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EVALUATION OF THE POSSIBILITY OF BOMB FLIGHT CONTROL

Grzegorz Kowaleczko, Edward Olejniczak
Mariusz Pietraszek, Andrzej Żyluk

Air Force Institute of Technology
Ksiecia Bolesława Street 6, 01-494 Warsaw, Poland
tel.: + 48261851310, fax: +48261851410
e-mail: g.kowaleczko@chello.pl

Abstract

This paper presents theoretical model dedicated to a guided bomb. A mathematical description of the six-degrees-of-freedom motion of the bomb is shown. Particular attention was paid on aerodynamic forces and moments generated by additional control fins mounted on the front part of the bomb. Exemplary results of a numerical simulation of bombing are submitted and conclusions focused on the possibility of flightpath control are formulated. The paper concerns on the equations of bomb spatial motion and kinematic relations expressed making use of moving coordinate systems, the common origin of which is located at the centre of mass of the bomb. The set of equations of the rotating motion about the centre of mass in the body-fixed reference frame is presented. Aerodynamic forces and moments acting on the bomb are described. Coefficients are determined using the PRODAS software with detailed geometry of the LB-10M bomb. The coefficients were determined for different Mach numbers from 0.4 to 0.8. The important task was research investigations of aerodynamic characteristics with a wind tunnel and a set of experiments in real bombing conditions.

Keywords: *airborne munitions, bomb flight, active bomb control, aerodynamic bomb, PRODAS calculations*

1. Introduction

A classical bomb is a kind of passive unguided airborne munitions, which has limited accuracy of hitting a target, particularly in real atmosphere conditions [1]. Therefore, to improve a degree of accuracy and to obtain possibility of active bomb control during a flight, theoretical and experimental research works are performed at the Air Force Institute of Technology [2]. They are dedicated to small LB-10M bomb, which was designed by AFIT research team in 2008. The weight of the bomb is 13 kg, and its length is equal to 0.645 m, a diameter of 0.11 m. This bomb is dedicated to training of precise bombing for Polish Air Forces. It is used at following planes: MiG-29, Su-22, TS-11 (Fig.1).

For this reason some modifications have been done. The LB-10M bomb, which originally has only four stabilizers F1 was equipped by additional four fins F2 (Fig.3). They allow you to active control of bomb trajectory with autonomous control system mounted on-board. The executive part of this system is composed of four fins mounted on the front part of the bomb. They are divided into two pair – each pair is controlled independently by changing of angle of attack (AoA). These fins produce aerodynamic forces and moments influencing on bomb motion.

Aerodynamic characteristics of the bomb have been determined using commercial software PRODAS [3]. Originally, PRODAS is dedicated to projectiles and missiles and is based on lot theoretical and experimental investigations [4]. Therefore, it allows only changing AoA of opposite fins in opposite directions, to produce rolling motion. While in the case of the LB-10M bomb the same deflection for each pair of fins is required. This problem was resolved comparing some aerodynamic derivatives calculated by PRODAS. It will be shortly described below.

The mathematical model of the bomb flight is based on Newton's laws [5-9]. It allows simulating spatial motion. Series of simulations with various fins' angles of attack allow to determine range of the guided bomb LB-10M.

Fig. 1. LB-10M bomb mounted on TS-11 plane

2. Equations of the problem

The equations of bomb spatial motion and kinematic relations are expressed making use of moving coordinate systems, the common origin of which is located at the centre of mass of the bomb (Fig. 2).

We shall apply a Earth-fixed system of coordinates $Ox_gy_gz_g$, the Oz_g axis of which is vertical and directed downwards, a system of coordinates $Oxyz$ attached to the bomb (body axes), where the Oxz and Oxy planes coincides with the symmetry plane of the bomb, and a system $Ox_ay_az_a$ attached to the air trajectory (velocity axes), in which the Ox_a axis is directed along the flight velocity vector $\overline{V}_{aer}$ and the Oz_a axis lies in the Oxz plane of the bomb.

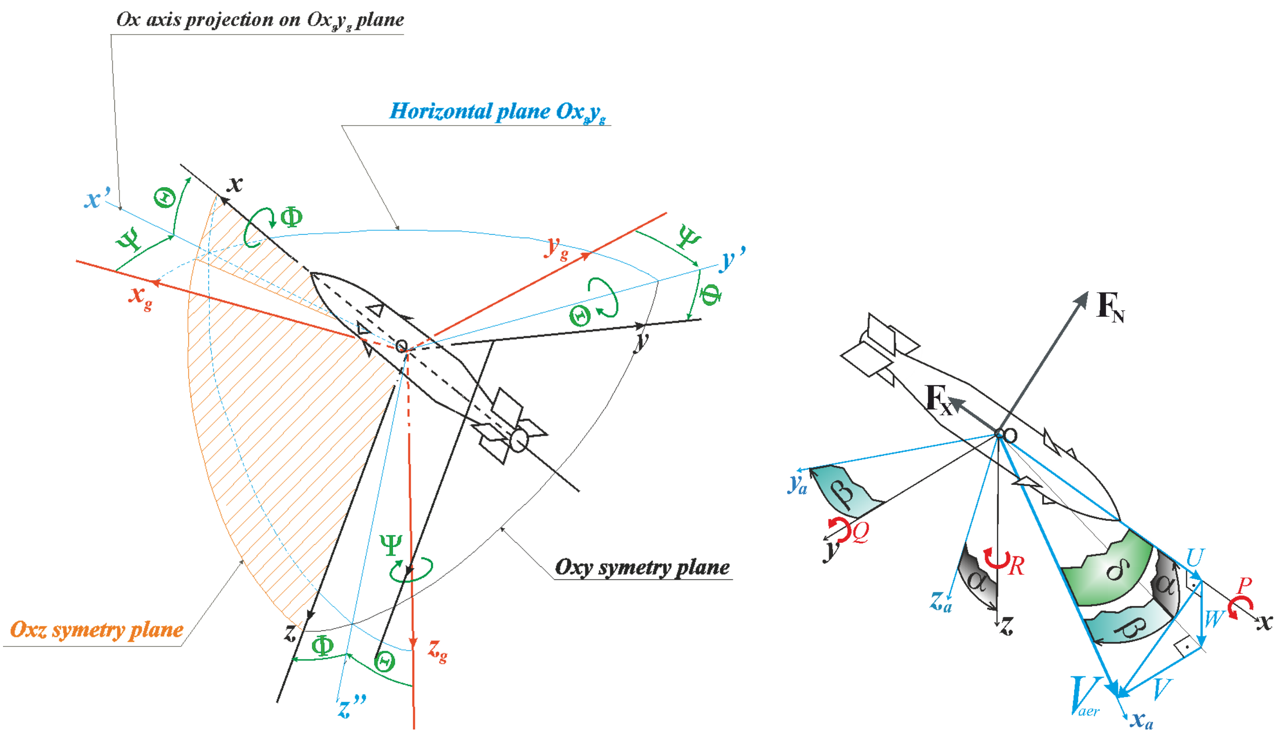

Fig. 2. Coordinate systems

The relative position of the Earth-fixed system $Ox_g y_g z_g$ and the body system $Oxyz$, attached to the aircraft is described by Euler angles: Ψ – the yaw angle, Θ – the pitch angle, Φ – the roll angle, while the relative position of the system $Oxyz$ and the system $Ox_a y_a z_a$ attached to the air trajectory – by the angle of attack α and the angle of sideslip β. Relations are as follows:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \mathbf{L}_{b/g} \begin{bmatrix} x_g \\ y_g \\ z_g \end{bmatrix}, \qquad \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \mathbf{L}_{b/a} \begin{bmatrix} x_a \\ y_a \\ z_a \end{bmatrix}, \tag{1}$$

where matrices have the forms:

$$\mathbf{L}_{b/g} = \begin{bmatrix} \cos\Psi\cos\Theta & \sin\Psi\cos\Theta & -\sin\Theta \\ \cos\Psi\sin\Theta\sin\Phi - \sin\Psi\cos\Phi & \sin\Psi\sin\Theta\sin\Phi + \cos\Psi\cos\Phi & \cos\Theta\sin\Phi \\ \cos\Psi\sin\Theta\cos\Phi + \sin\Psi\sin\Phi & \sin\Psi\sin\Theta\cos\Phi - \cos\Psi\sin\Phi & \cos\Theta\cos\Phi \end{bmatrix}, \tag{2}$$

$$\mathbf{L}_{b/a} = \begin{bmatrix} \cos\alpha\cos\beta & -\cos\alpha\sin\beta & -\sin\alpha \\ \sin\beta & \cos\beta & 0 \\ \sin\alpha\cos\beta & -\sin\alpha\sin\beta & \cos\alpha \end{bmatrix}. \tag{3}$$

The equations of motion of the mass centre have the following form in the $Oxyz$ system:

$$\begin{aligned} m(\dot{U} + QW - RV) &= X, \\ m(\dot{V} + RU - PW) &= Y, \\ m(\dot{W} + PV - QU) &= Z, \end{aligned} \tag{4}$$

where: m – the mass of the bomb, $\bar{V}_{aer} = [U,V,W]^T$ – the velocity vector, $\bar{\Omega} = [P,Q,R]^T$ – the vector of angular velocity, $\bar{F} = [X,Y,Z]^T$ – the resultant vector of forces, which is the sum of the weight and an aerodynamic force. Its component is determined by formulas:

$$F_x = -m\,g\sin\Theta - C_x \frac{\rho V_{aer}^2}{2} S, \tag{5a}$$

$$F_y = m\,g\cos\Theta\sin\Phi + \frac{\rho V_{aer}^2}{2} S \cdot \left[C_{N\delta}\left(\frac{-V}{V_{aer}}\right) + \left(\frac{R\,d}{V_{aer}}\right) C_{Nq} \right] + F_{y\_control}, \tag{5b}$$

$$F_z = m\,g\cos\Theta\cos\Phi - \frac{\rho V_{aer}^2}{2} S \cdot \left[C_{N\delta}\left(\frac{-W}{V_{aer}}\right) + \left(\frac{-Q\,d}{V_{aer}}\right) C_{Nq} \right] + F_{z\_control}, \tag{5c}$$

where:

C_x, $C_{N\delta}$, C_{Nq} – coefficients of aerodynamic axial and normal forces,
S – cross-sectional area of the bomb,
ρ – air density,

$$V_{aer} = \sqrt{U^2 + V^2 + W^2}. \tag{6}$$

The set of equations of the rotating motion about the centre of mass in the body-fixed reference frame is:

$$\begin{aligned} I_x \dot{P} &= L, \\ I_y \dot{Q} - (I_z - I_x)RP &= M, \\ I_z \dot{R} - (I_x - I_y)PQ &= N, \end{aligned} \tag{7}$$

where I_x, I_y, I_z are the inertia moments and $\bar{M} = [L, M, N]^T$ is the resultant aerodynamic roll, pitch and yaw moments of forces defined as follows:

$$L = \frac{\rho V_{aer}^2}{2} SdC_{lp}\left(\frac{Pd}{V_{aer}}\right), \tag{8a}$$

$$M = \frac{\rho V_{aer}^2}{2} Sd \cdot \left[C_{m\delta}\left(\frac{W}{V_{aer}}\right) + C_{mq}\left(\frac{Qd}{V_{aer}}\right)\right] + M_{control}, \tag{8b}$$

$$N = \frac{\rho V_{aer}^2}{2} Sd \cdot \left[C_{n\delta}\left(\frac{-V}{V_{aer}}\right) + C_{nq}\left(\frac{Rd}{V_{aer}}\right)\right] + N_{control}, \tag{8c}$$

where C_{lp}, $C_{m\delta}$, C_{mq}, $C_{n\delta}$, C_{nq} – coefficients of aerodynamic moments, d – diameter of the bomb. Because of bomb symmetry, one has $C_{n\delta} = C_{m\delta}$, $C_{nq} = C_{mq}$.

The equations of motion (4) and (7) should be completed by the following kinematic relations, which enable us to determine the angular position of the bomb with reference to the $Ox_gy_gz_g$ coordinate system:

$$\begin{aligned} \dot{\Psi} &= (R\cos\Phi + Q\sin\Phi)/\cos\Theta, \\ \dot{\Theta} &= Q\cos\Phi - R\sin\Phi, \\ \dot{\Phi} &= P + (Q\sin\Phi + R\cos\Phi)\tan\Theta \end{aligned} \tag{9}$$

and the relations for determining the position of the centre of mass in the Earth-fixed coordinate:

$$\begin{bmatrix} U_g \\ V_g \\ W_g \end{bmatrix} = \begin{bmatrix} \dot{x}_g \\ \dot{y}_g \\ \dot{z}_g \end{bmatrix} = \mathbf{L}_{b/g}^{-1}\mathbf{L}_{b/a}\begin{bmatrix} V \\ 0 \\ 0 \end{bmatrix}. \tag{10}$$

3. Aerodynamic coefficients

Aerodynamic forces and moments acting on the bomb were calculated using formulas (5) and (8). All coefficients were determined using commercial software PRODAS. For this reason, detailed geometry of the LB-10M bomb was implemented into the software (Fig. 3). As the result, courses of aerodynamic coefficients were obtained. They are shown in Fig. 4-7 as the function of Mach number for the bomb without fins F2 and with deflected fins. Angles of deflections were: 0°, 5°, 10°. Deflections were asymmetric.

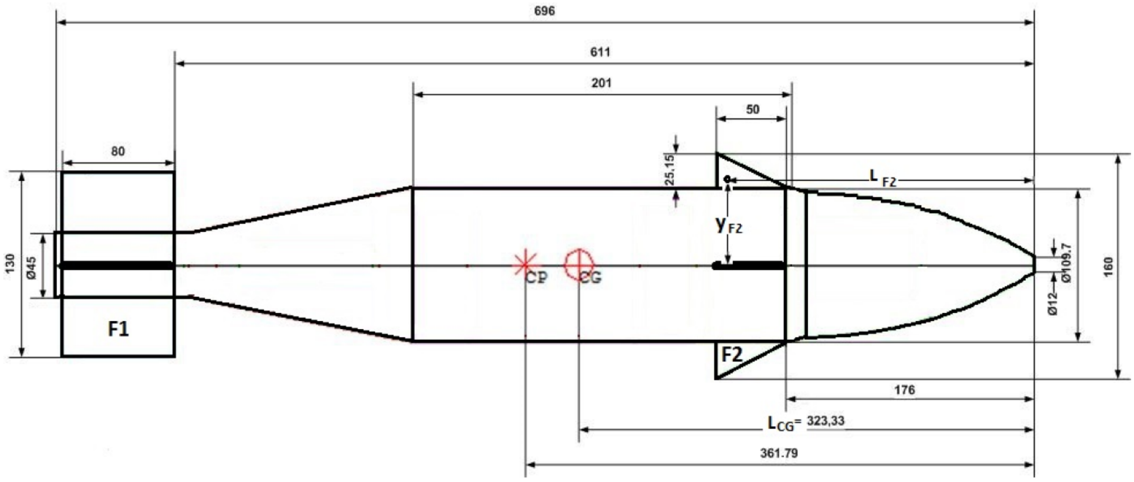

Fig. 3. Geometry of the LB-10M bomb

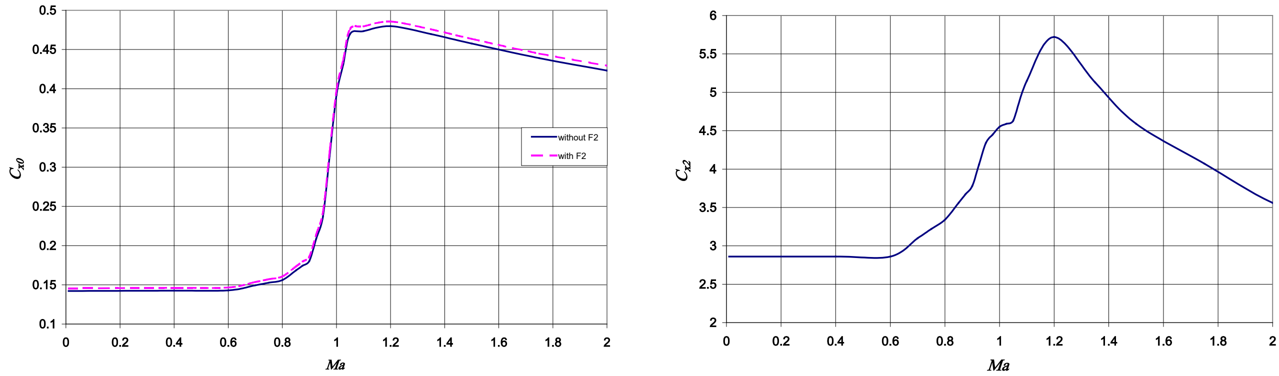

Fig. 4. Axial force coefficient $C_x = C_{x0} + C_{x2}\delta^2$

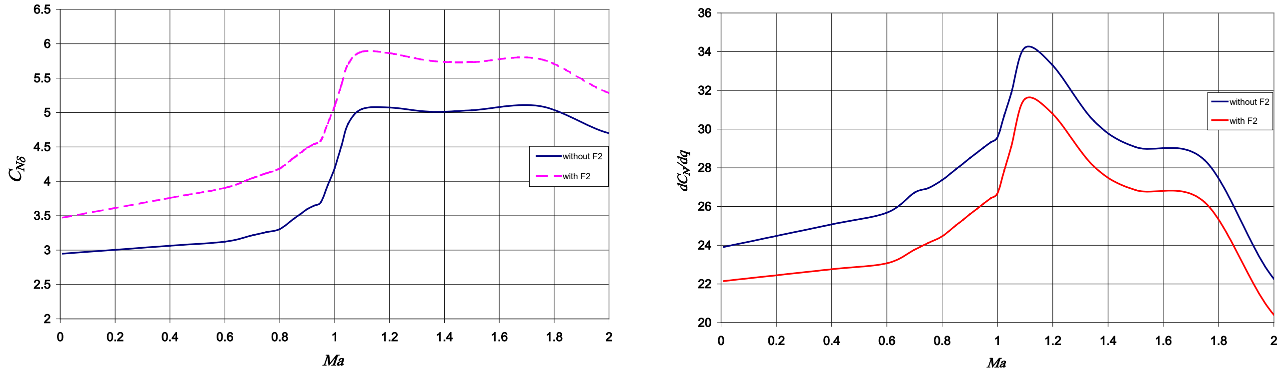

Fig. 5. Normal force coefficients

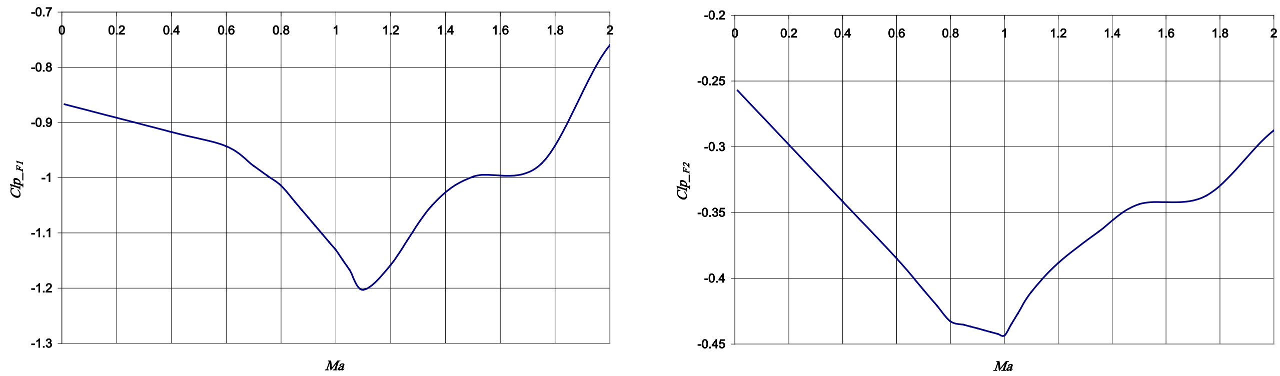

Fig. 6. Roll damping moment coefficients $C_{lp} \approx C_{lp\_F1} + C_{lp\_F2}$

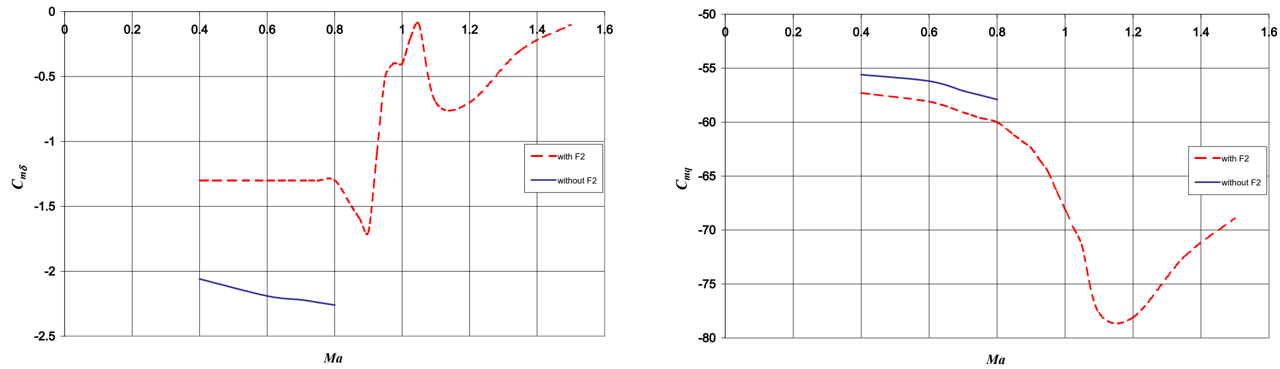

Fig. 7. Pitching moment coefficients

PRODAS calculates coefficients for the case of fins deflected in opposite directions (e.g. left fin – up and right fin – down). Therefore, it was necessary to try to recalculate obtained coefficient for the case of symmetric deflection of both fins. The main goal was to forces and moments, which determines reaction of the bomb to control. For this reason, some detailed characteristics generated by PRODAS were compared and discussed:

– for the whole bomb:
  - $C_m^{\delta} = \mathrm{d}C_m/\mathrm{d}\delta$ – a derivative of pitching moment coefficient with respect to the angle of nutation,
  - $C_m^{\bar{q}} = \mathrm{d}C_m/\mathrm{d}\bar{q}$ – a derivative of pitching moment coefficient with respect to the dimensionless angular velocity $\bar{q}$, where $\bar{q} = 0.5qd/V$,
– participation of stabilizers F1 and fins F2:
  - $C_{N\_F2}^{\delta} = \mathrm{d}C_{N\_F2}/\mathrm{d}\delta$ – a derivative of coefficient of normal force produced by F2 with respect to the angle of nutation;
  - $\bar{L}_{F2} = L_{F2}/d$ – the distance from the bomb nose to fins F2 centre of pressure measured in calibres;
  - $C_{l\_F2}^{\bar{p}} = \mathrm{d}C_{l\_F2}/\mathrm{d}\bar{p}$ – a derivative of rolling moment coefficient produced by F2 with respect to the dimensionless angular velocity $\bar{p}$.

Two variants of calculation were performed:

A – bomb with rear stabilizers F1 and without F2 fins,

B – bomb with rear stabilizers F1 and with F2 fins:

  B0 – for deflection of F2: $\delta_{F2} = 0°$,

  B5 – for deflection of F2: $\delta_{F2} = 5°$,

  B10 – for deflection of F2: $\delta_{F2} = 10°$.

3.1. Analysis of the pitching moment

Derivative $C_{m\_F2}^{\delta}$

The pitching moment produced by deflection of one pair of fins, F2 is equal to:

$$M_{F2} = C_{m\_F2} \frac{\rho V_{aer}^2}{2} S\, d\,. \tag{11}$$

It can also be calculated on the basis of the value of the force N_{F2} generated by one pair of F2 fins:

$$M_{F2} = l_{F2} \cdot N_{F2} = l_{F2} \cdot C_{N\_F2} \frac{\rho V_{aer}^2}{2} S\,, \tag{12}$$

where l_{F2} determines the distance between the pressure centre of fins F2 and the centre of mass. l_{F2} is measured along the longitudinal axis:

$$l_{F2} = L_{CG} - L_{F2} = L_{CG} - \bar{L}_{F2}\, d\,. \tag{13}$$

Comparison of formulas (11) and (12) give you:

$$C_{m\_F2}\, d = C_{N\_F2}\, l_{F2}\,. \tag{14}$$

Differentiating both sides of (14) with respect to the nutation angle, we have:

$$C_{m\_F2}^{\delta} = C_{N\_F2}^{\delta} \frac{l_{F2}}{d}\,. \tag{15}$$

This derivative can be also calculated based on data from PRODAS:

$$C_{m\_F2}^{\delta} = C_{m\_B}^{\delta} - C_{m\_A}^{\delta}\,. \tag{16}$$

Minuend on the right side corresponds to the variant B of calculations and it is the same for sub-options B0, B5 and B10. Subtrahend corresponds to the variant A. Comparison of calculations obtained by using equations (15) and (16) allows to check the correctness of the derivative $C_{N\_F2}^{\delta}$ generated by PRODAS. Tab. 1 shows various coefficients determined for different Mach numbers. The table shows that calculated by two ways values of the derivative $C_{m\_F2}^{\delta}$ are close each other.

Tab. 1. Various coefficients determined for different Mach numbers

Ma	$C_{N\_F2}^{\delta}$	$\bar{L}_{F2}$	$C_{m\_B}^{\delta}$	$C_{m\_A}^{\delta}$	$C_{m\_F2}^{\delta}$	
	PRODAS	PRODAS	PRODAS	PRODAS	formula (16)	formula (15)
0.4	0.6947	1.8569	–1.31	–2.06	0.75	0.76
0.6	0.7826	1.8609	–1.34	–2.19	0.85	0.856
0.7	0.8313	1.8646	–1.33	–2.22	0.89	0.91
0.75	0.8557	1.8665	–1.32	–2.24	0.92	0.925
0.8	0.88	1.8684	–1.31	–2.26	0.95	0.9513

Derivative $C_{m\_F2}^{\bar{q}}$

Similar calculations were performed for the pitching moment coefficient derivative with respect to $\bar{q}$. Differentiating formula (14), we have:

$$C_{m\_F2}^{\bar{q}} = C_{N\_F2}^{\bar{q}} \frac{l_{F2}}{d}. \tag{17}$$

Because PRODAS does not give the derivative $C_{N\_F2}^{\bar{q}}$, it was calculated indirectly:

$$C_{N\_F2}^{\bar{q}} = \frac{\partial C_N}{\partial\left(\dfrac{qd}{2V_{aer}}\right)} = \frac{2V_{aer}}{d}\frac{\partial C_{N\_F2}}{\partial q} = \frac{2V_{aer}}{d}\frac{\partial C_{N\_F2}}{\partial \delta}\frac{\partial \delta}{\partial q} = \left|\delta = \frac{q l_{F2}}{V_{aer}}\right| = 2C_{N\_F2}^{\delta}\frac{l_{F2}}{d}. \tag{18}$$

Hence, we get:

$$C_{m\_F2}^{\bar{q}} = 2C_{N\_F2}^{\delta}\left(\frac{l_{F2}}{d}\right)^2. \tag{19}$$

$C_{m\_F2}^{\bar{q}}$ derivative can also be calculated on the basis of the PRODAS data:

$$C_{m\_F2}^{\bar{q}} = C_{m\_B}^{\bar{q}} - C_{m\_A}^{\bar{q}}. \tag{20}$$

Comparison of calculations obtained by using equations (19) and (20) allows checking the correctness of the derivative $C_{N\_F2}^{\delta}$ generated by PRODAS. Tab. 2 shows various coefficients determined for different Mach numbers. The table shows that calculated by two ways values of the derivative $C_{m\_F2}^{\bar{q}}$ are close each other.

3.2. Analysis of the rolling moment

Derivative $C_{l\_F2}^{\bar{p}}$

The damping rolling moment produced by four fins F2 is equal to:

$$L_{damp\_F2} = C_{l\_F2}^{\bar{p}}\left(\frac{p\,d}{V_{aer}}\right)\frac{\rho V_{aer}^2}{2} S\,d\,. \tag{21}$$

Tab. 2. Various coefficients determined for different Mach numbers

Ma	$C^{\delta}_{N\_F2}$	l_{F2}/d	$C^{\bar{q}}_{m\_B}$	$C^{\bar{q}}_{m\_A}$	$C^{\bar{q}}_{m\_F2}$	
	PRODAS	formula (11)	PRODAS	PRODAS	formula (18)	formula (17)
0.4	0.6947	1.091	–57.3	–55.6	–1.7	–1.652
0.6	0.7826	1.087	–58.1	–56.2	–1.9	–1.848
0.7	0.8313	1.083	–59.1	–57.1	–2.0	–1.949
0.75	0.8557	1.081	–59.6	–57.5	–2.1	–1.9998
0.8	0.88	1.079	–60.0	–57.9	–2.1	–2.049

It can also be calculated on the basis of the value of the force F_{F2} generated by a single fin F2, which is a half of the force generated by the pair of F2 fins:

$$F_{F2} = \frac{1}{2} N_{F2} = C_{N\_F2} \frac{\rho V_{aer}^2}{4} S \,. \tag{22}$$

To calculate this force it is necessary to determine an angle of attack as the result of rolling motion with angular velocity p:

$$\alpha_{F2} = \frac{p\, y_{F2}}{V_{aer}}, \tag{23}$$

where y_{F2} is the distance from pressure centre of F2 to longitudinal axis Ox (see Fig. 3).
Therefore, we have:

$$F_{F2} = C^{\delta}_{N\_F2} \frac{p y_{F2}}{V_{aer}} \frac{\rho V_{aer}^2}{4} S \,. \tag{24}$$

The sum of rolling moments of all F2 fins gives:

$$L_{damp\_F2} = -4 y_{F2} F_{F2} = -C^{\delta}_{N\_F2} \frac{p}{V_{aer}} y_{F2}^2 \rho V_{aer}^2 S \,. \tag{25}$$

Comparing formulas (21) and (25) we obtain:

$$C^{\bar{p}}_{l\_F2} = -2 \left(\frac{y_{F2}}{d} \right)^2 C_{N\_F2} \,. \tag{26}$$

Because y_{F2} cannot be less than $0.5d$, it was assumed that $y_{F2}/d = 0.5$. Comparison of the results calculated according to (26) and given by PRODAS is presented in Tab. 3.

Tab. 3. Comparison of the results

Ma	$C^{\delta}_{N\_F2}$	$C^{\bar{p}}_{l\_F2}$	
	PRODAS	formula (26)	PRODAS
0.4	0.6947	–0.34735	–0.34158
0.6	0.7826	–0.3913	–0.38483
0.7	0.8313	–0.4156	–0.40876
0.75	0.8557	–0.42785	–0.42073
0.8	0.88	–0.44	–0.4327

Results show that calculated by two ways values of the derivative $C^{\bar{p}}_{l\_F2}$ are close each other.

Presented above calculation of derivatives of moment coefficients are based on knowledge of the derivative $C_{N\_F2}^{\delta}$. This is the derivative of normal force generated by one pair of opposing fins F2. The results demonstrate the compatibility of other derivatives obtained in the manner described above and calculated by PRODAS. Thus, $C_{N\_F2}^{\delta}$ may also be used to calculate the additional normal and lateral forces generated by the deflection of the pair of fins F2:

$$F_{y\_control} = \frac{\rho V_{aer}^2}{2} S \cdot C_{N\_F2}^{\delta} \delta_N , \tag{31}$$

$$F_{z\_control} = -\frac{\rho V_{aer}^2}{2} S \cdot C_{N\_F2}^{\delta} \delta_M , \tag{32}$$

where angles δ_N and δ_M symbolize deflections of two pairs of F2 fins in lateral and longitudinal motions, respectively. δ_M is positive if the leading edges of fins are facing up, δ_N is positive if the leading edges of fins are facing right.
These forces produce pitching and yawing moments:

$$M_{control} = -l_{F2} \cdot F_{z\_control} , \tag{33}$$

$$N_{control} = l_{F2} \cdot F_{y\_control} . \tag{34}$$

4. Results of simulations

Using the described above mathematical model of the bomb spatial motion series of simulations were performed. The main goal was to determine an effectiveness of fins F2 both in longitudinal and lateral motions. To achieve these goal simulations were done for three deflections of the fins: –10°, 0°, +10°. The case of 0° was compared with simulations performed with PRODAS. This allows estimating an accuracy of the developed model of the bomb spatial motion. Results are presented in Fig. 8-14. The initial bombing altitude was 2000 m and the initial velocity was 80 m/s. The bomb was in a horizontal position.

Figure 8 shows the bomb velocity for the longitudinal control δ_M. We can see that there is a full agreement between PRODAS calculations and the case $\delta_M = 0°$. For $\delta_M = –10°$ the course of velocity is the same as for $\delta_M = 0°$ but for $\delta_M = +10°$ the velocity is lower. For the lateral control (Fig. 9 – $\delta_N = \pm 10°$) the bomb velocity is a little smaller than for $\delta_M = 0°$. In the case of longitudinal control, a strong reaction of the pitch angle Θ is observed (Fig. 10). Without this control, the final value of the pitch angle is equal to –70°. For $\delta_M = –10°$ we have Θ = –42° and for $\delta_M = –10°$ there is Θ = –98°. This means that the trajectory is more flat for δ_M=+10° and more steep for $\delta_M =$ = –10°. An influence of lateral control on pitch angle is weak (Fig. 11).

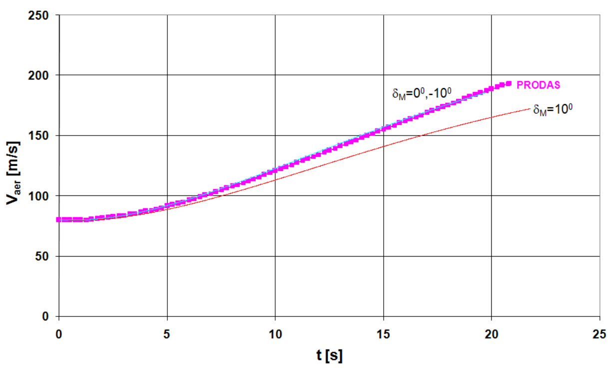

Fig. 8. Bomb velocity – longitudinal control

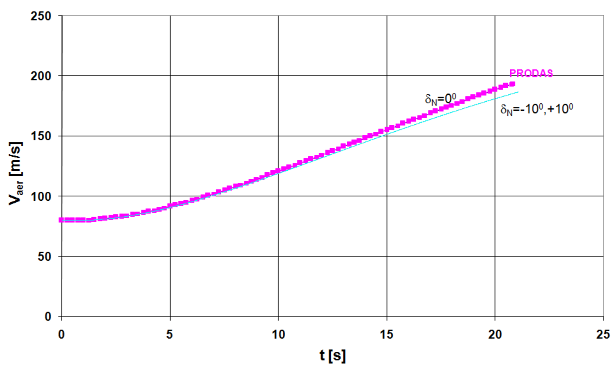

Fig. 9. Bomb velocity – lateral control

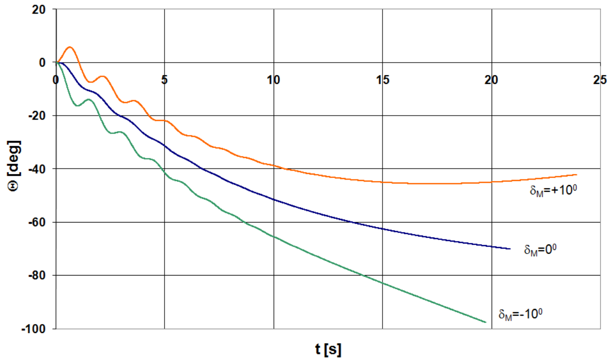

Fig. 10. Pitch angle – longitudinal control

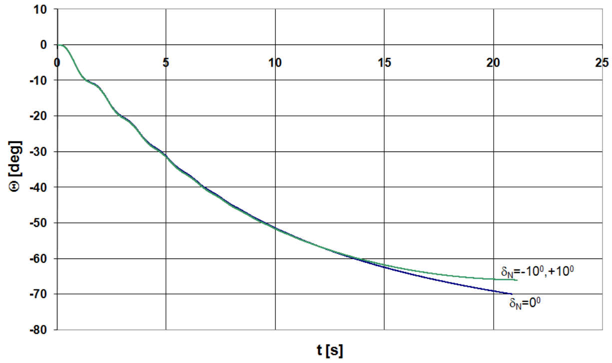

Fig. 11. Pitch angle – lateral control

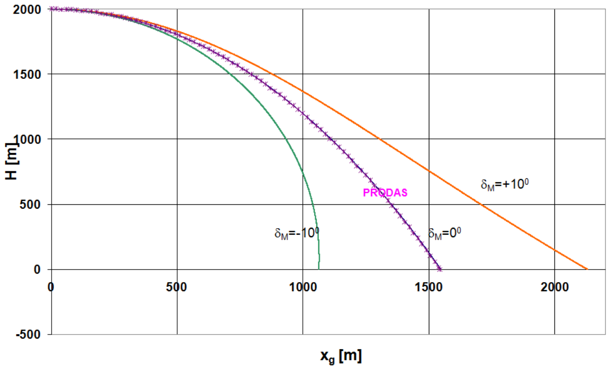

Fig. 12. Vertical trajectory of the bomb – longitudinal control

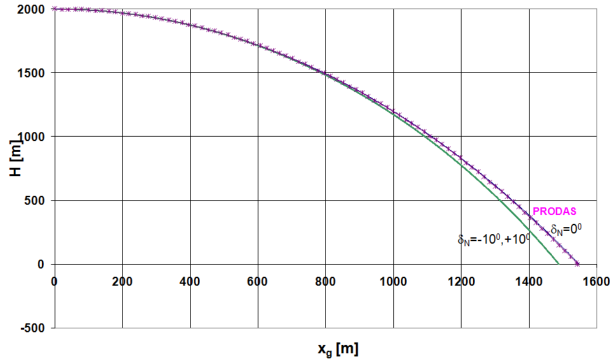

Fig. 13. Vertical trajectory of the bomb – lateral control

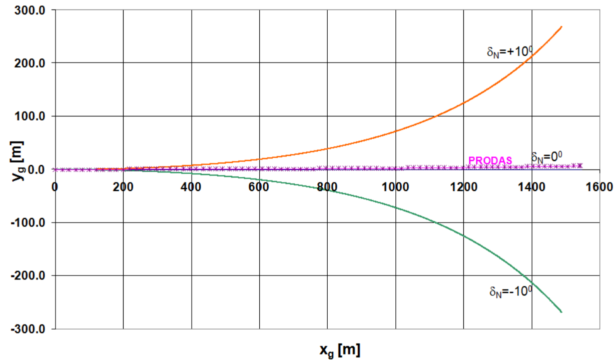

Fig. 14. Horizontal trajectory of the bomb – lateral control

Figure 12 confirms the earlier conclusions regarding the influence of longitudinal control δ_M on the bomb trajectory. The bombing range is from 1062 m to 2128 m. In the case of lateral control δ_N a slight decrease of bomb range is observed (Fig. 13). This control also causes lateral deviation in the range of ±269 m (Fig. 14).

5. Conclusions

The conducted analysis has proved that the additional fins are the effective method of bomb control both in longitudinal and lateral motions and they allow changing longitudinal and lateral ranges of the bomb. However, it must be emphasized that presented results are preliminary – only partial simulations were performed. Further theoretical studies should cover some variants of fins (a shape and an arrangement on the bomb) and some various initial conditions. Aerodynamic characteristics were calculated with PRODAS, which is not dedicated to symmetrical deflection of opposite fins. Therefore, it is very important to verify presented in this paper method of recalculations of derivatives. A separate issue is the development of an effective automatic control system. However, the most important task is to conduct research investigations of aerodynamic characteristics with a wind tunnel and, finally, a set of experiments in real bombing conditions.

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