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EXPERIMENTAL VALIDATION OF MATHEMATICAL MODEL DESCRIBING EXTERNAL STORES SEPARATION

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

Key words: external stores separation, aerodynamics interference, dynamics of aerial munitions

1. Introduction

One of the most important tests in the certification of a new weapon on a tactical aircraft is a safe separation test performed to demonstrate that the weapon can be deployed safely and effectively. Such tests typically involve evaluation of various conditions of airspeed, Mach numbers, and normal acceleration throughout a defined operational envelope, see for example Arnold and Epstein (1986), Cenko and Tessitore (1988), Cenko and Lutton (2000), Schindel (1975). To reduce the size of a 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 to determine the body movement based on local flow conditions. These tools have to accurately compute aerodynamic forces acting on the body and determine the dynamic response of the body to these forces.

An 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 was left to windtunnel testing, Covert (1981), Sadeh *et al.* (2001). Typically, numerous windtunnel and flight tests are performed to obtain sufficient carriage and trajectory data for a store to be certified for an 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 (see Beecham, 1971; Coste and Leynaert. 1982). However, with the progress of computational fluid dynamic (CFD), the prediction of carriage and trajectory data is possible. These numerical techniques can now overcome long lead times of wind tunnels and provide comparable results useful in aircraft/store analyses. Efforts to help reducing the time and cost required to certify a store for use are now beginning to be impacted by the use of computational fluid dynamics. A trajectory calculation is performed to integrate forces and moments acting on a body, and provide an accurate position of the body as a function of time. The most challenging task, so far, has been the mesh handling.

Geometric complexity of modern aircraft and stores, which may be outfitted with fins, guidance devices or release mechanisms, necessitates the use of complex meshes, consisying 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 several years, efforts to validate, demonstrate and accelerate the insertion of CFD methods into the store certification process for external store carriage and release have been undertaken. Barbero and Ferretti (1994) mentioned that in 1989 the clearance of the JSOW from the F-18 at the Mach 0.95 took more than 400 hours of wind tunnel testing and 20 flights. 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 (Cenko and Lutton, 2000). This reduction occurred because of wider application of numerical simulation techniques, including CFD methods. An extensive set of wind tunnel store carriage and separation data for the 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, calculation times of the order of 5 days on the CRAY YMP made such tools impractical for everyday use. It was demonstrated by Cenko and Lutton (2000) that a full-potential code could give results of similar quality in a fraction of time required for higher order codes.

Steady-state CFD methods have been used in conjunction with semi-empirical methods to predict a safe release. The surface pressure distributions are critical to an accurate trajectory and the resulting forces and moments acting on a 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 to mutually interfering multiple stores, see works Covert (1981), Lee *et al.* (2000), Nangia *et al.* (1996), Tomaro *et al.* (2000). Still, with the advancements made so far, these capabilities may not be sufficient when trying to predict trajectories for highly dynamic store separations. Particularly, a 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 in a wind tunnel. A time-accurate computation is therefore required to sufficiently predict the trajectory of a store.

The purpose of this paper 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.

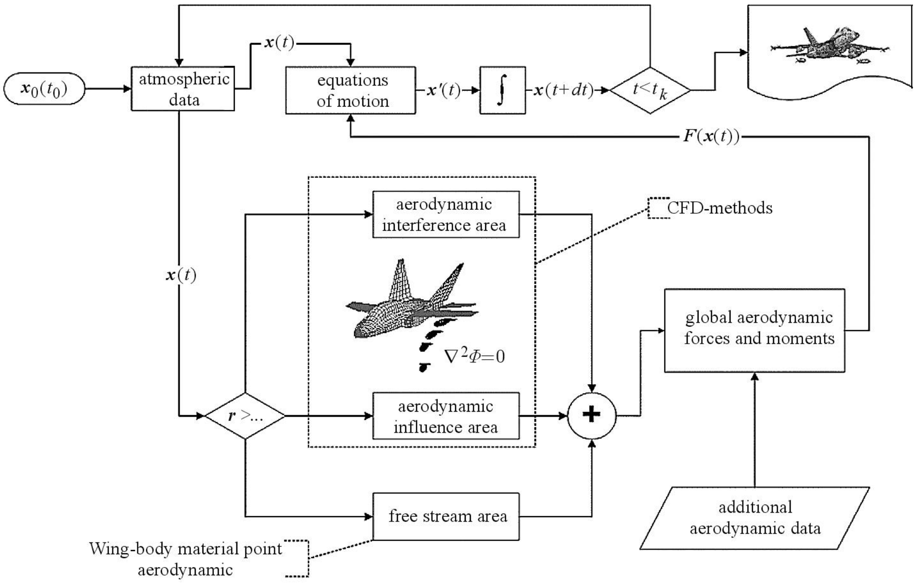

Fig. 1. Flow chart of the numerical model (cf. Lasek, 2002)

In this paper, the main emphasis is put on experimental validation of practical, cost-effective engineering solution to the complex problem with reasonable computational efficiency allowing the computer code to run on PC computers. The flow solver is based on a modified panel method (Lasek, 2002; Lasek and Sibilski, 2002), basing on Laplace's equations for the potential of disturbances. Since the object has been found in unstationary motion, the solution has been found by the *time-stepping method* (Katz and Plotkin, 2000) – it means that for every step time the wake vortex is suitably modified. The version of this code includes time metric terms to account for the movement of the mesh. Boundary conditions are set for either "steady-state" or "dynamic" conditions (see for example Cenko *et al.*, 1981; Tomaro *et al.*, 2000). The code obtains a flow solution for one time step based on newly moved grids received from the domain connectivity model, and outputs a new force and moment coefficients acting on the store to the six-degree-of-freedom model (see Fig. 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 steady-state carriage forces and moments as the input. For the moving body it is determined using the trajectory code with the steady-state carriage forces and moments as the input.

2. 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, and fully integrated with the flow solver, allow one to specify generalized point force routines for time or distance forces as well as to specify full constraints and model dependencies. Generalized thrust integration routines for multiple zones and surface patches are also obtainable.

To mark out forces and aerodynamic moments effected on an external store, we have used the modified panel method (see Katz and Plotkin, 2000; Lasek, 2002), basing on Laplace's equations for the potential of disturbances

$$\nabla^2 \varPhi = 0 \tag{2.1}$$

This equation is a modified form of an equation of motion of a fluid, on the assumption that the flow is unviscous, without separation and vortex-free (excluding wake vortex). The solution to the Laplace equation for the full velocity potential has the following form (Katz and Plotkin, 2000)

$$\varPhi(P) = -\frac{1}{4\pi}\iint\limits_{S_B}\Big[\sigma\frac{1}{r} - \mu\frac{\partial}{\partial n}\Big(\frac{1}{r}\Big)\Big]\,ds + \frac{1}{4\pi}\iint\limits_{S_W}\mu\frac{\partial}{\partial n}\Big(\frac{1}{r}\Big)\,ds + \varPhi_\infty(P) \tag{2.2}$$

The choice of the method was dictated by easy applicability and low cost of calculations, which makes the realization of the shown problem on PC computers possible. Since the object has been found in unstationary motion, the solution has been found by the *time-stepping method* (Katz and Plotkin, 2000) – it means that for every step time the wake vortex is suitable modified (Fig. 2). The disposition of singularities, which have been found from flow equations, exactly marks out the velocity field. The pressure disposition is calculated from the Bernoulli equation for an unstationary flowfield (Katz and Plotkin, 2000)

$$C_P = 1 - \frac{Q^2}{V^2} - \frac{2}{V^2}\frac{\partial \varPhi}{\partial t} \tag{2.3}$$

Aerodynamic loads calculated from solutions to Laplace's equations for the potential of disturbances did not include all components of the aerodynamic force, primarily

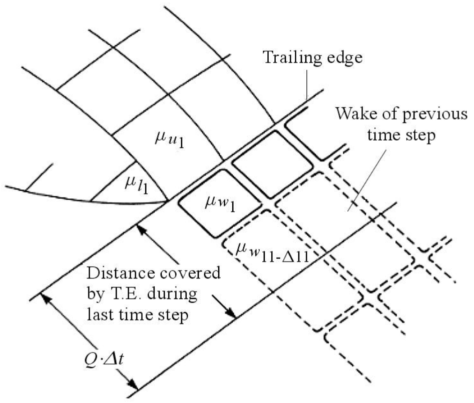

Fig. 2. Unstationary free wake vortex (cf. Katz and Plotkin, 2000)

the 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 one to calculate the drag force inducted by the lift force only. In the method presented above, the drag force component is calculated by making an assumption that on each panel an elementary skin friction drag force acts (see Lasek, 2002)

$$P_{x_{f_i}} = \frac{1}{2}\rho V_{C_i}^2 S_i C_{x_f} \tag{2.4}$$

That force acts conforming to the elementary airspeed vector on the panel. The elementary skin friction drag coefficient C_{x_f} can be calculated on the basis of literature data, empiric formulas, or wing tunnel investigations, (for example throughout dividing the total drag force (excluding the base drag force), measured at the zero lift force angle of attack), by dynamic pressure and whole streamlined surface. It can be mentioned that the proposed method of calculation of contact forces, enable, in a simple manner, taking into consideration the influence of those forces on aerodynamic moments acting on a store in an inhomogeneous field of flow velocities. Similarly, it is possible to take into consideration the base drag force acting on the store during calculations. It is possible (on the basis of investigations led at the Institute of Aviation (Krzysiak, 1987; Maryniak and Tarka, 1987; Lasek, 2002) that both the interference in the carrier-store system and the store angle of attack do not have significant influence on the base force coefficient C_{x_d}. Therefore, the base force can be calculated from the following formula

$$P_{X_d} = \frac{1}{2}\rho V_O^2 S_d C_{x_d} \tag{2.5}$$

In the case of shortage of empirical data, values of skin friction and base force coefficients can be calculated from the following empiric formulas (Lasek, 2002)

$$C_{x_f} = \frac{0.0315 A_C \mathrm{Re}_K^{-0.145}}{\sqrt{1-0.2M^2}} \frac{S_b}{S_K} \qquad\qquad C_{x_d} = (0.05 + 0.25M^2)\frac{S_d}{S_K} \tag{2.6}$$

where

$$A_C = 1.86 - 0.175\mathit{\Lambda}_K\sqrt{1-M^2} + 0.1\mathit{\Lambda}_K^2(1-M^2)$$

and $\mathit{\Lambda}_K = L_K/d$ is the aspect ratio of the store body, S_b – streamlined surface of the store body (excluding its bottom part), S_d – bottom part surface of the store body, S_K – cross-section surface of the store body, Re_K – Reynolds number for the store body.

Non-linear equations of motion of an aeroplane and 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. The following are used (see Maryniak, 1975):

- 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 the aircraft $\boldsymbol{V}_{0S}$, 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 the Euler angles mt_S, $\mathit{\Phi}_S$ and $\mathit{\Psi}_S$, 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.

Besides, we use:

- 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 $\boldsymbol{V}_O$, 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 the Euler angles $\mathit{\Theta}$, $\mathit{\Phi}$ and $\mathit{\Psi}$ (Fig. 3a), 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. 3b).

Usually, an aircraft is considered as a rigid body with moving elements of control surfaces. The gyroscopic moment of rotating masses of the engines is included. The whole system of equations should be completed with the following expressions: kinematic relations, kinematics of an arbitrary control system and control laws.

A mathematical model of an aircraft can be formulated in the following form (Lasek and Sibilski, 2002)

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}(t), \boldsymbol{u}(t)) \qquad \boldsymbol{x}(0) = \boldsymbol{x}_O \tag{2.7}$$

where the state vector is

$$\begin{aligned}\boldsymbol{x} \;=\; & [V_S, \alpha_S, \beta_S, P_S, Q_S, R_S, \mathit{\Phi}_S, \mathit{\Theta}_S, \mathit{\Psi}_S, x_{Sg}, y_{Sg}, z_{Sg},\\ & V, \alpha, \beta, P, Q, R, \mathit{\Phi}, \mathit{\Theta}, \mathit{\Psi}, x_g, y_g, z_g]^\top\end{aligned} \tag{2.8}$$

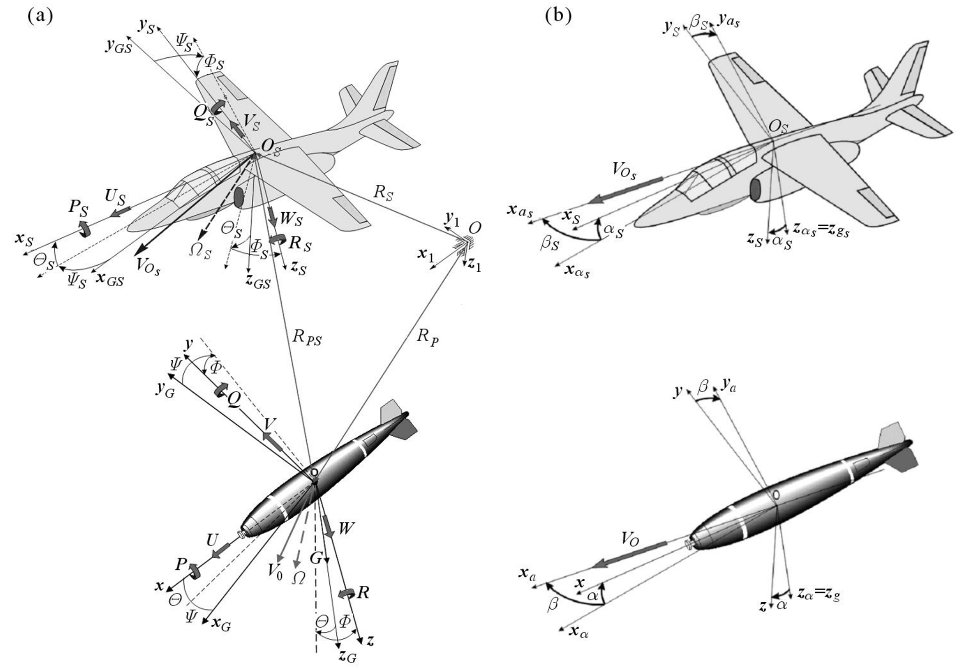

Fig. 3. Coordinates system attached to bodies (a) and attached to airflow (b) (cf. Lasek 2002)

and the control vector

$$\boldsymbol{u} = [\delta_H, \delta_A, \delta_V, \delta_F]^\top \tag{2.9}$$

where δ_H, δ_A, δ_V, δ_F are displacements of elevator, ailerons, rudder and power lever, respectively. The elements of the vector $\boldsymbol{f}$ can be found in Lasek (2002).

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

Calculations have been carried out for real conditions of an airdrop from the Su-22M4 fighter aircraft (Fig. 4). Solutions to numerical simulation of the airdrop have been used to formulate an experimental exploration program dependent on the modelling of a free drop of an external store in a subsonic windtunnel.

Fig. 4. Considered external store (cluster bomb) under the Su-22M4 wing

The obtained solutions considerably reduced of experimental explorations possible, which implied correctness of the elaborated mathematical model. Presently, at the Air Force Institute of Technology experimental investigations on the effect of the aerodynamic interference on the airdrop of external stores is being realised (see papers by: Żyluk and Winczura, 2000, 2004; Żyluk, 2002a,b, 2005; Żyluk and Lasek, 2004; Żyluk *et al.* (2004)). This problem was undertaken also by Żyluk in his PhD dissertation (2002). Figures 5 and 6 show a panel model of the Su22M4 fighter aircraft, panel models of considered stores, and stores under the aircraft wing. These experiments are intended to make a number of verifications of the shown method and to determine the area of possible usage.

The influence of the interference on aerodynamic characteristics of a cluster bomb are shown in Figures 7 and 8. Remembering that the results presented above were btained for the zero decalage of stabilisers, i.e. for an object completely symmetrical and for the zero angle of side-slip, the side and lateral characteristics should be zero. The results of calculations of aerodynamic characteristics versus the distance between the undercarriage and the wing with the aerodynamic interference taken into account, confirm that the biggest influence of the aerodynamic interference on the store flow is at the distance between the store and wing from 0 up to 4 store diameters.

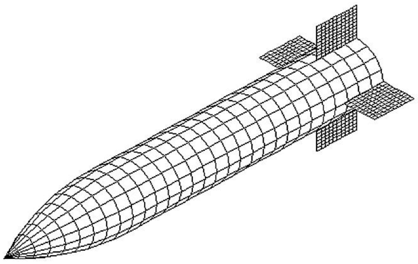

Fig. 5. Panel model of the external store (cluster bomb)

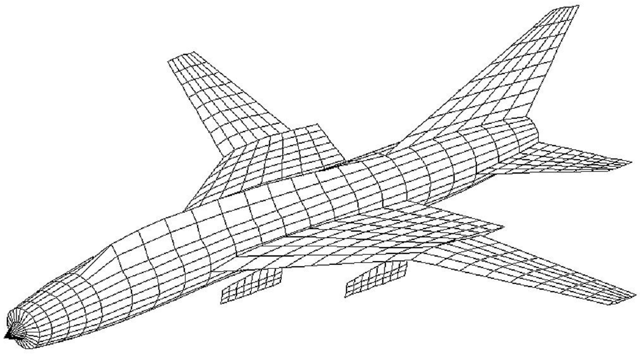

Fig. 6. Panel model of the Su-22M4 fighter aircraft

The analysis of calculations show good compatibility with the results of wind tunnel testing. Good compatibility can be noticed regarding the calculated drag coefficient with experimental results. That proves correctness of the methodology used in the process of estimating the aerodynamic drag (Fig. 7 and Fig. 8).

Results of numerical simulation of the airdrop are shown in Figures 9, 10 and 12. The free airdrop technique, applied in this approach, was based on the works of Goudie (1983) and Moore (1971). One can be state (see Fig. 11) satisfactory compatibility of the calculations (shown in Figs 9, 12) with experimental results registered by video cameras during the wind tunnel testing (Fig. 10) as well as the flight tests (see Figs 15 and 16). It can be noticed that the delay during the avoidance manoeuvre can cause collision between the aircraft and the store (see Fig. 12).

Figure 12 show the results of numerical simulations in conditions of the bombing maneuver during climbing flight with targeting to the take-off point. The results of calculations indicate much higher disturbances of the store flight course after the airdrop than in the case of bombing from a horizontal flight.

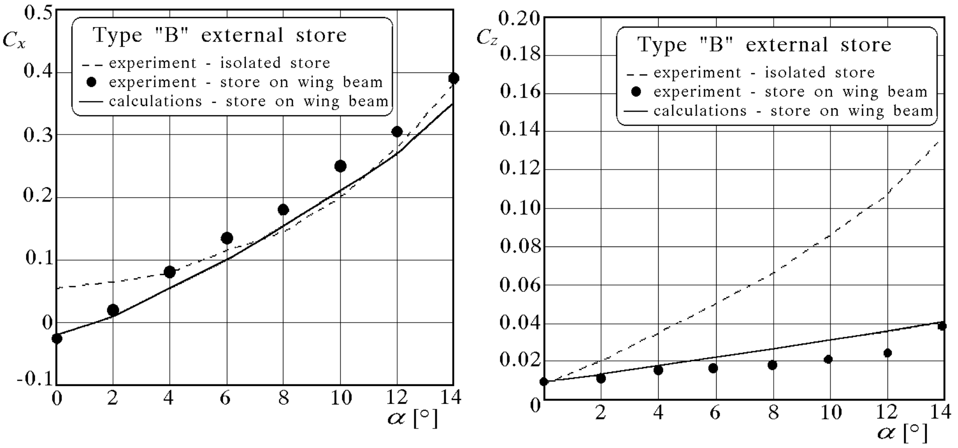

Fig. 7. Drag C_x, and lift C_z coefficients for an external store (on a wing beam) vs. the carrier-store system angle of attack

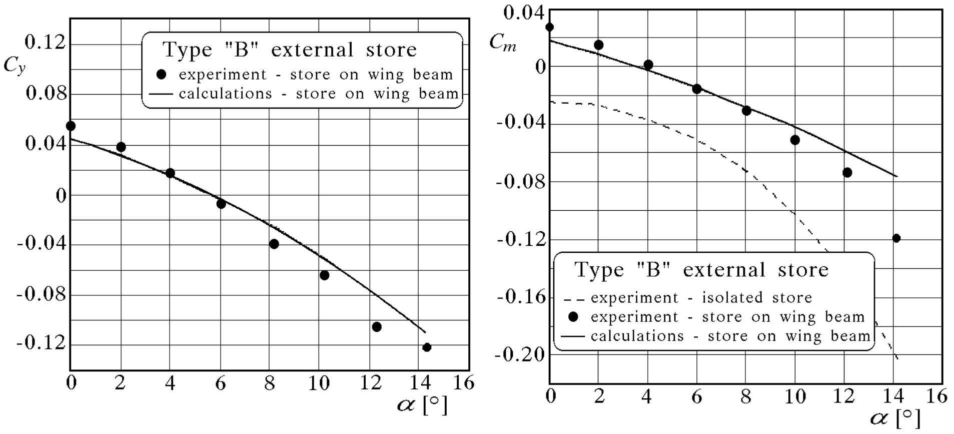

Fig. 8. Side force coefficient C_y and pitching moment coefficient C_m for an external store (on a wing beam) vs. the carrier-store system angle of attack

3.1. Experimental validation of mathematical model

The clearance of the cluster bomb was performed using a computational simulation as well as an actual flight and a wind tunnel-test. A validation of the mathematical model was approached at the Air Force Institute of Technology (AFIT) to provide our technical expertise to analyse the store separation using analytical tools, post flight data reduction as well as to provide recommendations for flight test planning (see works of Żyluk 2002a,b, 2005; Żyluk and Winczura 2000, 2004). With our inputs, a series of flight trials was planned and executed by Polish Air Force flight test pilots and AFIT engineers.

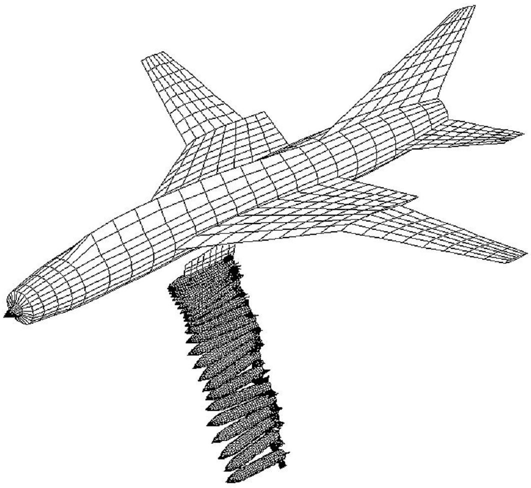

Fig. 9. Trajectory of an external store in the $Oy_{aS}z_{aS}$ plane; angle of attack $\alpha = 6°$, $\delta = 3°$ (cf. Lasek, 2002)

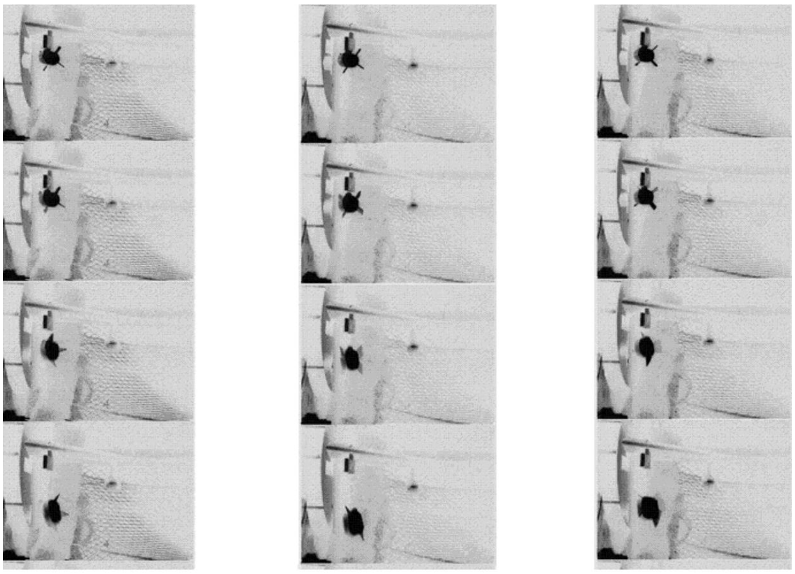

Fig. 10. Airdrop in wind tunnel testing – front view

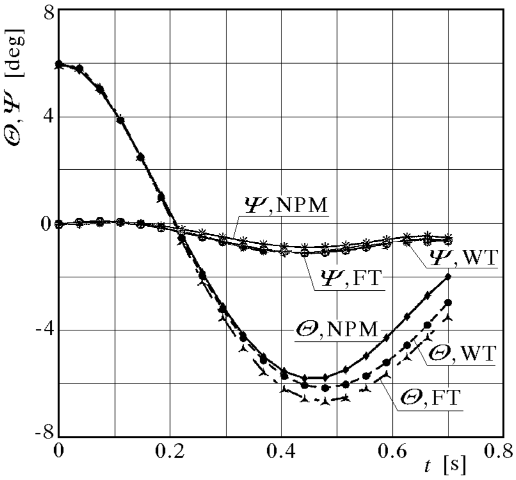

Fig. 11. Comparison between the flight and predicted trajectory for $AOA = 6°$, $h = 700\,\text{m}$, Ma $= 0.7$. NPM – nonlinear panel method; WT – free drop wind tunnel testing; FT – flight test

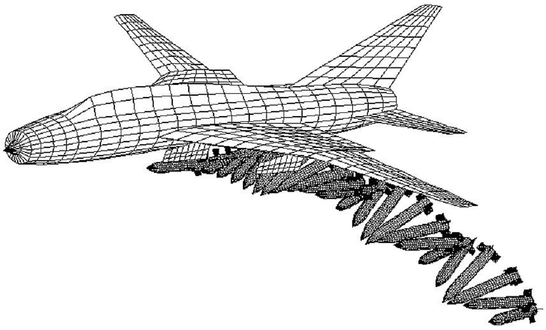

Fig. 12. Trajectory of an airdrop of a cassette bomb from climbing flight; angle of course $\gamma = 20°$, time of the drop 1 s, angle of attack $\alpha = 3°$ (cf. Lasek, 2002)

During the flight trials, on-board high-speed cameras and a video camera (Fig. 14) from the chase aircraft were used to capture the trajectory of the cluster bomb during the flight test. We provided our support services after each flight test in post-processing and analysing the trajectory of the separated store. The post-processed flight test data enabled us to refine our simulation and to make further recommendations for a safe separation of the next flight test point.

In the methods incorporating high-speed film cameras on the test aircraft which recorded 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

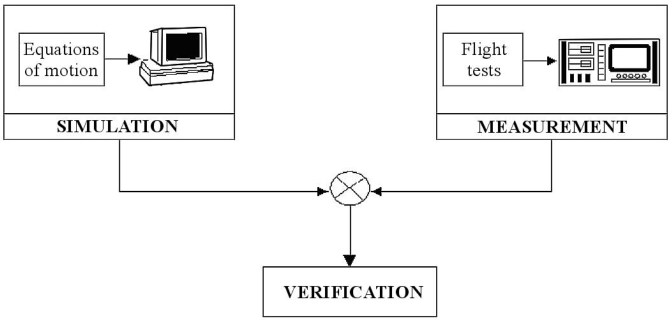

Fig. 13. Scheme of the clearance and validation of the external store mathematical model

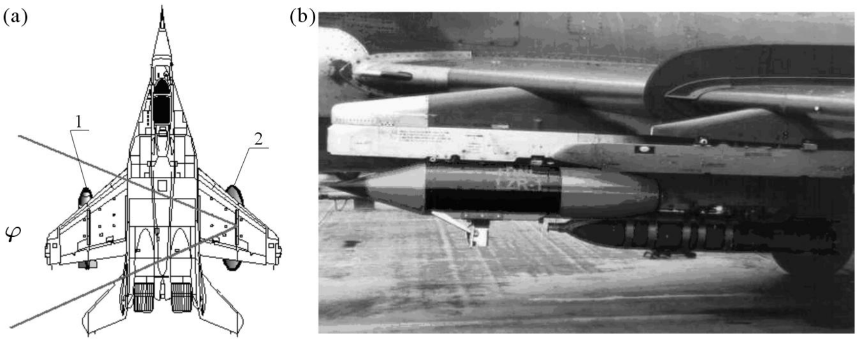

Fig. 14. Cassette with an on-board high-speed camera and a video camera

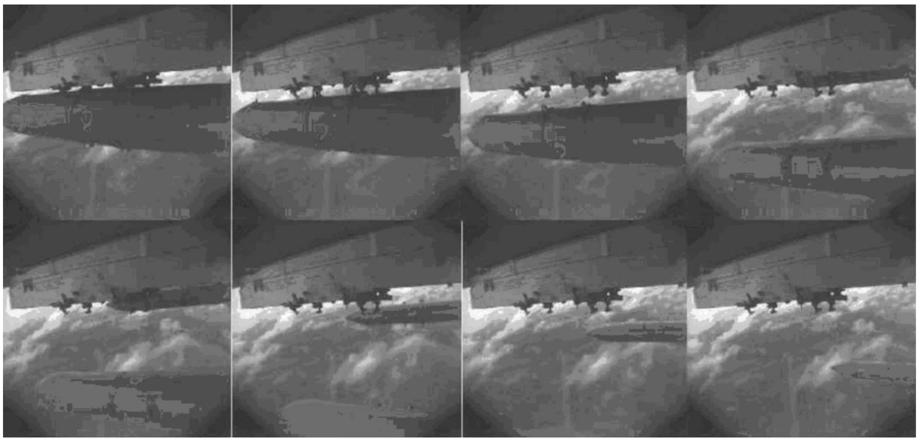

Fig. 15. Frame photos of an airdrop (on-board high-speed camera)

Fig. 16. Frame photos of an airdrop (high-speed camera on the following aircraft)

same mounted cameras. The quantitative data were essential to validate models so they could be used to improve the accuracy of weapon separation predictions.

High-speed video cameras can now be used in lieu of film cameras. A non-camera method of obtaining the 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 one that best suits the requirements of a specific test program (see for example works by Żyluk *et al.*, 2000; Żyluk, 2005).

The placement of accelerometers inside the projectile is shown in Figs 17 and 18. Basing on the mathematical model of the projectile, numerical simulations are performed. Acceleration of any projectile point can be found from the following formula

$$\boldsymbol{a}_A = \boldsymbol{a}_{SM} + \boldsymbol{\Omega} \times \boldsymbol{r}_A + \boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \boldsymbol{r}_A) \tag{3.1}$$

After simple calculations, remembering that the load factor is defined as $n = a/g$, we can obtain the following formulas

$$\begin{aligned} n_x &= \frac{1}{g}[a_{xSM} + (\dot{Q}y_A - \dot{R}z_A) + R(Qy_A + Pz_A) - x_A(Q^2 + R^2)] \\ n_y &= \frac{1}{g}[a_{ySM} + (\dot{R}x_A - \dot{P}z_A) + Q(Rz_A + Px_A) - y_A(P^2 + R^2)] \\ n_z &= \frac{1}{g}[a_{zSM} + (\dot{P}y_A - \dot{Q}x_A) + R(Px_A + Qy_A) - z_A(P^2 + Q^2)] \end{aligned} \tag{3.2}$$

These formulas can be used during the comparison process of the measured and calculated data.

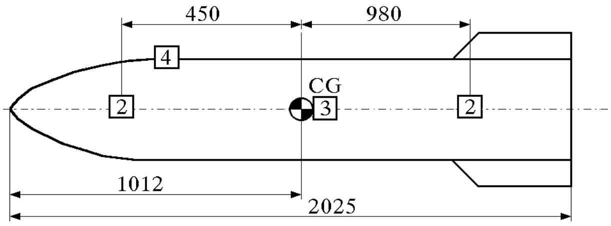

Fig. 17. Cluster bomb – placements of sensors; 2, 2, 3 – accelerometers, 4 – sensor of rotation

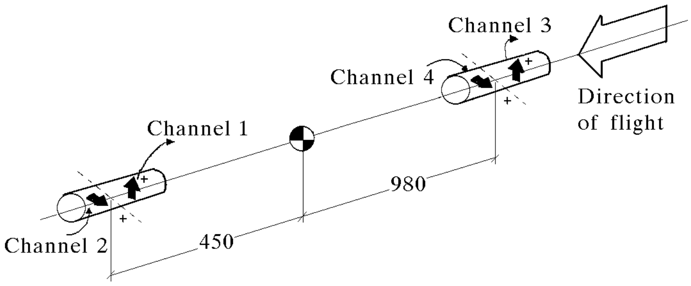

Fig. 18. Placements of accelerometers

The comparison between calculations and measurements is shown in Figs 19 and 20. One can notice good agreement between the calculations and measurements.

4. Conclusions

The capability to perform an engineering analysis and a simulation using the state-of-the-art Computational Fluid Dynamics (CFD) codes predicting a store separation with complex geometry, even at dynamic flight regimes, has been established in the paper. A significant reduction of flight test programs during the aircraft/store certification can be noticed. The validation of the computational analysis and wind tunnel tests may also be carried out using the Free Drop method in which models of scaled stores are released from an aircraft model in a wind tunnel and recorded using high speed orthogonal photography. It can be achieved also by 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 moving the store.

The results of calculations of characteristics of an isolated store show good compatibility with the results performed in a wind tunnel, especially for lower angles of attack ($\alpha < 10^\circ$). This phenomenon can be seen both for an isolated fuselage and for a complete store. Estimating the aerodynamic drag coefficient as a sum of the induced, frictional, and bottom drags gave results comparable to those obtained using

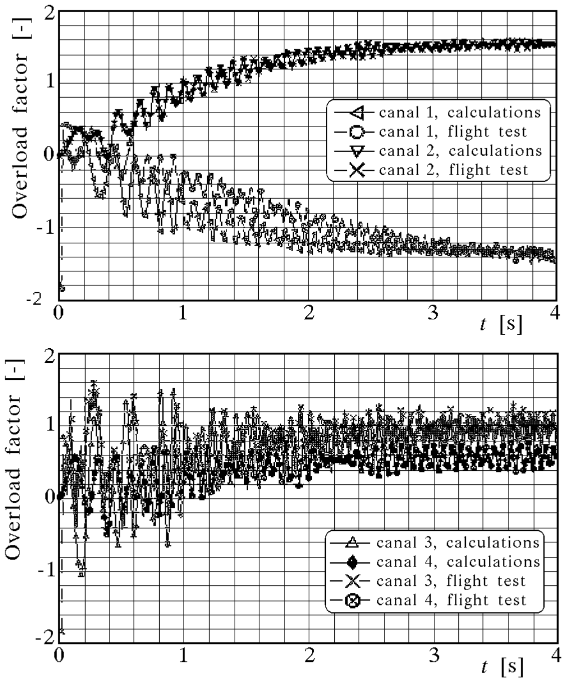

Fig. 19. Measured and calculated accelerations in canals 1, 2, 3, and 4

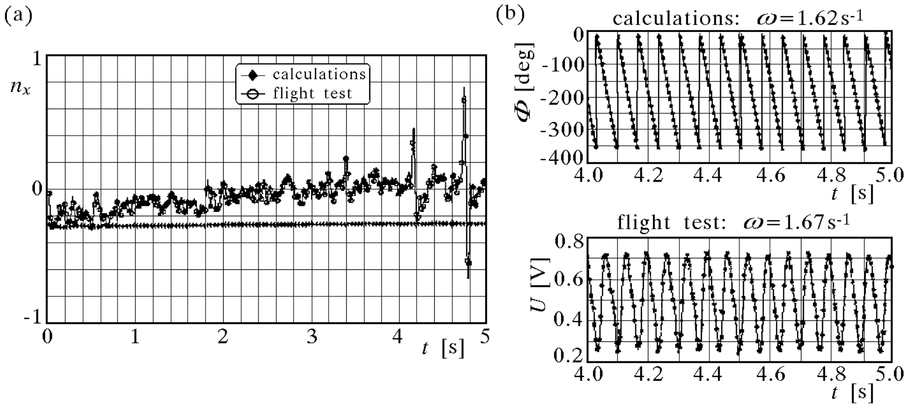

Fig. 20. Calculated and measured data – the longitudinal load factor and angular rates

experimental investigations. For an angle of attack $\alpha > 10^\circ$ greater differences in calculation results were noticed. This is probably caused by the presence of vortex wake (generated, among others, by the nose part of a body and control surfaces) and a simplified method of modelling the fixed vortex wake (vortex wake was assumed as a flat surface flowing with a direction of constructional axis of a store).

Yurkovich *et al.* (2001) presented a summary of the state-of-the-art unsteady aerodynamics applied to the analysis of dynamics for a high-performance military aircraft. The data presented there were based, to a large extent, on the authors' personal experience. It can be noticed that the computational fluid dynamics made a revolutionary impact on the steady state aerodynamics but developed over thirty years ago the doublet-lattice method which is still used in the analysis of dynamics of flight of aerial vehicles. Today, nothing has appeared that could offer a significant improvement. It is anticipated that the doublet-lattice method will be continuously used as an unsteady aero method for a long time in the future.

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Eksperymentalna walidacja matematycznego modelu opisującego proces odejścia podwieszenia z nosiciela

Streszczenie

W pracy przedstawiono ogólny model badań własności dynamicznych bomb lotniczych. Główny nacisk położono na praktyczne rozwiązanie złożonego problemu oddzielenia podwieszeń od nosiciela z uwzględnieniem interferencji aerodynamicznej. Opracowane algorytmy i programy komputerowe pozwalają na rozwiązanie tego zagadnienia na komputerach klasy PC. Model matematyczny zweryfikowano badaniami w tunelach aerodynamicznych i badaniami doświadczalnymi w locie.

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