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COMPARISON OF THE RESULTS OF INTERFERENCE AND NUMERICAL DETERMINATIONS OF STREAM DENSITY IN A SEPARATION ZONE

A. Yu. Mitin and A. N. Mikhalev

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Density fields in the separation zone are determined from interferograms of supersonic turbulent flow over a body. A comparison is made with the results of numerical calculations by a combined scheme.

The problem of varying the aerodynamic characteristics of blunt bodies by extending heads of various shapes out on a needle [1] requires the study not only of integral quantities but also of the local parameters of the streamline flow. The structure for the case of the flow of a supersonic stream over a cylinder with a disk head, known from calculations and a qualitative analysis of shadow pictures, is shown in Fig. 1. The complexity of the flow occurring between the disk and the cylinder (frontal separation zone) resulted in an attempt at a combined experimental and numerical investigation of it, some results of which are presented in this article.

Interferometric investigations of axisymmetric inhomogeneities have been made on a ballistic course for more than 15 years. The procedure of such an experiment and the operational experience are given in [2]. The interferograms analyzed below were obtained on a diffraction displacement interferometer based on an IAB-451 shadow instrument [3, 4]. Gratings with a frequency of 75 lines/mm served as the light splitters; with the OGM-20 laser wavelength of 694.3 nm and the focal length of the objective of 1918 mm the displacement of the interfering wave fronts was 100 mm. The investigated inhomogeneity occupied an area of 60 × 100 mm in a meridional cross section.

The model of a body of cylindrical shape with a disk head extended on a needle (with a relative disk size $d/D = 0.233$ and a disk extension $\ell/D = 1.4$, where D is the cylinder diameter) was thrown at a velocity corresponding to a Mach number 2.35 on a ballistic installation at a pressure of 1 atm. In Fig. 2 we present a fragment of an interferogram of the stream in the frontal separation zone, obtained with the interferometer adjusted for bands of finite width.

In constructing the path-difference function from an interference pattern of the turbulent zone we used a priori information about the flow over the body under consideration. The direction of variation of the path difference near the extrema and of the lines of inflection of the wave surface of the probe light was established through the fact that the detached mixing layer of the frontal separation zone is a region of reduced density with respect to the compressed shock layer.

Let us clarify, in accordance with [5], how density pulsations within the turbulent region and pulsations of its boundaries are transferred to the interference pattern. The interference method is inferior to the Schlieren method in sensitivity to the transmission of pulsations. At the same time, pulsations of the boundary of a turbulent region (mixing layer,

A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR, Leningrad.
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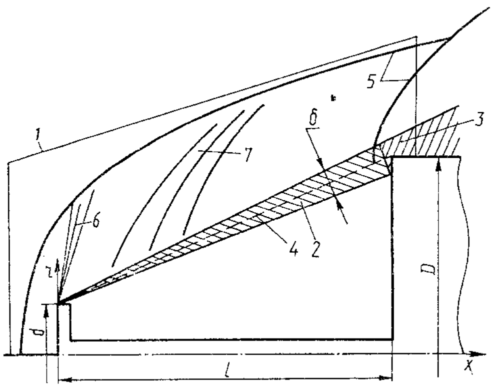


Fig. 1

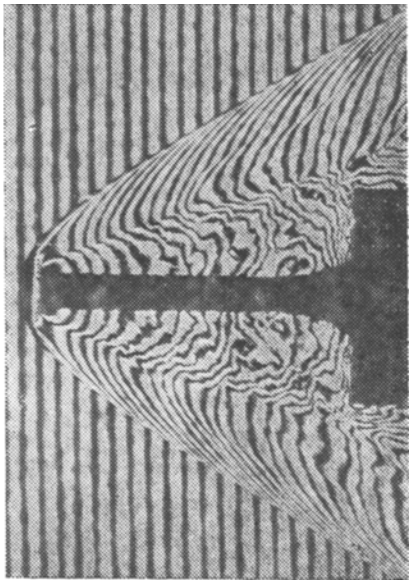


Fig. 2

Fig. 1. Diagram of flow over a body with a disk head: 1) boundary of calculation region; 2, 3) sections of the mixing layer taken into account and not taken into account, respectively, in the calculation of a section of the mixing layer; 4) line of symmetry of the calculated mixing layer; 5) shock waves; 6) rarefaction waves; 7) compression waves.

Fig. 2. Interferogram of flow over a model of a body with a disk head.

wake) are conveyed by an interferometer with a relatively large contribution compared with internal pulsations. On the example of the turbulent wake behind a sphere it has been shown that the output signal (deformation of bands) from pulsations of the boundary exceeds by a factor of 10 the signal from pulsations in the internal volume. When the schlieren method is used this signal ratio is 0.125, while for the method of a luminous point it is 0.033.

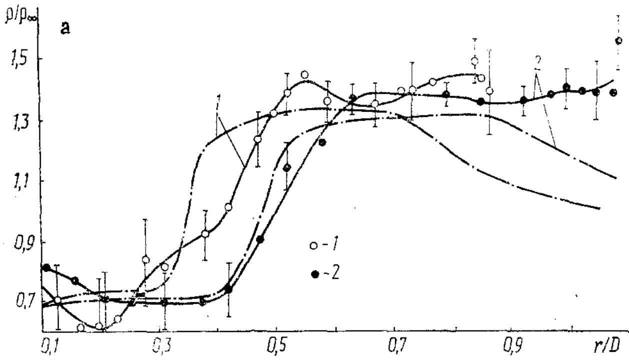
The disorderly appearance of the band pattern in a frontal separation zone in the analyzed interferograms is due mainly to pulsations of the boundaries of the mixing layers. From data of measurements of the coordinates of the bands in cross sections on both sides of the axis of the inhomogeneity we constructed path differences smoothed within limits of 0.3-0.5 band relative to the average curves. To verify the stability of the solution of the inverse problem for the given inhomogeneity we made a tenfold introduction of the maximum possible error in the path difference, distributed over the radius of the cross section in accordance with a random-number law. The dispersions of the dimensionless density for the 95% confidence interval are shown in Fig. 3. The average error in determining the density is about 4% in the shock-compressed region and 15% in the separation zone.

The flow over a body of this shape by a stream of ideal gas was calculated in [1] using the establishment method based on the finite-difference scheme of Godunov [6]. Such an approach to the modeling of separation flow over bodies reflects the actual features of the investigated flow and enables one to obtain the force loads on the body. However, the disagreement between the calculated and experimental data in the local and, in individual cases, in the integral characteristics of the flow reaches 30-40%.

An improvement in modeling was achieved by using a hybrid approach: a numerical solution of the Euler equations in the entire flow field, excluding the shear layer (Fig. 1), within the limits of which the Reynolds equations are solved. The latter are closed using the Prandtl convective model of turbulence, according to which the coefficient of turbulent viscosity ν_t is represented in the form

$$\nu_t = c_t \delta (u_{max} - u_{min}) \quad \text{for} \quad \delta = c_n x^*,$$

where u_{max} and u_{min} are the velocities from the outer and inner boundaries of the shear layer. The values of c_n = 0.089 and c_t = 0.015 were chosen from the interval of the empirical constants of [7]. The calculation was made without isolation of the gasdynamic discontinuities



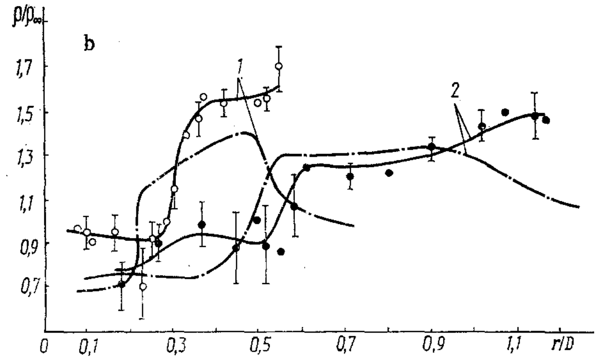


Fig. 3. Experimental and calculated (dash-dot curves) radial distributions of steam density in the field of flow over a model with a disk head in the cross sections: a. 1) x/D = 0.8; 2) 1.2; b. 1) x/D = 0.4; 2) 1.4.

and with adjustment of the grid under the bow wave and the mixing layer. The calculated data presented in Fig. 3a are in satisfactory agreement with the experimental data. The decreased density behind the shock wave is explained by its smearing out toward the outside stream in the calculation. A pronounced value of the density gradient (at $r/D < 0.45$ in the cross section $x/D = 0.8$ and at $r/D < 0.55$ in the cross section $x/D = 1.2$) indicates the position of the shear layer.

In the course of making the methodical investigations it was established, by comparing the results of calculations on different types of grids, that the grid used in the present case, adjusted under the position of the discontinuities, enables us to escape the influence of pattern viscosity within the shear layer to a considerable extent.

The coefficient of resistance C_x was determined by measuring the velocity decrease of the model in flight on the ballistic installation at zero angle of attack. By subtracting from it the coefficient of base resistance C_{xb} corresponding to the measurements of the base pressure, we obtained an estimate of the wave resistance C_{xw} of the model. In the experiment $C_{xw} = 0.334$; the value found from the calculation was $C_{xw} = 0.295$-0.3.

Thus, the pressure field behind the shock wave and in the separation zone, and hence the exchange of momentum between the external stream and the stream of circulating gas, are modeled with a sufficient degree of accuracy in the calculation. The exchange of energy is modeled less well. Outside the mixing layer all the energy exchange is determined by pattern effects — dissipation and heat conduction. In practice it turned out that the coefficient of pattern dissipation exceeds the coefficient of pattern thermal conductivity, as a consequence of which a buildup of thermal energy occurs in the separation zone. In the given case the calculated stagnation temperature T_0 near the needle exceeded its value in the undisturbed flow by 20%. On the basis of correctness of the pressure calculation, we can assume that the calculated values of the stagnation density are 20% lower. The observed mismatch between the calculated and experimental positions of the mixing layer (see Fig. 3a, b) is explained by the different positions of the point of stream separation in these cases (the leading and trailing edges of the disk in the experiment and calculation, respectively).

The random pulsations of the path difference on the interferograms comprised 5-8% of their maximum variation over the cross sections. An analysis by annular zones, under the assumption of overall axial symmetry, made it possible, by statistical smoothing of the path difference, to determine the average densities in the stagnant zone to within 15%. The quality of the numerical solution is improved when the bow shock wave is isolated or the grid is made finer in the shock layer (in the calculation of 10 cells in the shock layer). A modification of the calculating model is required to increase the accuracy of the solution in the separation zone: The Reynolds equations must be used jointly with any of the multiparametric models of turbulence in the entire separation zone.

NOTATION

d, disk diameter; D, body diameter; ℓ, disk extension; δ, thickness of the shear layer; x^*, coordinate along the shear layer; ν_t, turbulent viscosity; c_n, c_t, empirical constants; C_x, C_{xb}, C_{xw}, coefficients of total aerodynamic, base, and wave resistance.

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INFLUENCE OF THERMAL RADIATION ON THE STRUCTURE OF THE TEMPERATURE FIELD IN A TURBULENT FLOW

V. P. Kabashnikov and A. A. Kurskov

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The form of the structural function for temperature fluctuations in the turbulent flow of a radiation gas is set up theoretically.

An important characteristic of the temperature field in a turbulent flow is the structural function for the temperature [1], which is a dependence of the root-mean-square of the temperature difference at two points on the distance between them. The structural function characterizes the amplitude of the temperature fluctuations of different spatial scales and, therefore, also the microstructure of the temperature field.

The form of the structural function for nonradiation media was first set up in [2, 3]. The influence of radiation on turbulent temperature fluctuations was investigated in [4-8]. Paper [7], where conditions were indicated for which the times of radiative decay of the temperature perturbations of different scales are comparable to the times of hydrodynamic decay,

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