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SPECTRAL COMPOSITION OF WAVE NUMBERS OF LONGITUDINAL VORTICES AND CHARACTERISTICS OF FLOW STRUCTURE IN A SUPERSONIC JET

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UDC 533.6.011

Azimuthal nonuniformities of the distribution of the gasdynamic parameters have been discovered in the supersonic jet issuing from an axisymmetric nozzle in the off-design regime [1-5]. The absence of explanations for the described phenomenon in the works on jets [6-7] indicates the inadequate level of our knowledge of the structure of the supersonic jet. The existence of azimuthal nonuniformities in the initial segment of the jet has been identified, both with the aid of schlieren photographs, on which longitudinal bands are seen, and by direct measurement of the azimuthal distribution of the total pressure in the flow. These nonuniformities show up in jets issuing from nozzles of various dimensions with various gasdynamic parameters, indicating the high frequency of occurrence of this phenomenon, which is observed both in rarefied gas jets [1-2] and in jets at high Reynolds numbers [3-5]. The reproducibility of this phenomenon is confirmed by experiments [8], the results of which basically agree with the conclusions published in [3-5]. The possible cause for the onset of the observed azimuthal nonuniformity may be the coherent vortical formations of the Taylor–Görtler vortex type [3-5] in the shear layer of the jet discharging into a submerged space. This hypothesis is based on comparison of the experimental observations in free jets with the data from the recording of longitudinal vortices in the case of the attachment of both plane [9, 10] and axisymmetric [11, 12] flows. In the case of the discharge of an axisymmetric supersonic jet into a coaxial cylindrical channel with sudden expansion, it is noted that the "primary cause of the formation of longitudinal vortices is loss of stability of the boundary layer upon abrupt rotation of this layer, when the equilibrium between the centrifugal forces and the pressure forces is disrupted" [11]. Longitudinal vortical structures have also been observed in the zone of interaction of the supersonic jet with a liquid [12]. The vortical motion intensifies the mass exchange of the jet with the ambient medium, significantly alters the azimuthal and radial distributions of the total pressure and the Mach number, and also influences the configuration of the jet boundary. The inadequate level of our knowledge of the subject questions leads to the need for further studies of the conditions of the onset and transformation of three-dimensional disturbances in the shear layer of the supersonic jet. An analytic description of the Taylor–Görtler instability in supersonic jets in application to the existing experimental data was presented in [13-16].

In the present work we made a broad experimental study of the observed phenomenon, including probe measurements of the variations of the total pressure, the obtaining of data on the spectral composition of the wave numbers of the spatial nonuniformities, and laser visualization of the jet cross section.

1. The experiments were performed on a jet facility with use of the equipment described in [3-5]. The most significant difference between the present study and that performed previously lies in the use of a rotating nozzle, which made it possible to obtain data on the nature of the azimuthal nonuniformities in the entire jet flow field. In [3-5] the azimuthal angle variation range was 57°, in the present work the range was 360°. Other differences in the measurement technique will be noted below. The phenomenon was studied on an underexpanded supersonic air jet, discharging from an axisymmetric conical nozzle with exit section diameter $d_a = 0.02$ m into a submerged space. The Mach number of the jet at the nozzle exit was $M_a = 1.5$, and the degree of off-design (ratio of the pressure at the nozzle exit to the external pressure) was 4.15. The Reynolds number, based on the characteristic velocity of the jet at the nozzle exit, the dynamic viscosity in the submerged space, and the length of the first cell of the underexpanded jet, was $3.6 \cdot 10^6$.

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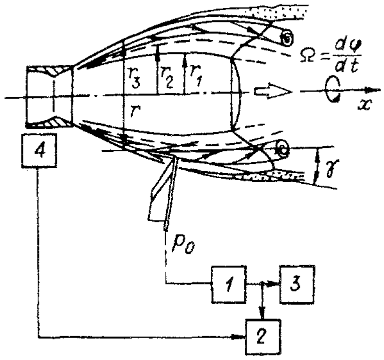

Fig. 1

Comparison of the results obtained on nozzles with different level of machining quality and, consequently, different degree of roughness of the inner surface of the nozzle, showed that there is a connection between the condition of the inner surface of the nozzle and the azimuthal nonuniformities in the jet. The basic results of the experiments performed to study the flow were obtained with the use of nozzles, the inner surface of which had a production finish defined by class-six accuracy, i.e., the roughness height did not exceed 2.5 μm. The existence of the connection between the roughness in the nozzle and the position of the vortices in the jet made it possible to use a nozzle, including its subsonic part, rotating about its axis. The nozzle was rotated at a constant angular velocity $\Omega = d\varphi/dt$, which was maintained to within 5%. The pressure in the nozzle facility prechamber was maintained constant to within 2%.

As the nozzle rotated, the discharging jet, "tied" to its inner surface, displaced together with the nonuniformities relative to the air pressure pickup, mounted on a micrometer traversing mechanism. The traversing mechanism provided displacement of the measuring instruments along the radius and the axis of the jet with accuracy 0.05 and 0.1 mm, respectively. The nozzle rotation angle φ was monitored with the aid of a selsyn pickup. The measurement scheme is shown in Fig. 1.

The study of the azimuthal distribution of the total pressure p_0 in the compressed layer of the jet was made by a Pitot tube with outside diameter 0.6 mm. The Pitot tube was connected with a pressure transmitter, the signal from which after passing through the amplifier 1 was recorded on the magnetic tape of the multichannel recorder 2. We used two channels of the recorder, one of which recorded the signal from the pressure sensor; the other recorded the signal from the nozzle rotation angle sensor 4. This recording system made it possible to find the correspondence between the measured total pressure and the azimuthal angle. The position of the sensing port of the Pitot tube in the jet was defined by the coordinates x and r (the longitudinal distance from the nozzle exit and the radial distance from the nozzle axis) and by the azimuthal angle φ. The direction of the streamline in the given section of the jet was determined in accordance with the current concepts on the structure of the flow with the aid of schlieren pictures. The air pressure probe was aligned with the streamline established in this way. Here we made use of the fact that the total pressure pickup is insensitive to flow deflection if the latter is less than 30°.

Concurrently with recording to the signal on the magnetic tape of the recorder, the input signal was fed to the two-coordinate plotter 3, where the relation $p_0(\varphi)$ was plotted. Figure 2 shows the dependence of the total pressure in the jet on the azimuthal angle φ with variation of the latter from 0 to 360°. The data correspond to the cross section located at the distance $x = 2d_a$ from the nozzle exit. Also shown is the graph of the variation of the total pressure along the jet radius $p_0(r)$, on which the points denote the values of p_0 corresponding to $\varphi = 0$ on the relations $p_0(\varphi)$ (lines 1-7), obtained with various radial positions of the Pitot tube (the values of the parameter r/r_a are shown above). On the graph of $p_0(r)$ there are noted the locations of the characteristic gasdynamic or geometric features of the jet: r_1 is the position of the caternary shock, r_2 is the coordinate of the total pressure peak in the jet compressed layer (which is at the same time the inner edge of the mixing layer), r_3 is the boundary of the jet, and r_4 is the distance to the place in the jet where the flow velocity is equal to the local speed of sound.

With regard to the form of the $p_0(\varphi)$ traces, the compressed layer $[r_1, r_3]$ splits into two characteristic regions. In the region $r_1 < r < r_2$ the relation $p_0(\varphi)$ is nearly a straight

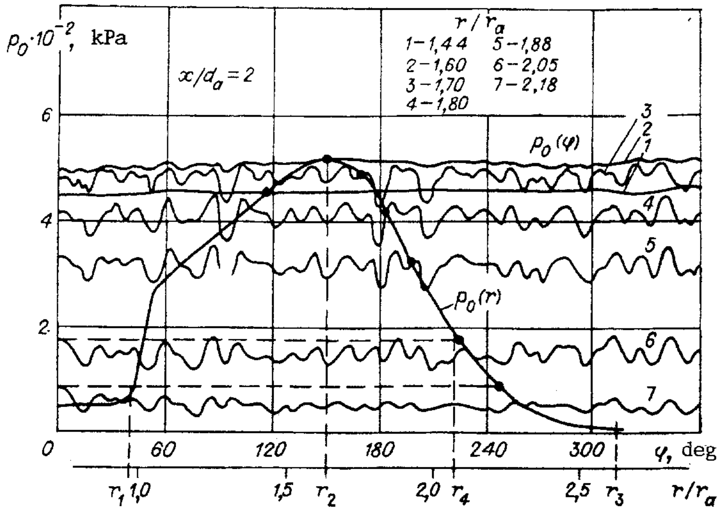

Fig. 2

line (trace 1), and increase of the total pressure to the maximal value of the relation $p_0(r)$ takes place nearly linearly, which corresponds to the inviscid supersonic approximation [7], where $d(U^2)/dr > 0$ (U is the average velocity).

The flow region $r_2 < r < r_3$, where $d(U^2)/dr < 0$, is the mixing layer, in which the three-dimensional disturbances that are being studied are observed. The azimuthal distribution of the total pressure in the mixing layer has a variational nature, and the amplitude of the variations is higher in the middle of the mixing layer. It was shown in [3, 5] that the amplitude of the variations of the distribution of the total pressure and the Mach number varies in the limits from 10 to 25% relative to the mean values.

This last observation agrees with the criteria for inviscid stability of subsonic boundary layers to Taylor–Görtler waves in the parallel flow approximation [16]. It was shown in [16] that for a concave wall the flow is stable with $d(U^2)/dr > 0$ and is unstable with $d(U^2)/dr < 0$. For the first cell of the supersonic underexpanded jet, its boundary can be examined as a concave wall, and, in accordance with the cited criterion, the flow in the region $[r_1, r_2]$ is stable, while in the region $[r_2, r_3]$ it is unstable, which is also seen from experiment.

Quite good reproducibility of the relation $p_0(\varphi)$ is observed, showing up in coincidence of the maxima and minima for the same values of the nozzle rotation angle for realizations obtained during various startups of the facility. This also shows up in reproduction of the characteristic features of the curves. The latter indicates the steady-state nature of the disturbances causing nonuniformity of the distribution of the gasdynamic quantities in the jet. The fluctuations of p_0 on the relation $p_0(\varphi)$ change, not only as a function of the governing quantities x and r but also as a function of the azimuthal angle φ. This property is characteristic for all the relations $p_0(\varphi)$ obtained in the study. We can suggest that this distribution of the gasdynamic quantities in the jet mixing layer is created by a family of longitudinal vortices of differing dimensions.

A significant systematic error of measurement of the gasdynamic quantities in the mixing layer of the nonisobaric jet may take place if we neglect the nonuniformity of the distribution of these quantities in the azimuthal direction. Figure 3 presents the dependence of the total pressure, measured by the Pitot tube, on the radial coordinate r for various azimuthal positions φ at the jet section $x = 2.3d_a$. The radial distribution profiles $p_0(r)$ were obtained for two characteristic values of the azimuth angle φ_c and φ_d. The difference between them illustrates the foregoing statement.

The relation $p_0(r)_c$ corresponds to the total pressure profile obtained with $\varphi = \varphi_c$, which corresponds to the local maximum on the curve of $p_0(\varphi)$; this point is indicated by the letter c. The profile $p_0(r)_d$ was obtained with $\varphi = \varphi_d$; it corresponds to the local minimum on the curve and is indicated by the letter d. These relations nearly coincide in the inviscid flow region and differ significantly in the mixing layer.

The quantitative estimate of the degree of difference of the noted profiles is determined by the parameter $\Delta p_0/\langle p_0\rangle$, which is the relative deviation of the difference of the

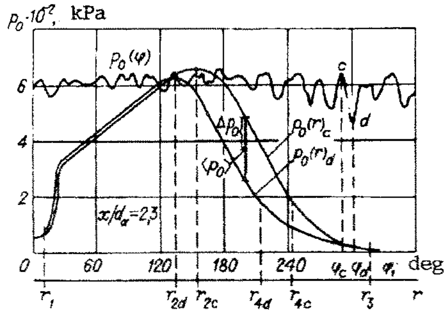

Fig. 3

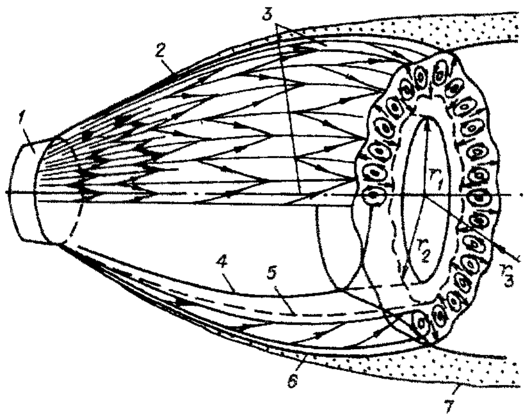
Fig. 4

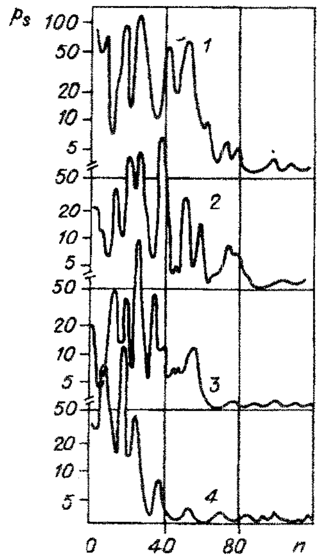

Fig. 5

measured total pressure from the average value, $\Delta p_0 = 0.5\ [p_0(r)_c - p_0(r)_d]$ for $r/r_d = 1.7$, $\langle p_0 \rangle = 0.5\ [p_0(r)_c + p_0(r)_d]$. The quantity $\Delta p_0/\langle p_0 \rangle \approx 0.4$.

We see from Fig. 3 that the maximal value of the total pressure that is recorded on the profile $p_0(r)_c$ is observed for $r = r_{2c}$, while on the profile $p_0(r)_d$ it is observed for $r = r_{2d}$. If we consider that these characteristic values of the radius correspond to the inner edge of the mixing layer, then we can see that the inner edge has the form of a wavy line with the amplitude $(r_{2c} - r_{2d})/(r_{2c} + r_{2d}) \approx 0.1$.

The values r_{4c} and r_{4d} (noted in Fig. 3) correspond to the points on the profile $p_0(r)$ where the Mach number in the mixing layer is equal to unity. Thus, from the probe measurement data the characteristic isolines in the jet mixing layer have a wavy form. No differences are noted in the experimental dependences of the static pressure on the radial coordinate for the different azimuthal angles.

Figure 4 shows the scheme of the flow in a supersonic underexpanded jet (1 is the nozzle, 2 is the jet, 3 are the longitudinal vortices, 4 is the caternary shock, 5 is the inner edge of the mixing layer, 6 is the supersonic jet flow boundary, 7 is the boundary of the jet).

2. A spectral analysis was made of the signal recorded on the magnetic tape in the form of the function $p_0(t)$ (t is the time, uniquely associated with the azimuthal angle φ). The analysis involves the obtaining of the frequency spectra, which correspond to the wave number spectra $p_s(n)$ (n is the wave number of the recorded disturbances). The dependence of the disturbances on φ, as in [16], is taken in the form $p \sim \cos(n\varphi)$. The frequency spectra were obtained with the aid of an SK4-72 spectrum analyzer. Reduction of the level of the parasitic side "lobes" in the spectrum was achieved with the use of a time window of the form

$$u(t) = 0{,}08 + (1/T_p)\sin(\pi t)$$

(T_p is the duration of the signal). The use of a time window of this type transforms the input signal to a signal of the form $p_0(t)u(t)$, which was used to obtain the frequency spectrum of the distribution of the nonuniformities and corresponded to the sought wave number spectrum $p_s(n)$. Figure 5 presents the amplitude spectra of the wave numbers of the azimuthal nonuniformities 1-4 for four sections of the jet $x/d_a = 1.0$, 1.5, 2.0, 2.5. The average total pressure as measured by the Pitot tube was $p_0 \approx 400$ kPa. The ordinate is the amplitude of the fluctuation of p_s, the abscissa is the wave number n. As a rule, recording on the magnetic tape was performed in the course of three revolutions of the nozzle about its axis. In the analysis of the spectrograms it was found that their form depends both on the analysis time t_p and on the location of the realization relative to the surface of the nozzle. A suitable measurement scheme was assembled for monitoring of these parameters. The filter passband width was $\Delta n = 1.5$. We note the presence in the spectrum of individual components of large amplitude in a limited range of wave numbers. For the sections located closer to the nozzle ($x/d_a = 1.0$ and 1.5), the spectral components are recorded in the range $n = 7$ to 75. Apparently this wave number spectrum is due to the presence in the mixing layer of the underexpanded jet near the nozzle exit section of both large-scale and small-scale

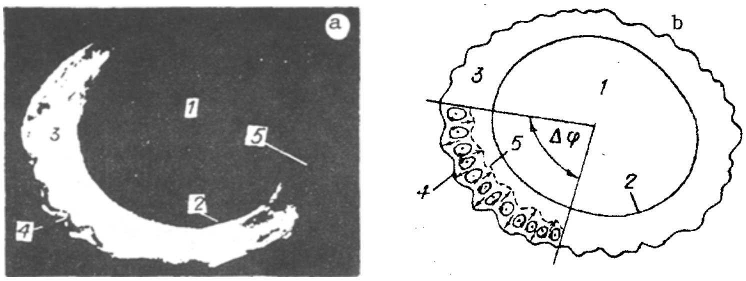

Fig. 6

vortices with domination of the vortical modes with n = 20-30. With increase of the distance from the nozzle (x/d_a = 2.0 and 2.5), the number of the individual components corresponding to large values of n decreases. At the same time there is a shift of the components of the spectrum into the region of small n. In the cross section x/d_a = 2.5 there are identified in the spectrum two components with wave numbers n = 7 and 18, to which there correspond pairs of Taylor—Görtler vortices with relative wavelengths λ/L = 0.066 and 0.026 ($L = 2\pi r_3$ is the circumference of the jet boundary at the given section). With increasing distance from the nozzle, in the process of restructuring of the vortical formations the small-scale vortices disappear and the large-scale vortices decay.

We noted previously the influence of the analysis time T_p and the location of the beginning of the analysis relative to the surface of the nozzle on the form of the spectra, i.e., dependence of the measured wave number spectrum on the azimuthal angle is observed. This indicates nonstationarity of the signal being studied if we examine this signal [$p_0(t)$ corresponds identically to the relation $p_0(\varphi)$] as a random time function. In reality the signal $p_0(t)$ is a determinsitic periodic signal with period equal to the time of a single revolution of the nozzle about its axis T_0. The spectra shown in Fig. 3 were obtained with $T_p = T_0$. The actually observed dependence of the form of the spectrum on the azimuthal angle can be explained as follows. The use of the time window described above leads to a situation in which the different segments of the relation $p_0(t)$ have different weight in obtaining the spectrogram. The differing nature of the relation $p_0(t) = p_0(\varphi)$ for different values of the azimuthal angle is explained by the influence of the natural roughness of the inner surface of the nozzle. As a rule the roughness is not identical for various segments of the nozzle surface and generates differing initial amplitudes of the disturbances, which influences the nature of the nonuniformities therefore recorded in the jet shear layer. The overall influence of the disturbances at the nozzle exit and in its boundary layer on the formation of three-dimensional nonuniformities at the outer edge of the compressed layer of the supersonic nonisobaric jet requires special study.

3. Visualization of the three-dimensional flow in the jet was performed with use of the "laser knife" method. This method is based on recording of the laser radiation scattered by the particles of the jet. This radiation is created in the form of a plane that is oriented perpendicular to the jet axis. The natural dust content of the jet was not sufficient, therefore we used a special smoke-creating device, located in the facility prechamber. A plane light beam ("laser knife") was formed with the aid of an optical system similar to that described in [18]. The light source was a continuous-duty argon laser of the LG 106 M-1 type with power 1.5 W. The optical system made it possible to establish the position of the knife at various sections of the jet. Figure 6a shows a photograph of the jet cross section x/d_a = 2.0, obtained with the aid of a camera located downstream at a distance of 0.25 m outside the jet stream. The angle between the direction of photography and the jet axis was 60°. The exposure time was about two seconds. Figure 6b shows a schematic of the flow, which is based on analysis of the results of the measurement of the flow parameters in the jet by the probe methods and visualization with use of the schlieren method. The following notations are used in the photograph and the schematic: 1 is the region of rarefied flow, 2 is the catenary shock, 3 is the compressed layer, 4 is the boundary of the jet, 5 is the inner edge of the mixing layer. Since in the supersonic jet the majority of the gas flows through the compressed layer, high concentration of the particles is observed in this layer, which leads to increase of the intensity of the scattered light. Figure 6a shows clearly the position of the catenary shock and the wavy outer boundary of the supersonic part of the jet mixing layer, which is due to outward radial migration of the high-head stream from the jet axis and entrainment of the quiescent low-head gas into the motion. This is caused by the

presence in the mixing layer of longitudinal vortices, with the neighboring vortices having opposite direction of rotation.

The difference between the pattern of jet cross section visualization with use of the "laser knife" (described herein) and the visualization patterns of [8] lies in the fact that in [8] the laser radiation is scattered by the mist that forms as the result of entrainment of the ambient gas into the high-velocity flow. In the present work the structure of the jet flow is visualized as the result of scattering on the smoke particles that are present in the jet stream.

We noted previously that the intensities of the nonuniformities are different for different azimuthal angles. The results of visualization with use of the "laser knife" correspond to this conclusion, which indicates the presence in the jet of longitudinal vortical formations of differing scales. The blurring of the image on the picture of one side of the jet cross section is caused by the fact that the jet was observed through the turbulent high-velocity jet stream.

Thus, the results of the experimental study of three-dimensional flow in the supersonic underexpanded jet confirm the presence in the outer part of the jet compressed layer of significant nonuniformity of the distribution of the gasdynamic quantities in the azimuthal direction. We have shown that ignoring of this situation may lead to the appearance of a systematic error in determining the gasdynamic quantities, reaching 40%. Spectral measurements of the wave numbers of the three-dimensional nonuniformities indicate a complex collection of interacting disturbances of differing scale. We observe enlargement of the structures in the downstream direction, which is probably caused by interaction of the structures with one another and with the stream. We consider that the quasiperiodic nonuniformity of the distribution of the gasdynamic quantities with respect to the azimuth of the peripheral region of the jet takes place under the action of disturbances, which may very likely be disturbances of the Taylor—Görtler vortex type.

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TAYLOR–GÖRTLER INSTABILITY IN A SUPERSONIC JET

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UDC 532.526+533

This paper is devoted to the numerical modeling of the characteristics and structure of a new (for supersonic jets) class of disturbances and some applications of the results to the interpretation of the experimental data presented in [1-3]. The object of this paper is to obtain basic data and to verify the model of the existence of the Taylor–Görtler instability in a free supersonic flow. The literature available to us does not contain any information about such investigations. This work is a detailed exposition of the results presented briefly in [3, 4].

We consider first the hypothesis that the flow contains stationary rotational disturbances of the type Taylor–Görtler waves (T–G), excited by additional centrifugal forces arising due to the curvature of the trajectories of the gas following the real cellular "barrel-shape" structure of a nonisobaric jet. This choice, from among existing alternative choices, one of which is described in [5], is dictated by the following circumstances. First, longitudinal bands, indicating the existence of azimuthal nonuniformities of the optical density, are recorded near the nozzle cutoff, where the trajectories of the gas are actually curvilinear. Second, under the experimental conditions (underexpanded jet with degree of underexpansion $N \sim 5$) a wide-band spectrum of noise is recorded; this precludes the appearance of strong nonlinear effects at such early stages, and the other nonlinearities will be second-order infinitesimals compared to the linear T–G waves. The weak effect of sharp gradients at the nozzle cutoff flow discontinuities is indicated by the fact that the intensity of the bands decreases with increaing surface smoothness under constant efflux conditions.

So, the hypothesis that stationary rotational disturbances exist in the initial section of the jet is most plausible. Within the framework of this hypothesis we performed numerical modeling of the characteristics of the waves, studied the dependences on the flow parameters, and analyzed the experimental data in order to retrieve the local values of the density and velocity of the flow.

1. Equations for the Disturbances. The flow scheme within the first cell ("barrel") of the jet is displayed in Fig. 1. A system of linearized equations for T–G-wave-type disturbances, which includes a number of assumptions to be discussed below, was constructed in [5]:

$$\begin{gathered} Uv_x' - [2Uu'/R_0] + p_r'/\rho_0 = 0, \quad Uw_x' + p_\varphi'/r\rho_0 = 0, \\ Uu_x' + U_r v' + [Uv'/R_0] + p_x'/\rho_0 = 0, \quad U(p'/a^2 - \rho')_x - \rho_{0r} v' = 0, \\ U\rho_x' + \rho_{0r} v' + \rho_0 (v_r' + w_\varphi'/r + u_x' + v'/r + [v'/R_0]) = 0. \end{gathered} \tag{1.1}$$

This system was constructed for a one-dimensional flow of a compressible, nonviscous, heat-nonconducting gas with the velocity field $\mathbf{u} = |\varepsilon v', \varepsilon w', U + \varepsilon u'|$, where v', w', u' are, respectively, the transverse, azimuthal, and longitudinal, components of the disturbances in the coordinates r, φ, and x; ρ' and p' are the disturbances of the density and pressure, respectively; $U = U(r)$ is the longitudinal component of the average velocity; ρ_0 is the

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