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TESTING OF THE FLUENT PACKAGE IN CALCULATION OF SUPERSONIC FLOW IN A STEP CHANNEL

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Nonstationary supersonic flow of a nonviscous gas in a step channel with Mach number M = 3 is calculated using the FLUENT package. The accuracy of predictions is analyzed on different types of grids, including those with dynamic local adaptation, and on numerical schemes of different approximation orders.

The universal software package FLUENT is presented by its developers as a flexible and efficient tool for numerical modeling of hydrodynamic and thermophysical processes, including sub- and transonic flows of viscous and nonviscous gases. This is predetermined in many respects by the fact that the employment of nonstructurized finite-difference grids in it allows consideration of gasdynamics and heat exchange in multidimensional regions of arbitrary geometry. Although universal packages similar to FLUENT have no limitations, in practice, on selection of the shape of the object calculated, they are nonetheless characterized by the problem of verification, related to ensuring the acceptable accuracy of numerical predictions on grids with the number of cells permitted by the available computational resources. The above problem arises, as a rule, from the necessity of representing the complex character of sometimes different-scale flow on corresponding grid structures, which in many situations is not entirely taken into account by the developers of packages. Below, we analyze numerical schemes of different approximation orders and adaptive grid structures realized in the FLUENT package with the example of calculation of the compressible flow of an ideal gas in a region of simple geometry; this flow is characterized by the formation of a nonstationary multielement shock-wave pattern.

The problem on supersonic flow in a channel with a step for Mach number M = 3 has been a popular test for comparison of the accuracy of different computational schemes over many years (see, for example, [1]). Of special interest is the degree of resolution of complex gasdynamic elements and phenomena — the nonstationary interaction of compression and rarefaction and Mach disks occurring in irregular interaction of shock waves with each other and with the walls — with the use of the selected numerical algorithm.

The calculation region represents a channel with an abrupt contraction. The inlet portion has a unit height; the length of the channel is equal to 3, and the step of height 0.2 is located at a distance of 0.6 from the left-hand inlet boundary of the region.

By the finite-difference method we solve the system of Euler equations [2, 3] for a perfect gas with an adiabatic exponent of $\gamma = 1.4$. For evaluation of the efficiency and accuracy of the numerical algorithm it is convenient to use a set of parameters whose initial state is close to unit values, i.e., in this case

$$\rho = 1.4\,, \quad u_x = 3\,, \quad u_y = 0\,, \quad p = 1\,, \quad \gamma = 1.4\,. \tag{1}$$

The above set of parameters determines the local velocity of sound $a = \sqrt{\gamma(p/\rho)} = 1$; the Mach number becomes numerically equal to the velocity of the incoming flow $M = u_x/a = u_x$. An implicit upwind scheme of second order of approximation with splitting of variables according to Roe [4–6] is employed for approximation of the Euler equations.

The set of parameters (1) is specified as the input boundary conditions. Nonflow conditions are set on impermeable channel portions. In the outlet cross section, the parameters of the flow are insignificant, since its outflow occurs with a supersonic velocity. As the initial conditions we assume that the entire channel is filled with gas; the parameters of the gas are equal to the parameters at the inlet boundary, which corresponds to an abrupt beginning of

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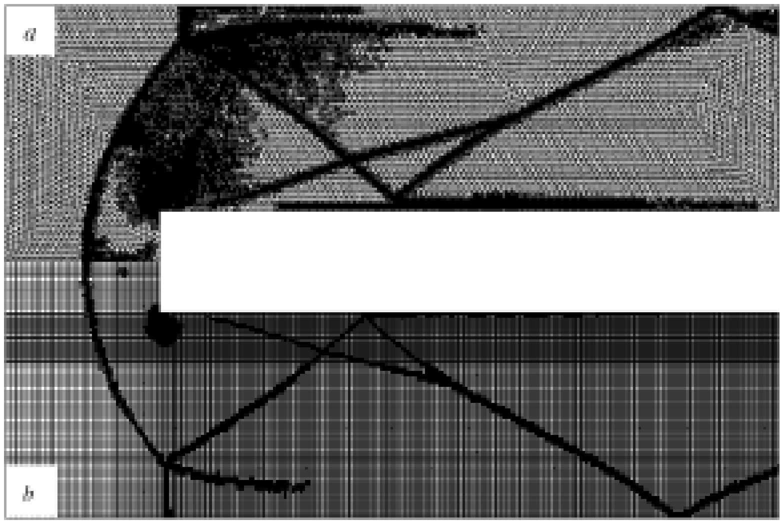

Fig. 1. Triangular (a) and tetragonal (b) computational grids locally adapted to solution (by the density field).

motion of the step channel with a supersonic velocity. The Courant number is set equal to 0.95, and numerical modeling of the nonstationary process is carried out with a fixed time step of 0.005, which is quite acceptable in the case of employment of the implicit scheme of second order of approximation in time. Twenty local iterations are performed at each time-integration step. It should be noted that a change from 10 to 20 in their number does not influence the solution of the problem.

To evaluate the accuracy of numerical predictions we have carried out the calculations on the following grids: (1) a uniform triangular grid with an initial number of nodes of about 8000 (Fig. 1a), (2) a nonuniform tetragonal grid with an initial number of nodes of about 35,000 (Fig. 1b), and (3) a uniform tetragonal grid with a number of (960 $\times$ 320) nodes of about 300,000. On the first two grids, numerical modeling is performed according to the scheme of second order of approximation. For highly accurate resolution of the nonstationary gasdynamic processes we use the algorithm of dynamic local adaptation of the grid [7–9] to the density gradient with four and two levels of fractionation for the first two grids. In the process of solution of the problem, the number of nodes increased from 8000 to 350,000; the fractionation and merging thresholds were selected equal to 0.01 and 0.02 (Fig. 1a) and 0.2 and 0.007 (Fig. 1b) respectively. On a grid of the third type, we have carried out numerical modeling of nonstationary flow in the step channel with the use of the schemes of first and second orders of approximation on a grid without local adaptation. As follows from Fig. 1, the local grid adaptation to the density gradient allows practical reproduction of the shock-wave structure of supersonic flow past the step, irrespective of the selected topology of the initial grid.

Figures 2 and 3 compare the isochoric fields calculated at the instant of time $t = 4$. The standard solution by which the accuracy of numerical predictions is evaluated has been taken from [1]. It is well known that a characteristic feature of the steady-state regime of flow past a step is the formation of a stationary curvilinear shock wave in front of it. Clearly, all the numerical approaches in question, combining the use of schemes of different approximation orders and computational grids of different types, have turned out to be advantageous only in representation of this structural element.

Let us briefly analyze the solutions obtained on a uniform dense grid using the schemes with different scheme diffusions (Fig. 2a and b). The scheme of second order of approximation correctly reproduces the flow structure occurring in interaction of the departed shock wave with the channel wall. This scheme yields correct predictions of the size and position of the upper Mach disk (despite the strong nonmonotonicity of the solution behind it). The scheme of first order somewhat understates the size of the Mach disk.

The two schemes (of both the first and second order) lead to the formation of a false Mach disk in diffraction of the reflected head shock wave on the step. Furthermore, in using them we were unable to reproduce the curvilinear wall shock occurring just behind the sharp edge of the step (the scheme of first order "smeared out" and the scheme of second order represented it incorrectly). On the whole, the employment of the schemes of both the first and second

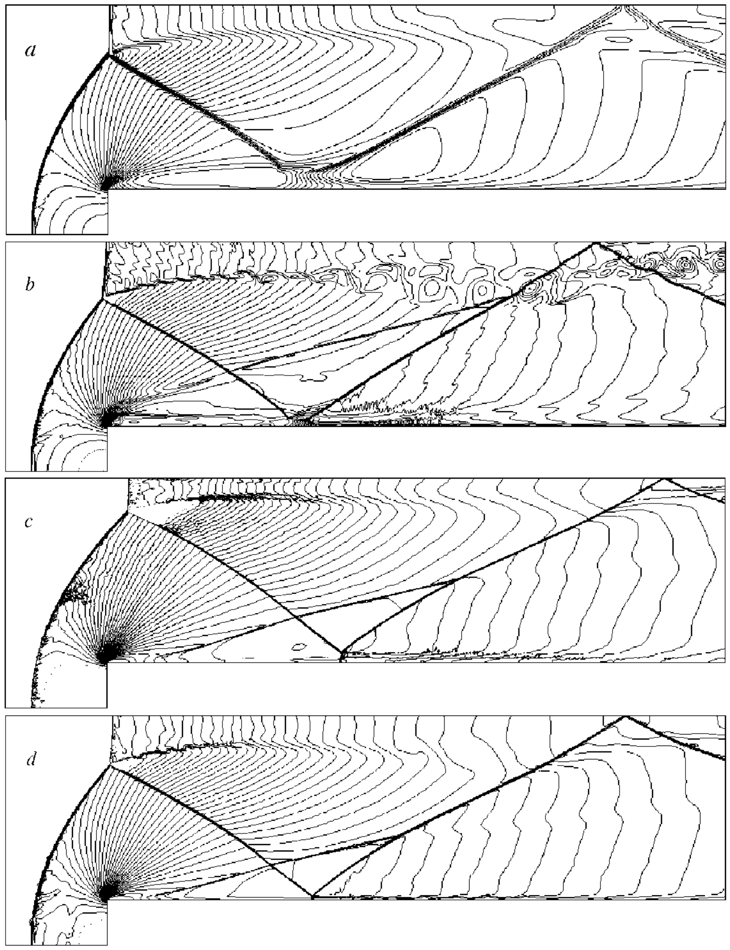

Fig. 2. Comparative analysis of the isochoric patterns at the instant t = 4, obtained using difference schemes of different approximation orders on regular and irregular computational grids: a uniform tetragonal grid (960 × 320) and schemes of first (a) and second (b) orders; a triangular adapted grid and a scheme of second order (c); a tetragonal adapted grid and a scheme of second order (d).

approximation order on a very detailed uniform grid with a number of nodes of 960 × 320 has not furnished satisfactory results.

The employment of adapted grids (Fig. 2c and d) allows detection of all the elements of the gasdynamic structure with the same, in practice, number of nodes as that for the selected detailed uniform grid. Very close results have been obtained on the grids of different topologies (triangular and tetragonal), which allows a conclusion on a certain degree of reliability of the predictions and adequacy of the computational algorithm. However, we should note certain dissonances which cause the errors of determination of the characteristics of flow in some zones singled out in Fig. 3. The stationary head shock wave calculated on the triangular grid interacts with the wall to form an upper Mach disk shorter than that predicted in [1] (of about 10% of the inlet length of the channel), which predetermines the displacement of the entire flow pattern to the right (Fig. 3, zone 3). The nonmonotonicity of the solution behind by the upper Mach disk and in the zone between the departed head shock wave and the step is clearly illustrated (Fig. 3, zones 2 and 4). At the same time, we have been able to reproduce quite accurately (according to [1]) the shock wave formed just after the refraction waves in the case of flow past the right angle of the step (Fig. 3, zone 5). We should also note the correct representation of shear layers in the zone of contact discontinuity coming from the triple point, i.e., the point of intersection of the upper Mach disk and the head shock wave (Fig. 3, zone 3). Secondary shock waves and their further interaction with the channel walls and with each other have been reproduced quite satisfacto-

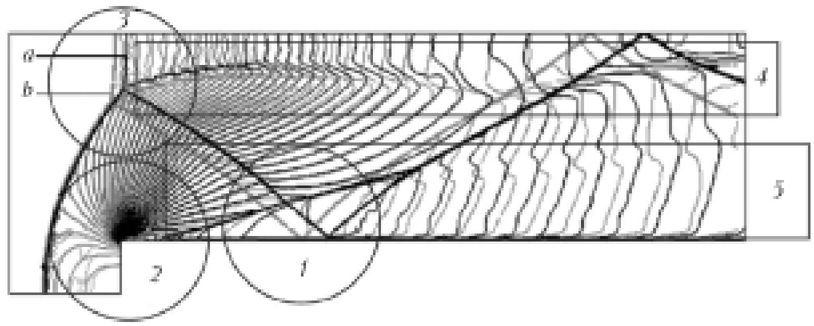

Fig. 3. Comparative analysis of the isochoric patterns (obtained on an adapted triangular grid using the FLUENT package (a) and presented in [1] (b)) in the case of supersonic flow past a step channel at $t = 4$.

rily, including the reflection of the secondary shock wave from the step (Fig. 3, zone 1). We note that the selection of the triangular adapted grid for comparative analysis of the solutions in Fig. 3 has been dictated by the fact that nonstructurized grids of such a type are most frequently used in the practice of employment of the FLUENT package. At the same time, a comparison of the patterns in Fig. 2c and d shows that the tetragonal grid topology allows better detection of the size and location of the Mach shock, preserving the nonmonotonicity of the solution behind it. As a consequence, the configuration of reflected shocks corresponds to the shock-wave structure of the standard solution to a greater extent [1].

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NOTATION

a, local velocity of sound; M, Mach number; p, pressure; t, time; u_x and u_y, longitudinal and lateral components of the velocity vector; γ, adiabatic exponent; ρ, density.

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