6. V. Ya. Neiland, "Asymptotic problems of the theory of viscous supersonic flows," Tr. TsAGI, No. 1529 (1974).
7. K. Stewartson, "Multistructured boundary layers on flat plates and related bodies," Adv. Appl. Mech., 14, (1974).
8. A. I. Ruban and V. V. Sychev, "Asymptotic theory of separation of a laminar boundary layer in an incompressible fluid," Usp. Mekh., 2, No. 4 (1979).
9. F. T. Smith and P. W. Duck, "Separation of jets or thermal boundary layers from a wall," Q. J. Mech. Appl. Math., 30, Pt. 2 (1977).
10. O. S. Ryzhov, "Instability of the propagation of a viscous jet along a wall," Zh. Prikl. Mekh. Tekh. Fiz., No. 2 (1982).
11. V. Ya. Neiland, "Toward an asymptotic theory of attachment of a supersonic flow," Tr. TsAGI, No. 1650 (1975).
12. P. L. Krapivskii and V. Ya. Neiland, "Separation of a boundary layer from the moving surface of a body in a supersonic gas flow," Uch. Zap. TsAGI, 13, No. 3 (1982).
13. I. I. Lipatov and V. Ya. Neiland, "Toward a theory of nonsteady separation and interaction of a boundary layer with a supersonic gas flow," Uch. Zap. TsAGI, 18, No.1 (1987).
14. M. Ablowitz and H. Sigur, Solitary Waves and the Inverse Problem Method [Russian translation], Mir, Moscow (1987).
15. D. R. Rizzetta, O. R. Burggraf, and R. Jenson, "Triple-deck solutions for viscous supersonic and hypersonic flow past corners," J. Fluid Mech., 89, Pt. 3 (1978).
16. V. A. Kazakov, "Highly implicit alternating-triangle method for solving problems of the asymptotic theory of boundary layers," Zh. Vychisl. Mat. Mat. Fiz., 25, No. 9 (1985).

MEASUREMENT OF TURBULENCE CHARACTERISTICS IN COMPRESSIBLE BOUNDARY LAYERS NEAR SEPARATION ZONES

A. A. Zheltovodov, V. A. Lebiga, and V. N. Yakovlev

UDC 532.526.5

Separated flows, distinguished by their great variety, are widely encountered in nature and in technology [1]. Until now, predicting their properties has been one of the most complex problems in fluid mechanics. Particular difficulties are encountered when analyzing turbulent separation due to the lack of a rigorous theoretical foundation. Most of the theoretical studies that have been conducted have involved the development of models of ideal liquids and gases and integral methods of jet and wake theory. Another focus has been the improvement of numerical methods of solving averaged Navier—Stokes equations with the use of semiempirical models of turbulence [2]. These directions of study have been taken in large part because of the available experimental data, which has been used to construct physical models of separated flows and to substantiate closing relations. In light of this, experiments now conducted in this field must necessarily be comprehensive in character.

The main difficulties encountered in experimentally studying compressible separated flows are related to measurements of turbulence characteristics in boundary layers. Such studies can be conducted on the basis of the use of laser-Doppler measurements of velocity or hot-wire anemometric instrumentation. Along with the familiar advantages and disadvantages of each method, the use of hot-wire anemometry allows the measurement of fluctuations of both gasdynamic and thermodynamic parameters. The presence of high-frequency pulsations of pressure, density, temperature, and velocity in a supersonic flow predetermines the requirements that must be met by hot-wire anemometric instruments and the measurement techniques. The possibility of broadly varying the temperature of the wire sensor T_W with a constant frequency range (which is necessary to separate pulsations of mass rate $\langle \rho u \rangle$ and stagnation temperature $\langle T_0 \rangle$) is the main advantage of direct-current hot-wire anemometers (DCA) compared to fixed-resistance hot-wire anemometers (FRA) [4]. Another important advantage is that the DCA makes it possible to measure the internal noise of the instrument.

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 3, pp. 108-113, May-June, 1989. Original article submitted September 17, 1987; revision submitted December 8, 1987.

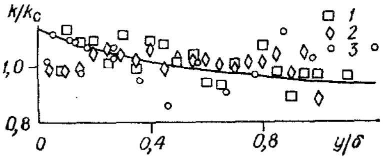

Fig. 1

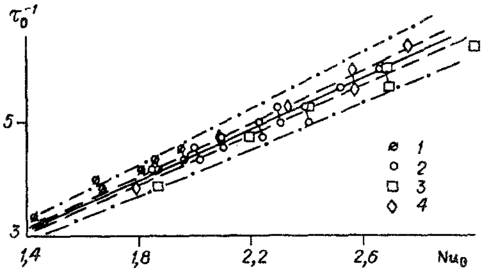

Fig. 2

To study turbulence characteristics in nonseparatd and separated flows with a Mach number $M = 2.95$ and Reynolds number $Re_1 = 28 \cdot 10^6$ m^{-1}, we used a TPT-3 direct-current hot-wire anemometer developed at the Institute of Theoretical and Applied Mechanics, Siberian Department, Academy of Sciences of the USSR. The working frequency range of the instrument was from 10 Hz to 200 kHz. Most of the measurements were made at a flow stagnation pressure $p_0 = 3.4 \cdot 10^4$ Pa and stagnation temperature $T_0 = 296(\pm 3)$ K under conditions whereby the surface of the model was adiabatic. The sensitive element of the sensors, made by the technology described in [5], was a tungsten filament with a diameter $d = 6$ μm and a length $\ell = 1.2$-1.5 mm. To alleviate the extensometric effect, we bent the filament before the tests. The relative magnitude of this deflection was 0.2-0.25 [6].

The principles underlying the method used to measure turbulence characteristics in supersonic flows with the DCA were outlined in [4]. In connection with certain features of such measurements when made in a boundarv layer as opposed to a free uniform flow, we also conducted other methodological studies.

In accordance with [4], the dependence of the Nusselt number on the sensor heating factor $a_w = (R_w - R_e)/R_e$ at $M \geq 1.2$ can be reduced to the form

$$\mathrm{Nu} = \mathrm{Nu}_0(1 - ka_w), \tag{1}$$

where Nu_0 is the Nusselt number at $a_w = 0$; R_w and R_e are the resistances of the sensor at the temperature T_w (with the degree of heating $a_w \neq 0$) and the reset temperature T_e ($a_w = 0$). The coefficient k is determined by the physical and geometric characteristics of the filament and by the parameters of the flow. For given flow conditions, it can be found from the above relation on the basis of calibration of the sensor during repeated heatings. With allowance for (1), the equation of thermal equilibrium between the heated filament and the flow can be used to obtain a relation for the DCA that will link time pulsations of mass rate $m' = (\rho u)'$ and flow stagnation temperature T_0' with pulsations of the temperature of the sensor T_w':

$$\tau \frac{dT_w'}{dt} + T_w' = \frac{R_w}{\alpha_* R_*}\left[-F_t \frac{m'}{m} + G_t \frac{T_0'}{T_0}\right]. \tag{2}$$

Here, τ is the time constant of the sensor; α_* is the temperature coefficient of resistance of the filament; R_* is the resistance of the filament at the characteristic temperature (for example, $T_* = 273.16$ K). The coefficients expressing the sensitivity of the DCA to fluctuations of mass rate F_t and stagnation temperature G_t are related to the corresponding coefficients of the FRA F_c and G_c:

$$F_t = \varphi F_c, \quad G_t = \varphi G_c \quad \left(\varphi = \frac{2a_w(1 - ka_w)}{1 - ka_w(a_w + 2)}\right). \tag{3}$$

With the thermal inertia of the sensor compensated for, Eq. (2) leads to the connection between fluctuations of voltage on the sensor E' and the parameters of the flow: $E'/E = -F_t(m'/m) + G_t(T_0'/T_0)$. The letters without primes pertain to the mean values of the parameters.

The change in the characteristics of the flow through the thickness of the boundary layer obviously has an effect on the sensitivity coefficients F_t and G_t; F_t is determined by the values of F_c and φ [Eq. (3)], while $F_c = (1/2)(\partial \ln \mathrm{Nu}/\partial \ln m) = (\sqrt{p_0}/4E^2)(\partial E^2/\partial\sqrt{p_0})$ can readily be found for the external flow on the basis of calibrations of the sensor for stagnation pressure p_0. These are described by the relation

$$E^2 = A + B\sqrt{p_0}. \tag{4}$$

The resulting values of the sensitivity coefficients F_t in different series of tests nearly coincided and corresponded satisfactorily to the results in [7-9]. The small differences in the coefficients G_t, determined by the relation $G_t = (\alpha_* R_* \eta T_0/R_e) - \varphi(\omega/2(1 - 2F_c)$, are attributable mainly to the change in stagnation temperature in the experiments in the range from 293 to 299 K and partly to the accuracy of k (η is the temperature reset factor and ω is an exponent in the temperature dependence of the viscosity coefficient and thermal conductivity). The linear dependence of the Nusselt number on the square root of the Reynolds numbers calculated from the diameter of the filament at M ≥ 1.2 [8] makes it possible to adopt a constant value $\partial E^2/\partial\sqrt{p_0}$ in the boundary layer. Thus, using the results of calibration of the sensors in the free flow in the form (4), we can then easily use values of E^2 measured in the boundary layer to determine the change in the coefficient F_c. Our estimates showed that the gradual increase in this quantity with movement of the sensor toward the line M = 1.2 does not exceed 4-5% of the value in the external flow.

Analysis of the results of measurement of k through the thickness of the boundary layer (determining the value of φ for fixed a_w (points 1-3 in Fig. 1)) showed that the qualitative character of its change is close to the expected pattern (the line in the figure) and corresponds to data from numerous calibrations of sensors in a free flow [4]. The same mean values were obtained for this quantity through the thickness of an undisturbed boundary layer (points 1) and a boundary layer (points 2 and 3) disturbed by discontinuities and rarefaction waves of different intensities ($k_c \simeq 0.2$). It can be seen that the expected maximum change in k is comparable to the scatter of the data, which for the proposed method and equipment may reach 20%. Allowance for the change in k through the thickness of the layer causes an additional increase in F_t. The total change in F_t in the supersonic part of the boundary layer was no greater than 10% in any of the cases examined. The change in the sensitivity coefficients will henceforth be considered when determining the profiles of the parameter fluctuations through the thickness of the boundary layer.

The thermal inertia of the filament in the TPT-3 is compensated for automatically through use of the semiempirical relation [4] $\tau = \tau_0(a_w + 1)/[1 - ka_w(a_w + 2)]$ for specified values of a_w and τ_0. Given a sufficiently low level of turbulence, such as in a free flow, the value of τ_0 is determined by the method substantiated in [8] – from electrical calibrating signals delivered to the sensor under working conditions. When measurements are made in a boundary layer, the presence of pulsations of fairly high intensity distorts the square signal seen on the oscillograph and thus makes this method more difficult to use. Also, such a correction for the time constant, which changes continuously through the thickness of the boundary layer, leads to an unacceptable increase in the duration of the experiment.

In connection with the above, when we made measurements in boundary layers, we determined τ_0 from local values of E on the basis of calibrations of the sensors in the external flow with a changing stagnation pressure (Reynolds number). Each value of τ_0 obtained in such calibrations by a standard method corresponds to a certain value of Nu_0, which can be found for known flow conditions from the value of E in the equation of heat balance between the filament and the flow. The thus-determined τ_0 and Nu_0 in calibrations in different wind tunnels at $a_w = 0.8$ and 0.6 (points 1, 3 and 3, 4, respectively, in Fig. 2) illustrate the satisfactory agreement with the relation $\tau_0 = \rho_w c_w d^2/(4\lambda_0 Nu_0)$ (solid line), which follows from the heat balance equation with allowance for Eq. (1). This substantiates the use of the given method (ρ_w and c_w in the last relation are the density and heat capacity of the filament material, λ_0 is the thermal conductivity of the gas at the stagnation temperature T_0). The length of the segments connecting the markers correspond to the graduations of the scale of the instrument for assigning τ_0 (0.01 msec). The width of the boundary, shown by the dot-dashed line, characterizes the accuracy of the assignment of τ_0 in a visual evaluation of the form of the signal on the oscillograph. It is worth noting that the scatter of the data for k characteristic of the boundary layer (20%) leads to a very small deviation from the exact relation (dashed lines). In principle, this makes it possible to ignore the change in k through the thickness of the boundary layer. The measurements in the boundary layer were made with correction of the time constant by the method described above. Ignoring the change in τ_0 leads to a substantial (by a factor of 2-3) reduction in the level of the measured signal near the surface. This evidently explains the behavior of the data in [10].

The above-described method was used to study turbulence characteristics in a supersonic flow (M = 2.95) about a body with equal compression and convergence angles (Fig. 3). Systematic studies conducted earlier by means of pneumometric and optical methods and visualization of limiting streamlines [11-13] made it possible to analyze features of the development of

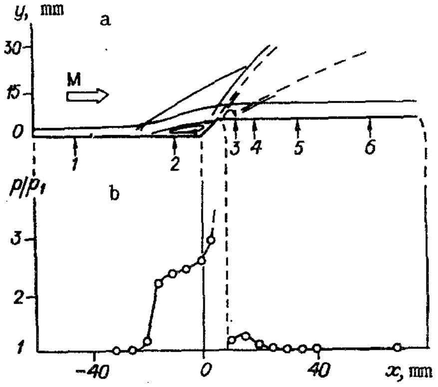
Fig. 3

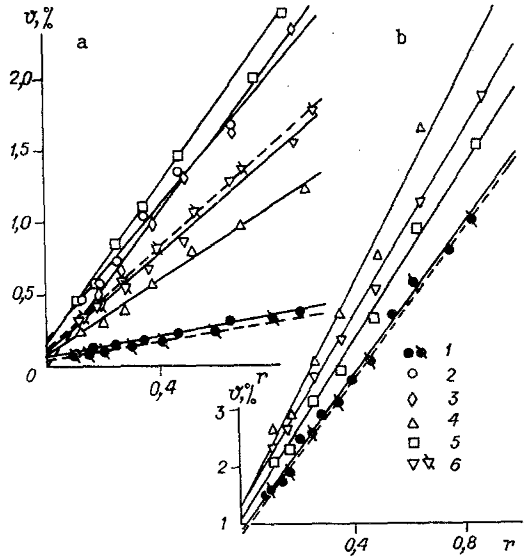
Fig. 4

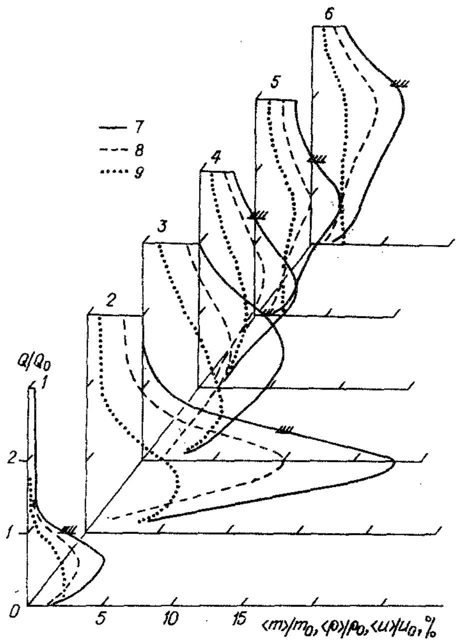
Fig. 5

separation zones and characteristics of the boundary layer with an increase in the angle of deflection of the compression surface β from 0 to 90°. In the general case (Fig. 3a, β = 45°), such a flow is characterized by the occurrence of separation ahead of the compression corner and beyond the rarefaction peak. The distribution of pressure p on the surface of the model is shown in Fig. 3b (p_1 is the static pressure in the incoming flow).

Measurements made in characteristic sections 1-6 (Fig. 3a) with different degrees of sensor heating were used to construct diagrams of the fluctuations in Kovasznay variables ϑ and r [14] (Fig. 4, points 1-6, respectively), which in turn made it possible to determine the magnitude and character of the fluctuations in the supersonic flow. The linear form of the diagrams corresponding to the external boundary of the boundary layer (Fig. 4a) is evidence of the predominance of the acoustic mode of pulsation. The slopes of the lines characterize the standard deviations of the mass-rate fluctuations, while the coordinates of the points of intersection with the y axis correspond to the fluctuations of stagnation temperature. Under the conditions examined here, the level of the fluctuations of stagnation temperature is nearly an order of magnitude lower than the level of fluctuations of mass rate. Figure 4b shows the corresponding diagrams at points of the fluctuation maxima in the boundary layer. Their character is similar in this case to the results obtained in [10, 15] for an undisturbed boundary layer. Considering the relative level of the temperature and mass-rate fluctuations and the values of the sensitivity coefficients, it becomes evident that the signal from the sensor in the boundary layer is determined mainly by pulsations of mass rate. This conclusion validates the assumption made previously.

Additional flow features are characterized by the resulting profiles of fluctuations of different parameters thrugh the thickness of the boundary layer in sections 1-6 (Fig. 5). The measurements were made in the regions where $M \geq 1.2$. Lines 7-9 show the distribution of the RMS fluctuations $\langle \rho u \rangle$, $\langle \rho \rangle$, and $\langle u \rangle$ referred to the mean values $(\rho u)_0$, ρ_0, and u_0 in the incoming flow. The vertical coordinate is the running integral discharge Q referred to the discharge through the boundary layer in the first section. The dashed horizontal line segments show the local thicknesses of the layer corresponding to $u/u_e = 0.99$ (u_e is the local velocity of the external flow). The distribution of the density and velocity pulsations (lines 8 and 9) was calculated with the assumption that the pressure pulsations were small [8]. Comparison of these results with results obtained independently in [16] by means of a laser velocimeter and a hot-wire anemometer confirmed the validity of this assumption under the conditions of interaction of a discontinuity with a boundary layer.

The data (Fig. 5) show that there is a substantial increase in turbulence behind shock waves and a reduction in turbulence behind the rarefaction waves. The part of the boundary layer behind the last perturbation typically develops under conditions of increased turbulence relative to the undisturbed flow. Behind the vertex of the rarefaction angle, the pulsations decrease most rapidly over a distance corresponding to two-three boundary-layer thicknesses. One feature worth noting is an increase in the level of turbulence near the surface behind the rarefaction waves. At $\beta = 8°$, this led to the appearance of a distinct second maximum in the profile of mass-rate fluctuations. The appearance of the second maximum is connected with the development of a new layer in the wall region. Here, the old boundary layer acts as the external flow and is characterized by an increased level of turbulence [12, 13]. The more uniform distribution of the pulsations for $\beta = 25$ and $45°$ is evidently connected with the intensive mixing effect of Görtler vortices seen in the vicinity of attachment regions in the case of flows with separation. The data obtained here also show that velocity pulsations are predominant only in the wall region, where compressibility effects are small.

LITERATURE CITED

1. P. Chen, Separated Flows [Russian translation], Vols. 1-3, Mir, Moscow (1972-1973).
2. L. V. Gogish, V. Ya. Neiland, and G. Yu. Stepanov, "Theory of two-dimensional separated flows," Itogi Nauki Tekh. Ser. Gidromekh., 8 (1975)
3. J. G. Marvin, "Turbulence modeling for computational aerodynamics," AIAA J., 21, No. 7 (1983).
4. V. A. Lebiga, "Aspects of measurement of turbulence characteristics of compressible flows," in: Methods and Techniques of Aerophysical Investigations [in Russian], ITPM Sib. Otd. Adak. Nauk SSSR, Novosibirsk (1978).
5. V. S. Kosorygin, "Laboratory complex for preparing miniature hot-wire anemometers with a heated filament," Paper submitted to VINITI, 2.08.82, No. 4166—82, Novosibirsk (1982).
6. V. A. Lebiga and V. V. Chernykh, "Measurement of turbulence at supersonic flow velocities," in: Aeromechanics [in Russian], Nauka, Moscow (1976).
7. V. A. Lebiga, "Experimental study of the turbulence characteristics of flows at supersonic velocities," Author's Abstract of Candidate's Dissertation, Engineering Sciences, Novosibirsk (1977).
8. L. S. G. Kovasznay, "The hot-wire anemometer in supersonic flow," J.A.S., 17, No. 9 (1950).
9. P. Bestion, J. Gaviglio, and J. P. Bonnet, "Comparison between constant-current and constant-temperature hot-wire anemometers in high-speed flows," Rev. Sci. Instrum., 54, No. 11 (1983).
10. A. J. Leiderman and A. Dimetriades, "Turbulent shear stresses in a boundary layer in a compressible fluid," AIAA J., 17, No. 7 (1977).
11. A. A. Zheltovodov and A. A. Pavlov, "Study of flow in a supersonic separation zone before a step," Preprint, ITPM Sib. Otd. Adak. Nauk SSSR, Novosibirsk (1979), No. 1.
12. A. A. Zheltovodov, É. Kh. Shilein, and V. N. Yakovlev, "Developed turbulent boundary layer under conditions of mixed interaction with shock and rarefaction waves," Preprint, No. 28—83, ITPM Sib. Otd. Ada. Nauk SSSR, Novosibirsk (1983).
13. A. A. Zheltovodov, A. A. Pavlov, É. Kh. Shilein, (E. H. Schilein), and V. N. Yakovlev, "Interconnection between the flow separation and the direct and inverse transition at supersonic speed conditions," in: Laminar-Turbulent Transition: IUTAM Symp., Novosibirsk (1984), Springer-Verlag, Berlin (1985).
14. L. S. G. Kovasznay, "Turbulence in supersonic flow," J. A. S., 20, No. 10 (1953).
15. M. Acharya, K. K. Khorstmen, and M. I. Kassoi, "Effect of the Reynolds number on turbulence characteristics in boundary layers of compressible flows," AIAA J., 17, No. 4 (1979).

16. W. C. Rose and D. A. Johnson, "A study of shockwave turbulent boundary-layer interaction using laser velocimeter and hot-wire anemometer techniques," AIAA Paper No. 95, New York (1974).

STABILITY OF A SUPERSONIC BOUNDARY LAYER BEHIND A FAN OF RAREFACTION WAVES

A. D. Kosinov, A. A. Maslov, and S. G. Shevel'kov UDC 532.526

A problem which has recently become increasingly important is determination of the flow characteristics in regions of the interaction of a supersonic boundary layer with flow irregularities such as a fan of rarefaction waves, a shock wave, etc.

For turbulent boundary layers, the most important characteristics are those which give information both on the average flow and on turbulent heat- or mass-transfer parameters. The problem of the effect of rarefaction waves on a turbulent boundary layer was examined in [1], as an example. For laminar boundary layers, the problem of the stability of flows with irregularities is of the greatest interest. In regions of nonuniform flow, the flow being examined is either accelerated or slowed by a pressure gradient. There has not been sufficient study of the effect of pressure gradients on stability characteristics.

Of the theoretical studies, we should mention [2-4]. The authors of these studies used similarity solutions of boundary-layer equations to establish the stabilizing role of a negative pressure gradient at supersonic velocities. It was shown that the effect of the gradient is diminished by intensive cooling of the surface. A negative pressure gradient has a greater stabilizing effect for the second mode of perturbation than for the first mode.

It was noted in [5] that flow near curved surfaces is not self-similar. Also, the authors of [5] used exact boundary-layer equations to study the stability of a supersonic laminar boundary layer during rotation of the flow. They investigated the case of flow over a convex surface, ensuring rotation of the flow at a certain angle with a specified radius of rotation. Stability in this case was evaluated by means of the gradient Reynolds number and was calculated on the basis of the Dan—Lin equations. It was established that, in the case of flow about a convex wall, a supersonic laminar boundary layer is more stable than in the case of an initial boundary layer on a flat wall.

We do not know of any experimental studies of the stability of gradient flows. At the same time, reliable methods have been developed in recent years for studying the stability of nongradient boundary layers with the use of artificially introduced three-dimensional wave packets [6].

The goal of the present study is to experimentally investigate the stability of a supersonic laminar boundary layer behind a fan of rarefaction waves by means of artificial perturbations.

1. The experiments were conducted in supersonic wind tunnel T-325 at the Institute of Theoretical and Applied Mechanics, Siberian Branch of the Soviet Academy of Sciences. The dimensions of the working part were 200 × 200 mm. The Mach number of the incoming flow M = 2.0, while the Reynolds number $Re_1 = 6.5 \cdot 10^6$ m^{-1}. As the model, we used a steel cone with a cylindrical tail section. The angle at the vertex was 10°, and the diameter of the cylindrical part was 38 mm. Perturbations in the flow were recorded with a TPT-4 dc hot-wire anemometer. We used sensors with a tungsten filament 6 μm in diameter and about 1.2 mm long. The measurements were made along the longitudinal coordinate on a line passing through the maximum of the fluctuation distribution with respect to the normal coordinate directly behind the inflection point on the surface.

The model was secured to the rod of a traversing gear at the center of the work part. The model was set at a zero angle of attack and was moved along the flow (along the x coordi-

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 3, pp. 113-117, May-June, 1989. Original article submitted January 20, 1988.

0021-8944/89/3003-0447$12.50