STREAMWISE VORTEX STRUCTURES IN A SUPERSONIC JET SHEAR LAYER

V.I. Zapryagaev, N.P. Kiselev, and A.V. Solotchin

Institute of Theoretical and Applied Mechanics SB RAS,
630090 Novosibirsk Russia

From the viewpoint of pure science, the interest to studying the flow structure of high speed jet shear layers is provoked by the rich variety of physical phenomena in supersonic jet shear layers. Such studies are also of considerable practical significance that causes from the wide use of mixing processes in ejectors, propulsion systems, and some other apparatus. The stationary streamwise vortices in supersonic jet shear layers remain a leading subject of much investigation considering possible intensification of mixing processes at the jet boundary of flows.

Previous works devoted to the study of streamwise vortex structures in supersonic jet shear layers have been reviewed in [1, 2]. The flow pattern of a supersonic jet was found to include a system of stationary streamwise vortices. These vortices manifest themselves most distinctly in the first cell of the jet, being also clearly registered throughout the whole shear layer but not in the inner part of the jet. It should be noted that such streamwise vortex structures were also studied in [3, 4]. The spectral composition of the vortices was examined in [5] in order to establish regularities in their downstream development and perform a direct comparison with numerical simulations [6]. However, the increments for these vortices display a too complex behavior as functions of the azimuthal wavenumber [5].

Such an intricate behavior of the increment with the azimuthal wavenumber may be a consequence of nonlinear character of the interaction between different flow modes. Another reason may lie in the more complex radial amplitude distribution of individual modes corresponding to the streamwise vortices. The present work describes a detailed study of the radial amplitude distribution of various azimuthal modes in an underexpanded supersonic jet.

The experiment aimed at examination of the streamwise vortex structures of such a jet was carried out on a vertical jet facility in the Institute of Applied and Theoretical Mechanics, SB RAS. With this object in view, we performed detailed measurements of radial and azimuthal distributions of the total pressure measured by a Pitot probe with the outer diameter 0.6 mm. The measurements were carried out on a supersonic jet exhausted from a convergent M_a=1.0 nozzle with the nozzle exit radius R_a = 10 mm. The nozzle pressure ratio was $N_{pr}=P_o/P_h=5.0$, where P_o is the stagnation pressure and P_h is the pressure in the ambient medium. In the experiments, a traversing gear was used to scan the flow with the Pitot tube along the x and r coordinates, where x is the distance from the nozzle exit section and r is the radial distance. The azimuthal coordinate φ was controlled by rotation of the nozzle with the help of a stepping motor. The measurements were made on a cool air jet exhausting into ambient space. The signal from the pressure sensor was measured by an automated PC-based data acquisition system equipped with a ten bits analog-to-digital converter.

Figure 1,*a* shows the jet structure and the cross-sections x/Ra = 2.0; 2.5, and 3.0 (A, B, and C) in which the detailed measurements of the radial and azimuthal dependences of the Pitot pressure Pt(r, φ) were performed. The measured radial distributions of pressure in the three cross-sections are shows in Fig. 1,*b*. The abrupt pressure rise at r/Ra = 0.3-0.6 is due to the barrel compression shock. The shear-layer thickness increases in the downstream direction, although the highest pressure registered at the internal edge of the shear layer remains almost constant.

The Pitot-pressure distributions over the azimuthal coordinate were measured with a 1o step. The dependences Pt(φ) measured in the cross-sections A, B, and C for almost identical values of the radial coordinate are shown in Fig. 2,*a*. Figure 2,*b* shows typical dependences for the Pt/Po ratio which was calculated for three values of the radial coordinate in the cross-section A. The azimuthal distributions of pressure display distinct maxima and minima at one and the same angles

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Abstract

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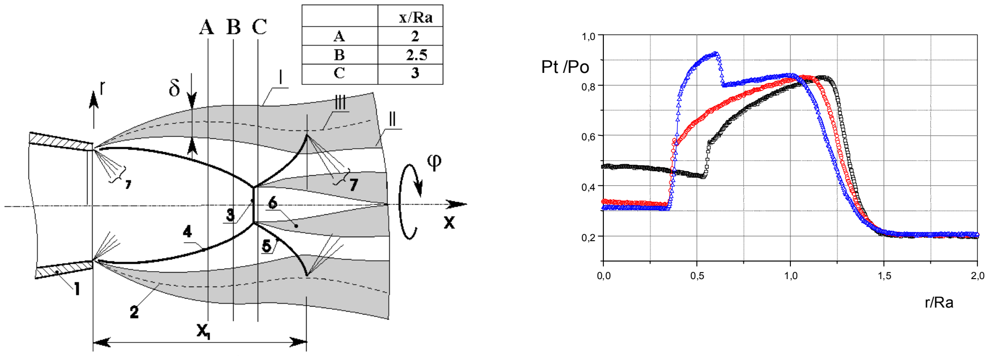


a) *b*)

Fig. 1.

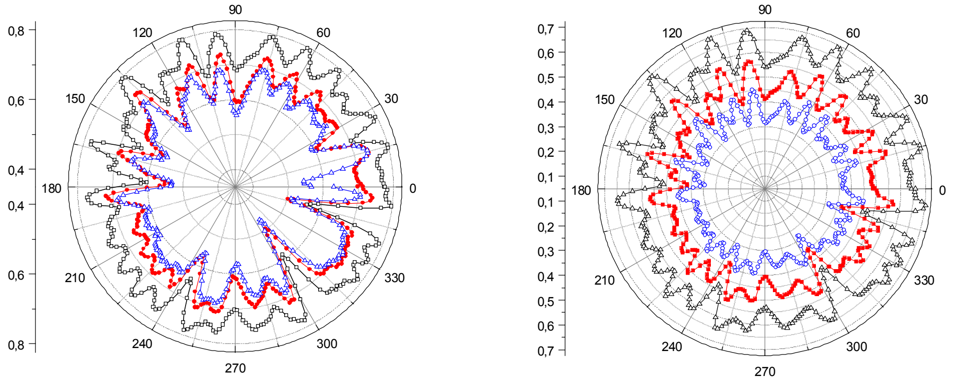
a: Diagram of the initial part of the supersonic under expanded jet (Ma = 1) exhausting from the convergent nozzle. I – jet edge; II – internal shear layer boundary; III – shear-layer centerline. x, r, and φ are the cylindrical coordinates; 1 – nozzle; 2 – shear layer (of thickness δ); 3 – Mach disk; 4 and 5 – barrel and reflected compression shocks; 6– shear layer behind the triple point; 7– expansion fan.
b: Radial Pitot pressure profiles measured in the cross-sections A (x/Ra = 2, squares), B (x/Ra = 2.5, circles), and C (x/Ra = 3, triangles).

φ, which observation is indicative of the steady-state character of the steamwise vortices in the jet shear layer, proving simultaneously good reproducibility of detected azimuthal disturbances.

In the shear layer of the flow, 15 to 18 azimuthal dependences Pt(φ) were obtained for each jet cross-section. Typical locations of the Pitot tube for the cross-section A (designated with the numbers 1-15) are shown in Fig. 3,*a*.

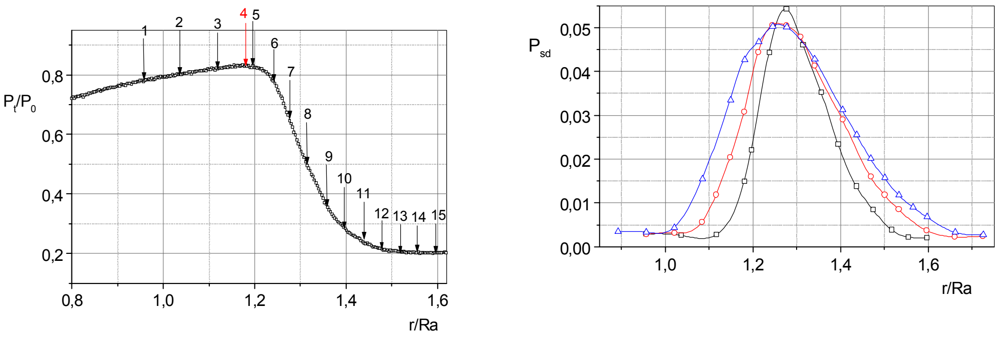
The root-mean-square amplitude P_{sd} of pressure fluctuations was calculated for each azimuthal dependence of the normalized Pitot pressure P_t/P_o. Figure 3,*b* shows the obtained distributions of P_{sd}, which are seen to display similar shapes for all the three jet cross-sections. The root-mean-square amplitude of pressure fluctuations is seen to never exceed 0.055, its maximum being observed in the middle part of the shear layer, at the point $r/R_a \approx 1.28$.

Data on the spectral composition of azimuthal disturbanses are known to be extremely useful in verification of physical models for the formation and development of vortex structures in shear layers. The dependence of P_t/P_o on the azimuthal angle φ was expanded into a Fourier



a) *b*)

Fig. 2. Azimuthal distribution of the Pitot pressure.
a) – at a fixed values of the radial coordinate (r/Ra ≈ 1.25) in the three jet cross-sections: A – squares, B – circles, and C – triangles; *b*) – in the cross-section A at three fixed values of the radial coordinates, r/Ra = 1.28 (triangles), 1.32 (squares), and 1.36 (circles).



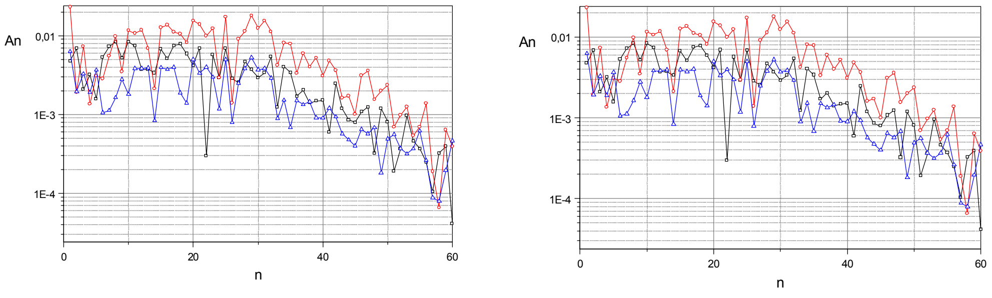
a) *b*)

Fig. 3.
a) Radial distribution of the Pitot pressure at x/Ra= 2, the numbers 1 to 15 denote the radial coordinates at which the azimuthal distributions Pt(φ) were measured.
b) Root-mean-square amplitude of pressure fluctuations in the jet cross-sections A (squares); B (circles); and C (triangles).

rows with using the natural period, 360°. The amplitude A_n corresponds to an azimuthal wavenumber n. Typical spectra $A_n(n)$ are shown in Fig. 4.

The spectrum $A_n(n)$ display a complex character, which depends on the nozzle surface roughness and on the regularities of the development of streamwise vortex structures in the shear layer. In the present study, primarily attention was concentrated on revealing the cross-sectional distribution of spectral components in the shear layer. With this aim in mind, we plotted individual spectral components A_n for some Fourier amplitudes taken at different values of the azimuthal wavenumber n versus the relative radius r/R_a (see Fig. 5, a – h). Here, only the data for the first forty azimuthal modes are shown because the amplitude of some Fourier modes with n>40 was found to decrease markedly, rapidly approaching the noise level, as was the case, for instance, with the amplitude $A_{n=43}$=0.0004 for the cross-section C (see Fig. 4,b).

The A_n vs r/R_a dependences display different radial behavior of their amplitudes. The difference is both in the radial position of the maximum and in the different general appearance of the amplitude function $A_n(r/R_a)$ for different values of the azimuthal wavenumber n. Different modes exhibit different numbers of maxima, for instance, one maximum (for the azimuthal modes n= 7, 8, 10, 21, 22, 23, 25…) or two maxima (for n= 6, 9, 24…). A similar behavior of the amplitude functions $A_n(r/R_a)$ is also displayed by other jet cross-sections. An amplitude function with one maximum may be interpreted as resulting from a one-layered set of streamwise vortices whose length depends on



a) *b*)

Fig. 4. Fourier amplitude versus azimuthal wavenumber for the cross-section A at three values of the radial coordinate, r/Ra= 1.2 (squares), 1.32 (circles), and 1.44 (triangles) (*a*) and for a fixed value of the radial coordinate r/Ra= 1.28 at the jet cross-sections A (squares), B (circles), and C (triangles) (*b*).

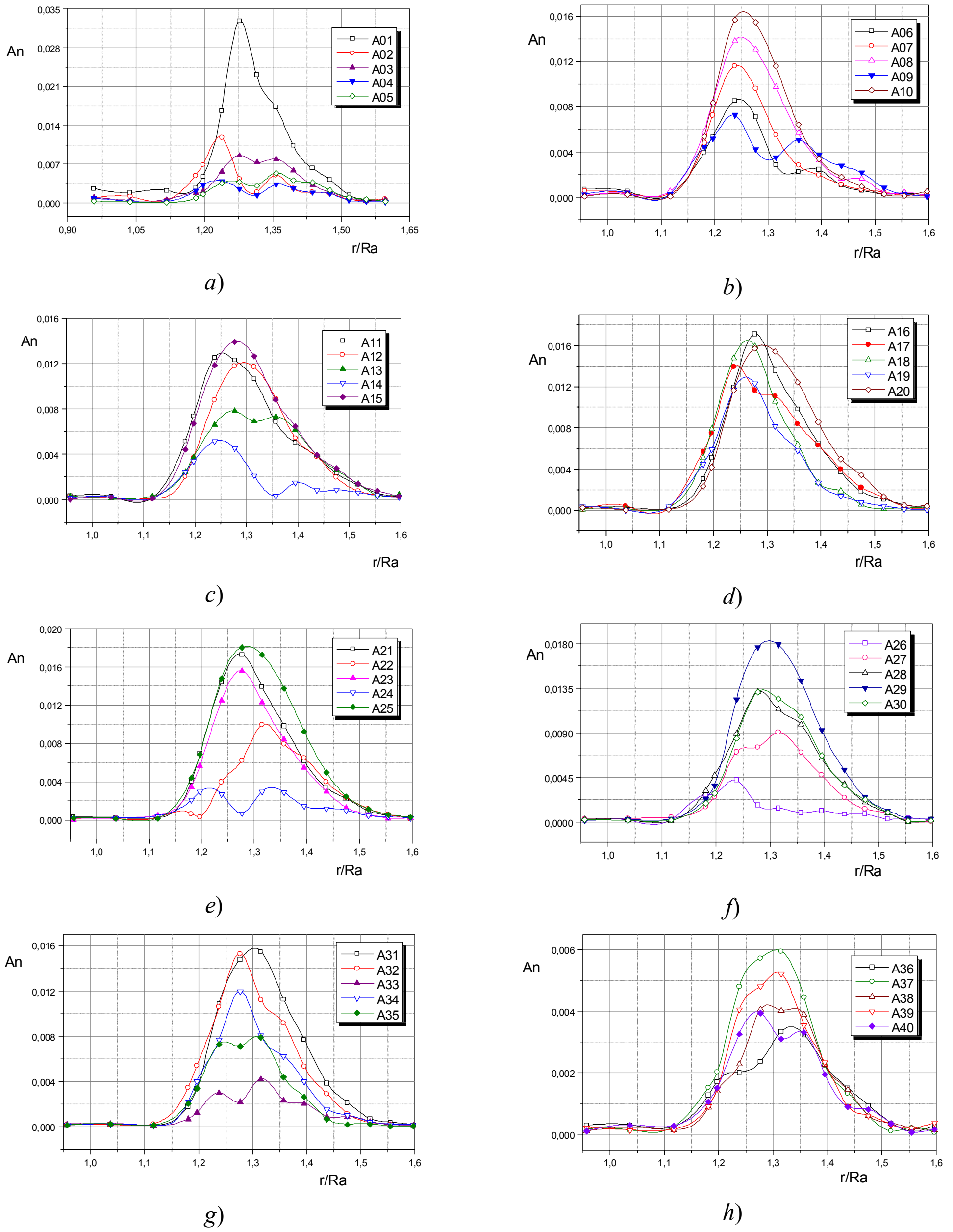
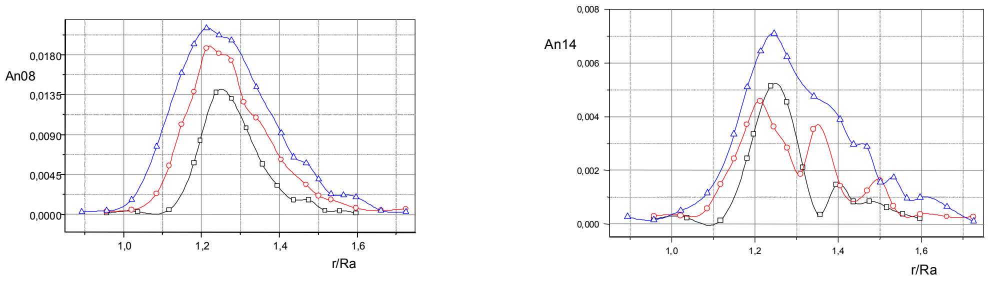


Fig. 5. Radial distributions of the Fourier components for various azimuthal wavenumbers n in the cross-section A (x/Ra= 2.0): *a*) n = 1-5; *b*) n=6-10; *c*) n = 11-15; *d*) n=16-20; *e*) n= 21-25; *f*) n= 26-30; *g*) n= 31-35; and *h*) n= 36-40.

the wavenumber. Manifestation of two or more local maxima in the radial distribution of an amplitude function may be interpreted as stemming from realization of a two- or multi-layered system of streamwise vortices in the jet shear layer for a given azimuthal wavenumber.

The general appearance of the radial distribution of the amplitude function may be different for different cross-sections (A, B, and C). Figure 6,a shows the radial amplitude functions



a) *b*)

Fig. 6. Radial amplitude functions for the cross-sections A (squares); B (circles); and C (triangles); *a* – n = 8; *b* – n = 14.

$A_n(r/R_a)$ for the azimuthal mode n=8 with one maxima displayed approximately in the middle of the shear layer. For the mode n=14, a curve $A_n(r/R_a)$ with two humps is observed for the cross-section A, a curve with three humps for the cross-section B, and roughly a single-humped curve with one clear-cut maximum for the cross-section C. Thus, the general appearance of the amplitude function for stationary streamwise vortices for the mode n= 14 in the cross-section A points not just to shift of the amplitude maximum as we go from one measurement cross-section to another, but also to variation of the general character of this dependence.

The above observation plays a substantial part in the formation of the spatial structure of the supersonic-jet shear layer flow. In the experimental determination of the spatial increments of steady-state perturbations [5] it was implicitly assumed that the flow-perturbation maximum lies in the middle of the shear layer. The obtained experimental results point to a necessity of more accurate determination of the increments of stationary streamwise vortices in the jet shear layer. When determining the increments, it is maxima in neighboring, closely spaced cross-sections that should be compared.

In conclusion, it should be noted that the experimental results obtained in the present study point to a much more complex spatial structure of supersonic-jet shear layer. In the shear layer of the initial supersonic-flow region, steady-state streamwise vortex structures with various values of the azimuthal wavenumber are observed. The shape of the amplitude functions for the radial amplitude distribution of azimuthal modes varies along the flow, clearly differing among different azimuthal modes.

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REFERENCES

1. **Glaznev V.N., Zapryagaev V.I., Uskov V.N. et al.** Jet and Nonstationary Flows in Gasdanamics. Novosibirsk: Publishing House of Siberian Branch of Russian Academy of Sciences, 2000. 200 p. (in Russian).
2. **Zapryagaev V.I.** A method of mixing process control in a shear layer of a supersonic nonisobaric jet // Mechanics of Passive and Active Flow Control: Proc. of the IUTAM Symp., Gottingen, Germany, 7-11 September 1998 /Edited by G.E.A. Meier and P.R. Viswanath. Kluver Academic Publ., 1998. P. 101-106.
3. **Arnette S.A., Sammimy M., Elliott G.S.** On streamwise vortices in high Reynolds number supersonic axisymmetric jets // Phys. Fluids A, 1993.Vol. 5, No.1. P. 187-202.
4. **Krothopalli A., Strykowski P.J., King C.J.** Origin of streamwise vortices in supersonic jet // AIAA J. 1998.Vol. 36, No. 5. P. 869-872.
5. **Zapryagaev V.I., Bobrikov N.G.** Investigation of the streamwise vortices in a shear layer of the initial region of the supersonic underexpanded jet // Turbulence in High Speed Compressible Flows: Proc. of the EUROMECH 403, Futuroscope-Poitiers, France, 2-4 November, 1999 / Ed. J.P. Bonnet, S. Barre. P. 63-72.
6. **Terekhova N.M.** Streamwise vortices in axisymmetric jets // J.Appl. Mech. Tech. Phys. 1996. Vol. 37, No. 3. P. 339-349.