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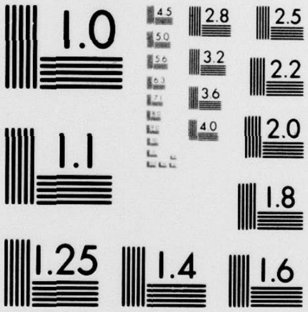
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FINAL REPORT

ON

UNSTEADY LAMINAR FLOW

TO

Director, Fluid Dynamics Program
Mathematical and Information Sciences Division
Office of Naval Research
United States Navy
Under Contract No. N00014-77-C-0650

by

Principal Investigator K.C. Wang
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Work performed under the subject contract (from October 1977 to January 1980) was aimed at developing the methodology for computing unsteady laminar boundary layers with flow reversal and establishing a new unsteady separation criterion. ~~We have completed~~ THE calculation of two-dimensional, unsteady boundary layers based strictly on the analogy with the steady, three-dimensional problems, HAS BEEN COMPLETED. The results demonstrated the validity of ~~our~~ THE proposed unsteady separation criterion. As a pre~~c~~lude to understanding the

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SUMMARY

Work performed under the subject contract (from October 1977 to January 1980) was aimed at developing the methodology for computing unsteady laminar boundary layers with flow reversal and establishing a new unsteady separation criterion. We have completed calculation of two-dimensional, unsteady boundary layers based strictly on the analogy with the steady, three-dimensional problems. The results demonstrated the validity of our proposed unsteady separation criterion. As a preclude to understanding the full, three-dimensional, unsteady problem, we also treated an unsteady symmetry-plane boundary layer. Initial test calculations were successful, but the bulk of the computation remains to be carried out.

I. INTRODUCTION

Unsteady viscous flow phenomena are of fundamental importance in many practical aerospace applications. Besides occurring from laminar instability and transition at high Reynolds number, unsteady flow may arise either when the free stream is unsteady or when the body experiences some unsteady motion. Examples of the latter include the accelerating (or decelerating) motion during take-off (or landing) operations and the periodic motion of rotating machineries or vehicles (such as helicopters, turbines, etc.).

The state of research into the unsteady aspects of the laminar boundary layer theory is rather unsatisfactory compared to that for the steady case. Even for two-dimensional problems, complete solutions are still scarce, while basic questions like unsteady separation and unsteady reversed flow remain unsettled. Erroneous concepts on these matters still prevail in the literature, whereas three-dimensional, unsteady problems are virtually untouched.

II. RESEARCH OBJECTIVES

The objective of this research program was to investigate the basic aspects of two-dimensional, and then three-dimensional, unsteady viscous flows. To obtain concrete results and definitive conclusions without excessive efforts, we simplified the problems by following the boundary layer approach instead of the semi-Navier-Stokes or full Navier-Stokes approach. We particularly focused on developing a methodology for calculating reversed flow and establishing a workable criterion for determining unsteady separation.

Although the problem of a suitable criterion has been considered before by a number of researchers, we felt it was far from being resolved. Consequently, we proposed a new unsteady separation criterion and devoted most of our efforts during the contracting period to demonstrating the validity of the proposed criterion with specific examples.

Whereas existing separation criteria are patterned after those for two dimensional, steady separation, our criterion arises from a different viewpoint: Generalization by analogy from that of three-dimensional, steady separation.

General unsteady separation in three-dimensions was also considered. A basic requirement for the general, unsteady, three-dimensinal separation criterion is that it must consistently include both the known steady, three-dimensional separation criterion and the proposed unsteady, two-dimensional separation criterion as special cases. Our proposed criterion meets these requirements.

III. APPROACH

We used the analogy approach to the two-dimensional, unsteady boundary layer problem, i.e., a methodology analogous to that for solving the three-dimensional, steady boundary layer problem was applied to solve the two-dimensional unsteady boundary layer problem. The theoretical basis for this approach was the observation that the respective systems of governing equations embody a similar mathematical structure. Both systems contain one boundary-value and two initial-value independent variables; in other words, they are hyperbolic along two coordinate (including time) directions and elliptic along the third (normal to the body surface) direction. Based on this similarity, we extended, several years ago, the concept of the zones of influence and dependence for the steady, three-dimensional case to the unsteady, two-dimensional case, even though the number of equations for each case differed.

In the present work, the unsteady analogy was further explored on several fronts. First, the comprehensive computing program and associated computational logics and procedures developed previously for the steady, three-dimensional problems were converted for the present, unsteady two-dimensional applications by simple redesignations of variables. We then applied the concepts for calculating reversed cross-flow over an inclined body of revolution (a typical steady, three-dimensional problem) to calculation of the unsteady, two-dimensional reversed flow -- valid as long as the respective dependence rules are satisfied. An immediate implication of the calculabilitiy of unsteady reversed flow is that the vanishing of skin friction, which marks the beginning of flow reversal, no longer signifies separation nor automatically invalidates the boundary layer concept.

The unsteady analogy was further extended to deal with the question of unsteady separation. For steady, three-dimensional flows, separation line has been defined as an envelope of the limiting streamlines. This envelope criterion, originally based on flow visualization experiments, has since been reaffirmed by available numerical solutions. During the present research, an analogous envelope criterion for determining unsteady separations was proposed and demonstrated.

Based on our conviction that future research into unsteady flow should focus more on three-dimensional problems, we also undertook, as a first step, to investigate the unsteady boundary layer along the symmetry plane of an inclined body of revolution. Previously, we considered the steady counterpart and obtained results that revealed new three-dimensional features of fundamental significance. We expect that similar situation may also occur for the unsteady case. Three-dimensional unsteady flow characteristics are expected to be significantly different from our current understanding based on two-dimensional or axisymmetrical cases. In particular, the open separation phenomenon we found in the three-dimensional steady case would also be present in the corresponding unsteady case. The way in which an open separation developed as the boundary layer grows from an impulsive start is, for example, very intriguing and may shed some light on the previously unexplored structure of three-dimensional unsteady flow.

IV. DISCUSSION AND RESULTS

From our investigations of two-dimensional unsteady separation, we concluded that the existing unsteady separation criteria (MRS criterion, after Moore, Rott and Sears; unsteady Goldstein singularity (1) criterion) remain unproven.

Although the solutions of Williams and Johnson (2) demonstrated the MRS criterion, the special assumptions used there reduced the problems essentially to steady ones for which the validity of the MRS criterion was not in doubt. The cylinder solution by Telionis and Tsahalis (3) gave support to the Goldstein singularity criterion, but this solution had been subsequently contradicted by later calculations. Apart from the basic validity question, both of these criteria are inconvenient to apply; in addition, their extension to three-dimensional cases has not been shown.

To analogously apply the envelope separation criterion for steady, three-dimensional flow to the two-dimensional, unsteady flow, pertinent equations were formally transformed from one to the other; similar limiting streamlines were defined in the x, t-plane for the unsteady case; and the envelope of those limiting streamlines was proposed as a new unsteady separation criterion. This criterion determines separation without relying on usual indications, such as rapid increase of boundary layer thickness, etc., and it is also consistent with the criterion for general unsteady separation in three dimensions.

Analogous to the three-dimensional, steady case, separation for the two-dimensional, unsteady case can also be classified as "open" or "closed", i.e., the separation line defined as an envelope of the limiting streamlines does not or does divide the x, t-plane into two unconnected regions. To illustrate these types of separation, two previously studied examples were recalculated: unsteady response to a sudden change of the Howarth steady problem (closed separation) and unsteady growth for an impulsively started circular cylinder from rest (open separation).

Results confirmed envelope formation by analogous unsteady limiting stream lines, and the separation so determined was compared to that of Telionis and Tsahalis'. For the first problem, (closed separation) agreements were noted in general trends of the separation line in relation to the zero skin-friction line, but discrepancies were found in actual locations of these lines. Also the Telionis-Tsahalis results showed a much faster approach toward the final steady-state condition than did ours. For the second problem (open separation), results for the zero skin-friction line agreed very well, but those for the separation line were entirely different. Our separation was determined by convergence to an envelope of the limiting streamlines, theirs by the singularity criterion. Our calculations detected no singularity at the place and time shown by their calculations. Moreover, we predicted separation at larger times.

Our prediction appeared to be in good agreement with that of Van Dommelen and Shen based on a Lagrangian approach. Although our results for the vanishing skin friction point and the boundary layer thickness also agreed well with those by Cebeci (5), yet the separation conclusions reached were very different. He contended that no separation occurred at any finite time, we concluded just the opposite. Interestingly, however, both we and Cebeci claimed to agree with the general conclusion of Proudman and Johnson (6).

We also described general unsteady separation in three dimensions based on the application of a steady, three-dimensional criterion at successive instants of time. This method simulates the usual sequence of observing an unsteady flow, and does not necessarily imply a quasi-steady approach. Alternatively, it may be seen as applying the unsteady, two-dimensional criterion to staggering fixed coordinate planes. Hence, the three-dimensional, unsteady separation we proposed includes both the steady, three-dimensional separation and the unsteady, two-dimensional separation as special cases. Our unsteady, three-dimensional separation criterion differed from that of Eichelbrenner (7) which contained the closed type of separation but not the open type.

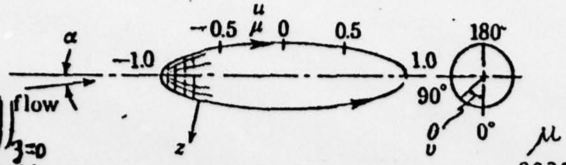
The details of our work were documented in the report:

Wang, K.C., "Unsteady Boundary Layer Separation," Martin Marietta Laboratories TR 79-16c, April 1979.

Subsequent calculated results and comparisons with other work will soon be incorporated into a revised version for journal publication.

Work on the unsteady boundary layer along the symmetry plane of an inclined ellipsoid of revolution is well under way. The detailed formulation, change of computing program, and generation of initial profiles have all been completed. Initial calculations have been successful, and different grid steps in time as well as along the symmetry plane have been tested to determine optimal mesh sizes for conserving computing time. However, the bulk of the calculations for this work remains to be carried out. Table I illustrates the recently calculated skin frictions on both the windside and the leeside of the body at small times.

TABLE I. SKIN FRICTIONS



Windside
Time = 0.039

μ	$\frac{1}{\sqrt{R}}\left(\frac{\partial u}{\partial \zeta}\right)_{\zeta=0}$	$\frac{1}{\sqrt{R}}\left(\frac{\partial}{\partial \zeta}\left(\frac{\partial v}{\partial \theta}\right)\right)_{\zeta=0}$
-.99398	.12546+01	.10033+01
-.94398	.24761+01	.70803+00
-.89398	.27551+01	.70590+00
-.84398	.28577+01	.68144+00
-.79398	.29090+01	.66267+00
-.74398	.29472+01	.64745+00
-.69398	.29726+01	.63463+00
-.64398	.29933+01	.62561+00
-.59398	.30125+01	.61893+00
-.54398	.30290+01	.61352+00
-.49398	.30432+01	.60902+00
-.44398	.30558+01	.60519+00
-.39398	.30670+01	.60188+00
-.34398	.30771+01	.59898+00
-.29398	.30862+01	.59639+00
-.24398	.30946+01	.59407+00
-.19398	.31023+01	.59194+00
-.14398	.31094+01	.58998+00
-.09398	.31160+01	.58815+00
-.04398	.31221+01	.58642+00
.00602	.31278+01	.58476+00
.05602	.31331+01	.58315+00
.10602	.31379+01	.58157+00
.15602	.31424+01	.57999+00
.20602	.31465+01	.57839+00
.25602	.31502+01	.57675+00
.30602	.31534+01	.57502+00
.35602	.31560+01	.57318+00
.40602	.31579+01	.57118+00
.45602	.31590+01	.56895+00
.50602	.31589+01	.56640+00
.55602	.31573+01	.56341+00
.60602	.31534+01	.55981+00
.65602	.31462+01	.55530+00
.70602	.31337+01	.54943+00
.75602	.31122+01	.54139+00
.80602	.30739+01	.52959+00
.85602	.30002+01	.51053+00
.90602	.28339+01	.47463+00
.95602	.23171+01	.38344+00

Leeside
Time = 0.005

μ	$\frac{1}{\sqrt{R}}\left(\frac{\partial u}{\partial \zeta}\right)_{\zeta=0}$	$\frac{1}{\sqrt{R}}\left(\frac{\partial}{\partial \zeta}\left(\frac{\partial v}{\partial \theta}\right)\right)_{\zeta=0}$
-.99300	.27604+01	-.91072+00
-.89300	.92958+01	-.17295+01
-.79300	.97020+01	-.17484+01
-.69300	.97681+01	-.17427+01
-.59300	.97803+01	-.17396+01
-.49300	.97713+01	-.17375+01
-.39300	.97515+01	-.17361+01
-.29300	.97249+01	-.17348+01
-.19300	.96931+01	-.17338+01
-.09300	.96565+01	-.17327+01
.00700	.96146+01	-.17317+01
.10700	.95664+01	-.17306+01
.20700	.95102+01	-.17294+01
.30700	.94431+01	-.17279+01
.40700	.93605+01	-.17261+01
.50700	.92546+01	-.17238+01
.60700	.91087+01	-.17204+01
.70700	.88893+01	-.17152+01
.80700	.85032+01	-.17058+01
.90700	.75576+01	-.16827+01
.91200	.74701+01	-.16805+01
.91700	.73751+01	-.16783+01
.92200	.72713+01	-.16758+01
.92700	.71576+01	-.16731+01
.93200	.70322+01	-.16701+01
.93700	.68933+01	-.16668+01
.94200	.67384+01	-.16632+01
.94700	.65644+01	-.16592+01
.95200	.63675+01	-.16547+01
.95700	.61425+01	-.16496+01
.96200	.58826+01	-.16438+01
.96700	.55784+01	-.16372+01
.97200	.52169+01	-.16296+01
.97700	.47784+01	-.16207+01

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