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Experimental Investigation of the Structure of Disturbances from Two Pulsed Sources in the Flat-Plate Supersonic Boundary Layer

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Abstract—The work is devoted to the development of a new experimental method for entering controlled disturbances with a given frequency-wave structure into a supersonic boundary layer. Experimental data on the formation of disturbances from two pulsed sources (pulsed glow discharge) in the laminar flat-plate boundary layer at the Mach number equal to 2 are given. The experiments were carried out in the T-325 wind tunnel of ITAM SB RAS. The localized sources were spaced out at the same distance from the leading edge of the plate at 6 mm from each other spanwise. Flow pulsations were measured using a hot-wire probe of constant temperature anemometer, the signal was recorded synchronously with ignition of the discharges. This made it possible to distinguish the pulsations from the discharges against the background of random uncontrolled "natural" pulsations of the boundary layer. The spatial-temporal and frequency-wave structure of the generated disturbances from a single or two discharges, operating synchronously or with a time delay, are analyzed. It is found that the maximum difference in the structure of disturbances from one and two sources is observed in the central region, while at the side boundaries of the disturbances, the pulsations are close in all considered cases. In the wave spectra of disturbances from two discharges, nodes and antinodes are formed. Their position is determined by the distance between the sources and the time delay in their operation.

Keywords: experiment, supersonic boundary layer, source of controlled disturbances, pulsed glow discharges

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At present, it is generally accepted that the transition of a laminar boundary layer to the turbulent state is a complex process of the onset (excitation) of disturbances of various types, their development, interaction with each other and mean flow that leads to the turbulent regime. One of the approaches to studying the development of turbulence in boundary layers is the experimental study of the evolution of controlled disturbances. Disturbances with fixed initial parameters are introduced into the flow, which makes it possible to determine the wave characteristics of the development of disturbances and carry out a quantitative comparison with the results of calculations. In experiments at supersonic flow velocities, the most developed method for excitation of controlled pulsations is the glow discharge ignited in a local region of the experimental model. In the case of periodic discharge ignition, a disturbance is formed in the boundary layer, which has a narrow frequency and a wide transverse wave spectrum (wave trains). This approach makes it possible to study the early stages of the laminar-turbulent transition in two- [1–3] and three-dimensional [4, 5] supersonic boundary layers. In the case of the pulse action, a disturbance (wave packet) localized in space and time is formed in the boundary layer; this approach makes it possible to study the development of disturbances in a wide frequency-wave spectrum. In experiments [6–9], localized perturbations were introduced into the supersonic boundary layer using a pulsed glow discharge ignited on the surface of the model.

Detailed numerical and experimental studies are required to determine the mechanisms of interaction of disturbances at the late stages of the laminar-turbulent transition in high-speed boundary layers. In problems of studying the nonlinear stage of development, the initial structure of pulsations can play an important role. In the numerical studies the initial disturbance can be specified using dynamic boundary conditions, while it is possible to set the parameters of disturbances at the input. In the calculations, spatially localized disturbances sources that have a wide transverse wave spectrum are also used. Similar to experiments, both periodic [10] and localized [11–13] in time impact on the boundary layer is considered. Another approach [14] is as follows: waves or wave packets are specified and their parameters are calculated according to the linear theory of stability [15, 16], or pulsations characteristic of flight conditions are introduced [17]. Correct experimental modeling requires a method of excitation of controlled disturbances in the boundary layer, such that the disturbance parameters (amplitude, frequency and transverse-wave composition, phase ratios of spectral components, etc.) could vary over a wide range. The methods used today at high velocities, which are based on a single localized source, do not make it possible to control all the parameters. A possible way is the excitation of controlled disturbances by a complex of several spaced sources which allow to shift the phases of the source signals in time.

At low subsonic flow velocities, multicomponent disturbance sources are successfully used in studies of the laminar-turbulent boundary layer transition. For the first time, such an approach at subsonic flow velocities was applied in [18], where the effect of superposition and subtraction of controlled disturbances was shown. Further development of this approach led to the creation of a multicomponent disturbances source, with the help of which perturbations with initial parameters varied over a wide range are introduced into the boundary layer [19–21].

In the case of high free-stream velocities, the approach of multicomponent sources of controlled disturbances is much less developed. In [22], several electric discharges were used as a source of periodic controlled perturbations. The discharges were located uniformly on the surface of the cone in the azimuthal direction and operated synchronously at a certain frequency. It was assumed that such a system of sources would generate controlled disturbances with a distinguished peak in the wave spectrum. However, the paper does not provide detailed data on the frequency-wave structure of the generated disturbances.

In [23], computational and experimental studies were carried out on the development of controlled periodic disturbances with a narrow frequency spectrum generated in the flat-plate boundary layer by two point sources. In the case of synchronous operation of two sources, the formation of nodes and antinodes in the wave spectra was observed, a shift in the position of nodes and antinodes in the wave spectrum being observed in the presence of a phase shift. This corresponds to the interference of waves generated by separated sources of disturbances. The studies have shown that the structure of controlled periodic disturbances introduced into the supersonic boundary layer may be modified by changing the operating source parameters.

In [24], the formation and development of disturbances from two synchronous pulsed sources in the laminar boundary layer on a plate were simulated numerically at the Mach flow number M = 2. The sources were located on a line parallel to the leading edge. The studies were carried out in the case of a single and two synchronous pulsed sources at various distances between them. It was found that in the cases under consideration, the growth of disturbances downstream depends on the distance between the sources. It was shown that this is due to the appearance of disturbances in the wave spectra of nodes and antinodes at all frequencies. This can be described by the interference of waves from sources. The position of nodes and antinodes is determined by the distance between the sources, which determines the wave structure of disturbances and their development in the physical space.

The aim of the present study is to develop the experimental method for entering controlled localized perturbations into the supersonic boundary layer with the possibility to modify their frequency-wave structure using two sources. The data of experimental studies of the space-time and frequency-wave structure of disturbances from a single and two pulsed discharges, operating synchronously or with a time delay, in the supersonic flat-plate boundary layer at the Mach number equal to 2 are given.

EXPERIMENTAL SETUP

The experiments were carried out in the T-325 supersonic wind tunnel of ITAM SB RAS. The flow parameters are as follows: the Mach number M = 2, the unit Reynolds number $Re_1 = \rho_\infty U_\infty/\mu_\infty = (6 \pm 0.1) \times 10^6\ m^{-1}$, where ρ_∞, U_∞, and μ_∞ are the density, the velocity and the viscosity in the free-stream flow. The flow stagnation temperature is $T_0 = 295 \pm 1$ K. In Fig. 1 we have reproduced the diagram of the experiment. The studies were carried out on a flat-plate model with the sharp leading edge, installed in the test section at zero angle of attack. The width of the model was equal to 200 mm (full width of the test section of T-325) and the length was equal to 370 mm. The x-coordinate was directed along the flow and reckoned from the leading edge of the model, the z-coordinate was directed along the model edge and is reckoned from the middle of the model. In T-325, at the specified flow parameters, on the flat-plate

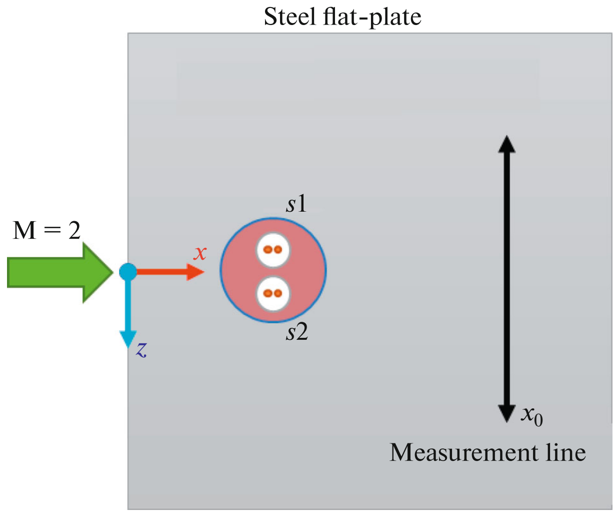

Fig. 1. Diagram of the experiments.

model with the sharp leading edge, laminar-turbulent transition is observed at the Reynolds number, calculated on the thickness of the boundary layer, $\mathrm{Re}_\delta = (\mathrm{Re}_1 x)^{0.5} > 1100$.

The experimental model was equipped with two sources of controlled disturbances. The sources were located in the central region of the model at 30 mm from the leading edge ($\mathrm{Re}_\delta \approx 424$). The distance between the sources was equal to 6 mm (source coordinates $z_{s1,2} = \pm 3$ mm). Such a distance is justified by the technical possibility of installing sources on the model, the characteristic scales of localized disturbances generated by similar sources (10–20 mm in the transverse direction [7, 8]), and calculations [24] in which the maximum increase in small-amplitude disturbances was obtained. The source of perturbations is a pulsed glow discharge ignited between two electrodes isolated from each other and from the model. The insulator and electrodes are brought to the surface of the model and polished flush, the centers of the electrodes being located on a line parallel to the free-stream flow.

In Fig. 2 we have conventionally shown the scheme of ignition of the glow discharge. It is based on high-voltage DC switching using high-speed high-voltage keys controlled by pulse signals from a two-channel generator. In all the presented experiments, the discharge ignition frequency in the experiments was equal to 312.5 Hz, and the discharge duration was equal to 25 µs. In the experiments, the voltage drop across the electrodes during the discharge was 640–690 V, the discharge current was 14–16 mA. The high voltage on the electrodes and the discharge current indicate that in these studies the glowing discharge regime is observed. The electric energy on the discharge in a single pulse is equal to 0.2–0.3 mJ.

Pulsations and mean flow of the boundary layer were measured using a constant-temperature hot-wire anemometer. The hot-wire probe was made of single tungsten wire about 1.7 mm long and 10 µm in diameter. The wire overheating was 0.8; in this case, the hot-wire anemometer signal is associated mainly with the mass flow pulsations [25].

The mean hot-wire anemometer voltage was measured using a digital voltmeter. The pulsating signal of the hot-wire anemometer and the impulse signals controlling the ignition of the discharge were simultaneously recorded by a 4-channel analog-to-digital converter L-card E20-10. At each measurement point, four signal realizations were recorded, each about 0.4 s long, with the sampling frequency of 2.5 MHz for each channel. When processing the initial data, the recorded signals were divided into 520 realizations of the "flight" of disturbances from the discharge. Then the ensemble-averaged fluctuation traces were computed, which made it possible to isolate the controlled disturbances generated by the discharges from the background of random natural pulsations of the boundary layer. The hot-wire anemometer signal dividing was carried out along the fronts of the control signal.

In our studies the measurements with a hot-wire probe were carried out in the transverse direction (along the z-coordinate) at a distance of 80 mm ($\mathrm{Re}_\delta \approx 693$) from the leading edge of the experimental model in the supersonic part of the boundary layer in the region of the maximum level of natural fluctuations. In the measurement area, the mean mass flow rate was $\rho U \approx 0.7\rho U_\infty$, where ρU_∞ is the free flow mass flow rate.

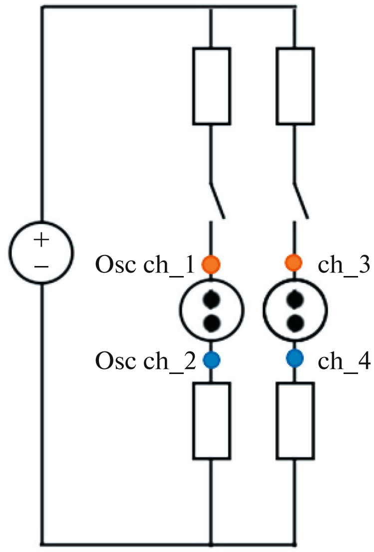

Fig. 2. Scheme of the discharge ignition.

From the measured data, the mass flow pulsations normalized by the mean local flow were determined as follows:

$$m'(t) = \frac{(\rho U)'}{(\rho U)_{\text{loc}}} \times 100\% = \frac{e'(t)}{EQ} \times 100\%,$$

where $e'(t)$ is the pulsating signal, E is the mean hot-wire anemometer voltage, and $Q = 0.25$ is the coefficient of sensitivity to mass flow fluctuations [25].

To study the frequency-wave structure of controlled disturbances excited by sources, the amplitude spectra of pulsations obtained using the discrete Fourier transform were analyzed. Also, the amplitude spectra were analyzed in terms of the transverse wave number β at various frequencies:

$$A_{f\beta}(f, \beta) = \left| \frac{\sqrt{2}}{T\delta_0} \sum_{l,k} m'(z_l, t_k) \exp(i2\pi f t_k - \beta z_l) \Delta t \Delta z \right|,$$

where $T = 1$ ms is the duration of the analyzed oscillograms and $\delta_0 = 1$ mm is the characteristic boundary layer thickness in the measurement region.

RESULTS

The measurements were carried out for four variants of source operation, namely, with a single source, with synchronous operation of two sources, and with a time delay of discharge ignition of 40 and 60 μs. In Fig. 3 we have reproduced experimental data in the form of isolines of mass flow pulsations in the (z, t) plane, measured at a distance of 80 mm from the leading edge of the model when one source, two synchronous sources, and in the case of sources with a time delay are operating.

In the case of a single source in the measurement region, the disturbances from the discharge in the transverse direction has the size of about 10 mm and is symmetric about the position of the source in the transverse direction ($z = -3$ mm). The following components can be distinguished in the disturbances structure: a central defect on the line behind the source ($z = -3$ mm), the maximum instantaneous deviation of the mass flow rate from the mean value is observed and amounts to about 19% of the local base flow; lateral negative pulsations with a maximum amplitude of about 3% at $z \approx 0$ and –6 mm, the front of these pulsations has a slope; positive pulsations with the maximum deviation from the mean flow at $z \approx -2$ and –4 mm. In general, the observed structure of disturbances from the single pulsed discharge agrees with previous experimental results [7, 8], despite the fact that the amplitude of the central defect differs, which is associated with a higher discharge energy in this work.

As for of a single source, in the case of synchronous ignition of two pulsed discharges at $z = \pm 3$ mm high-intensity flow defects generated by the discharges and negative and positive side pulsations can be

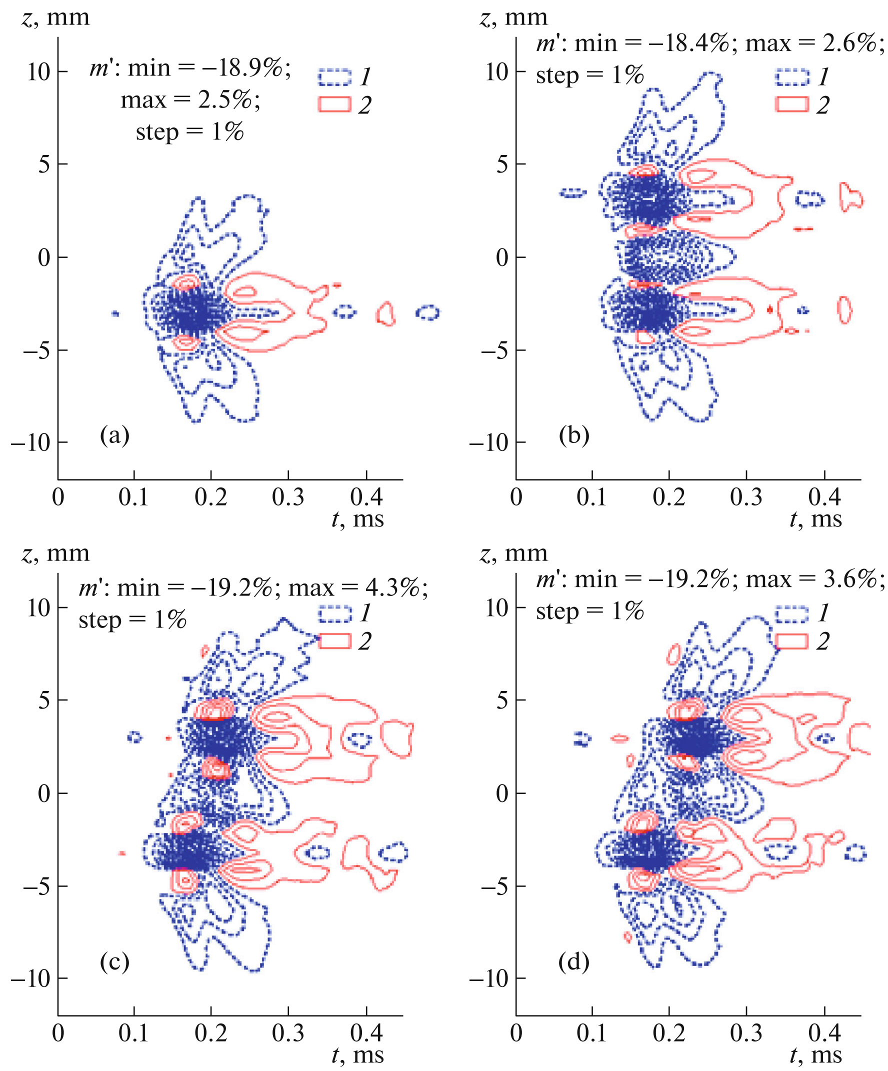

Fig. 3. Contours of the mass flow rate pulsations (m') in the (z, t) plane: a single source (a); two synchronous sources (b); two sources with a time delay of 40 μs (c); and two sources with a time delay of 60 μs (d), curves *1* correspond to negative pulsations and *2* to positive pulsations.

distinguished. In the neighborhood of $z = 0$ mm, the greatest difference in the structure of the generated perturbation from the case of a single source is observed; this corresponds to a defect with the maximum deviation from the mean flow of about 9%. At the outer boundary of the disturbance, the amplitude and shape of pulsations are unchanged. A similar picture, in which the differences in the structure of controlled disturbances are observed only in the region between sources, was also observed in numerical simulation of generation of disturbances from two pulsed sources in the supersonic boundary layer [24], as well as in studies of periodic disturbances from two sources [23].

In the presence of a time delay in the operation of pulsed sources (the discharge at $z = 3$ mm is ignited later than the discharge at $z = -3$ mm), differences in the shape of pulsations are also observed only in the region between the sources, and the disturbance as a whole becomes oblique.

In Fig. 4 we have reproduced the oscillograms of the mass flow rate pulsations (Figs. 4a, 4c, and 4e) and their amplitude-frequency spectra (Figs. 4b, 4d, and 4f) for various disturbance regions under different discharge operating modes. In the neighborhood of $z \approx -6$ mm (Figs. 4a and 4b), the pulsations have similar shapes in all cases. The pulsation amplitude coincides in the cases of ignition of one and two synchronous discharges, while in experiments with a time delay, pulsations with the higher amplitude are observed. This is due to the measurement error associated with the fact that the hot-wire anemometer probe was replaced with another one for the reason of destruction. This led to the need to re-set the position of the probe in the boundary layer and the position of the probe relative to the model surface was changed, i.e., the measurements were taken in a slightly different layer. The pulsation spectra are also similar in all cases. In this region, the frequency composition of the pulsations is limited to a range of up to 30 kHz. There is a peak in the frequency range of 12–30 kHz; according to calculations [24], the greatest disturbances growth is observed in this frequency range.

In the region $z \approx -3$ mm (Figs. 4c and 4d) which corresponds to the measurements behind one of the discharges, in all cases a high-intensity mass flow defect is observed. In all the regimes, this defect has the similar shape and amplitude. The frequency spectra are also similar in all cases. No distinguished peaks are observed in the spectra, and the amplitudes are significantly greater than the noise level only in the frequency range up to 40 kHz.

At $z \approx 0$ mm (Figs. 4e and 4f), where the greatest differences in the structure of perturbations from a single and two discharges are observed, in the case of a single discharge, the oscillogram of pulsations and the spectrum are similar in shape and amplitude to the results obtained at $z \approx -6$ mm (Figs. 4a and 4b). In the case of simultaneous ignition of the discharges, the shape of oscillograms and the frequency composition do not change, and the pulsation amplitude increases approximately by three times as compared to the case of a single discharge. The time delay in the discharge ignition leads to a modification of the shape and spectral composition of the disturbances. When the time delay is equal to 40 μs, the peak in the high-frequency (12–30 kHz) region of the spectrum is significantly shifted to the high-frequency region as compared to the cases of a single and two synchronous sources. With an increase in the time delay in the discharge ignition to 60 μs, no shift of this peak relative to synchronous ignition of the discharge is observed.

It can be concluded that in the case of two sources located in parallel to the leading edge, the maximum differences in the structure of perturbations from discharges as compared with the case of a single source are observed in the central region. In the studied configuration of sources, it is possible to influence on the amplitude-frequency composition of the generated disturbances using a time delay in operation of sources.

In Fig. 5 we have reproduced the frequency-wave spectra of the disturbances introduced into the boundary layer by discharges in the form of amplitude isolines in the (f, β) plane. In the case of a single source (Fig. 5a), thee waves with transverse wavenumbers in the region $\beta = \pm 1-2$ rad/mm, i.e., the waves inclined with respect to the free-stream flow, have the highest amplitude. It should be noted that in studies [24], performed by numerical simulation of the development of small-amplitude disturbances for close flow parameters in the flat-plate boundary layer, the most growing waves are with $\beta \approx \pm 0.9$ rad/mm. This differs from the most intense disturbance waves in these experiments. This difference may be due to the fact that in these experiments the disturbances are not small and their growth may exhibit non-linear effects. On the other hand, it is possible that the used source of controlled disturbances initially introduces a disturbance into the boundary layer, in which the waves with large β have high amplitude.

In the case of synchronous ignition of two discharges (Fig. 5b), antinodes and nodes are observed in the spectrum of controlled disturbances. Their positions are the same for different frequencies. A similar appearance of nodes and antinodes in the wave spectrum of disturbances was observed in calculations [24], while the values of β at which nodes are observed are the same as in these experiments.

In the presence of a time delay in the operation of sources of controlled disturbances (Figs. 5c and 5d), nodes and antinodes are also observed in the frequency-wave spectra, however, the values of the transverse projection of the wave vector β, at which they are observed, depend on the frequency. This dependence changes with variation in the time delay.

Nodes and antinodes in the wave spectra were observed earlier in numerical and experimental studies on the development of periodic [23] and localized [24] perturbations from two spatially separated sources in a supersonic boundary layer. The appearance of nodes and antinodes is attributable to the interference of waves from sources. A disturbance generated at a specific frequency by a single source can be represented as the sum of plane waves with various wavenumbers and amplitudes. Then the result of their superposition can be presented in the following for

$$\sum_j A_j \cos\left(2\pi f t + \beta_j (z - z_0) + \alpha_j x\right)$$
$$+ \sum_j A_j \cos\left(2\pi f (t + \tau) + \beta_j (z + z_0) + \alpha_j x\right)$$
$$= 2\sum_j A_j \cos\left(2\pi f \left(t + \frac{\tau}{2}\right) + \beta_j z + \alpha_j x\right) \cos\left(\pi f \tau + \beta_j z_0\right),$$

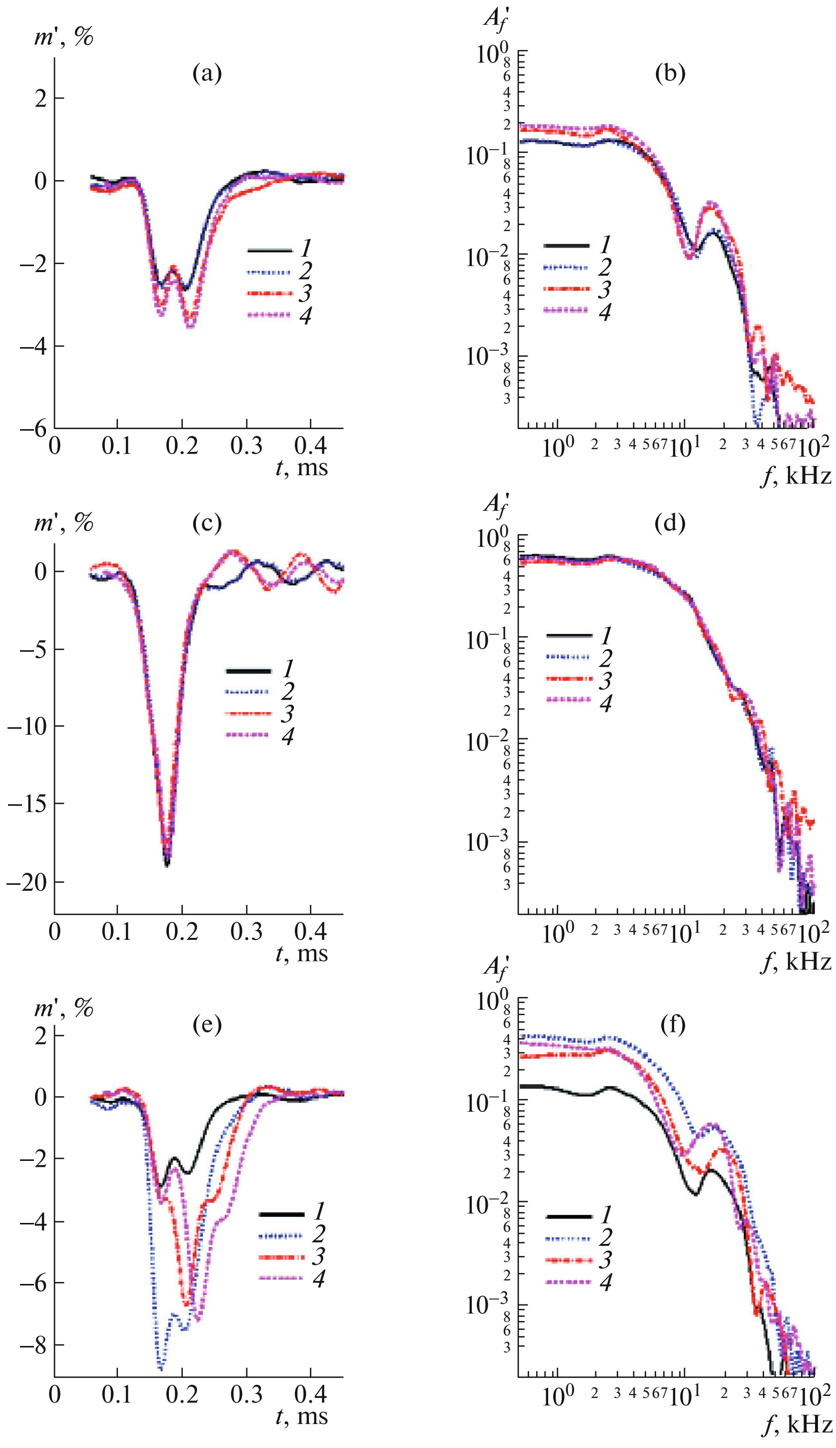

Fig. 4. Oscillograms (a, c, e) and amplitude-frequency spectra (b, d, f) of the pulsations for $z \approx -6$ (a, b), -3 (c, d), and 0 mm (e, f): curves *1* correspond to a single source, *2* to two synchronous sources, *3* to two sources with a time delay of 40 μs, and *4* to two sources with a time delay of 60 μs.

where α and β are the longitudinal and transverse wavenumbers, τ is the time delay in the source operation, and $z_0 = 3$ mm is half of the distance between sources. The last multiplier on the right-hand side of the expression determines the position of the antinodes and nodes in the wave spectrum. Their location in the spectrum is determined by the distance between the sources and the time delay in their operation. Zero amplitude (nodes) correspond to the values $\beta = \pi(0.5 + n - f\tau)/z_0$, where n is an integer, and the

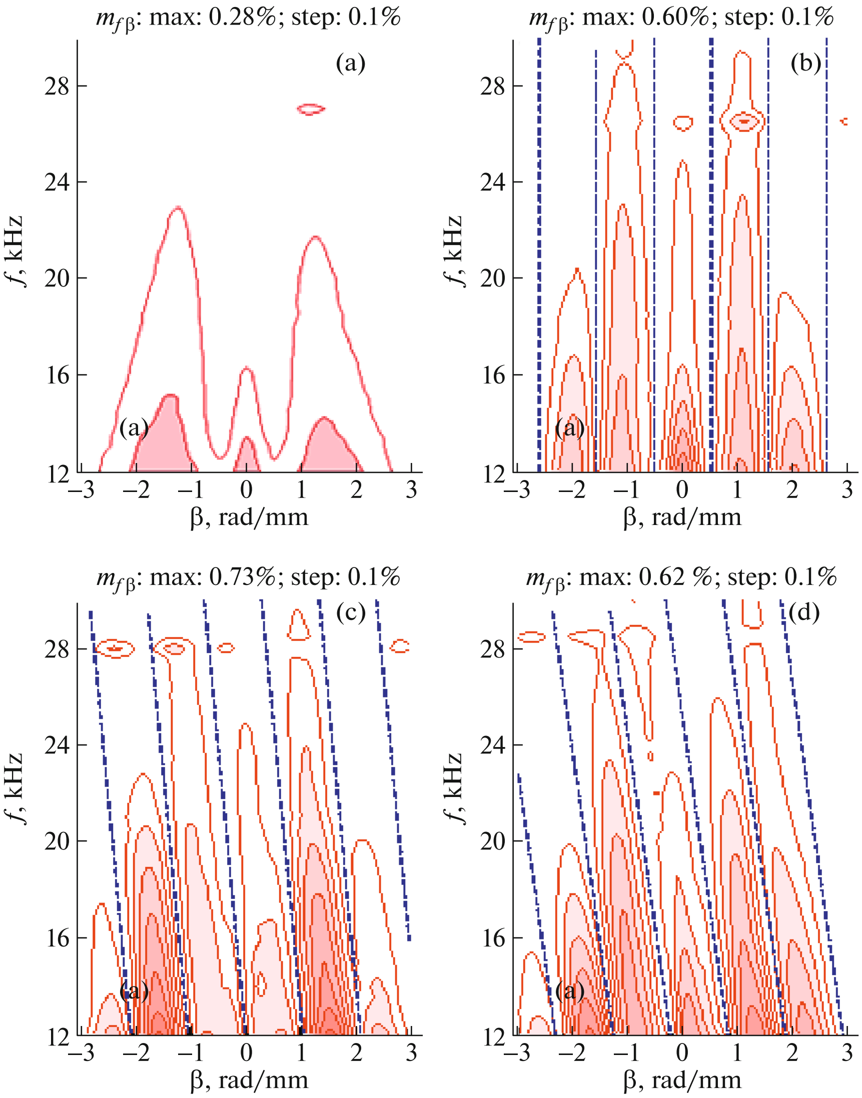

Fig. 5. Frequency-wave spectra of controlled perturbations: a single source (a), two synchronous sources (b), two sources with a time delay of 40 μs (c), and two sources with a time delay of 60 μs (d).

slope angle ϕ of the lines on which the nodes are located in the plane (f, β) can be defined as $\phi = \arctan[-z_0/(\pi\tau)]$. In Figs. 5b, 5c, and 5d, the results of calculating the position of nodes in the (f, β) plane are shown by dashed curve. As can be seen, in the wave spectra of disturbances from pulsed discharges, the position of nodes is in good agreement with the above calculations on wave interference.

Note that in [23, 24], in which the same effects were observed in the formation of controlled disturbances from two separated sources in the supersonic boundary layer, the investigations were carried out for small-amplitude disturbances whose development was consistent with the linear stability theory. In the experiments, the results of which are presented for the first time in this paper, the amplitude of disturbances is higher, but the nodes and antinodes are also observed, and their locations are well predicted by wave interference.

SUMMARY

A new method of generation of controlled disturbances in the supersonic boundary layer using two pulsed glow discharges has been developed. Experimental studies of the formation of localized perturbations from one and two sources in the flat-plate boundary layer at the Mach number M = 2 for various time delays in their operation have been carried out. Disturbance sources were located on a line parallel to the leading edge of the plate model.

It is shown that the maximum differences in the structure of disturbances from one and two sources are observed in the central region, while on the side boundaries of the disturbance the pulsations are similar in all cases considered. The time delay in the source operation leads to change in the amplitude-frequency composition of disturbances from discharges.

In the case of the operation of two sources, the nodes and antinodes are formed in the frequency-wave structure of disturbances whose position in the (f, β) plane is determined by the distance between the sources and the time delay in the discharge ignition. Qualitatively, this can be described by linear interference of waves from two sources. It has been experimentally shown that it is possible to modify the frequency-wave structure of controlled disturbances by varying the time delay in the discharge ignition.

Using the results obtained in this study, it is possible to configure the sources in such a way to introduce controlled disturbances of a complex frequency-wave spectrum into the boundary layer.

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