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EXPERIMENTAL STUDY OF STABILITY OF STRONGLY UNDEREXPANDED LAMINAR FREE AND IMPACT JETS

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The growth rates of density fluctuations in the mixing layer of strongly underexpanded low-density jets are measured by the electron-beam technique within the range of Reynolds numbers $\mathrm{Re}_L = 50$–230. *Regimes of self-induced oscillations are determined for these flow conditions in the case of a jet incident normally onto a finite-size target. Results on the frequency of pressure oscillations on the target are obtained and compared with the spectra of the growth rates of density fluctuations in the mixing layer of free jets. It is shown that self-induced oscillations cannot be sustained because of the development of instability in the mixing layer of the jet.*

Self-oscillatory interaction of supersonic gas jets with targets has been studied since late 1920s [1] and has found wide application in engineering. These oscillations arise for a certain combination of gas-dynamic and geometric parameters of the "jet–target" system. As a result of long-time experimental studies, detailed pictures of the motion of gas-dynamic discontinuities in the flow field of the jet were obtained, the distributions of static pressure and pressure oscillations on the target were measured, the regions of existence and the amplitude–frequency characteristics of oscillations were determined, and the effect of the Mach number and jet-pressure ratio on flow characteristics was studied. Nevertheless, despite the large volume of experimental data, the mechanism of sustaining oscillations in such jet systems has not been adequately studied. Actually, all models involved to explain this phenomenon are hypotheses on the mechanism of energy generation and feedback channel in a self-oscillatory system "jet–target." The mechanism of synchronization of the development of oscillations in the jet by the feedback channel is important both from the viewpoint of model representations of the process of self-induced oscillations and in using technologies and devices that employ the phenomenon of unsteady interaction of the jet with the solid surface.

Glaznev and Demin [2] and Powell [3] proposed models, where the energy of oscillations enters from an unsteady mixing layer, and the feedback is performed by acoustic waves propagating in the ambient medium from the target to the nozzle. Various mechanisms of sustaining self-induced oscillations were proposed in [4–7]; these models are based on the hypothesis on the inner channel of the feedback of the self-oscillatory system. The main processes are developed in the region between the normal shock wave and the target.

The models may be verified by analyzing the effect of ambient conditions on the amplitude–frequency characteristics of self-induced oscillations and phase relations between the time-dependent positions of the elements of the gas-dynamic flow structure (shock waves and jet boundary) and individual flow parameters (pressure on the target and nozzle edge). The corresponding experiments were performed in [8–11]. In [8–10], the chain of external feedback was broken by screening the jet root from the acoustic field generated by the jet hitting the target. In [11], the "jet–target" system was located in a coaxial cocurrent supersonic flow. Among comparatively recent researches, the experiments of [12, 13] should be noted, where the acoustic feedback was suppressed by sound interference on a disk and by placing the jet system into a cocurrent subsonic flow. The presence of a channel of external feedback was established in [8, 9, 13], and the dominating role of the channel with internal feedback was demonstrated in [10–12]. In the numerical experiments of [14, 15], the external region of the jet was eliminated from calculations,

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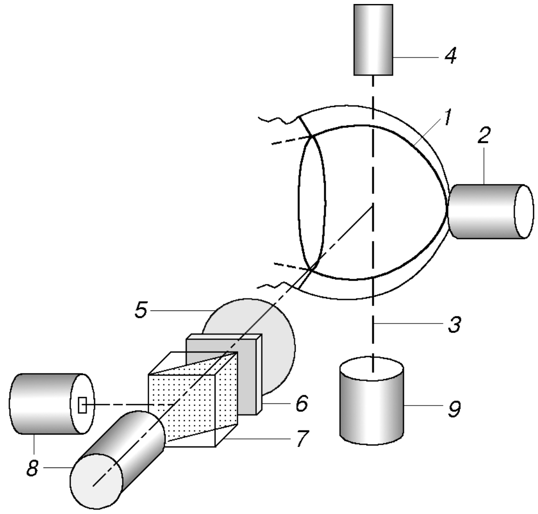

Fig. 1. Measurement scheme: 1) nitrogen jet; 2) nozzle; 3) electron beam; 4) electron gun; 5) fast lens; 6) optical filter; 7) light splitter; 8) photomultipliers; 9) collector of electrons.

the ambient temperature was increased by a factor of 1.5, a sound-absorbing screen was placed near the nozzle, and the ambient medium was considered as a cocurrent supersonic flow. In all cases, the character of oscillations remained unchanged, which follows from the model with external feedback. At the same time, the calculations of [16] showed a significant effect of perturbations in the ambient medium on emergence of oscillations. The above contradictions were partly resolved in [12]. Nevertheless, new experimental approaches have to be used to finally solve the problem.

Qualitatively new information on this problem may be obtained from the experimental results of [17–19], where the self-oscillatory interaction of the jet and the target was studied within the range of low Reynolds numbers Re_L of a purely laminar exhaust jet. In the field of the laminar flow, the capability of the mixing layer to increase perturbations generated by an external acoustic field at the jet root becomes significantly lower because of viscous dissipation. At the same time, the structure of discontinuities in the shock layer near the target still corresponds to the range of high Reynolds numbers. The frequency characteristics of self-induced oscillations obtained in [17–19] correspond to the characteristics of self-induced oscillations under conditions of interaction of dense turbulent jets and targets. It should be noted that the boundaries of the zones of existence of these self-induced oscillations are also in satisfactory agreement [19]. Nevertheless, to solve the problem considered, it is necessary to measure the amplifying properties of the mixing layer of a laminar jet. In the case of a negative growth rate of perturbations at frequencies of self-induced oscillations, we can rather definitely say that the mixing layer of the jet and acoustic waves in the ambient medium are not implicated in the process of oscillations.

The growth rate spectra of density perturbations in the mixing layer of strongly underexpanded laminar jets are measured in the present work. The measurement results are compared with the frequency of self-induced oscillations for jets incident onto finite-size targets for the same flow conditions.

1. Measurement Technique. The measurements were performed by the method of electron-beam fluorescence [20] in the test section of the T-327A hypersonic wind tunnel, which is used as a highly productive vacuum test bench. A nitrogen jet escaped from a sonic nozzle ($\mathrm{M}_a = 1$) of diameter $d_a = 1$ mm. The characteristics of density perturbations in the mixing layer of strongly underexpanded free jets were studied for Reynolds numbers $\mathrm{Re}_L = 50$, 70, 125, 165, and 230 [$\mathrm{Re}_L = \mathrm{Re}_*(P_0/P_{\mathrm{out}})^{-1/2}$ is the Reynolds number based on the length of the wave structure of the jet L and flow parameters at the jet axis, where Re_* is the Reynolds number based on the flow parameters in the nozzle-exit section and nozzle diameter, P_0 is the stagnation pressure of the gas in the plenum chamber of the nozzle, and P_{out} is the pressure in the test section of the wind tunnel, which was measured by a McLeod mercury manometer]. Since the pressure in the test section of the wind tunnel was not adjusted, the jet-pressure ratio n was different for different values of Re_L and equal to 660, 1340, 2400, 6000, and 10,000.

The measurement scheme is shown in Fig. 1. A nitrogen jet escaped from the nozzle into the test section of the T-327A wind tunnel, which was evacuated by mechanical pumps with a total power of 6 m^3/sec. The

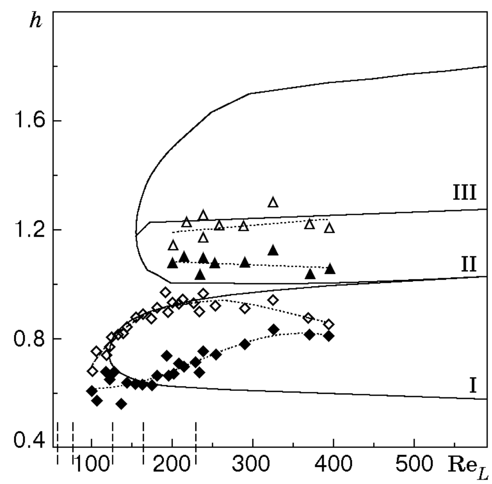

Fig. 2. Boundaries of the region of self-induced oscillations: the solid cures show the data of [17, 18], the dashed curves are approximated boundaries of the regions of existence of oscillations, the vertical dashed lines show the values of Re_L for which the growth rates of perturbations in the free jet were measured, the filled and open points refer to the lower and upper boundaries of the onset of self-induced oscillations obtained in the present work; the regions of existence of axisymmetric oscillations are marked by I and II (regions I has the central shock and region II has an X-shaped structure) and the region of existence of azimuthal oscillations of the wave structure of the impact jet is marked by III.

probing electron beam was generated by an electron gun with a system of differential evacuation. The intensity of nitrogen fluorescence was measured by an optical system consisting of a fast lens, optical filter, light splitter, and two photomultipliers. The electron current was determined from the current to the collector. The function of each element of the registration system and the procedure of initial processing of photomultiplier signals are described in detail in [20]. The electron beam pierced the jet along its diameter. The flow field was scanned in individual cross sections of the jet with periodic displacement of the optical axis of the diagnostic system along the electron beam. The measurements were also performed with continuous motion of the nozzle relative to the electron beam and periodic displacement of the optical axis along the electron beam. The results presented in this work were obtained by both methods. The fields of the mean density and density fluctuations were reconstructed by procedures developed for wake-flow measurements [21].

The longitudinal phase velocity of density perturbations C_x was measured. The measurement technique for the phase velocity by the optical system was described in [20, 21]. The measurements were performed in the mid-section of the first cell of the jet for $\mathrm{Re}_L = 230$ based on 20 mm. The value of C_x was normalized to the flow velocity at the jet centerline.

The experiments on self-oscillatory incidence on a circular finite-size target 40 mm in diameter were performed for conditions of measurement of density fluctuations in free jets. An LKh610 gauge for pressure oscillations was embedded into the center of the target to measure the amplitude and frequency of pressure oscillations on the target. By means of a traversing gear, the distance between the nozzle and the target could be varied in a wide range. The signal from the gauge for pressure oscillations was registered by an NO-67 magnetograph and analyzed by an SK-72 spectrum analyzer. The frequencies and amplitudes of pressure oscillations on the target were determined in the spectral analysis in order to determine the onset and frequency of the discrete tone. These experiments were performed within the Reynolds number range $\mathrm{Re}_L = 50$–600.

2. Measurement Results of the Characteristics of Self-Induced Oscillations. Figure 2 shows the boundaries of the regions of oscillations [h is the distance between the nozzle and the target $x_{\rm t}$ normalized to the characteristic size of the first cell of the jet: $h = x_{\rm t}/(d_a \mathrm{M}_a \sqrt{kn}\,)$, where k is the ratio of specific heats]. The filled points (lower boundary) and the open points (upper boundary) correspond to the onset of self-induced oscillations. The regions of existence of self-induced oscillations are bounded by the dotted curves. The solid curves show to

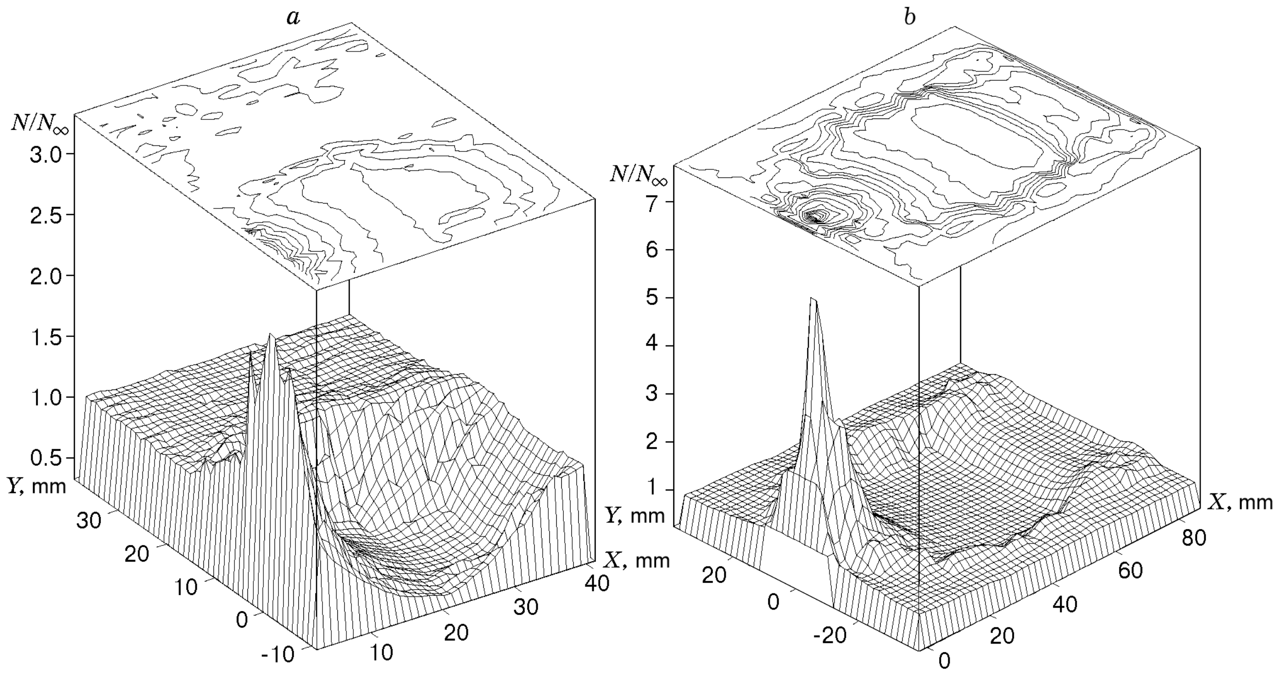

Fig. 3. Density fields of the jets for $\mathrm{Re}_L = 70$ (a) and 230 (b).

the boundaries of three regions of existence of self-induced oscillations of strongly underexpanded jets hitting the target, which were obtained in [17, 18] for smaller jet-pressure ratios ($n \leqslant 500$). Regions I and II correspond to axisymmetric oscillations of the wave structure of the impact jet and region III refers to azimuthal oscillations. The regions of existence obtained in the present work are in good agreement with regions I and II obtained in [17, 18], despite the large difference in the jet-pressure ratios. Stable oscillations in region III could not be obtained in this study. The reason may be the extremely high jet-pressure ratio. Good agreement of the regions of existence of self-induced oscillations indicates the governing influence of the ratio of the target size and the scale of the wave structure of the jet on the process of self-induced oscillations, which is observed for dense turbulent jets. This allowed us to obtain a generalized region of existence of self-induced oscillations [22].

3. Measurement Results in the Free Jet. The vertical dashed lines in Fig. 2 correspond to Reynolds numbers Re_L for which the growth rate of density perturbations were measured in the mixing layer of free jets. The fields of the mean density in jets were measured for the same conditions. Figure 3 shows the density distributions in the free jet for $\mathrm{Re}_L = 70$ and 230. The wave structure is rather blurred for the lower Reynolds number and clearly expressed for the higher one. This result is in agreement with the data of [6], where the value $\mathrm{Re}_L \approx 100$ separates the regions of existence of rarefied jets with a blurred wave structure and laminar jets with a formed wave structure.

Figure 4 shows the profiles of the mean density and total density fluctuations measured in the diametral direction in the mid-section of the first cell of the wave structure of the jet for $\mathrm{Re}_L = 230$. The maximum of density fluctuations is located immediately behind the density maximum related to the barrel shock wave in the jet. The distribution of density fluctuations is in qualitative agreement with that in the shock layer on the body, where the jet flow upstream of the barrel shock plays the role of external hypersonic flow.

Figure 5 shows the characteristic spectrum of density fluctuations in the region of the maximum of total oscillations. The fluctuations are concentrated in the low-frequency range of the spectrum. The character of the spectra remains unchanged in measurements outside the flow field of the jet. Figure 5 also shows the spectrum of the dimensionless longitudinal phase velocity of density perturbations C_x measured in the region of the maximum of total density fluctuations for $\mathrm{Re}_L = 230$. The error in phase velocity is 10%. The longitudinal phase velocity is close to the dimensionless velocity of convection of perturbations in supersonic jets, which equals 0.7–0.8 (see, for instance, [13]) and is supersonic for all exhaust conditions.

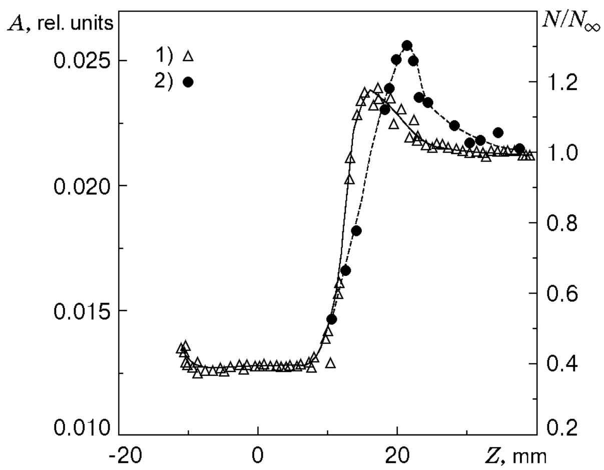

Fig. 4. Profiles of the mean density (points 1) and total density fluctuations (points 2) in the mid-section of the jet.

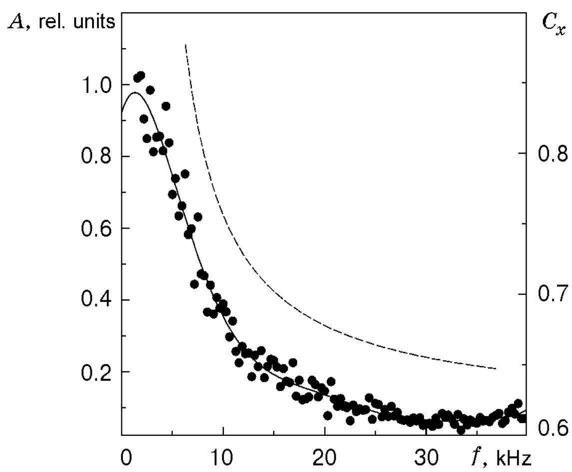

Fig. 5. Typical spectrum of density fluctuations in the region of the maximum of oscillations (points) and the spectrum of the convection velocity of perturbations (dashed curve).

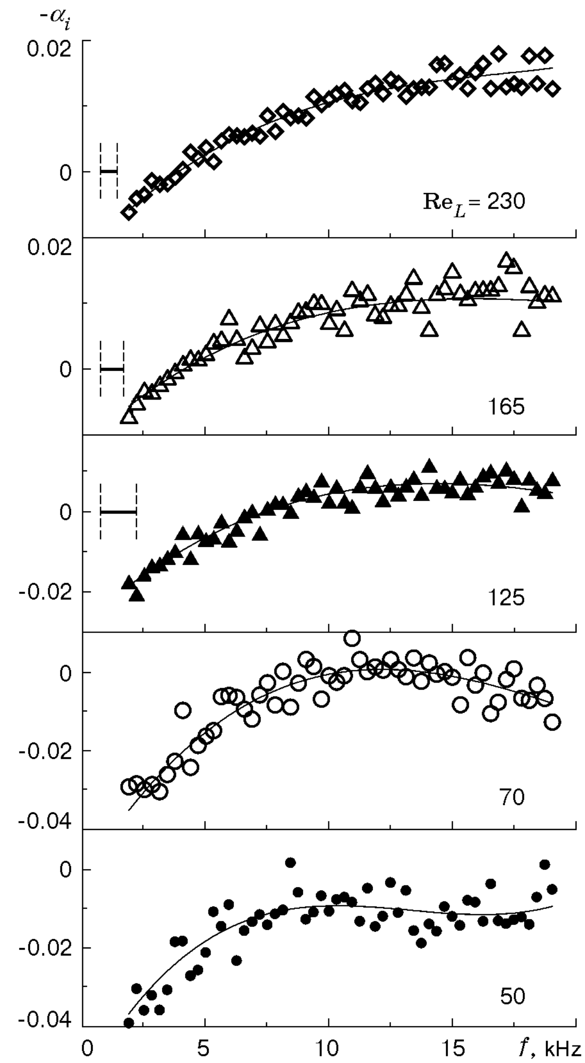

Fig. 6. Spectra of the growth rate of density perturbations in the free jet and the frequency ranges of self-induced oscillations of the impact jet (horizontal sectors).

The growth rate of density perturbations $-\alpha_i$ was calculated in a standard manner along the line of the maximum of total oscillations in the compressed layer of the jet. The value of $-\alpha_i$ was determined in the interval between the cross section next to the nozzle, where the barrel shock can be identified, and the cross section corresponding to the Mach disk position. The cross section of the maximum jet diameter was generally located near the nozzle exit. The value of $-\alpha_i$ was normalized to the characteristic thickness of the laminar mixing layer.

Figure 6 shows the measured growth rate of density perturbations $-\alpha_i$ as a function of the frequency f for five values of Re_L shown in Fig. 2. The common feature for all graphs is the negative growth rate of perturbations in the low-frequency region. The increased scatter in data with decreasing Re_L is related to the increase in statistical noise of measurements with decreasing density of the jet.

For the growth-rate spectra with $\mathrm{Re}_L = 125$, 165, and 230, the horizontal sectors at the level of zero increment show the frequency ranges of pressure oscillations at the target, which were obtained for these conditions of jet exhaustion. In all three cases, the growth rate in these intervals is negative.

4. Results and Discussion. Despite the low pressure in the ambient space (less than 27 Pa), the overall pattern of jet exhaustion and sound generation is similar to the pattern of exhaustion of dense jets. Acoustic oscillations in the ambient medium, which are generated by an expanding jet on the target in the regime of self-induced oscillations, may induce perturbations in the mixing layer of the laminar jet. Nevertheless, the measurements showed that perturbations in the free jet are not amplified in this case, i.e., the scheme of energy transfer to jet oscillations by the channel of amplification of perturbations in the shear layer of the jet is not employed [2, 3]. This allows us to argue that the mechanism of self-induced oscillations with internal feedback is dominating under these conditions.

It is shown that the mixing layer of the free laminar jet does not amplify perturbations. At the same time, an intense acoustic field generated by the expanding jet on the target in the regime of self-induced oscillations may change the mean flow parameters that affect stability of the mixing layer. It should be noted that the target cannot exert a direct effect on the mixing layer upstream of the expanding jet. The reason is the supersonic velocity of perturbations in the mixing layer, which is confirmed by direct measurements of the longitudinal phase velocity. The effect may be caused only by the transfer of perturbations in the form of acoustic waves over the ambient space. However, the deformation of the mean flow field requires a highly intense acoustic action, whereas the reason for "triggering" of the mechanism of self-induced oscillations and the growth of intensity of the acoustic field around the jet in the case of the negative growth rate of perturbations in the initially laminar jet is not clear yet. This leads to the conclusion on the dominating role of the processes with internal feedback [4–7].

The processes with increasing perturbations in the mixing layer and synchronization of perturbations by means of acoustic waves in the ambient medium should be manifested at the periphery of the united zone of existence of self-induced oscillations of turbulent jets [22], where the effect of mass-flow-rate mechanisms becomes weaker.

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