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Guidance impulse algorithms for air bomb control

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Abstract. In this paper, some results of research concerning the development of guidance of bombs were presented. The paper presents conceptions of an impulse (gasodynamic) control system, the measurement unit based on IMU/GPS signals and control algorithms based on predicted trajectories. The presented results of simulation research are based on the numerical model of the bomb and real signals from measurement devices.

Key words: control, flying objects, control algorithms, air bombs, automatic flight control systems.

1. Introduction

The papers focuses on the problem of guiding small flight objects like bombs. The author described a new method of an impulse (gasodynamic) control of these objects. The contemporary development of air-launched weapons is mostly oriented on the design of precision guided munitions. The percentage of guided weapons in all instruments of war used from air is greater in each subsequent military conflict.

Over the last ten years the development of controlled bombs has been closely connected with Global Positioning System and Inertial Navigation System. Especially since GPS has reached full availability, many navigation systems of guided missiles and bombs base on INS/GPS. Joint Direct Attack Monition is a well-known example [1]. There are also other constructions like AASM carried out by SAGEM and SPICE carried out by RAFAEL. All these bombs are aerodynamically controlled [2].

The advantage of applying this type of weapon is that it allows precise bombing of enemy positions, even in the vicinity of their own position and the lack of visibility. Precision bombing using guided bombs can also share a much more effective bombing. We can reduce the number of required flights, and make precision bombing from high altitudes. With the possibility of attack from a greater distance we can drop a bomb successfully outside from the scope of direct air defence. In addition, one round allows us to attack several objectives simultaneously (Fig. 1). These advantages can reduce our own losses. During Operation Desert Storm about 18% of dropped bombs were controlled bombs. In Operation Iraq Freedom, 66% of dropped bombs were controlled bombs.

One of the possibilities of development of guided bombs is taking advantage of new concepts for control of the object. In the presented control systems, the bomb which rotates around the main symmetry axis and is controlled with the use of small single – use rocket engines with a thrust directed normally to the main axis of symmetry of the object. The gasodynamic steering kit is proposed instead of the aerodynamic one. The system based on a set of one time used impulse engines and INS/GPS navigation. It can correct the flight trajectory only about 700m from the uncontrolled one. But the control system's hardware is simpler than in the aerodynamic one. There are immovable devices on the bomb's board. It gives them the potential to be cheaper and more reliable than systems with aerodynamic control. The similar gasodynamic control system is successfully used in a guided mortar missile STRIX. The bomb which uses the presented control system, can be dropped from an altitude of about four to ten thousand meters. The whole fall takes about twenty to fifty seconds. In this concept, guided bombs will not have the range as long as JDAM has, but will be potentially cheaper and have less complicated hardware. They can be used for precision bombing at the battlefield.

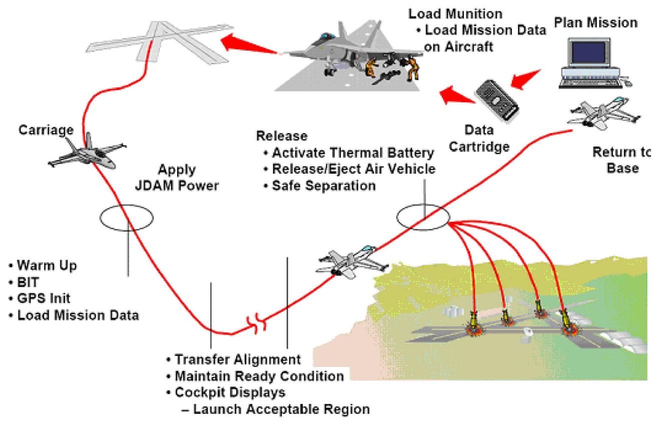

Fig. 1. Joint Direct Attack Monition concept of operations [Boeing materials]

2. Gasodynamic control system

The task of the control engines set is to correct the course of the bomb in the second phase of the flight, when the pitch angle is smaller than $-45°$. The homing control system is to direct it to the target, to achieve a direct hit. Correcting rocket engines are located in a cylindrical unit, arranged radi-

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ally around the periphery. Each correction rocket engine can be fired individually only once in a selected radial direction (Fig. 2).

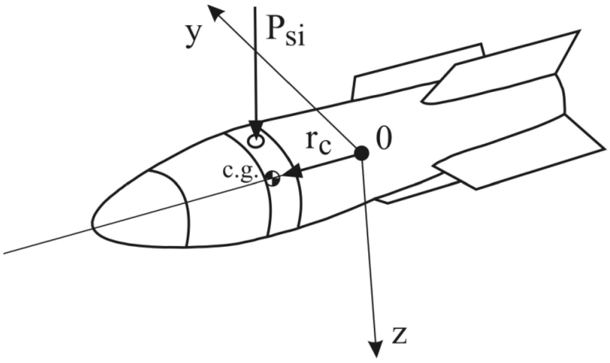

Fig. 2. Set of impulse engines

The correction engine set is placed close to the gravity centre of the bomb. When the rocket engine is fired, the course of the controlled object is changed instantaneously. By successive firing of several rocket engines, the object is steered with high precision onto the target. The chosen steering system gives a very fast response to the guidance signals.

The time of the correction engine work should be as short as possible. Tests have shown that this time should not be longer than 25% of the time of a bomb's single full rotation. During this time, the impulse of the correction engine changes the bomb's course, which leads the bomb main symmetry axis.

A single channel direct discontinuous impulse control method imposes requirements on a control quality for optimal correcting engines firing algorithm and good dynamic stability of the missile. This control method, in contrast to an aerodynamic control method, does not require any compromise between stability and controllability, because the stability value of the bomb is not limited. However, this method makes the algorithms of the correcting engines firing more complicated. The sequence of the correcting engines firing should allow for the minimal unbalance of the bomb. This algorithm should give the value of the mean effect of control proportional to the control signal value. More details concerning the presented kind of control are given in [3] and [4].

Nonlinear simulation model of air bomb

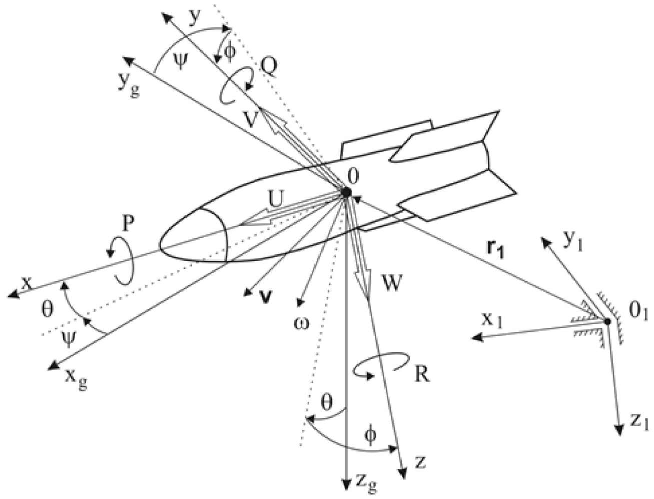

Fig. 3. Co-ordinate systems

The bomb equations of motion are derived in the coordinate system 0xyz (Fig. 3) [3, 5] fixed to the bomb's body. The center 0 of the system is placed at the arbitrary point in the bomb axis of symmetry. The 0x axis lays in the axis of bomb symmetry and is directed forward. The Oy axis is perpendicular to the axis of bomb symmetry and points "right", the Oz axis points "down".

The bomb translations and attitude angles are calculated in the inertial co-ordinate system $0_1x_1y_1z_1$; the center of this system 0_1 is placed at an arbitrary point on the earth surface. The 0_1z_1 axis is placed along the vector of gravity acceleration and it points down. The $0_1x_1z_1$ plane is horizontal, tangent to earth surface, the 0_1x_1 axis points to the North and 0_1y_1 axis to the East [6].

The relationship between bomb state vector $\mathbf{x} = [U\ V\ W\ P\ Q\ R]^T$ and vector describing position and attitude $\mathbf{y} = [x_1\ y_1\ z_i\ \varphi\ \theta\ \psi]^T$ is given by:

$$\dot{\mathbf{y}} = \mathbf{T}\mathbf{x}. \tag{1}$$

The matrix $\mathbf{T}$ has the following structure:

$$\mathbf{T} = \begin{bmatrix} \mathbf{T_v} & \mathbf{0} \\ \mathbf{0} & \mathbf{T_\Omega} \end{bmatrix}, \tag{2}$$

where the velocity transformation matrix $\mathbf{T}_V$ has the form

$$\mathbf{T_V} = \begin{bmatrix} \cos\theta\cdot\cos\psi & \sin\theta\cdot\sin\varphi\cdot\cos\psi - \cos\varphi\cdot\sin\psi & \cos\varphi\cdot\sin\theta\cdot\cos\psi + \sin\varphi\cdot\sin\psi \\ \cos\theta\cdot\cos\psi & \sin\theta\cdot\sin\varphi\cdot\cos\psi + \cos\varphi\cdot\sin\psi & \cos\varphi\cdot\sin\theta\cdot\cos\psi - \sin\varphi\cdot\sin\psi \\ -\sin\theta & \sin\varphi\cdot\cos\theta & \cos\varphi\cdot\cos\theta \end{bmatrix} \tag{3}$$

and the transformation matrix for angles $\mathbf{T_\Omega}$ is

$$\mathbf{T_\Omega} = \begin{bmatrix} 1 & \sin\varphi\cdot tg\theta & \cos\varphi\cdot tg\theta \\ 0 & \cos\varphi & -\sin\varphi \\ 0 & \sin\varphi\cdot\sec\theta & \cos\varphi\cdot\sec\theta \end{bmatrix} \tag{4}$$

The roll angle ϕ, the pitch angle θ and the azimuth angle ψ describe the attitude of the bomb (Fig. 4) and the vector $\mathbf{r}_1 = [x_1, y_1, z_1]$ describes the bomb position in the $0x_1y_1z_1$ system of co-ordinates.

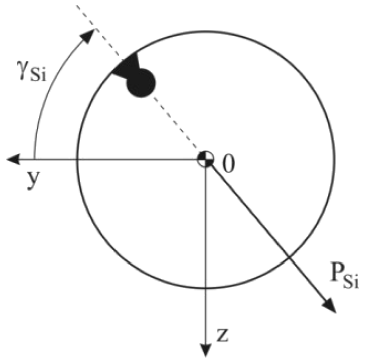

Fig. 4. Position of the impulse engine

The bomb equations are obtained by summing up inertia (left hand side of the equation), gravity $\mathbf{f_G}$, aerodynamic $\mathbf{f_A}$ and control $\mathbf{f_S}$ loads (forces and moments) acting on object:

$$\mathbf{A\dot{x}} + \mathbf{B(x)x} = \mathbf{f_A}(\mathbf{x}, \mathbf{y}) + \mathbf{f_G}(\mathbf{y}) + \mathbf{f_S}(\mathbf{y}.k_s, n_s), \tag{5}$$

where k_S is the control signal which activates the impulse engine and n_S is the number of the active engine.

The left hand side of Eq. (5) describes the inertia loads in bomb frame of reference. The inertia matrix $\mathbf{A}$ has the following form:

$$\mathbf{A} = \begin{bmatrix} m & 0 & 0 & 0 & 0 & 0 \\ 0 & m & 0 & 0 & 0 & S_x \\ 0 & 0 & m & 0 & -S_x & 0 \\ 0 & 0 & 0 & I_x & 0 & 0 \\ 0 & 0 & -S_x & 0 & I_y & 0 \\ 0 & S_x & 0 & 0 & 0 & I_x \end{bmatrix} \tag{6}$$

where m is the aircraft mass, S_x is the object static mass moment and I_x, I_y, I_z are the bomb moments of inertia.

The gyroscopic matrix $\mathbf{B(x)}$ is calculated as follows:

$$\mathbf{B(x)} = \mathbf{\Omega(x)A}, \tag{7}$$

where matrix of velocities and rates $\mathbf{\Omega(x)}$ has the following form:

$$\mathbf{\Omega(x)} = \begin{bmatrix} 0 & -R & Q & 0 & 0 & 0 \\ R & 0 & -P & 0 & 0 & 0 \\ -Q & P & 0 & 0 & 0 & 0 \\ 0 & -W & V & 0 & -R & Q \\ W & 0 & -U & R & 0 & -P \\ -V & U & 0 & -Q & P & 0 \end{bmatrix}. \tag{8}$$

The vector of gravity force acting on the body is calculated as:

$$\mathbf{f_g(y)} = mg \cdot \begin{bmatrix} -\sin\theta \\ \cdot\theta \cdot \sin\varphi \\ \cos\theta \cdot \cos\varphi \end{bmatrix} \tag{9}$$

where g is gravity acceleration.

Point 0 is placed at the bomb's center of gravity, the vector of moment from gravity forces is equal:

$$\mathbf{m_g(y)} = \mathbf{r_C} \times \mathbf{f_g(y)}, \tag{10}$$

where $\mathbf{r_C} = [x_C \ 0 \ 0]^T$ is the vector of the center of gravity position in the bomb system of coordinates (Fig. 2).

Combining (9) and (10), the vector of gravity loads acting on the bomb is calculated as follows:

$$\mathbf{f_G(y)} = [\mathbf{f_G} \ \ \mathbf{m_g(y)}]^T. \tag{11}$$

The bomb has a set of impulse engines placed at the bomb body around the center of gravity (Fig. 2). The vector of i-th impulse engine force has the following form:

$$\mathbf{f_{Si}}(\mathbf{y}, k_S, n_S) = P_{Si} \cdot k_S \begin{bmatrix} 0 \\ -\cos\gamma_{Si} \\ \sin\gamma_{Si} \end{bmatrix}, \tag{12}$$

where P_{Si} is the value of engine thrust, γ_{Si} is the angle of engine position (Fig. 4).

The number of engine n_S gives information about thrust and an angle position of a specific engine. The control signal k_S is used to activate the engine and is calculated using control error and actual bomb attitude. It can have the value of 0 or 1.

The vectors of moment from impulse engine forces of each engine are equal:

$$\mathbf{m}_{Si}(\mathbf{y}) = \mathbf{r_C} \times \mathbf{f}_{Si}(textbfy, k_S, n_S). \tag{13}$$

The vector of impulse engines loads acting on the bomb is calculated from (12) and (13) as follows:

$$\mathbf{f_S}(\mathbf{y}, k_S, n_S) = [\mathbf{f}_{Si}(\mathbf{y}, k_S, n_S) \ \ \mathbf{m}_{Si}(\mathbf{y})]^T. \tag{14}$$

The bomb aerodynamics loads are calculated using coefficients describing loads acting on the whole object. The force and moment vectors are calculated as follows:

$$\begin{aligned} \mathbf{f_a}(\mathbf{x,y}) &= \frac{1}{2}\rho(z_1) \cdot |\mathbf{v}|^2 \cdot S \cdot \begin{bmatrix} C_X(\mathbf{X}) \\ C_Y(\mathbf{X}) \\ C_Z(\mathbf{X}) \end{bmatrix}, \\ \mathbf{m_a}(\mathbf{x,y}) &= \frac{1}{2}\rho(z_1) \cdot |\mathbf{v}|^2 \cdot S \cdot l \cdot \begin{bmatrix} C_R(\mathbf{X}) \\ C_M(\mathbf{X}) \\ C_N(\mathbf{X}) \end{bmatrix}, \end{aligned} \tag{15}$$

where S is the maximum area of the bomb body cross-section in $0yz$ plane (Fig. 5), l – the bomb length, $\rho(z_1)$ – air density, $\mathbf{v}$ – vector of linear velocity.

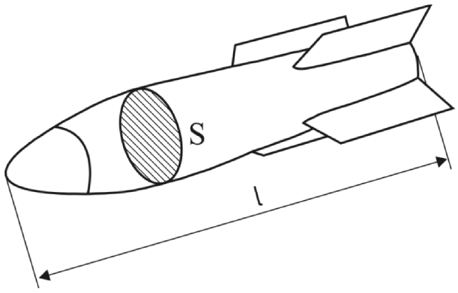

Fig. 5. Bomb aerodynamic parameters

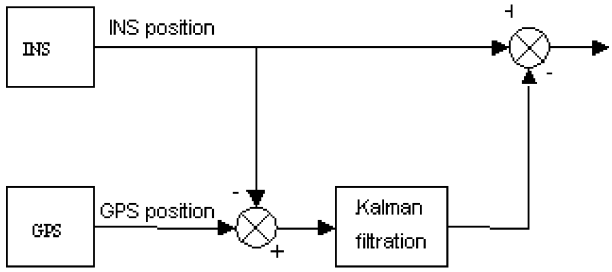

Fig. 6. INS and GPS systems coupled by Kalman filtration

The aerodynamic force C_X, C_Y, C_Z and moments C_R, C_M, C_N coefficients obtained from CFD (Computational Fluid Dynamics) calculations. They depend on bomb airspeed, angle of attack and slip.

The aerodynamic loads in the equations of motion are calculated as:

$$\mathbf{f_A}(\mathbf{x,y}) = [\mathbf{f_a}(\mathbf{x,y}) \ \ \mathbf{m_a}(\mathbf{x,y})]^T. \tag{16}$$

The bomb stabilizers generate the aerodynamic moment in x axis. The moment value depends on the angle of incidence, area, shape and position of stabilizers, bomb air speed, angle of attack and the angle of sideslip.

The equations of bomb motion are combined with model of the control system. The control system calculates the control signal and selects the proper impulse engine.

3. Control system overall description

3.1. Navigation method. Usually, inertial navigation systems can only provide an accurate solution for a short period of time [7]. The INS accelerometers produces an unknown bias signal that appears as a genuine specific force. This is integrated to produce an error in position. In addition, the INS software must use an estimate of the angular position of the accelerometers when conducting this integration. Typically, the angular position is tracked through an integration of the angular rate from the gyro sensors [8]. These also produce unknown biases that affect the integration to get the position of the unit. The GPS gives an absolute drift-free position value that can be used to reset the INS solution or may be blended with it by using a mathematical algorithm such as a Kalman filter [1, 9]. The angular orientation of the unit may be inferred from the series of position updates from the GPS [10, 11]. The change in the error in position relative to the GPS may be used to estimate the unknown angle error. In the presented concept of the bomb's impulse control system, the whole flight takes about 20–50 seconds. It is too much to use INS only. In the presented control system, INS/GPS coupled by Kalman filtration is used (Fig. 6).

For simulations, signals from stationary measurement were registered. These stationary signals were treated as disturbances and errors from GPS and IMU. Signals were registered by the IMU Microstrain 3DM-GX2 and the GPS Novatel FlexPak G2L. Registered disturbances were added to information from bomb model in blocks GPS and IMU (Fig. 7a-b).

a)

b)

Fig. 7. a) GPS – Novatel FlexPak G2L, b) IMU – Microstrain 3DM-GX2

3.2. Control low and algorithms. Figure 8 shows the block scheme of the control system. Control is realized by the set of impulse correction rocket engines. It is a single channel control. Measurement and control signal processing is realized in two channels (azimuth and elevation). PD controllers are used in both channels. Based on these two control signals, control unit prepares the value C_{val} and decides whether the next rocket control engine has to be activated or not. If the decision is positive, the control system must also count angle C_{ang} (bomb has a rotation around the main symmetry axis x) and time to start up the next engine.

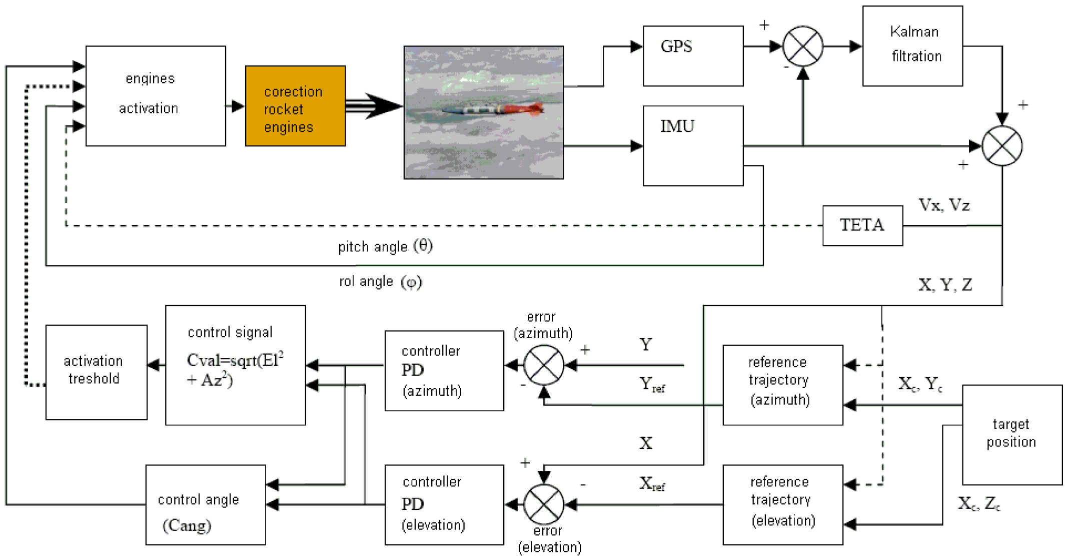

Fig. 8. Block scheme of bomb's guidance system

The goal of the bomb's guidance system is to give the bomb a trajectory which will finally lead them closely to the target. A control system is designed to change the movement of the bomb in such a way that its flight path will be as close as possible to the reference guidance trajectory [11, 12]. Our control system has a discontinuous impulse character. The system uses one-propellant rocket engines with shorten operating time (0.05 s). The number of rocket engines' impulses, during the entire flight of the control bomb, is limited. this reason, it is important for their effective use. The control system uses a three- point guidance method. To prepare a reference flight trajectory, coordinates of the target (Rc) and the point of a control system work beginning (R1) in the system (X_g, Y_g, Z_g) are used (Fig. 6). The point at which the flight control system starts work was chosen after a preliminary analysis of simulations. Bombs' dynamics analysis showed that the largest impact on the distance of the point of bomb's fall, in relation to the without control flight trajectory, was in the last phase of the flight. In the initial phase of flight, when the pitch angle is small, control impulse energy is used mainly to the height control and it has a small impact on the accuracy. By this reason, the use of the control system engines in the initial phase of flight is not very effective. The biggest part of the energy is wasted for the height control. It is reasonable to resign from the control in the initial phase of the flight, because the amount of correction engines is limited. Test simulations have shown that the presented method is effective when the control starts at the moment when the bomb reaches the pitch angle equal to approximately $-45°$. The described above point R1 represents the position at which the pitch angle is equal to $-45°$.

The position error value, which is the input value for regulators, is linear and is determined in two separate channels:

Azimuth (plane parallel to the Xg, Yg)

Elevation (plane parallel to the Xg, Zg)

In two channels (azimuth and elevation) errors are calculated in two separate flat trajectory models. The current position of the bomb is projected on planes (S_0, Xg, Yg) and (S_0, Xg, Zg). The error is defined as the difference of the bomb's coordinate location to the corresponding reference trajectory coordinate (x_{ref}, y_{ref}). The current bomb position and the position where the bomb should be placed at the moment is measured. Figure 9 illustrates the geometry of error measurement.

The azimuth channel reference trajectory is defined as a function of $y = y_{refAz}$ (x).

The elevation channel reference trajectory is defined as a function of $x = x_{refEl}$ (z).

Control is divided into two perpendicular channels in the field of the measurement. The control executive system is a single channel one (rotating bomb and correction engines set). Two channels in the process of measurement have been applied because of the different dynamics nature of the control of bomb's course and range. The use of curves as a flat trajectory model simplifies calculations. The ideal solution would be to determine the control error as the distance between the point of the current location of the bomb and the curve of reference trajectory. Due to the complicated procedure for calculating the distance from the point of the curve and the required high frequency of operation of the guidance, the simplified method has been used. In the azimuth channel the error is calculated as the difference between the current coordinate y and the coordinate y_{refAz} and is calculated for the current value of x:

$$Er_{Az} = y - y_{refAz}(x). \tag{17}$$

By the reason that the angle between the horizontal component of the flight speed and direction Xg is small (in terms of a few degrees), the error made by the use of the rectangular component of the distance has negligible value. The elevation error of the channel is calculated as the difference between the current coordinate x and the coordinate x_{refEl} and is calculated for the current value of z:

$$Er_{El} = x - x_{refEl}(z). \tag{18}$$

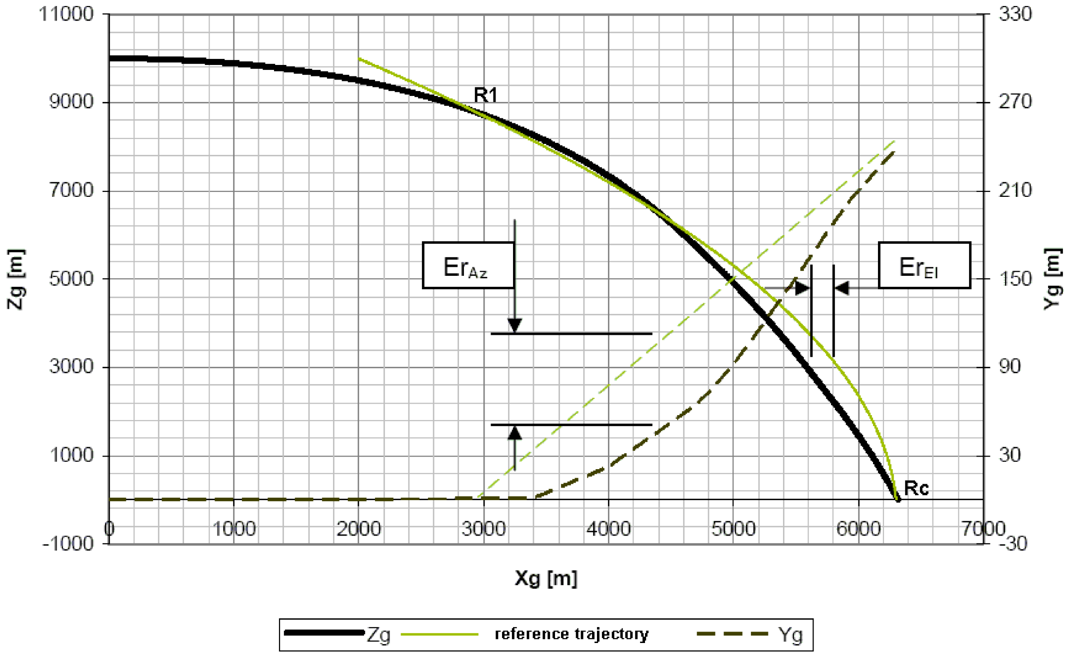

Fig. 9. Scheme of azimuth and elevation errors measurement

In the case of the elevation channel, the situation is not as convenient as in the case of the azimuth channel. Nevertheless,, control start since the bombs' pitch angle $= -45°$ and, at the same time, the pitch angle at the time of the bombs' fall is about $-80°$, the error made by the simplification of the value measurement is reduced during the flight.

3.3. Reference trajectory. A straight line is the easiest form to designate the reference trajectory. To create the reference trajectory as a straight line we need only coordinates of the guidance beginning and coordinates of the target position. The algorithm has a closed form of the calculation of coefficients of a straight line equation, that is,

$$y = ax + b, \tag{19}$$

For the bombs' azimuth control, straight lines, used as reference trajectories, give satisfactory results. But for the control in the elevation channel, the method is not satisfactory. The projection of the flight path on the vertical plane is strongly curved, so the straight line approximation is a far-reaching simplification. For the effective control more advanced method is needed. The parabola is a theoretical form of a ballistic trajectory of the object in a vacuum, it appears natural to use it as a simple approximation of the trajectory of the flying object. The method of describing a parabola as a function of z(x) did not give good results. Better results were achieved when the parabola was determined as the function of x(z). Simulations showed that the reference trajectory determined in this way is closer to the actual trajectory of the bomb. In addition to the force of gravity, it is also under influence of aerodynamic forces and moments.

An appointment of the parabola equation coefficient requires three equations. Assuming that the bomb hits the target vertically, the equation reduces to the form:

$$x = az^2 + c, \tag{20}$$

and the system of equations to 2×2:

$$x_c = a{z_c}^2 + c, \qquad x_1 = a{z_1}^2 + c, \tag{21}$$

where the unknowns are a and c.

Given different pitch angles, we have the parabola equation $x = az2 + bz + c$. In this case, only coordinates of the goal and the point of control beginning are available. By this reason, the third equation uses the value of pitch angle at the time of target hit:

$$dx/dz = \tan(\pi/2 - \theta) \tag{22}$$

and derivative parabola equation:

$$dx/dz = 2az + b. \tag{23}$$

We get the 3×3 system of linear equations with unknowns a, b, c:

$$\begin{gathered} x_c = a{z_c}^2 + bz_c + c, \quad x_1 = a{z_1}^2 + bz_1 + c \\ \tan(\pi/2 - \theta)|_c) = 2az_c + b. \end{gathered} \tag{24}$$

In the above solution, we obtain the coefficients of the parabola equation.

The value of the pitch angle, at the time of the target hit, must be estimated on the base of numerical simulations and tests. This value will be variable depending on the drop's height and the initial speed. For our simulations, values of the pitch angle form range $-90°$ and $-88°$ were tested.

The bomb flight path obtained as a result of the simulation is different from the parabola. This is due to the reduction of the speed of the object in the initial phase of the flight. To obtain a better approximation of the optimal flight trajectory it is possible to apply a higher degree of curve. The use of this solution requires addressing two important issues: a larger number of coefficients to a higher degree of curve. It would be necessary to estimate the coordinates of several points on the intermediate bomb's flight trajectory, a larger dimension of the system of equations lead to need bigger processors capacities. In the presented work, the following reference trajectories were used: the parabolic one for the elevation control and the straight line for the azimuth.

4. Results

Simulation tests showed interesting results and possibilities of the described control method and algorithms. The paper shows only two cases (Figs. 10–13) but to count CEP (Circular Error Probable) value, we made ten simulations for each case with targets in ten different positions. Targets were selected randomly in the range of 400 m from the uncontrolled bomb drop point.

In the presented cases, CEP counted for bombs with ideal navigation was about 21 meters. CEP counted for bombs guided with errors from INS/GPS system was about 25 meters. It shows that, at this level of accuracy, the system is quite robust to navigation errors during the flight. We the observe that final results of control processes for the ideal and real navigation are similar but the control system needs to use more correction engines impulses for guidance process. The average is 11 correction impulses for system with the ideal navigation and 14 impulses for system with navigation with errors from INS/GPS.

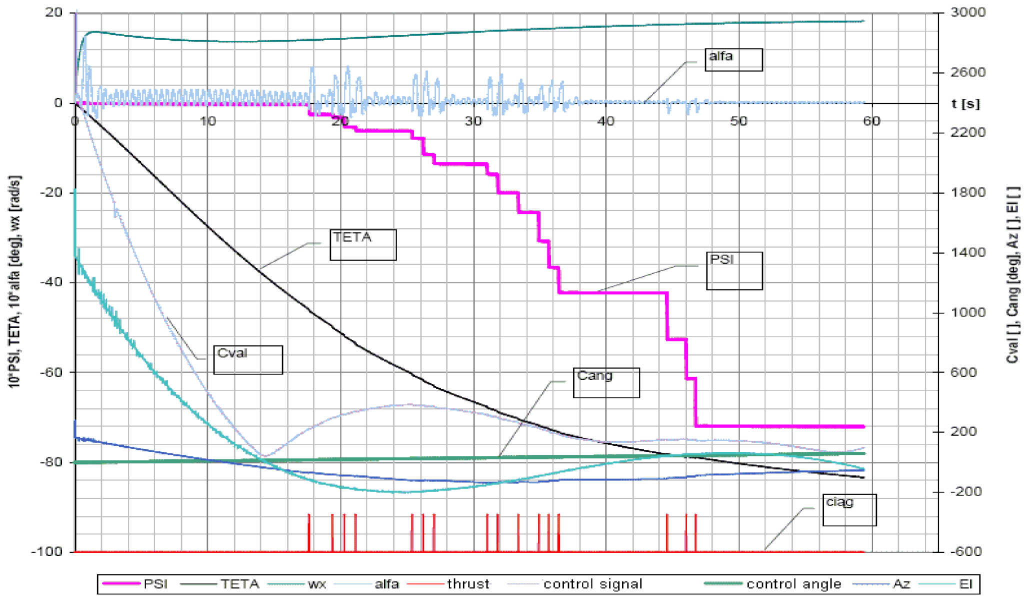

Fig. 10. Flight with parameters: single engine thrust 2000 N, bomb's drop altitude 10000m, initial speed 800 km/h, reference trajectories azimuth – straight line, elevations- parabolic curve, ideal navigation. Flight and control parameters

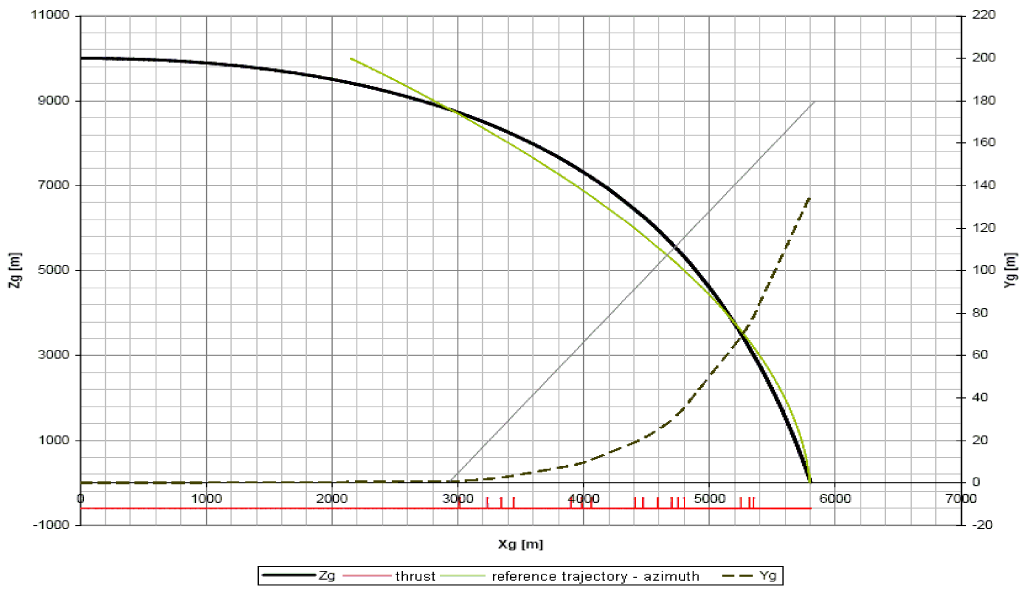

Fig. 11. Flight with parameters: single engine thrust 2000 N, bomb's drop altitude 10000 m, initial speed 800 km/h, reference trajectories azimuth – straight line, elevations- parabolic curve, ideal navigation. Trajectories (azimuth and elevation projections) and reference trajectories (azimuth and elevation)

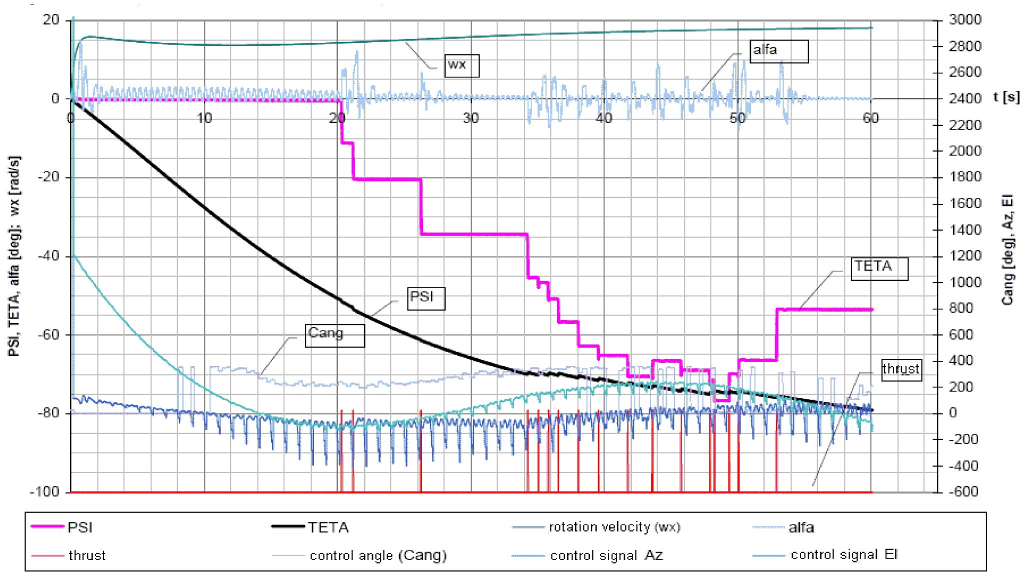

Fig. 12. Flight with parameters: single engine thrust 5000 N, bomb's drop altitude 10000 m, initial speed 800 km/h, reference trajectories (azimuth – straight line, elevations- parabolic curve), INS/GPS navigation. Flight and control parameters

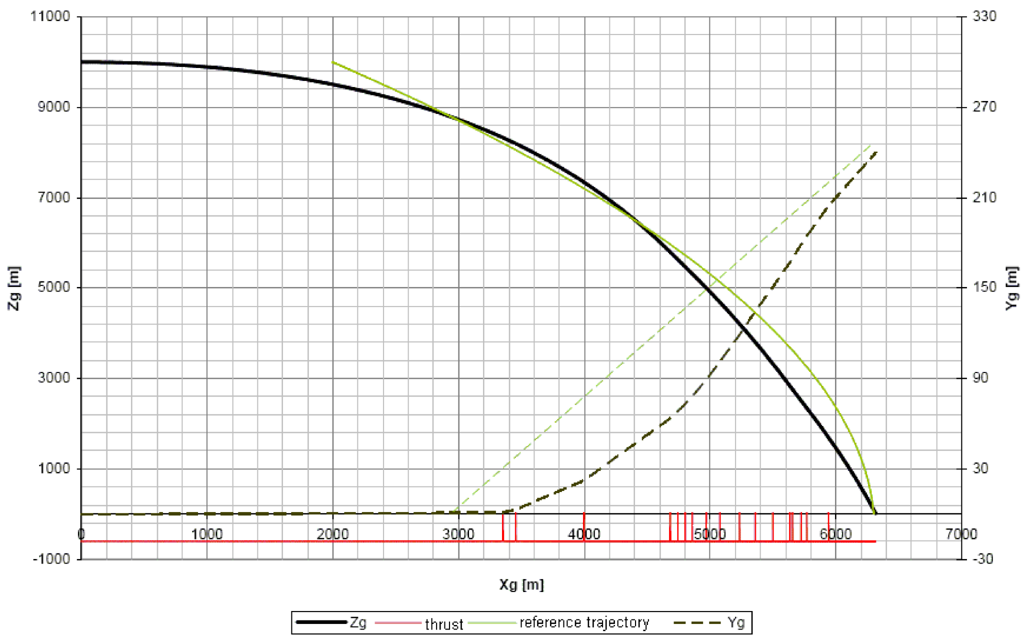

Fig. 13. Flight with parameters: single engine thrust 5000 N, bomb's drop altitude 10000 m, initial speed 800 km/h, reference trajectories (azimuth – straight line, elevations- parabolic curve), INS/GPS navigation. Lower figure flight trajectories (azimuth and elevation projections) and reference trajectories (azimuth and elevation)

Figures 10 and 11 present the results of simulation flight having the following parameters: single engine trust 2000 N (engine's work time $t_k = 0.05$ s, spin velocity w_x is about 30 rad/s), bomb's drop altitude 10000 m, initial speed 800 km/h. The flight was realised with ideal navigation. Figure 11 shows trajectories (azimuth and elevation projections) and reference trajectories (azimuth and elevation) and moments of engines set activities. We can observe how the bomb realised reference trajectories in the azimuth and elevation plane. In this case single engine thrust 2000 N is a little too small for the effective control. Figure 10 presents some flight parameters: alfa – angle of attack, TETA – pitch angle, PSI – yaw angle, thrust of engine set, w_x – bomb's angular velocity, Cval – control signal, Cang – engine thrust optimal direction, Az – control signal from azimuth channel regulator, El – control signal from elevation channel regulator. As has been shown, the flight control process is stabile and performed well.

Figures 12 and 13 present the results of simulation flight with similar parameters to those in Figs. 10 and 11 but we used more effective correction engines with thrusts 5000 N each. Another difference is that we used "real navigation" – errors registered from stationary real measurement devices of GPS and Inertial Measurement Unit.

As has been demonstrated,5kN engines realised the flight trajectory better in both control channels (azimuth and elevations). We do not observe any control system negative reactions for errors from GPS and IMU.

5. Summary

Series of simulations done to assess the performance of the designed system showed that it is possible to apply the investigated control system for the bomb. With the launch condition chosen: altitude 10 000 m speed 800 km/h, the achieved accuracy (CEP) was about 25 m. Numerical experiments have shown large possibilities of the objects' control by the influence on the motion of their gravity centre. It is possible to use the set of impulse correction rockets to control falling objects such as bombs. The amount of 20 correction engines is enough to control the bomb. To control a 100 kg bomb, 5kN thrust of correction engines is needed.

There is a problem with a guidance algorithm for an impulse control. Traditional methods are insufficient. The limited amount of the control impulse and better effectiveness with attack from steep trajectory make the guidance with straight line trajectory useless. This problem is particularly apparent in the longitudinal control channel of an air bomb. The numerical experiments and simulations showed that the possibility of using a parabola trajectory is good enough for the guidance process. There are positive results of using these methods. A parabola is mathematically a non-complicated curve; therefore, it is easy to calculate on board during the guidance process of an air bomb.

To make simulation more realistic there were added error values from the real measurement elements. Experiments showed that during the work with real signals the method still works correctly.

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