Aerodynamics and Flight Dynamics Simulation of Basic Finner Supersonic Flight in Aeroballistic Experiment

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Abstract. This paper presents some results of aerodynamics and flight dynamics modeling of Basic Finner supersonic flight in an aeroballistic experiment [1]. Three dimensional surface based on the experiment description was formed. Unstructured tetrahedral volume mesh is formed after it. Aerodynamics computations were done by software package for CFD numerical computation of free form high-speed vehicle ug3D developed in the Institute for Problems in Mechanics. Obtained from CFD calculations aerodynamic coefficients became initial data for unguided Basic Finner flight dynamics calculations. Flight dynamics computations were done by developed solver MODIN for typical high speed vehicles flight dynamics calculations [2]. Six degrees of freedom motion without considering Earth rotation and form are adopted. Results of experimental and obtained numerical aerodynamic coefficients and flight parameters data comparison are also presented.

1. Introduction
The key objective of this paper is the demonstration of developed software packages abilities to perform a full technological cycle of supersonic vehicles computer simulation from 3D surface geometry creation to flight trajectories calculations.

The main goal of this paper is a description of fully coupled computational fluid dynamics (CFD)/Six degree-of-freedom motion (6-DoF) computations of finned projectiles at high supersonic velocities as well as a description of some results of developed computer codes of aerodynamics and flight dynamics calculations validation based on aeroballistic experiments data [1].

Obtained from CFD calculations aerodynamic coefficients were compared to experimental database as a part of developed CFD ug3D solver validation but also became initial data for flight dynamics calculations. 6-DoF motion computations were made by developed solver MODIN using calculated and experimental aerodynamic coefficients as initial data. This sequence of calculations allows evaluating the accuracy of both ug3D and MODIN in their application area and quality of «virtual vehicle» computer simulation with regard to aeroballistic experiment data.

2. Object description
Basic Finner configuration has been well studied as a calibration model for different types of aeroballistic ranges and wind tunnels and as a reference projectile for dynamic stability research is considered [1]. Thereby many experimental data of aerodynamic coefficients and flight dynamics parameters from wind tunnels and aeroballistic ranges are available.
The object of research is a symmetrical projectile consisting of a cone nose blunted by the small-radius sphere 10 degrees and a 0.03 m caliber cylindrical fuselage body [1]. Four rectangular fins with a simple blunted wedge profile and a 0.09 m wingspan located in the tail. Total length of the object is 0.3 meters.

There are experimental data for different fin cant angles of 0°, 2°, 4° for spinning motion creation. Within the framework of this paper in 3D computer surface creation and aerodynamics simulation only 0° fin cant is considered. Flight dynamics computations were done with both 0° and 4° cant angles. Model configuration is presented at figure 1 (dimensions in calibers).

![Figure 1. Model configuration (dimensions in calibers 1 cal = 0.03 meters).](image URL)

Reference length and reference area for further aerodynamic coefficients calculations are $l_{ref} = 0.03$ m and $S_{ref} = 0.0007$ m$^2$ respectively. Finner barycentre for aerodynamic moments evaluation is located at the symmetry axis at the distance of $x_{cg} = 0.165$ m from the projectile’s nose. Mass inertial characteristics for flight dynamics calculations are presented in the table 1. They do not change during the flight since in the aeroballistic experiment. We assume that Basic Finner is a body of constant mass moving by inertia without thrust.

| Table 1. Basic Finner mass inertial characteristics. |
|-----------------------------------------------------|
| Projectile’s mass, $m$ kg | 1.58 |
| Axial moment of inertia, $I_x$ kg·m$^2$ | 0.000192 |
| Transverse moments of inertia, $I_y, I_z$ kg·m$^2$ | 0.00979 |

3. Surface geometry creating and volume mesh generation
For the Basic Finner computer simulation CAD surface was created considering all the features based on the object’s geometry (figures 2–5).

Next step is a volume mesh generation. 3D CAD geometry was exported to a mesh generator [3-5]. Developed CFD solver ug3D can use both structured and unstructured grids, but in this case a 2.7 million cells unstructured tetrahedral volume grid was generated (figure 6). Grid has a cell refinement near the sphere-blunted cone nose (figure 7), cone-cylinder junction (figure 8) and fins blunted leading edges (figure 9).
In the ambient flow area maximum cell size is 28 mm. Tetrahedron’s size near the sphere-blunted cone nose tip, cone-cylinder junction and fins blunted leading edges is 0.09 mm. Generated meshes quality was evaluated by the common criteria [6-8]. Separately the aspect ratio for any triangular cell of the surface mesh and any tetrahedral cell of the volume mesh does not exceed 4 and 6 respectively. Equiangle skew for triangle elements is less than 0.7 and not more than 0.8 for tetrahedral cells. Generated mesh models meet the requirements for effective CFD solver ug3D performance.

![Figure 2. Total view of Basic Finner CAD surface.](image1)

![Figure 3. Side view of Basic Finner CAD surface.](image2)

![Figure 4. Basic Finner’s blunt nose CAD surface.](image3)

![Figure 5. Blunt fin CAD surface.](image4)

![Figure 6. Generated mesh general view.](image5)

![Figure 7. Cell refinement near the nose.](image6)
4. Aerodynamics simulation

Basic Finner aerodynamics calculations were made by a software package developed in the Institute for Problems in Mechanics Russian Academy of Science for numerical aerodynamics simulation of complex-form high-speed vehicles ug3D [9–10].

4.1. Numerical method

For numerical simulation of aerodynamics of Basic Finner we assume that the flow is governed by the compressible Navier-Stokes equations which describe the conservation of mass, momentum, and energy in a viscous fluid. The working fluid is assumed a calorically perfect gas, and the ratio of specific heats is assumed to be 1.4. For viscous flow problems, Sutherland’s law is used to compute the molecular viscosity and a constant laminar Prandtl number of 0.72 is used to compute the thermal conductivity.

The flow solver ug3D is a density based cell center finite volume Navier-Stokes solver and can be considered as a Godunov-type solver. In order to achieve second order spatial accuracy, a piecewise linear reconstruction MUSCL approach is used [11].

The inviscid numerical fluxes may be computed using a variety of exact or approximate Riemann solvers. We implemented the most popular solvers in our flow solver. For the work shown here, most of the computations have been performed using the Advevctive Upstream Splitting Method (AUSM) of Liou and Steffen [12]. This flux function is rather computationally cheap and is applicable for viscous flow calculation.

The gradient needed for the linear reconstruction can be computed by either the cell based Green-Gauss approach or the least-square method [11]. Usually the weighted least square method is used in ug3D as the default reconstruction method. In order to prevent any overshoot for the reconstructed variables and the generation of oscillations in the regions of large gradients or shocks, the limiter of Barth and Jespersen [11], Venkatakrishnan’s limiter [13], and Michalak and Ollivier-Gooch limiter [14] are incorporated into the ug3D solver.

The velocity and temperature gradients for viscous fluxes are calculated using either a Green-Gauss or least-squares method at all grid cell centroids as described in above and then averaged to obtain the gradients at the cell faces. However, it was demonstrated that this approach would lead to the decoupling of the solution on quadrilateral or hexahedral grids [15]. In order to reduce the decoupling error of the method the correction [16] is applied.
For temporal discretization, both the second and third-order accurate explicit TVD Runge-Kutta methods [17] are available. A spatially varying time step is used, with a blending of inviscid and viscous time-step constraints.

4.2. Initial data for aerodynamics modeling

Besides the generated tetrahedral unstructured grid, we need to determine free stream parameters to start aerodynamical simulation. Since one of the main goals of this work is to validate developed computer codes for aerodynamics and flight dynamics calculations, the main interest is provided by experimental data obtained in aeroballistic range experiments. Specialty of this type of experiments is in the free uncontrolled flight of the object after its launch from the gun in the aero-ballistic range with a certain initial velocity. Schematic view of the aeroballistic range is presented at figure 10.

Figure 10. Schematic view of DREV Aeroballistic Range [18].

Used experimental aerodynamic characteristics are determined by 6-DoF reduction from the free-flight trajectories measured in the Aeroballistic Range DREV (Defense Research Establishment Valcartier) [18]. Initially moving in the gun barrel, the object is located in the sabot, which splits up into 2 pieces after exit the barrel due to its aerodynamic profiling. Duration of the free flight is limited by the length of Aeroballistic Range (approximately 220 m) and depends on the initial velocity (figures 11-12). Initial velocity is set by the solid fuel mass putting in the sabot and in the DREV subsonic as well as high supersonic launches were conducted with the range of initial velocities of 0–1500 m/s.

Figure 11. Photo of DREV Aeroballistic Range [18].

Figure 12. Typical shadowgraph of aeroballistic experiment [18].
Due to developed software packages specificity five shots with high supersonic initial velocities were chosen from the wide range of available free-access experimental data. Appropriate initial free stream conditions of each selected shot are presented in table 2.

**Table 2. Initial conditions of selected shots.**

| Shot number | 17   | 05   | 26   | 23   | 01   |
|-------------|------|------|------|------|------|
| Mach number, $M_\infty$ | 2.413 | 2.97 | 3.337 | 4.127 | 4.42 |
| Sound velocity, $a$ m/s | 343.41 | 343.85 | 343.52 | 343.83 | 343.8 |
| Density, $\rho$ kg/m$^3$ | 1.17843 | 1.17484 | 1.20303 | 1.18066 | 1.18122 |

4.3. Aerodynamics calculation results

In accessible experimental data sources aerodynamic normal force and pitch moment coefficients are given as an angle of attack (AoA) derivative. For each selected shot two calculations were done for angles of attack values of $\alpha = 0^\circ$ and $\alpha = 5^\circ$ to validate ug3D code. The coefficients in this case are determined by formulas (1):

$$c_y^\alpha = \frac{c_y}{\sin \alpha}, \quad m_z^\alpha = \frac{m_z}{\sin \alpha}$$  \hspace{1cm} (1)

Three-dimensional gas-dynamic distributions for different Mach numbers and angles of attack are presented as an illustration of computation results. For example, density and Mach number distributions for minimum considered value of initial velocity $M_\infty = 2.41$ with angle of attack $\alpha = 5^\circ$ and for maximum considered value of initial velocity $M_\infty = 4.42$ with $0^\circ$ angle of attack are presented at figures 13–14 and 15–16 respectively.

![Figure 13. Density distribution $M_\infty = 2.41$, $\alpha = 5^\circ$.](image13)

![Figure 14. Mach number distribution, $M_\infty = 2.41$, $\alpha = 5^\circ$.](image14)
The figures 17–18 show density gradient compared to analytical solution [19] of the attached conical shock wave deflection angle. This comparison is correct since the projectiles nose is a cone with a very small blunt radius. The attached conical shock wave deflection angle can be calculated through the equation

$$
\text{ctg}(\theta) = \text{tg}(\beta) \left[ \frac{(\gamma + 1)}{2} \frac{M^2_\infty}{M^2_\infty \sin^2 \beta - 1} - 1 \right],
$$

(2)

where $\beta$ – attached shock wave deflection angle; $\theta$ – half-cone angle; $\gamma$ – heat capacity ratio.

Analytical results are presented in table 3. There is an excellent agreement of numerical calculations results with the sharp cone analytical solution despite three-dimensional surface used in CFD calculations has a blunted nose.

**Table.3.** Results of analytical solution for the attached conical shock wave deflection angle.

| Shot number | 17     | 01     |
|-------------|--------|--------|
| Mach number, $M_\infty$ | 2.413  | 4.42   |
| Conical shock wave deflection angle, $\beta^\circ$ | 29.203 | 16.951 |
The figures 19–21 show results of ug3D solver validation comparing the obtained results of aerodynamics simulation with selected experimental data. Comparison of aerodynamic integral characteristics such as axial force, normal force and pitch moment coefficients is presented. Above-mentioned coefficients are determined at a body-referenced frame. Body-referenced frame aerodynamic forces coefficients are related with airspeed reference frame coefficients by the following equations:

\[
\begin{align*}
  c_{u} &= c_{x} \cos \alpha + c_{y} \sin \alpha \\
  c_{n} &= c_{y} \cos \alpha - c_{x} \sin \alpha
\end{align*}
\]  

\[(3)\]

**Figure 19.** Comparison of calculated axial force coefficient with experimental data.

**Figure 20.** Comparison of calculated normal force coefficient with experimental data.

**Figure 21.** Comparison of calculated pitch moment coefficient with experimental data.

There is an excellent agreement between calculated axial force coefficient and experimental data. Computed normal force and pitch moment coefficients derivatives approximate experimental data satisfactorily. Computational error of axial force, normal force and pitch moment coefficients derivatives with regard to experimental data does not exceed 10%, 5% and 10% respectively.


5. Flight dynamics simulation

Flight dynamics computations were carried out with the solver MODIN for typical high-speed vehicles flight dynamics cases. During the sabot separation from the projectile in aeroballistic experiment, the object is inevitably exposed to external forces. This determines the initial angular velocity of detached projectile and oscillatory character of projectile’s further motion.

5.1. Equations of motion

Since in this case the projectile under consideration is an uncontrolled vehicle performing an oscillatory and rotation motion in all planes, it is necessary to use the spatial model of object’s motion with 6 degrees of freedom. Because of trajectory’s limitation by the Aeroballistic Range 220 meters length (figure 10) and because the characteristic flight time does not exceed 0.2 seconds, it makes sense not to consider Earth’s form and angular rotation influence and atmosphere parameters variations. Because of considering the object as a rigid body the effect of elastic deformations on aerodynamic coefficients is neglected.

Thus 6-DoF equations of motion of the unguided projectile without thrust take the following form (4) [20]:

\[
\begin{align*}
\dot{mV} &= -X_a - mg \sin \theta; \\
\dot{mV} \dot{\theta} &= Y_a \cos \gamma_a - Z_a \sin \gamma_a - mg \cos \theta; \\
-\dot{mV} \cos \theta \dot{\psi} &= Y_a \sin \gamma_a + Z_a \cos \gamma_a; \\
I_\alpha \dot{\omega}_\alpha &= M_\Sigma - (I_\alpha - I_\gamma) \omega_\alpha \omega_\gamma; \\
I_\psi \dot{\omega}_\psi &= M_\Sigma - (I_\psi - I_\gamma) \omega_\psi \omega_\gamma; \\
I_\phi \dot{\omega}_\phi &= M_\Sigma - (I_\phi - I_\gamma) \omega_\phi \omega_\gamma; \\
\dot{\psi} &= \left( \omega_\gamma \cos \gamma - \omega_\alpha \sin \gamma \right) / \cos \theta; \\
\dot{\theta} &= \omega_\gamma \sin \gamma + \omega_\alpha \cos \gamma; \\
\dot{\gamma} &= \omega_\alpha - \psi \sin \theta; \\
\dot{L} &= V \cos \theta \cos \psi; \\
\dot{H} &= V \sin \theta; \\
\dot{Z} &= -V \cos \theta \sin \psi.
\end{align*}
\]

Where \(X_a, Y_a, Z_a\) – dimensional aerodynamic drag, lift and side forces in airspeed referenced frame; \(M_a, M_y, M_\phi\) – dimensional aerodynamic roll yaw and pitch moments; \(\theta\) – flight path angle; \(\psi\) – course angle; \(\gamma, \psi, \theta\) – Euler angles (roll, yaw and pitch); \(g\) – gravitational acceleration; \(L, H, Z\) – center of gravity coordinates; \(\gamma_a\) – kinematic roll angle, determined by equations (5) by the Euler angles, angles of attack \(\alpha\) and slip \(\beta\).

\[
\begin{align*}
\sin \beta &= \cos \theta \left[ \sin \theta \sin \gamma \cos (\psi - \psi) - \cos \gamma \sin (\psi - \psi) \right] - \sin \theta \cos \theta \sin \gamma; \\
\sin \alpha &= \left[ \cos \theta \sin \gamma \cos (\psi - \psi) + \sin \gamma \sin (\psi - \psi) \right] - \sin \theta \cos \theta \cos \gamma \cos \beta; \\
\sin \gamma_a &= \left[ \cos \alpha \sin \beta \sin \gamma - \cos \beta \sin \alpha \sin \beta \cos \gamma \cos \beta \sin \gamma \right] / \cos \theta.
\end{align*}
\]

5.2. Initial data for flight dynamics modeling

In order to calculate the spatial motion of symmetric unguided projectile without thrust (according to (4)) it is necessary to possess initial data on the aerodynamic coefficients of axial, normal forces along with roll, pitch moments and damping roll and pitch moments. Projectile’s mass, axial and transversal inertia moments and center of gravity location are also required.

Mass inertia characteristics are shown in table 1. Calculated within the framework of this paper and experimentally obtained aerodynamic coefficients of axial and normal forces and pitch moment are
presented in figures 19–21. Roll, yaw and pitch damping moments as well as roll moment due to fin cant $\delta = 4^\circ$ were taken from experimental aerodynamic database (figures 22–25), because in this paper aerodynamics calculations were made without damping and roll motion.

It should be noted that the experimental damping moments coefficients calculations use non-dimensional angular velocity rates. The dimensional damping moment is determined from the damping coefficient by the following equation

$$M^o = m^o \cdot \bar{\omega} \cdot q \cdot S_{ref} \cdot l_{ref},$$

where $\bar{\omega} = \omega \cdot l_{ref} / 2V$.

Figure 22. Pitch damping moment as a function of Mach number.

Figure 23. Roll moment due to fin cant as a function of Mach number.

Figure 24. Roll damping moment coefficient as a function of Mach number.

Figure 25. Magnus moment coefficient as a function of Mach number.

For the developed flight dynamics solver MODIN validation two experimental shots from the table 2 were chosen. One of them (shot number 26) with a roll motion produced by fin cant angle $\delta = 4^\circ$, and the other – number 01 without fin cant.

Dependences of the total angle of attack, and pitch and yaw angles to range of flight are presented in [1]. However, to set the initial state vector in accordance with equations of motion (4) we need to know initial values of the flight path and course angles as well as roll, yaw and pitch angular
velocities. Table 3 shows chosen values of initial state vector variables for flight dynamics simulation of two experimental shots.

**Table. 3. Initial state vector.**

| Shot number | 01 | 26 |
|-------------|----|----|
| Mach number | 4.42 | 3.33 |
| Fin cant angle $\delta$, ° | 0 | 4 |
| Flight path angle $\theta$, ° | 0.125 | 0.1 |
| Course angle $\psi_c$, ° | -3 | 0 |
| Pitch angle $\theta$, ° | -0.2 | 0 |
| Yaw angle $\psi$, ° | -3.5 | 0 |
| Roll angular velocity $\omega_x$, °/c | 0 | 6303 |
| Yaw angular velocity $\omega_y$, °/c | -25 | -3 |
| Pitch angular velocity $\omega_z$, °/c | -13 | 0 |

5.3. **Flight dynamics calculation results**

As a result of uncontrolled finned projectile flight dynamics calculations, comparisons of calculated trajectory parameters such as pitch, yaw angles and total angle of attack with experimental data are presented. The influence of using calculated and experimental initial aerodynamic characteristics in yaw and pitch channels on computed and experimental trajectories agreement is evaluated.

Figures 26–28 present obtained numerical results comparison with experimental data for shot 01 without rotation motion. Here and further, the blue line illustrates results of 6-DoF motion simulated with experimental aerodynamic characteristics, the red line - with calculated ones. The experimental data are marked with circles. Equation for total angle of attack is presented below

$$\alpha_{tot} = \sqrt{\alpha^2 + \beta^2}.$$  \(1\)

**Figure 26.** Simulated and measured yaw angle of a non-spinning case with respect to range of flight (Shot 01).

**Figure 27.** Simulated and measured pitch angle of a non-spinning case with respect to range of flight (Shot 01).
High output values of Euler angles and total AoA are observed in non-rotation case but the motion is stationary with all angles oscillation damping. Excellent agreement between calculated and experimental data is also registered.

For the shot number 26 with rotation caused by fin cant angle $\delta = 4^\circ$ we can see a slightly worse match between experimental and calculated trajectory parameters, but the character of parameters changing by time and the oscillation period are quite the same. Lower values of Euler angles and total AoA due to rotational motion are also observed. High quality of obtained results in all considered cases (at figures 26–31 blue and red lines almost completely merge) allows to draw a conclusion about the legitimacy of application of the developed software packages for coupled CFD/6−DoF computations for aeroballistic experiments modeling and prediction of objects aerodynamic characteristics and flight dynamics parameters at unattainable regimes for experimental facilities.
5.4. Roll motion stability analysis

Within the framework of this paper special attention is focused on dynamic stability of rolling motion analysis. The value of the Magnus moment coefficient which is increasing due to angular velocity growth as the projectile flies down the range plays an important role in dynamic stability analysis. The steady spin rates of 4° fin cant is approximately 125 degrees per meter [1]. In spin stabilized projectiles ballistics oscillatory motion determination to fast nutational and slow precessional motion is accepted [21]. Firstly, the preliminary analysis was done using the established ballistics equations for yaw damping factors of the nutation and precession arms (8). The criterion of object’s dynamic stability is that damping factors are negative.

\[
\lambda_\text{n} = \frac{\rho S_{\text{ref}}}{4m} \left[ -c_{\text{ref}} \left( 1 - \frac{1}{\sigma} \right) + \frac{k_2^2}{2} \left( 1 + \frac{1}{\sigma} \right) \frac{m_{\text{ref}}}{\sigma} + \frac{k_{\text{m}}^2}{\sigma} \right]; \\
\lambda_\text{p} = \frac{\rho S_{\text{ref}}}{4m} \left[ -c_{\text{ref}} \left( 1 + \frac{1}{\sigma} \right) + \frac{k_2^2}{2} \left( 1 - \frac{1}{\sigma} \right) \frac{m_{\text{ref}}}{\sigma} - \frac{k_{\text{m}}^2}{\sigma} \right]; \\
k_1^2 = \frac{md^2}{I_x}, k_2^2 = \frac{md^2}{I_y}, \sigma = \sqrt{1 - \frac{1}{s_x} s_y} = \frac{2I_x l_5^2 \omega^2}{\pi I_y \rho m' c V^2 d^2}. 
\]

For shot number 26 the nutation and precession damping factors were calculated. With the angular velocity growth the precession motion loses its stability earlier. Corresponding precession damping factor versus angular velocity ratio is presented at figure 32. In this case the projectile loses its stability approximately at 120 degrees per meter while nutation factor is still less than zero. In the experiment the aeroballistic range length is finite and the projectile doesn’t have enough time to grow angular velocity for dynamic stability lost which is obtained at the range of 200–210 meters approximately. This fact explains that there are no divergent oscillations observed in shot number 26 in Aeroballistic Range experiments – the rolling angular velocity just did not have enough time to reach the instability area.

So now we can take a look at the trajectory parameters such as total AoA and yaw angle after the projectile losing its stability (figures 34-35). Character of the total angle of attack evolution (figure 34) before reaching 200 meters range is definitely stable with damped oscillations. After reaching the instability spin rates the total AoA median curve have an increasing form. Herewith the oscillations remain stable. This suggests that after the loss of stability of slow precession oscillatory motion the fast nutational motion is still stable at the same roll angular velocities. The yaw angle evolution
(figure 35) before the 200 meters borderline is definitely stable as well. But it became divergent after the borderline. These numerical results confirm the preliminary analysis conclusion that 120 degrees per meter is the limit spin rate for dynamically stable motion.

Figure 32. Precession damping factor versus roll angular velocity (Shot 26).

Figure 33. Roll angular velocity with respect to range of flight (Shot 26).

Figure 34. Total angle of attack with respect to range of flight (Shot 26).

Figure 35. Yaw angle with respect to range of flight (Shot 26).

6. Conclusion
This paper demonstrates abilities of developed software packages to perform full technological cycle of high supersonic vehicles computer simulation from three-dimensional surface geometry creation to flight trajectory calculations. To provide CFD calculations 3D CAD surface was created and unstructured tetrahedral volume mesh was generated.

Developed CFD ug3D solver was successfully validated by comparison of Basic Finner aerodynamic coefficients of axial, normal force and pitch moment with experimental data obtained in DREV Aeroballistic Range [18].

Developed 6–DoF motion MODIN solver was successfully validated by comparison of trajectory parameters of yaw, pitch and total angle of attack evolution with Aeroballistic range experimental data
using fully experimental aerodynamic database as well as obtained by ug3D solver Basic Finner aerodynamics calculations.

For Basic Finner configuration without fin cant angle there is an excellent agreement between calculated and experimental trajectory parameters. For a case with rotation caused by fin cant angle δ = 4° a slightly worse match between experimental and calculated trajectory parameters, but the character of parameters evolution in time and the oscillation period are quite the same. High quality of obtained results in spinning and non-spinning cases allows to draw a conclusion about the legitimacy of application of the developed software packages for coupled CFD/6-DoF computations for aeroballistic experiments modeling and prediction of objects aerodynamic characteristics and flight dynamics parameters at unattainable regimes for experimental facilities.

Dynamic stability of rolling motion analysis was carried out as well. Numerical results of spinning motion confirm the preliminary analysis conclusion that 120 degrees per meter is the boundary spin rate for dynamically stable motion.

Thus it may be concluded that developed ug3D and MODIN solvers allows to obtain a great accuracy results in their application area, and they can be successfully applied at coupled CFD/6-DoF calculations of high supersonic vehicles what is confirmed by comparison with established experimental data.

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