wake. The present work examines why such a phenomenon should occur near the trailing edge and how the flow there differs from that near the leading edge.

At an early stage after the impulsive start of the ellipse, as shown in Fig. 1, the flow near the leading edge resembles that around a stagnation point and that near the trailing edge is approximately one with flow directions reversed. Using a simplified model, the leading edge flow is approximated by a stagnation-point flow on an infinite plate facing a stream, whose solution under boundary layer approximations is known. However, by reversing the stream direction to simulate the flow near the trailing edge, the behavior of the boundary layer there is radically changed. Effects of various parameters on the boundary layer structure are then studied by modifying this standard model. For example the orientation of the body surface is simulated by allowing the far flow to incline at an angle, and the unsteady translational and rotational motions of the surface are approximated by giving the plate certain prescribed normal and tangential velocities. To simulate the effect of body curvature, the flat plate may be replaced by a circular cylinder. In this way a set of geometrically simple yet physically meaningful problems is formulated; most of the problems can be solved using classical boundary layer solution techniques. This study may shed some light on the explanation of many unsteady flow phenomena, such as the differential lift generation abilities of an ellipse with different eccentricities as shown in Fig. 3. The basic solutions may also be used for the prediction of the occurrence of leading edge separation, its suppression and control.

Question III. This question is concerned with the classical Kutta-Joukowski theorem that $L'=\rho U\Gamma$, in which Γ is the circulation computed along a closed path around a lifting body according to the inviscid theory. In a realistic fluid with viscosity, then, how should Γ be computed?

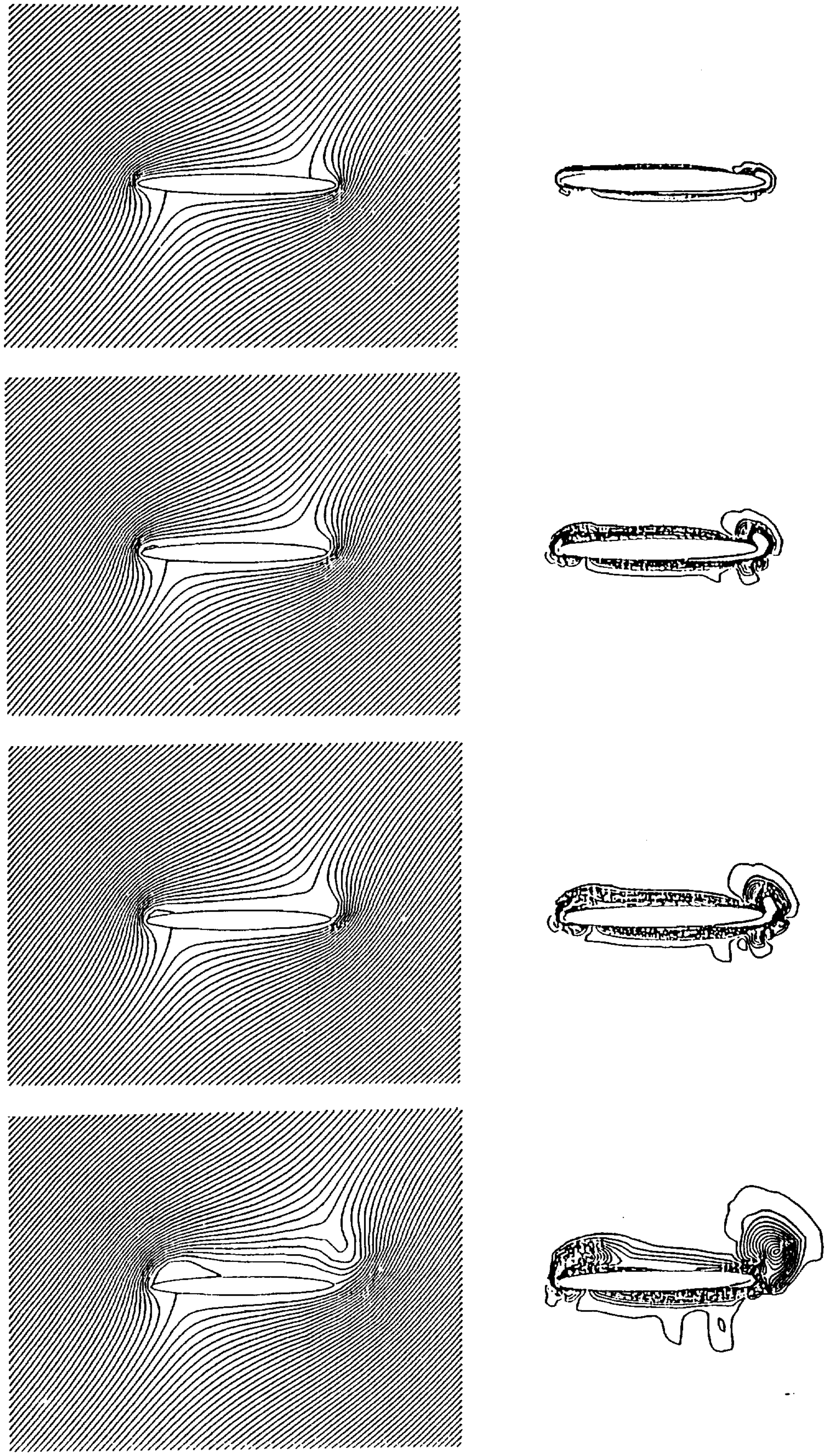
When the no-slip condition is applied on a body without rotation, the circulation around a path coinciding with the body surface is zero. By choosing closed paths further and further away from the body, the computed circulation will first increase but will decrease later, and finally will approach zero again because the total vorticity generated by a translational body vanishes. It appears quite difficult to find an appropriate closed path that contains all the vorticities responsible for the lift, even if the wake vorticities are far from the body. Despite the fact that a satisfactory solution has not yet been found, various attempts to find an answer will be described.

ACKNOWLEDGMENT

This work is sponsored by the Air Force Office of Scientific Research (AFSC) under Contract F49620-88-C-0098.

FIGURE 1: $\eta_1 = 0.1, \alpha = 45$, $Re = 200$

Streamlines — Equi-Vorticity Lines



t=0.012

t=0.036

t=0.1

t=0.3

FIGURE 2: $\eta_1 = 1.0, \alpha = 30°, Re = 200$

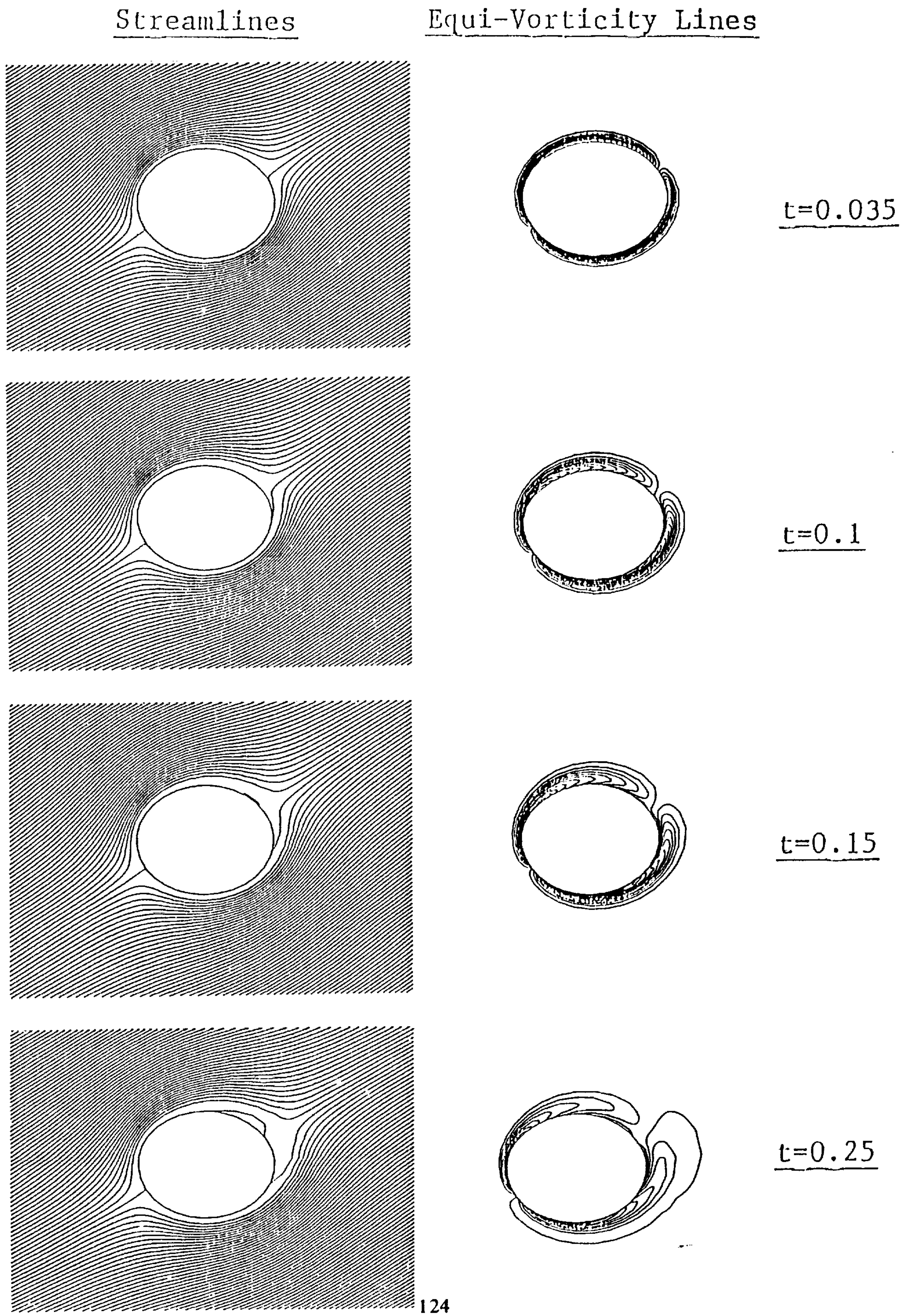


FIGURE 3: C_L vs. time for elliptic cylinders.

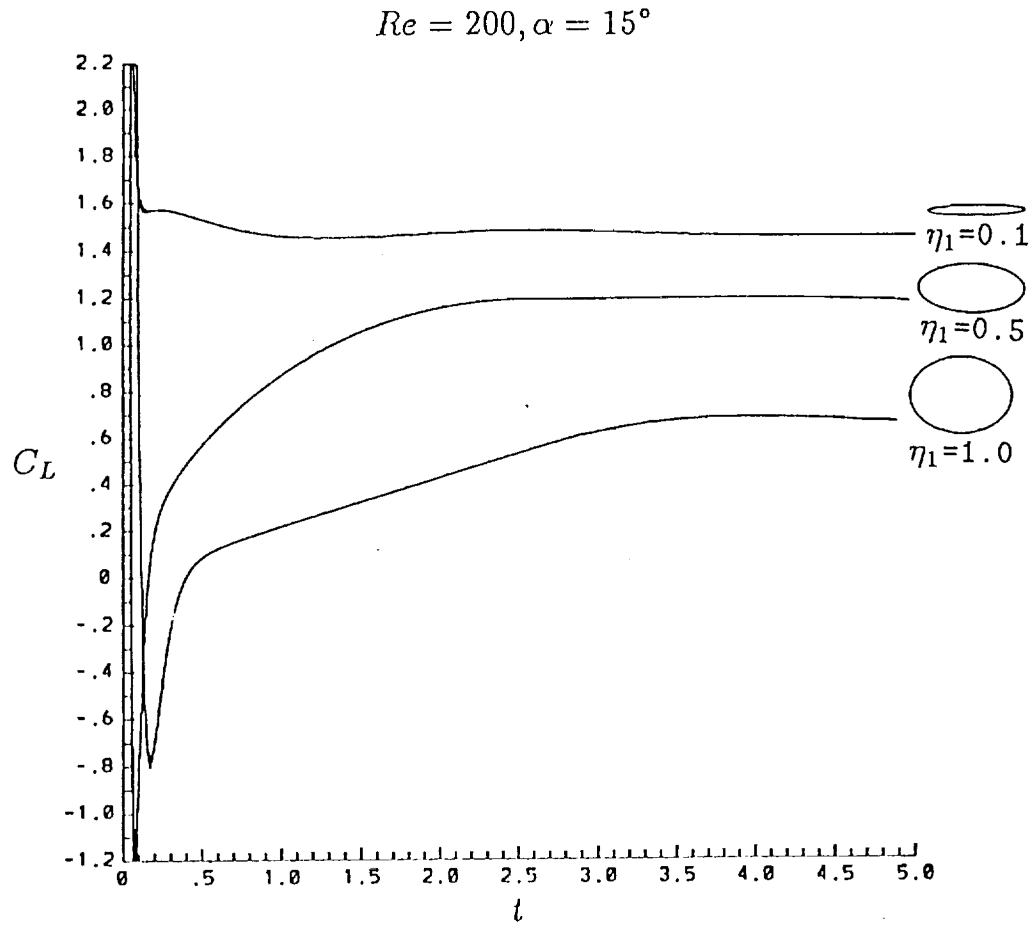
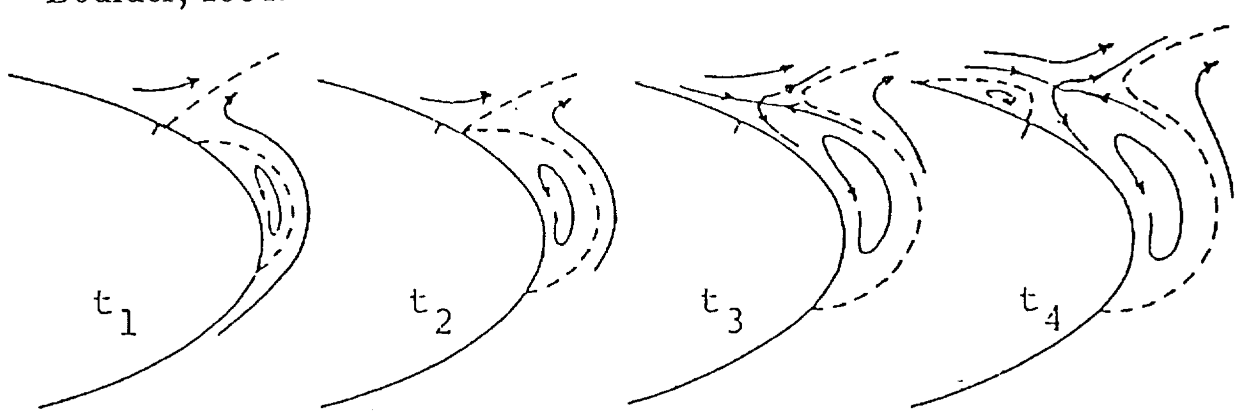


FIGURE 4: Evolution of flow pattern near the trailing edge of an abruptly started elliptic cylinder.

Taken from D. F. Billings' Ph.D. Thesis, University of Colorado at Boulder, 1984.



Factors affecting movement of zero streamline in stagnation-point flow:

- Direction of flow
- Unbalanced vorticity
- Orientation of far flow
- Body curvature
- Motion of body surface

Conclusion

Position of the zero streamline changes in an unsteady stagnation-point flow ; it moves from a low into a high vorticity region.