Experimental and computational research of supersonic and hypersonic flow around cube shaped fragments in the air

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Abstract. A numerical and experimental research of supersonic and hypersonic air flow round cubic fragments, differently oriented relative to the direction of the incoming flow was carried out. The results of visualizing supersonic airflow round cubic fragments are rendered by two methods: a theoretical one, based on a mathematical model by way of numerical solution of the Reynolds-averaged complete Navier-Stokes equations, and an experimental one using shadowgraphy.

1. Introduction
For ground aerodynamic testing, a research method in the aeroballistic shooting range is widely used [1], [2], [3]. In it the test object is shot into free flight with desired initial conditions of the speed and angle of attack from a powder or light-gas installation. During the flight, optical tools of external measurements multiply register the test object’s positions at fixed moments, and the object’s center of mass linear and angular coordinates at these moments are later determined [4]. In testing small size bodies, for example, fragments, there appear a number of special features as compared to the standard tests. The uncertainty of prior knowledge about such elements motion character and their runaway from the registration zone caused by aerodynamic forces on the faces angularly oriented relative to the direction of flight reduce the number of recorded positions and restrict to determining only linear coordinates. To obtain operational comparative information at such tests, it is reasonable to have test experiment-calculated data on reference bodies motion aerodynamic properties, the bodies being of the same material and the same size.

2. Methods
The results of the numerical and experimental research of supersonic flow round cubic fragments differently oriented relative to the direction of the incoming flow are presented below. The results of visualizing supersonic flow round cubic-shaped bodies are presented by two methods; a theoretical one based on the mathematical model numerical solution and an experimental one using the method of shadow photoregistration [5].

A cube with the characteristic face size of 8 mm was the tested object. Several domains of different sizes with the same initial flow velocity ($M = 7$) were examined to determine how the size of the
computational domain effects the nature of the flow round the cube and the drag coefficient. Based on symmetry conditions, only a quarter of the whole domain surrounding the cube was taken. The rated domain used in further studies how the initial flow velocity effects the drag coefficient and the flow picture around the cube is 90×50×50 mm.

2.1. Visualization of processes in supersonic flow of cubic fragments by numerical simulation

The chosen simulation method consisted in a numerical solution of Reynolds-averaged Navier-Stokes equations supplemented with $k - \varepsilon$ turbulence model.

Aerodynamic forces and moments acting on the object’s streamlined surface are estimated as a result of the solution. The flowing gas conditions of the rated volume: pressure, density, temperature, speed distribution fields are also estimated. The results can be displayed as contour distributions of flow parameters in the volume and on the body surface, and as relevant graphs for any selected section.

The constructed finite-volume grid was adapted twice after 1000 and 2000 calculated iterations for flow conditions with initial velocity $M = 10$. The original grid consisted of 317500 cells, and the adapted grid consisted of 976340; 1754320 cells.

Three-dimensional calculation of the process of external flow round the cube by a supersonic flow of compressible gas was carried out taking into account the corresponding boundary conditions on the surface of the cube and on the walls of the computational domain. The complete Reynolds-averaged Navier-Stokes [6], [7], [8] equations supplemented by a two-parameter turbulence model were solved. The range of the considered initial flow velocities was $2 – 10 \, M$, the equation of the ideal gas state was used for the air. In the process of calculation, the complete fields in the domain volume of all parameters of the flowing gas were estimated, the cube drag coefficient was evaluated.

The distributions of pressures, velocities round the streamlined cube ($M = 9$ with the initial face and vertex orientation, $M = 10$ with the initial edge orientation) are presented in figures 1-2.

**Figure 1.** Distribution of pressure fields (Pa) in the air of a hypersonic flow around the cube differently orientated to the incoming flow: $a$) - face, $b$) – edge, $c$) – vertex.
Figure 2. Distribution of velocity fields (m/s) in the air of a hypersonic flow around the cube at different cube orientations relative to the incoming flow: a) - face, b) – edge, c) – vertex.

2.2. Visualization of the process of supersonic flow by shadow photoregistering

The bodies tested were made of the alloy ("tungsten – nickel – iron") and had a size 8×8×8 mm (weight 8.7 g) with the initial orientation to the incoming flow by face, edge and vertex. The external linear coordinates and flight time on the flight path were registered at at least 12 points on the length of the measuring area of over 50 m in an aeroballistic shooting range.

Tests of cubic-shaped bodies at initial throwing speeds \( V < 2 \) km/s were carried out by shooting out the test object from a powder ballistic installation with a caliber of 23 mm. In these experiments, in addition to external parameters, wide-format shadow spectra of the flow were obtained (see figure 3).

Figure 3. Visualization of the flow around the cube at the supersonic speed with different orientations \((a, b, c)\) of the body.
The data of external measurements of the position of the center of mass obtained in each particular experiment were used to determine the drag force coefficient by solving a system of differential equations of motion, which, to the greatest extent, (at the minimum of the weighted sum of the squares of the residuals of the calculated and measured coordinate values) is consistent with the measurement data.

As test objects under the same test conditions, objects of the ball shape from the same material with a diameter of 10.4 mm were studied.

3. Results
The results of numerical simulation as the dependence of the drag coefficient $C_x$ on the Mach number with different orientations of the cube to the incoming flow, face, edge and vertex, are presented in figure 4.

Figure 4. The dependence of the drag coefficient on the Mach number of the cube differently orientated to the incoming flow: a) - face, b) - edge, c) - vertex.

Figure 5 shows the intermediate experimental dependence of the drag force coefficient $C_x$ on the Mach number $M$ of the cubic-shaped body in the range of $M_{mid} = (0.8 \div 3.8) M$ with an accuracy of $2\sigma \leq 2\%$. $C_x (M)$ of the cube is assigned to the area of the midsection of a sphere, equal in volume.

If the initial speeds of various cubic fragments are hypersonic, it should be noted that the cubes, which do not have a predominant aerodynamic orientation, are statically stable in flight and retain orientation from the beginning of the ablation (figure 6).
Figure 5. Experimental dependence of the drag force coefficient of the cube on the Mach number. Convention: ● – for a sphere with diameter 10.4 mm; ■, ▲, ♦ - for cube 8×8×8 mm oriented by face, edge and vertex respectively.

Figure 6. X-ray image of a cube from "tungsten – nickel – iron" alloy in flight at $M=13.3$.

4. Conclusion
A computational and experimental research of supersonic motion of cubic fragments with different initial orientation relative to the direction of the incoming flow was carried out. Experimental spectra and the calculated flow distribution of pressures, densities, temperatures, speeds round the streamlined cube were obtained. As a result of experimental testing, the average experimental dependences of the drag force coefficients of $C_x(M)$ in the range of Mach numbers from 0.8 to 3.8 in the absence of overburning and thermomechanical destruction were obtained. In this case, the experimental data on the balls are in good agreement with the known experimental data. The experimental dependence of the cubes was obtained with an error of $2\sigma \leq 2\%$ and does not depend on the initial orientation of the test object in the barrel channel of the ballistic installation. In addition, as shown by shadow patterns in the area of 20 m from the output section of the barrel channel, due to rotation, the initial orientation of the
fragment may change during the flight, which leads to a convergence of the $C_x (M)$ values. In this regard, the numerical results have additional value and allow to draw a conclusion about the reasonable transfer of part of the solved problems from expensive experiments to mathematical modeling. In the presence of ablation in the case of throwing with hypersonic speeds, fragments of the initial cubic shape become statically stable in further flight.

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