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On Nonlinear Aspects of Hypersonic Boundary-Layer Stability

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Introduction

LINEAR boundary-layer stability theory was slow to be accepted by the scientific community. This was primarily because the wind-tunnel experiments of that time could find no evidence of the instability waves predicted by theory, and there seemed to be no connection between linear stability theory and transition.[1] The classic experiments of Schubauer and Skramstad[2] completely changed the opinions. Previous wind tunnels had high freestream turbulence levels, which completely obscured the existence of small boundary-layer disturbances. The low-turbulence wind tunnel of Schubauer and Skramstad provided the first demonstration of the existence of instability waves in a laminar boundary layer, their connection with transition, and the quantitative description of their behavior by the theory of Tollmien and Schlichting. These experiments, as well as subsequent experiments, provided verification that linear stability theory adequately decribed the onset of small disturbance growth and the growth characteristics of the disturbances in a subsonic laminar boundary layer. In the following years, linear stability theory found wide applications in the description of instability parameters and in the prediction of transition for subsonic flows. When hypersonic wind-tunnel stability experiments were contemplated, there was concern whether the freestream disturbances would be low enough to permit the detection and study of the second-mode instability disturbances predicted by the linear stability theory of Mack.[3-5] Second-mode disturbances are high-frequency, acoustical-type disturbances that are unique to high Mach number boundary layers. First-mode disturbances are lower-frequency disturbances similar to the Tollmien-Schlichting disturbances of incompressible flow. Linear stability theory predicts the existence of both first- and second-mode disturbances in a hypersonic boundary layer, with the second-mode disturbances being the major instability. Kendall's pioneering stability experiments[6] provided some important answers. Stability experiments at a Mach number of 4.5 indicated that disturbances of all frequencies grew monotonically larger in a region of the boundary layer extending from the flat plate leading edge to the predicted location of instability, i.e., in a region where linear stability theory indicated that the boundary layer should be stable for all disturbance frequencies. This early growth of disturbances was attributed to the forcing mechanism of the strong freestream sound field generated by the turbulent boundary layer on the nozzle wall. Additional experiments at a freestream Mach number of 8.5 found a different situation. In this case, the initial disturbance growth was as described by linear theory. The second-mode disturbances of linear stability theory were clearly observed, and they were the dominant instability. Subsequently, stability experiments[7-11] at $M_\infty = 8$ in a different wind tunnel provided additional confirmation of second-mode disturbances. In addition to the first- and second-mode disturbances identified by linear stability theory, all of the above-mentioned hypersonic stability experiments observed disturbance growth at higher frequencies. The identity of the higher frequency disturbances is not certain; however, there is strong evidence to indicate that they are nonlinear disturbances. The dominant frequencies of these disturbances were two and three times the most unstable second-mode frequencies, suggesting that they were harmonics of the second mode. They were not observed until significant second-mode growth had occurred. Also, Mack[5] has stated that unstable frequencies in the frequency range in question do not exist in linear stability theory.

It cannot be assumed, on the basis of its verification for low-speed flows, that linear stability theory will adequately describe the instabilities in a hypersonic laminar boundary layer. Even though stability experiments have verified the existence and dominance of second-mode disturbances in a hypersonic boundary layer, this is only the first step in the evaluation process of determining how well linear stability theory describes hypersonic boundary-layer instabilities. It must also be verified that linear stability theory can adequately handle important second-mode characteristics, such as identifying the most unstable frequencies, obtaining their growth rates, and locating the neutral branches. Furthermore, the experiments have indicated that nonlinear disturbances were a significant factor. An evaluation of nonlinear effects must be a prerequisite to the application of linear stability theory to hypersonic problems.

Some hypersonic experimental results, obtained through the use of hot-wire anemometry, are shown to illustrate the scope of the problems involved. These data demonstrate that the rapidly growing second-mode disturbances obtain relatively large amplitudes (which could possibly exceed the limits of a small-disturbance assumption), that high-frequency disturbances (presumably nonlinear disturbances) were present, and that linear stability theory was not able to predict the measured disturbance growth rates.

Results and Discussion

Figure 1 (from Ref. 8) shows the fluctuation spectra at the location of peak energy in the boundary layer in a pictorial format to illustrate the growth of the disturbances in a hypersonic laminar boundary layer (A = disturbance rms amplitude in arbitrary units). The hypersonic boundary layer was very selective in the frequency of the most amplified disturbances. There was evidence of a tuning effect of the boundary layer, and the most amplified disturbances had a wavelength of approximately twice the boundary-layer thickness. The "tuned" disturbances (in the frequency range from about 70 to 150 kHz) were identified as second-mode disturbances. These rap-

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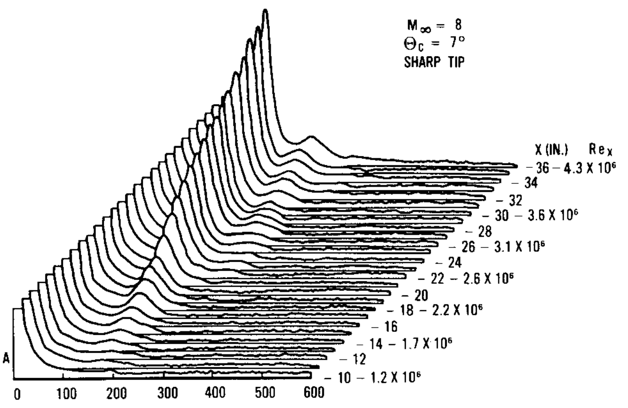

Fig. 1 Boundary-layer fluctuation spectra.

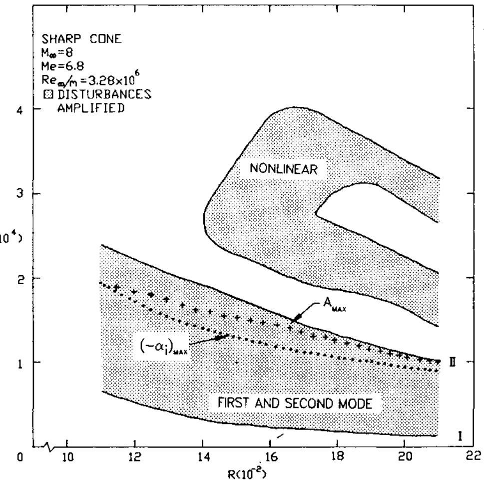

Fig. 2 Experimentally derived stability diagram.

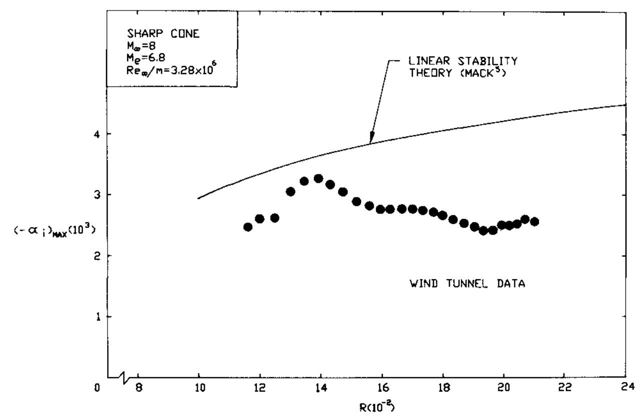

Fig. 3 Second-mode maximum amplification rates.

idly growing second-mode disturbances soon obtained a relatively large amplitude and could possibly present problems in the applicaton of a stability theory based upon the assumption of small disturbances. Second-mode disturbances large enough to be observed by optical flow visualization techniques have been reported (e.g., Ref. 7). The disturbance growth at frequencies higher than the second-mode disturbances are believed to be nonlinear disturbances. The mean flow boundary-layer profiles still had the characteristics of a laminar boundary layer at the end of the model, in spite of the existence of the large disturbances.

Figure 2 is a stability diagram derived entirely from the experimental data of Ref. 8. The nondimensional frequency is F $[2\pi f/(u_e Re/ft)]$, and R is the square root of the length Reynolds number ($\sqrt{Re_x}$). The two neutral branches (I and II) enclose the combined first- and second-mode unstable regions. The lower-frequency portion of this region is predominately a first-mode unstable region, and the lower neutral branch (I) corresponds to first-mode instability. That is, this neutral branch relates to the experimentally detectable critical Reynolds number and the initial disturbance amplitude of first-mode disturbances. Second-mode instabilities are the major boundary-layer instability and occupy the upper portion of the unstable region. The maximum disturbance amplitudes ($A_{\max}$), the maximum amplification rates $(-\alpha_i)_{\max}$, and the upper neutral branch (II) are all associated with second-mode instabilites. Above the second-mode upper neutral branch is a stable region. The neutral branch lines at higher frequencies enclose the unstable region believed to contain nonlinear disturbances. The nonlinear disturbances were observed at a relatively low Reynolds number of 1.9×10^6 ($R=1400$), and their growth rates were nearly as large as the second-mode growth rates. Transition was estimated to occur at a Reynolds number of approximately 4.8×10^6 ($R=2200$), based upon the observation (data not shown) that the second-mode disturbances had obtained their peak amplitude and started to decay, and disturbances at second-mode neighboring frequencies started to grow (spectral dispersion). Thus, the high-frequency nonlinear disturbances were not confined to a small region associated with the breakdown of laminar flow, but existed for a large portion of the laminar boundary layer (i.e., in a boundary layer where the mean profiles were those of a laminar boundary layer).

Because of their earlier start, the second-mode disturbances always had larger amplitudes than the high-frequency nonlinear disturbances, and presumably the second-mode disturbances were responsible for causing transition. There was, however, a change in the growth characteristics of the second-mode disturbances that occurred at $R\simeq1400$, the same condition at which nonlinear disturbances were first observed. At this condition, the growth rate of the major second-mode disturbances changed from increasing with increasing Reynolds number to that of decreasing with increasing Reynolds number. Figure 3 illustrates these results and includes stability calculations by Mack[5] for the conditions of the experiment. Mack commented that all linear stability calculations for self-similar boundary layers give the trend of $(-\alpha_i)_{\max}$ increasing with increasing Reynolds number. Not only are there large differences between the experimental and calculated growth rates, but the trends are different. For this case, linear stability theory did not predict the growth rates obtained in experiment. The reason for this discrepancy is unknown; however, there is concern that the linearized stability equations did not adequately describe the disturbance growth rates after the appearance of the nonlinear disturbances. Additional experiments are required to further investigate differences between linear stability theory and experimental data and to determine if the differences are related to nonlinear effects. Also, it is important to determine whether the early appearance of nonlinear disturbances is a general hypersonic boundary-layer characteristic associated with the rapidly growing second-mode disturbances or whether they are uniquely related to the wind-tunnel environment.

Important information about the influence of the wind-tunnel environment could be obtained if stability experiments could be performed in a tunnel where the freestream disturbance spectrum is "quiet" in the frequency range corresponding to the potentially most unstable boundary-layer disturbances. There are two approaches that can be taken in this direction. One method is to control the wind-tunnel environment, as in a quiet tunnel. NASA Langley Research Center has pursued this approach for several years and currently has a promising Mach 6 nozzle design. The other approach is to control the frequency of the most unstable disturbances, i.e., making their frequencies high enough to exceed the noisy environmental disturbance limit of existing wind tunnels. Calculations indicate that the windward meridian of a cooled, 7-deg half-angle cone at $\alpha = 4$ deg and a unit Reynolds number of 3.28 million per meter will result in a condition where most of the second-mode frequencies exceed the measurable disturbance frequency of the wind-tunnel freestream. Plans are being made to perform such experiments, and this will provide a unique opportunity to investigate hypersonic transition phenomena at a condition that is representative of what will be expected in flight. One important aspect of these forthcoming experiments will be to investigate the influence of a quiet environment on the nonlinear aspects of hypersonic boundary-layer transition and hopefully aid in determining the adequacy of linear stability theory for predicting hypersonic boundary-layer disturbance growth rates.

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Influence of a Favorable Pressure Gradient on the Growth of a Turbulent Spot

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Introduction

A RECENT overview of current knowledge on the turbulent spot was given by Riley and Gad-el-Hak.[1] Flow visualizations[2,3] and multipoint measurements of either velocity or temperature[4] have indicated that a spot contains several coherent structures within it. These structures have also been identified in a turbulent boundary layer,[5] and Bandyopadhyay[6] has noted several features that a turbulent spot and a turbulent boundary layer have in common. The present investigation represents part of a study whose long-term aim is to assess the influence of a pressure gradient on the organized motion of a turbulent boundary layer.

It seemed natural to focus first on the spot, since it provides a more controlled environment than a turbulent boundary layer. Wygnanski[7] noted that a favorable pressure gradient should slow down the growth process and, therefore, enable a more detailed analysis of transition than would be possible in the absence of a pressure gradient. The study of a favorable pressure gradient on the spot is also of practical value, since the leading edges of airfoils where the spots first form are regions of favorable pressure gradient and convex curvature, the effect of the latter being also stabilizing. The present Note, which considers the effect of a favorable pressure gradient on the overall three-dimensional development of a spot, complements and extends the study of Wygnanski.[7] Apart from comparing the three-dimensional growth rates with those obtained for zero pressure gradient, the present Note examines the effectiveness of different similarity coordinates in describing the global evolution of the spot with and without a pressure gradient. This latter aspect has not been previously addressed in the literature.

Experimental Arrangement and Conditions

The measurements were made in the working section of a low-speed, open-circuit-type blower wind tunnel of dimensions 5.4 m long, 0.89 m high, and 0.15 m wide when the walls are parallel. The position of one wall is adjustable to permit the pressure gradient to be easily changed. The aluminum plate over which the laminar boundary layer develops is vertical and is heated to about 10°K above the ambient temperature, i.e., $\Delta T = T_w - T_1 = 10$°K, where T_w and T_1 are the wall and freestream temperatures, respectively. As in the experiments of Antonia et al.,[4] the amount of heat introduced is small enough for temperature to act as a passive marker of the spot. The turbulent spot was triggered at a frequency of 1 Hz by a small jet of air issuing from a 3 mm diam hole, 300 mm from the contraction exit ($x = 0$), where the boundary-layer thickness is about 5 mm.

All measurements were made with a nominal reference freestream veloctiy U_s of 4.8 ms^{-1} at the location of the disturbance ($x_s = 0$). The hot wire (5 μm diam, Pt-10% Rh, 1.5 mm length) used for velocity measurements was operated with a DISA 55M10 constant temperature anemometer. For the temperature measurements, a single cold wire (0.6 μm diam, Pt-10% Rh, 1.0 mm length) was used with an in-house constant current (0.1 mA) circuit. The spot trigger signal and the cold wire signal were digitized at a sampling frequency of 3200 Hz and recorded on magnetic tape. Before introducing the spot, the quality of the laminar flow was checked by measuring the velocity and temperature profiles at several x stations for both zero and favorable pressure gradients. The pressure gradient $\mathrm{d}P/\mathrm{d}x$ is related to the exponent m in the freestream velocity variation $U_1(x) = Kx^m$ by $m = -(x/\rho U_1^2)\,\mathrm{d}P/\mathrm{d}x$. For the pressure gradient considered here, $m = 0.05$. For both $m = 0$ and $m = 0.05$, reasonable agreement was found between measurement and the Blasius or Pohlhausen distributions.

Before calculating ensemble averages, the location of the leading edges (LE) and trailing edges (TE) of the spot were detected. (The terms LE and TE are commonly used in the spot literature and are retained here. LE and TE refer to the downstream and upstream boundaries, respectively, of the spot.) Since histograms of t_{LE} and t_{TE}, the leading and trailing edge arrival times relative to the spot trigger, indicated a larger variation in t_{LE} than in t_{TE}, t_{LE} was used in forming ensemble averages. To avoid spurious spots, only those spots with a t_{LE}

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