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Investigation of controlled disturbances development from two sources in supersonic boundary layer

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Abstract
The paper presents experimental results and results of direct numerical simulation of the development and interaction of controlled disturbances from two point sources in a supersonic flat-plate boundary layer at Mach 2.5. For the introduction of controlled disturbances into the boundary layer, the normal component of the mass flow rate was varied in the calculations. In the experiment, periodic glow discharges at a frequency of 20 kHz were used. The work presents a comparison of experimental and theoretical calculated data. The paper discusses the effects inherent in the interaction of unstable controlled disturbances from two sources operating synchronously.

1. Introduction

Laminar-turbulent transition in the boundary layers is one of the fundamental problems in fluid dynamics, which has great practical significance. One of the most informative methods for the experimental study of laminar-turbulent transition in boundary layers is the initiation of artificial pulsations. Controlled input of artificial disturbances with given parameters allows one to study their development and compare them with the results of the theory and calculations. Today, for the case of supersonic flow velocities in the boundary layer, single localized sources are most often used to excite controlled disturbances. Controlled disturbances from them have a wide wave spectrum, which allows to study the development of disturbances with different angles of inclination. Such an approach is effective in studying linear and weakly nonlinear evolution of disturbances both in the boundary layer on a flat plate and on a swept wing [1, 2].

Earlier, in studies at low subsonic flow speeds with the help of several sources, attempts were made to simulate the interaction of disturbances, as well as to control the laminar-turbulent transition process. In [3], in the boundary layer of a flat plate, Tollmien-Schlichting waves were introduced from a vibrating ribbon and from a number of holes or a slit on the model surface. It was found that, depending on the phase relation between the introduced disturbances, it is possible to control the position of the transition point from laminar to turbulent flow. In addition, the method of generating disturbances from several localized sources is effective in studying the mechanisms of interaction of disturbances. Thus, in [4], it was found that stationary waves are amplified in the separation zone on a flat plate model and high-frequency pulsations are excited when controlled disturbances are introduced through two slits on the model surface.

For the case of supersonic flow velocities, as in the subsonic case, the study of laminar-turbulent transition using controlled disturbances from several sources seems promising. Such an approach was used in [5], where in the boundary layer of a cone, using a set of localized sources of controlled disturbances, instability waves were generated as the most growing waves according to the linear theory. However, in this work, measurements were carried out only for different values of the longitudinal coordinate and the wave spectrum of the disturbances was not determined. For the development of the method of generation of controlled disturbances by several localized sources in the boundary layers at supersonic flow velocities, detailed studies are needed. The purpose of this work is to experimentally and numerically simulate the development and interaction of traveling unstable disturbances from two localized sources in a supersonic boundary layer on a flat plate at Mach number 2.5.

2. Numerical and experimental setup

During the calculations, the motion of gas is described by the known Navier-Stokes, continuity, energy and state equations. In this calculations c_p = 1006.43 J/kg·K (c_p – specific heat at a constant pressure) and thermal conductivity

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was taken in according to the kinetic theory. The temperature of the main flow was set equal T_r = 128.8 K. Mach number was taken M = 2.5, pressure was equal to 4800 Pa and it corresponded to unit Reynolds number $Re_1 = (U\rho/\mu)_\infty = 8\cdot10^6$/m.
The computational domain is schematically presented in Figure 1. A′BCD′ is the plate with the disturbance sources. The following coordinate system was used in the calculations and experiment: the *x*-axis is aligned with the incoming flow, the *z*-axis is parallel to the leading edge of the model, and the *y*-axis is normal to the plate surface. The origin of the coordinate system was located on the leading edge, and the value *z* = 0 mm corresponds to the symmetry line of the model (see Fig. 1). Sources of controlled disturbances were holes with a diameter of 1 mm on the surface of the model. In the calculations, two sources of disturbances that are 6 mm apart from each other and located at *z* = ±3 mm. The sources were installed at a distance of 30 mm from the leading edge of the model. Length of a plate equaled 140 mm, before a plate the area of 5 mm was set. Conditions of an adiabatic wall were realized on a plate. Height of the computational domain approximately corresponded to about 20 mm, and on the upper border (EFGH) nonreflecting boundary conditions were laid down. Width of the domain was set equal 40 mm, and it was enough that controlled disturbances from the source extinguished on lateral borders. Moreover, on the sides ABHE and DCGF there are non-reflecting boundary conditions, which means that the fluctuations on the walls were set equal to zero during the calculation. In this case, the side walls were installed at such a distance along the *z*-axis, so that they did not affect the disturbances excitation and development downstream. Conditions of the oncoming flow were laid down on border ADFE. Exit conditions were set on the border BCGH.

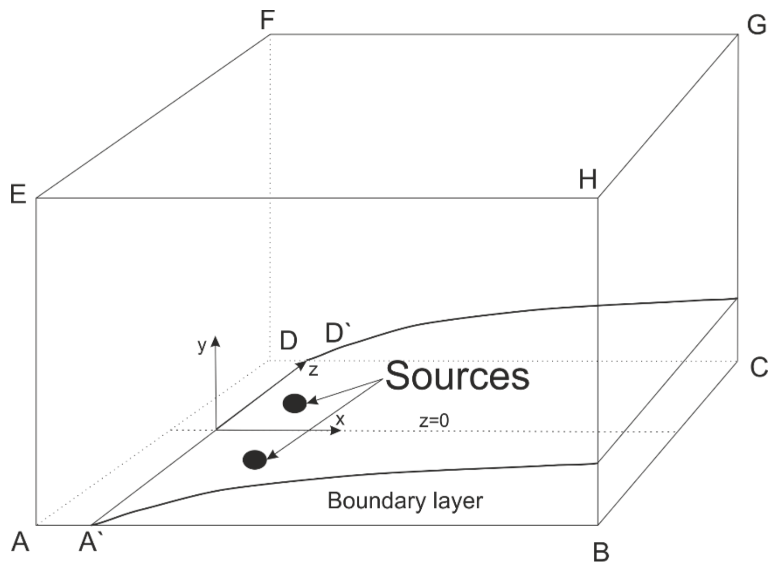

Figure. 1 Scheme of flat plate model, coordinate systems used, sources and computational domain

In this work, the following structured grid was chosen: the quantity of cells on *x*-coordinate was equal 1200, on *z* – 200 and on *y* – 400. Also, the condensation at the surface of the model on *y*-coordinate was used. For the solution of the task the program complex ANSYS was used [6]. To solve the three-dimensional Navier-Stokes equations in the framework of this problem, we used a density-based solver and an implicit scheme of MUSCL of the third order. The splitting of convective flows was made with using the AUSM method. The problem was solved in two stages. At the first stage, the stationary problem was solved. At the second stage, the task was solved in the presence of a periodic disturbances, which were created by the air injection through a holes. Disturbances were a normal component of the mass flow, whose amplitude was distributed in time by law $|\sin(2\pi ft)|$, where f=10 kHz. It means that disturbances at a frequency of 20 kHz from each source of disturbances are introduced into the boundary layer. Note that this article discusses the synchronous operation of two sources. This means that the phase shift was chosen to be zero. Duration of calculation equaled 1000 microseconds, the time step was equal 10^{-2} μs.
Experiments were performed in a T-325 long-duration blowdown low-noise supersonic wind tunnel, at the Institute of Theoretical and Applied Mechanics, Siberian Branch of the Russian Academy of Sciences, at Mach number M = 2.5 and unit Reynolds number $Re_1 = (8\pm0.1)\cdot10^6$ m^{-1}. A steel flat plate with a sharp leading edge and a couple of localized sources of controlled disturbances were used as an experimental model. The plate had the following dimensions: width – 200 mm, length – 370 mm, thickness – 10 mm. The leading edge thickness did not exceed 0.1 mm. The model was fixed in the central plane of the test section at approximately a zero angle of attack with an alignment error of 0.06°.
According to the calculations, two sources of controlled disturbances were located at a distance of 30 mm from the leading edge of the model at values of the transverse coordinate *z* = ± 3 mm. The design of each source is similar to those used in the works [1, 2]. A discharge chamber located inside the model and connected with the boundary layer

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through a hole of 0.4 mm diameter was used. An electrode inserted was installed inside the camera and was isolated from the model. The discharge was ignited when the sufficient voltage between the electrode and the model is achieved. To excite controlled disturbances inside the sources, a glow discharge was ignited at a frequency of approximately 20 kHz. The ignition circuit is shown in Figure 2. It consists of a high voltage source, ballasts for limiting the discharge current and two high-voltage high-speed switches. Control of switches is performed using a two-channel pulse generator. The generator creates pulses with a duration of approximately 10 μs with a repetition rate of 20004.6 Hz. The generator channels, as in the calculations with two sources, were synchronized (phase shift was set to 0°). When the signal comes to the switch, it opens and the parasitic capacitance of the source of controlled disturbances starts charging. When the breakdown voltage is reached, a glow discharge is ignited, during burning of which the voltage drop across the electrodes remains constant. After 10 μs, the switch receives a zero signal and it closes, and the discharge is interrupted.

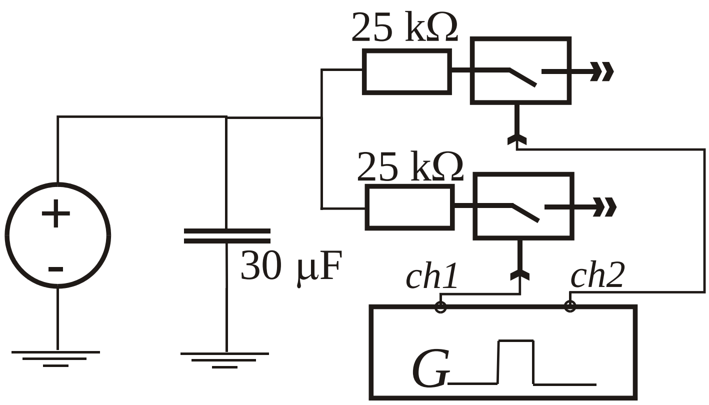

Figure. 2 The ignition circuit

Pulsations in a supersonic flow were measured using constant-temperature hot-wire anemometer (CTA). A tungsten wire of 10 μm in diameter and 1.7 mm in length was used. The overheat rate of the hot-wire probe was set to 0.7–0.8, and it means that the measured disturbances up to 95% consisted of mass flow fluctuations (m'). The dc output voltage (E) of the anemometer was measured with an Agilent 34401A digital voltmeter. The anemometer pulse signal (e') was digitalized with a 12-bit analogue-digital convertor (ADC). The ADC sampling frequency was 750 kHz. At each measurement point, 8 signal realizations of 65536 points were recorded synchronously with the discharge ignition. Non-dimensional mass flux pulsations were calculated using the following formula:

$$m'(t) = \frac{(\rho U)'}{\overline{\rho U}} \approx \frac{e'(t)}{S_{\rho U} \cdot E}, \qquad \textbf{(1)}$$

where $\overline{\rho U}$ is the local mass flux, $S_{\rho U} \approx 0.25 \pm 0.01$ is the hot-wire probe sensitivity for mass flow pulsations. The stagnation temperature during the experiments was in the range 283–288 K. Therefore, the variation of the overheat ratio of the hot-wire probe was insignificant.

Hot-wire probe was installed in the supersonic part of the boundary layer in the region of the maximum level of disturbances. This allows us to use the calibration of the hot-wire anemometer obtained in supersonic flow. In this layer mean mass flow is about $\overline{\rho U} \approx 0.7(\rho U)_\infty$. A trajectory of the probe was parallel to the leading edge at a constant distance to the plate surface. Cross section was measured at x = 100 mm from the leading edge. The probe was moved in the z-directions with the help of traversing gears with which the wind tunnel was equipped.

The spectral analysis was conducted to obtain the detailed information about the evolution of the controlled disturbances. The wave spectra are analyzed.

3. Results

Calculations were carried out with a single source of disturbances located along the center line of the plate symmetry (x = 30 mm from the leading edge of the model, z = 0 mm) and for the case when two sources of disturbances worked synchronously. Figure 4 shows the isolines of total disturbances (for all frequencies) in section x = 100 mm from the leading edge of the model in both cases. Here is the ratio of the instantaneous amplitudes of the mass flow rate pulsations to the average mass flow rate locally. Solid red lines – positive amplitudes, dotted blue – negative. The step

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between the lines is 0.001%, the maximum value of the amplitudes of the isolines in absolute value is 0.011%. In isolines, there is a positive and negative defect of the mean flow. An expansion of the wave trains and its spreading towards positive and negative values of the transverse z-coordinate is observed. In the case of a single source of disturbances, the formation of side "petals" is observed downstream, having a slope in the coordinates (t, z). In the case of two sources of disturbances, "petals" are formed in the region $|z| > 3$ mm, in the place where there is no influence from the neighboring source of disturbances. In the central part of the computational domain (near $z = 0$ mm), one can see the disturbances interaction downstream. In this case, it is a sequential alternation of positive and negative defects of mass flow. Note that in the case of synchronous operation of sources, the pattern of isolines is symmetric about the center line $z = 0$ mm.

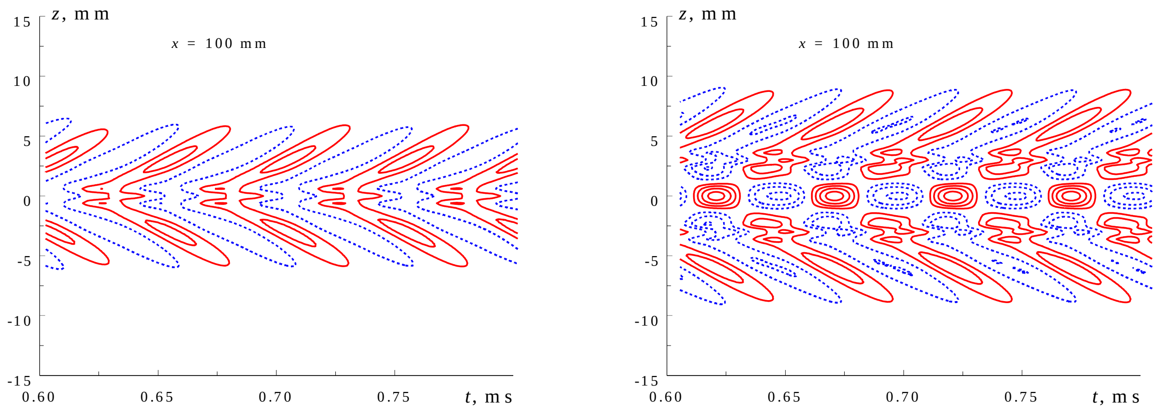

Figure. 4 Isolines of total disturbance amplitudes for single discharge (left) and two discharges working synchronously (right)

The discrete Fourier transform and corresponding β-spectra of the development of disturbances downstream are presented in Figure 5. In the case of a single discharge, there are two symmetric maximum perturbations located at $\beta = \pm 1.08$ rad/mm, which grow downstream. This is consistent with experiments on a flat plate under controlled conditions [1]. Another picture in the β-spectra is observed for two sources of disturbances operating synchronously. Thus, again there is an increase in the amplitude of disturbances, but we can see the presence of several maxima in the β-spectra, as well as several nodes where the amplitude of the disturbances is almost zero, namely at $\beta = \pm$ 0.52, 1.56, 2.6, 3.68 rad/mm. In a simplified form, this effect can be explained as follows: in the boundary layer, the disturbances at the point (x, z) are the sum of monochromatic waves from two sources

$$\sum_i A_i \sin(2\pi f t + \beta_i(z - z_0) + \alpha_r x) + \sum_i A_i \sin(2\pi f t + \beta_i(z + z_0) + \alpha_r x), \quad \textbf{(2)}$$

where the amplitude $A_i(\beta_i)$ is determined after the Fourier transform and where the summation is performed over all transverse wave numbers β_i, z_0= 3 mm - source positions. According to the known formulas, the formula (2) can be reduced to the form:

$$2\sum_i A_i \sin(2\pi f t + \beta_i z + \alpha_r x)\cos(\beta_i z_0). \quad \textbf{(3)}$$

Under the sign of summation, the expression $\sin(2\pi f t + \beta_i z + \alpha_r x)$ defines the spectrum from a single source. $2\cos(\beta_i z_0)$ determines the modulation of the spectrum of a single source upon transition to the disturbance spectrum from two sources operating synchronously. So, it is possible to determine the nodes in the beta spectrum, based on the expression:

$$\beta_i^0 = \frac{\pi}{2z_0} + \frac{\pi n}{z_0}, \quad \textbf{(4)}$$

where n is an integer. This expression gives the values ±0.52, 1.57, 2.61, 3.66 rad/mm, which is in accordance with the values obtained in the calculation. Also, the presence of a factor of 2 explains the observed doubling of the amplitude of the main peak. Note here, that other wave characteristics of wave trains development from a single source and two sources operating synchronously such as the dispersion dependence $\alpha_r(\beta)$ and amplification rates $\alpha_i(\beta)$ match with each

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other. Thus, for the most unstable disturbances at $\beta = \pm 1.08$ rad/mm, the angle of inclination of the wave to the oncoming flow is ±71°, which is again in agreement with the results on a flat plate [1].

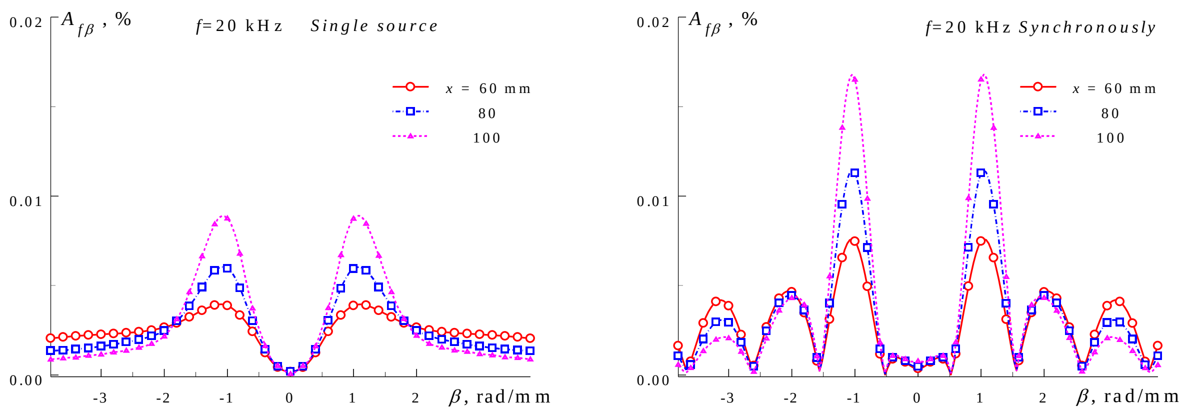

Figure. 5 Amplitude β-spectra of disturbances at f = 20 kHz for single discharge (left) and two discharges working synchronously (right)

The experiments also took place in conditions when the sources of disturbances worked synchronously and with single discharge. In both cases disturbances were measured at a distance of x = 100 mm from the leading edge. The measurements were performed in the supersonic part of the boundary layer in the region of the maximum level of pulsations. The anemometer probe moved parallel to the leading edge of the model.

Amplitude spectra of disturbances for transverse wave numbers β for x = 100 mm are presented in Figure 6 for single discharge and two discharges working synchronously. In aim for comparison, Figure 6 shows both experimental data and data obtained using DNS. In the case of a single discharge, it can be seen that the spectra in the calculation and experiment have the same shape with two symmetric peaks, which is in accordance with [1]. Note, that in experiments, controlled perturbations are distinguished in the range of wave numbers β = -2.5–2.5 rad/mm. Outside this range, the amplitude of the controlled disturbances is much less than the natural pulsations of the boundary layer. We also note that the amplitude of controlled disturbances in direct numerical simulation is much less than in experimental studies. Nevertheless, in the results with two sources working synchronously, there is also a qualitative agreement between experimental and calculated data. In the experiments, there are several maxima in the beta spectrum, as well as several nodes, where the amplitude of the disturbances is small. The values of wave numbers β of nodes and antinodes in experiment and calculations are close.

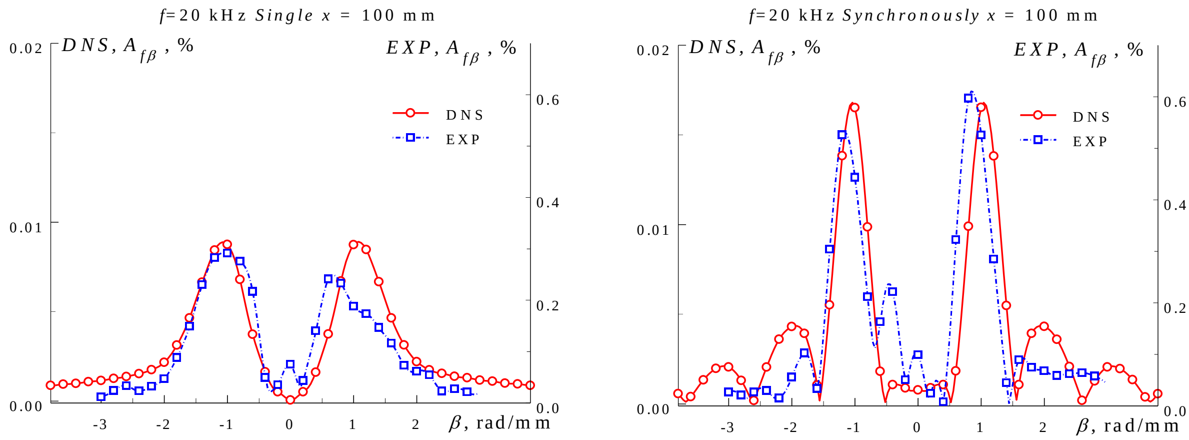

Figure. 6 Amplitude β-spectra of disturbances at f = 20 kHz in experiment and DNS for single discharge (left) and two discharges working synchronously (right)

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4. Conclusion

A numerical and experimental study of the development and interaction of controlled disturbances from two point sources in a supersonic boundary layer on a flat plate with a Mach number 2.5 has been carried out. In the case of a single source of pulsations, the characteristics of the development of a wave train, obtained in calculations and experiment are in accordance with previously performed experiments in a supersonic boundary layer on a flat plate. In the case of two sources of disturbances operating synchronously, the calculations revealed the effect of the interaction of two wave trains, which resulted in the formation of a characteristic interference pattern in the β-spectra with a set of several nodes and antinodes. Experimental results revealed the same effect and are in accordance with the calculations in the framework of direct numerical simulation.

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