HYPERSONIC INSTABILITY WAVES MEASURED ON A FLAT PLATE AT MACH 6

T. Roediger, H. Knauss, E. Kraemer,
Institute of Aerodynamics and Gas Dynamics (IAG),
Universität Stuttgart
Pfaffenwaldring 21,
70569 Stuttgart, Germany.
roediger@iag.uni-stuttgart.de

D. Heitmann, R. Radespiel
Institut of Fluid Mechanics (ISM),
Technische Universität Braunschweig,
Bienroder Weg 3,
38106 Braunschweig,
Germany.

B.V. Smorodsky, D.A. Bountin,
A.A. Maslov,
Khristianovich Institute of Theoretical and Applied Mechanics SB RAS,
630090 Novosibirsk,
Russia.

1 Introduction

The premise of the experiments described here is to study laminar-turbulent transition of hypersonic boundary layers (BL) on a flat plate in two different hypersonic facilities. The fundamental theoretical framework for investigations of compressible BL transition constitutes Mack’s linear stability theory (LST) [7]. He demonstrated that hypersonic BLs contain besides vorticity disturbances (first mode), multiple acoustical instability modes (Mack modes). The first of these Mack modes, the second mode, is the most dominant and most unstable disturbance mode in such planar hypersonic flat-plate BLs. The dominance of the second-mode instability was shown in extensive experimental studies for conical BLs and the results agree well with theoretical LST predictions (see review by Stetson [12] and references therein). However, experiments studying planar BLs (flat plate: [5], [14], hollow-cylinder: [13]) show that the “second-mode disturbances appear to play only a minor role in the transition process”. Low frequency disturbances seem to dominate the flow. The disturbances grow in a frequency band that is typical for the first mode and even in a range that LST predicts to be stable. A dominance of the second mode could not be observed. The issue of the planar-versus-conical BL anomaly is extensively discussed in [13], including comparisons with previous experiments, parameter effects like noise level, unit Reynolds number dependency etc. The instabilities of planar BL appear to be fundamentally different from the conical case. Several question were raised (e.g. different receptivity to freestream disturbance, prediction by LST etc.) and many aspects of this phenomenon remain unclear.

Most of the stability experiments mentioned above were conducted using hot-wire anemometry. In scope of the above questions, there are several drawbacks to this technique for the determination of growth rates of instability waves: Besides the limited frequency response and mechanical strength of hot-wires, their downstream influence excludes simultaneous streamwise amplitude measurements. Non-intrusive techniques for simultaneous measurements using streamwise arrays would permit a more precise determination of growth rates. Therefore, surface mounted measurement techniques (here: commercial pressure sensors [9] and ALTP heat flux gauges [10]) with high spatial and temporal resolution are used in the present experiments. Instability waves are measured by a staggered array of these single-point sensors and spatial amplification rates are determined from quantitative amplitude spectra of fluctuations of surface pressure and heat flux, respectively. The spectra show two dominant disturbances, one growing in the low-frequency range for a certain unit Reynolds number regime, and a second present in the frequency range typical for the second-mode instability. Comparisons of the growth rates of the latter disturbance mode with linear stability theory computations exhibit a good agreement of amplification rates in the early stages of the transition process at least for the ALTP measurements.

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2 Facilities

Hypersonic Ludwieg Tube Braunschweig (HLB). The HLB operates at a nominal Mach number of M=6 in a unit Reynolds number regime of $3 \times 10^6$ at conventional noise level. A schematic of the HLB is shown in Figure 1. It consists of a driver tube which is separated from the low pressure section by a fast-acting valve. The driver tube is heated along the first 3 m upstream of the valve. The heated section accommodates the amount of gas that is released during one run. The valve consists of a streamlined center body on the tube axis. The pneumatically driven valve opens within 20 ms and closes after the expansion wave has passed back and forth within the tube. The resulting test time with constant pressure and temperature is 60-80 ms depending on the initial driver tube pressure. The low pressure part consists of nozzle, test section, diffuser and a dump tank (6 m$^3$). A more detailed description of the facility can be found in [2].

The nozzle maintains an opening half angle of 3° which results in slightly expanding flow in the test section with Mach numbers between 5.8 and 5.95 depending on the axial position and on the unit Reynolds number. The driver tube pressure is recorded with an accuracy of ±1%. The driver-tube temperature is measured during the run by two fast thermocouples. It must be noted that the measured temperature difference between the upper and lower measurement position can be as high as 30K due to temperature stratification. The mean value, however, is not proven to be the total temperature at the height of the model in the test section. An uncertainty of ±1% is estimated in the determination of the total temperature. The uncertainty in the determination of the Reynolds number resulting from the uncertainties in total temperature, pressure and Mach number in the test section yield an uncertainty of about ±2% in the relevant unit Reynolds number range. The noise level is between 1% and 1.5% depending on the unit Reynolds number and the position in the test section [4]. For the experiments described later, a position slightly off tunnel axis was chosen in a region with lower noise level.

![Figure 1. Schematic of the Hypersonic Ludwieg tube Braunschweig](image)

TRANSIT-M. The experiments at ITAM were carried out in the TRANSIT-M facility. This facility provides supersonic and hypersonic flows of high Reynolds numbers in a Mach number range M= 4-8. Air is heated up by ohmic heaters and stored in the plenum chamber under pressure up to 200 bar. After the opening of the fast-acting valve, air flows via the settling chamber to the test section through the contoured nozzle of 300 mm exit diameter. Then the gas is recompressed by a diffuser and flows to the vacuum tank. The running time is about 110-200 ms for the present M=6 experiments, limited by the size of the vacuum tank (6.5 m$^3$). Since the flow conditions change during the run, the unit Reynolds number $Re_{unit}$ decreases by approximately 20% during the measurement period of 200 ms. To account for the change, the measurement period is subdivided into several intervals. Within each interval variations of $Re_{unit}$ do not exceed ±2% and the flow is treated as steady.

3 Model and Instrumentation

Instrumentation. The model used in the HLB experiments was instrumented with a stream-wise, staggered array arrangement of fast-response ALTP heat flux and pressure sensors. Figure 2 shows their arrangement (“p” stands for pressure sensor, “A” represents an ALTP heat flux gauge). The ALTP heat flux gauges allow for highly time-resolved heat flux measurements up to the 1 MHz range. Its working principle is based on the Transverse Seebeck Effect. The output signal is directly proportional to heat flux density and it has been used in previous studies.
of hypersonic BL transition [6]. For a detailed description of the working principle, structure and calibration procedure of the sensor, the reader is referred to [10].

The active area of the ALTP gauges used in the present experiments is $2 \times 0.4$ mm$^2$ limiting the spatial resolution in the streamwise direction to 0.4 mm. The gauges are calibrated by exposure to laser light radiation and have a sensitivity between 80 to 122 $\mu$V/(W/cm$^2$). The total uncertainty of the calibration procedure is estimated as 5.5% [10]. In addition, the amplitude-frequency response (AFR) characteristics of the measurement system is taken into account in order to determine absolute values of wave amplitudes. The AFR characteristics are measured by dynamic laser beam calibration using the modulated output of a diode laser in a frequency range between 1 kHz and 1 MHz. A more detailed description of the dynamic calibration procedure can be found in [11]. Low-noise amplifiers with signal conditioning were used for the amplification of the mean value (low-pass filtered DC-branch, nominal GAIN 8000) and the fluctuations (high-pass filtered AC-branch, GAIN 5000).

Commercial pressure sensors of type M131A32 manufactured by PCB Piezotronics were used in the experiments. The sensors were flush mounted in the model surface and the diameter of their sensing area is 3.18 mm. Power was supplied to the pressure sensors using an instrument supplied by the manufacturer (PCB 482A22), which at the same time also performed signal conditioning. According to the manufacturer’s specification the resonance frequency of the pressure sensors is larger than 1 MHz and the output signal is high-pass filtered at 10 kHz. The sensors are calibrated in a shock tube by the manufacturer and have sensitivities between 150 and 167 mV/psi. For details on the the measurement technology the reader is referred to the manufacturer’s website [9]. A 16 bit transient recorder PCI-express card (Spectrum M2i.4652) was used for data acquisition. The card allowed a maximum sampling rate of 3 MS/s.

Flat Plate Models. Two flat-plate models were used in the experiments because of the quite different test chamber size of the two facilities.

A 440 mm long and 200 mm wide flat plate was installed in the TRANSIT-M facility. The 10°-beveled leading edge was sharp and uniform as possible. The plate was mounted on a sting downstream of the plate and was aligned with the tunnel axial centerline. It did not span the whole tunnel width, hence leaving space between the tunnel side walls and the right and left edges of the plate. Only one single-point, ALTP heat-flux gauge was placed at the centerline of the plate at a distance of $x=226$ mm from the leading edge. Therefore, the calculation of spatial amplification rates is not possible for these experiments.

The test chamber size of the HLB allowed the installation of a longer flat-plate model with a size of $630 \times 200$ mm$^2$ in length and width, respectively. The leading edge was sharp and beveled with an angle of 4°. In order to minimize 3-D effects, triangular supersonic edges (330 mm long, 70 mm wide, each) were attached to the sides along the front part of the plate. The flat plate was installed $\sim$90 mm off the the tunnel axis in order to avoid a conical compression wave that is known to focus on the axis within the test section. The plate had a small negative angle of attack in reference to the geometric axial centerline in order to account for the weak expanding flow in the test section, mentioned above. Yet the uncertainty of a small angle of attack and non-parallel flow remains. Future investigation should check the angle of attack more carefully e.g. by additional measurements of boundary layer profiles along the plate. In order to allow a direct comparison of amplification rates, four fast-response ALTP heat flux (“A”) and four PCB pressure gauges (“p”) were installed in a single-point, staggered, line array with a spacing of 16 mm as shown in Figure 2. The gauges were installed in two circular inserts (two out of three) with a diameter of 90 mm and flush mounted in order to minimize surface roughness. The first sensor of Insert 2 was

![Figure 2. Schematic of the flat plate model used in HLB experiments](image-url)
positioned 192 mm from the leading edge, and the first one of Insert 3 at a distance of 284 mm.

4 Data Analysis

Data Processing. In the TRANSIT-M experiments, the measurement period is subdivided into 5 or 6 equal intervals (depending on run time) in order to account for the variation of unit Reynolds number during the run. The resulting intervals were split into samples of 512 points each with overlapping of 200 points. Every sample was Fourier transformed and the obtained spectra were averaged within a single interval.

In the HLB experiments, a time period of 40 to 70ms was evaluated depending on the available measuring time of each single run. The heat flux and pressure values were calculated from voltage fluctuations using the specific calibration factors of the sensors. The resulting signals were divided into overlapping windows with an constant size of 800 samples each and an overlap of 500 samples. The windows were multiplied with a normalized Exact Blackman window and Fourier transformed. The absolute values of the complex-conjugate amplitudes were added and averaged over all windows. In the same way an equivalent period of the data measured directly before the start of the tunnel was processed. The power spectra of both transforms were subtracted. Hence, the uncorrelated electronic noise and disturbances are eliminated from the resulting amplitude spectra. For some low-noise experimental data the power spectral subtraction of background noise yielded negative amplitude values at some frequencies. These values were set to zero. The accuracy of this preliminary noise-subtraction method remains to be evaluated in detail.

Amplification rates. For the calculation of the amplification rate in x-direction, the relation given by Mack [7]

\[-\alpha_i = \left( \frac{1}{A} \right) \left( \frac{dA}{dx} \right)\]

(1)

with negative values of \(\alpha_i\) denoting amplification, was simplified for the calculation of the amplification rates between single-point sensors. If \(\alpha_i\) is constant, exponential amplitude growth can be assumed leading to

\[-\alpha_i = \ln\left(\frac{A_2}{A_1}\right) \frac{x_2-x_1}{A_2} \quad \text{if} \quad A_1 > 0 \quad \text{and} \quad A_2 > 0\]

\[-\alpha_i = 0 \quad \text{else}\]

with \(A_1\) and \(A_2\) being the wave amplitudes after noise subtraction at two consecutive sensors and \((x_2 - x_1)\) being the surface distance between those sensors.

It must be noted, however, that the assumption of constant \(\alpha_i\) is only of limited validity because the distance between the sensors is fairly large and several times the wavelength of the investigated instability waves. Especially in regions of large changes of the amplification rate, this assumption results in an averaged amplitude ratio and might deviate from predictions of local linear stability theory.

5 Linear Stability Theory Calculations

Spatial amplification rates are computed from LST for comparison with the experimentally obtained results. The flat plate BL at zero angle of attack was computed by means of self-similar flat-plate compressible boundary layer equations [15]. Wall temperature, Prandtl number and specific heat ratio are assumed to be constant. Sutherland’s law is used for the viscosity. In addition, the flow is assumed uniform in the streamwise flow close to the surface. Local linear stability analysis of the BL is performed in the framework of the eigenvalue problem for Lees-Lin equations [16], which have been integrated numerically by means of the method of orthonormalizations [3]. Spatial growth rates of the instability waves are determined by eigenvalues as function of the flow stagnation parameters and wave frequency.

6 Experimental and Computational Results

TRANSIT-M experiments. Figure 3(a) shows amplitude spectra of pulsations of heat flux measured by the ALTP at the location \(x=226\) mm. The Reynolds number \(Re_e\), used in the diagrams, is calculated with reference to edge conditions of the flat plate BL and x-coordinate along the plate. Due to the decreasing free-flow parameters, the evolution of the spectra can be seen with changing unit
Figure 3. Heat flux spectra for variation of unit Reynolds number at x = 226 mm each obtained in one single run: (a) \( \text{Re}_e = 2.46 \div 3.30 \times 10^6 \); (b) \( \text{Re}_e = 3.86 \div 5.20 \times 10^6 \).

Reynolds number during one single run. For the smallest Reynolds numbers the spectra indicate a laminar boundary layer state. A peak at \( \sim 120 \text{ kHz} \) is presumably the second-mode disturbance, since the amplified frequency range is typical for second mode (see LST calculations discussed later). It is clearly seen that the peak is shifted with increasing Reynolds number, showing an imperative characteristic of the second mode. At the same time, the amplitude of the disturbance level grows. For the highest Reynolds number, another peak in low frequency band appears. This low-frequency disturbances has also been detected in HLB experiments, described later. The origin of this peak is not clearly understood and will be discussed in the following section in more detail.

Figure 3(b) shows ALTP spectra at the same location but for higher unit Reynolds number. For the lowest Reynolds number in this figure, the peak of the second-mode disturbances is distinctively noticeable. Disturbance amplitudes grow with increasing Reynolds number as observed previously. Due to the nonlinear interaction, both the lower and higher frequency portions of the spectrum are starting to fill in and the second mode disappears at \( \text{Re}_e \approx 4.36 \times 10^6 \) and finally the boundary layer becomes turbulent at \( \text{Re}_e = 4.9 \div 5.2 \times 10^6 \).

Figure 4. (a) Pressure spectra for variation of unit Reynolds number at x=284 mm ; (b) Heat flux spectra (AFR corrected) for variation of unit Reynolds number at x=300 mm.
HLB experiments. Figure 4(a) displays surface pressure amplitude spectra for variation of Reynolds number at the fixed location x=284 mm. In the spectral range below 50 kHz, four discrete pressure disturbances are visible. Their magnitude increases with rising (unit) Reynolds number, however their frequency remains constant. Disturbances in the low-frequency range were also detected in the TRANSIT-M experiments and their likely origin will be discussed later in more detail by means of contour plots and calculation of amplification rates.

The amplitude and frequency of the peak between 80 to 150 kHz increase with rising Reynolds number. This feature is characteristic for...
BL instability modes. The spectral range corresponds well to the amplified frequencies typical for second-mode instability, predicted by LST calculations. A first harmonic of the second mode is also visible at ∼180 kHz for a certain Reynolds number range. The peak at ∼300kHz was also observed in other experiments [1] and is thought to be an effect of the sensors (although it is far below the resonant frequency given by the manufacturer).

Figure 4 shows the amplitude spectra of heat flux (AFR corrected) measured by an ALTP gauge at x=300 mm for variation of Reynolds number. In the range between 60 to 150 kHz, a behavior similar to the one detected by the pressure sensor is visible. The amplitude and frequency of the peak increase with Reynolds number, also confirming the detection of the second mode by the ALTP in a similar frequency (∼120 kHz) and close Re_e-range (TRANSIT-M: Re_e ≈ 2.46; HLB: Re_e=2.26 ± 2.66) in the two different facilities, HLB and TRANSIT-M.

The heat flux spectra in the low-frequency range (<60kHz) show instead of several discrete peaks, as present in the pressure spectra, only one single dominant peak. Its frequency increases with unit Reynolds number and its amplitude grows and decays in a certain Reynolds number range. Disturbances in this low frequency range seems to be amplified at lower unit Reynolds number and strongly damped past a certain Reynolds number (∼1.4 E6). In the Reynolds number range between 1.4 ÷ 1.6 E6, this low-frequency disturbance coexists with the higher-frequency disturbance, presumably second mode.

Figure 5 and 6 show contours of heat flux and pressure spectra for a variation of Reynolds number at a fixed x-location. All pressure and heat flux spectra at the same unit Reynolds number were captured simultaneously. These contours are tailored to trail and identify the evolution of the second mode along the plate. Therefore, the frequency is normalized by boundary layer edge conditions, calculated from measured stagnation conditions. All normalized plots show that the frequency of the second mode scales well with $f x/(U_e \sqrt{Re_e})$. The maximum collapses for all pressure and heat flux contours to a constant value of $f x/(U_e \sqrt{Re_e}) \approx 0.020 ÷ 0.022$. In the early stages
of the transitions process at the most upstream x-positions (Fig. 5(a) and 6(a)), the second mode is detectable for Reynolds numbers as low as ~1.2 E6. At later stages, the superposition of the low-frequency disturbance smears the peak of the second mode for low Reynolds numbers. Please note that the contour coloring levels are different for each single plot. The maximum “sensitivity” of the color level is increased in downstream direction. Thereby individual features of each contour are enhanced. For example, the broadening of the second-mode peak with rising Reynolds number is clearly visible. In addition, the superposition of the second-mode with the low-frequency disturbance is characterized in more detail. In contrast to the second-mode instability, the low-frequency disturbance seems not to scale with Reynolds number. The amplitude of the peaks grows and broadens centered around a fixed unit Reynolds number of ~4.5 E6/m (best visible in Fig. 5 / 6 (b) + (c)). Beyond a certain unit Reynolds number, the disturbances in the low frequency band are strongly damped which would not be typical for a BL instability mode like first mode. The two characteristics mentioned, might indicate that the disturbance is created from acoustic noise or interaction of acoustic disturbances with the flat plate BL. However, this is only speculation and receptivity mechanisms remain unclear, especially because a similar disturbance could not be found in cone experiments under the same flow conditions [1], [4]. Other explanations or sources have to be investigated in future experiments like e.g. disturbances traveling from the lower side of the plate [8], leading-edge inhomogeneity and roughness influence. Moreover, the low-frequency disturbance appears to have a strong influence on the second-mode instability. The modes seem to superimpose and merge in the later stages of BL transition. The quality of the heat flux and pressure spectra allows the calculation of spatial growth rates. The following comparison with LST computations might give a first indication of the extent of influence.

Figure 7 shows the amplification rates ~α vs. normalized frequency calculated from (a) pressure spectra between x=284mm and x=316 mm and (b) ALTP heat flux spectra between x=300 mm and x=332 mm. Qualitatively, the rates obtained from pressure and heat flux are similar. The maximum growth rate of the fundamental and first harmonic are about the same in the extended frequency range displayed in Figure 7. However, a quantitative comparison shows that maximum growth rates measured by the pressure sensors are systematically lower than the one detected by ALTPs for the same Re_e. It must be noted that the pressure spectra are not AFR corrected, however, this might only play a minor role in this frequency range and remains to be verified. Furthermore, maximum amplification rates of the fundamental measured by the ALTP appear at slightly lower normalized frequencies. This discrepancy can also have its reason in the systematical downstream displacement of the ALTP gauges in reference to the pressure sensors. In addition, the range of amplified frequencies measured by the ALTP seems to be somewhat broader than the one detected by the pressure sensors. These two features, could imply that a stronger influence of the superposition with the low-frequency disturbance on the ALTP signal exists, since the decaying rates with Reynolds number indicate an already advanced stage of BL transition. However, growth rates for lower Reynolds number could only be calculated from ALTP signals. The small amplitudes of pressure fluctuation created by the waves were below the detectable limit of the pressure sensors at further upstream positions (the front pressure sensors is located 16 mm upstream of first ALTP sensor). Figure 8(a) shows the amplification rates calculated from ALTP spectra between x=208mm and x=240 mm (most upstream, spacing Δx= 32 mm), resulting into 1.19 E6 ≤ Re_e ≤ 1.87 E6. Figure 8(b) depicts the later stages of transition in a detailed view (expan-
sion of Fig. 7) as comparison with the earlier stages in Figure 8(a). The bandwidth of amplified frequencies for lower Reynolds numbers is considerably smaller than for later stages of transition. LST calculations were carried out for the complete Reynolds number range and the results are also shown in Figure 8(a) and (b). A small shift in normalized frequencies of the maximum rates predicted by LST and by the experiments in the early stages (Fig.8(a)) is visible. This could be due to the slightly expanding flow in the test section or small angle of attack that would change the assumed edge Mach number. Relatively good agreement of maximum growth rates is found in the early stages of transition (∼7.5% discrepancy for $Re_e = 1.19 \times 10^6$). With increasing Reynolds number, however, the discrepancy with LST predictions increases. The experiments produce larger growth rates and reach maximum values of $-\alpha_i \approx 40/\text{m}$ for $Re_e = 1.82 \div 1.87 \times 10^6$ before the rates decay. These discrepancies have to be studied in more detail by experiments using a sensor array with smaller spacing in streamwise direction. Since the distance between the sensors was several times the wavelength of the second-mode waves and the mid-position of the gauges was used for evaluation of local linear stability theory results.

7 Conclusions

According to the authors’ knowledge for the first time BL instability waves on a flat plate in hypersonic flow were detected by means of several flush mounted pressure and heat flux sensors of high frequency response, arranged in a positioning of streamwise alignment to the flow. Simultaneous multiple local measurements of pressure and/or heat flux fluctuation although only captured on the surface and not in the BL, allows to detect instability waves. Spectral analysis of the pressure and/or heat flux sensor signals result in dominant frequencies, which correlate with unit Reynolds number and show unambiguously the existence of the second mode, the dominant instability in this Mach number range. A growth of fluctuation amplitudes for both kind of sensors could be determined in a good agreement and were compared with LST.

A detection of a possible first instability mode directly in the relevant lower-frequency range of the BL could not be attained. Dominant frequencies found in this lower range are not unit Reynolds number dependent and might have their origin in the oncoming free-flow of the test section or most likely in disturbances generated in the flow, passing the support structure on the lower side of the plate model.

An extensive analysis of the spectra, derived from the totality of all pressure and heat flux measurements, shows that there might be a superposition of low frequency disturbances with the second mode instability in the state close to transition.

An examination of the low-frequency disturbances and their origin seems recommendable eventually by means of a hot-wire mode analysis of the free-flow in the test section of the Ludwieg tube. Another alternative could be also a controlled experiment with selective disturbance frequencies in the relevant range of the first mode under present flow conditions determined by LST.

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Section IV


