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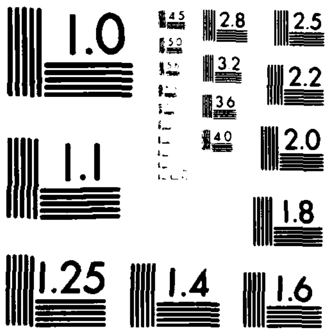

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Final Report on ONR N00014-77-C-0033

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I. Introduction

This research, from 1/1/81 through 5/31/84, was basically supported by an original grant plus one renewal. It began as the follow-through of the work on unsteady boundary-layer separation previously under AFOSR sponsorship. The approved budget was sufficient for slightly more than one graduate assistant full-time. Thus the mainstay on the project had been L. L. van Dommelen, who was thus able to finish his thesis and clarify certain issues of immediate urgency. A new student (T. Y. Wu) was brought in toward the end of the support period for continuation, and underwent training to apply and refine the Lagrangian technique developed by van Dommelen. Unfortunately the support from ONR was soon terminated.

The central theme of research under this grant had been the study of phenomena of unsteady boundary-layer separation, emphasizing but not restricted to the Lagrangian description. Advances were planned to follow the initial works of Shen and Nenni (1975), Shen and van Dommelen (1977), Shen (1978a, 1978b). Historically, in the classical two-dimensional laminar case, flow reversal and vanishing wall shear define steady separation over a fixed wall. But they obviously do not play the same role when the flow is either unsteady or the wall is moving (Sears and Telionis (1971, 1975)). Observations of the separated flow over a rotating circular cylinder in a uniform steady stream led to the now well-known MRS-criterion, which may be paraphrased as follows: Relative to a suitable set of moving coordinates, separation occurs when the local streamwise velocity and the vorticity are both zero. Since the moving coordinates are unspecified, it really means that separation must occur along the locus of zero-vorticity, but is moving with an unknown local streamwise velocity. In a sense, the MRS only specifies zero vorticity as a necessary condition.

In most boundary-layer literature, separation is visualized as the failure of streamlines in adhering to the wall. But streamlines are coordinate dependent. Thus over a moving wall, the streamline orientation is not a precisely definable parameter. Features invariant to coordinate transformation are the particle paths and the vorticity distribution. Indeed, all visualization studies of separated flow patterns watch the particle movements. The particle paths of course coincide with the streamlines in steady flow. We therefore proposed to focus on the path lines by going to the Lagrangian description. The theoretical importance of the path lines was clearly seen in the asymptotic analysis of Nenni (1976), Shen and Nenni (1975). We have further emphasized that the Lagrangian description unifies the steady and unsteady cases without the need of separate postulates.

The conceptual superiority of Langrangian description for separation studies was vindicated by the discovery that separation is identifiable by the occurrence of a singularity (in the boundary-layer approximation) along the path line. Furthermore, the singularity is determined by the stationary point of the forward displacement, thus much more amenable to numerical treatment than the 'infinity' associated with the same singularity in Eulerian computations of separating boundary layer. These were established in Shen and van Dommelen (1977). Physically the singularity, and hence separation, results from the overtaking of the slower-moving particles by the faster-moving ones in the back--much like the shock-formation due to wave-steepening in inviscid compressible flows. This was pointed out in Shen (1978a).

In the following we shall summarize mainly the subsequent achievements during the period under ONR support. A list of publications and theses ends the report.

II Achievements under ONR support

While the basic formulation and the theoretical aspects were outlined in Shen and van Dommelen (1977), the numerical example offered therein had to do with the time evolution of the boundary layer over a circular cylinder in a uniform stream, from an initial set of data (specified) until separation occurs at a spatial location. The computational aspects turned out to be much less troublesome in comparison with the Eulerian schemes, and both the separation time and location can be accurately determined. We might recall that these results came out at the time when the unsteady boundary-layer singularity was considered 'fiction' by many experts, based on the best available Eulerian computational information. Our attempt to publish this work in the *Journal of Fluid Mechanics*, well-known for its scientific standard, met with determined resistance. The snub, however, served a useful purpose of forcing more refinements to be made. Furthermore, the benchmark case of an impulsively-started circular cylinder, attacked by various Eulerian schemes, was resolved for comparison. The numerical results were presented at the IUTAM Congress (van Dommelen and Shen, 1980a) and published as van Dommelen and Shen (1980b). The more complete theoretical considerations were described in van Dommelen and Shen (1982), at which time the skeptics had been by and large finally won over.

The basic theory in the above discussions dealt with the fixed wall case. In view of the motivation of the MRS-criterion, it was apparent that the moving wall effect on separation should be better understood. Observations of the separated flow over a rotating cylinder (Ludwig, 1964; Taneda, 1977) show that the patterns are different over the opposite sides of the cylinder. Relative to the downstream moving wall, the separation pattern is receding upstream into the unseparated region. Relative to the upstream moving wall, the separation pattern is advancing into the already separated region. Intuitively, one would anticipate that the upstream-moving wall case should create more difficulty with a boundary-layer theory. This was demonstrated by an example due to Inoue (1981), who used a parabolized Navier-Stokes scheme.

The local interaction between the inviscid flow and the boundary layer near separation eliminates the exaggerated singularity in boundary-layer theory, steady or unsteady, which has its origin from a specified pressure distribution. For post-separation behavior, a solution must be sought jointly in the inviscid and the viscous regions--commonly referred to as the interaction theory. For steady flow over a fixed wall, the pioneering work due to Sychev (1972) described the local flow near separation in terms of the Kirchhoff streamline theory and a triple-deck structure. Numerical solutions have been given by Smith (1977) and Korolev (1980). The case of a downstream moving wall, or separation moving upstream relative to the wall was treated in Sychev (1980). The main difference is, of course, the details in the 'lower deck' wall-layer. In Shen and van Dommelen (1982) and van Dommelen and Shen (1983a), this problem was re-examined but a smoother and more natural transition between the wall layer and the separated vortex sheet was proposed. The interactive solution was then constructed by a new procedure that provides the pressure adjustment in a least-square sense. The resulting flow shows the particles of low forward velocity to suffer a rapid but smooth slowing-down prior to the pressure plateau, thus forcing the layer above to form an essentially free shear-layer. There is no more singularity but the picture remains the same as concluded from the Lagrangian boundary-layer theory. According to the solution, the resolution needed in the separation vicinity is $O(Re^{1/3})$--which should serve as a guideline for numerical analysis. An application of the methodology to the steady and fixed wall case is reported in van Dommelen and Shen (1984), the results showing agreement with those due to Smith and Korolev mentioned above. The case of upstream moving wall is described in van Dommelen and Shen (1983b).

Off the main track of unsteady separated flows for incompressible fluids, limited efforts were devoted to compressible problems. In Shen and Chen (1982), the unsteady boundary layer caused by moving shock over a flat plate, the original Lam-Crocco (1959) problem, was revisited according to recent ideas of the 'singular parabolic equation', as well as from a computational viewpoint. This was meant to be the preparation for separated flows with shock boundary-layer interaction. A companion work was the thesis of Kim (1982), which studied the compressibility effects on semi-similar unsteady boundary-layer flows with separation. The prototype problem solved was the semi-similar Howarth problem: the free-stream velocity $U = 1 - \xi$, $\xi = x/(1 + At)$, A = const. Effects of the Mach number and wall temperature on the initiation of separation, for instance, were determined. These results are believed to be the only ones specifically dealing with compressibility effects on unsteady separation. Publication has been delayed because of a desire to refine and add to the results. Unfortunately, the departure of Kim after a serious illness led to an interruption.

A final publication from this project is van Dommelen and Shen (1985), which deals with the unsteady growth of the boundary layer at the rear stagnation point, first studied in Proudman and Johnson (1962). It turns out to have a most interesting mathematical feature that exponentially small terms in the solution, at large distances from the wall, must be carefully monitored in constructing the solution. The importance of this work lies in its impact on further numerical studies of more general unsteady cases where similar local features may be present.

Prior to the departure of van Dommelen we brought in a new graduate assistant, T. Y. Wu, to continue the research. His assignment was to apply and improve van Dommelen's Lagrangian scheme, for calculating cases of more practical interest, starting with the impulsively started elliptical cylinder at an angle of attack. Wu participated in the rear stagnation-point problem, performing most of the detailed work for van Dommelen and Shen (1985), and then completed the solution of the elliptical cylinder problem for fineness ratios 2:1 and 4:3, at angles of attack 0^o, 9^o, 45^o and 54^o. His efforts in both the rear stagnation-point and the elliptical cylinder problems are described in a M.S. thesis

(Wu, 1985). For the elliptical cylinder, the most important aspect is the confirmation of the two types of separation: one occurring near the trailing edge and the other near the leading edge. At zero or small angles of attack, adverse pressure gradient begins in the mid-chord region and separation occurs as a result of the growing bubble of reverse-flow spread forward from the rear stagnation point, much like the circular cylinder. At larger angle of attack, the peak suction is reached very close to the leading edge, giving rise to a second bubble of reverse flow in its vicinity. Both the leading-edge and trailing-edge bubbles can lead to separation. As for the boundary-layer singularity, no difference from the circular cylinder was expected and none was found. These results are being prepared for publication. Continuation of Wu's research was to include investigations of the sharp trailing-edge effects and also the separation of oscillating airfoils. They were suspended after termination of the project.

An invitation was received and accepted, with Dr. van Dommelen as co-author, to contribute an article on unsteady boundary-layer separation to Volume 16 of the *Annual Review of Fluid Mechanics*, to be published in late 1984. A preliminary version, summing up his views, had in fact been drafted by van Dommelen soon after his departure for Florida. The needed revisions, however, could not be pursued because of the changing circumstances. No final version was submitted to the *Annual Review of Fluid Mechanics*.

III List of Publications and Theses

(a) Publications

1. Van Dommelen, L. L. and S. F. Shen (1980), *The Spontaneous Generation of the Singularity in a Separating Boundary Layer*, **J. Comp. Phys.**, 38:125-140.

2. Van Dommelen, L. L. and S. F. Shen (1982), *The Genesis of Separation*, in **Numerical and Physical Aspects of Aerodynamic Flows**, ed. T. Cebeci, 293-312, Springer Verlag, New York.

3. Shen, S. F. and Y. M. Chen (1982), *The Unsteady Compressible Boundary Layer over a Semi-Infinite Flat Plat Caused by a Moving Shock*, in **Numerical Properties and Methodologies in Heat Transfer**, ed. T. M. Shih, 361-374. Hemisphere, Washington.

4. Shen, S. F. and L. L. van Dommelen (1982), *A Bifurcation-Free Interaction Solution for Steady Separation from a Downstream Moving Wall*, AIAA Paper-82-0347.

5. Van Dommelen, L. L. and S. F. Shen (1983), *An Unsteady Interactive Separation Process*, **AIAA J.**, 21(3):358-362.

6. Van Dommelen, L. L. and S. F. Shen (1983), *Boundary Layer Separation Singularities for an Upstream Moving Wall*, **Acta Mechanica**, 49:241-254.

7. Van Dommelen, L. L. and S. F. Shen (1984), *Interactive Separation from a Fixed Wall*, in **Numerical and Physical Aspects of Aerodynamic Flows II**, ed. T. Cebeci, Springer Verlag, New York, pp. 393-402.

8. Van Dommelen, L. L. and S. F. Shen (1985), *The Flow at a Rear Stagnation Point Is Eventually Determined by Exponentially Small Values of the Velocity*, **J. Fluid Mech.**, 157:1-16.

(b) Theses

1. Van Dommelen, L. L. (1981), *Unsteady Boundary Layer Separation*, Ph.D. Thesis, Cornell University, Ithaca, New York.

2. Kim, S. K. (1982), *Numerical Solutions of Compressible Semi-Similar Boundary Layer Equations Including Separation,* M.S. Thesis, Cornell University.

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

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