THE DYNAMIC OF IMPULSE CONTROLLED SMALL FLYING OBJECTS

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Abstract. In the paper author analyzed the problem of gasodynamic impulse control systems designed for small flying objects. Author focused on two cases of these objects: an air bomb and a mortar missile. In the paper was described the problem of impulse control small objects dynamic and solutions of control systems for both cases. The presented control system is based on a set of one time used impulse engines. The engines are mounted around the flying object. There are not movable devices on the object board. The correcting impulses from the rocket engines are perpendicular to main symmetry axis of an object and influence directly the centre of gravity of the guided munitions. Author compare results of simulation and field tests for air bombs and mortar projectiles.

Keywords. automatic control, air bombs,

1 Problem description

In this paper a new concept of a control system for small flying objects was described. The gasodynamic steering kit is proposed instead of aerodynamic one. The system based on a set of one time used impulse engines. It can correct the flight trajectory only about 700m from the uncontrolled one. But the control system's hardware is very simple. There are not movable devices on the object's board. It makes them the potential to be cheaper and more reliable than systems with aerodynamic control. Similar gasodynamic control system is successful used in guided mortar missiles like STRIX carried out by SAAB and BOFORS. Also I Poland were developed program RAD for mortar98mm. Author described the simulation tests for mortar missile and air bomb. Model for mortar missile was verified during the field tests. For the air bomb aerodynamical coefficients were calculated during wind tunnel tests. Guidance and navigation systems used during simulations were described in another papers. Impulse gasodynamic systems can be use for precision attack at the battlefield.

The object is controlled by a set of impulse correction engines. Engines are mounted around the object. The correcting impulses from rocket engines are perpendicular to main symmetry axis of the flying object and influence directly the center of gravity of the guided munitions. Impulse rocket engines, used only one time each, correct the flying trajectory. The presented solution of the control system with impulse correction engines needs slow spin of the object. The aft section is fitted with fins to give the missile aerodynamic stability and the angular velocity. The fins are immediately unfolded after the drop or barrel lived and their fixed cant angle gives the object a slow spin (about 20rad/s for air bomb and 60rad/s for mortar missile). The rotation velocity of both objects depend on the velocity of flight. The much less range than in case of aerodynamic control objects require that bombs or missiles have to be accurately launched over the targets' operating area. The control system is active only in the last steep phase of flight. At the next phase of flight object is automatically guided to the target. As was said earlier the first and necessary condition of target interception and successful attack is to launch the bombs into such an area.

2.Dynamics of flying objects' impulse control.

Classic methods of control of a flying object make assumptions that:

- steering forces initially change the moment acting on an object, than this moment rotates the object around its gravity center;
- supporting surfaces get necessary angles of attack and produce steering forces.

This way, the object is turned at first around the mass center, than this movement effects on the mass center velocity vector. This solution is characterized by inertia and a "long" time gap between control system's decisions and its commands execution. This effect delays the control. This is an important fault in a situation when the precision guidance of the object to the target is needed in a short time, or when control process needs a very quick reaction to the information coming to the object. The whole guided phase lasts for about 15 to 20 seconds. This fault can be limited by the direct action on the motion of the gravity center. In the presented method, the control of the missile is performed by the set of the correction rocket engines. These engines are acted on the gravity center of the object (figure 1).

In this method of a flying object control we make assumptions that:

- steering forces first exert an influence on the object gravity center;
- the rotation around the gravity center is an effect of a gravity center translation and an aerodynamic interaction.

Solution of this kind gives more effective influence on the speed vector. The block scheme of an object dynamic is shown in figure 1.

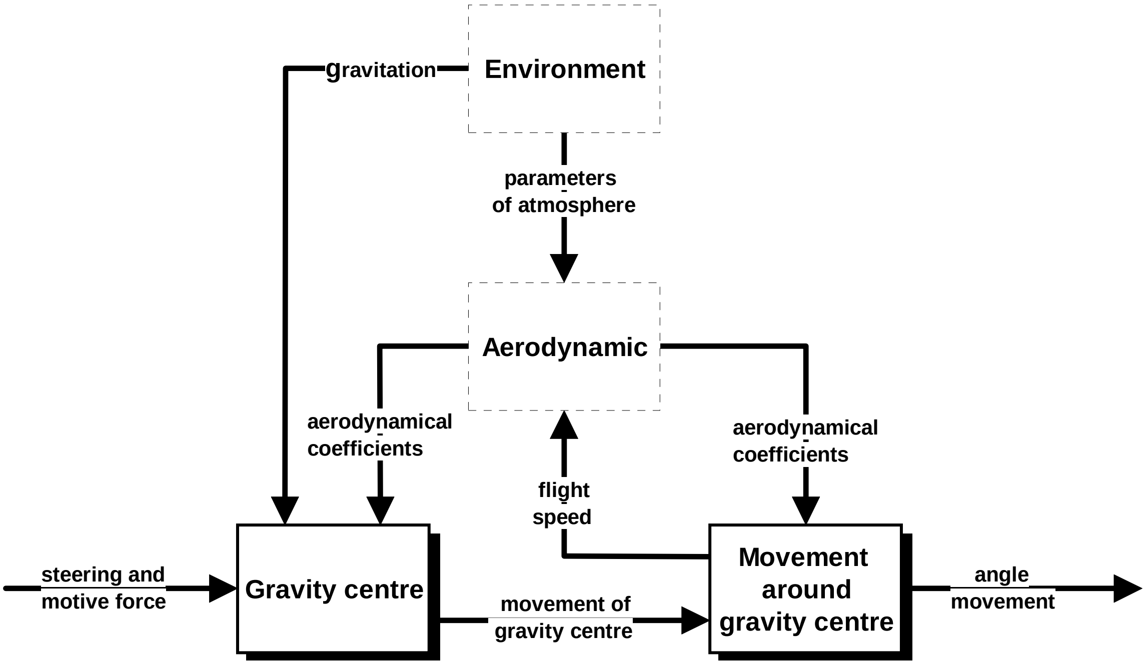

Figure 1. Block scheme of the object dynamic.

At the rotating object, one channel is used to control the object in both horizontal and vertical planes. It can be realized by a gasodynamic impulse acting on to the object gravity center. Method was described in more details in papers [2] and [5]. This solution can give us a precision object guiding to the attacked target. It also makes the operation of servo control system easier. A complicated mechanics of the aerodynamic servo is not needed, either. Also on board power demand for gasodynamic system is much less than in aerodynamic one. Electric energy supplies only electronic devices, not control surfaces. It makes equipment on the missile board smaller and easier to made, but it complicates the guidance logic and dynamics of the object controlled flight.

3. Control devices and realization method

As it was mentioned before the bomb is controlled by a set of impulse correction engines. Engines are mounted around the bomb. The correcting impulses from rocket engines are perpendicular to main symmetry axis of the flying object and influence directly to the center of gravity of the guided munitions (figure 2.). Impulse rocket engines, used only one time each, correct the flying trajectory. In our simulations we tested different number of correction engines from 12 to 20. The tracking technique also makes it possible to introduce several course corrections in a rapid succession. If it is necessary, all rocket correction engines can be used for the control process in the last few seconds of the flight.

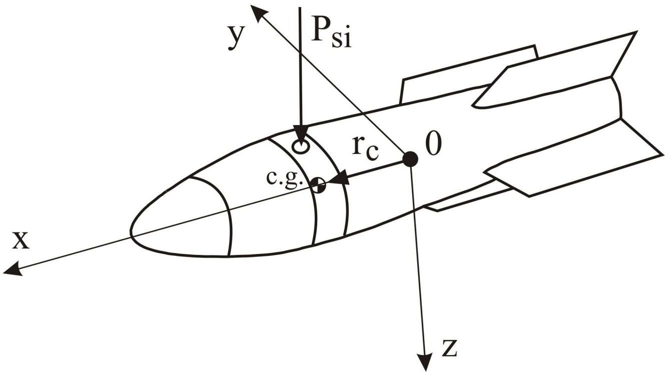

Figure 2. The impulse engine force.

The task of the rocket engines set is correction of the course of the object in the second steep phase of the flight, when the pitch angle is below -45^o. Earlier control system is ineffective. In the case of mortar missile control process starts when the controlled object is at the altitude 1000 over ground and is limited by seeker range. Control system is homing it to the target, to achieve a direct hit. Correcting rocket engines are located in a cylindrical unit, arranged radial around the periphery. Each one can be fired individually only once, in a selected radial direction.

The correction engine set is placed close to the center of gravity of the projectile. When the single rocket engine is fired, the course of the bomb is changed instantaneously. By successive firing of several rocket engines, the object is steered with the high precision into the target. The chosen steering system gives a very fast response to the guidance signals. The direction of control forces depends on the time of firing of the control engine. The time, of control engines firing, depends on the target direction, the position of consecutive correction engines, the roll angle and the angular velocity along the **x** axis ω_x. The time of the correction engine work t_k should be as short as possible. Tests have shown that this time shouldn't be longer than ¼ time of the object one turn (figure 5). During this time, the impulse of the correction engine changes the missile course, which leads the object 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 controlled object. This control method, in contrast to an aerodynamic control method, doesn't require any compromise between stability and controllability, because the stability value of the bomb isn't limited. However, this method makes algorithms, of the correcting engines firing, more complicated. The sequence of the correcting engines firing should be such that the unbalance of the munitions is minimal. This algorithm should gives the mean value of the effect of control proportional to the control signal value.

Dynamic of presented control method was described in more details in [2] and [6].

4. Mortar missile guidance system

At the spinning object, one channel is used to control the object in both horizontal and vertical planes. It can be realized by a gasodynamic impulse acting on to the object gravity centre. This solution gives a quicker object reaction to the seeker information and consequently more precise object guiding to the attacked target. It also makes the operation of servo control system easier. A complicated mechanics of the aerodynamic servo is not needed, either.

The presented guided system concept is original and simple. It doesn't use gyroscopic devices and uses only one-dimensional and non-movable seeker [2]. The seeker consists of a single line of detectors. The whole control process is realized in a coordinator system attached to the rotating missile. It makes equipment on the missile board smaller and easier to made, but it complicates the guidance logic and dynamics of the object controlled flight.

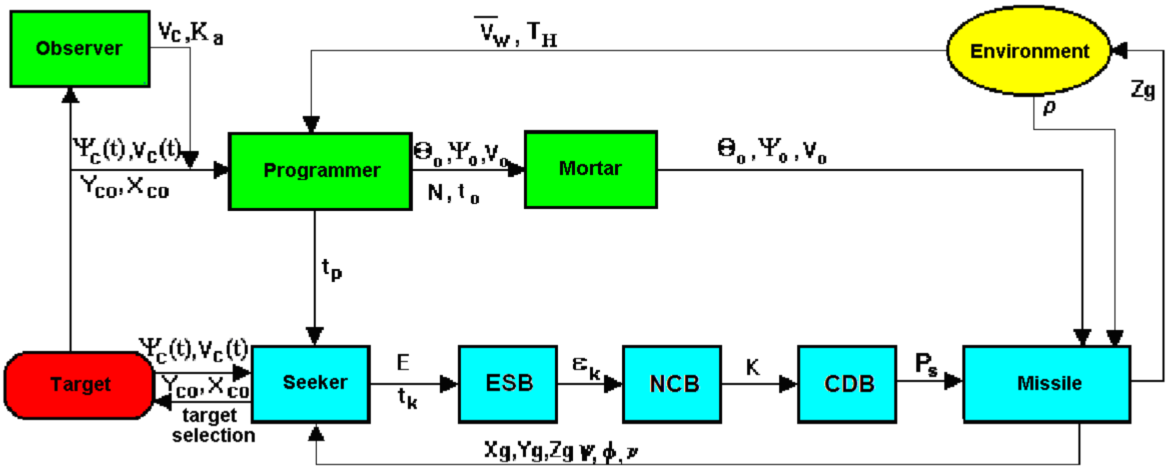

Figure 4. Block scheme of the missile control system. ESB error signal block, NCB navigation and control block, CDB control devices block.

The general block scheme of the control system is shown in Figure 4. This scheme illustrates basic functions of the system. Its main features are:

- The seeker with a single, one-dimensional mosaic detector, connected to the rotating object; the goal position is measured once at the each turn,
- ESB (the error signal block) converts the pulse signal E from the seeker into a linear one, and also realizes filtration and prediction of the signal from the detector,
- NCB (the navigation and control block) starts the control process, estimates the objects attitude and generates the control signal K,
- CDB (the control devices block) is a set of one-time-used rocket correction engines.

When the target is selected, it is tracked during the rest of the flight of the projectile. The error angle κ between the centre of the target and the projected impact point of the missile is continuously monitored. As soon as this angular error or angular error time derivative exceeds a reference value, one or several rocket correction engines are fired in an appropriate direction to bring the value of the error close to zero. The impulse of the rocket correction engines passes through the centre of gravity of the projectile, which gives the instantaneous course correction when the rocket is fired.

$$K = k_a\left(\varepsilon + T_f \frac{d\varepsilon}{dt}\right).$$ missile control law [1]

K - control signal from NCB navigation and control block;

ε - error

k_a - gain;

T_f - differential constant.

Values of parameters T_f and k_a are adaptable and depend on the missile dynamic and the target position.

By the continuous calculation of the predicted impact point relative to the predicted target position (at the impact time), it is possible to use the proportional navigation, which avoids any influence of the target movement, the wind effects etc.

The tracking technique also makes it possible to introduce several course corrections in a rapid succession. If necessary, all rocket correction engines can be used for the control process in the last few seconds of the flight.

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

The decision when the correcting rocket engine should be fired depends on the value of the control error. The frequency of firing of the correcting engines N is defined as the number of rotations of the mortar missile between the correcting engines firing. N increases with the control signal value K. The direction of control forces depends on the time of firing of the control engine. The time of control engines firing depends on the target detection angle, the position of the correction engine, the roll angle and the angular velocity along the **x** axis ω_x.

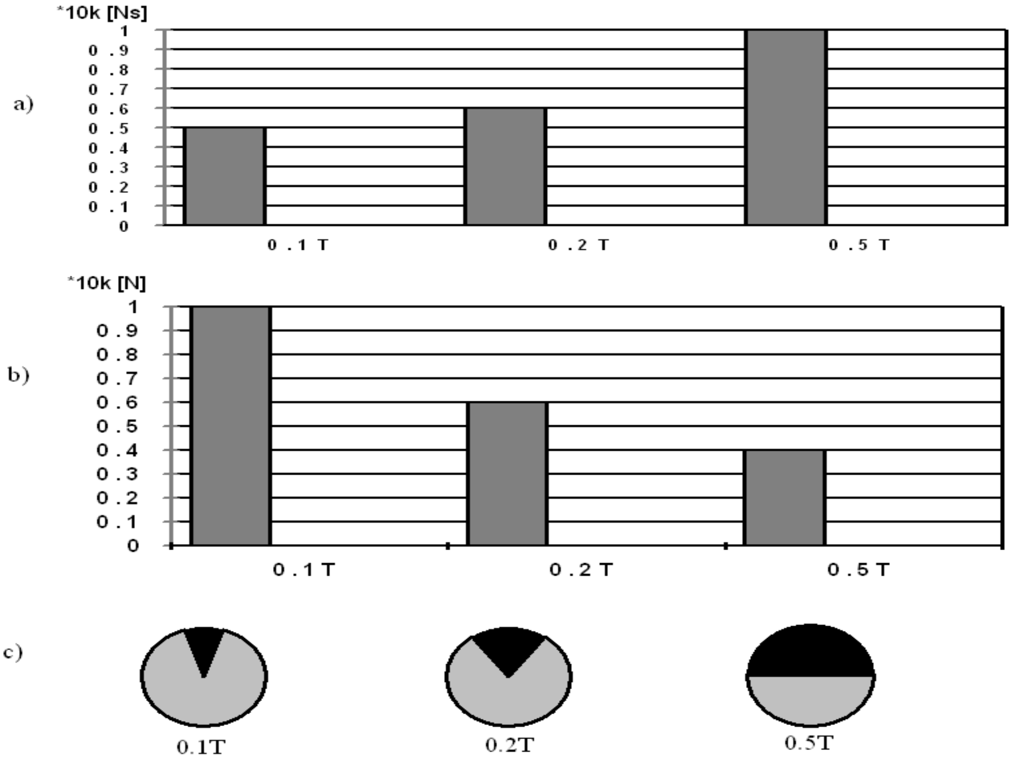

Figure 5. Change of value of:

a) The control impulse,

b) The control force dependence on the correcting engine work time,

c) The work time (black color) in proportion to the single rotation time.

5. Air bomb control system.

Block scheme of the control system shows figure 6. Similar like incase of mortar missile, 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 prepare the value C_{val} and make the decision, if the next rocket control engine have to be activated or not. If the decision is positive control system must also count the angle C_{ang} (bomb has a rotation around main symmetry axis x) and time to start up the next engine. Bomb guidance system navigation is based on GPS/INS system [1].

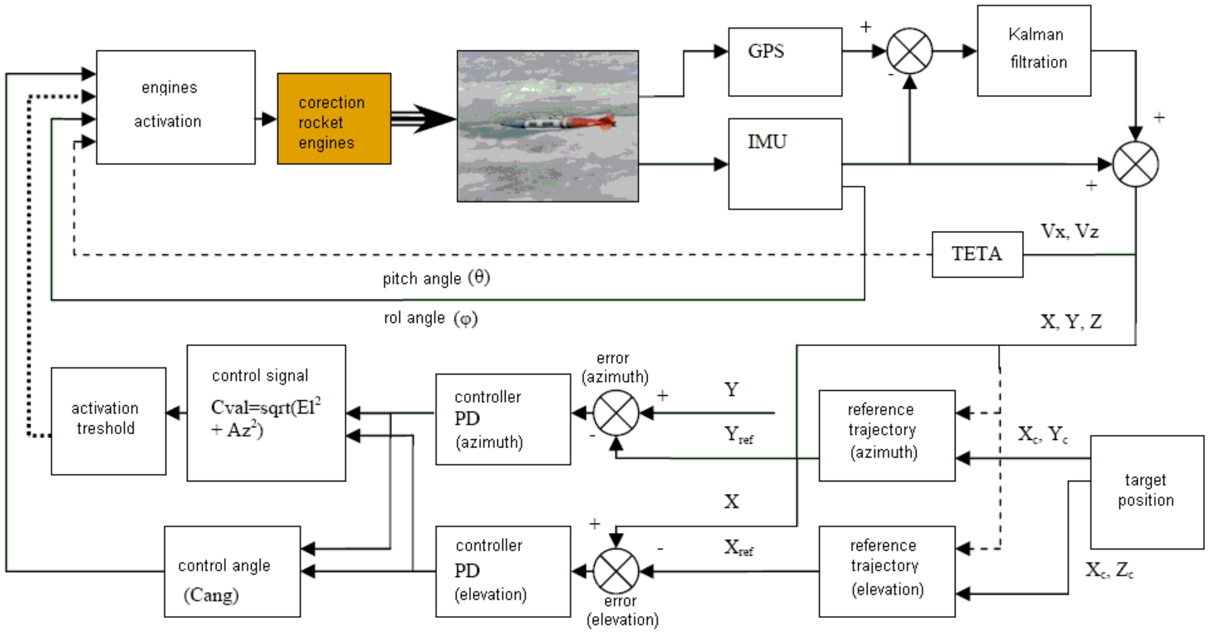

Figure 6. Block scheme of control system.

The goal of the bomb's guidance system is to give to the bomb such 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. Our control system has a discontinuous impulse character. The system use a one-propellant rocket engines with short operating times (0.05s). Number of rocket engines' impulses, during the entire flight of the control bomb, is limited. By this reason, it is important for their effective use. Control system use a three points 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 (Xg, Yg, Zg) are used (figure 4). The point at which the flight control system beginning work, was chosen after preliminary analysis of simulations. Bombs' dynamics analysis showed us, 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 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 most 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 presented method is effective when the control starts at the moment when the bomb reaches the pitch angle equal about -45^{o}. Described above point R1 represents the position at which the pitch angle is equal to -45^{o}.

The position error value, which is the input value for regulators, is a 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 flat trajectory models. The current position of the bomb is projected on the plane (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 at the moment is measured. Geometry of error measurement illustrates figure 4.

Control system was described in more details in [7]

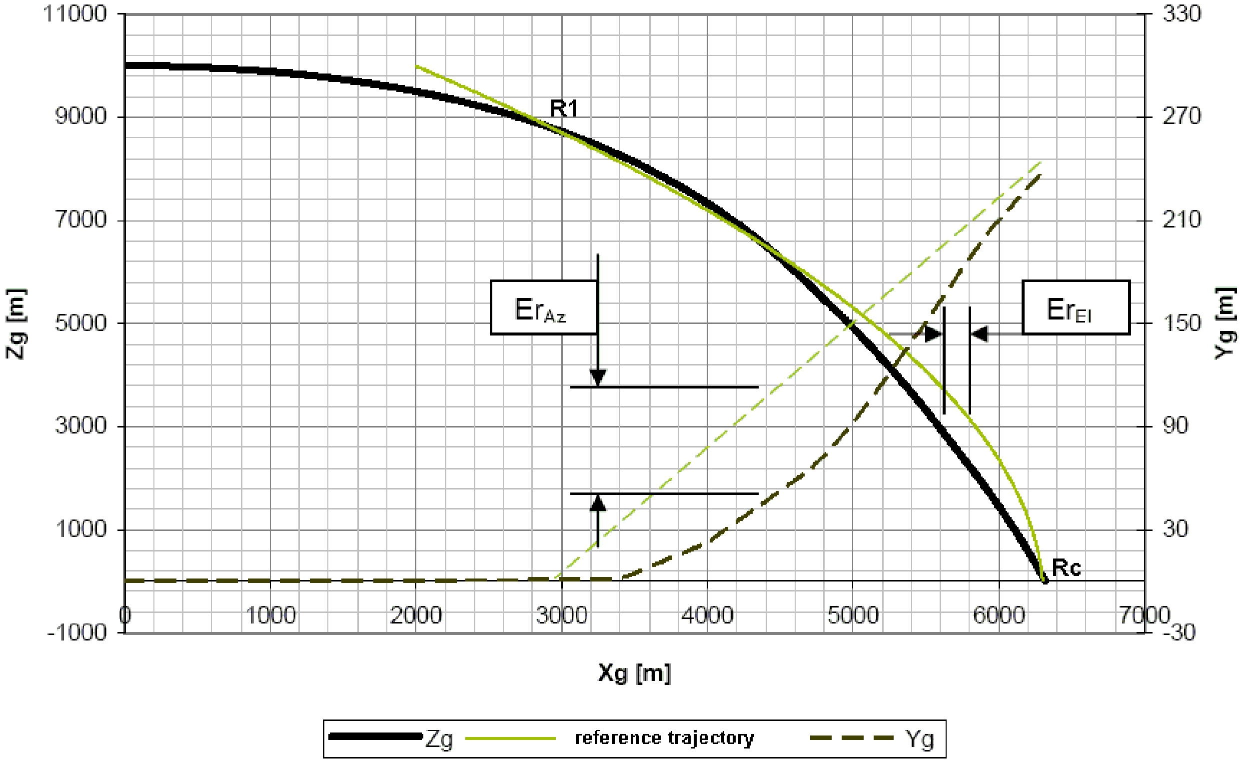

Figure 7. Scheme of azimuth and elevation errors measurement.

6. Results

The aim of the study was to find dynamic properties and possibilities of the impulse control of the flying object by the presented methods. The investigations were carried out on a numerical model of dynamics of the control missile. The model was prepared in a Matlab/Simulink environment. It was a system of differential equations. The model was non-linear and discontinuous. It described space motion of the bomb in all phases of the flight, from the drop to the impact to the target. The description of movement is sufficiently general for the investigation (analysis) of the control process with differential guided methods.

At figure 8 flight trajectory for bomb with mass 100kg dropped from 4 000m, with initial speed V=180m/s. Bomb has 20 rocket control engines. Engine thrust P=10kN, engine's work time t_k=0.05s. Spin velocity ω_x is about 30 rad/s. Figure 8 presented comparison trajectories for guided and ballistic flight. Bomb can reach target with error less than 10m in range about 700m far from the uncontrolled fall point. Figure 9 presents time changes of the pitch angle Θ during the control flight. We can see that control process started since about 15 second. It means that first 1000m in Zg axis is the ballistic phase of the flight.

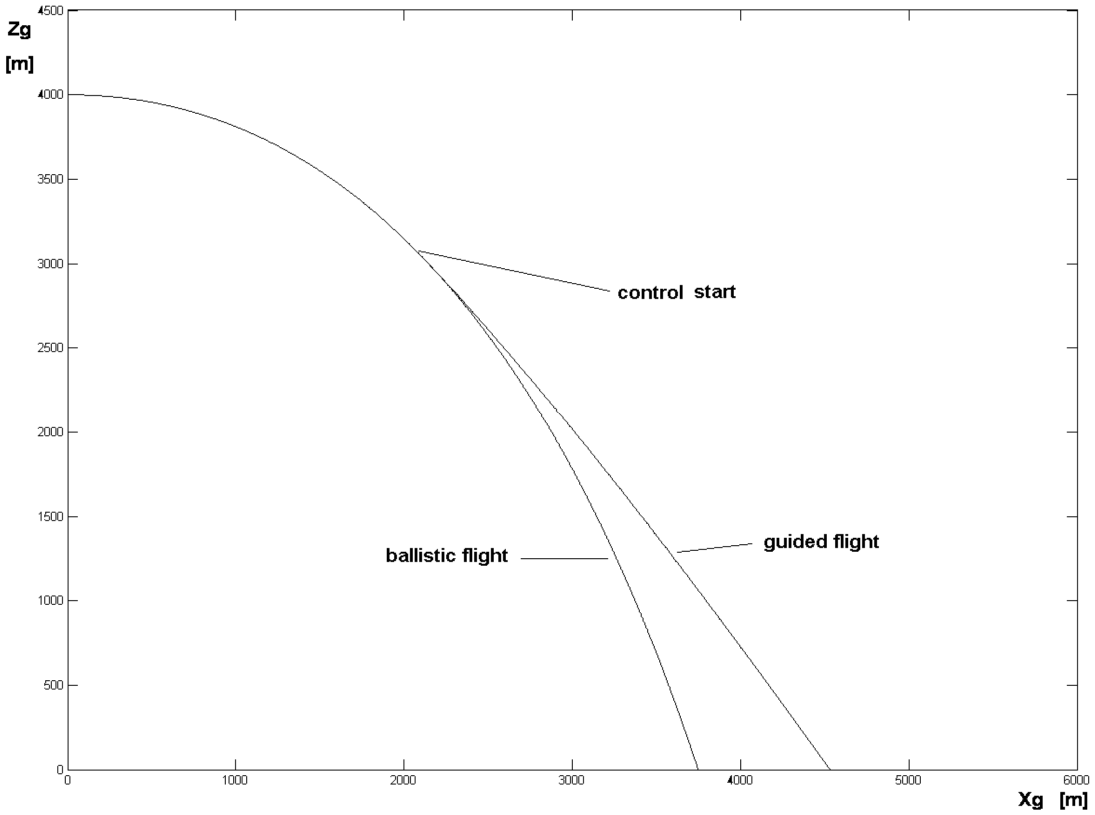

Figure 8. Control and ballistic bomb’s flight trajectory. Control is realized by 20 correction engines.

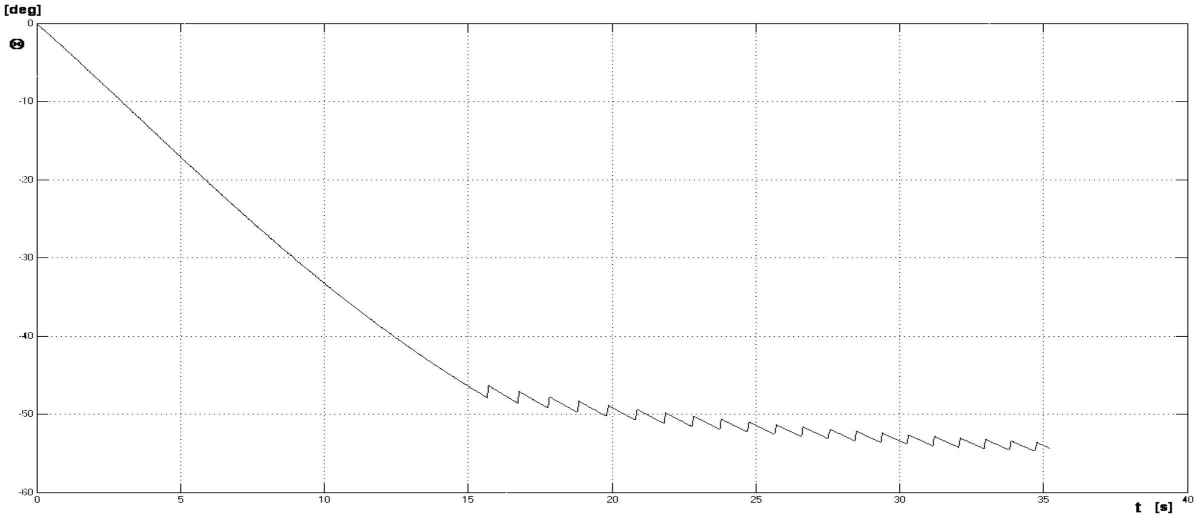

Figure 9. Pitch angle during bomb’s control flight. Control is realized by 20 correction engines.

Figure 10 shows flight trajectory for bomb with 12 rocket control engines. Another flight conditions are similar like at the case from figures 10 and 11: mass 100kg, bomb is dropped from 4 000m, initial speed V=180m/s, engine thrust P=10kN, engine’s work time t_k=0.05s. Spin velocity ω_x is about 30 rad/s. Figure 10 presented comparison trajectories for guided and ballistic flight. Bomb can reach target with error less than 10m in range about 400m far from the uncontrolled fall point. Figure 11 presents time changes of the pitch angle Θ during the control flight. Similar to figure 11 that control process started at about 15 second. It means that first 1000m in Zg axis is the ballistic phase of the flight.

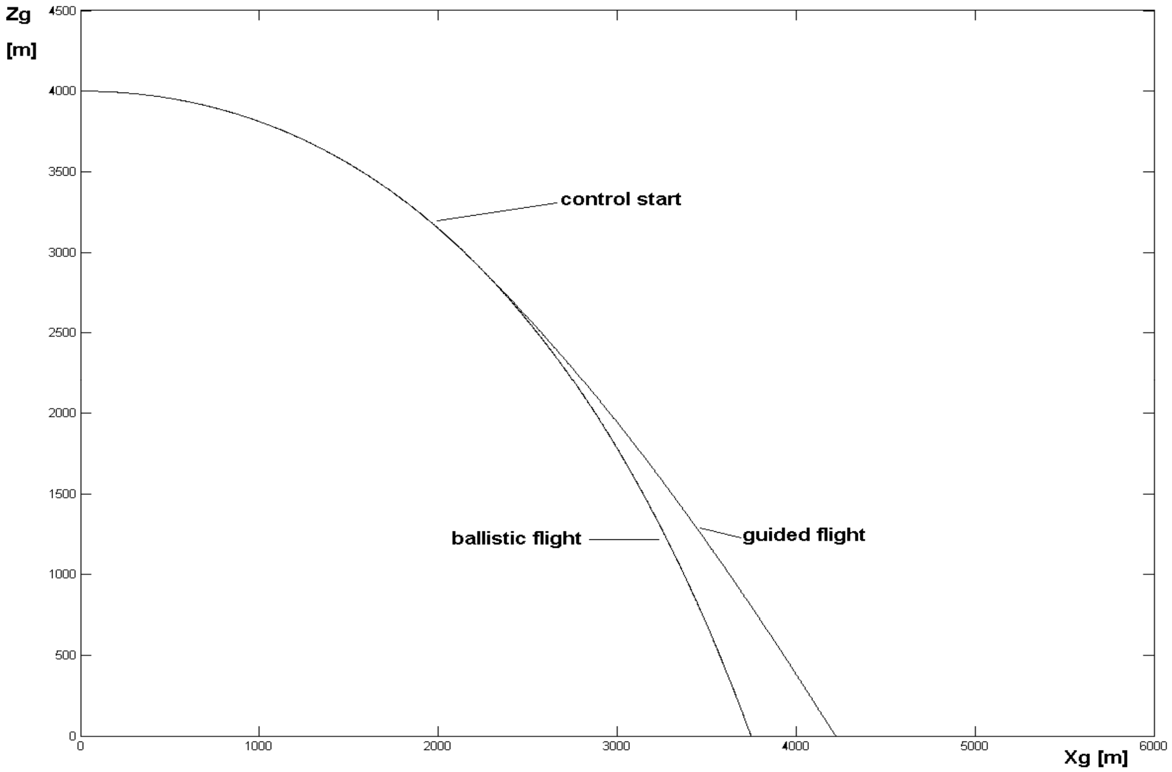

Figure 10. Control and ballistic bomb’s flight trajectory. Control is realized by 12 correction engines.

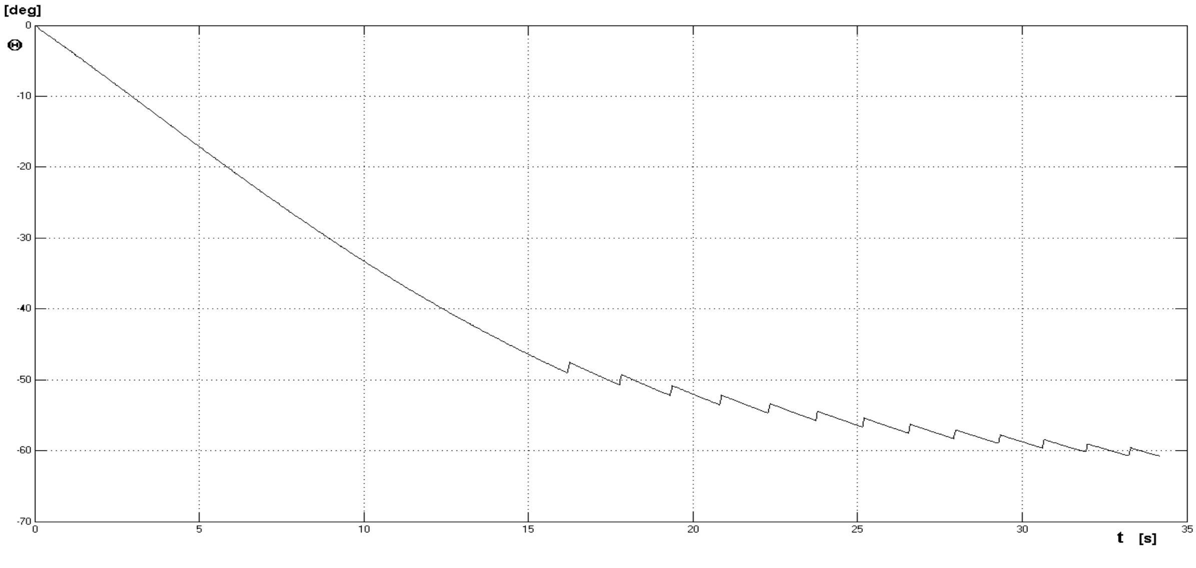

Figure 11. Pitch angle during bomb’s control flight. Control is realized by 12 correction engines.

6.1 Mortar missile

Figure 12 shows changes of the angular error κ and error value E measured by the seeker during the guidance process. In this case, the target is 3500m far from the launcher and the missile initial speed is 170m/s. The angular error κ is a real value of error shown as the dashed line. E is an equivalent measured by the seeker with a 16 elements detector line. The error is measured as the angle between the main symmetry axis and the seeker-target axis. The primary signal of the error E is measured once at the each rotation and has an impulse character. The value E is treated as constant till the next measure impulse signal of this value. In the situation when the seeker has a finite number of detector elements, the signal from the seeker has a discrete character. In Figure 12, one can see that the missile found the target with the error of 4,5°. Next is the guidance phase, when this first error is reduced to the value less than 1°. Like in the previous case, the huge error during last milliseconds of the flight is an effect of the assumption that the target is a point. The final result is the impact with the error of 1.2m from the target point. Figures 13.a,b,c show another parameters of the flight for the case from Figure 12.

Figure 14 shows the guidance at the same condition like at Figure 12 but the error is measured as an angle between the speed vector axis and the seeker-target axis. We can compare results from both cases. The seeker from the second cases (Figure 14) does not influence the angle of attack. Similarly as in Figure 12, one can see that the missile finds the target with an error of 4,5°. The next is the guidance phase, when the first error is reduced to less than 0.5°. The final result is the hit with an error of 0.8m from the target point. From this comparison, one can see that control quality of the missile is better when the seeker is suspended on an universal (Cardan) joint. However, it is hardly possible to use the seeker with the Cardan suspension in the mortar missile. Figures 15.a,b show other parameters of flight for the case from Figure 14.

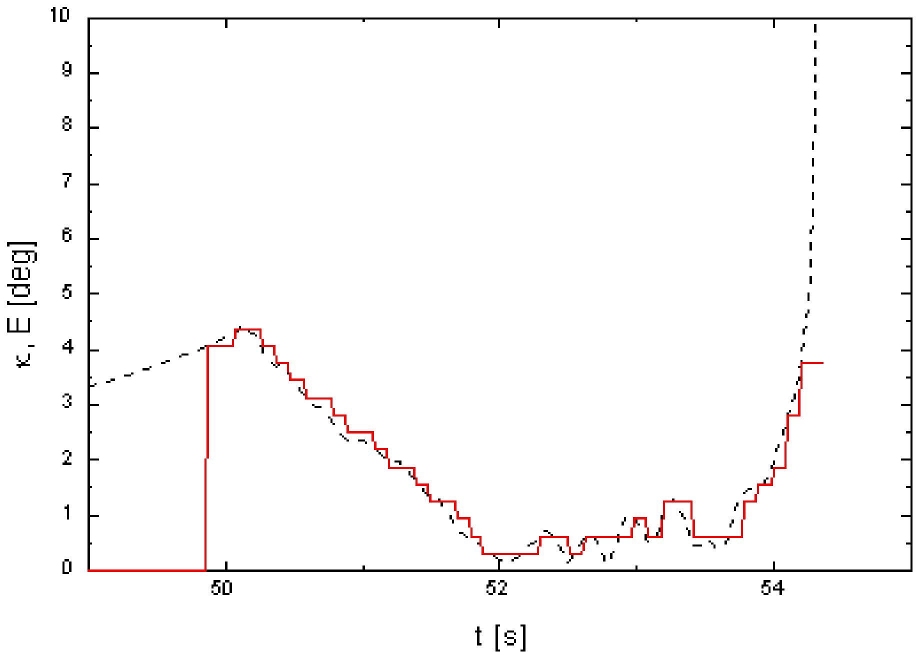

Figure 12. The angular error κ (dash line) and the error value E measured by the Seeker (solid line) during the guidance phase of the missile motion (flight). The error is measured as an angle between the main symmetry axis and the seeker-target axis. The attack from 1000m with the initial speed V=160m/s, parameter N=2.

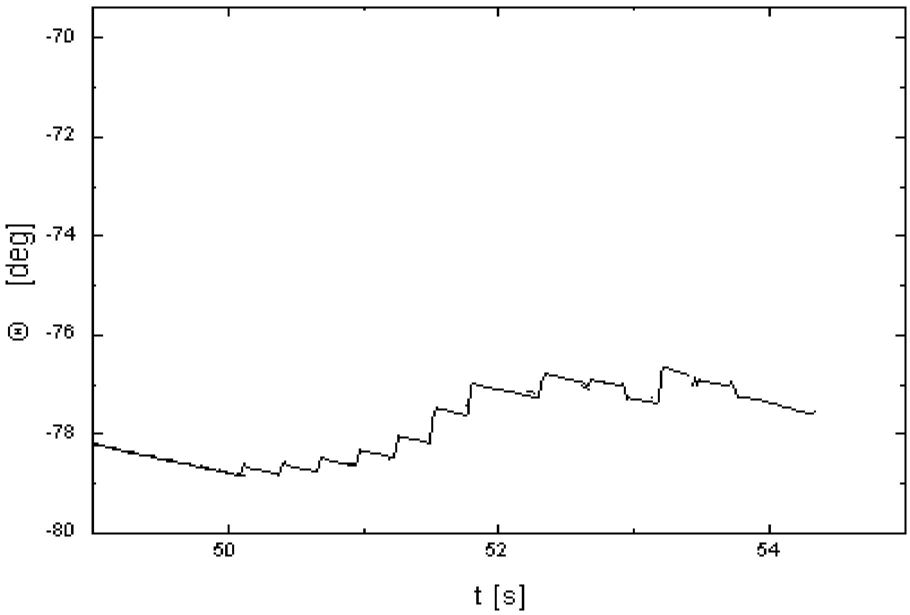

Figure 13.a

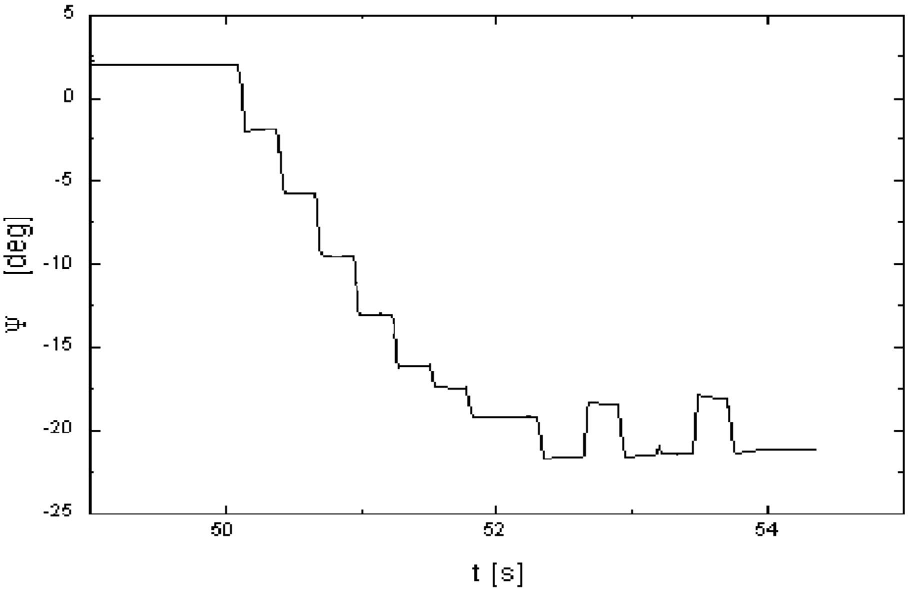

Figure 13.b

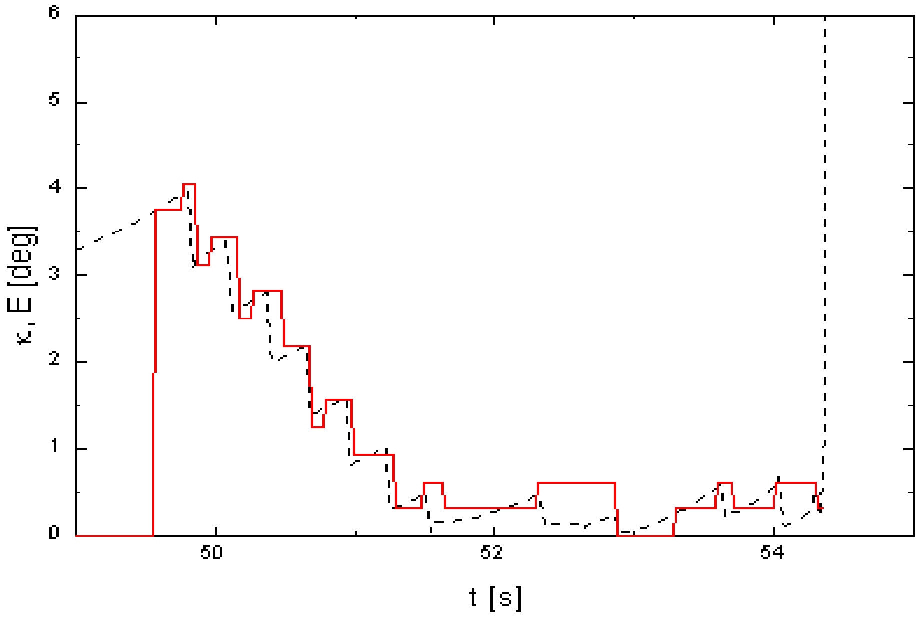

Figure 14. The angular error κ (dash line) and the error value E measured by the Seeker (solid line) during the guidance phase of the missile. The error is measured as an angle between the speed vector axis and the seeker-target axis. The attack at the same conditions like in Figure 12.

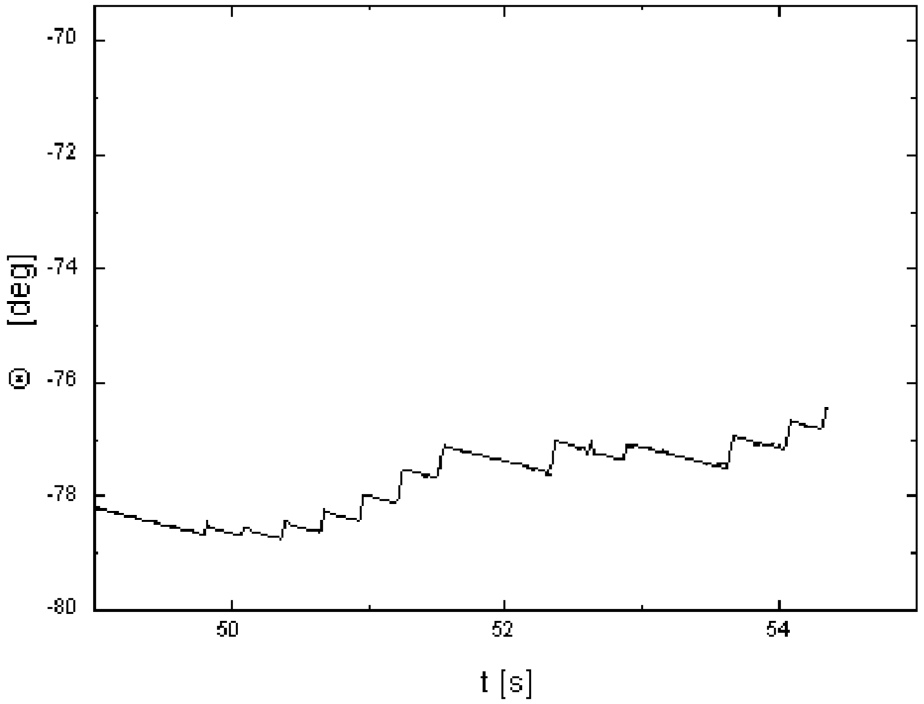

Figure 15.a

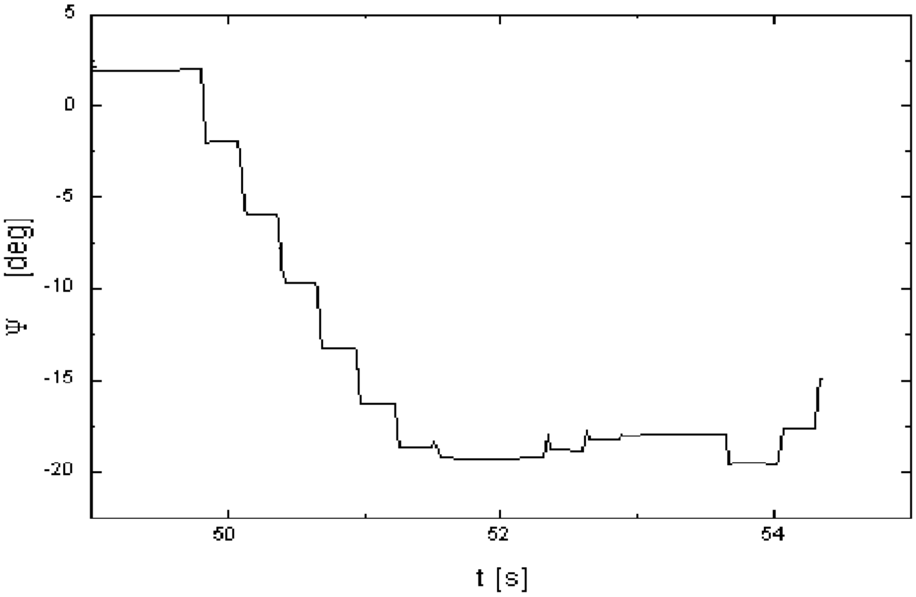

Figure 15.b

6.2 Air bomb

Figures 16 and 17 present some results from simulation. All simulations have following parameters: mass 100kg, drop from 10 000m, initial speed V=220m/s. The control process was realized by 20 correction engines (engine thrust P=5kN, engine’s work time t_k=0.05s, spin velocity w_x is about 30 rad/s). Figures 16 present control processes with the ideal navigation. Figures 17 present control processes with navigation signal with errors from INS/GPS systems. In 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 the system is quite robust to navigation errors during the flight time. We can 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.

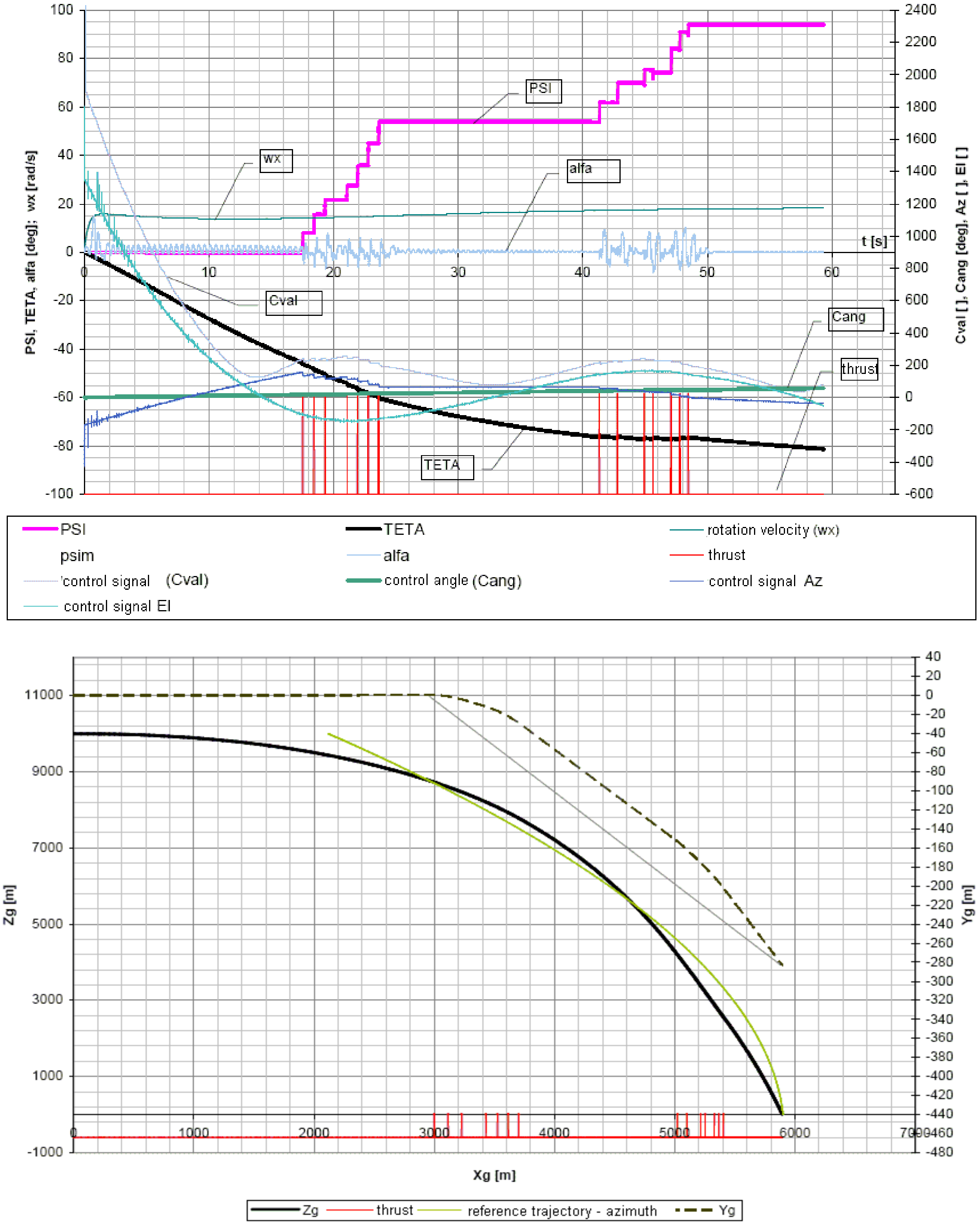

Figure 16 Flight with parameters: single engine trust 5000N, bomb's drop altitude 10000m, initial speed 800km/h, reference trajectories (azimuth - straight line, elevations- parabolic curve), ideal navigation.
Upper figure flight and control parameters; Lower figure flight trajectories (azimuth and elevation projections) and reference trajectories (azimuth and elevation).

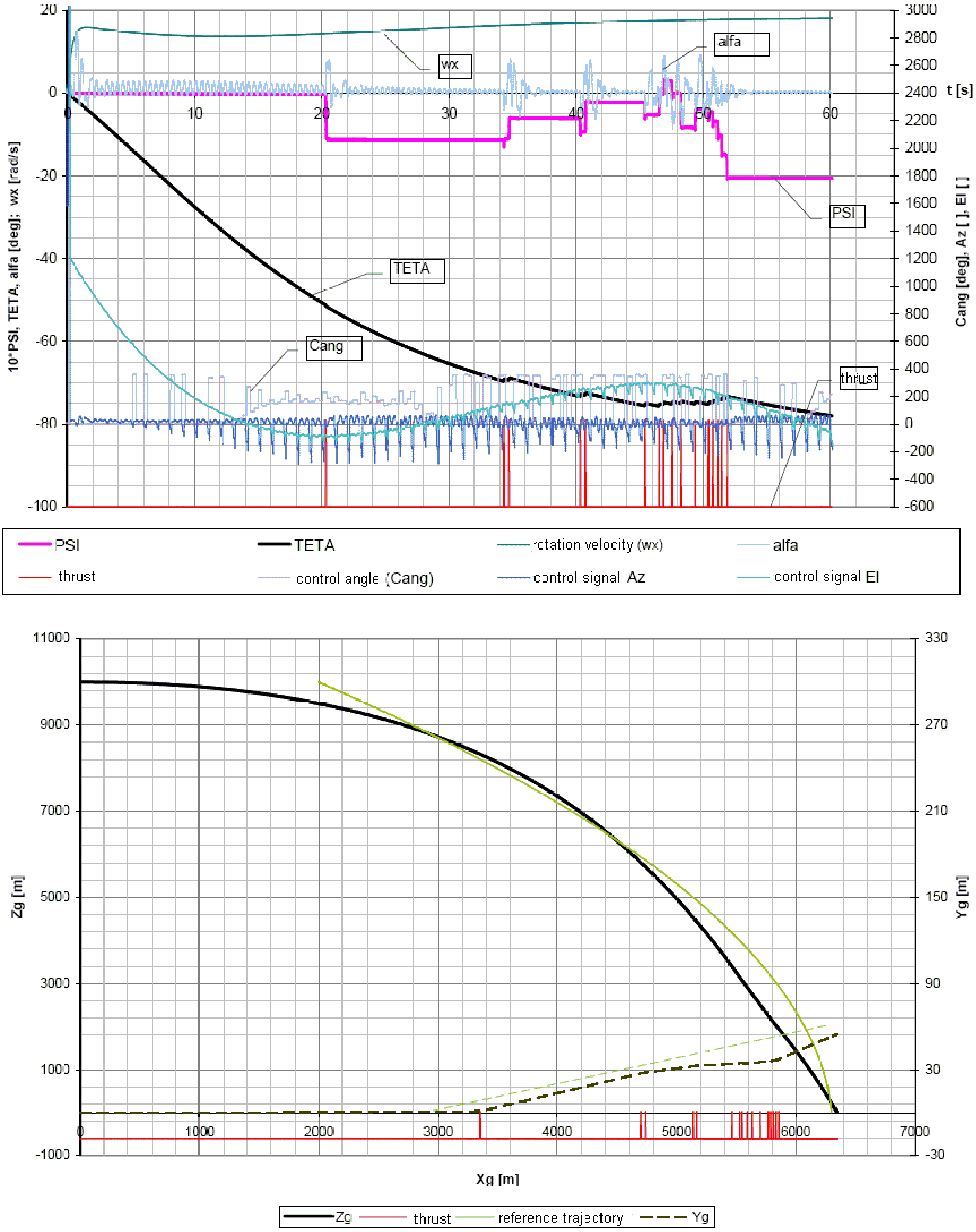

Figure 10 Flight with parameters: single engine trust 5000N, bomb's drop altitude 10000m, initial speed 800km/h, reference trajectories (azimuth - straight line, elevations- parabolic curve), INS/GPS navigation.
Upper figure flight and control parameters; Lower figure flight trajectories (azimuth and elevation projections) and reference trajectories (azimuth and elevation).

7. Conclusion

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 impulse correction rockets to control falling objects like, for example, mortar control missiles and bombs. The accuracy and control quality, attainable, at the phase of a computer simulation, gives good prognostics for the possibilities of practical use. This method of control leads to more complicated control algorithms but makes the servo control easier to perform. The servo has only the correction rocket engine set and the electrical system of initiation.

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