A detailed examination of spectra $P(f,M)$ at various Mach numbers M reveals that the pattern of the fine structure remains largely unchanged. The degree of similitude is tested over the frequency band spanning 1-6 k Hz. The ensemble average of the suitable normalized fine structures, $(P(f,M)-\bar{P}(M))/[(P(f,M)-\bar{P}(M))^2]^{1/2}$, is found to be independent of Mach number and has a value of 0.85.

Summary

It appears that the phenomenon of diffraction is largely responsible for the observed fine structure. Despite precautions of wrapping the jet nozzle and the microphone boom with fiberglass blankets, some acoustic energy is reflected.

Acknowledgments

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Counterrotating Streamline Pattern in a Transitional Separation Bubble

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Introduction

THE prediction of the interaction between a transitional separation bubble and the inviscid flowfield that often exists at the leading edge of an airfoil is a formidable problem that has recently been the subject of several theoretical studies based on interacting boundary-layer theory. Vatsa and Carter[1] developed a semi-inverse interaction technique—ALESEP (Analysis of Leading-Edge Separation)—for the calculation of airfoil leading-edge transitional separation bubbles in which an inverse finite-difference boundary-layer analysis was solved iteratively through displacement thickness coupling with a Cauchy intergral perturbation analysis for the inviscid flow. In this approach, the streamwise convection of momentum was set to zero (FLARE approximation[2]) in the reversed-flow region to provide a stable forward-marching boundary-layer calculation. It has been observed in the predictions of a number of transitional separation bubbles using this technique that the reversed-flow velocity can be as large as 28% of the boundary-layer edge velocity. For flows with large reversed-flow velocities that occur in transitional separation bubbles due to the intense vortex formed near reattachment, an evaluation of the FLARE approximation was made[3] to estimate the error, if any, that arose from its use. A windward difference scheme was implemented into the ALESEP code and the results were compared with those obtained previously using the FLARE approximation. It was found that even for large reversed-flow velocities, the FLARE approximation produced comparable results with the windward differencing approach for the predicted pressure, locations of separation and reattachment, and displacement thickness. However, use of of the windward differencing procedure has revealed a new separation bubble structure not found in previous inviscid-viscous interaction calculations. A second, counterrotating bubble was found to exist under the primary separation bubble for a case with high reversed-flow velocities.

Inviscid-Viscous Interaction Analysis

The viscous solution technique used in the ALESEP interaction analysis is the inverse boundary-layer procedure developed by Carter.[4] In this procedure, the boundary-layer equations are transformed through the use of Levy-Lees-type variables and the normal component of velocity is represented in terms of a perturbation stream function. The numerical solution of the transformed equations for the pressure gradient parameter and the boundary-layer edge velocity is performed using an implicit finite-difference technique which is first-order accurate in the stream direction and second-order accurate in the normal direction. The Cebeci-Smith[5] two-layer model is used for the turbulent eddy

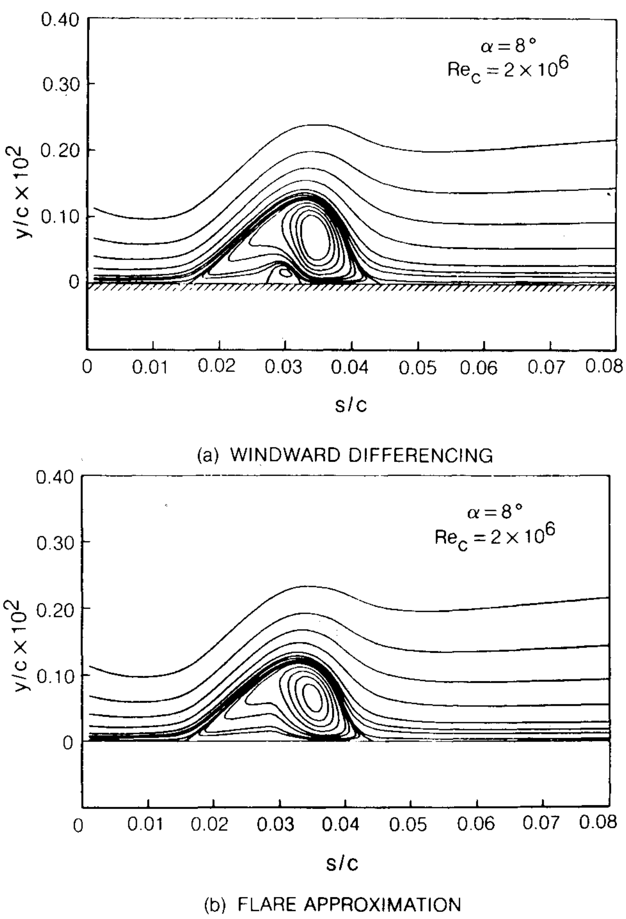

Fig. 1 Transitional separation bubble streamline pattern: NACA-0010 airfoil (modified).

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viscosity. Transition is modeled using the Dhawan and Narasimha[6] intermittency distribution over a prescribed location.

In the finite-difference representation of the streamwise convection term of the transformed boundary-layer momentum equation, the Reyhner-Flugge Lotz (FLARE) approximation is implemented in regions of reversed flow by setting this term to zero. A more exact treatment of this term was pursued in this study by using a windward differencing scheme. This scheme represents the streamwise convection term with a backward difference for attached flow, and a forward difference in separated flow. Since the marching direction of the boundary-layer calculation is always in the freestream direction, the information required to calculate the forward difference of the streamwise velocity component must come from the results of the previous global iteration.

The local inviscid analysis used in the ALESEP interaction procedure assumes that the disturbance field induced by the presence of a transitional separation bubble can be treated as a small disturbance to the global airfoil flow. The global or reference airfoil solution has been calculated with the GRUMFOIL code developed by Melnik et al.[7] in which instantaneous transition to turbulent flow was assumed at the point of laminar separation. It is concluded, on the basis of a perturbation analysis,[3] that the disturbance field created by the displacement thickness induced by a transitional bubble can be represented by a lineal source distribution placed on the airfoil surface at the transition site. The change in the displacement surface speed relative to that obtained from the reference solution is determined from a Cauchy integral[1] of the net lineal source distribution between that which represents the transitional separation bubble and that of the reference displacement surface.

The inviscid-viscous interaction iteration procedure used in the present analysis was developed by Carter.[8] This semi-inverse procedure combines the previously described inverse boundary-layer technique and the direct Cauchy integral inviscid analysis through an update formula which relates the change in the displacement thickness to the predicted difference between the inviscid and viscous velocities at the edge of the boundary layer.

Results and Discussions

The results obtained with the ALESEP inviscid-viscous interaction code using the windward differencing operator[3,9] have been compared to solutions presented by Vatsa and Carter[1] using the same code with the FLARE approximation. A particular case which has proven to be very interesting is the NACA-0010 airfoil tested experimentally by Gault[10] at an 8-deg angle of attack and a chord Reynolds number of 2×10^6. This case has the largest reversed-flow velocity ($u/u_e = -0.28$) of any case analyzed thus far. A 71×100 point grid was used in the tangential and normal directions, respectively, with the minimum spacing located at the wall in the transverse direction and in the transition region in the stream direction. The onset of transition was located at $s/c = 0.0283$ with a transition length of 0.0161.

The predicted pressure and skin-friction distributions[3,9] using the windward and FLARE approximations are quite similar with both schemes predicting the same locations for separation and reattachment. However, use of the windward differencing scheme has revealed a small region of forward flow in the interior of the separation bubble which was not present when the more approximate FLARE scheme was used. The impact of this difference is dramatically seen in the viscous streamline patterns shown in Fig. 1. In contrast to the FLARE results, use of the more accurate windward scheme has revealed the existence of a second counter-rotating bubble inside of the primary separation bubble. Physically, such a structure is known to exist in separated flows as evidenced by several figures in the excellent compilation on flow visualization recently published by Van Dyke.[11] Grid refinement and convergence studies[3] have been performed to ensure that this major change in the streamline pattern is an accurate solution to the governing equations.

A comparison between the results using the windward and FLARE schemes was also made for the Gaster[12] series I-IV experiment and the NACA 66_3-0018 airfoil tested experimentally by Gault.[10] For these cases, in which the maximum reversed-flow velocity ratios were $u/u_e = -0.15$ and -0.08, respectively, only minor differences exist between the predicted results using the windward and FLARE approximations. Examination of the computed flowfields show that the streamline patterns and velocity profiles of the windward and FLARE calculations are nearly identical and only the single primary bubble structure exists for these flows.

Conclusions

Introduction into a viscous-inviscid interaction analysis of a more accurate treatment through windward differencing of the convection terms in a reversed-flow region has been shown to yield an interesting counterrotating streamline pattern in a transitional separation bubble on a NACA-0010 airfoil. Previous calculations made with the approximate FLARE procedure had shown the existence of a single primary bubble structure for the flow. Despite the difference in the recirculating streamline pattern, the overall pressure and skin-friction distributions predicted by the windward and FLARE treatments in the interaction analysis were nearly the same. Other cases that were computed, which had smaller reversed-flow velocities, revealed only a single primary bubble structure for both the windward and FLARE treatments.

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