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EXPERIMENTAL AND THEORETICAL INVESTIGATION OF BOUNDARY-LAYER INSTABILITY MECHANISMS ON A SWEPT LEADING EDGE AT MACH 3.5

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OUTLINE

The figure below gives a brief outline of the experimental and theoretical investigation of boundary-layer instability mechanisms on a swept leading edge at Mach 3.5.

O REVIEW OF TRANSITION MECHANISMS ON SWEPT-LEADING EDGES

O SWEPT-CIRCULAR CYLINDERS TESTED IN MACH 3.5 PILOT QUIET TUNNEL

- MEASURED RECOVERY TEMPERATURES
- OIL FLOW STUDIES

O COMPARISON OF THEORY AND EXPERIMENT

O REVIEW OF STABILITY THEORY

TWO MECHANISMS GENERALLY CAUSE TRANSITION IN THE LEADING-EDGE REGION OF SWEPT WINGS

Spanwise contamination and cross-flow instability are outlined in the figure below.

1. SPANWISE CONTAMINATION

   SOLVED IN THE EARLY '60's BY:

      STRONG LOCAL SUCTION, LEADING-EDGE SUCTION FENCES, X-21

      PROTRUDING FAIRED BUMP ATTACHED TO THE WING LEADING EDGE
      BRITISH HANDLEY PAGE

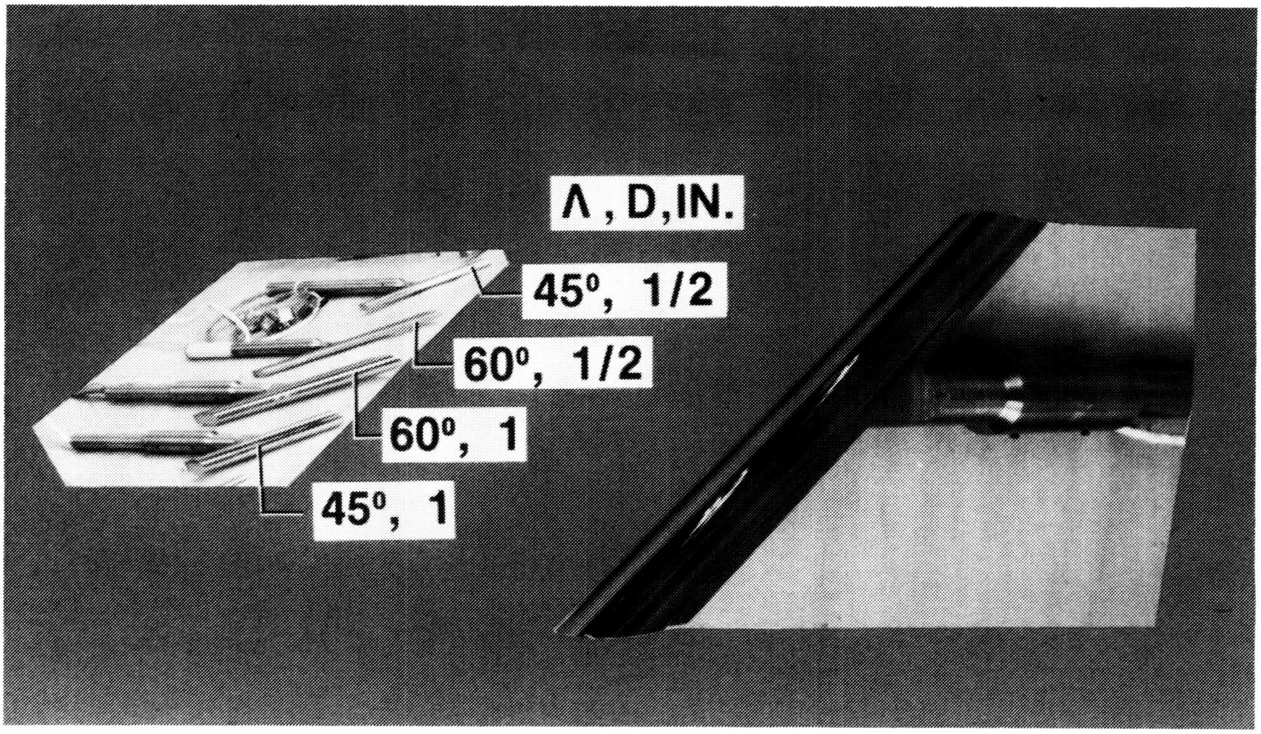
2. CROSS-FLOW INSTABILITY

   FIRST OBSERVED BY GRAY AS REGULARLY SPACED STREAKS IN SURFACE COATINGS

      STREAKS CAUSED BY CO-ROTATING VORTICES RESULTING FROM THE INFLECTIONAL INSTABILITY OF THE CROSSFLOW BOUNDARY-LAYER PROFILES IN THE UPSTREAM REGIONS OF SWEPT WINGS

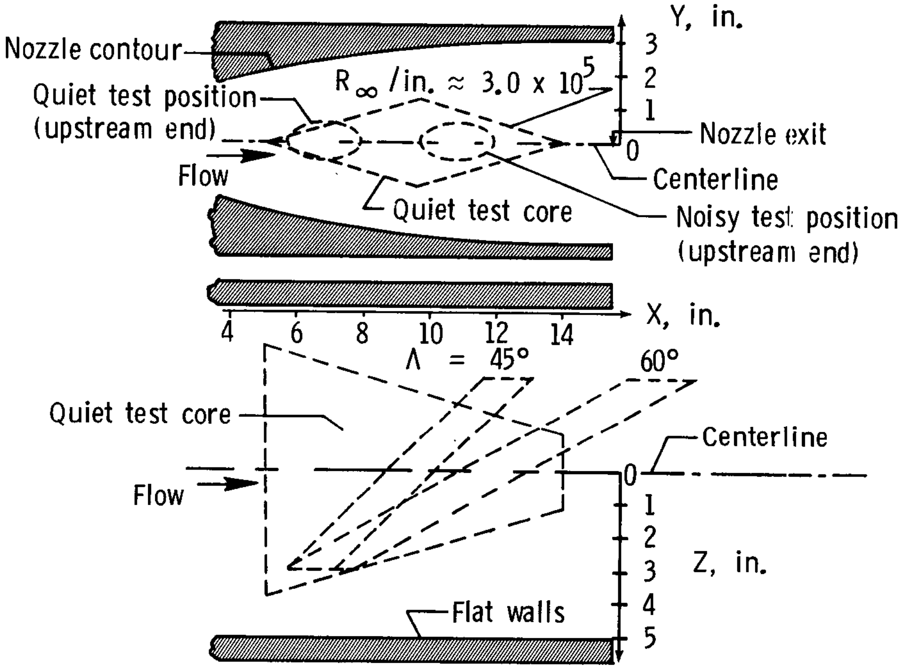
PHOTOGRAPH OF SWEPT-CYLINDER MODELS

The models consisted of .030-inch thick stainless steel cylindrical shells 1/2- and 1-inch outside diameters with both ends sealed and cut-off parallel with the free-stream flow direction as illustrated by the photograph. Chromel-alumel thermocouple wires of .010-inch diameter were spot welded to the inside surface of the shells at 1/4-inch intervals along the entire length of the attachment lines. The surfaces of the models were maintained clean and polished with a finish of less than 10 rms micro-inches.



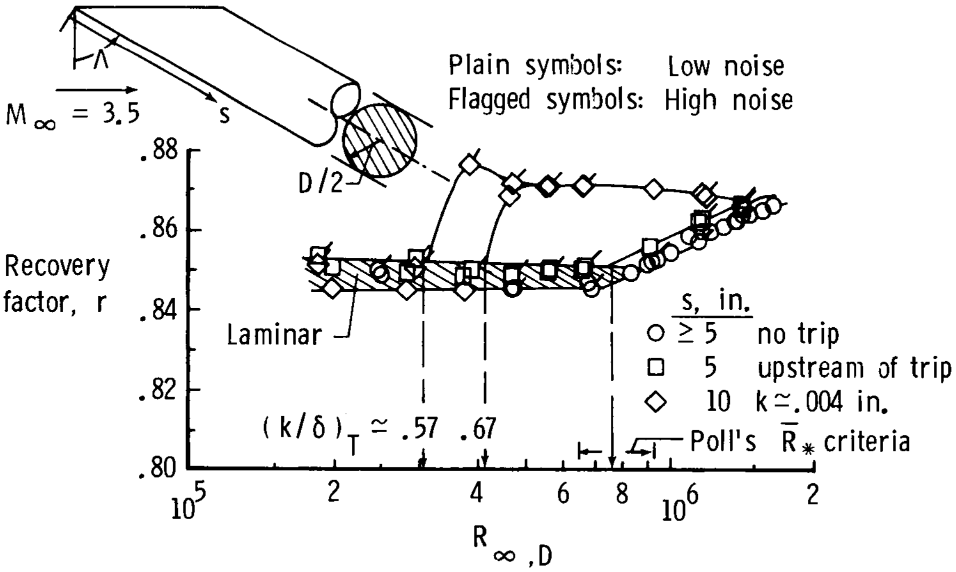
ONE-INCH DIAMETER SWEPT CYLINDERS IN MACH 3.5
PILOT LOW-DISTURBANCE TUNNEL

The models are shown mounted in the nozzle at upstream and downstream positions with respect to the quiet test core. In the upstream "quiet" test position and with the bleed valve open, the forward tips of the models were located 5.8-inches downstream from the nozzle throat (see ref. 1). For $R_\infty = 3 \times 10^5$ about 85 percent and 70 percent of the attachment line spans on the $\Lambda = 45°$ and 60° models, respectively, were exposed to the extremely low noise levels. As unit Reynolds number is increased, transition moves upstream on the nozzle walls and thus the corresponding location of increasing noise measured along the centerline also moves upstream. This results in a greater percentage of the attachment line span being exposed to high noise levels. In the downstream "noisy" test position and with the bleed valve closed, the entire model was exposed to noise levels ranging from .2 to .5 percent.



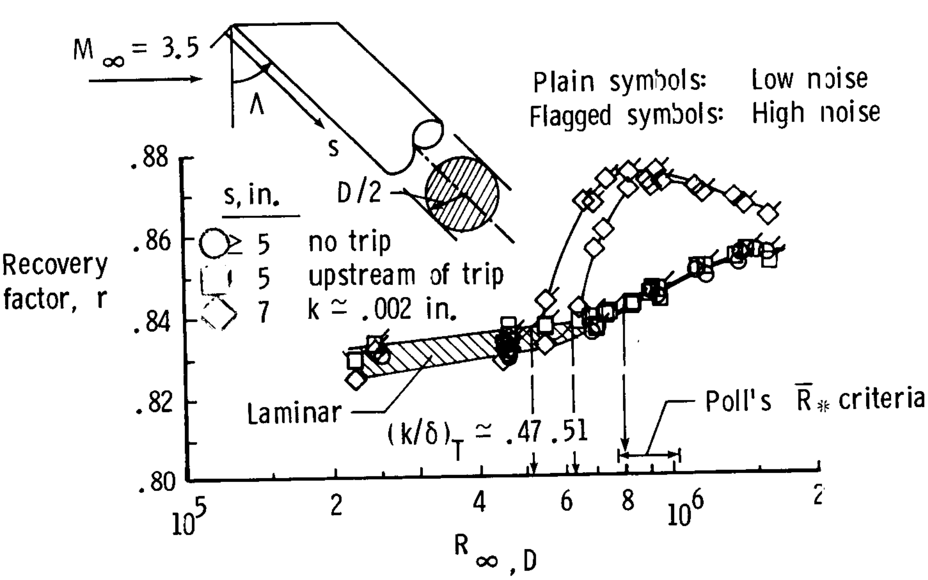
TRANSITION ON THE ATTACHMENT LINE

Recovery factors obtained at both low and high noise conditions for $\Lambda = 60°$ are summarized here where r is plotted against $R_{\infty,D}$ for selected values of s from several runs (Ref. 1). The trip height is k=.004 inch and the trip was located at s=6 inches for these data. The results for no trip (circle symbols and s = 5 in.) and also upstream of the trip (square symbols and s = 5 in.) show transition at $R_{\infty,D} \simeq 7.5 \times 10^5$ for both low and high noise (flagged symbols). This transition Reynolds number is in agreement with Poll's criteria (Ref. 2). However, downstream of the trip (s = 10 in.) transition occurs at lower values of $R_{\infty,D} \simeq 3$ or 4×10^5 depending on the tunnel noise. Clearly, the tunnel noise appears to enhance the effect of the trips but has no effect when there is no trip.



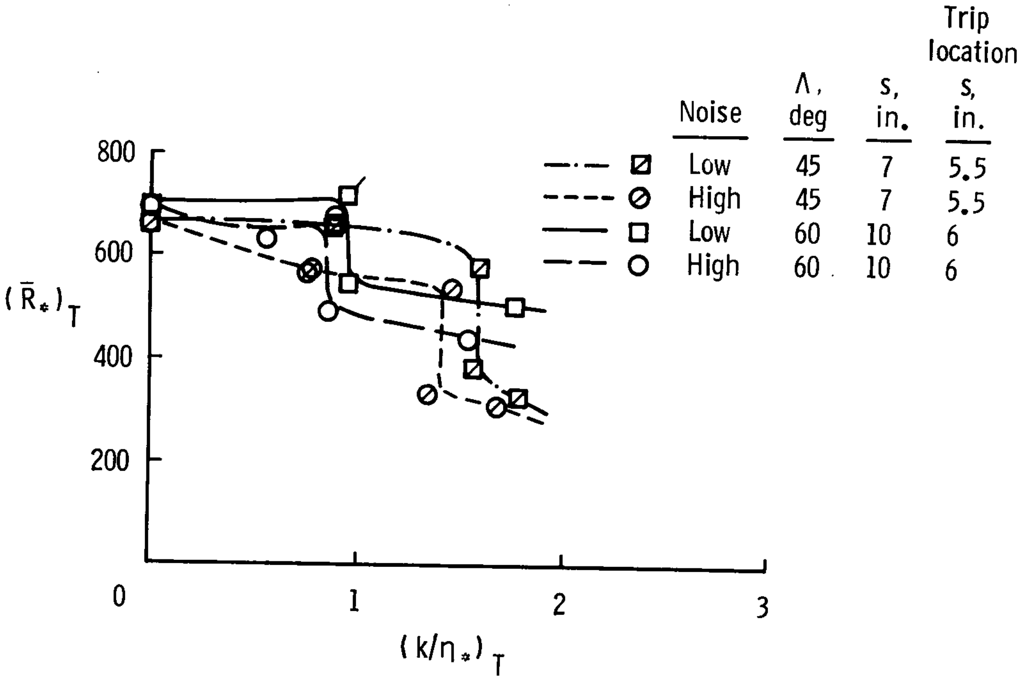
TRANSITION ON THE ATTACHMENT LINE

Typical effects of tunnel noise and a trip on attachment line transition for the $\Lambda = 45°$ model are shown in the figure. Data without a trip and with a trip height (h) = .002-inches are presented for a Reynolds numbers range of $2 \times 10^5 < R_{\infty,D} < 1.7 \times 10^6$. The trip was located at s = 5.5 inches for these data. The high tunnel noise enhances the effect of the trip for $5 \times 10^5 < R_{\infty,D} < 6.5 \times 10^5$. Upstream of the trip (s = 5 in.) or with no trip, transition occurred at $R_{\infty,D} \simeq 7 \times 10^5$ independent of tunnel noise. This value of $(R_{\infty,D})_T$ is somewhat smaller than Poll's $\bar{R}_*$ criteria (Ref. 2) for no end disturbances in low-speed flow and is also somewhat smaller than the Bushnell/Huffman supersonic criteria of $(R_{\infty,D})_T > 8 \times 10^5$ (Ref. 3).



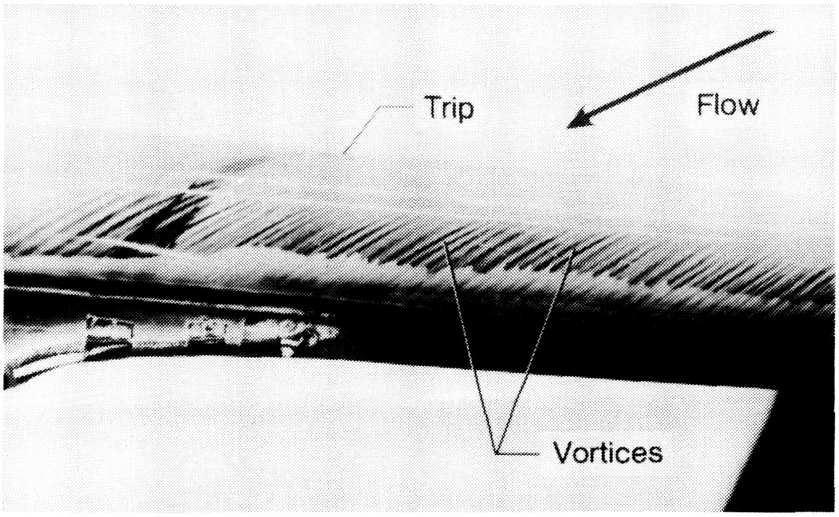
EFFECTS OF TRIP HEIGHT AND NOISE ON ATTACHMENT-LINE TRANSITION

To facilitate comparisons with Poll's data for trip wires in low-speed flow (Ref. 2), the local reference temperature parameters $\bar{R}_*$ and k/η_* are plotted for all the present transition-onset data for the $\Lambda = 45°$ and 60° models and D = 1-inch. The trend of $(\bar{R}_*)_T$ with $(k/\eta_*)_T$ are similar to those of Poll with respect to the effects of "critical" roughness heights. These critical roughness heights correspond to the values of k/η_* where the transition Reynolds numbers are first reduced significantly as k/η_* is increased. Thus, for $\Lambda = 45°$, the critical values are $k/\eta_* \approx 1.4$ and 1.6 for high and low noise, respectively. For $\Lambda = 60°$, the critical values are $k/\eta_* \approx 0.85$ and 0.95 for high and low noise, respectively. These latter values may be compared with Poll's critical values for $\Lambda \approx 60°$ of $d/\eta = 0.6$ to 0.8. Poll's subcritical values of $\bar{R}_T$ were approximately 600 to 750, depending on the distance from the trip. It is apparent that the present subcritical values of $(\bar{R}_*)_T$ for both sweep angles and the critical k/η_* values for $\Lambda = 60°$ agree reasonably well with Poll's values for $\Lambda = 60°$.



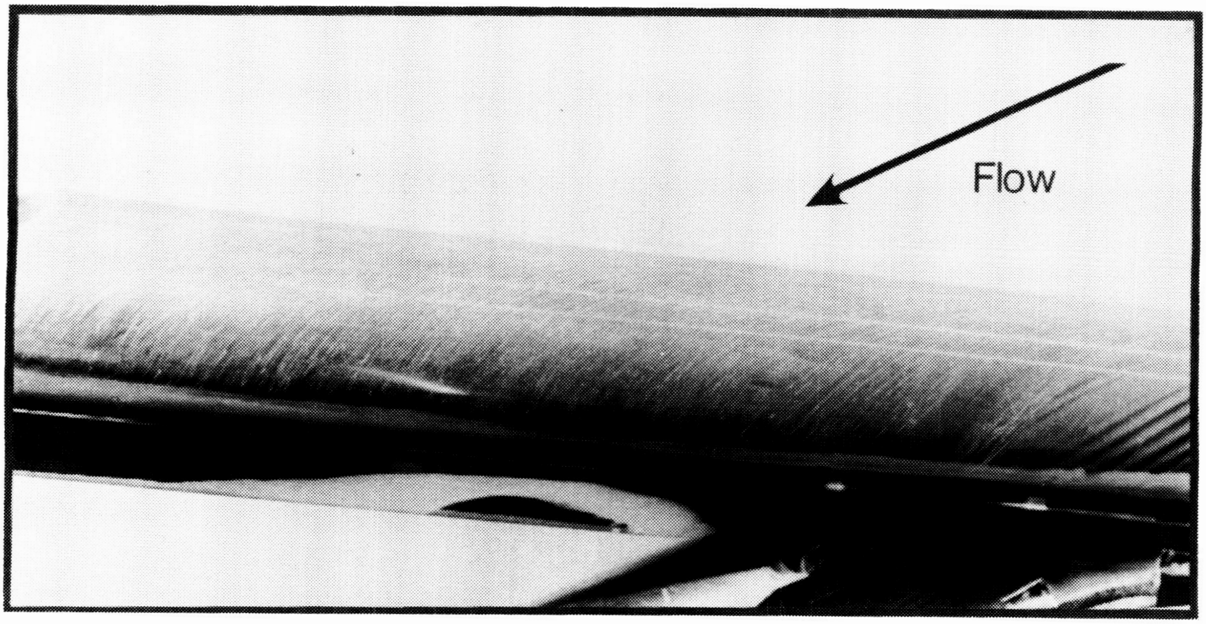
OIL FLOW PATTERNS WITH TRIP (K = .004-IN.) AT $S = 6\text{-IN.}\ \Lambda = 60^\circ,\ D = 1\text{-IN.},\ R_{\infty,D} = 4.6 \times 10^5$

Typical photographs of oil flow patterns on the $\Lambda = 60^0$ model are shown in this figure. Also shown is a small trip (identified in the picture, of height h = .004-inch, which results in $k/\delta = .7$) fixed to the attachment line at 6-inches from the upstream tip of the model. For this run, the wavelength of the vortices measured from the more closely spaced oil-flow streaks, increased from $\lambda = .03$ to .04-inch as the angular distance from the attachment line is increased from $\theta = 70^\circ$ to 90°. Normalized by the attachment boundary-layer thickness, these values give $\lambda/\delta_s = 5$ to 7 for this Reynolds number of $R_{\infty,D} = 4.6 \times 10^5$.



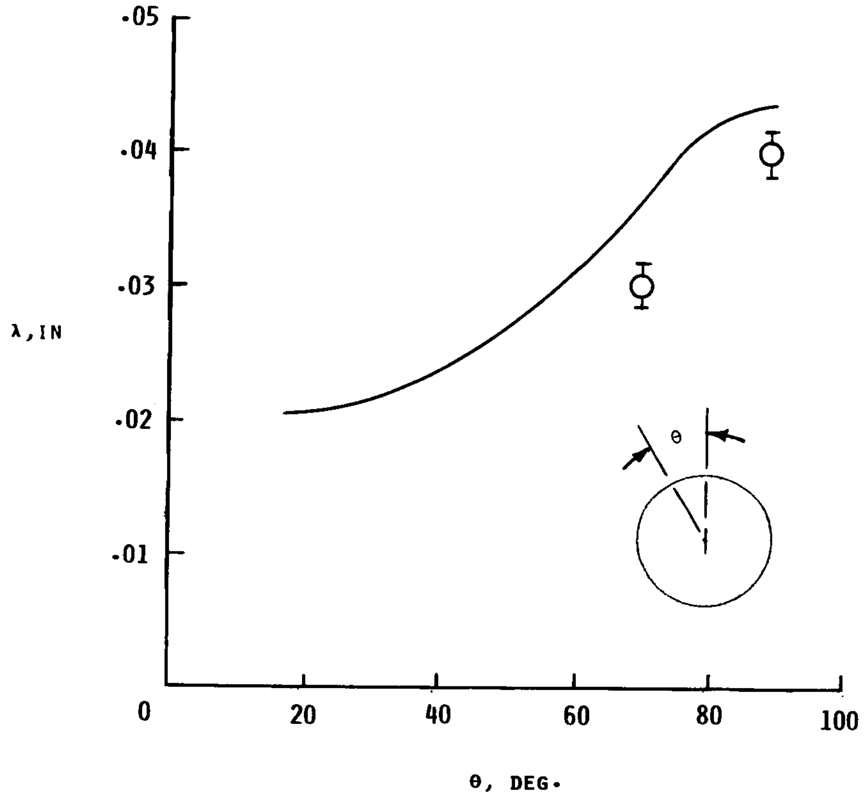
OIL FLOW PATTERNS DOWNSTREAM OF TRIP

This figure shows more of the downstream part of this model for the same run. The wide streaks have been completely obliterated downstream of the trip by turbulent boundary-layer flow.



COMPARISON OF THEORY AND EXPERIMENTS

The stability of three-dimensional boundary-layer flow on the 60° swept cylinder was examined for $R_{\infty,D} = 4.6 \times 10^5$. Compressible linear stability equations were solved by the method used in reference 4. Computed wavelength of the most amplified stationary cross-flow disturbances is plotted in the figure as a function of the azimuthal angle θ from the attachment line. The figure also contains wavelength values measured on the oil flow photographs. Both the magnitude of the wavelength and its variation with θ are well predicted by the theory.



WAVE-LENGTH OF STATIONARY CROSS-FLOW DISTURBANCES. $R_{\infty,D} \approx 4.6 \times 10^5$

INSTABILITY OF BOUNDARY LAYER ON SUPERSONIC SWEPT ATTACHMENT LINE

The instability of a boundary layer at the attachment line of a swept cylinder was theoretically investigated. The results of this investigation are documented below.

0 CALCULATIONS USING COMPRESSIBLE LINEAR STABILITY THEORY PERFORMED FOR

$\Lambda = 60^0$ AND $M_\infty = 3.5$

0 BOUNDARY LAYER SUBJECT TO TOLLMIEN-SCHLICHTING TYPE INSTABILITY

0 OBLIQUE WAVES WITH WAVE ANGLES AROUND 60° ARE MOST AMPLIFIED

0 COMPUTED CRITICAL REYNOLDS NUMBER IS $R_\theta = 240$.

0 WALL COOLING IS STABILIZING. EXAMPLE: THE CRITICAL REYNOLDS NUMBER DOUBLES IF

$T_W/T_{AD} = .8$

0 ATTACHMENT LINE BOUNDARY LAYER SUBJECT TO FINITE AMPLITUDE SUBCRITICAL

INSTABILITY. DISTURBANCES SUCH AS WALL ROUGHNESS MAY CAUSE PREMATURE

TRANSITION

INSTABILITY OF BOUNDARY LAYER IN SWEPT LEADING-EDGE REGION

The figure below outlines the results regarding the instability of a boundary layer on the attachment line of a swept cylinder at Mach = 3.5.

- COMPRESSIBLE LINEAR STABILITY ANALYSIS OF THE THREE-DIMENSIONAL BOUNDARY LAYER HAS BEEN PERFORMED BOTH FOR THE STATIONARY AND NON-STATIONARY WAVES
- CROSS-FLOW VELOCITY PROFILE DOWNSTREAM IN ATTACHMENT LINE HAS INFLECTION POINT AND THUS IS SUBJECTED TO INVISCID (RAYLEIGH) INSTABILITY
- COMPUTATIONS SHOW THAT NON-STATIONARY WAVES AMPLIFY MORE THAN THE STATIONARY ONES

CONCLUSIONS

1. Transition is affected by wind-tunnel noise only when roughness is present.

2. Local $\bar{R}_*$ Reynolds number and k/η_* are useful correlation parameters for a wide range of free stream Mach numbers.

3. Stability theory is in good agreement with the experimental cross-flow vortex wavelength.

REFERENCES

1. Creel, T. R.; Beckwith, I. E., and Chen, F.-J.: Transition on Swept Leading Edges at Mach 3.5. Accepted for publication in the Journal of Aircraft. October 1987.

2. Poll, D. I. A.: Transition Description and Predictiion in Three-Dimensional Flows. Agard-R-709, June, 1984.

3. Bushnell, D. M., and Huffman, J. K.: Investigation of Heat Transfer to a Leading Edge of a 76° Swept Fin With and Without Chordwise Slots and Correlations of Swept-Leading-Edge Transition Data For Mach 2 to 8. NASA TMX-1475, 1967.

4. Malik, M. R.: COSAL - A Black-Box Compressible Stability Analysis Code for Transition Prediction in Three-Dimensional Boundary Layers. NASA CR-165915, 1982.