calculations using a more general model of potential flow of an ideal fluid [5, 6]. In doing this, some discrepancy of quantitative results was also observed, which grows with increasing power of the source of disturbance. However, this does not cause any qualitative disparity in the results (the value of α in this case reaches 0.7). Note also that within the limits of another approximate model (the Green–Hardy model), soliton generation is computed right up to $F_h = 1.4$ [2]; no reason being noted for cessation of generation for $F_h > 1.4$.

Thus, it would seem that the possibility of generating solitons with amplitudes and velocities markedly exceeding the limiting values of these parameters for steady waves is explained not so much by the weak nonlinearity of the model being used as by the nature of the phenomenon, to wit, the presence of a forcing term which significantly reduces the degrees of freedom of the resultant solitons. However, one can probably expect some reduction in the upper boundary of attainable values for F_h for the more general models, due to the loss of stability of large-amplitude waves (the development of wave instability with increasing power of the source of disturbance has been noted in experiments [4] and was observed by the author while doing numerical calculations of the problem that uses a potential model [5, 6]).

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INFLUENCE OF THE OUTER FEEDBACK LOOP PARAMETERS ON THE FREE OSCILLATIONS OF THE FLOW OF AN UNDEREXPANDED JET PAST A FINITE OBSTACLE

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The oscillation interaction of supersonic gas jets with obstacles was studied at the end of the 1920s [1] and has found broad application. However, the problem of the mechanism supporting the oscillations remains obscure. Virtually all hypotheses which purport to explain this phenomenon are based on channels of direct and feedback coupling of the freely oscillating jet–obstacle system. These hypotheses can be divided into two basic groups: feedback is accomplished by waves in the shock layer between the obstacle and the central shock wave [2-4]; or feedback is accomplished by sound waves which propagate in the medium surrounding the jet [5]. These models with equal plausibility describe the motion of the flow elements as observed in shadowgraphs, and they determine the pulsation frequency with reasonable accuracy. However, they do not permit determination of the region in which oscillations take place; nor do they explain the jump in frequencies. An attempt was made in [6] to work with both models and to find their regions of applicability. On the basis of a schlieren analysis of the interaction of a weakly underexpanded jet with an obstacle, it was shown that outer feedback dominates when the obstacle diameter d_o exceeds the diameter of the exit nozzle cross section d_a by a factor of four or more ($d_o/d_a > 4$); on the other hand, inner feedback dominates when $d_o/d_a < 2$: the physical meaning of this criterion has

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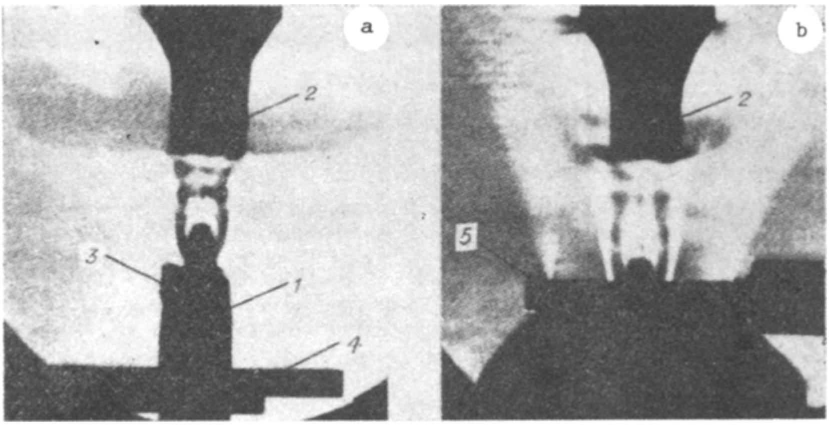

Fig. 1

not been explained. The issue of the role of feedback channels is extremely important both for the models representing the oscillation process, and for practical use in technology.

In this situation, it is natural to validate the models by analysis of the effect of changing the external conditions on the amplitude–frequency characteristics of the free oscillations. Such investigations were carried out in [7-9], where outer feedback was interrupted by shielding the jet core region [7, 8], and by placement of the jet–obstacle system in a sheathing coaxial supersonic flow [9]. Contradictory results were obtained in [7-9]: the shortcomings of these works lies in their lack of more than one measurement, their choice of experimental methods, and interaction parameters that are nonoptimal for model validation.

Numerical experiments were done in [4, 10] consisting of: excluding the inner region of the jet from the calculation, changing the gas temperature in the surrounding medium by a factor of 1.5, and placing a sound-absorbing screen outside the jet; and imparting supersonic sheathing motion to the medium surrounding the jet. In all of these cases no change took place in the nature or the amplitude of the oscillations.

In this work, we study the effect of the velocity with which acoustic waves pass from the obstacle to the nozzle and their intensity near the nozzle edge on the amplitude–frequency and phase characteristics of free oscillations during flow of an underexpanded air jet past the end of a finite cylinder. The results obtained here are analyzed using the two fundamental mechanisms of free oscillations in such jet systems.

1. A diagram of the experiment is shown in Fig. 1. The underexpanded jet of cold air flows out from a conical sonic nozzle with acute rim 1 (Fig. 1a) of diameter $d_a = 10^{-2}$ m and flows past the plane end of cylinder 2 of relative diameter $\bar{d}_o = d_o/d_a = 2.3$. The degree of choking of the jet n was varied from 5 to 30; the nozzle–obstacle spacing $\bar{x}_o = x_o/d_a$ could be varied over a wide range during experiment.

Pressure pulsations were measured using two piezoceramic I4131 gauges with receiver section diameters of $3 \cdot 10^{-3}$ m and a 60 kHz limiting frequency. One of these was attached to the center of the obstacle, the other near the nozzle edge. Gauge signals and information on the pressure in the forechamber and the position of the obstacle were recorded on an N067 magnetograph in a frequency band of up to 20 kHz. During signal processing, the autospectrum of the pulsations and the inverse correlation functions of the first harmonics were determined in order to find the signal phase shift.

The intensity of the acoustic pulsations at the nozzle edge was varied from 0 to 30 dB by moving the sound-reflecting disk 4 along the nozzle axis. Disks of diameters $6 \cdot 10^{-2}$, $9.5 \cdot 10^{-2}$, $1.15 \cdot 10^{-1}$ m were used to achieve the greatest extent of pulsation modulation as a function of oscillation frequency; the range of disk placement was 4-12 calibers along the flow above the nozzle edge. In this way it was possible to change smoothly the effectiveness of the feedback with less disturbance of the jet flow than in [7, 8].

The propagation velocity of signals along the inner feedback loop was varied smoothly by increasing the velocity of the subsonic coaxial sheathing stream in which the jet–obstacle system was placed (Fig. 1b). The sheathing stream flows out of the insufflation nozzle 5 which has a relative diameter of 7 calibers of the central nozzle. The range of Mach numbers for

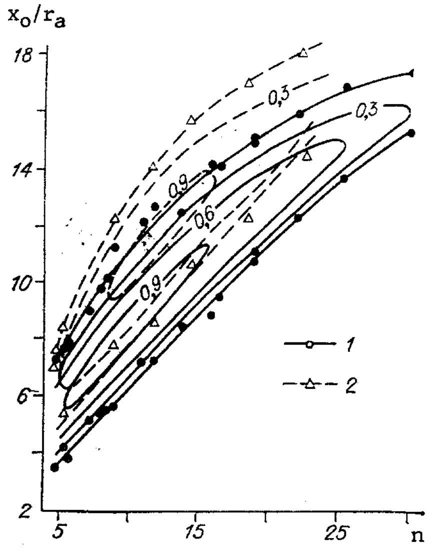

Fig. 2

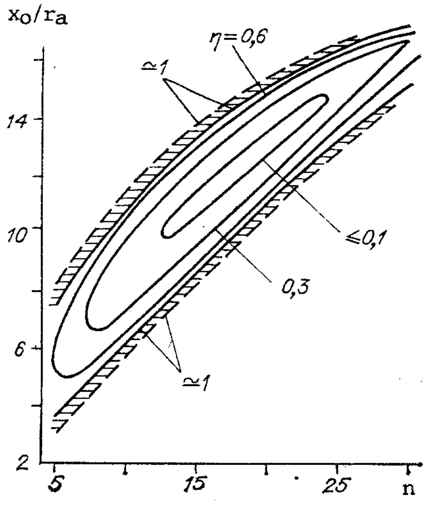

Fig. 3

the sheathing stream was M_∞ = 0-0.7. The edge of the central jet nozzle was placed level with the edge of the insufflating nozzle. To prevent flow separation, the inner form of the central nozzle tapers smoothly to its edge. In addition, gauge 3 was located in this case in front of the compression region of the insufflation nozzle, three insufflation nozzle diameters upstream to reduce its disturbance of the sheathing stream. Measurements of the total head show that the azimuthal nonuniformities in the sheathing stream do not exceed 5%. Experiments in subsonic streams make it possible to trace the genesis of measurements and to show their connection with the phenomenon; this is not so in [9], where the connection with the initial process is difficult to show.

2. Figure 2 curve 1 (for $M_\infty = 0$) shows the experimentally determined region of free oscillations in the absence of an insufflating nozzle and of a sound-reflecting disk. Here contours of equal pressure pulsation amplitude at the obstacle are shown. Unity corresponds to a 192-194 dB pulsation level.

When the sound-reflecting disk is moved along the nozzle axis, the level of pressure pulsation (specifically, the first harmonic) at the nozzle edge changes. This is related to the interference of the soundwaves incident on and reflected from the reflecting disk. It was observed that the level of the first harmonic of the pulsation at the obstacle ΔL_o depends on both the level of the first harmonic of the pulsation at the nozzle edge ΔL_a and on the position of the point (n, $\bar{x}_o$) in the free-oscillation region (Fig. 2). At the edge of this region, the connection with the change is stronger, while at the center, it is weaker. If a coefficient of proportionality of the change η is introduced ($\Delta L_o = \eta \Delta L_a$, ΔL_a, ΔL_o in logarithmic units), then its distribution in the free oscillation region can be depicted in terms of contours of equal values of η (Fig. 3). The contours are obtained by approximating the measurements, carried out with 2.0 step size in n and a 1.0 step size in $\bar{x}_0$. Moreover, the presence of the sound-reflecting disk somewhat expands the region of free oscillations. The hatching in Fig. 3 shows the 60% confidence interval, where oscillations were detected which arise when the disk is moved and which lie beyond the boundaries of the region shown in Fig. 2. For these oscillations $\eta \approx 1$. In the center of the free-oscillation region, $\eta < 0.1$, since the pulsation level at the nozzle edge must be quite high (≈170 dB at the center of the free-oscillation region) in order for the interference field at the obstacle to cause an additional change of 2 dB in the pulsation level at the obstacle.

3. Insufflating the jet–obstacle system by a subsonic sheathing flow shifts the free-oscillation region to larger $\bar{x}_o$ (see Fig. 2, curve 2, for $M_\infty = 0.62$). In this case the shift in boundaries of the region is proportional to the value of $\bar{x}_o$ of each point on the boundary. The relative shift of the boundary can be described by the following empirical relations

$$(\bar{x}_o/\bar{x}_o^0) \simeq (1 + M_\infty^{2,9}) \pm 0{,}06$$

for the lower boundary, and

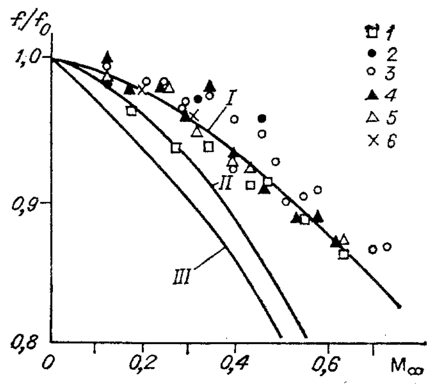

Fig. 4

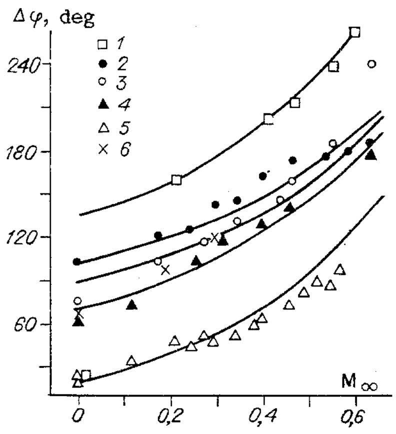

Fig. 5

$$(\bar{x}_0/\bar{x}_0^0) \simeq (1 + 0{,}47\mathrm{M}_\infty^{2{,}7}) \pm 0{,}03 \qquad (3.1)$$

for the upper boundary of the free-oscillation region. With increasing M_∞ of the insufflating flow, the absolute maximum of the pressure pulsation intensity at the obstacle is unchanged (within the limits of measurement accuracy) and is close to 192 dB. The form and position of contours of equal intensity also change little, and are similar to those shown in Fig. 2.

Figure 4 shows the results of measuring the pressure pulsation frequency at the obstacle with increasing M_∞ for the insufflating flow. Here data for the conditions of outflow intersecting the free-oscillation zone for M_∞ = 0 and 0.62 are: point 1 corresponds to n = 9.5; $\bar{x}_0$ = 7.8; 2) 11; 11; 3) 12.2; 10.7; 4) 11.5; 10; 5) 9.5; 9; 6) 14.5; 10.7. The observed change in relative frequency of the pulsations can be approximated by (curve 1 in Fig. 4):

$$f/f_0 \simeq (1 - \mathrm{M}_\infty)^{0{,}14}.$$

Figure 5 shows the results of measuring the phase shift between the first harmonic of the pressure pulsation at the obstacle and the nozzle as a function of M_∞. The phase data were corrected for the distance from the nozzle edge to the gauge and for the change in axial velocity of the insufflating flow in the compression section of the nozzle. The outflow conditions correspond to those of Fig. 4. The rather large value for the phase shift, exceeding 90°, with change in the velocity of the sheathing flow is of note.

4. Let us analyze these results from the viewpoint of the fundamental models of the process. Figure 4 shows the change in the relative frequency of the oscillations as a function of M_∞, computed according to models with outer feedback ([5, 6], curves II and III). The calculations were done for n = 11, with a convection velocity of the disturbance at the jet boundary of u_c, obtained using [11]

$$u_c \simeq 0{,}7\, u_b + 0{,}3\, u_\infty, \qquad (4.1)$$

where u_b is the velocity at the jet boundary [5]; and u_∞ is the velocity of the sheathing flow. The value of the mean position of the central shock wave used in the calculations was estimated based on data from [12]. In accordance with the models of [2-4], the oscillation frequency does not depend on external conditions, but is completely determined by conditions in the shock layer in front of the obstacle. Comparison with experiment shows that there is qualitative agreement with the models of [5, 6], but the quantitative discrepancy is quite large for both models.

Figure 5 shows the computed relation for the change in the phase difference for the first harmonic of the pressure pulsation at the obstacle and at the nozzle. It is assumed that the phase changes only as a result of retardation of the propagation velocity of the sound waves in the intersecting flow, and as a result of the observed change in the oscillation frequency (Fig. 4). The distance from the nozzle to the mean position of the central shock wave was used as the characteristic length in the calculations [12], since it is just this section of the outer flow that acts on the velocity of the sound waves propagating toward the nozzle. The starting assumptions are supported by the satisfactory qualitative and

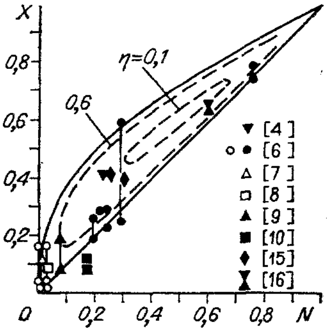

Fig. 6

quantitative agreement of the calculated curves and experimental points. In models with outer feedback, the large measured value of the phase change is assumed to be due to the presence of a compensating mechanism for the phase growth in the oscillation cycle, since the sum of the phases in all of the cycle segments must equal 360°. The sole mechanism for decreasing the phase is related to the increase in the convective velocity of the disturbance at the jet boundary [see (4.1)]. However, estimates clearly show that this mechanism is inadequate; it in fact leads to a drop in frequency (curves II, III in Fig. 4). Another possible channel for compensation of the phase growth might be a decrease in the nozzle—obstacle spacing. In this case, the path traversed by the signal along the loop is shortened, as is part of the direct coupling path along the jet boundary. This leads to a shift in the free-oscillation region to smaller x_0. In experiments the inverse pattern is observed [see (3.1)].

On the other hand, in models with inner feedback, the difference in phases along the sections of the oscillation cycle does not depend on external conditions and any change in the pulsation phase at the nozzle edge is admissible. The shift in the free-oscillation region to larger x_0 can be explained by an increase in the longitudinal dimension of the first jet cell in the sheathing flow. The growth of x_0 for the upper zone boundary (3.1) is in good agreement with the increase in relative cell length of the jet wave structure ℓ/ℓ_0 in a subsonic sheathing flow, as predicted in [13] and approximated by

$$l/l_0 \simeq 1 + 0{,}375\,M_\infty^{2,5}.$$

Thus, it can be asserted that the behavior of the phase difference and the position of the free oscillation zone with growth in the sheathing flow velocity are for the most part in agreement with the models of [2-4].

According to the outer feedback model, the pressure pulsation level at the nozzle edge exerts a considerable influence on the oscillation intensity, since it determines the efficiency of the feedback loop. In inner feedback models, this parameter does not affect the formation of the oscillation cycle. In this case, the data shown in Fig. 3 can be interpreted as a manifestation of the dominant influence of the first mechanism at the boundaries of the free-oscillation region, and of the second at the center. In the remaining cases, both feedback channels play a role. On the other hand, for strongly nonlinear oscillations characteristic of the central part of the oscillation zone, the condition that the initial and final disturbances in the oscillatory system be proportional is not satisfied: even small disturbances can cause maximal pulsations at the obstacle (relaxation oscillations). In connection with this the magnitude of pulsation suppression of 30 dB at the nozzle which is achieved in the experiments is insufficient to break down the outer feedback loop. This prevents unambiguous determination of the basic mechanism supporting the oscillations in the jet system.

These results can be made to compare consistently with the results of [4, 6-10] with the help of an analysis of their place in the generalized zone of free oscillations [14]. The solid line in Fig. 6 shows the generalized zone with the jet—obstacle interaction parameters from [4, 7-10] and from works cited in review [6] superimposed. Data from [15, 16] are also plotted, from calculations using models with inner feedback channels. Here X and N are the generalized nozzle—obstacle spacing and the degree of choking of the jet, respectively. The open symbols denote results of those studies in which the dominating influence of the outer feedback channel is known; the filled symbols, that of the inner feedback channel. For comparison, Fig. 6 shows the contour $\eta = 0.1$ and 0.6 of Fig. 3. It is clear that the outer feedback channel manifests itself at the periphery of the zone, while the inner channel does so in the central region of the oscillation zone. This is in complete agreement with the distribution of the coefficient η along the zone, and indicates the existence of intrinsic regions of applicability for each of these models of the process.

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