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SUPERSONIC SEPARATED FLOW OVER A SWEPT COMPRESSION CORNER

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ABSTRACT

An experimental study of the shock wave boundary layer interaction ahead of a compression corner mounted on a flat plate was made. Three characteristic flow regimes (cylindrical , conical and mixed) were observed. Results of the study give support to the "Shock Detachment Hypothesis" which predicts the transition between the cylindrical and conical flow regimes.

INTRODUCTION

In supersonic flow over a compression corner mounted on a flat plate, a shock-wave is formed ahead of the compression corner. The adverse pressure gradient caused by the shock-wave propagates upstream through the subsonic portion of the boundary-layer developing on the flat plate. The interaction of the shock-wave with the boundary-layer can lead to flow separation if the shock-wave is sufficiently strong. In the case of swept compression corners, the resulting interaction is too complex for significant analytical treatment and, therefore, experimental data are necessary to understand the flow physics. Such data are reported by Refs. 1, 2 and 3. A numerical solution of the separated flow problem is given by Horstman (1985).

A sketch of the swept compression corner geometry is given in Fig. 1. The quantities α and λ are the compression angle and sweep angle, respectively. The separation angle β is defined as the angle between the separation line and the spanwise direction z. Settles and Teng (1984) report the existence of two distinct flow regimes which are referred to as cylindrical and conical. The separation line and the corner line make an angle with each other in the conical flow regime ($\beta \neq \lambda$) , whereas the two lines are parallel in the cylindrical flow ($\beta = \lambda$) . Settles and Teng (1984) propose the "Shock Detachment Hypothesis" which states that the transition from the cylindrical flow to the conical flow regime is due to the detachment of the shock-wave that is otherwise attached to the corner for small α and λ.

The present paper reports results of an experimental study carried out at Mach numbers between 1.8 and 2.2. Data were obtained by oil flow visualization and static pressure measurements. A third flow regime was observed in addition to the cylindrical and conical flow regimes. The new regime reveals itself when the Mach number to the corner line (M_n) is around one. Results of the study lend support to the "Shock Detachment Hypothesis."

EXPERIMENTS

The experiments were conducted in the 60 by 30 mm Trisonic Wind Tunnel at the Istanbul Technical University. This facility is a continuous tunnel operating at atmospheric stagnation conditions. The free-stream Mach number was varied by changing the shape of the Laval nozzle upstream of the test section. The free-stream Reynolds number per unit length was $12.7\text{x}10^6$ (1/m) at Mach 2.2.

The model geometry is defined by the parameters α, λ, t and L which are shown in Fig. 1. The models were made of plexiglas (L= 50 mm, t= 3 and 4 mm) and were mounted on the side wall of the tunnel. Approximately 30 models with various values of α and λ were used in the experiments. The calculated thickness of the fully-developed turbulent boundary-layer on the tunnel side wall was approximately 8 mm at the test section. The fact that the model thickness t was smaller than the boundary-layer thickness δ was an interesting feature of the present study. In all previous studies of the flow, t was larger than δ and the interaction was "dimensionless," that is, the model thickness did not impose a length dimension on the interaction characteristics. The interaction of the present study was probably dimensional. However, this could not be verified by increasing the model thickness systematically due to tunnel blockage at large t values.

Oil flow visualization was made to observe the topology of the skin-friction line pattern on the flat plate. A mixture of titanium dioxide, oleic acid and engine oil was used in oil flow visualization. The separation angle (β) was measured from the oil flow photographs taken during a tunnel run with an accuracy of ± one degree. Due to the end effects of the model and tunnel side walls , only the central part of the oil accumulation line was considered in making the separation angle measurements.

Static pressures on the flat plate ahead of the compression corner were measured by using a mercury multimanometer. The models were mounted on a rotatable base which was instrumented with a row of 19 pressure taps spaced 1.5 mm apart near the compression corner. The row of pressure taps scanned the flow field with 10 degrees of rotations while the model was also rotated in order to keep its orientation fixed with respect to the free-stream.

DISCUSSION OF RESULTS

Oil flow visualization revealed three characteristic flow regimes. Fig. 2 gives a schematic description of the flow regimes which are named as cylindrical, conical and mixed. The separation line, the shock-wave and the corner line are denoted by the letters S, W and C, respectively. L_s is the separation distance measured between the separa-

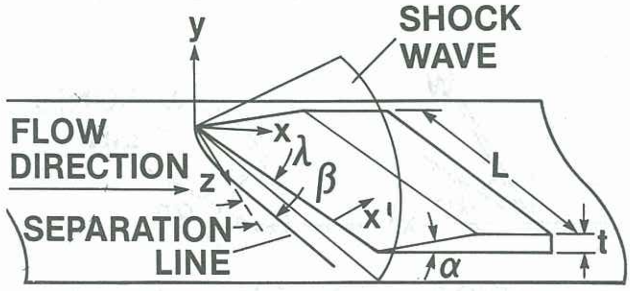


Fig. 1 A schematic description of the swept compression corner geometry

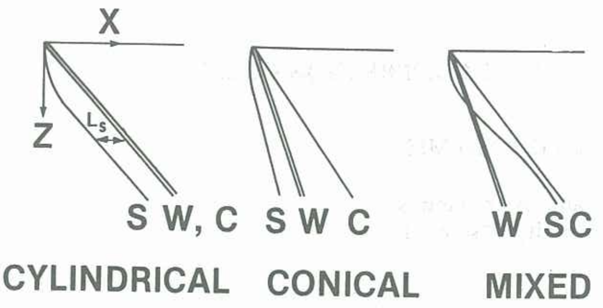


Fig. 2 A schematic description of the characteristic flow regimes

tion line and the corner line in the streamwise direction x. In the cylindrical regime, L_s increases with increasing z and reaches an asymptotic value which remains constant for larger z values. In the conical regime, L_s increases monotonically with z and is a linear function of the spanwise distance for large z values. Due to the existence of inception lengths, the cylindrical and conical flow regimes were originally called "quasi- cylindrical" and "quasi-conical" in Ref. 3. The third flow regime, which is called the "mixed flow", can be perceived as a mixture of the conical and cylindrical regimes. In the mixed flow, L_s first increases and then decreases with increasing z before reaching a constant value.

Figs. 2 and 3 depict the hypothesized cross-sections of the three-dimensional shock-wave in the flat plate plane (x-z) and in the (x'-y) plane where the x' direction is perpendicular to the corner line. In Fig. 3, α_n is the compression angle normal to the corner. The value of α_n is equal to arctan (tanα/cos λ). The mixed flow is observed to occur for M_n values around one (M_n = M cos λ). It can be hypothesized that in the conical and mixed flows, M_n values are not large enough to deflect the flow by angle α_n. Thus, there exists a detached shock-wave and a subsonic flow region ahead of the corner line. It can be further hypothesized that in the mixed flow, the shock wave is not strong enough to cause boundary-layer separation at large spanwise distances. Consequently, as shown in Fig.2 , the separation line (oil accumulation line) crosses the inviscid shock projection and runs parallel to the corner line for large z values. In the case of glancing shock-wave boundary-layer interactions, Korkegi (1973) report that incipient boundary-layer separation occurs when the Mach number normal to the skewed shock-wave is 1.2. A check on the applicability of Korkegi's criteria to the flow of the present study could not be made because the shock angle in the x-z plane was not known.The fact that the model thickness was smaller than the boundary-layer thickness may have played a role in bringing the effective Mach number down and causing the mixed flow.

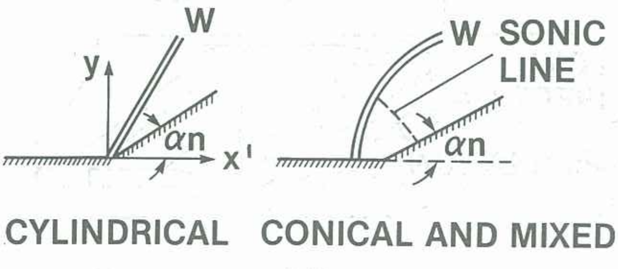
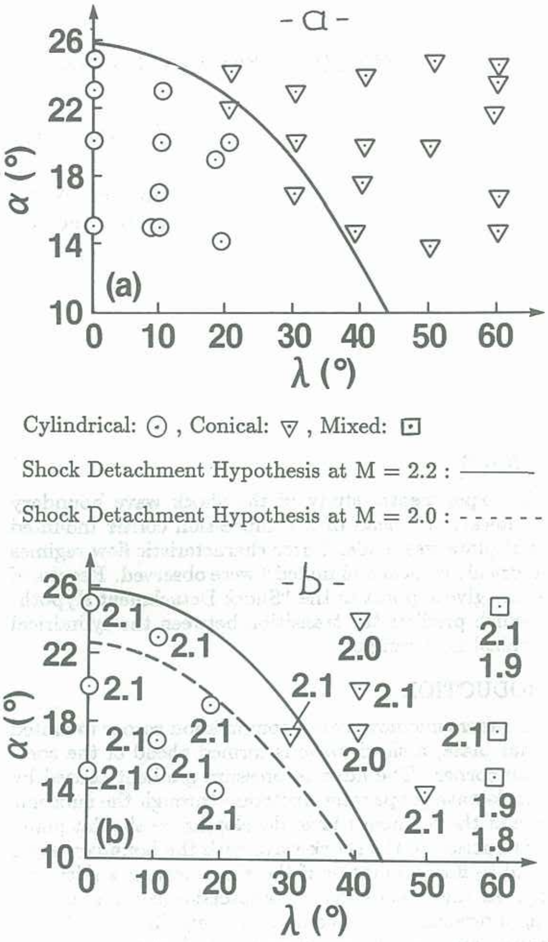


Fig. 3 Hypothesized shock-wave patterns in the x'-y plane



Cylindrical: ⊙ , Conical: ▽ , Mixed: ⊡

Shock Detachment Hypothesis at M = 2.2 : ———

Shock Detachment Hypothesis at M = 2.0 : - - - - - -

Fig. 4 Characteristic flow regimes on (α,λ) diagrams

The characteristic flow regimes observed for various models at Mach 2.2 are shown on a (α, λ) diagram in Fig. 4-a. The boundary between the cylindrical and conical regimes as predicted by the "Shock Detachment Hypothesis" is also shown. Fig.4-b shows the characteristic flow regimes at various Mach numbers on a (α, λ) diagram. The numerals under the symbols indicate the Mach numbers.The model thickness is 4 mm for the data presented in Fig. 4. The shock detachment boundaries at Mach 2.0 and 2.2 are shown by two separate curves. Observation of conical flows for (α, δ) pairs below the shock detachment curve is also reported by Settles and Teng (1984) . This is probably due to a decrease of the effective Mach number within the boundary-layer.

Fig.4 shows that the mixed flow regime is observed at Mach numbers smaller than 2.2 when the Mach number normal to the corner line (M_n) is around one. Settles and Teng (1984) did not report the mixed flow probably because of the fact that the minimum value of M_n in their experiments was 1.5. The "Shock Detachment Hypothesis" was proposed on the basis of experimental data obtained at a single Mach number of 2.95 (Ref. 3). The results presented in Fig. 4 lend support to the validity of this hypothesis. Low-speed data obtained in the present study showed that the cylindrical flow was the only regime existing in subsonic flow. This characteristic of the subsonic flow, which is free from shock-waves also provides an indirect support for the validity of the "Shock Detachment Hypothesis."

Figs. 5 and 6 show the static pressure contours on the flat plate in the cylindrical and conical flow regimes , respectively. The Mach number is 2.2 and the model thickness is 3 mm. The dashed lines indicate the separation lines as determined by oil flow visualization. The numerals on the contours denote the ratio of p/p_∞ where p_∞ is the

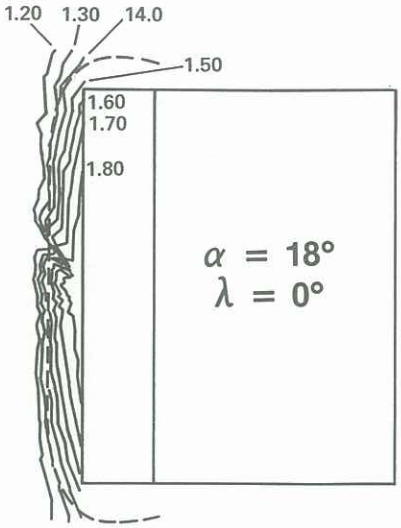


Fig. 5 Static pressure contours in cylindrical flow

undisturbed pressure upstream of the interaction. Accuracy of p/p_∞ values is believed to be ± 0.05. The wriggle in the contours near the model centerline is likely to be due to a disturbance reflecting from the side wall. Except for the end regions of the models , the approximately cylindrical and conical symmetry of the pressure fields is readily observable in Figs. 5 and 6 , respectively.

CONCLUSIONS

An experimental investigation of the supersonic turbulent separated flow over a swept compression corner was made. Conclusions of the study can be listed as follows:

1- Three characteristic flow regimes referred to as cylindrical, conical and mixed were identified.

2- The mixed flow regime was observed to occur when the Mach number normal to the corner was around one.

3- The high speed data obtained in the study lent direct support for the validity of the "Shock Detachment Hypothesis."

4- Indirect support for the validity of the "Shock Detachment Hypothesis" was provided by the low speed data which showed that the turbulent subsonic flow was always cylindrical.

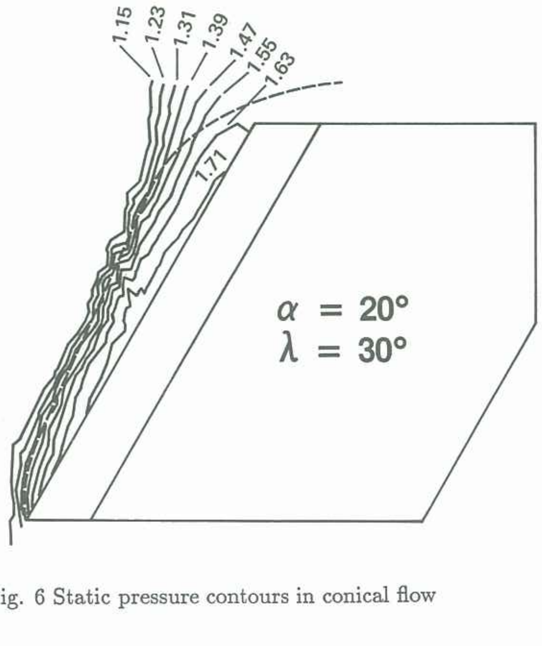


Fig. 6 Static pressure contours in conical flow

ACKNOWLEDGEMENT

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