INVERSE FEEDBACK MECHANISM IN SELF-OSCILLATIONS IN FLOW OF AN UNDEREXPANDED SUPERSONIC JET AGAINST A PLANAR OBSTACLE

V. N. Glaznev

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Self-oscillations arising in flow of an underexpanded supersonic jet against an obstacle belongs to the class of gasdynamic problems in which, in spite of a history of study over many years, there is no single opinion among investigators on a number of basic questions associated with their initiation and maintenance of the oscillations. This refers to the greatest degree to self-oscillations arising in flow of an underexpanded supersonic jet against a planar obstacle perpendicular to the jet axis. Here the degree of underexpansion $n > 1$ is such that the radius of the Mach disk of the corresponding free jet regime is comparable with the radius of the exit section of the nozzle r_a, while the obstacle is at a distance x_{ob} from the nozzle not exceeding the length of the first "barrel" of the jet. Between the Mach disk and the obstacle there is subsonic flow (Fig. 1), at least in the near-axis region. This is the type of jet flow, accompanied by intense oscillations, that has been selected by investigators for a long time as a specific object of study, as indicated in [1], where the main question was quite clearly defined, the mechanism of inverse feedback in the self-oscillatory system, and the main contemporary ideas on this were correctly described, though briefly. It should be stressed that in flows of supersonic underexpanded jets against an obstacle the self-oscillations that arise vary in their physical nature. For example, in flow of a jet into a cavity an external acoustic feedback is not required for sustaining the oscillations. Therefore, the set of conditions mentioned above, selecting the type of self-oscillations examined, is important in principle. Because of the above comments it is important to classify the self-oscillations arising in flow of an underexpanded supersonic jet against an obstacle, with respect to the mechanism for their generation and maintenance. The first step in this direction was made in [2] by Powell, a well-known investigator of self-oscillations in jet flows.

The present paper continues the cycle of studies by Glaznev et al. [3], Glaznev and Demin [4], and Glaznev [5, 6] and others to provide an experimental and theoretical formulation and basis of a model for generation and maintenance of oscillations in the jet-obstacle system described above. It describes new, more detailed and impressive experimental results to indicate, in contrast with the statements of Groshkov et al. [1], that an external acoustic feedback has a resolving influence on the amplitude and frequency characteristics of the self-oscillations examined.

The tests were carried out on a jet of cold air under the following conditions: the nozzle Mach number was $M_a = 1.5$, the degree of underexpansion of the jet $n = 8$, the radius of the nozzle exit section was $r_a = 10^{-2}$ m, and the distance from the nozzle to the obstacle was $x_{ob}/r_a = 8.5$. The obstacle was the planar end face of a cylinder of radius $r_{ob}/r_a = 6.0$. Under these conditions intense oscillations of frequency $f = 2300$ Hz are excited in the system (at the center of the obstacle the level of pressure oscillations is $L \approx 200$ db), the oscillations satisfying the condition $fx_{ob}/a \approx 0.6$, characteristic of the so-called low-frequency oscillations (the strong instability region in the terminology of [1]). Here a is the sound speed in the space surrounding the jet. Figure 1 shows schematically the equipment, the jet structure, and the measurement system, including a type LKh-610 piezo-sensor to measure the pressure oscillations at the center of the obstacle, the preamplifier 2, the type C5-3 spectral analyzer 3, the oscillograph 4, and the type N-110 chart recorder 5. With this system one can record the spectrum of the pressure oscillations in the acoustic frequency range, observe the pressure oscillations on the oscilloscope screen, and measure the amplitude of the pressure oscillations for arbitrary chosen frequencies from the range indicated. The accuracy of frequency measurement is 2-3%, and of amplitude measurement ≈5%.

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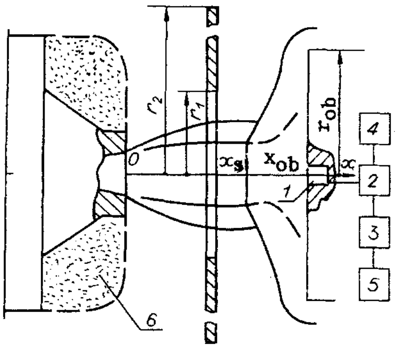

Fig. 1

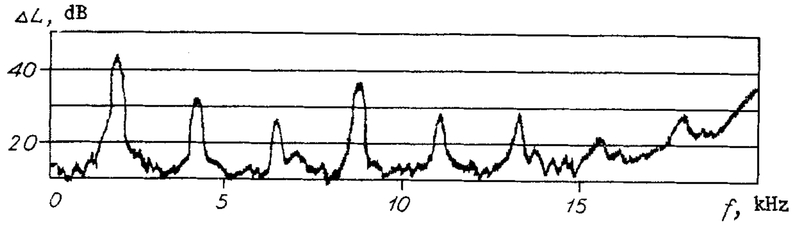

Fig. 2

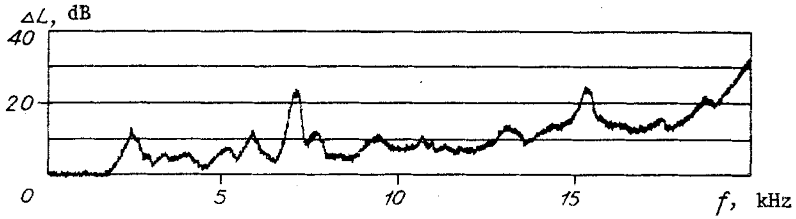

Fig. 3

The basic idea of the experiment is as follows. In the opinion of Glaznev et al. [3], Glaznev and Demin [4], and Glaznev [5, 6] the inverse feedback in the self-oscillation system considered is accomplished by an acoustic wave which radiates into the external space of a jet expanding over an obstacle (the so-called fan) during its oscillatory motion, in a direction parallel to the jet axis. At the jet base an acoustic wave generates vortex-type perturbations. Therefore, to confirm the above concept of the role of an external acoustic wave one must act on it in some way without changing the jet flow regime. If as a result of this action the characteristics of the oscillations change appreciably, the statement is proved. In the series of tests described we chose the following two methods of action. 1. A change in the "acoustic conditions" in the vicinity of the nozzle unit was curtained off with a thin sheet of "porolon" of thickness $\delta \approx (2\text{-}3)\cdot 10^{-2}$ m (item 6 in Fig. 1), the material being an efficient sound absorber. However, the lining of the nozzle of thickness $\delta = 10^{-2}$ m remained open. In the second test there was no "porolon" curtain (at a distance of $\ell \approx 4\cdot 10^{-2}$ m to the left of the nozzle exit plane at x = 0 we positioned a heavy flat metal surface as an efficient sound reflector). 2. The nozzle unit was curtained off with "porolon," as in Method 1, but between the nozzle and the obstacle we set up an acoustic screen. It was a flat circular disk, a brass plate of thickness $3\cdot 10^{-3}$ m with a circular aperture in the center, set up coaxially with the jet. Its outer radius $r_2 = 0.2$ m = const, and its inner radius r_1 was variable (a set of disks was used). The screen was mounted on a traverse mechanism, allowing it to be moved in the direction of the jet axis in the range $0 \le x_s < x_{ob}$. Special steps were taken to avoid vibrations of the screen.

We shall now describe and comment on the main results. Figures 2 and 3 show spectrograms of pressure oscillations at the center of the obstacle, relevant to the first method of action. The level of the pressure oscillations L(f) relative to the reference value $p_0 = 2\cdot 10^{-5}$ N/m² can be calculated from the expression $L(f) = L_0 + \Delta L(f)$ ($L_0 = 137.8$ dB = const) for both spectrograms. The spectrogram of Fig. 2 corresponds to the first situation, with

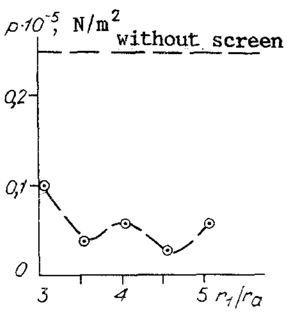

Fig. 4

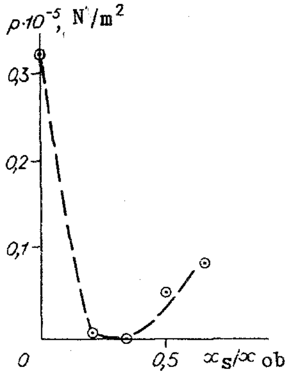

Fig. 5

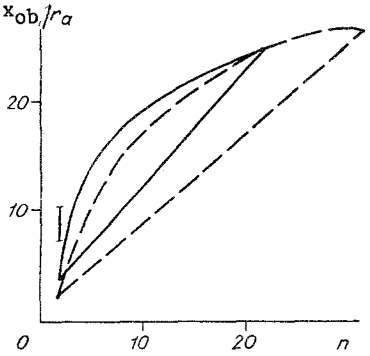

Fig. 6

the vicinity of the nozzle unit curtained off with "porolon." In this case, because of the negligibly small sound reflection from the "porolon" layer, in the external acoustic field near the jet there is an acoustic wave traveling from the obstacle to the nozzle, a situation that is optimal in amplitude and phase respects for exciting and maintaining self-oscillations. In this system oscillations are excited at frequency $f = 2300$ Hz with a first tone amplitude of $L \approx 180$ dB, plus a set of strong overtones up to the eighth. The spectrogram of Fig. 3 corresponds to the second situation, when there was no "porolon" curtain. The presence of the metal surfaces as good sound reflectors in the vicinity of the nozzle unit creates a complex interference field at the jet base in the plane $x = 0$. This destroys the amplitude-phase conditions assigned by an external acoustic wave and required for excitation of oscillations. Indeed, the oscillations are not excited: The first tone can scarcely be seen above the noise, and its frequency is changed, and the overtones vanish completely; new frequencies appear, and the second level is reduced sharply. The spectral composition of the oscillations varies qualitatively and quantitatively. Our comments on Figs. 2 and 3 may be disputed, since no measurements were made in the acoustic field, and the comments are based on conventional ideas of acoustics. But the following result is not in doubt: The oscillations can be suppressed completely, by varying only the acoustic conditions in the vicinity of the nozzle unit. Here all the attributes determined by the jet flow regime and required for excitation of oscillations, in the opinion of Gorshkov et al. [1], who give another explanation of the phenomenon of self-oscillations, remain unchanged.

The results are equally convincing from the tests with acting on the external acoustic wave using screens. Figure 4 illustrates the influence of the screen inner radius, with unchanged screen location at $x_s/x_{ob} = 0.5$, on the amplitude of the first tone of the oscillations. The maximum jet radius in the chosen discharge regime is $r_*/r_a \leq 2.5$, and therefore, for all values of r_1 shown in Fig. 4, the jet has not interacted gasdynamically with the screen. The amplitude of the pressure oscillations decreased by a factor of 10 for $r_1/r_a = 4.5$, compared with the case of the unperturbed acoustic field. The nonmonotonic variation of the oscillation amplitude for r_1 increasing monotonically results from sound diffraction in the screen orifice, which also indicates the leading role of the external acoustic wave in the mechanism of the self-oscillations examined. As even more effective result was obtained during variation of the screen position (Fig. 5), with a fixed size of inner aperture $r_1/r_a = 4.0$. The complete suppression of oscillations for $x_s/x_{ob} \approx 0.33$ and the nonmonotonic amplitude variation with increase of x_s, due to diffraction effects, convincingly confirm the above idea as to the role of the external acoustic wave.

We now analyze the results of the tests of [1], where the authors tried to show that it (the external acoustic feedback — noted by the present author) does not play the main role in generating unsteady flow in a shock layer. For this purpose they chose a jet discharge regime ($M_a = 2.0$, $n = 6.52$), where there are self-oscillations in some range of x_{ob}, and then blowing begins with a supersonic flow with $M_\infty = 2.365$. In the range $7.2 \leq x_{ob}/r_a < 10.2$ strong periodic oscillations are recorded with frequencies close to the expected values. Since in conditions of supersonic external blowing acoustic waves cannot propagate from the obstacle to the nozzle in the external part of the jet boundary, and there are no oscillations, the authors conclude that an external acoustic wave is not important as an inverse feedback mechanism for exciting and maintaining the kind of self-oscillations that they discuss in each of their papers. At first glance the authors' logic is impeccable. However, there are some circumstances that should be examined.

Figure 2 of [1] shows schlieren photographs and the flow schemes of two jets: without secondary flow ($M_a = 2.0$, $n = 6.52$ – Fig. 2a), and with supersonic secondary flow ($M_a = 2.0$, $n = 1.74$ – Fig. 2b). It is not difficult to see that this is a case of two different jets, and two different flows. But it is known that the stability of any flow is uniquely determined, other (boundary) conditions being equal, by its hydrodynamic structure. The fact of coincidence of the oscillation frequencies in the two cases is a necessary but not a sufficient condition for the self-oscillations to have the same excitation mechanism. For example, in flow into a semi-open tube of both a supersonic underexpanded jet and a subsonic jet self-oscillations occur of similar frequency $f \approx a/4L_1$ (L_1 is the tube length). However, they are completely different in nature.

We now compare the results of [1] with those of [7, 8] as to regions of existence of oscillations. Figure 6 shows the regions of existence of oscillations in the conventional coordinates $x_{ob} - n$ for the conditions of the experiment of [1]: $M_a = 2.0$, $r_{ob}/r_a = 2.8$. The solid closed curve bounds the region of existence of oscillations, obtained in [8], and the broken curve shows that obtained in [7], and the intercept of the solid straight vertical line ($n = 1.74$; $7.2 \le x_{ob}/r_a < 10.2$) denotes the range of nozzle–obstacle distances in which Gorshkov et al. [1] recorded oscillations. A comparison of the results shown in Fig. 6 indicates that the oscillations recorded in [1] do not fall in the region of existence of self-oscillations of [7, 8] in the jet with an obstacle without secondary flow. The oscillations recorded in [1] and studied in [3-8] are of a different physical nature. The positive result of [1] is the following: It was established experimentally that a supersonic weakly underexpanded jet (the Mach disk was practically absent), in flow against a two-dimensional obstacle, in some range of nozzle–obstacle distance excites self-oscillations for which the external acoustic feedback is not important.

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