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Experimental Investigation of Instabilities in Hypersonic Laminar Boundary-Layer Flow

Abstract

Hot-wire measurements are made in the laminar boundary layer of a flat plate and a cone at Mach 5. These measurements do not show the expected dominance of high-frequency second-mode instabilities, predicted by linear stability theory and found in other experiments. The growth of natural disturbances within a broad frequency band up to 50 kHz on the flat plate and up to 200 kHz on the cone can be observed.

Introduction

To develop an understanding of the physical processes involved in laminar-turbulent transition in hypersonic boundary-layer flows it is necessary to perform detailed boundary-layer stability experiments, rather than obtaining only the transition location.

The most detailed hypersonic boundary-layer stability experiments are conducted by Stetson *et al.* (1992) on a cone at a free-stream Mach number of 8. These investigations show a distinct dominance of second-mode instabilities. The measured amplification rates of second-mode instabilities are in good agreement with theoretical results recently obtained by e.g. Simen (1993) and Simen, Kufner & Dallmann (1993) using Thin Layer Navier Stokes solutions for the basic flow and local stability analysis with conical metric for the instability analysis. In contrast, measurements in the laminar boundary layer of a flat plate by Kendall (1975) and Wendt, Simen & Hanifi (1995) and for a hollow cylinder by Stetson *et al.* (1991) do not show the expected dominance of high-frequency second-mode instabilities. However, the growth of natural disturbances with rather low frequencies, partly growing in a frequency band that was predicted to be stable by linear stability theory, can be observed. It has to be determined whether the discrepancy between linear stability theory and planar boundary-layer instability experiments is a feature of the planar boundary layer or whether other effects (e.g. a noisy wind-tunnel characteristic) are responsible for the differences mentioned above.

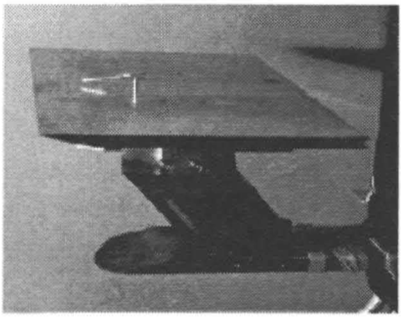
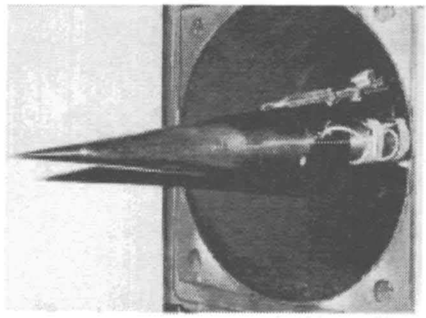

Figure 1: Experimental setup showing the flat plate and the cone both with mounted hot-wire probes in the Ludwieg tube.

Experimental apparatus

Wind tunnel

The experiments are conducted in the Ludwieg-tube wind tunnel of DLR Göttingen. The range of possible test Mach numbers is $M_\infty \approx 3$ to $M_\infty \approx 12$, and the Reynolds number can vary between $Re_\infty/l \approx 1.5 \times 10^6$ m^{-1} and $Re_\infty/l \approx 80 \times 10^6$ m^{-1}. A detailed description of the facility and its operational characteristics is given by Ludwieg *et al.* (1969).

Models

For the boundary-layer investigations a flat plate and a cone are used. The aluminum flat plate is 300 mm long and 10 mm thick, and it spans the full test section width of 500 mm. The sharp leading edge has a bevel angle of 11.6°. The cone is 500 mm long with a half angle of 7° and a sharp tip. The cone is made of steel and has a wall thickness of 5 mm. The nose is exchangeable, and the frustum can be divided in two parts allowing further instrumentation inside the cone. Fig. 1 shows the experimental setup of the flat plate and the cone with mounted hot-wire probes in the Ludwieg tube.

Test conditions

The Mach number for all the experiments presented here is $M_\infty \approx 5$. For the boundary-layer measurements on the flat plate and on the cone almost constant charge conditions of $p_{t,0} \approx 5$ bar and $T_{t,0} \approx 110$ °C are used, which results in a unit Reynolds number of $Re_\infty/l \approx 7.5 \times 10^6$ m^{-1}. In the case of the cone the Reynolds number at the boundary-layer edge is $Re_{\infty,e}/l \approx 9.3 \times 10^6$ m^{-1}.

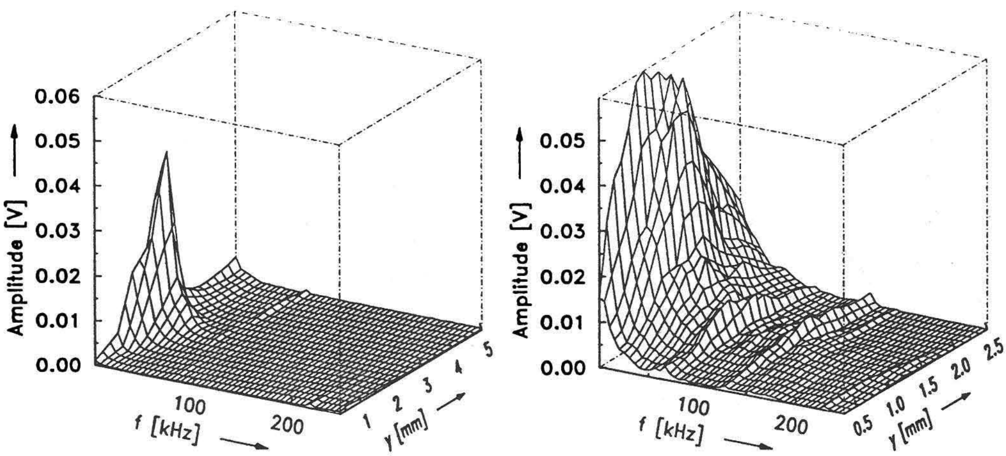

Figure 2: Disturbance amplitude spectra for the flat plate (left, R=995) and the cone (right, R=1950) as a function of the wall distance.

Hot-wire anemometry

For the measurements a single wire probe with a tungsten wire of 1.25 mm length and 5 μm diameter is operated by a constant temperature anemometer. In all the experiments the wire is operated at a high overheat ratio to assure that the wire is mainly sensitive to mass-flow fluctuations (Kovásznay, 1950; Morkovin, 1956). This is proved by a wire calibration in the free stream of the Ludwieg tube at different stagnation temperatures, while keeping the stagnation pressure constant. This calibration cannot be used for the boundary-layer measurements, since the different temperatures and mass flows -according to the boundary-layer profiles- cannot be resolved by a single-wire probe.

Results

The unit Reynolds number in the flat plate experiments is $Re_\infty/l = 7.5 \times 10^6$ m^{-1}, which results in local Reynolds numbers ranging from $Re_x \approx 0.4 \times 10^6$ ($R \approx 650$) to $Re_x \approx 1.7 \times 10^6$ ($R \approx 1300$). In the cone experiments the unit Reynolds number is $Re_\infty/l \approx 9.3 \times 10^6$ m^{-1}, which results in local Reynolds numbers from $Re_x \approx 0.7 \times 10^6$ ($R \approx 840$) to $Re_x \approx 4.4 \times 10^6$ ($R \approx 2100$). At a fixed unit Reynolds number the range of the local Reynolds number is only dependent on the range of possible probe locations. Here R is the Reynolds number based on the local Blasius length, $R = \sqrt{Re_x}$.

The measurement of profiles in the laminar boundary layer of the flat plate and the cone reveals disturbance-amplitude profiles with a strong peak at approximately 75 % of the boundary-layer thickness. This peak is typical for an unstable laminar boundary layer. The boundary-layer profiles also show growing maximum disturbance amplitudes with increasing distance from the leading

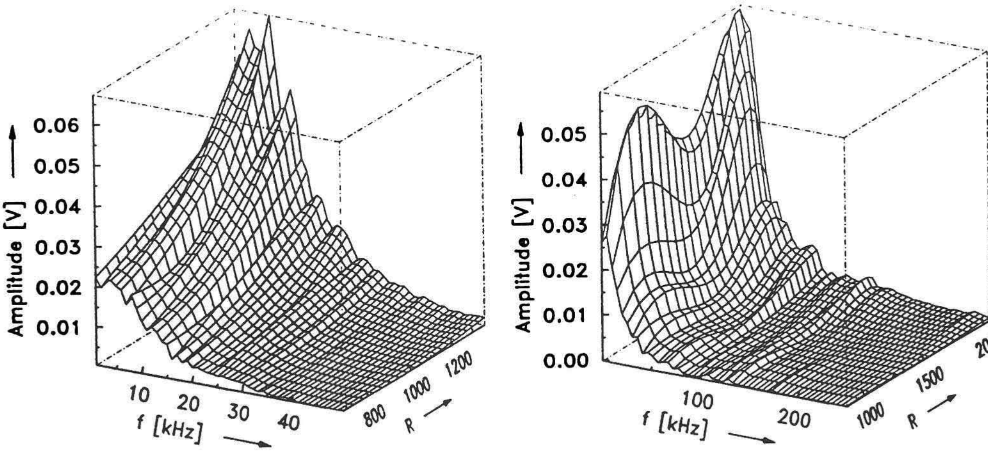

Figure 3: Maximum disturbance-amplitude spectra for the flat plate (left) and the cone (right) as a function of the nondimensional streamwise position.

edge of the flat plate and the tip of the cone, respectively. To obtain information about the frequencies contributing to the maximum disturbance amplitudes in the laminar boundary layer, fluctuation spectra are calculated and plotted against the distance normal to the wall, as shown in Fig. 2.

A broad frequency band up to an upper frequency limit of 50 kHz contributes to the peak of the disturbance amplitude for the flat-plate case. The region above 50 kHz, especially above 100 kHz, where linear stability theory predicts second-mode disturbances, does not contribute to the disturbance level significantly. In the case of the cone a broad frequency band up to an upper frequency limit of 200 kHz -what is in the first- and second-mode frequency range- contributes to the peak of the disturbance amplitude. In both cases the upper frequency limit slightly increases with increasing Reynolds number, but the difference between the flat plate and the cone case cannot only be explained by a Reynolds-number effect.

The fluctuation spectra at the peak positions of the disturbance amplitudes in the laminar boundary layer are calculated at different streamwise positions. These disturbance spectra are plotted against the dimensionless free-stream position R in Fig. 3.

For the flat-plate case one can clearly observe a growth of disturbance amplitudes with increasing streamwise position R in the significant frequency range. For the cone the behaviour of the disturbance amplitudes is a little different: After a first increase of the maximum disturbance amplitude with increasing streamwise position it slightly decreases in the region between $R \approx 1200$ and $R \approx 1500$ to increase again further downstream. This slight decrease of the maximum disturbance amplitude cannot yet be explained. One possible cause might be measurement uncertainties. Another possible cause might be nonlinear instability effects. Calculations with nonlinear stability theory (which is not yet

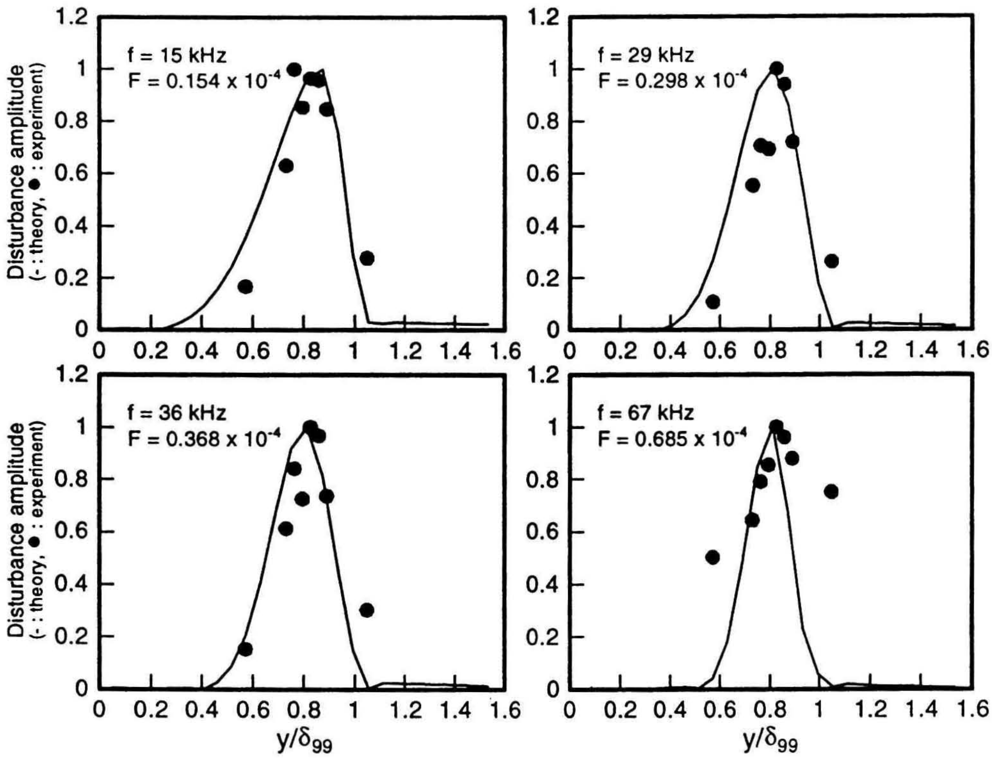

Figure 4: Profiles of experimental and theoretical, band-limited, disturbance amplitudes for various frequencies ($\Delta f = 500$ Hz, $R = 1050$, flat-plate case).

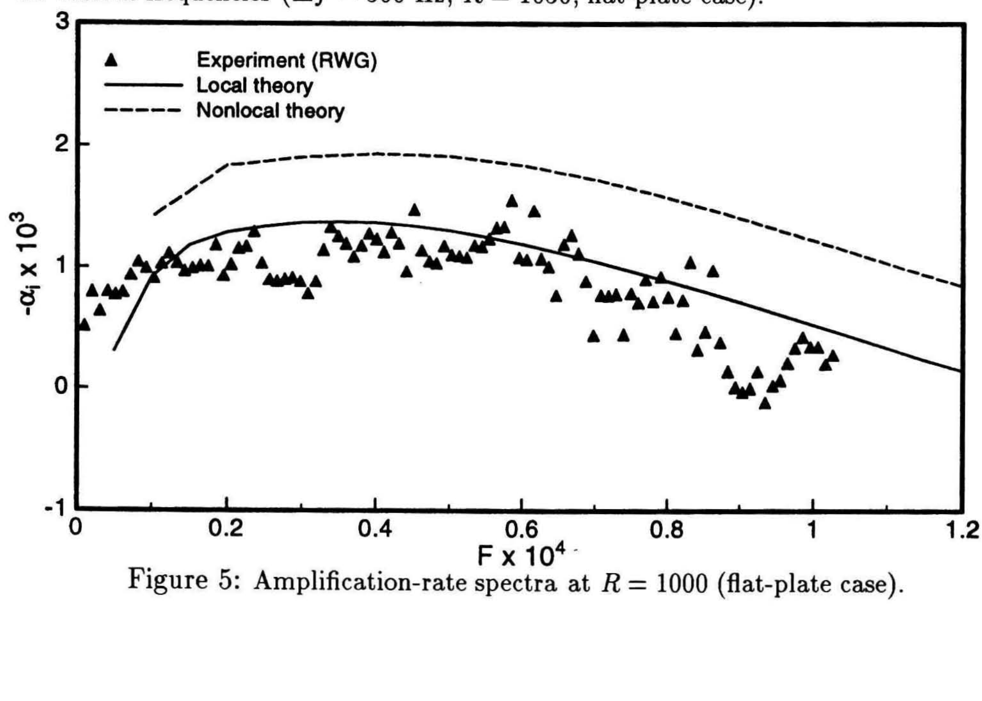

Figure 5: Amplification-rate spectra at $R = 1000$ (flat-plate case).

available) might give an answer regarding whether this is a reasonable explanation.

Finally, some results of further data analyses are presented for the flat-plate case only.

At the local Reynolds number $R = 1050$ the band-limited ($\Delta f \approx 500$ Hz) disturbance amplitudes are computed and compared with theoretical results obtained by Simen & Hanifi (1994, private communication). They carry out a nonlocal linear instability analysis based on maximum amplified mass flow fluctuations and obtain amplitude profiles for four different frequencies. In Fig. 4 results of this comparison are shown.

The location of the maximum values is in close agreement for all frequencies, although the boundary-layer thickness in the experiment can only be determined within an uncertainty of $\Delta y/\delta = \pm 0.05$. The shapes of the disturbance-amplitude profiles, i.e. the form of a sharp peak near the boundary-layer edge, also closely agree. Only for $f = 67$ kHz the experimentally determined profile is significantly wider than the theoretical one. As already mentioned, in the frequency range above 50 kHz the maximum values in the spectra of the anemometer voltage are in the range of the free-stream disturbance amplitudes. Hence the boundary-layer mass-flow fluctuation profiles may be contaminated by free-stream noise, which would explain the deviation from theory.

The comparison of experimental and theoretical results in Fig. 5 shows good agreement of amplification-rate spectra from the experiment and local instability analysis for a Reynolds number of $R \approx 1000$. Since the theoretical data represent the amplification of oblique first-mode instability waves, the experimentally observed disturbance growth can be regarded as an amplification of oblique first-mode instabilities.

It is surprising that the nonlocal instability analysis, which additionally takes into account the variation of the basic and disturbance flow in the direction of the spatial amplification, and thus models the experimental conditions more completely than the local analysis, consistently yields higher amplification rates than the experiment. On the theoretical side this might be explained by the use of similarity profiles for the modeling of the basic flow. Thus the effect of interaction of the viscous boundary-layer flow with the inviscid free-stream is not taken into account. With this effect included, the theoretical amplification rates are reduced, as the interaction yields a negative pressure gradient in free-stream direction, which is known to stabilize first-mode waves (see Simen, 1993).

Conclusions

Hot-wire measurements inside of the laminar boundary layer on a flat plate and a sharp cone show disturbance amplitude profiles with a maximum at approximately 75 % of the boundary-layer thickness. This type of disturbance-amplitude profiles is typical for unstable hypersonic boundary layers. But the expected dominance of a high-frequency disturbance growth, as predicted by linear stability theory, cannot be confirmed. Only streamwise growth of natural disturbances within a broad frequency band up to 50 kHz and 200 kHz for the flat plate and the cone respectively, can be observed. Hence, lower frequency disturbances seem to dominate the transition process of the hypersonic flat-plate boundary-layer flow in the Ludwieg tube.

A main result of the comparison between fluctuation measurements within the hypersonic flat-plate boundary-layer flow and a local or nonlocal instability analysis is that the experimentally observed disturbance growth can be regarded as an amplification of oblique first-mode instability waves.

Amplified disturbances can be identified for the cone in the unstable first and second mode frequency range, but no dominance of amplified high-frequency second-mode disturbances is found in the experiments.

References

Kendall, J. M. 1975 – Wind tunnel experiments relating to supersonic and hypersonic boundary-layer transition, *AIAA J.* **13**, 290-299.

Kovásznay, L. S. G. 1950 – The hot-wire anemometer in supersonic flow, *J. Aeronautical Sciences* **17**, 565-572.

Ludwieg, H., Grauer-Carstensen, H. & Hottner, Th. 1969 – Der Rohrwindkanal der Aerodynamischen Versuchsanstalt Göttingen, Jahrbuch 1969 der DGLR, 52-58.

Morkovin, M. V. 1956 – Fluctuations and hot-wire anemometry in compressible flows, AGARDograph 24.

Stetson, K. F., Thompson, E. R., Donaldson, J. C. & Siler, L. G. 1991 – A comparison of planar and conical boundary-layer stability and transition at a Mach number of 8, AIAA Paper, 91-1639.

Stetson, K. F. & Kimmel, R. L. 1992 – On hypersonic boundary-layer stability, AIAA Paper, 92-0737.

Simen, M. 1993 – Lokale und nichtlokale Instabilität hypersonischer Grenzschichtströmungen, DLR FB 93-31.

Simen, M., Kufner, E. & Dallmann, U. 1993 – *Effects on transition of hypersonic flows based on local and nonlocal instability analysis*, AIAA Paper 93-5143.

Wendt, V., Simen, M. & Hanifi, A. 1995 – An experimental and theoretical investigation of instabilities in hypersonic flat plate boundary layer flow, *Phys. Fluids* **7**, 877 - 887.

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