Hypersonic Flow over a Rearward Facing Step

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Nomenclature

α = the primary expansion angle
h = step height, 0.35 in.
M = Mach number
P = pressure
P_{t_2} = impact pressure
Re = Reynolds number
T = temperature
X,Y = the streamwise and normal coordinates

Subscripts

o = denotes the stagnation condition
w = denotes the condition immediately preceding the step
∞ = denotes the property in the unperturbed freestream

1. Introduction

SEPARATION and reattachment of boundary-layer flows have been under extensive investigation in recent years. This phenomenon is significant on high-speed aircraft in which the performance is degraded by separated flows and various components damaged due to intense heating at reattachment. The rearward-facing step problem is a characteristic example of separated flow. It is our intention to investigate this problem at hypersonic speeds.

The flowfield far upstream and downstream of a step is well understood. These regions can simply be analyzed by boundary-layer theory. However, in the step region the boundary-layer approximation is invalid[1,2] and the most intricate phenomenon of the entire flowfield encountered. One realizes that the pronounced downstream disturbance can be transmitted upstream through the subsonic portion of the shear layer. However small, this "upstream" feeding will perturb the flow near the trailing edge of the wedge. The stream separates from the vertical surface of the step and forms a recirculating region. This recirculating flow is entrained by the expanding shear layer which eventually reattaches downstream of the step. The supersonic portion of the shear layer undergoes a rapid expansion around the upper corner of the step. A complex wave system establishes in the corner region to align the flow parallel to the dividing streamline. At supersonic speeds these compression waves coalesce to form the well-known lip shock.[3,4] However, for hypersonic flow a lip shock is not detected.[3,5]

The foregoing brief description of flowfield indicates that the step region is characterized by a strong viscous-inviscid interacting phenomena. In a sense, the inertia and viscous effects are of equal order of magnitude and the viscous and inviscid dominated regions have to adjust significantly to accommodate each other. Several significant advances have been made in treating the rearward-facing step problem.[1-3] Probably the most rigorous method for investigating this problem is due to Roache et al.[1] However, their compressible flow calculations lack accuracy due to a very coarse computing mesh for higher Reynolds numbers. To overcome this drawback of limited computer capacity, an iterative numerical matching scheme between the viscous and viscous-dominated regions may be implemented. The present analysis attempts to establish that the method of rotational characteristics is appropriate to describe the inviscid dominated region downstream of the step.

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2. Calculations of the Inviscid Region

Weinbaum[4] indicates that the supersonic portion of the shear layer over a corner can be approximated by the method of rotational characteristics to the order of $Re^{-1/2}$. To complete his analysis for an expanding boundary layer over a sharp corner, he resolved the problem by means of a parametric study of the initial external Mach number and the prescribed pressure distribution. The method of rotational characteristics was adopted in our analysis. The numerical program used in the present analysis is described in Ref. 6. This program is capable of handling imbedded shocks and discontinuous contour geometry.

The supersonic portion of the shear layer emanating from the trailing edge of the wedge expands inviscidly around the corner.[4,5] The primary expansion angle α for the present calculation was 30° with respect to the freestream. This angle corresponded to that obtained from the oil film study on reattachment.[5] The initial conditions for this numerical calculation were provided by a boundary-layer calculation over the leading wedge and a simple model for the embedded separated flow region. In essence, we considered a straight streamline parallel to the trailing plate (Fig. 1), preceded by a straight dividing streamline. This streamline originated at a Mach number equal to 1.1 located above the step with an inclination of the prescribed primary expansion angle (30°).

The impact pressure distributions corresponding to the aforementioned apparent body shape downstream of step were calculated from the characteristics solution. Reasonable agreement was observed between the data and the calculated results. However, notable differences appeared in the outer edge of the free-shear layer. In anticipation of the possible error of the initial Mach-number profile at the trailing edge of the wedge, and to study the upstream feeding phenomena, a finite difference boundary-layer computation was performed over the wedge. A slight deviation from the similar solutions was observed in the lower portion of Mach-number profile. The effect of upstream feeding was artificially introduced by fitting a curved streamline around the upper corner of the step with a radius of curvature of five times the local boundary-layer thickness. A further refinement was also imposed on the apparent body shape far downstream of the step by replacing the straight streamline with a calculated displacement contour. The expansion angle was altered to permit a continuous contour of this apparent body in the reattachment region. The impact pressure distributions corresponding to the modified apparent body downstream of the step are presented in Fig. 2 for four streamwise locations.

3. Test Results

The tests were conducted in the Aerospace Research Laboratories' 20-in. Hypersonic Wind Tunnel. The rearward-facing step model was the same one described in a previous experimental program.[5,7]

The present test conditions are in a regime in which both separation and reattachment should be laminar.[8] The presented data were obtained from the zero angle-of-attack situation, for which the calculated Mach number immediately upstream of the step is 6.7. The corresponding Reynolds number is 0.31×10^6. For this case, we cannot identify an imbedded lip shock by either the Schlieren system or the impact pressure survey. The separation point, detected by the oil film technique, was found at a distance about 0.063 in. downstream of the corner on the vertical face. This result tends to substantiate the findings of Hama.[3] The reattachment point was determined to be 0.531 in. downstream of the step.

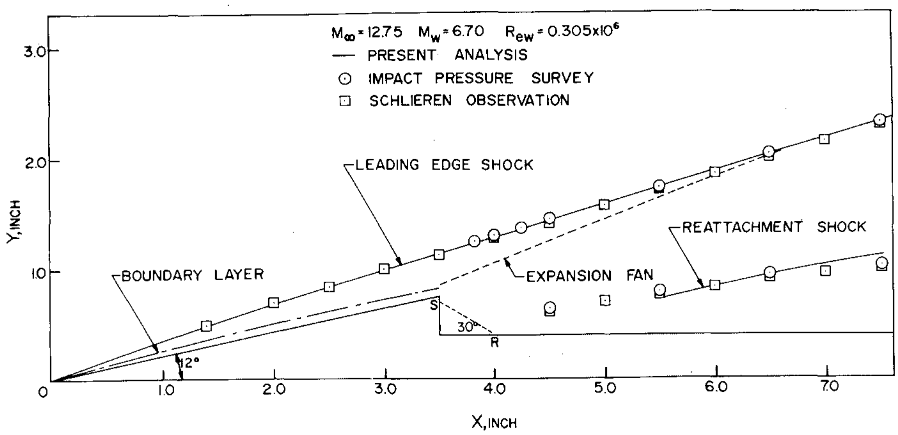

Fig. 1 Schematic of the rearward facing step model and flowfield.

In Fig. 3, we present the surface pressure distribution downstream of the step. There is no evidence of a pressure plateau, but rather an almost immediate rise of the pressure to a peak beyond which it approaches an asymptote.[5,7]

The impact pressure survey was conducted in the flowfield downstream of the step. Four surveyed streamwise locations are presented here. The tested locations were 0.328, 1.0, 2.0, 3.0 in. downstream of the step. The data are presented in Fig. 2. In the separated region, except for the leading-edge shock, no obvious shock waves were detected. A single reattachment shock wave was barely detectable at a distance of one in. downstream of the step. The strength of the reattachment shock increases as it propagates downstream.

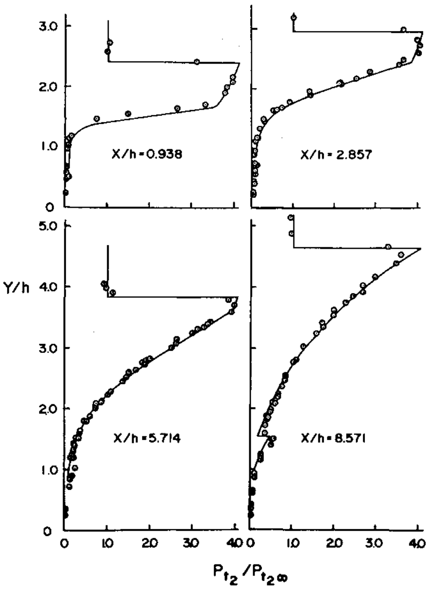

Fig. 2 Impact pressure comparison between experimental and rotational characteristics computations.

The shock shape detected by the impact pressure survey is given in Fig. 1. The agreement between the Schlieren system and impact pressure data are well within experimental error. The expanding shear layer emanating from the corner can be observed to grow rapidly. At a distance of about two in. downstream of the step, the expansion fan eventually reaches the leading-edge shock and the gradient of the impact pressure in the plane perpendicular to the testing surface decreases consideraby (Fig. 2). No uniform flowfield existed between the leading shock and reattachment shock.

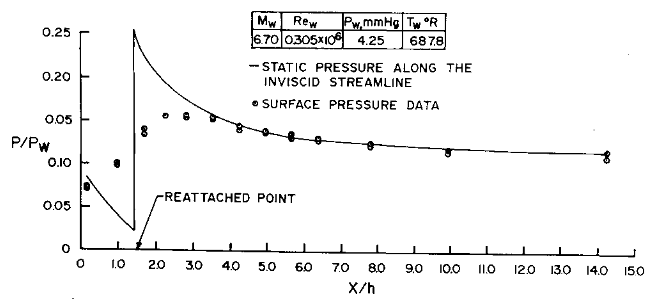

Fig. 3 Static pressure comparison downstream of the step.

4. Conclusions

The comparison between the static pressure data on the model surface and the calculated results along the outer boundary of the imbedded separated region has its own particular significance (Fig. 3). The drastic deviation at the shock discontinuity in the separated region is obviously due to the interaction between inviscid and viscous region. This pressure difference must be supported by the recirculating flow. However, the pressure difference vanishes in the region adjacent to and downstream of the reattachment point. This evidence demonstrates that the boundary-layer behavior is restored after the flow is reattached. The separated flow region of the rearward-facing step clearly cannot be analyzed by a conventional boundary-layer analysis.

The critical confirmation of the hypothesis of an inviscid dominated region relies on the comparison between the calculated results and the measured impact pressure data. Excellent agreement in the impact pressure comparisons is exhibited in the immediate region downstream of the step (Fig. 2). The notable deviations between the calculated results and the measurements are indicated in Fig. 2 in the vicinity of the reattachment shock. This comparison indicates a progressively magnified discrepancy as the flow proceeds further downstream.[5] The calculated reattachment shock shape displays the identical trend as that of the calculated impact pressure in comparison with the experimental measurements. The maximum deviation in shock location between the calculations and measured data is 6% (Fig. 1).

The preceding discussion reveals that the majority of the flowfield is primarily an inviscid phenomena. The viscous dominated region is rather limited but the separated flow region exerts an influence over the entire flowfield. In this sense, the flowfield exhibits a strong viscous-inviscid interaction behavior. We have shown that rotational characteristics can be applied successfully to analyze the inviscid dominated region.

On the other hand, the complete flowfield must be determined by a numerical matching scheme between the rotational characteristic solution and the imbedded viscous region evaluated by the Navier-Stokes' equations.

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Accelerating Sphere—Wake Interaction

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Introduction

IT is the purpose of this Note to show briefly that an accelerating sphere in free fall (at intermediate Reynolds numbers) undergoes fluctuating lift (lateral) and drag forces that are directly related to an asymmetric vortex shedding phenomenon.

In a recent article,[1] Roos and Willmarth reported the drag and lift (lateral) forces acting on spheres. They observed that during the acceleration portion of the sphere's motion, there appears to be no relationship between the fluctuating drag and lift forces. From this evidence they quite reasonably suggest that "the first few cycles of vorticity shedding in the sphere wake must be axially symmetrical." This is very likely to be true in their case of an accelerating sphere constrained by a sting, since they observed that "the sting support had a significant stabilizing effect on the sphere wake." However, the present experiments show that in the absence of a sting support, the fluctuating lift during acceleration is directly connected to the asymmetric vortex shedding.

Experimental Apparatus

The experiments were conducted in a plexiglas water tower of 240-cm height and square cross section of 30 cm on each side. The lower half of the tank was reinforced by aluminum angles at the corners, held in place by bands of steel wire separated by a distance of 5 cm.

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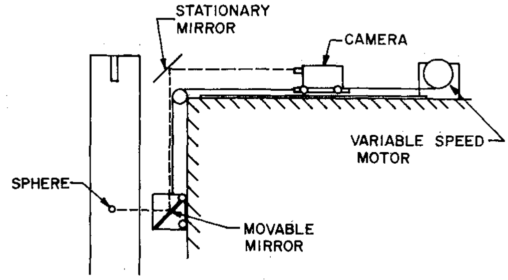

Fig. 1 Schematic of experimental apparatus.

Since the purpose of the experiment was to view the near wake of the sphere, it was decided to use spheres somewhat larger than those employed in previous free fall experiments.[2–4] The spheres chosen were table tennis balls filled with solids of varying densities ranging from wax through clay. The use of liquid-filled spheres was rejected since this would alter the dynamics of the system. One of the most successful methods of filling the spheres was to inject a gelatin solution into the sphere by the use of a hypodermic needle. The gelatin set, and the spheres thus produced had an over-all density somewhat greater than that of water and produced an intermediate Reynolds number motion.

A problem of some concern in freely falling sphere experiments in general and accelerating sphere experiments in particular is that of releasing the sphere with a minimum disturbance. Magnetic releasing mechanisms have been employed in the past but were of no help in this case since no metal spheres were to be used. Schafrir[4] used a vacuum system to hold the sphere. Such a system was attempted but the disturbance it caused was beyond the allowable limits for the acceleration investigation (although it appears to be sufficient for steady-state free fall experiments). The method chosen to release the spheres in the present experiment is a simple tube of inside diameter slightly greater than the outside diameter of the sphere. The spheres moved very slowly through the tube, taking on the order of 5 min to fall 20 cm and thus were released at sensibly zero velocity.

The data were recorded by photographing the spheres as they accelerated. Films were taken at 32 frames/sec as well as with a Nikon camera with a motor drive capable of taking 4 frames/sec. A tracking mechanism was constructed to allow the camera to follow the spheres accurately. A schematic of the tracker is shown in Fig. 1. The essential feature of the tracker is that the focal distance remains constant as the sphere falls. The camera rides on rails, its speed and direction being controlled by a variable speed aircraft motor con-

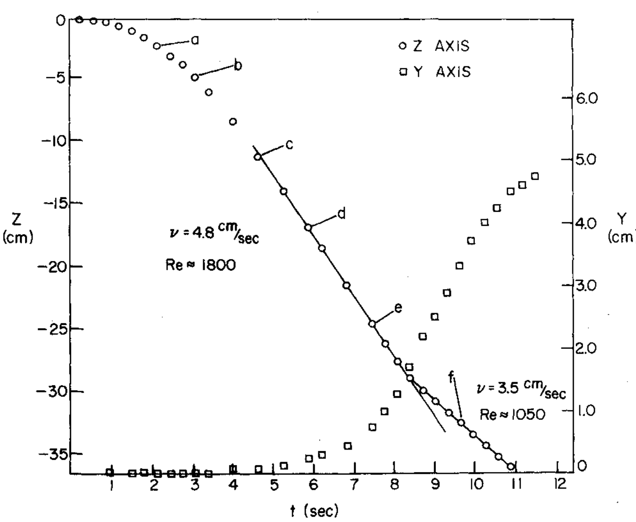

Fig. 2 Accelerating sphere trajectory.