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NUMERICAL AND EXPERIMENTAL INVESTIGATION OF RECEPTIVITY OF HYPERSONIC VISCOUS SHOCK LAYER TO NATURAL AND ARTIFICIAL DISTURBANCES

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Abstract. The problem of receptivity and development of disturbances in a viscous hypersonic shock layer on a flat plate is investigated both numerically and experimentally. The direct numerical simulations and experimental measurements are performed at the free-stream Mach number M = 21, the Reynolds number based on the plate length $\mathrm{Re}_L = 1{:}44{\cdot}10^5$, and the flow stagnation temperature $T_0 = 1200$ K.

1. INTRODUCTION

Advanced research in stability of a hypersonic boundary layer and its receptivity to external forcing include studying flows with strong viscous-inviscid interaction. At high Mach numbers and moderate Reynolds numbers (conditions corresponding to hypersonic flight at high altitudes), the flow structure between the surface and the bow shock wave (SW) is a combination of a thick boundary layer and a thin zone of an inviscid flow behind the SW, which is the so-called viscous shock layer. Stability and receptivity of such flows have not been adequately studied yet. There are two main problems here: 1) it is impossible to use simplified assumptions usually used to describe the process of stability loss at low Mach numbers and 2) it is extremely difficult to model real high-velocity flows in experiments. The way out is a comprehensive approach including research in hypersonic low-enthalpy wind tunnels and direct numerical simulation of evolution of disturbances in the shock layer with further approaching the real flight conditions.

In view of this concept, the present paper describes comprehensive numerical and experimental studies of disturbance evolution in a hypersonic viscous shock layer on a flat plate at a very high Mach number ($M_\infty = 21$) and moderate Reynolds numbers $Re_L = (1.44 \div 4.32)\cdot 10^5$. The mean flow field and the parameters of density fluctuations in the shock layer were measured in a T-327A hypersonic nitrogen wind tunnel based at ITAM SB RAS.

2. NUMERICAL FORMULATION OF THE PROBLEM

2.1. Governing equations

A hypersonic flow past an infinitely thin flat plate of length $L = 240$ mm, aligned at zero incidence, was considered. Two-dimensional Navier-Stokes equations written in the form of a system of conservation laws were solved by a high-order shock-capturing scheme. The details of the numerical method were described in [1,2]. Concerning the properties of the ambient medium, the gas was assumed to be perfect and to have constant specific heats. The gas viscosity was calculated by Sutherland's formula with parameters corresponding to nitrogen. The plate itself was assumed to have a constant surface temperature.

The computational domain was a rectangle, some part of its lower side coinciding with the plate surface. A steady flow was first calculated with the boundary conditions on the left and upper boundaries being set in the form of a uniform hypersonic flow directed along the x axis. On the right boundary, the solution was extrapolated from inside the computational domain. As the rarefaction effect was rather considerable in the problem considered (the slip velocity on the plate surface is 17% of the free-stream velocity at the leading edge and 8% at the trailing edge), the boundary conditions on the plate surface took into account the velocity slip and temperature jump. The results of modeling a steady flow demonstrated good agreement with the values of the Mach number and mean density measured in the shock layer [1,2].

The shock layer is excited by external acoustic waves superimposed on the uniform free stream or blowing/suction introduced on the plate surface near the leading edge (see Fig. 1).

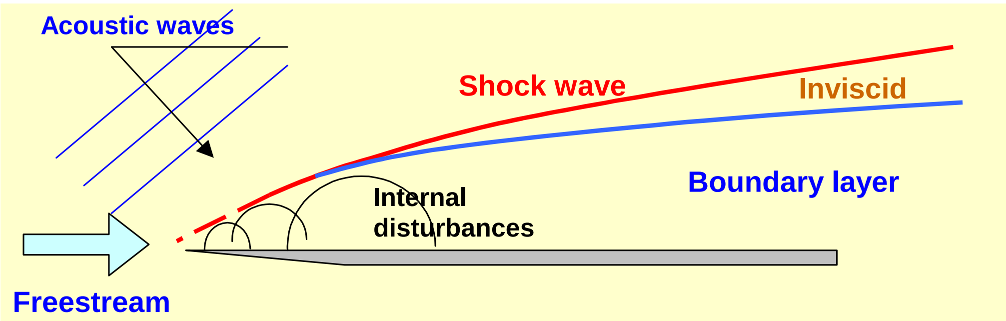

Figure 1. Schematic of the flow in viscous hypersonic shock layer excited by external and/or internal disturbances.

2.2. Problem of interaction of the viscous shock layer with acoustic disturbances

Then the problem of interaction of a viscous shock layer with external acoustic disturbances propagating in the streamwise direction was solved. The variables on the left boundary were set as a superposition of the steady main flow and a planar monochromatic acoustic wave:

$$\begin{pmatrix} u' \\ v' \\ p' \\ \rho' \end{pmatrix} = A \begin{pmatrix} \pm\cos\theta \\ \mp\sin\theta \\ 1 \\ 1 \end{pmatrix} \exp\left[i\left(k_x x + k_y y - \omega t\right)\right].$$

Here u', v', p', ρ' are the fluctuations of the longitudinal and transverse velocity, pressure, and density, respectively, θ is the angle of propagation of the external acoustic wave, A is the disturbance amplitude, t is the time, $k_x = k\cos\theta,\quad k_y = -k\sin\theta$ are the components of the wave vector related to the frequency $\omega = 2\pi fL\ /c_\infty$ by the dispersion expression $k = \frac{\omega}{\left(M_\infty \cos\theta \pm 1\right)}$. In the above-given relations, the upper (lower) index corresponds to the fast (slow) acoustic wave. In dimensionless relations, the density and temperature disturbances are normalized to their free-stream values, the velocity perturbations are normalized to the velocity of sound in the free stream c_∞, and the pressure disturbances are normalized to $\rho_\infty c_\infty^2$.

The disturbance amplitude A equal to 0.028 was used in the computations, though the overall range of the amplitude was A= 0.001 ÷ 0.04. The angles of acoustic waves θ were chosen in the range from -10° to 45°. Angles smaller than -10° were not used because the shock layer in this case was in the "acoustic shadow" of the plate, and the problem of diffraction of acoustic waves on the leading edge of the plate was not considered.

2.3. Problem of interaction of the viscous shock layer with artificial disturbances

In the experiment, artificial disturbances in the form of periodic injection and suction were locally introduced from the leading edge of the plate. In the numerical solution of the problem, they were modeled by imposing the following boundary condition for the transverse flow rate at a certain part of the surface near the leading edge of the plate:

$$\rho v'\big|_{y=0} / \rho_\infty c_\infty = A \sin\left(\pi \frac{x - x_1}{x_2 - x_1}\right) \sin 2\pi ft$$

Here v′ are the velocity fluctuations in the direction normal to the plate surface, ρ is the local density, A is the amplitude, and x_1 and x_2 are the boundaries of the region where the controlled disturbances were introduced (the distance between these two values was 0.02). The symbol «∞» indicates free-stream parameters. Except for that, the computations were performed in the same manner as in the case of external acoustic disturbances [1,2].

After introduction of disturbances, the Navier-Stokes equations were integrated until the unsteady solution reached a steady periodic regime. The uniform grid used contained $N_x = 1050$ cells in the streamwise direction and $N_y = 240$ cells in the transverse direction. Up to 20 processors of the Siberian Supercomputer Center were used in the computations.

3. WIND-TUNNEL MEASUREMENT TECHNIQUE

The experiments were performed in a T-327A hypersonic nitrogen wind tunnel based at ITAM SB RAS at a Mach number M_∞ = 21, Reynolds number per meter Re1∞

= $6 \cdot 10^5$ m^{-1}, stagnation temperature T_0 = 1200 K, and wall (surface) temperature T_w = 300 K. The model used in the experiments was a flat plate 240 mm long with a sharp leading edge 100 mm wide, and width of the trailing edge of 80 mm.

Natural disturbances, acoustic waves emitted by the turbulent boundary layer near the nozzle throat. The mean density distributions and the amplitude spectra of density fluctuations at different points of the shock layer were measured by the electron-beam fluorescence technique. The details of the electron-beam measurement technique can be found in [3]. The measured spectra of density fluctuations (Fig.2a) within the shock layer made it possible to calculate the growth rate of density disturbances along the plate.

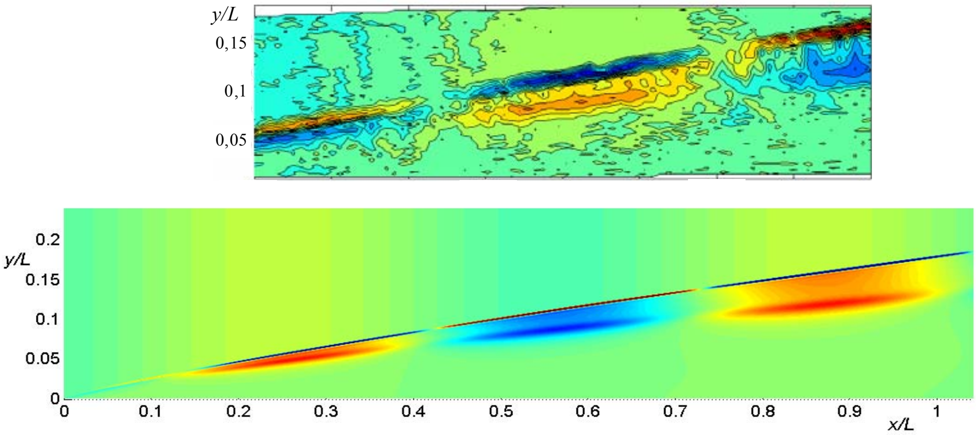

Figure 2. Flow of instantaneous density fluctuations in experiment (a) and on the basis of computation (b) for external slow wave at a frequency *f*=9 kHz.

Artificial disturbances, periodic disturbances were introduced into the shock layer by an oblique cylindrical gas-dynamic whistle located under the plate in the vicinity of the leading edge [4]. Based on these data, the fields of density fluctuations were constructed to be compared with the computed results; an example is shown in Fig. 3.

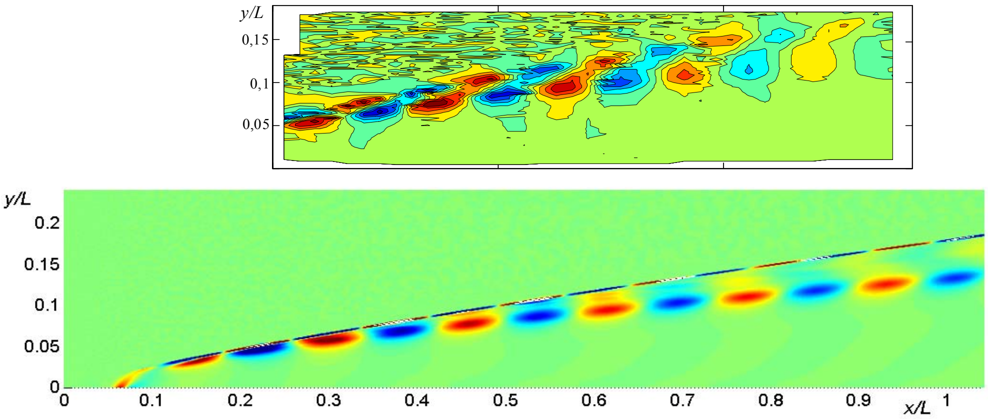

Figure 3. Flow of instantaneous density fluctuations in experiment (a) and on the basis of computation (b) for disturbances induced by a whistle (periodic blowing-suction) at a frequency *f*=40 kHz.

4. RESULTS

In a hypersonic shock layer under the action of external acoustic waves of slow and fast modes and of artificial disturbances in the form of periodic blowing-suction, the main wave processes occur on the shock wave and on the upper boundary of the hypersonic boundary layer (BL) with vortex disturbances dominating [1-2]. The fluctuating characteristics of the flow in the hypersonic shock layer have a typical form with two maximums; the greater maximum is located on the SW, and the location of the second maximum coincides with the BL edge (Fig. 2). This is clearly seen both in the field of instantaneous contours of density fluctuations (Fig. 3b) and in the distributions of the mean-square fluctuations (Fig.2b).

Excellent agreement of mean density, total pressure, and Mach number distributions across the shock layer resulted from the numerical simulations and experiments has been observed. Also, computational and experimental results are compared very favorably for the streamwise amplitude variation of instability waves, their growth rates, and their distributions across the shock layer − see Fig. 4. The simulations of density fluctuations turned out to be in good agreement with the computations by the locally parallel linear stability theory with allowance for the influence of the shock wave [5] for the wall temperature of the model T_w = 300 K.

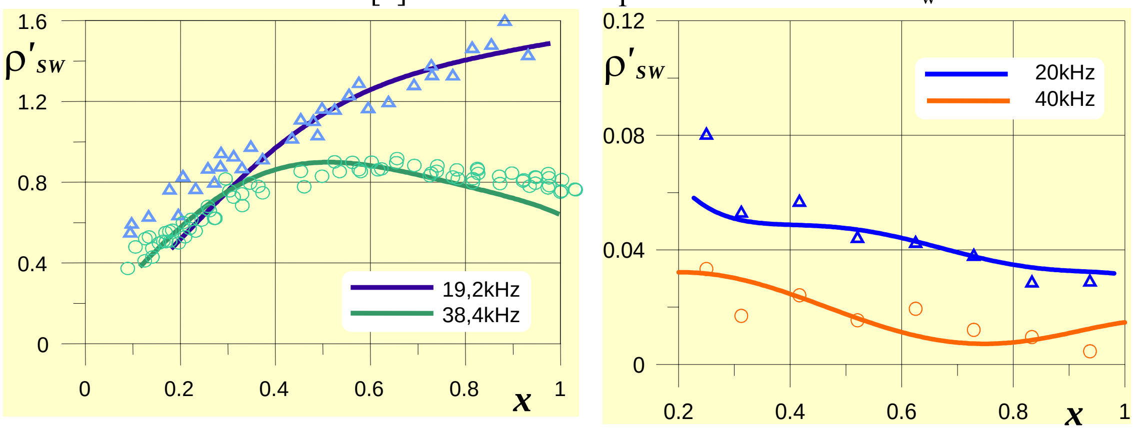

Figure 4. Evolution of disturbances excited by acoustic waves (a) and by blowing-suction (b) of different frequencies in numerical simulations (solid line) and experiments (symbols).

A parametric study of the characteristics of the field of disturbances in a hypersonic shock layer is performed for a varied angle of propagation and frequency of external acoustic disturbances [6], with varied intensity and frequency of the injection-suction disturbances and location of the source of disturbances with respect to the leading edge of the plate [7].

Numerical simulations show that, in addition to the conventional receptivity mechanism, amplification of disturbances crossing the shock wave is of great importance for generation of hydrodynamic instability waves at high Mach numbers. Two maximums of density fluctuations in the shock layer are observed; one of them is located on the shock wave itself, and the other is located in the region of rapid variations of the mean temperature and density near the external edge of boundary layer. Visualization of the numerical results displays pairs of counter-rotating vortices between two maximums. It seems that vortical disturbances play a dominating role in the development of shock layer instability. This is in agreement with the linear theory of interaction of small disturbances with a shock wave by McKenzie and Westphal (1968), which predicts, at the present conditions, that no acoustic disturbances is transmitted across the shock wave and the shock wave oscillations resulted from its interaction with external sound waves should generate in the shock layer only entropy-vortical disturbances.

The control of boundary layer laminar-turbulent transition is of great importance for design of perspective hypersonic vehicles. Numerical simulations show that the characteristics of instability waves generated by a blowing-suction (Fig.5b) are similar to those excited by the external acoustic field (Fig.5a). As a result, blowing-suction of the corresponding amplitude and phase can be used to delay significantly, by means of destructive interference, the development of the shock layer instability. The effect of instability suppression has been demonstrated numerically (see Fig.5c) and later confirmed in experiments with controlled disturbances.

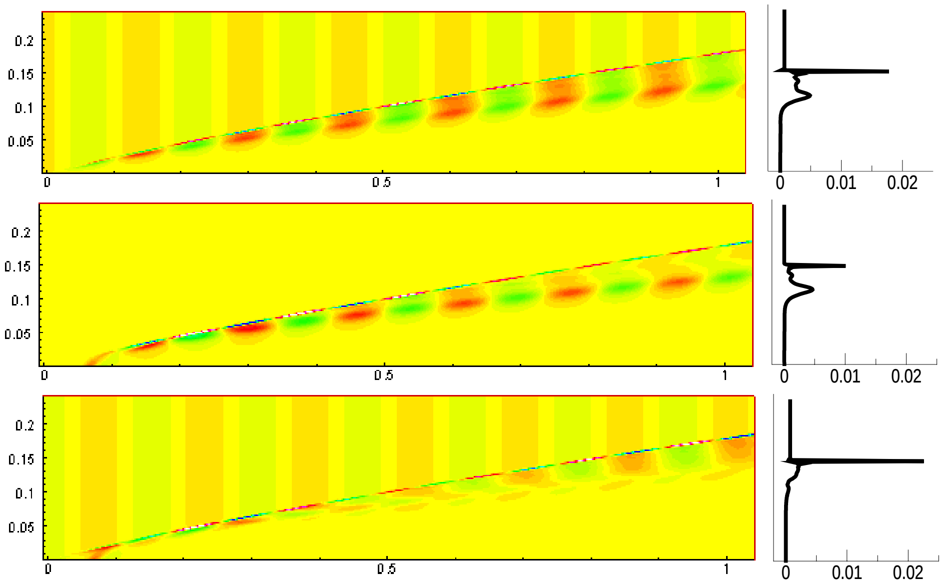

Figure 5. Evolution of disturbances excited by slow acoustic waves (a) and by blowing-suction (b) and by both in opposite phase (b).

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