Evaluation and Experimental Validation of Low Costs CFD Based Mathematical Model describing External Stores Separation

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ABSTRACT

This work consists the concepts and some results of solutions for aircraft – external store configuration interference. The main emphasis is placed on practical, cost-effective engineering solution of the complex problem with reasonable computational efficiency allowing the code to run on PC computers. Prediction of external stores separation trajectories is an important task in the aerodynamic design area having the objective to define the operational, release envelopes. To attain this purpose it was developed technique based on the Non-linear Panel Method with unsteady free wake formulation. The comparison with the flight test as well as wind tunnel investigations have proved the reliability of this methodology.

1.0 INTRODUCTION

One of the most important tests in the certification of a new weapon on a tactical aircraft is the safe separation test performed to demonstrate that the weapon can be deployed safely and effectively. These tests typically involve evaluating various conditions of airspeed, Mach numbers, and normal acceleration throughout a defined operational envelope [1, 20]. To reduce the size of the flight test program, wind tunnel tests or computational methods are used to predict potential "hot spots" or trouble areas within the defined envelope. After analyzing the predictions, a flight test matrix is developed to test the worst case conditions. Once the flight tests have been successfully completed, a deployment envelope is recommended to the fleet. The basic characteristic of store separation analysis is the presence of a body that moves in the computational domain as a result of its interaction with the computed flow field. This means that in addition to the need for a dynamic mesh, tools are also required that determine the body movement based on the local flow conditions. These tools need to accurately compute the aerodynamic forces on the body, and determine the dynamic response of the body to these forces.
Accurate prediction of the trajectory of a store released from an aircraft is critical in assessing whether the store can be released safely as well as if it will accurately reach its target. The trajectory of stores released in aircraft flowfields has always been difficult to predict. Traditionally, the task to obtain the necessary data has been left to windtunnel testing. Typically, numerous windtunnel and flight tests are performed to obtain sufficient carriage and trajectory data for a store to be certified for Air Force use. This process can take up to several years and is required for each loading configuration of a store on a particular aircraft. However, with the advancement of computational fluid dynamic (CFD) techniques, the prediction of carriage and trajectory data is possible. These techniques can now overcome the long lead times of the wind tunnel and provide comparable results useful in aircraft/store analyses. Efforts to help reduce the time and cost required to certify a store for use are now beginning to be impacted by the use of

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computational fluid dynamics. A trajectory calculation is performed to integrate the forces and moments on the body, and provide an accurate position of the body as a function of time. The most challenging of these tasks, by far, is the mesh handling. The geometric complexity of modern aircraft and the stores, which may be outfitted with fins, guidance devices or release mechanisms, necessitates the use of complex meshes, comprised mostly of tetrahedral elements. The remeshing schemes need to be robust and deliver high quality meshes that can be relied upon for accurate aerodynamic load predictions at each time step. Since thousands of time steps may be needed for an accurate analysis, depending on such factors as the release speed or aircraft speed, the mesh handling also needs to be done in a time-efficient manner. Over the several years there have been undertaken efforts to validate, demonstrate and accelerate the insertion of CFD methods into the store certification process for external store carriage and release. For example in 1989 it took more than 400 hours of wind tunnel testing and 20 flights to clear the JSOW from the F-18 to Mach 0.95. In 2000 the MK-83 JDAM was cleared after 60 hours of wind tunnel testing and five flights to the full F-18 aircraft envelope of Mach 1.3 [2, 5]. This reduction occurred because of wider application of numerical simulation technique, including CFD methods. An extensive set of wind tunnel store carriage and separation data for CFD code validation were made available for a generic wing and store geometry. Although Euler and thin layer Navier Stokes solutions were in good agreement with these test data, solution times on the order of 5 days on the CRAY YMP made such tools impractical for everyday use. It was demonstrated [4] that full-potential code could give results of similar quality in a fraction of the time required for the higher order codes.

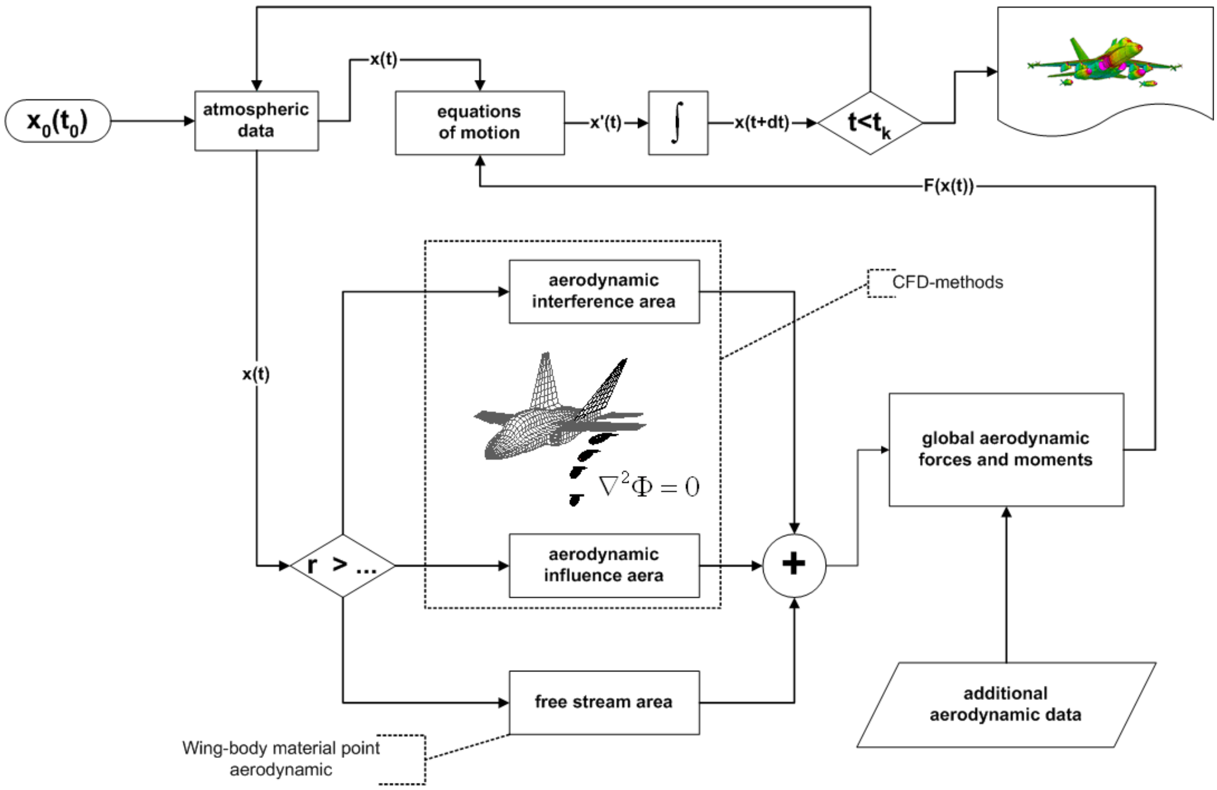

Figure 1: Flow chart of numerical model

Steady-state CFD methods have been used in conjunction with the semi-empirical methods to predict safe release. The surface pressure distributions are critical to an accurate trajectory, and the resulting forces and moments acting on the store when in the captive position. Various researchers have shown encouraging predictions of steady-state surface pressure distributions and store loads in interference flowfields. These range from carriage or near carriage predictions [14, 18, 22] to mutually interfering multiple stores. Still, with the advancements made so far, these capabilities may not be sufficient when trying to predict trajectories for highly dynamic store separation cases. Particularly, the store released from within weapons bays, multiple store releases, fuel tank releases, and releases during maneuvers, are store-separation cases that are very difficult or currently impossible to simulate within the wind tunnel. A time-accurate computation is therefore required to sufficiently predict the trajectory of the store. The purpose of this article is to demonstrate the accuracy and technique of a time-accurate CFD approach to predict the trajectory of a finned body released from a generic wing-pylon configuration at subsonic speeds.

This paper presents the possibilities of using of Unsteady Panel Methods in process of narrowing of windtunnel testing as well as flight test, during the investigations of a new external store, from the safety of flight point of view. The main emphasis is placed on practical, cost-effective engineering solution of the complex problem with reasonable computational efficiency allowing the computer code to run on PC computers. The flow solver is based on modified panel method [13], basing on Laplace's equations for potential of disturbances. Since the object has been found in unstationary motion, the solution has been found by *time-stepping method* [11] – it means that for every step time the wake vortex was suitably modified. The version of this code includes the time metric terms to account for the movement of the mesh. The boundary conditions are set for either "steady-state" or "dynamic" [6, 21] conditions. The code obtains the flow solution for one time step based on the newly moved grids received from the domain connectivity model, and outputs the new force and moment coefficients acting on the store to the six-degree-of-freedom model (see figure 1). The flow solver can run on PC computers. The dynamic part starts where the new location for the moving body is determined using the trajectory code with the steady-state carriage forces and moments as input. For the moving body it is determined using the trajectory code with the steady-state carriage forces and moments as input.

2.0 MATHEMATICAL MODEL

The 6-DOF module is coupled with the Non-linear Panel Method flow solver to provide aerodynamic analysis for bodies in relative motion. The salient features of the 6-DOF module include:

- Rigid body motion formulation is based on theory of Etkin,
- Fully integrated with the flow solver allows o specify generalized point force routines for time or distance forces, as well as specify full constraints and model dependencies

Generalized thrust integration routines for multiple zones and surface patches

To mark out forces and aerodynamic moments effected on external store we have used the modified panel method [11, 13], basing on Laplace's equations for potential of disturbances.

$$\nabla^2\Phi = 0 \tag{1}$$

This equation is a modificated form of fluid equation of motion, after making an assumption for unviscous, without flow separation and vortex-free flow (excluding wake vortex). The solution of Laplace's equation for the full velocity potential has the following form:

$$\Phi(P) = -\frac{1}{4\pi}\iint_{S_B}\left[\sigma\frac{1}{r} - \mu\frac{\partial}{\partial n}\left(\frac{1}{r}\right)\right]ds + \frac{1}{4\pi}\iint_{S_W}\mu\frac{\partial}{\partial n}\left(\frac{1}{r}\right)ds + \Phi_\infty(P) \tag{2}$$

The choice of method was dictated by an easy application and low cost of calculations, which makes possible the realization the shown problem on PC computers. Since the object has been found in unstationary motion, the solution has been found by *time-stepping* method [11, 13] – it means that for every step time the wake vortex was suitable modified (Fig. 2).

The disposition of singularities, which has been found from flow equations, exactly marks out the velocity field. The pressure disposition is calculated from the Bernoulli equation for unstationary flowfield [11].

$$C_P = 1 - \frac{Q^2}{V^2} - \frac{2}{V^2}\cdot\frac{\partial\Phi}{\partial t} \tag{3}$$

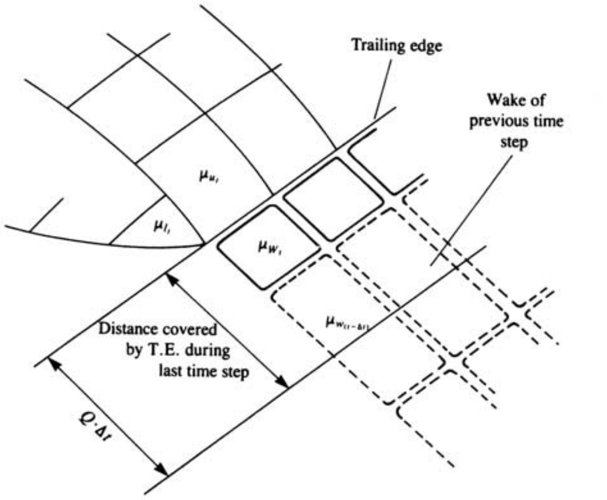

Figure 2: Unstationary free wake vortex (cf. [11])

Aerodynamic loads calculated from solutions of Laplace's equations for potential of disturbances didn't include all of components of aerodynamic force, primarily drag force acting on the body. Therefore there is a need to evaluate the drag force components using other sources of information, because the panel methods enable to calculate drag force inducted by the lift force only.

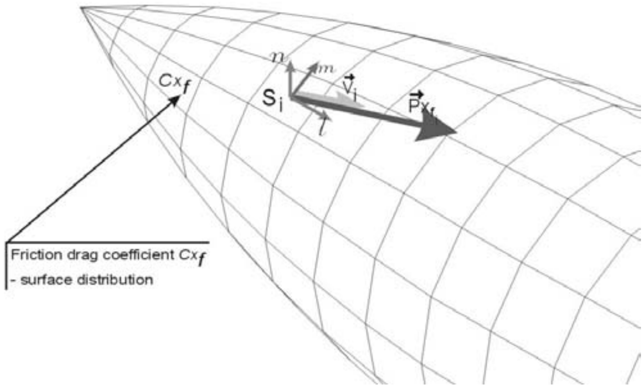

Figure 3: Method of allowing for skin friction drag

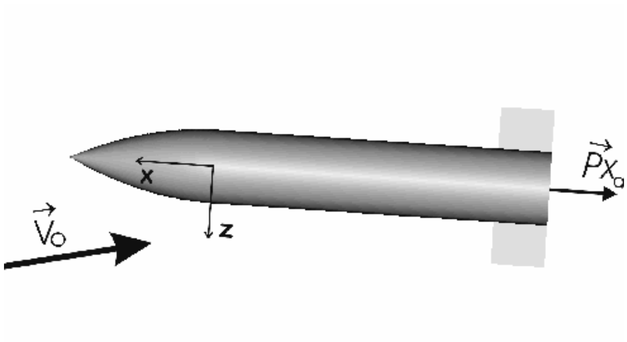

Figure 4: Scheme of taking into consideration of base drag during calculations

In the method presented above the drag force component is calculated by making an assumption that on each panel elementary skin friction drag force acts (Fig. 3).

$$P_{X_{f_i}} = \tfrac{1}{2}\rho V_{C_i}^2 S_i C_{X_f} \qquad (4)$$

That force acts conforming to elementary airspeed vector on panel. Elementary skin friction drag coefficient Cx_f can be calculated on the basis of literature data, empiric formulas, or wing tunnel investigations, (for example throughout dividing of total drag force (excluding base drag force), measured at zero lift force angle of attack), by the dynamic pressure and whole streamlined surface. It can be mentioned, that proposed method calculation of contact forces, enable in simple manner taking into consideration, influence of those forces on aerodynamic moments acting on store in inhomogeneous field of flow velocities. In similar manner, it is possible taking into consideration store's base drag force during calculations (Fig. 4). It is possible, (on basis of investigations lead in Institute of Aviation [12, 16]), admit, that both interference in carrier-store system and store angle of attack haven't significant influence on base force coefficient Cx_d . Therefore the base force can be calculated from the following formula:

$$P_{X_d} = \tfrac{1}{2}\rho V_0^2 S_d C_{X_d} \qquad (5)$$

In the case of shortage of empirical data, values of skin friction and base force coefficients can be calculated from the following empiric formulas [13]:

$$C_{X_f} = \frac{0.0315 A_C \mathrm{Re}_K^{-0.145}}{\sqrt{1-0.2M^2}} \cdot \frac{S_b}{S_K} \qquad (6)$$

$$C_{X_d} = \left(0.05 + 0.25M^2\right)\frac{S_d}{S_K} \qquad (7)$$

where: $A_C = 1.86 - 0.175\Lambda_K\sqrt{1-M^2} + 0.1\Lambda_K^2\left(1-M^2\right)$, $\Lambda_K = L_K/d$ aspect ratio of store body, S_b streamlined surface of store body (excluding store's bottom part), S_d bottom part surface of store body, S_K cross-section surface of store body, Re_K Reynolds number for store body. The dynamical equations of motion have been found from generalized momentum equations in body system of equations Oxyz (Figure 5) [13].

Non-linear equations of motion of the aeroplane and the kinematic relations will be expressed by using moving co-ordinate systems, the common origin of which is located at the center of mass of the aeroplane. It is used [15]:

- a system of co-ordinates $O_Sx_Sy_Sz_S$ attached to the aircraft (the $O_Sx_Sz_S$ plane coinciding with the symmetry plane of the aircraft);
- a system of co-ordinates attached to the air flow $O_Sx_{aS}y_{aS}z_{aS}$ in which the Ox_{aS} axis is directed along the flight velocity vector of aircraft $\mathbf{V}_{0S}$ and the O_Sz_{aS} axis lies in the symmetry plane of the aircraft and is directed downwards.

The relative position of the vertical system $Ox_1y_1z_1$ and the system $O_Sx_Sy_Sz_S$, attached to the aircraft is described by Euler angles Θ_S, Φ_S and Ψ_S, while the relative position of the system $O_Sx_Sy_Sz_S$ and the system $O_Sx_{aS}y_{aS}z_{aS}$ attached to the airflow - by the angle of attack α_S and slip angle β_S.

- a system of co-ordinates Oxyz attached to the aircraft (the Oxz plane coinciding with the symmetry plane of the aircraft);
- a system of co-ordinates attached to the air flow $Ox_ay_az_a$ in which the Ox_a axis is directed along the flight velocity vector $\mathbf{V}_0$ and the Oz_a axis lies in the symmetry plane of the aircraft and is directed downwards.

The relative position of the vertical system $Ox_1y_1z_1$ and the system Oxyz, attached to the bomb is described by Euler angles Θ, Φ and Ψ (Fig. 5a), while the relative position of the system Oxyz and the system $Ox_ay_az_a$ attached to the airflow - by the angle of attack α and slip angle β (Fig. 5b).

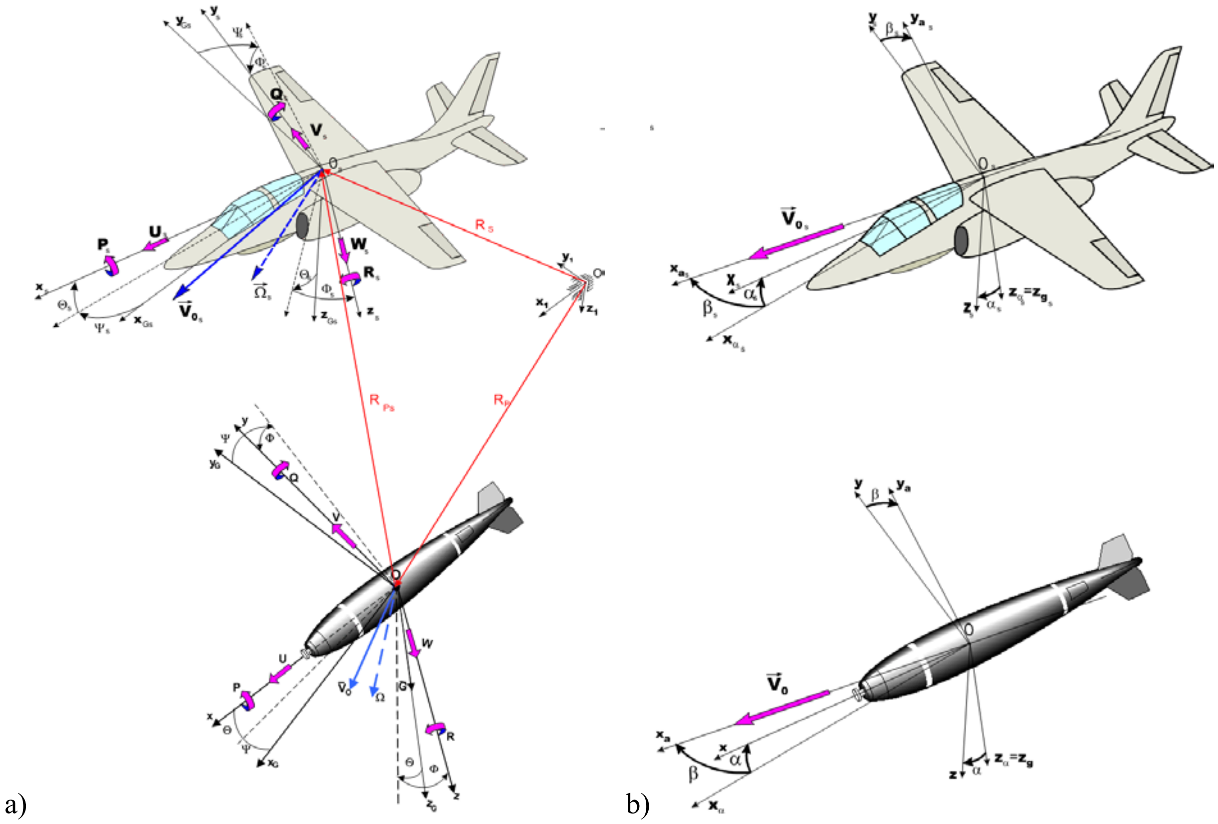

Figure 5: Systems of coordinates: a) attached to bodies, and b) attached to airflow (cf. [13])

Usually aircraft is considered as a rigid body with moving elements of control surfaces. Gyroscopic moment of rotating masses of the engines is included. Total system of equations should be completed with the following expressions: kinematic relations, kinematics of an arbitrary control system and the control laws.
The mathematical model of aircraft can be formulated in the following form [16]:

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}(t), \mathbf{u}(t)), \qquad \mathbf{x}(0) = \mathbf{x}_0 \tag{8}$$

where:

- state vector

$$\mathbf{x} = [V_S, \alpha_S, \beta_S, P_S, Q_S, R_S, \Phi_S, \Theta_S, \Psi_S, x_{Sg}, y_{Sg}, z_{Sg},\ V, \alpha, \beta, P, Q, R, \Phi, \Theta, \Psi, x_g, y_g, z_g]^T \tag{9}$$

- control vector

$$\mathbf{u} = [\delta_H, \delta_A, \delta_V, \delta_F]^T \tag{10}$$

where: $\delta_H, \delta_A, \delta_V, \delta_F$ are displacements of, elevator, ailerons, rudder, power lever respectively, elements of vector **f** can be found in ref. [13]:

Equations of motion of aircraft should be completed with equations of engine dynamics [15]:

- equation of engine rotation.

$$\tau_1 \tau_2 \ddot{n} + (\tau_1 + \tau_2)\dot{n} = K\left[Q_p(t - \tau_0) - Q_{p0}\right] \cdot n \tag{11}$$

where: n - angular velocity of a rotor, τ_0, τ_1, τ_2- time-constants, K - amplification factor, Q_p - discharge of fuel for actual engine's angular velocity and for actual aircraft's altitude and airspeed, Q_{p0} - discharge of fuel, calculated for sea level conditions and when V=0; time-constants are non-linear functions of engine's angular velocity, aircraft's altitude, air density; pressure and temperature on fight altitude.

- equation of thrust is following:

$$T = T_0(n_T)\left(\frac{\rho}{\rho_0}\right)^{0.7}\left(A + BMa + CMa^2\right) \tag{12}$$

Discharge of fuel is following function:

$$Q_p(t) = \mathrm{f}_1(\delta_F(t)) \tag{13}$$

The integrated motion module can be applied using a prescribed motion, by solution of the 6DOF equations of motion based on the aerodynamic and other loads, or with a combination of the two approaches. Routines to model a time-varying mass, constrained rotation and/or translation, and point forces such as ejectors, are included. Several solution algorithms and turbulence models are available, allowing the user to apply the most appropriate for the problem of interest. Outputs of the code are designed to provide the analysis with the required information in a convenient format. Detailed kinematics and dynamic information is output for moving body problems. Aerodynamic loads can be integrated over the entire missile or on individual parts. The aerodynamic loads can be output as coefficients or dimensionally. Flow variables at specific points in the mesh system can be monitored. Shear forces and pressure forces can be identified separately.

3. RESULTS

The calculations have been carrying over for the real conditions of airdrop from the Su-22M4 fighter aircraft (Fig. 6). The solutions of numerical simulation of the airdrop have been used to elaboration the experimental exploration program dependent on modelling of free drop of the external store in subsonic windtunnel. The obtained solutions made considerable reduction of experimental explorations possible, what suggests the correctness of the elaborated mathematical model. Presently in the Air Force Institute of Technology there are carrying on experimental exploration that concern the influences of aerodynamic interference on airdrop of external stores. Figs 7–8 show the panel model of the Su22M4 fighter aircraft, the panel models of considered stores, and those store under aircraft wing. Those experiments are going to make possible the numbers verifications of shown method and to determinate the area of possible usage.

Figure 6: Considered external store (cassette bomb) under the Su-22M4 wing

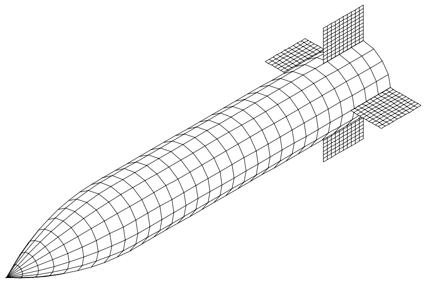

Figure 7: Panel model of the external store (type "A" and "B" of cassette bomb)

The influence of interference on aerodynamic characteristics of a cassette bomb are shown in Figs. 9, and 10, and for given extent of bomb's position with respect to a plane's wing looks as follows:

- insignificant for the course of symmetrical characteristics (i.e. lift coefficient, induced drag and pitching moment).
- significant and grows with the increase of an angle of attack, for side and lateral characteristics for non-zero angles of attack.

Remembering that results presented above were obtained for a zero decalage of stabilisers, i.e. for the object completely symmetrical and for a zero angle of side-slip, side and lateral characteristics should be zero. The results of aerodynamic characteristics' calculations versus the distance between undercarriage and the wing, taking aerodynamic interference into account, confirm that the biggest influence of aerodynamic interference on a store's flow is in the distance (between store and wing) from 0 to 4 store's diameters.

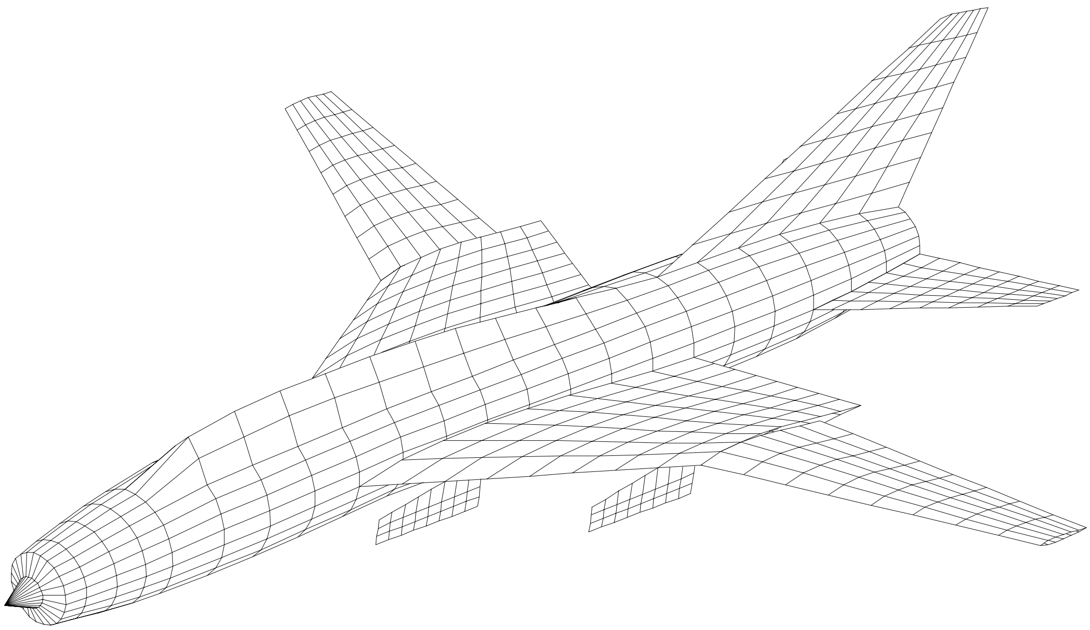

Figure 8: Panel model of the Su-22M4 fighter aircraft

The analysis of calculations show good compatibility with the results of wind tunnel testing. It can be noticed good compatibility of calculated drag coefficient with experimental results. That proves correctness of methodology used in process of estimating of aerodynamic drag. (Figs 9, 10)

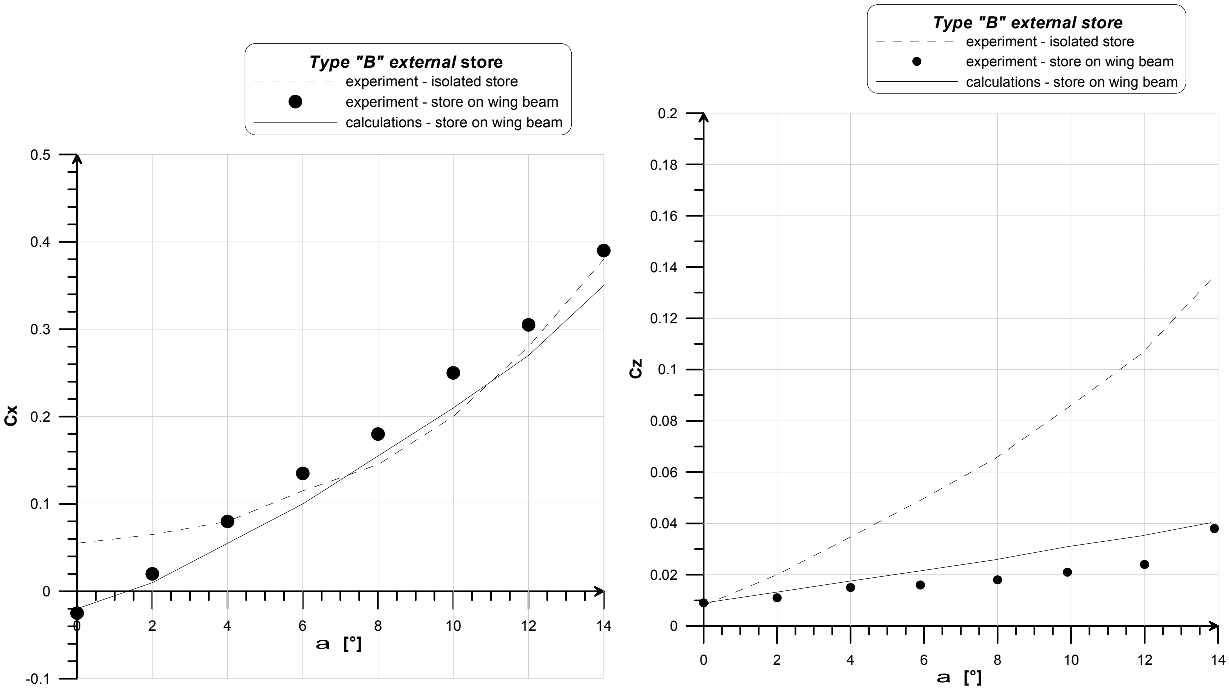

Figure 9: External store (on wing beam) drag coefficient Cx, and lift coefficient Cz, vs. carrier-store system angle of attack

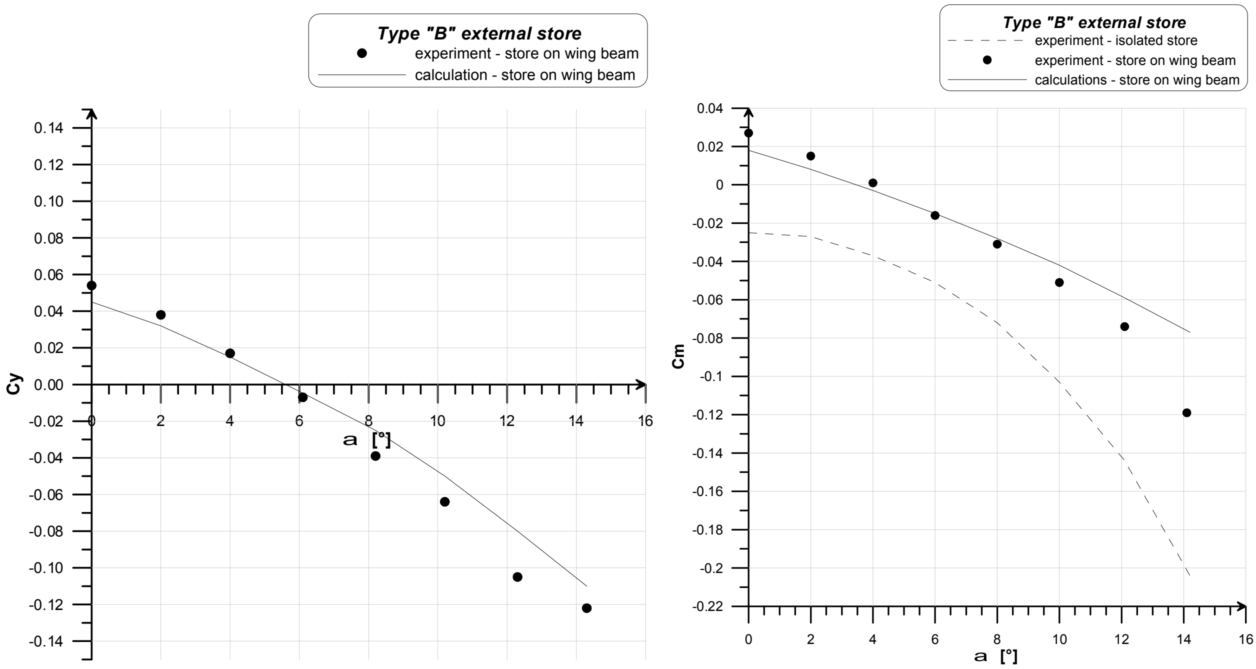

Figure 10: External store (on wing beam) side force coefficient Cy, and pitching moment coefficient Cm vs. carrier-store system angle of attack.

Results of numerical simulation of airdrop are shown in Figs. 11 –13. It can be stated, the satisfactory compatibility with experimental results registered by video cameras in wind tunnel testing (modelling of a free airdrop) – see the Fig. 16 and the frame photos (Fig. 14, 15), and flight tests data (Figs. 19, 20).

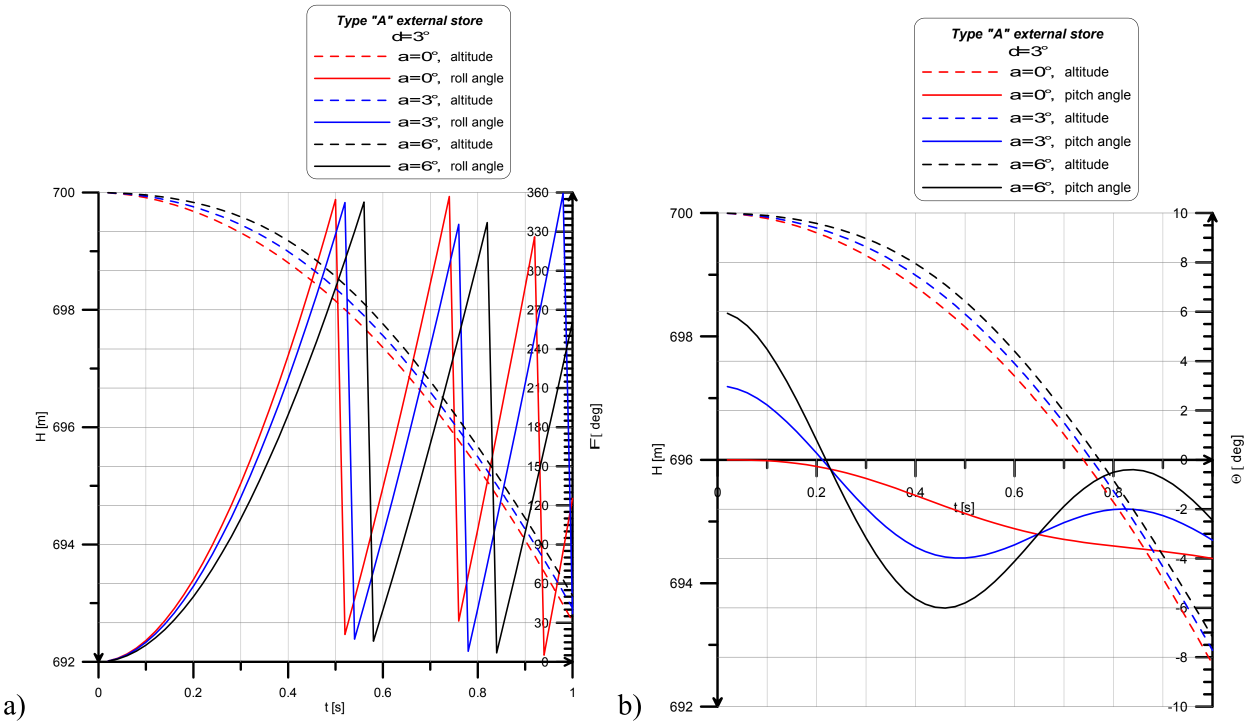

Figure 11:External store roll (a) and pitch (b) angle versus time, decalage δ=3°

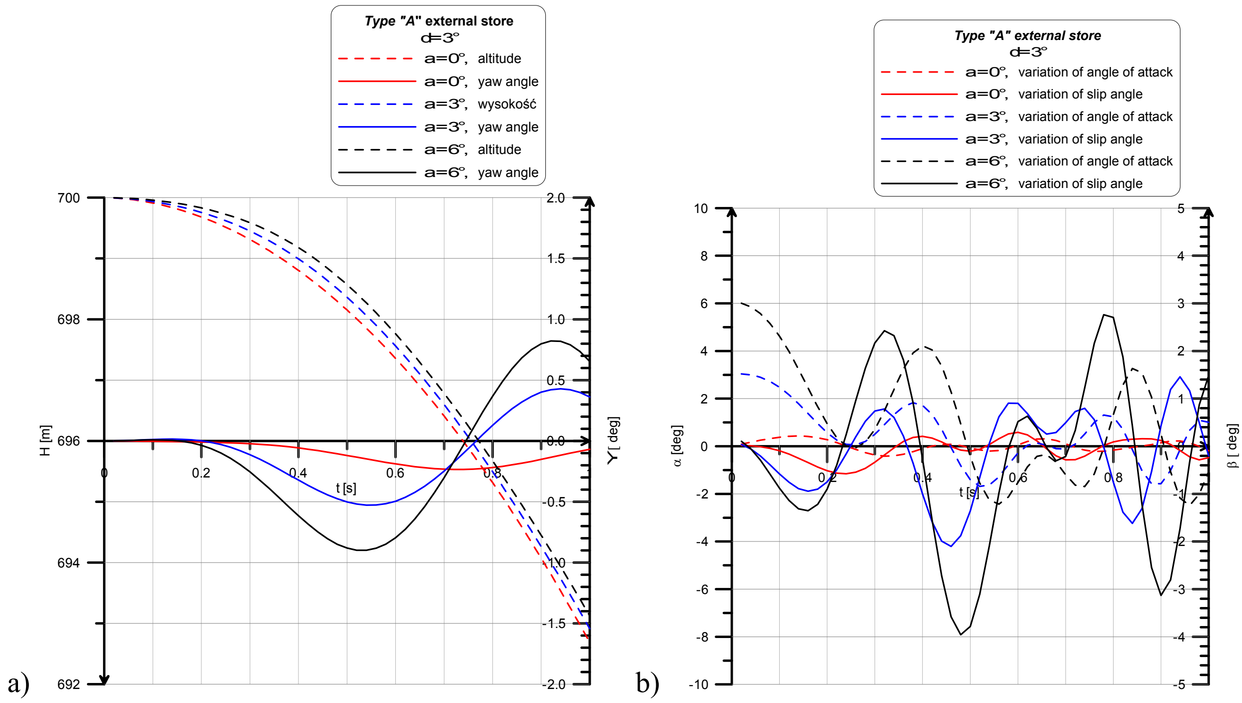

Figure 12: External store yaw angle (a) and angle-of-attack (b) versus time, decalage δ=3°

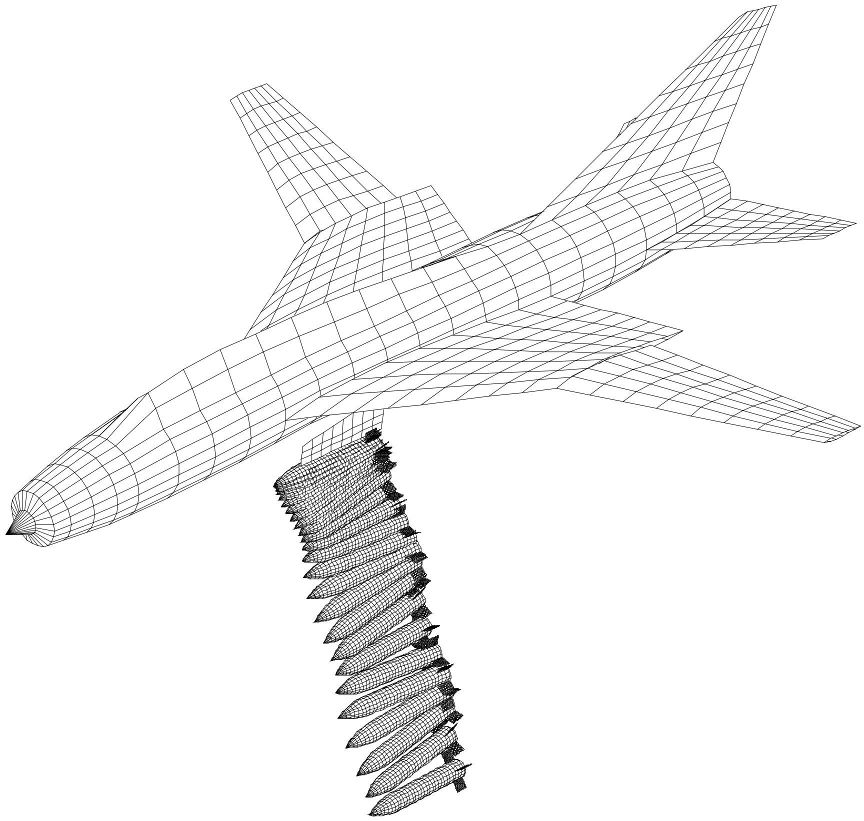

Figure 13: The trajectory of an external store in $OY_{sa}Z_{sa}$ plane, angle of attack $\alpha=6^o$, $\delta=3^o$

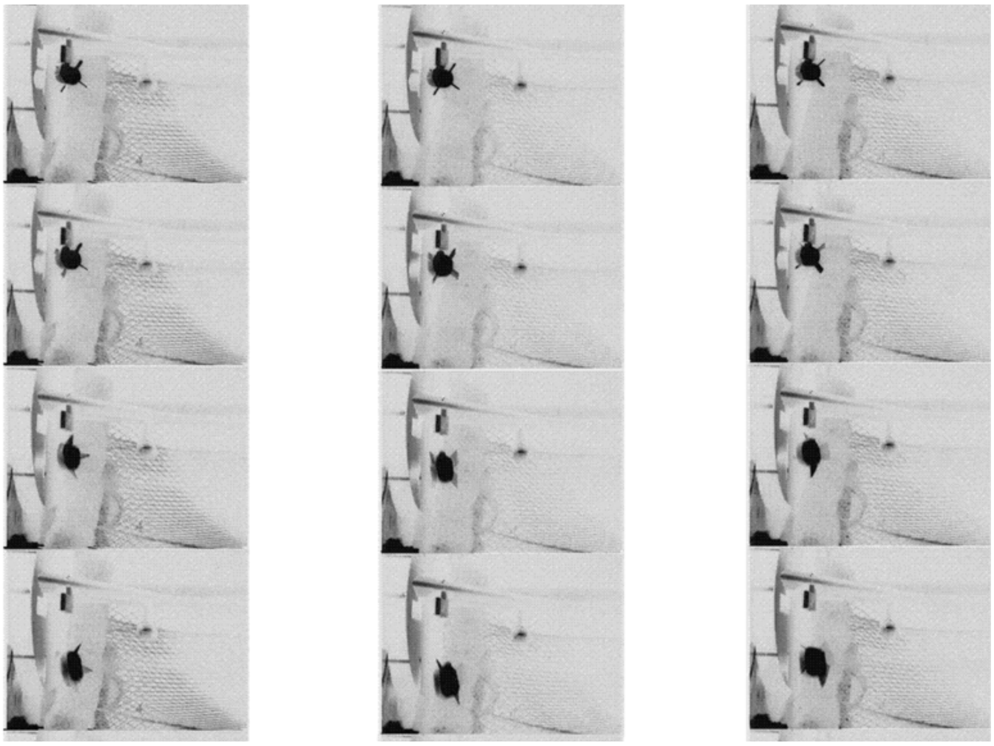

Figure 14 Airdrop - wind tunnel testing – front view

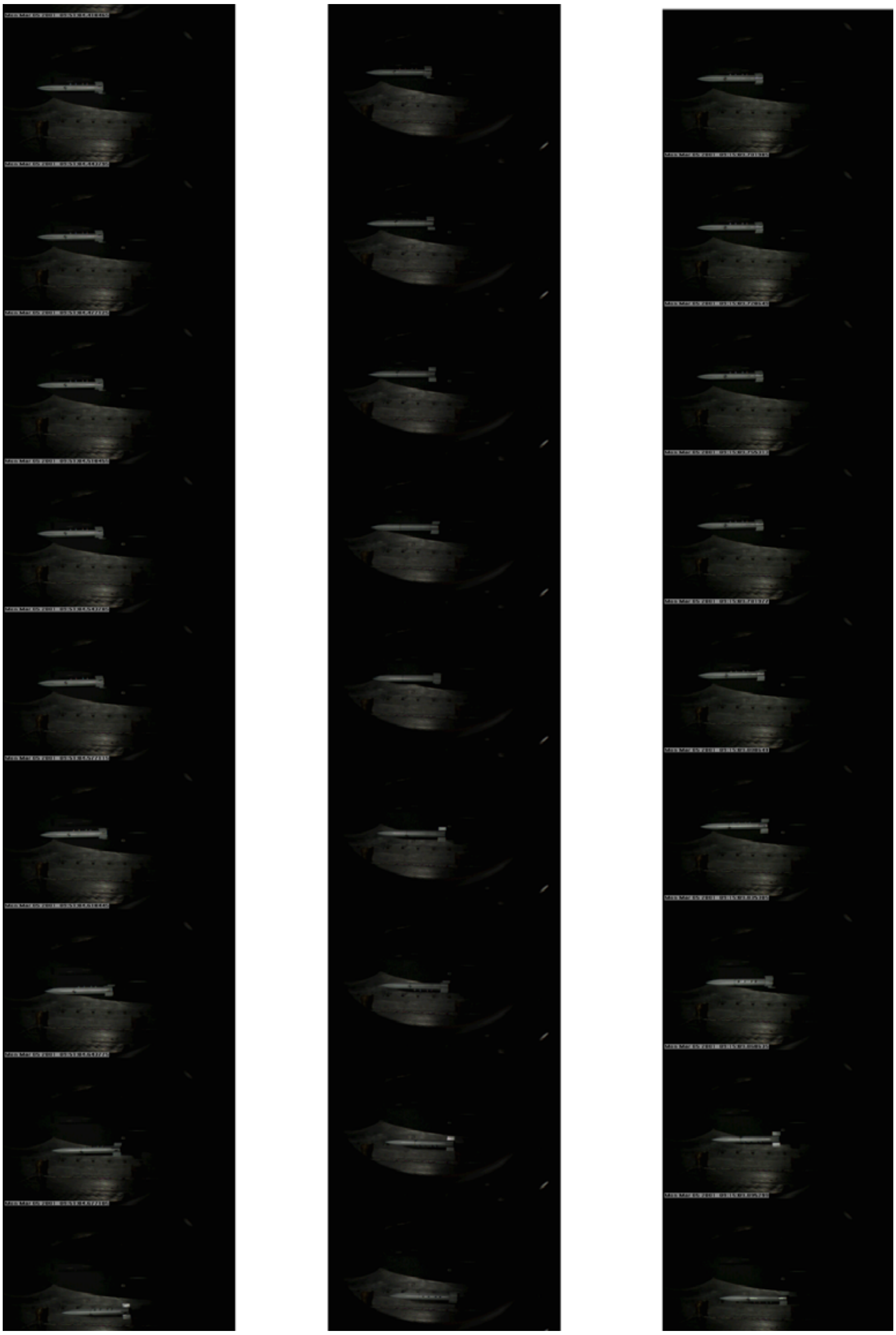

Figure 15: Airdrop - wind tunnel testing side view.

Cases of calculations beyond of the possibilities of a wind tunnel testing are shown in Figs. 17. It can be noticed that a delay during performing of an avoidance manoeuvre can cause collision between aircraft and a store. The highest influence of aerodynamic interference on a store's movement was observed in case of an empty fuel tank's drop [7, 17, 19],

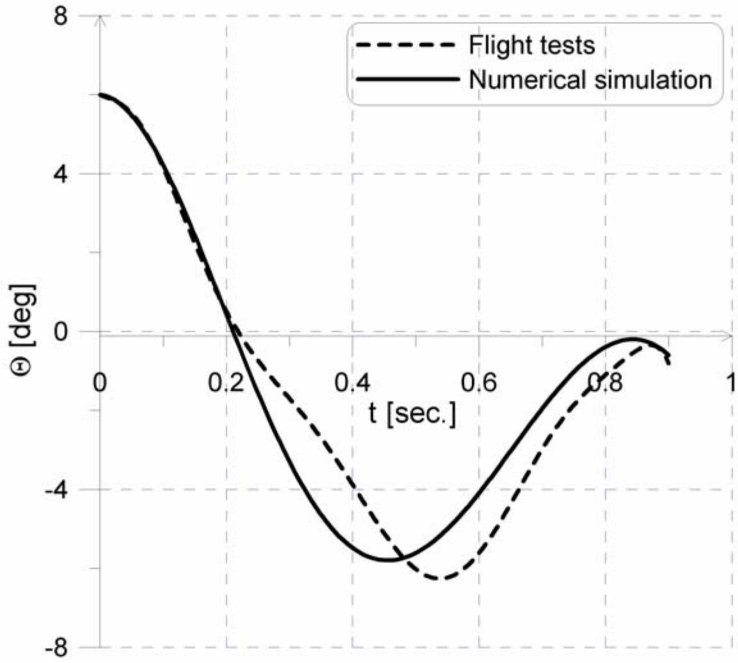

Figure 16 Comparison between flight and predicted trajectory for AOA=6°, h=700m, Ma=0.7

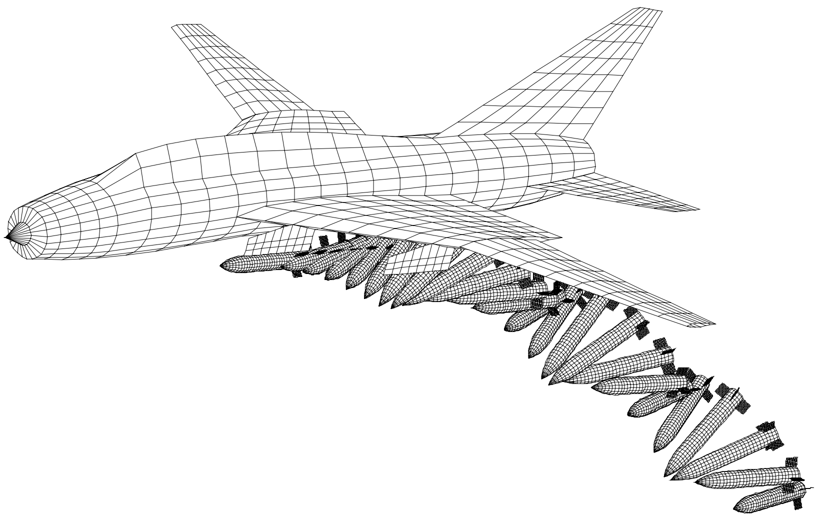

Figure 17: Trajectory of an airdrop of cassette bomb from climbing flight, angle of course γ=20° , a time of a drop 1s, angle of attack α=3° .

Fig. 17 show the results of numerical simulations in conditions of bombing maneuver during climbing flight with targeting to take-off point. The results of calculations indicate much higher disturbance of a store's flight course after an airdrop then in case of bombing from horizontal flight

3.1. Experimental Validation of Mathematical Model

The clearance of cassette bomb was performed using computational simulation as well as actual flight and wind tunnel-test. Validation of mathematical model was approached by Air Force Institute of Technology (AFIT) to provide our technical expertise to perform the store separation analysis using analytical tools, post flight data reduction, as well as to provide recommendations for flight test planning (see Fig. 18).

With our inputs, a series of flight trials was planned and executed by the Polish Air Force flight test pilots and AFIT engineers.

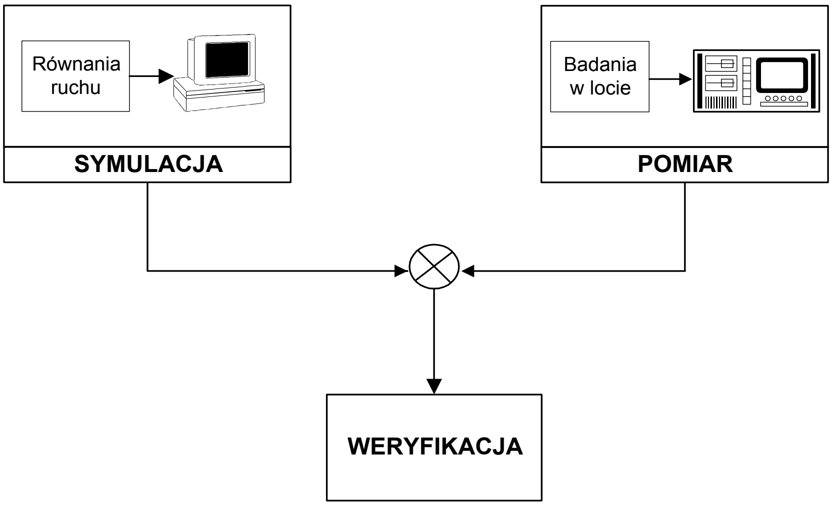

Figure 18: Schema of clearance and validation of external store mathematical model

During the flight trials, on-board high-speed cameras and a video camera (see Fig. 19) from the chase aircraft were used to capture the trajectory of the cassette bomb during flight test. We provided our support services after each flight tests in post-processing and analysing the trajectory of the separated store. The post-processed flight test data enabled us to refine our simulation, and make further recommendations for the safe separation of the next flight test point.

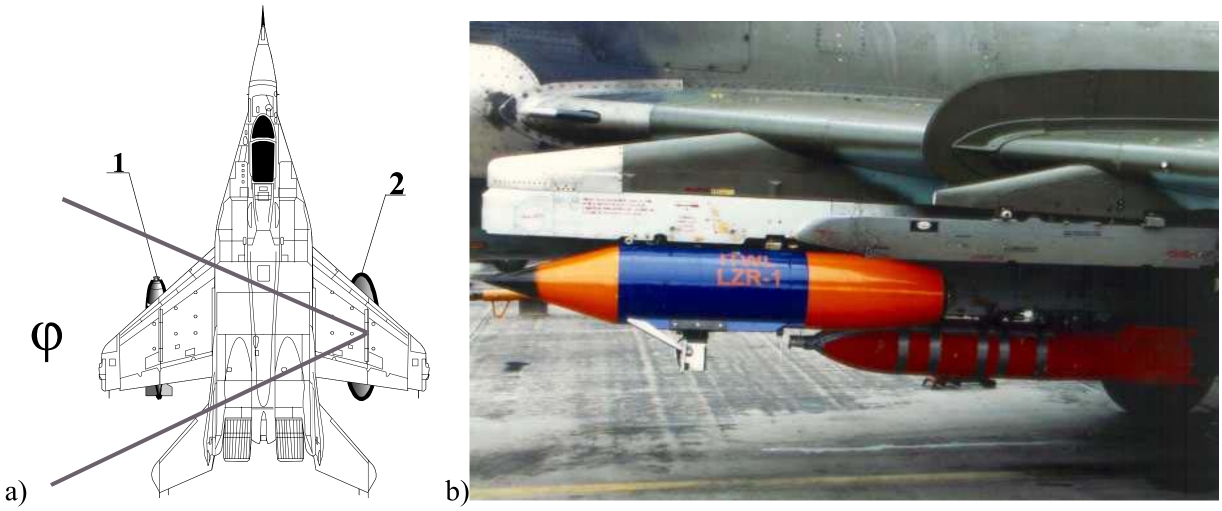

Figure 19: Cassette with on-board high-speed camera and a video camera

In the methods consisted of mounting high-speed film cameras on the test aircraft to record the separation event, the data were limited by the speed of the cameras and provided only qualitative results. Photogrammetry, the science of making accurate measurements from photographs, was adopted to obtain quantitative data from the same aircraft mounted cameras. Quantitative data were essential to validate models so they could be used to improve the accuracy of the weapon separation predictions. High-speed video cameras can now be used in lieu of film cameras. A non-camera method of obtaining quantitative data involves the use of sensors mounted in the test store with a transmitter to telemeter the data real-time. The Air Force Institute of Technology (AFIT) has developed the capability to use all of the aforementioned methods, employing the one that best suits the requirements of the specific test program.

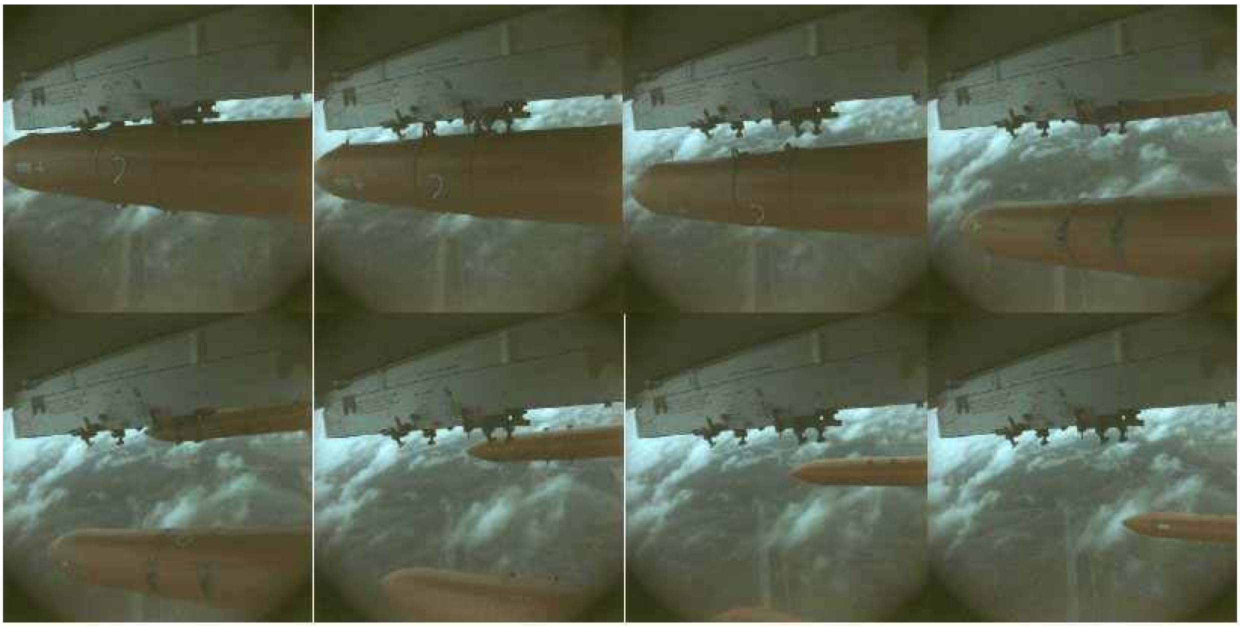

Figure 20: Frame photos of airdrop (on-board high-speed camera)

Figure 21: Frame photos of airdrop (high-speed camera on following aircraft)

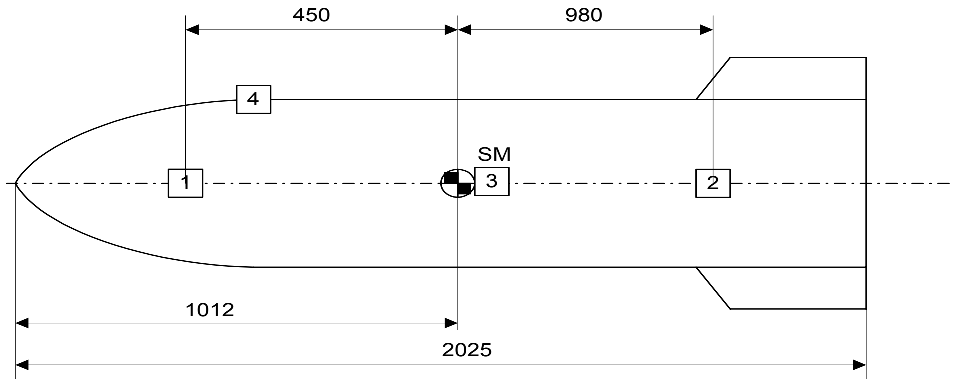

Figure 22: Cassette bomb - displacements of sensors; 2, 2, 3 – accelerometers, 4 sensor of rotation

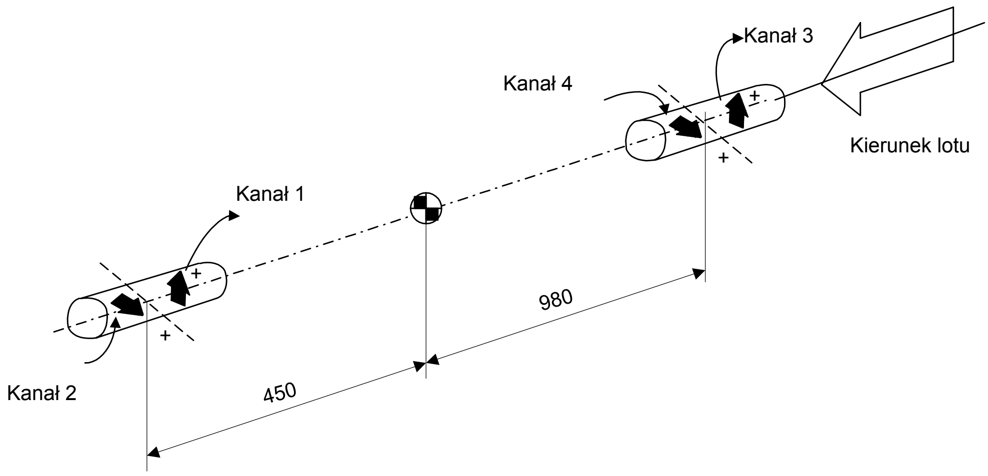

Figure 23: Displacements of accelerometers

The displacement of accelerometers inside of the projectile is shown in Figs. 22 and 23. Basing on mathematical model of the projectile there are performed numerical simulations. Acceleration of any aircraft point can be found from the following formula:

$$\mathbf{a}_A = \mathbf{a}_{SM} + \boldsymbol{\Omega} \times \mathbf{r}_A + \boldsymbol{\Omega} \times \left(\boldsymbol{\Omega} \times \mathbf{r}_A\right) \tag{14}$$

And after some simple calculations, remembering, that load factor is defined as: $n = a/g$ we can obtained the following formulas:

$$n_x = \frac{1}{g}\left[a_{xSM} + \left(\dot{Q}\, y_A - \dot{R}\, z_A\right) + R\left(Q \cdot y_A + P \cdot z_A\right) - x_A\left(Q^2 + R^2\right)\right]$$

$$n_y = \frac{1}{g}\left[a_{ySM} + \left(\dot{R}\, x_A - \dot{P}\, z_A\right) + Q\left(Rz_A + P \cdot x_A\right) - y_A\left(P^2 + R^2\right)\right] \tag{15}$$

$$n_z = \frac{1}{g}\left[a_{zSM} + \left(\dot{P}\, y_A - \dot{Q}\, x_A\right) + R\left(P \cdot x_A + Q \cdot y_A\right) - z_A\left(P^2 + Q^2\right)\right]$$

That formulas can be used during process comparison measured and calculated data.

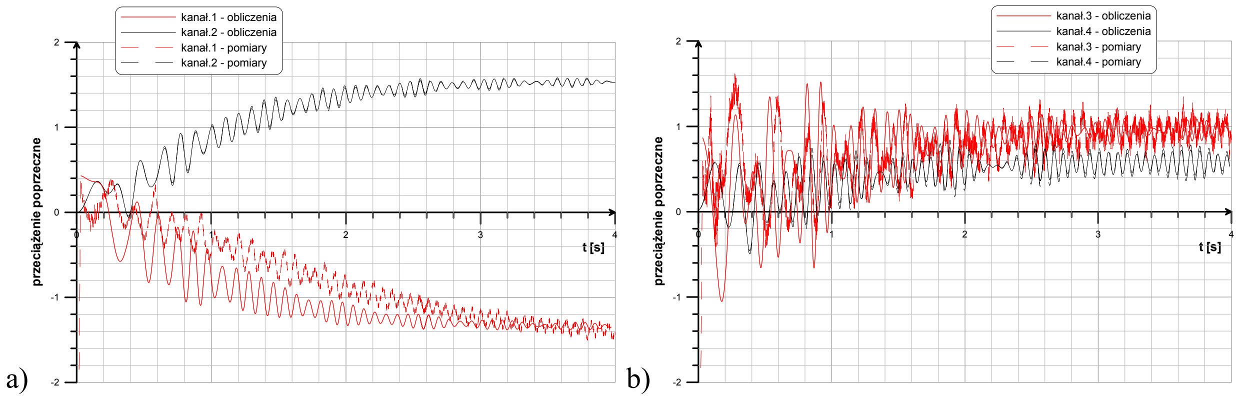

Figure 24: Accelerations measured and calculated in canals 1, 2, 3, and 4.

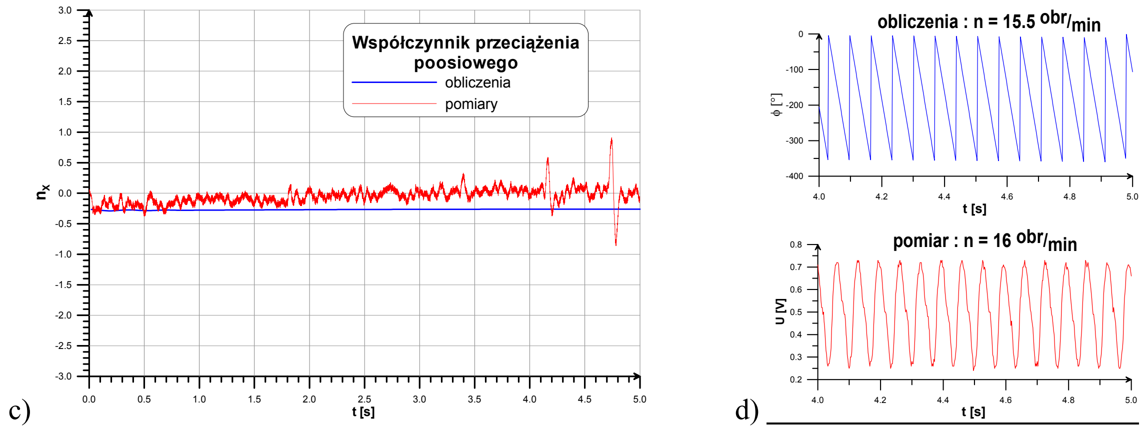

Figure 25: Calculated and measured data – longitudinal liad factor, and angular rates

The comparison between calculations and measurements are shown in Figs 24 a, 24b, 25 a, and 25 b. It can be stated good agreement between calculations and measurements.

3. CONCLUSIONS

Concluding, we have established the capability to perform engineering analysis and simulation using state-of-the-art Computational Fluid Dynamics (CFD) codes to predict store separation behaviour with complex geometry, even at the more dynamic, higher speed region. It can be noticed significant reduction of flight test programs, during aircraft/store certification. The validation e computational analysis, windtunnel tests may also be carried out using the Free Drop method - whereby scaled store models are released from the aircraft model in the windtunnel, and recorded using high speed orthogonal photography, or the Captive Trajectory System - which is based on the interaction of measured store forces and moments with an "on-line" equation-of-motion solver, with a mechanism for moving the store
The results of calculations of isolated store's characteristics show good compatibility with the results performed in a wind tunnel, especially for lower angles of attack ($\alpha<10^o$). It can be seen both for isolated fuselage and for a complete store. Estimating aerodynamic drag's coefficient as a sum of drags: induced, friction, and bottom gave results comparable to the ones obtained using the experimental investigations. For an angle of attack $\alpha>10^o$ a bigger difference in calculations' results are noticed. This is probably caused by the presence of vortex wake (generated, among others, by nose part of a body and control surfaces) and a simplified method of modelling of fixed vortex wake (vortex wake was assumed as flat surface flowing with a direction of constructional axis of a store)

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DISCUSSION EDITING

Paper No. 19: Evaluation and experimental Validation of low cost CFD based mathematical Model describing external store separation

Authors: Wieslaw Buler,Leszek Loroch,Krzysztof Sibilski, Andrzej Zyluk

Speaker: Krzysztof Sibilski

Discussor: Ronald Deslandes

Question: 1. What was the scale of the AC you used in the drop tests?

2. What kind of scaling method did you use for the dynamical properties of the drop test models?

3. Do you think that CFD can replace WT droptesting?

Speaker's Reply: 1. We used the 1:13 (of 8%) scale of the AC in the WT drop tests.

2. We used "light scaling method" in our drop tests. It means, that during the WT tests the equality of Froude (Fd) and Strouhal (St) numbers was ensured. Additional, the properties $(P_A/Q)_{WT} = (P_A/Q)_{airdrop}$ were ensured. (where P_A – aerodynamic force, Q-weight of modes and store respectively.

3. I think, that CFD methods radically reduced the WT tests, but in critical flight requires, the WT testing will be still unreplacable.

Discussor: G. Moretti

Question: Do you think that your mode will work in transsonic realtime?

Speaker's Reply: Our code doesn´t work in transsonic flow engine. We are thinking about including transsonic flow models in the new version of the mode.

Discussor: M. Tutty

Question: 1. How do you predict or establish ejection characteristics for the SU-22 Ejector Racks?

2. Are you planning to incorporate active separation / autopilot or tail operation sequences?

Speaker's Reply: 1. We don´t include ejection characteristics. We modelled the free drop case only, but we can include model of pyrotechnic ejector. The characteristics of that ejector we know from telemetry testing.

2. It depends on the plans of the SU-22 modernization.