Three-Dimensional Effects in Shock Detachment from a Wedge

H. G. Hornung* and H. Schoeler†
DVLR-AVA, Göttingen, Federal Republic of Germany

Introduction

CONSIDER first the *plane* inviscid supersonic flow of a perfect gas over a symmetrical wedge whose plane of symmetry is aligned with the freestream. If the wedge angle is sufficiently small, the shock wave caused by the flow deflection is not strong enough to decelerate the flow to subsonic speed. No information can then travel upstream of the leading edge of the wedge, to which the shock must therefore be attached. Furthermore, no information about the finite extent of the wedge can reach the leading edge. Thus, the flow near the leading edge does not "know" anything about the only length scale in the problem, with the necessary result that the shock is straight there. This situation is drastically modified as soon as the wedge angle is increased to a value where the shock is just strong enough to cause the flow to become subsonic. At that point, the shock wave becomes curved and, with further increase in the wedge angle, it becomes detached from the leading edge. The remarkable simplicity of the entirely supersonic flow is thus destroyed—when subsonic regions exist—by the availability of information about a length scale. A sketch of the two configurations is given in Fig. 1.

The effect of interest here is the gradual nature of the process of shock detachment as the wedge angle is increased. This continuous behavior is not self-evident, although it is undisputed in transonic flow. Certainly, the straight-shock solution breaks down by a discontinuous process at a particular wedge angle: information about the length of the wedge becomes available *suddenly*. It may be that the range of deflection angles over which the detachment distance grows is related to the fact that the deflection angle just causing the flow to become sonic (δ_s) is smaller than the maximum deflection angle possible with an attached shock (δ_m). Thus, there exists a small range of δ in which the shock is attached, but the postshock flow is subsonic. This range decreases rapidly with increasing Mach number, which may be taken as a suggestion that the rate at which the detachment distance increases as the wedge angle is increased may become greater at high Mach numbers. Indeed, a set of experiments in argon at $M=16$ confirm this expectation.[1]

Hornung and Smith[1] used the rate of growth of the detachment distance as an indication of the relaxation effects in dissociating gas flows. A comparison of measurements in relaxing and perfect gas flows gave good confirmation of this phenomenon. However, it was pointed out in Ref. 1 that other mechanisms could also tend to reduce the rate of growth.

In the present Note, we concentrate on the effect of finite aspect ratio on the rate of growth of the detachment distance with increasing wedge angle in a high Mach number perfect-gas flow. The aim is to obtain quantitative information about this effect from an experimental investigation.

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*Director. Member AIAA.

†Research Scientist, Institute for Experimental Fluid Mechanics.

The Experiment

Using the notation of Fig. 1, the dimensionless detachment distance may be written formally as a function of five parameters,

$$\Delta/w = f_1(\delta, M, \gamma, Re, \Lambda) \tag{1}$$

where Re is the Reynolds number based on w, γ the ratio of specific heats of the gas, and Λ the aspect ratio $L/w \cdot \sin\delta$ of the wedge, L being its transverse extent. Other effects such as flow conicity are disregarded here, as we wish to single out the effect of Λ. (The flow conicity may be avoided effectively in an experiment by proper contouring of the nozzle that generates the flow.) For sufficiently high Reynolds number, Δ/w becomes independent of Re since the boundary-layer displacement thickness decreases rapidly with increasing Re. A good indication of whether the Reynolds number is sufficiently high is the difference between the experimentally observed and the theoretical inviscid value of δ_m. This is because, to a first approximation, the displacement thickness increases the effective wedge angle.

At fixed values of M and γ and for sufficiently high Re (to be checked later by experiment), Eq. (1) degenerates to

$$\Delta/w = f_2(\delta, \Lambda) \tag{2}$$

This defines the framework of the present experiment.

One of the facilities available for supersonic flow at the DFVLR Göttingen is the Ludwieg tube, which is described in

Table 1 Experimental conditions

Test gas	Dry air
Effective nozzle reservoir pressure	35 bar
Mach number	6.0
Effective nozzle reservoir temperature	460 K
Test section diameter	500 mm
Steady running time	0.35 s
Re (based on $w=5$ cm)	1.7×10^6

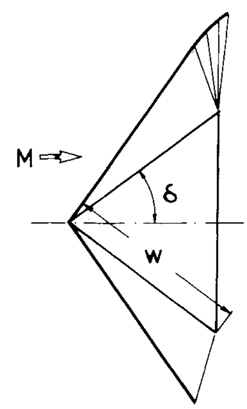


Fig. 1a Entirely supersonic flow with attached shock.

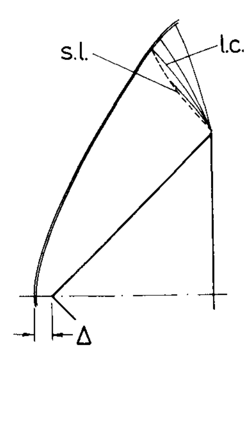
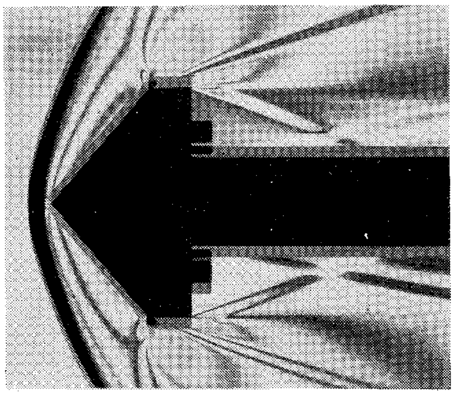


Fig. 1b Supersonic flow with embedded subsonic region, detached shock (s.l. = sonic line, l.c. = limiting characteristic).



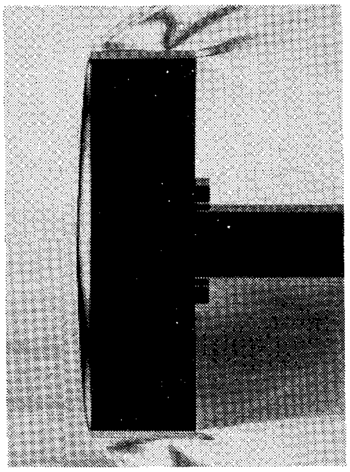


Fig. 2 Differential interferograms of flow over a wedge ($\delta = 50$ deg, $M = 6$, $\Lambda = 4.33$, $Re = 10^6$).

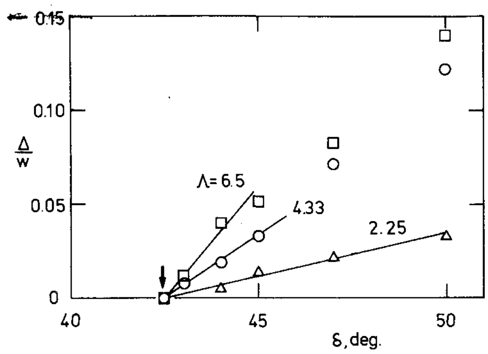


Fig. 3 Behavior of detachment distance for various values of Λ. Note comparison with theoretical value of δ_m (arrow).

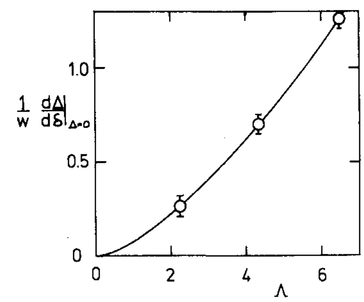


Fig. 4 Incipient rate of growth of Δ/w continues to increase with increasing Λ even at $\Lambda = 6.5$.

detail by Ludwieg et al.[2] For the present experiments, the conditions chosen are given in Table 1.

Although quantitative evaluation of the density field was not contemplated in this experiment, the schlieren system of the Ludwieg tube was converted to a differential interferometer by adding a pair of Wollaston prisms and a pair of polarizers. This is a fairly inexpensive modification that gives a quantitative measure of a chosen component of the density gradient in two-dimensional flowfields. Black-and-white copies of two color interferograms are shown in Fig. 2. The two interferograms show the flow from two mutually perpendicular directions. Figure 2a views the flow in the direction of the symmetry plane of the wedge. From an inspection of Fig. 2b, it is clear that the flow is by no means two-dimensional; thus, the fringes may not be interpreted as lines of constant density gradient.

In order to test the flow conditions, it is interesting to study an attached flow over a wedge with $\delta = 40$ deg (at $M = 6.0$ and $\gamma = 1.4$, $\delta_s = 42.3$ deg). The attached shock angle measured from this flow was 57.8 ± 0.3 deg. At this shock angle, the theoretical inviscid value of δ is 40.3 deg. Thus, any effect of the boundary-layer displacement thickness is so small as to be barely significant in the light of experimental error.

The models were tested at 10 values of δ between 40 and 50 deg and three values of Λ. An attempt was also made to simulate infinite aspect ratio by attaching end plates to the models. This proved to be unsuccessful because the strong bow shock on the model caused the boundary layer on the end plates to separate, thus causing even more serious three-dimensional effects than were present without them.

Results

Interferograms such as those of Fig. 2a (see Ref. 3 for details) show that, while the shock is certainly straight at $\delta = 40$ deg, it shows distinct curvature at $\delta = 42$ deg, although the sonic condition lies at $\delta_s = 42.3$ deg. This is because the shock angle becomes infinitely sensitive to changes in δ in the vicinity of the detachment point. Thus the boundary-layer displacement effect may not be neglected here. Nevertheless, the point at which detachment is first seen agrees quite well with the theoretical maximum deflection angle. This may be seen in Fig. 3, which plots Δ/w vs δ and shows the results for all aspect ratios. An extrapolation to zero Δ yields a value of $\delta_m = 42.5 \pm 0.3$ deg. This is in good agreement with the theoretical value of 42.44 deg.

In the limiting case of $\Lambda \to 0$, one might expect the incipient rate of growth of the detachment distance to go to zero and become independent of Λ. Using this in a plot of the experimental results (Fig. 4), it may be seen quite clearly that the incipient rate of growth continues to grow with Λ at an increasing rate even at $\Lambda = 6.5$.

Conclusions

1) The agreement of some measured parameters of wedge flow with inviscid theory indicates that it is reasonable to design an experiment on the basis of Eq. (2) in the Ludwieg tube.

2) End plates must not be used to simulate infinite aspect ratio at hypersonic conditions. Also, their use should be examined by flow visualization at all conditions.

3) The incipient rate of growth of the shock detachment is highly sensitive to the aspect ratio. It rises at an increasing rate with increasing aspect ratio. At the highest aspect ratio tested (6.5), the rate at which it increases shows no sign of decline.

References

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[3]Hornung, H. G. and Schoeler, H., "Three-Dimensional Effects in Shock Detachment from a Wedge," *Proceedings 14th International Symposium on Shock Tubes and Waves*, edited by R. D. Archer and B. E. Milton, New South Wales University Press, Aug. 1983, pp. 175-184.