Mathematical modeling of safe payload separation using logos software on chimera-type grids

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Abstract. One of the most important problems in the development of air weapons is the separation of air weapons from the aircraft. Carrying out this type of tests is expensive, time-consuming and dangerous, so separation and prediction of the trajectory of air weapons using numerical simulation becomes an important part of the study. In this work, a full-scale model of F-18 and a full-scale model of air weapons GBU-31 JDAM were used to test the planned trajectory of separation of air weapons from the wing. The transonic flight mode with Mach number $M=0.962$ was considered. The Navier-Stokes and Euler equations were used for numerical modeling, considering the effect of the fluid viscosity effect on the flight path of air weapons during separation from the wing.

1. Introduction
The separation of air weapons from aircraft is the most important issue in the context of the integration process of air weapons. Detailed engineering analyses, wind tunnel blowdown and flight tests are required. Considering the latest achievements in the field of computational methods, numerical analysis may in some cases replace flight tests, wind tunnel tests and impact assessment tests of air weapons in the process of aircraft equipment certification [1-3]. Proven computational methods can be used to complete the separation process of air weapons. This will lead to a cost–effective and time efficient integration study. Similar problems were considered in articles [4] and [5], which simulated the separation of cargo from the wing at transonic speed. The geometric model in the articles considered was a wing, pylon and cargo. This approach does not take into consideration the impact of the bevel of air flow from the fuselage of the aircraft, which leads to insufficient accuracy of modeling the trajectory of the cargo at separation from the wing. In the present work we consider mathematical modeling of the separation of the aircraft destructor GBU-31 JDAM [6] from the aircraft F-18 with the help of Logos software product [7] to check the engineering approach at transonic speed. The results of mathematical analysis are compared with experimental data.

2. CFD modelling
The process of creating any CFD (computational fluid dynamics) model consists of several stages, the main of which are the following:

- selection of the physical model;
- selection and justification of assumptions and simplifications of physics and geometry of the problem;
- creation or import of geometric model into a grid generator;
• creation of a calculation grid in a grid generator;
• import the computational grid into the solver and specify boundary and initial conditions as well as parameters of the computational code solver;
• receipt of the solution;
• analysis of results and model verification.

The software product LOGOS was used to generate a calculation grid and as a solver. The description of the discrete model and the results of the analysis will be described in detail in the following sections.

3. Geometric model

For this task, the model was developed in the NX program. The geometry of the investigated object is a full-scale model of the aircraft with hinged air weapons (figure 1). The general view of air weapons separated in the process of mathematical modeling is shown in figure 2.

![Figure 1. General types of full-scale aircraft model with air weapons.](image1)

![Figure 2. General view of the aircraft to be separated in the process of numerical modeling.](image2)

Table 1 shows the main characteristics and geometric dimensions of air weapons used in mathematical modeling [8]:

### Table 1. Parameters of air weapons.

| Parameter                        | Value |
|----------------------------------|-------|
| Weight of air weapons, kg        | 934   |
| Length of air weapons, m         | 3.86  |
| Center of gravity, m             | 1.42  |
| Moment of inertia (roll) $I_{xx}$, kg$\times$m$^2$ | 28.714 |
| Moment of inertia (pitch) $Y_{xx}$, kg$\times$m$^2$ | 545.717 |
| Moment of inertia (yaw) $Z_{xx}$, kg$\times$m$^2$ | 545.717 |

### 4. Calculation area and discrete model

On the basis of the geometrical model, the flow area (figure 3) is constructed, which is a sphere (sphere radius $S_{sphere}$=499 m), the dimensions of which are selected so that boundary conditions do not significantly affect the flow near the wall.

![Figure 3. Flow area.](image)

The ideal gas is modeled as the environment. The boundary condition "free flow" (FREESTREAM) is set at the outer limits of the computational domain, with the parameters shown in table 2. FREESTREAM is a type of boundary condition in which static pressure, temperature, Mach number, flow direction vector, turbulence intensity and stirring length are specified. (The intensity of turbulence is 1%, the scale of turbulence is $1.4\times10^{-5}$ m). To model the turbulence, the model SA (Spalarta-Almaras) with the 2nd order reconstruction and the High $y^+$ wall function was used. A two-stage approach to solving the problem was applied. Stationary RANS solution was used as initial initialization of physical quantity fields for non-stationary calculation. The time step for non-stationary calculation was $5\times10^{-3}$ s.

### Table 2. Calculation mode parameters.

| Calculation mode parameter          | Value   |
|------------------------------------|---------|
| Mach number                        | 0.962   |
| Undisturbed flow rate, m/s         | 320.15  |
| Angle of attack, deg.              | 0.46    |
| Diving angle, deg.                 | 43      |
| Pressure of undisturbed flow, Pa   | 80194.4 |
| Temperature of undisturbed flow, K | 275.6   |

In this task, a discrete model is constructed of truncated hexahedrons with boundary layers. The current problem was solved on Chimera type grids [9, 10]. The Chimera approach allows for calculations...
in which each solid has its own grid, considering the peculiarities of shape and flow regime. The computing process on Chimera-type grids takes into account the presence of overlaps and provides interaction of separated grids. This method provides interaction of topologically unrelated regions as a single whole and allows to obtain quality results. To ensure effective numerical modeling of mobile body flow processes, it is necessary to implement algorithms based on sliding mesh. This technology guarantees the constancy of the mesh topology of the calculation model and has no disadvantages inherent in methods based on adaptive and deformable grids. The computational process of the method of calculation on grids with overlapping is based on the following steps:

1. Marking procedure, including:
   a) determination of counting and non-counting cells;
   b) generation of new boundary conditions;
2. Building an interpolation template including donor and acceptor cells.

Discrete model of F-18 and air weapons GBU-31 JDAM are presented in figures 4–6.

**Figure 4.** Type of discrete model of F-18 aircraft.

**Figure 5.** Type of discrete model of air weapons GBU-31 JDAM.

**Figure 6.** Type of discrete model in cross-section.
In the process of discrete model development and on the basis of preliminary calculations the characteristic grid parameters presented in table 3 have been selected.

Table 3. Characteristic grid parameters.

| Discrete model parameters       | Value    |
|--------------------------------|----------|
| Number of cells (million)      | 12.5     |
| Total thickness of prismatic layers (m) | 0.0089   |
| Thickness of the wall layer (m) | 0.0002317|
| Number of prismatic layers     | 10       |

5. Forces of the enforced separation mechanism

In the process of separation of air weapons from the aircraft, the force of the enforced separation mechanism is applied to the aircraft. Forces of enforced separation mechanism \( F_1 \) and \( F_2 \) (figure 7) act on air weapons for 0.1 s.

Figure 7. Scheme of forces of enforced separation
(Nose distance from air weapons to \( F_1 \) - 1.24 m; Distance from the nose of air weapons to \( F_2 \) - 1.75 m).

The force values of the enforced separation mechanism depending on time are presented in table 4 [11].

Table 4. Force values of the enforced separation mechanism.

| Time, s | \( F_1 \), N | \( F_2 \), N |
|---------|--------------|--------------|
| 0       | 431.456      | 431.456      |
| 0.01    | 916.288      | 991.904      |
| 0.02    | 2361.888     | 1258.784     |
| 0.03    | 4683.744     | 2441.952     |
| 0.04    | 21007.904    | 4394.624     |
| 0.05    | 20643.168    | 20941.18     |
| 0.06    | 20202.816    | 20607.58     |
| 0.07    | 19633.24     | 20140.54     |
| 0.08    | 18926.24     | 19508.93     |
| 0.09    | 0            | 18872.86     |
| 0.1     | 0            | 0            |
6. General equations

For numerical simulation of the separation of air weapons from the aircraft, the software product LOGOS was used with the use of Euler and Navier-Stokes equations.

Euler equations:

Three-dimensional Euler equations are solved using the finite volume method:

$$\frac{\partial}{\partial t} \int_V W dV + \oint F \cdot dA = \int_V H dV,$$

where the vectors $W$ (the vector of the conserved flow variables), $F$ (the vector containing the inviscid fluxes) are defined as:

$$W = \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ \rho E \end{pmatrix}, F = \begin{pmatrix} \rho v \\ \rho v u + p i \\ \rho v v + p j \\ \rho v w + p k \\ \rho v E + p v \end{pmatrix},$$

and the vector $H$ contains source terms such as body forces and energy sources.

Here $\rho$, $E$ and $p$ are the density, total energy per unit mass and pressure of the fluid, respectively; $u$, $v$, $w$ – velocity vector projections; $i$, $j$, $k$ - unit vectors.

Navier-Stokes equations:

Unsteady three-dimensional turbulent flows of viscous heat conducting gas are described by a system of Navier-Stokes equations averaged by Reynolds, which are solved using the finite volume method. The system of governing equations for a single-component fluid, written to describe the mean flow properties, is cast in integral Cartesian form for an arbitrary control volume $V$ with differential surface area $dA$ as follows:

$$\frac{\partial}{\partial t} \int_V W dV + \oint [F - G] \cdot dA = \int_V H dV,$$

where the vectors $W$ (the vector of the conserved flow variables), $F$ (the vector containing the inviscid fluxes) and $G$ (the vector containing the viscous fluxes) are defined as:

$$W = \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ \rho E \end{pmatrix}, F = \begin{pmatrix} \rho v \\ \rho v u + p i \\ \rho v v + p j \\ \rho v w + p k \\ \rho v E + p v \end{pmatrix}, G = \begin{pmatrix} 0 \\ \tau_{xi} \\ \tau_{yi} \\ \tau_{zi} \\ \tau_{li} v_j + q \end{pmatrix},$$

and the vector $H$ contains source terms such as body forces and energy sources.

Here $\rho$, $E$ and $p$ are the density, total energy per unit mass and pressure of the fluid, respectively; $\tau$ is the viscous stress tensor and $q$ is the heat flux; $u$, $v$, $w$ – velocity vector projections; $i$, $j$, $k$ - unit vectors.

Total energy $E$ is related to the total enthalpy $H$ by

$$E = H - p/\rho$$

where:
\[ H = h + \frac{|v|^2}{2} \]  

Here \( h \) is sensible enthalpy.

7. Simulation results
A numerical simulation of the separation of air weapons from the wing for Macha \( M = 0.962 \) for 0.5 s was performed. The results of numerical modeling were compared with experimental data [12]. Figures 8–13 show graphs for comparing the results of numerical modeling with the results of the experiment with regard to the position and orientation of air weapons in space:

**Figure 8.** The trajectory of the center of gravity of air weapons at coordinate X.

**Figure 9.** The trajectory of the center of gravity of air weapons at coordinate Y.
**Figure 10.** The trajectory of the center of gravity of air weapons at coordinate Z.

**Figure 11.** Angular orientation trajectory in space (yaw).

**Figure 12.** Angular orientation trajectory in space (pitch).
Comparison of experimental data with the results of numerical modeling shows a satisfactory alignment of the trajectory of the center of gravity of air weapons on the X, Y, Z coordinates, the difference of which is ~0.01-0.3 m. Comparing the trajectories of angular orientation in space, it should be noted that the satisfactory alignment of the results with the experimental data, the difference which is ~5-8 degrees.

The results of numerical modeling in 3D are shown in figure 14.

**Figure 13.** Angular orientation trajectory in space (roll).

**Figure 14.** Results of numerical modeling in 3D.
8. Conclusion
A numerical simulation of the separation of air weapons from the aircraft was performed. In this paper we used full-scale models of F-18 aircraft and GBU-31 JDAM aircraft to model the separation of cargo from aircraft. The transonic mode with the number of Mach $M=0.962$ was considered. Comparison of experimental data with the results of numerical modeling shows a satisfactory alignment of the trajectory of the center of gravity of air weapons on the $X$, $Y$, $Z$ coordinates, the difference in which is $\sim 0.01-0.3$ m. Comparing trajectories of angular orientation in space, it is necessary to note satisfactory coordination of results with experimental data which difference is $\sim 5-8$ degrees.

Based on the results of the work performed, it can be concluded that the presented engineering approach can be used in forecasting the trajectory of separation of cargo from the aircraft. When using this approach to predict the trajectory of cargo movement, it is worth paying special attention to the correctness of the input data (location of the center of gravity and values of inertia moments for air weapons), which significantly affect the accuracy of numerical modeling.

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