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Parametric Study of Unsteady Flows Near Blunted Cylinders, Giving Off Opposite Jets

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ABSTRACT

Interactions of uniform supersonic streams with blunted cylinders, giving off opposite supersonic jets from forehead surfaces, are studied. Two-dimensional Euler equations are solved by an implicit Runge-Kutta scheme. Unsteady compressible flows near blunted bodies, giving off supersonic opposite jets, are found in previous author investigations for free stream Mach numbers $1 \le M_\infty \le 1.3$. This interval of free stream Mach numbers, for which unsteady flows exist, is extended to $1 \le M_\infty \le 1.7$ here.

Keywords : *Euler Equations, Runge-Kutta Scheme, Self-Oscillatory Flows*

I. INTRODUCTION

Significant part of self-oscillatory compressible flows consists of jet flows. These unsteady jet flows may be classified into some families: 1. Flows near supersonic jets, inflowing to forward facing cavities (see, for example, [1-4]); 2. Jet impinging on a plate [5-13]; 3. Unsteady compressible flows near blunted bodies, giving off supersonic opposite jets from forehead surfaces [14-16].

Investigations [14-16] gave a start to the family 3. Self-oscillatory regime of flows near blunted bodies with opposite jets were found in [15-16] at free stream Mach numbers, closed to 1. Here initial interval is studied and unsteady flows near blunted cylinders are found for larger free stream Mach numbers.

Flow self-oscillations are supposed to be resulted from resonance interactions of flow "active" elements, namely, elements, which amplify disturbances. The hypothesis is used that contact discontinuities and intersection points of shocks with shocks or shocks with contact discontinuities compose the flow set of "active" elements. A search for new unsteady flows is carried out by investigations of flows, containing the most number of "active" elements. Calculated here flow fields contain shocks, contact discontinuities and intersection points. So, these flows may be waited to produce self-oscillations, according to the proposed mechanism of the flow unsteadiness.

II. CFD DESIGN APPROACH

The problem geometry may be seen in fig. 1. Solid walls are shown by bold lines. Opposite supersonic jets outflow from nozzles in forehead parts of blunted cylinders. These jets are supposed to be spherically symmetrical. Jet velocities at exits of nozzles are normal to spherical surfaces.

Boundary conditions for computations are zero value of the normal velocity and extrapolation relations for all other variables on the body surface, extrapolations on the outflow boundary at right side numerical domain (see fig 1), prescribed variables on the inflow forehead boundary and on the spherical boundary, corresponding to the opposite jet, zero value of the radial velocity and extrapolations on symmetry axis.

An implicit conservative third Runge-Kutta scheme [17] is modified and is employed here. To avoid solutions with false unsteadiness, which may appear when flows are studied, closed to really unsteady flows, the Smagorinsky artificial viscosity [18] is used:

$\mu=\rho|S|(C_s\Delta)^2$, $|S| = (2S_{ik}S_{ik})^{1/2}$,

$S_{ik} = (\partial u_i/\partial x_k + \partial u_k/\partial x_i)/2$,

$\Delta = \Delta\xi\Delta\eta\,(x_\zeta y_\eta - y_\zeta x_\eta)/$

$/(\mathrm{Min}(\Delta\xi^2(x_\zeta^2+y_\zeta^2), \Delta\eta^2(x_\eta^2+y_\eta^2)))^{1/2}$,

where functions $x=x(\xi,\eta)$, $y=y(\xi,\eta)$ perform mapping of the unit square $\{0\le\xi\le1,\ 0\le\eta\le 1\}$ to a curvilinear quadrangle on the plane of physical variables, $\Delta\xi=1/N_\zeta$, $\Delta\eta=1/N_\eta$, N_ζ, N_η - numbers of intervals of the quadrangular mesh in unit square, C_s - constant, which is chosen in trial computations, $C_s=0.85$. As a result of usage of this artificial viscosity initial third order of method decreased till second order. The 590×544 mesh is used.

Numerical calculations deal with dimensionless variables. These variables are defined as relations of initial variables and next parameters of the undisturbed flow or the body size: p_∞ - for pressure, ρ_∞ - for density, $\sqrt{p_\infty/\rho_\infty}$ - for velocity, r (blunt radiuses of cylinders) – for space variables, $r/\sqrt{p_\infty/\rho_\infty}$ - for time.

III. UNSTEADY FLOWS NEAR BLUNTED BODIES

Unsteady compressible flows near blunted cylinders, giving off supersonic opposite jets, are defined by five control parameters: M_∞, M_{jet}, ρ_{jet}, P_{jet}, σ_{jet} - free stream and jet Mach numbers, jet density, jet pressure, jet half-angle. Large number of control parameters makes systematic parametric study of these flows too expensive. So a search for self-oscillatory flows with free stream Mach numbers, exceeding 1.3, is performed step by step. Initial set of control parameters, providing the most intensive self-oscillations at free stream Mach number M_∞ =1.3 (flows with this Mach number are presented in [15]), is used in trial computations at Mach number M_∞ =1.4. Then control parameters are changing (but Mach number M_∞ =1.4 is fixed) to get more intensive oscillation. New set of these parameters, which provides the most intensive oscillations, is used at next free stream Mach number, which exceeds previous Mach number by step 0.1. This procedure is repeated step by step. Results of this search are presented in table 1.

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

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

where $\overline{p'^2}=\sum_n (p_n-\bar{p})^2/N$, p_{ref}=20mkPa/p_∞, p_∞ =101325Pa (the air pressure under normal conditions) is used since dimensionless variables are dealt here. Sound pressure levels at the intersection point of spherical and cylindrical parts are presented in sevenths columns of the table below.

Table : *Sound pressure levels.*

N	M_∞	M_{jet}	P_{jet}	P_{jet}	σ_{jet}	SPL,db
1	1.4	4.5	0.233	0.465	arcsin(0.4)	162.9
2	1.4	5.5	0.157	0.459	π/6	169.1
3	1.4	5.5	0.250	0.347	arcsin(0.4)	176.9
4	1.4	5.5	0.250	0.289	π/6	179.8
5	1.5	5.5	0.250	0.289	π/6	176.9
6	1.5	5.5	0.250	0.347	π/6	173.8
7	1.6	5.5	0.250	0.362	arcsin(0.4)	166.1
8	1.6	5.5	0.250	0.289	π/6	178.4
9	1.7	5.5	0.250	0.289	π/6	178.2
10	1.7	5.5	0.250	0.347	π/6	176.2

Fig. 1 shows density distribution for the unsteady flow near the spherically blunted cylinder. This flow corresponds to variant 1 in the table. It should be noted, that contact discontinuity near the cylinder bound is disturbed by waves.

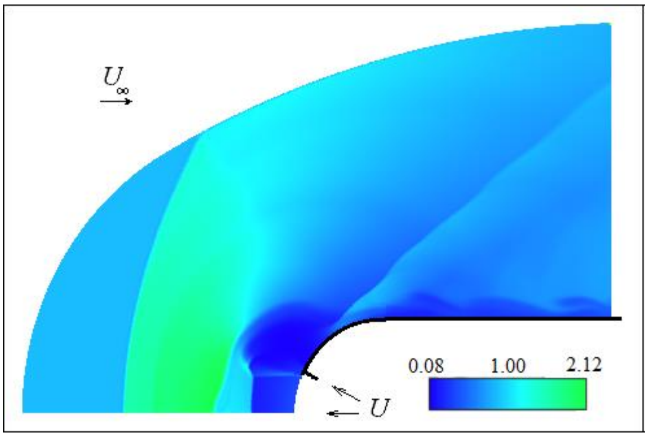

Fig. 1. The density distribution, M_∞ =1.4.

Fig. **2** shows the pressure history at the interface point of spherical and cylindrical parts of the body. It may be seen that there are both fast vibrations with the period τ=1.42 and slow vibrations with the period T=5τ

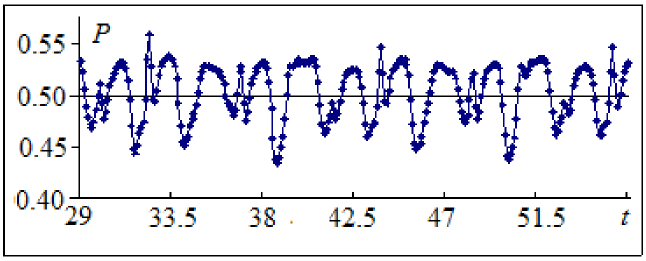

Fig. 2. The pressure history, M_∞ =1.4.

Fig. **3** shows the density distribution for the flow, presented in table in line 6. The density distribution shows shock waves moving from the body bold region to the main forehead shock wave. Vortexes, appearing near the body bold and moving downstream along the cylinder, are seen in this fig.

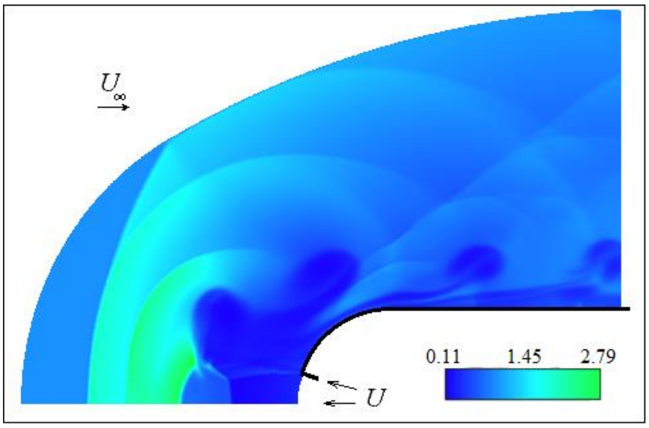

Fig. 3. The density distribution, M_∞ =1.5.

Fig. 4 shows the pressure history for the flow 6 (see table) at the interface point of spherical and conical parts of the body. If to see at this fig. attentively, two main vibrations may be seen. Fast vibrations have the period τ=1.81 and slow vibrations have the period T=4τ.

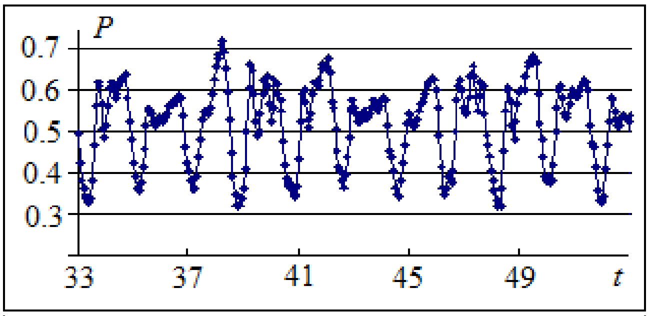

Fig. 4. The pressure history, M_∞ =1.5.

Fig. **5** shows the density distribution for the flow, presented in table in line 9. The density distribution shows shock waves moving from the body bold region to the main forehead shock wave. Vortexes, appearing near the body bold and moving downstream along the cylinder, are seen in this fig.

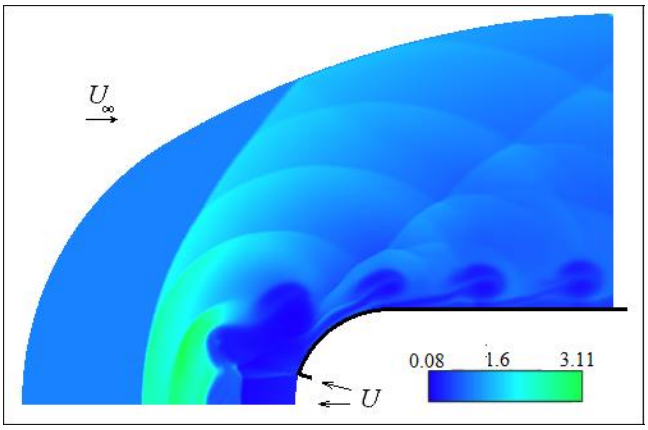

Fig. 5. The density distribution, M_∞ =1.7.

Fig. 6 shows the pressure history for the flow number 9 (see table) at the interface point of spherical and cylindrical parts of the body. Nearly periodical dynamic with the period τ=1.33 is shown at this fig.

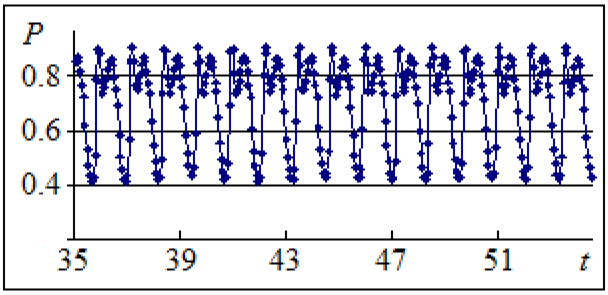

Fig. 6. The pressure history, M_∞ =1.7.

IV. CONCLUSION

Interactions of supersonic streams with blunted bodies, giving off supersonic jets, are studied. Previous investigations [14]-[16] allowed to find unsteady regimes of these interactions at free stream Mach numbers $1 \le M_\infty \le 1.3$. Self-oscillatory flows at Mach numbers $1.3 \le M_\infty \le 1.7$ are observed in recent investigation.

Unsteady flows, considered here, are defined by five control parameters: M_∞, M_{jet}, ρ_{jet}, P_{jet}, $б_{jet}$. Only little part of 5D space of control parameters is studied in [15-16] and here. Both CFD modelling and experimental study are necessary to get more understanding of unsteady flows physics near blunted bodies, giving off opposite jets.

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