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SELF-SUSTAINED OSCILLATIONS IN SUPERSONIC OVEREXPANDED IMPACT JETS

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The influence of geometric and gas-dynamic parameters on the flow structure and parameters of self-sustained oscillations in supersonic overexpanded jets interacting with a normally located plane finite obstacle is studied experimentally and theoretically. It is found that the geometric Mach number and the half-angle of nozzle expansion exert a significant effect on the interaction process. A comparison of experimental and numerical data allows one to find a possible reason for the emergence of self-sustained oscillations in overexpanded impact jets.

It was shown [1, 2] that self-sustained oscillations in overexpanded impact jets (in contrast to underexpanded jets) exist only at high Mach numbers ($\mathrm{M}_a = 4$ [2]). It should be noted that most available results were obtained for jets exhausted from conical nozzles with half-angles $\theta_a \leqslant 10^\circ$, where the angle of inclination of the velocity vector of the flow leaving the nozzle to the axis has a minor effect on the shock-wave structure of the jet. It is also known that an increase in the cone half-angle θ_a has a significant effect on the flow character and shock-wave structure of the free jet [3, 4]. Thus, the typical features of the flow and the influence of the half-angle θ_a on self-sustained oscillations arising in overexpanded impact jets are studied in the present paper.

The experimental studies were performed in a supersonic blow-down wind tunnel (stagnation temperature $T_0 = 290$ K). The facility was equipped by a traversing gear providing displacement of the obstacle (cylinder with a flat end face) along the jet axis. The distance covered was determined by the electric-contact technique. Supersonic jets were formed by a conical Laval nozzle with a geometric Mach number $\mathrm{M}_a = 3$, nozzle half-angle $\theta_a = 15^\circ$, and nozzle-exit radius $r_a = 9$ mm, which was located in the receiver.

Pressure oscillations on the obstacle $p(\tau)$ were measured by an LKh-611 piezoelectric pressure gauge with a frequency range of 10–$5\cdot 10^4$ Hz. Instantaneous oscillations amplified by a 00 011 microphone amplifier of a 01 021 noise dosimeter of the RFT company (transmission band of 200 kHz) was recorded on the tape of an NO-67 magnetograph (range of reproduced frequencies of 40 kHz). In the course of the experiment, we also determined the integral level of pressure oscillations at the stagnation point of the obstacle (at the exit of the indication block 02 022) $\Delta L^0 = 20\log(\sigma/p_w) - L_n$. Here σ is the effective value of $p(\tau)$, $p_w = 2\cdot 10^{-5}$ Pa is the acoustic pressure of the audibility threshold, and L_n is the level of wide-band noise. The frequency range of the dynamic path consisting of the gauge, noise dosimeter, and magnetograph is greater than 40 kHz with a deviation of the amplitude–frequency characteristics ±3 dB. The pattern of the overexpanded jet flow around the obstacle obtained by a Schlieren device was photographed on the film or registered by a CCD camera.

At the first stage of investigations, the gas parameters at the nozzle exit were unchanged, and the obstacle was gradually moved away from the nozzle along the jet axis (the signal from the gauge was recorded continuously). The distance h at which self-sustained oscillations occur was determined (hereinafter, all linear dimensions are normalized to the nozzle-exit radius r_a); then, experiments with fixed values of h were performed to study the characteristics of the self-oscillatory process. The obstacle radius r_{obs} was varied.

To analyze the amplitude–frequency characteristic of self-sustained oscillations, we used a set of equipment and a data processing technique similar to those described in [5]. The study was performed for the following values of the governing parameters: nozzle diameter $d_a = 18$ mm, ratio of specific heats $\gamma = 1.4$, $\mathrm{M}_a = 3$, nozzle-pressure ratio $n = 0.38$–0.8, $r_{\mathrm{obs}} = 1.56$, 1.92, and 4.14, and $h = 2$–6.

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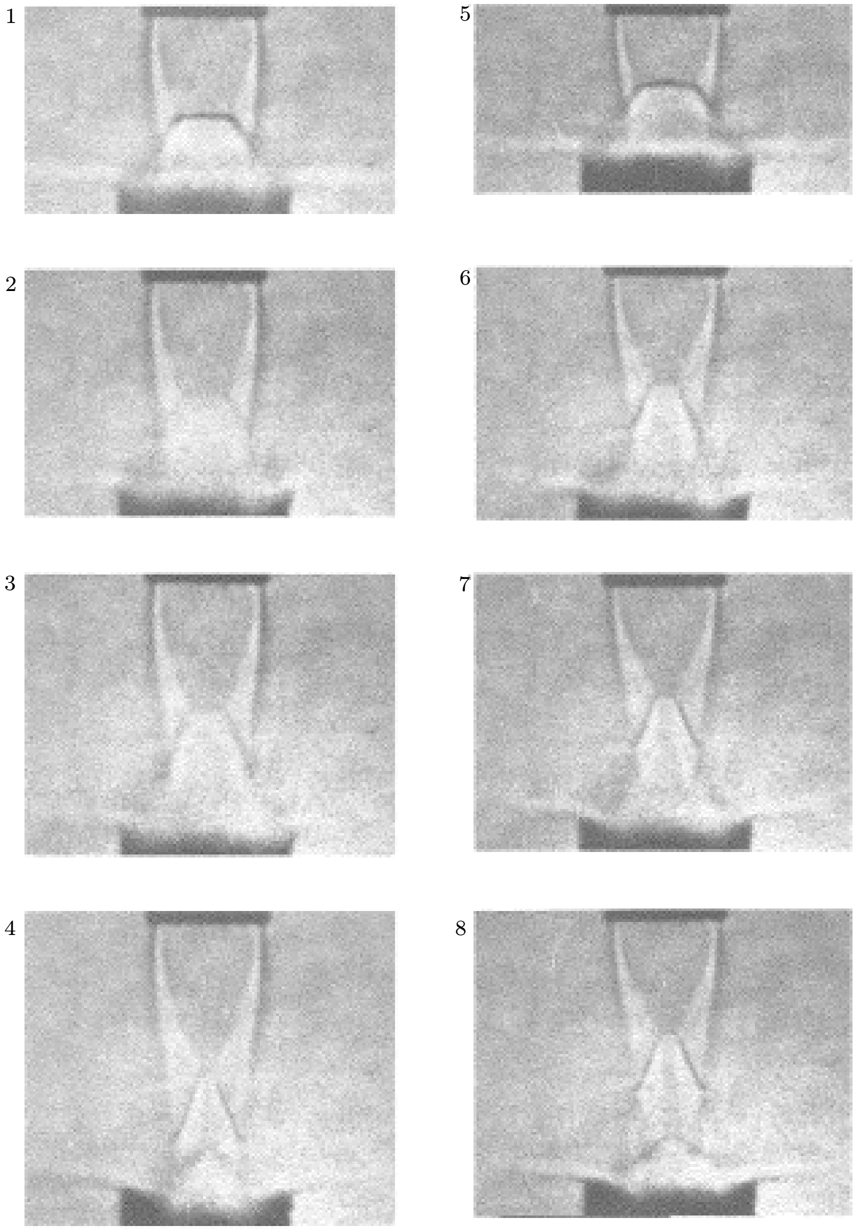

Fig. 1. Shock-wave pattern of a supersonic overexpanded jet flow around an obstacle: frames 1–4 refer to $n = 0.6$ and $h = 3$ (1), 3.75 (2), 4.43 (3), and 4.87 (4); frames 5–8 refer to $n = 0.45$ and $h = 2.5$ (5), 4.02 (6), 4.25 (7), and 4.75 (8).

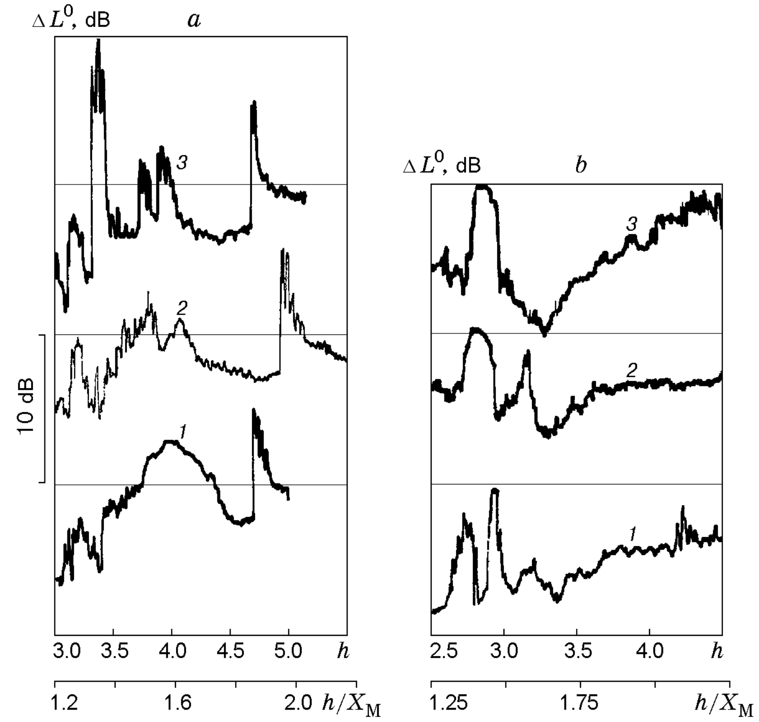

Fig. 2. Integral level of pressure oscillations in the center of a finite obstacle for $n = 0.6$ (a) and 0.45 (b): curves 1–3 refer to $r_{\rm obs} = 1.56$, 1.92, and 4.14, respectively.

Figure 1 shows the shock-wave pattern in an overexpanded impact jet for various values of the parameter h. It follows from the analysis of the visualization results that a gradual increase in h leads to jumplike destruction of the steady flow: self-sustained oscillations accompanied by a significant increase in the integral level of oscillations ΔL^0 arise in the impact system "overexpanded jet–obstacle" (Fig. 2) ($X_{\rm M}$ is the distance to the Mach disk in the free ambient jet).

An analysis of Figs. 1 and 2 shows that self-sustained oscillations (Schlieren pictures Nos. 2, 3, 6, and 7 in Fig. 1) can arise not only for $\mathrm{M}_a = 4$ (see [2]) but also for $\mathrm{M}_a = 3$ and $\theta_a = 15°$ (in [1, 2], in the above-mentioned range of nozzle-pressure ratios n, the values of θ_a are lower). As in underexpanded impact jets, the self-sustained oscillations are characterized by significant variation of the shock-wave structure and by pressure oscillations of high amplitude and comparatively low frequency (the oscillations have a clearly expressed periodic character). The frequency spectra of pressure oscillations on the obstacle acquire discrete components, which are significantly higher than the overall level of continuous noise of the jet.

As in the case of underexpanded jets, the sectors of variation of the integral level $\Delta L^0 = \Delta L^0(h)$ (see Fig. 2a) have clearly expressed boundaries corresponding to the emergence and termination of self-sustained oscillations. The transition from unsteady interaction to a flow with an undisturbed first barrel corresponds to the formation of a steady shock-wave structure upstream of the obstacle (Schlieren pictures Nos. 4 and 8 in Fig. 1) and to a drastic increase in ΔL^0 (see Fig. 2a).

Figure 3 shows the boundaries of the regions of existence of self-sustained oscillations in the generalized coordinates $h/(r_{\rm obs}\mathrm{M}_a^{0.5})$ and $n\mathrm{M}_a^{0.5}/r_{\rm obs}^2$. The limiting distances h were determined by the increase and decrease in the value of ΔL^0 and also by a comparison of the curves $\Delta L^0(h)$ with the shock-wave structure around the obstacle. An analysis of data in Fig. 3 shows that, despite some difference in the length of unsteady flow regions, which was found previously for underexpanded impact jets, the results obtained are in good agreement with the known concepts of the mechanism of self-sustained oscillations and correlate well with the results of Serov and Sobolev for $\mathrm{M}_a = 4$ [2].

To find the relationship between the shock-wave pattern arising in the impact jet and various flow regimes, a theoretical calculation and a parametric analysis of the characteristics of a free overexpanded jet were performed. The flow in the nozzle and in the region of isentropic flow of the ambient jet for $n \leqslant 1$ was simulated by the flow from a supersonic spherical source. The shock wave incident onto the axis was constructed on the basis of

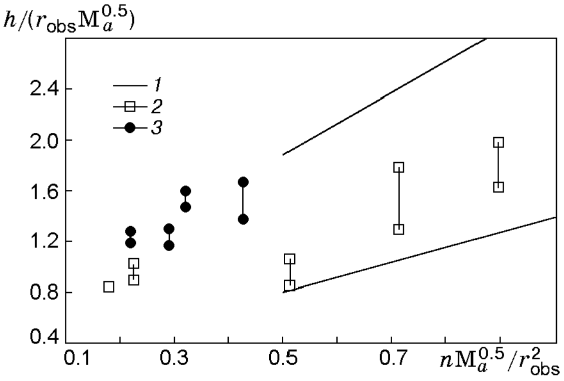

Fig. 3. Regions of existence of self-sustained oscillations: points 1 and 2 refer to the data of [6] and [2], respectively; points 3 refer to the data of the present work.

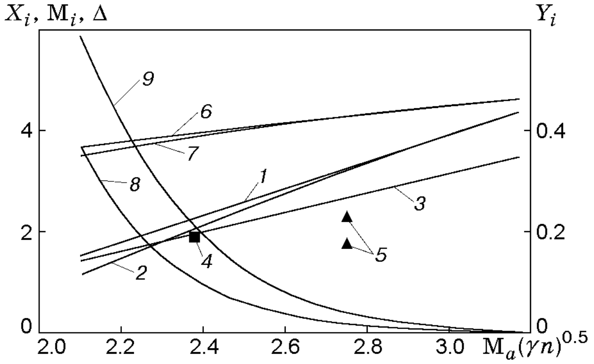

Fig. 4. Positions of triple shock-wave configurations in a supersonic overexpanded ambient jet and the corresponding characteristic Mach numbers M_i: $X_{\rm st}$ (curve 1), $X_{\rm opt}$ (2), $X_{\rm M}$ (3), distance Δ for $n = 0.45$ (4) and 0.6 (5), $\mathrm{M}_{\rm st}$ (6), $\mathrm{M}_{\rm opt}$ (7), $Y_{\rm st}$ (8), and $Y_{\rm opt}$ (9).

differential conditions of dynamic compatibility on the shock [7], which allow one to describe the shock by an ordinary differential equation if the flow parameters from the source are known. Using this technique, one can calculate triple shock-wave configurations at each point of the shock on the basis of the known flow field. The Mach disk in the ambient jet is defined as a steady Mach configuration with a normal incident shock [7].

The parametric analysis of triple configurations [8, 9] shows that there exist optimal triple configurations in which the relations of some gas-dynamic variables (total pressures, dynamic pressures, etc.) behind the reflected and incident shocks reach extreme values. The intensities of shock waves that arrive at the shock-branching point and lead to the appearance of optimal triple configurations are determined analytically in [8, 9].

The use of methods for constructing the incident shock, calculating triple configurations, and identifying optimal triple configurations allowed us to analyze the shock-wave structure in an overexpanded impact jet. An analysis shows that, in an axisymmetric ambient jet with $\mathrm{M}_a > 2.5$ and $n \leqslant 0.8$, a steady Mach configuration arises downstream of the optimal triple configuration.

Thus, for constant M_a, n, γ, and θ_a and certain values of h, the central shock detached from the obstacle arrives within the region of the optimal triple configuration and ensures a peripheral maximum of variables at the triple point. Such a situation favor choking of the central flow region, which, in accordance with [10], is the main reason for the emergence of self-sustained oscillations.

Experimental data at which self-sustained oscillations are observed and calculation results for optimal triple configurations are compared in Fig. 4. The calculations show that optimal triple configurations are always located upstream of steady Mach configurations. In Fig. 4, we compare the position of the steady Mach configuration and the position of the Mach disk $X_{\rm M}$ found experimentally for a free overexpanded ambient jet (curve 3) within a wide range of the parameter of similarity $\mathrm{M}_a(\gamma n)^{0.5}$. The mean distance Δ between the central shock wave and the obstacle in the self-oscillatory regime with the obstacle moving away from the nozzle is also plotted in Fig. 4 (points 4 and 5).

An analysis of Fig. 4 gives the following results:

— The difference in curves 1 and 3 can reach 15–28% with variation of the nozzle-pressure ratio $n = 0.45$–0.8; the reason for this difference is the accepted idealization of the flow in an overexpanded free jet (simulation by a spherical source);

— The Mach numbers M_i ahead of the steady Mach configuration (curve 6) and the optimal triple configuration (curve 7) reach significant values: $\mathrm{M}_{\mathrm{st}} = 3.63$–$4.66$ and $\mathrm{M}_{\mathrm{opt}} = 3.46$–$4.67$;

— The transverse size of the steady Mach configuration Y_{st} (Mach disk radius) for a half-angle $\theta_a = 15°$ and $n = 0.65$–0.7 is negligibly small; the region of extreme parameters is located in the compressed layer of the free jet (curve 9 is significantly higher than curve 8);

— Self-sustained oscillations arise if the central shock wave detached from the obstacle arrives within the region close to the Mach disk of the free jet (points 4 and 5), where, according to the model considered, there are regions of extreme parameters of the compressed layer (regions of optimal triple configurations).

Thus, the model proposed offers an explanation to the emergence of self-sustained oscillations for $\mathrm{M}_a < 4$. It is found that the nozzle half-angle, the obstacle diameter [11], and the parameter h/X_{M} characterize the jet–obstacle interaction process and should be taken into account in constructing models of emergence and sustaining of unsteady regimes.

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