Unsteady Interaction Of The Supersonic Jet, Issuing From Butt-End Of Cylinder, With The Contrary Supersonic Free Stream

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***Abstract*—CFD studies of supersonic flow near plain end of cylinder, giving off opposite supersonic jet, are carried out. Two-dimensional Euler equations of a polytropic gas with the specific heats ratio 1.4 are solved. Case of free stream Mach number 1.5 is considered. The explicit second order Godunov type method and the implicit Runge-Kutta method are applied. Flow regime with intensive nearly periodical self-oscillations is observed.**

Keywords—Euler equations; CFD studies; self-oscillations; compressible flows

1. Introduction

Two new families of unsteady flows are found in [1-5]. Namely, new family of self-oscillatory flows near the pair cylinder - open channel was found by numerical search in [1-2], where free stream Mach numbers of 3.5 to 7.5 are considered. Two unsteady regimes are observed in calculations. Another new family contains self-oscillatory interaction of supersonic flows near a blunted cylinder, giving off supersonic opposite jet [3-5].

This paper is devoted to continuation of numerical investigations [3-5]. Namely, new form of tube end is considered. As a result, pattern of shock waves and contact discontinuities in a flow near this tube became more complicated, which is conducive to appearance of self-oscillations.

2. Euler equations solving design

Numerical calculations deal with dimensionless variables. These variables are defined as relations of initial variables and next free-stream parameters or the body size: p_∞ - for pressure, ρ_∞ - for a density, $\sqrt{p_\infty/\rho_\infty}$ - for a velocity, r_{tub}=y(E)-y(G) (the cylinder radius, see fig.1) – for space variables, $r_{tub}/\sqrt{p_\infty/\rho_\infty}$ - for time.

2.1 Boundary conditions

A computational domain and a mesh may be seen in fig. 1. All flow field parameters are prescribed at inflow boundaries AB and *BC:* P=1, ρ=1, $U= M_\infty(\kappa)^{1/2}$. V=0. Conditions at cylinder surface boundaries *DE, EF* are zero value of the normal velocity and extrapolation relations for all other variables. Opposite supersonic jet outflows from a nozzles in forehead parts (boundary FG) of blunted cylinders. All flow field parameters are prescribed at this boundary: $P=P_{jet}$, $\rho=\rho_{jet}$, V=0,

$U=M_{jet}.(\kappa\ P_{jet}/\rho_{jet})^{1/2}$. Extrapolation relations are used at the outflow boundary *CD* (see fig 1), zero value of the radial velocity and extrapolations are used at symmetry axis *AG*.

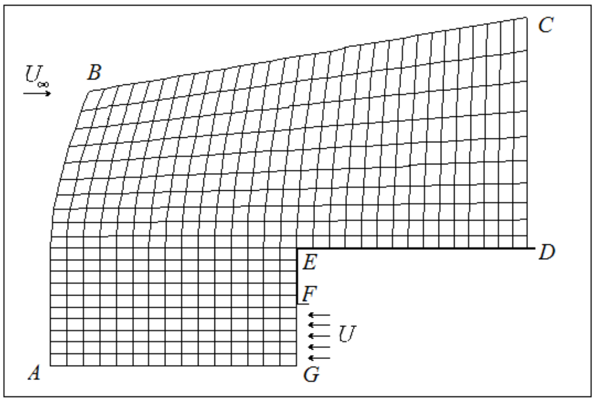

Fig. 1. Mesh and CFD domain schematic representation

2.3. Finite difference methods for Euler equations solving

The implicit conservative Runge-Kutta method [6] and the second order two step version of the Godunov conservative method [7] are used. Approximate linear solution of Riemann problem is applied in last one. Algorithms of slopes limitation of left and right extrapolation curves are used to damp false oscillations near discontinuities. Review of such algorithms of damping false oscillations is presented in [8].

Grids 401 × 601 and 801 × 1201 are used in calculations. To provide stability of explicit Godunov method the interval 0.25-0.35 of CFL numbers is kept for Godunov method in present computations. Runge-Kutta method computations are provided with double time steps. So this method turns out to be more effective, then Godunov method, despite the fact that Runge-Kutta method requires more operations for one time step.

Both methods are realized for the case when computational domain is a curvilinear quadrangle with curvilinear quadrangular excisions (present domain contains only one excision, see fig. 1). These codes allow carrying out calculations without dividing complicated domains into subdomains.

3. Results and discussions.

The intensity of flow oscillations may be measured by sound pressure level at some point:

$$SPL=10\ \mathrm{Log}_{10}(\overline{p'^2}/p_{ref}^2),\quad \overline{p'^2}=\sum_n (p_n-\overline{p})^2/N,$$

p_{ref} =20mkPa/p_∞ ,

where p_∞ =101325*Pa* (the air pressure under normal conditions) is used since dimensionless variables are dealt here.

Flow with free stream Mach numbers 1.5 is calculated by Godunov and Runge-Kutta methods. Two meshes 401 × 601, 801 × 1201 are used.

3.1 Mesh 401 × 601 flow calculations.

Fig. 2a shows density distribution, fig. 2b show pressure histories at the cylinder edge (point E at fig. 1) for the flow with the free stream Mach number M_∞ =1.5. The jet Mach number is M_{jet} =2.0, jet pressure is P_{jet} =0.7P_∞, jet density is ρ_{jet} =0.35ρ_∞. Geometry control parameters are L_{cyl} =2.0 (the cylinder length), R_{cyl} =1.0 (the cylinder radius), r_{jet} =0.433 (the jet radius). Godunov method data (G. 2 m) are shown at below part of fig.2b, Runge-Kutta method data (*R.K.m*) are shown at upper part of this fig. Godunov type method data are pictured in fig. 2a.

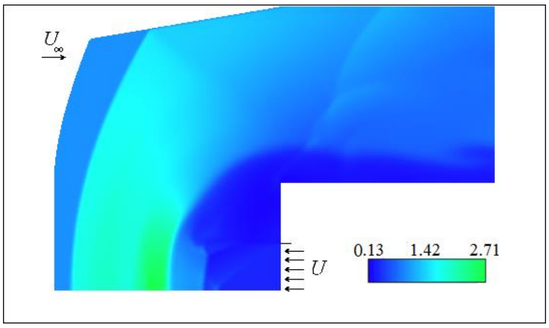

Fig. 2. M_∞ =1.5, the density distribution

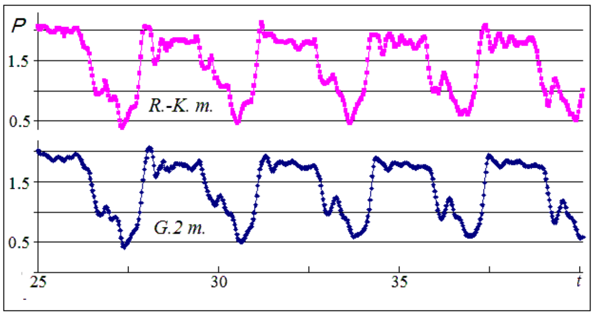

Fig. *3. M* $_\infty$ =1.5, pressure histories

Density histories, presented in fig. 3, illustrates that this flow is nearly periodic. Calculations for Runge-Kutta method data result the *T*=3.12 period, calculations for Godunov method data result the *T*=3.21 period. Similarly, SPLs are calculated for both data. Calculations for Runge-Kutta method data result the SPL=187.9db, calculations for Godunov method data result the SPL=187.5db.

Flow fields dynamics during one period after the final instant *t*=40.0 (see fig. 3) is calculated by the Runge-Kutta method. Density distributions are shown in figs. 4*a* - 4*d* for time instants *t*=40.0+*T*/4 (fig. 4*a*), *t*=40.0+*T*/2 (fig. 4*b*), *t*=40.0+3*T*/4 (fig. 4*c*) and *t*=40.0+*T* (fig. 4*d*), correspondingly.

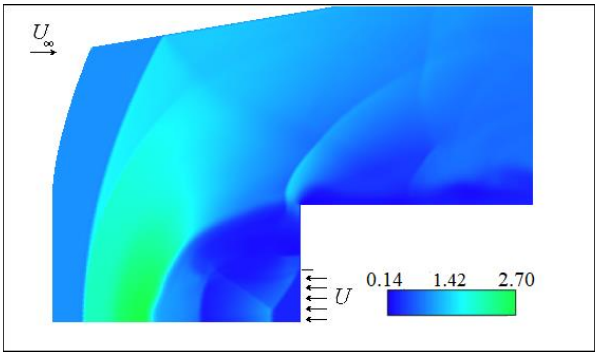

Fig. 4a. The density distribution, *t*=40.0+*T*/4

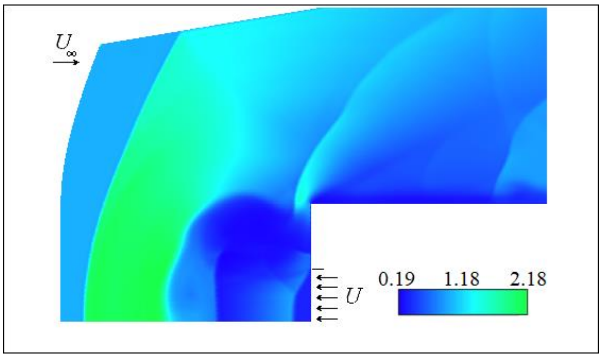

Fig. 4b. The density distribution, *t*=40.0+*T*/2

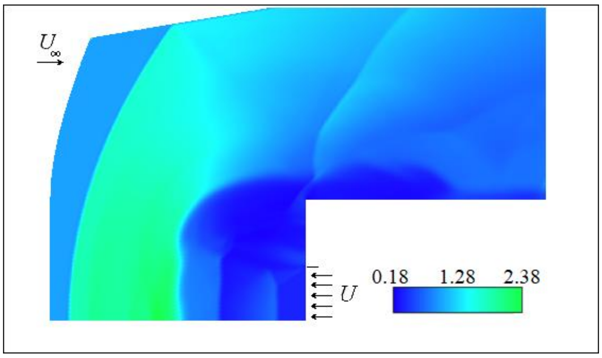

Fig. 4c. The density distribution, *t*=40.0+3*T*/4

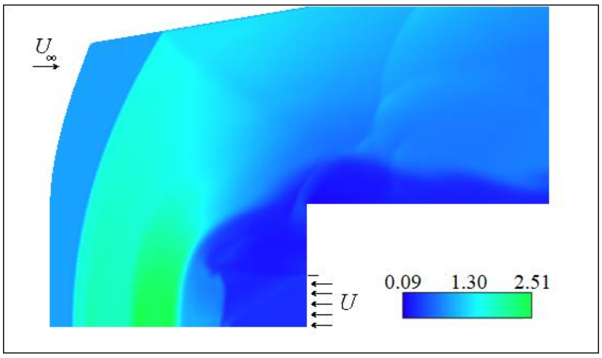

Fig. 4d. The density distribution, *t*=40.0+*T*

It can be seen that two shock waves appear and disappear through oscillation period. First shock wave is located near the cylinder edge (point E in fig. 1), second shock wave starts from the nozzle edge (point – F in the fig. 1) and moves to symmetry axis. This shock wave is reflected from symmetry axis with forming Mach lambda configuration.

3.2 Mesh 801 × 1201 calculations.

Figs. 5a, 5b show density distributions, pictured for Godunov type method data and for Runge-Kutta method data for time instant t=40.0 (see fig. 3). The shock wave near the cylinder edge (point *E* in fig. 1) is absent, jet is braked by two shock waves.

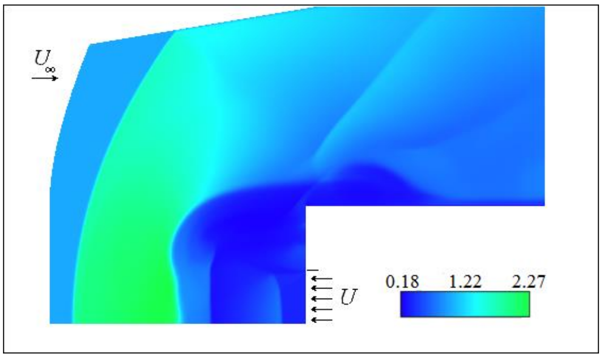

Fig. 5a. The density distribution, Godunov type method data

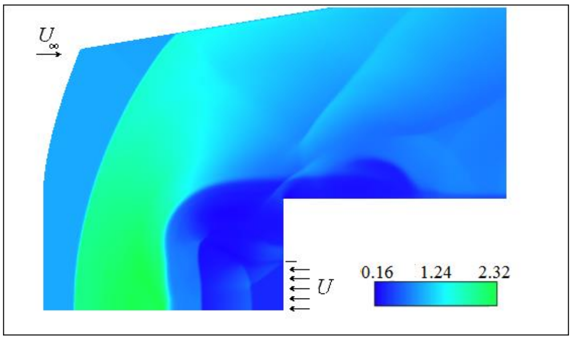

Fig. 5b. The density distribution, Runge-Kutta method data

Pressure histories for this flow are shown in fig. 6. These histories show nearly periodical behavior similarly to behavior, represented in fig. 2b. It is interesting to compare periods of oscillations and SPLs for the 401 × 601 mesh and similar values for the 801 × 1201 mesh. Calculations for Runge-Kutta method data result the *T*=3.24 period, calculations for Godunov method data result the *T*=3.29 period. These values are in agreement with the 401 × 601 mesh values. Calculations for Runge-Kutta method data result the SPL=187.9db, calculations for Godunov method data result the SPL=187.5db. These values are in agreement with the 401 × 601 mesh values.

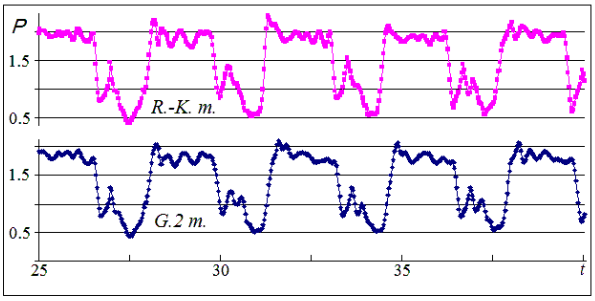

Fig. 6. *Pressure histories, the 801 × 1201 mesh.*

4. Conclutions

Supersonic unsteady flows near a cylinder, giving off supersonic opposite jet, are studied. The cylinder with plain buff-end is considered. Flow regime with intensive nearly periodical self-oscillations is observed.

Two methods are applied in calculations of unsteady flow. Meshes 401×601 and 801×1201 are used. Comparison of data, received by different methods with usage of different meshes shows, that different SPLs have small deviation from middle SPL, oscillation periods have small deviation from middle period. It seems that increasing of grid number is necessary to get more accurate numerical local flow parameters. Necessity of increased grid number may be caused by complexity of the considered flow.

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