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AN EXPERIMENTAL INVESTIGATION OF NATURAL DISTURBANCES IN A HYPERSONIC BOUNDARY LAYER ON A FLAT PLATE

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The occurrence of turbulence in the boundary layer of aircraft at hypersonic speeds is caused by complex wave phenomena that have not been adequately explored so far. Several new experimental papers devoted to investigating the structure of disturbances in a gradient-free boundary layer at free-stream Mach numbers $M_\infty = 5$–8 have been published recently. Most of the experiments were performed on conical models [1–4]. These studies were mainly focused on the high-frequency second mode of disturbances, and the experiments were performed in continuous-flow blowdown wind tunnels. Experimental results on the stability of natural disturbances in the boundary layer of a flat plate are presented in [5, 6]. The experiments were performed in an intermittent wind tunnel — Ludwig tunnel (the run time is ~100 msec). In these studies, the second mode of disturbances was not recorded, and it was concluded that the flow instability was determined by the first low-frequency mode of disturbances.

Measurements on cones have been performed by different authors, compared time and again, and generally recognized. The experiments of [5, 6] were performed for a flat plate and only in one experimental facility. Therefore, it seems reasonable to replicate the experiments in a continuous-flow blowdown wind tunnel under similar experimental conditions for the sake of comparison of results.

The Institute of Theoretical and Applied Mechanics of the Siberian Division of the Russian Academy of Sciences (ITAM SD RAS) has gained experience in investigating the stability of hypersonic flows. Methods for measuring the parameters of natural disturbances have been developed [7–9], and hypersonic wind tunnels are available. Thus, the objective of this work is to develop a technique for studying natural disturbances at hypersonic speeds, to investigate the development of natural disturbances in the boundary layer of a flat plate in a blowdown wind tunnel, and to compare the results with the data of [5, 6].

The characteristics of natural disturbances were studied experimentally at $M_\infty = 6$ in a laminar boundary layer on a heat-insulated plate with a sharp leading edge. The model was a flat steel plate 10 mm thick. Its planform was a trapezoid 250 mm long with bases of 140 and 110 mm. The sweep angle of the model edges was $14°30'$. The radius of the edge bluntness was less than 0.05 mm. The model was placed horizontally at zero angle of attack in the central plane of the test section of a wind tunnel.

The experiments were performed in a T-326 wind tunnel with nozzle exit diameter of 200 mm [10]. The experimental stagnation pressure was $P_0 = 10$ atm. The stagnation temperature was $T_0 = 380$ K, which corresponds to the test-section unity Reynolds number $\mathrm{Re}_1 = 12.5 \cdot 10^6\ \mathrm{m}^{-1}$.

The plenum-chamber stagnation pressure and temperature were measured in the course of the experiment to determine the flow parameters. The static pressure of the model surface P_w, the plate temperature T_w, and the pressure behind the normal shock P_0' were recorded to find the average boundary-layer parameters (velocity U and Mach number M). The pressure was measured by strain gages, and the temperature was measured by thermocouples. A Pitot sensor 0.25 mm high was used to measure P_0'. Fluctuations were measured by a DISA-55D01 constant-temperature hot-wire anemometer. Sensors with a tungsten wire 5 μm in diameter and 1.5 mm long were used in the experiments.

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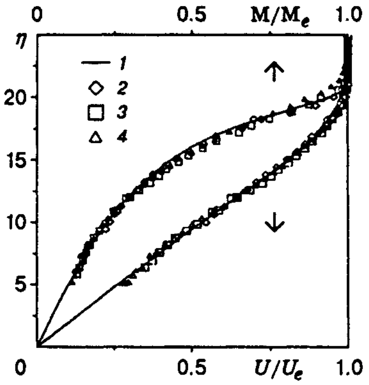

Fig. 1

The signals from the sensors were recorded by an automated data acquisition and processing system based on a CAMAC-IBM PC complex with an analog-to-digital converter, a commutator, voltmeters, and pulse counters.

The hot-wire sensors and the Pitot probe were fixed at the sting of a three-component traversing gear. Attachment of the sensors to the model in the y direction was determined from electric contact with the model. The measurement accuracy for the x coordinate (reckoned from the leading edge of the model along the plate) was 0.1 mm, and that for the y coordinate (reckoned from the model surface normally to it) was 0.01 mm.

Because of the comparatively low temperature of tungsten oxidation in air (~600 K), the maximum possible superheat of the hot wire is 0.4. At small superheats, the frequency characteristic of the anemometer deteriorates; therefore, the maximum disturbance frequencies measured in the experiments were limited to 100 kHz, which corresponded to the dimensionless frequency $F = 2\pi f/\mathrm{Re}_1 U_e = 0.62 \cdot 10^{-4}$ (the subscript e indicates the boundary-layer-edge parameters).

When a constant-temperature hot-wire anemometer is used, the hot-wire anemometer noise is usually assumed to be smaller than the measured fluctuations and, hence, it can be ignored. The high-frequency disturbances of the boundary layer (~100 kHz) have a very small amplitude, and the hot-wire anemometer noise should be taken into account in measurements of these disturbances. When the sensor is in a gas at rest, there are no flow fluctuations, and the intrinsic anemometer noise can be measured. When the sensor is put in a gas flow, the measured noise does not change if the mean sensor voltage resistance, and the anemometer setting are the same.

The hot-wire superheat and the flow parameters were chosen in such a way that the mean voltage of the sensor and its resistance in the flow (in the layer of maximum disturbances) are the same as those in the gas at rest at the same adjustment of the hot-wire anemometer.

When the hot-wire sensor is moving across the boundary layer, the mean voltage changes; therefore, the hot-wire anemometer noise, and, hence, the flow disturbances can be accurately measured only in the layer of maximum fluctuations.

The sensor superheat was fairly high in the experiments, so that mass-flow fluctuations made a major contribution to the hot-wire signal. The hot-wire sensor was not calibrated. This did not affect the measured growth rate $-\alpha_i$, since the linear stage of the development of disturbances was studied. When the eigenfunctions were measured, the absence of calibration did not affect the results for the following reasons. The maximum of the disturbances was located near the upper edge of the boundary layer ($y/\delta \approx 0.83$, where δ is the boundary-layer thickness), where the noise was accurately subtracted, and the sensitivity coefficients changed insignificantly. The fluctuations damped rapidly when approaching the model surface.

Figure 1 shows the measured mean boundary-layer parameters in the form of curves of the Mach number M/M_e and velocity U/U_e, normalized by the corresponding values at the boundary-layer edge, versus the

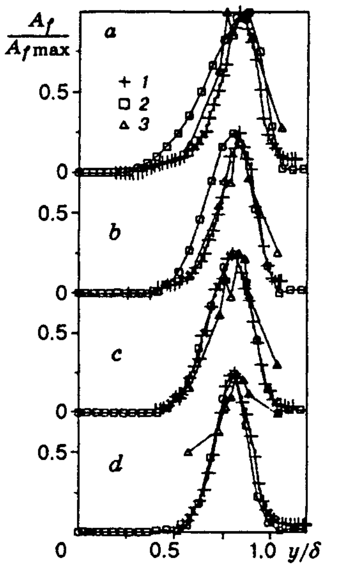

Fig. 2

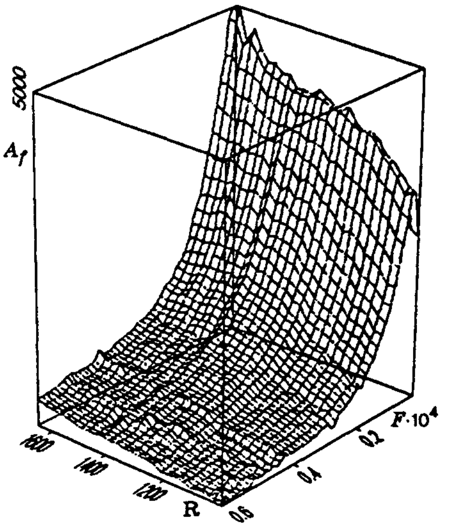

Fig. 3

Blasius coordinate $\eta = y\sqrt{\mathrm{Re}_1/x}$. Curve 1 is the calculation of the boundary-layer equations, and points 2–4 are the experimental data obtained for Reynolds numbers R = 1117, 1253, and 1340, respectively ($\mathrm{R} = \sqrt{\rho_e U_e x/\mu_e}$, ρ is the density, and μ is the dynamic viscosity). The Reynolds number was varied by changing the x coordinate. The Mach-number distribution was obtained from the Rayleigh formula for the measured values of P_w and P_0'. The modified Crocco integral was used for velocity calculations. The experimental and calculated results are in good agreement. This indicates that a gradient-free flow with a self-similar boundary layer formed in the experiments on a flat plate.

The eigenfunctions of natural disturbances were measured as follows. The variable component of the signal of the hot-wire anemometer was amplified by a U2-8 selective amplifier, which yielded the r.m.s. value of the signal with a given frequency A_f. The hot-wire sensor moved along the y coordinate, and the constant sensor voltage E and the r.m.s. signal were stored in the computer. The measurements were performed for 10 frequencies (10, 20–100 kHz) and R = 1050 and 1350 (the Reynolds number was varied by displacement along the x coordinate). The mean voltages were repeated in different tests with an accuracy of ±1%, which showed good reproducibility of the results. The distributions of disturbances versus the y coordinate were similar for all frequencies. The maximum of the fluctuations is near the upper edge of the boundary layer ($y/\delta \approx 0.83$), where the disturbances exceed the free-stream disturbances by more than an order of magnitude. The position of this maximum is the same for all eigenfunctions, and the deviations from the mean value are ±3%. With approach to the wall, the amplitude of the disturbances decrease rapidly.

Figure 2 shows the distributions of fluctuations normalized by their values at the maximum versus y/δ for R = 1050 [points 1 are the experimental results obtained in the present work for $F = 0.183 \cdot 10^{-4}$, $0.297 \cdot 10^{-4}$, $0.360 \cdot 10^{-4}$, and $0.62 \cdot 10^{-4}$ (Fig. 2a–d), and curves 2 and 3 are the computations of stability equations with allowance for the nonparallel flow in the boundary layer and the experimental results at $\mathrm{M}_e = 5$ [6] for $F = 0.154 \cdot 10^{-4}$, $0.298 \cdot 10^{-4}$, $0.398 \cdot 10^{-4}$, and $0.685 \cdot 10^{-4}$ (Fig. 2a–d)]. Good agreement of the data can be noted.

Let us concentrate on Fig. 2d. The experimental results of [6] are presented only for the vicinity of the maximum of fluctuations; a rapid decrease in the values of fluctuations was not observed with distance from the maximum. The noise of the hot-wire anemometer was not subtracted in [6], and it is probably about half the maximum amplitude for disturbances with frequency $F = 0.685 \cdot 10^{-4}$. Thus, the results obtained in [6] for disturbances with frequencies $F = (0.685\text{–}1.03) \cdot 10^{-4}$ were apparently distorted by the hot-wire

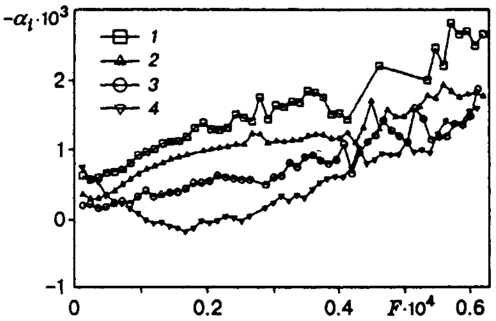

Fig. 4

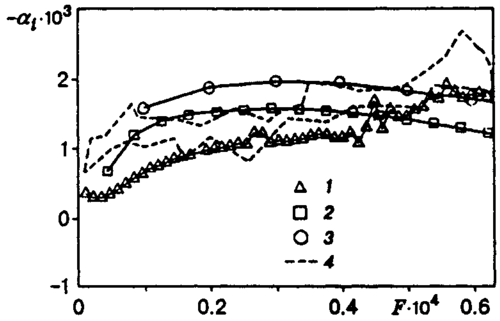

Fig. 5

anemometer noise. In the present work, the eigenfunction was almost completely recovered, and this confirms the legitimacy of the procedure of eliminating the hot-wire noise.

Further hot-wire measurements were performed in the layer of maximum fluctuations in the standard manner [7–9]. When the sensor was moved along the x coordinate, the mean sensor voltage was kept constant by simultaneous displacement of the sensor along the y coordinate. The fluctuation maxima were on the curve $E = \text{const}$ and $y/\delta = \text{const}$, which corresponded to the curves of equal velocity and temperature. Therefore, the sensitivity of the sensor remained unchanged, and the electric signals could be directly compared.

Figure 3 shows the measured spectra in the layer of maximum fluctuations $A_f(F)$ for different R. Note that the data for the ranges R = 1000–1450 and 1450–1650 were obtained in different experiments and are in good agreement.

The growth rates of disturbances $-\alpha_i = (1/2A_f)\, \partial A_f / \partial \mathrm{R}$ were calculated from the measured spectra of disturbances at the maxima of the fluctuations. For this, 8–10 values obtained for different x were used to construct a second-order approximation curve by the least-square method, and then the values of the derivative were found. Comparison of the values of $-\alpha_i$ obtained in different experiments showed that, for low frequencies ($F < 0.4 \cdot 10^{-4}$), the accuracy and reproducibility of the results are good, while the data at high frequencies show a great spread. This is explained by the fact that, as can be seen from Fig. 3, the amplitudes of the fluctuations decrease greatly.

Figure 4 shows the experimental curves of the growth rates of disturbances versus the frequency F for R = 1065, 1200, 1400, and 1580 (points 1–4). For R = 1065–1400, the disturbances of all frequencies are increasing, their growth rate decreasing with an increase in the Reynolds number. High-frequency fluctuations have large growth rates. A region of stable disturbances ($-\alpha_i < 0$) with frequencies $F = (0.1\text{–}0.25) \cdot 10^{-4}$ appears for R = 1580.

Figure 5 shows the values of $-\alpha_i$ for R = 1200 obtained in the present work, and the results of calculation of the stability equations using the local theory and the theory taking into account the flow nonparallelism (points 1–3, respectively) [6]. Curve 4 limits the spread of the experimental points obtained in [6]. Since the experimental and calculated parameters (M and Re_1) differ only slightly, it is believed that the results agree fairly well.

Thus, a method for measuring the characteristics of natural disturbances at hypersonic speeds is developed in the present paper. The results obtained are in good agreement with the measurements performed in the Ludwig tunnel.

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