Numerical simulation of a hypersonic flow over HB-2 model using UST3D programming code

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Abstract. Numerical modeling of a flow over HB-2 model using UST3D programming code was carried out. Aerodynamic coefficients dependencies from Mach number and angle of attack were compared to various experimental tests results. Good accordance of the numerical method predictions with empirical data was demonstrated. The numerical simulation has provided an extra UST3D code validation in application to aerodynamic calculations of hypersonic flows.

1. Introduction

Standard or calibration models are frequently quoted while conducting numerical and experimental studies both for investigating experimental facilities accuracy or numerical methods validation on well-known aerodynamics. Hypersonic ballistic model HB-2 represents one of two hypersonic ballistic configurations proposed by Supersonic Tunnel Association in 1960. Later in 1963 configurations HB–1 and HB–2 were included into the set of Advisory Group for Aerospace Research and Development (AGARD) reference models and currently are of great use for experimental and numerical hypersonic test techniques validation \cite{1}. HB-2 has analytical shape patterned in figure 1; it consists of a blunted cone, cylinder, and flare. The latter makes difference between the two models, HB-1 model geometry having no flare.

There are several reference experiments concerning HB–2 aerodynamics that can be found in literature. One of the most reliable known tests was conducted in the 1.27 m Hypersonic Wind Tunnel (HWT) of Japan Aerospace Exploration Agency (JAXA) \cite{2}. HWT is a blowdown cold type wind tunnel with nominal Mach number of 10 and thanks to its functional scheme the flow properties at the test section can be estimated relatively accurately (Mach number uncertainty is less than 0.3\%). A six-component balance (Nissho LMC-6522-33/Z100) was used in the experiment to perform force measurements. Mach number was estimated from the stagnation pressure and temperature measured at the reservoir together with the pitot pressure measured in the test section.

Experimental results from tests carried out in AT-303 wind tunnel (ITAM, Russia), ARC1, R3 wind tunnels (ONERA, France), Von Karman Facilities high-speed wind tunnel (VKF, AEDC, USA), and from German Aeronautics Centre experiments (Deutsche Versuchsanstalt fur Luftfahrt – DVL, Germany) are also cited in several available sources \cite{3, 4}.
Some numerical results obtained by research groups focusing on computational modelling of HB–2 hypersonic aerodynamics amplify the database of free access and can be useful for comparative analysis [4, 5].

This paper is dedicated to UST3D code numerical method validation conformably to hypersonic flow problems on the HB–2 test example. The method will be presented in a general way in Section 2, more complete information can be found in [6, 7]. Principal results, their analysis and comparison with experiments will be discussed in Section 3 followed by overall conclusion on the method applicability to the considered range of problems.

2. Numerical method
Numerical simulation was performed using UST3D (Unstructured Splitting Tetrahedral 3–Dimensional) code developed in Laboratory of Radiation Gas Dynamics (A. Ishlinsky Institute for Problems in Mechanics of the Russian academy of sciences) [6, 7]. The computational algorithm is based on spatial Navier-Stokes equations solution using modified method of splitting on physical processes [8, 9, and 10]. In Cartesian coordinates the system of equations has the following form:

$$\frac{\partial U}{\partial t} + \frac{\partial Ec}{\partial x} + \frac{\partial Fc}{\partial y} + \frac{\partial Gc}{\partial z} = \frac{\partial Ev}{\partial x} + \frac{\partial Fv}{\partial y} + \frac{\partial Gv}{\partial z},$$

where $U = (\rho, \rho u, \rho v, \rho w, \rho E)^T$ is conservative variables vector; $Ec = (\rho u, \rho u^2 + p, \rho uv, \rho vw, \rho wu + pu)^T$, $Fc = (\rho v, \rho uv, \rho v^2 + p, \rho vw, \rho vw + pv + pu)^T$, $Gc = (\rho w, \rho uw, \rho vw, \rho w^2 + p, \rho wv + pw + pw + pw)^T$ are convective terms projections; $Ev = (0, \tau_{xx} , \tau_{yy} , \tau_{zz} , \tau_{xy} + \nu \tau_{yx} + \nu \tau_{zx} - q_x^T)$, $Fv = (0, \tau_{yy}, \tau_{zz}, \tau_{xy} + \nu \tau_{yx} + \nu \tau_{zy} + \nu \tau_{zy} + \nu \tau_{zy} - q_y^T)$ are viscous terms projections; $\rho$ is density; $u, v, w$ – velocity projections; $E$ – specific energy, $\tau_{ij}$ – viscous tensor components; $q_i$ – heat flux projections.

For the equations closure the ideal gas law is used:

$$p = (\gamma - 1) \rho \left[ E - \frac{1}{2} (u^2 + v^2 + w^2) \right],$$

where $\gamma = 1.4$ – heat capacity ratio of air.

In present work the flow was simulated under laminar regime. Two unstructured tetrahedral meshes counting 1.4 and 3 millions of cells were used. Computational domain is patterned in figure 2, where the applied boundary conditions are indicated as well. Symmetry boundary condition which coincides with the pattern plane was applied to reduce computational costs. Time step is chosen automatically by UST3D algorithm according to condition on final discrepancy limitation.

In the numerical modeling the cylinder diameter D was set to 1 m. Nominal flow conditions were chosen corresponding to JAXA experiment conditions (Run with $M_{\infty} = 9.6$) and were calculated for each Mach number accordingly to indicated values of stagnation parameters.
3. Results and discussions

Since the computational software is adapted for using on tetrahedral grids and therefore in its actual state is not intended for heat flux calculations, the current research is focused on force loads estimation. A set of calculations of a flow over HB-2 configuration with varying Mach number and angle of attack was performed. Figure 3 shows drag coefficient plot as a function of Mach number obtained in the calculation in comparison with experimental data given in [3]. Here $C_A$ is the axial force coefficient including the base drag of the model and $C_{AF}$ is the axial force coefficient of the model without base drag (forebody axial force), i.e.:

$$C_{AF} = C_A - \frac{(p_\infty - p_b) A_b}{q_\infty A},$$

where $p_b$ – base pressure, $p_\infty$, $q_\infty$ – static and dynamic pressure of the incoming flow, $A = \pi D^2/4$ – reference area, $A_b$ – base area. Difference in integral characteristics computed on 1.4 and 3 million meshes was revealed to be less than 1% of the absolute value, thus here and later only results for mesh of 1.4 millions of cells are plotted.

Figure 3. Drag coefficient comparison with experimental data: 1, 1, a – ONERA, 2 – VKF, 3 – DVL, 4 – Sandia, 5 – ITAM, balance measurements (1-5), integral of pressure over the surface (1, a).

As it can be seen from the figure, the numerical results are in good agreement with experiments in the whole range of hypersonic Mach numbers, a noticeable mismatch occurring only for Mach number
\(M_\infty = 2\). The shaded zone includes high Mach numbers for which uncertainty of experiment predictions is too significant and therefore only approximate bounds of characteristic values could be marked [3].

![Mach number fields](a), (b), (c)

**Figure 4.** Mach number fields for
- \(M_\infty = 3\) (a),
- \(M_\infty = 9.6\) (b),
- \(M_\infty = 16.5\) (c).

![Shadowgraph](Figure 5. Shadowgraph from AT-303 experiment \((M = 9.7, \alpha=12^\circ)\) compared to the flow structure obtained in numerical simulation \((M = 9.6, \alpha=10^\circ)\).

**Figure 5.** Shadowgraph from AT-303 experiment \((M = 9.7, \alpha=12^\circ)\) compared to the flow structure obtained in numerical simulation \((M = 9.6, \alpha=10^\circ)\).

Figure 4 represents flow structure transformation appearing with increasing Mach number. In figure 5 the flow shadowgraph made during experiment in AT-303 for \(M_\infty = 9.7, \alpha=12^\circ\) is compared to the flow structure obtained in numerical simulation for \(M_\infty = 9.6, \alpha=10^\circ\).

Angle of attack variation was investigated under incoming Mach number \(M_\infty = 9.6\) accordingly to the conditions fixed in JAXA experiment report. Figure 6 illustrates how the flow structure changes under different angles of attack.
Aerodynamic coefficients of forebody axial force and normal force depending on angle of attack are depicted in figures 7 and 8. The final discrepancy between numerical predictions and empirical values lies within bounds of 10% for $C_{AF}$ and of 1% for $C_N$ estimation.

The assumption that the hypersonic flow under considered conditions can be modeled with laminar approximation required, however, some additional approval. The anxiety was roused by relatively high typical Reynolds numbers. For example, the unit Reynolds number in JAXA experiment ranged from $0.9 \times 10^6$ to $4.3 \times 10^6$ per meter. Various turbulence models with reference to high-speed flow over HB–2 model were treated by research group from Belgrad using ANSYS Fluent 16.2 CFD software in [4], where it was shown that turbulence effect on pressure distribution is not very significant (see figure 9). In figure 9 surface pressure corresponding to incoming flow Mach number $M_\infty = 4.0$ is normalized by stagnation pressure $p_0$ behind the shock wave. Pressure distribution obtained in current research is patterned with blue line. The curve is rather close to the experimental and numerical results given in [4], although UST3D a little bit overestimates pressure values near the flare. This mismatch can be related to computational errors coming from using tetrahedral meshes, calculus from [4] being carried out on hexahedral mesh.

A similar comparison of pressure distribution over HB–2 model with JAXA experimental results and numerical results from [5] was made for computation using UST3D with incoming flow Mach number $M_\infty = 9.6$.

**Figure 6.** Mach number fields for $M_\infty = 9.6$, $\alpha = -10^\circ$(a), $0^\circ$(b), $30^\circ$(c).

**Figure 7.** Computed forebody axial force coefficient $C_{AF}$ compared to JAXA experimental results.
number $M_\infty = 9.6$ (figure 10). The same behavior as for $M_\infty = 4.0$ of the distribution plot is noted, numerical results are slightly overstated in flare region.

![Figure 8. Computed normal force coefficient $C_N$ compared to JAXA experimental results.](image)

![Figure 9. Dimensionless pressure distribution along the model length for $M_\infty = 4.0$ in comparison with AEDC experimental results and numerical results from [4].](image)

4. Conclusion
UST3D code was testified on a classical example of a flow over hypersonic model. Incoming flow Mach number and angle of attack were varied for the purpose of covering wide range of test conditions. It was shown that UST3D integral characteristics predictions correspond to experimental evidence with good for engineering calculation accuracy. A tendency of pressure level overestimation near sharp geometry elements is noticed. The mentioned defeat could be in all probability levelled by employing finer or hexahedral meshes in cases when more precise information on pressure distribution is required.

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Figure 10. Dimensionless pressure distribution along the model length in comparison with JAXA experimental results and numerical results from [5].

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