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GUIDANCE SYSTEM OF SMART MORTAR MISSILE

The paper presents application of guidance system for small, smart mortar missile. The presented control system is simple and inexpensive. It is based on a set of one time used impulse control engines and linear coordinator rotating with controlled object. Engines are mounted around the missile. There are no movable devices on the projectile board. The correcting impulses from rocket engines are perpendicular to main symmetry axis of the flying object and influence directly the centre of gravity of the guided missile. In the paper, authors describe the whole control system of the missile. Particular attention is focused on seeker and control devices. Numerical analysis presents some cases of the missile controlled flights.

1. Introduction

The idea of smart mortar missiles started two decades ago. The development of microelectronic created the possibility of constructing guided projectiles for indirect fire. During last twenty years, we can observe development of guided mortar missiles. Owing to the advantages of these constructions, mortars became popular and wide-spread weapons, used by all armies in the world. Quick firing is one of these advantages. First devices were built as antitank missiles. The missile Merlin constructed by British Aerospace Defence (today BAE SYSTEMS) was prepared for 81 mm mortar. Another construction developed in cooperation of SAAB Missiles and Bofors companies, the Strix missile, was prepared for a 120 mm mortar. Both constructions were “fire and forget” projectiles. The next ones were Russian missile Gran and German missile Bussard. In this century, new programs have been launched, like PGMM carried out by Lockheed Martin and Fireball carried out by Israeli IAI. The contemporary development of guided mortar missiles is mainly focused on precision guiding to a goal pointed by laser designation.

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These kinds of missiles are guided from upper hemisphere. The projectile is fired from a mortar and controlled only at the last steep phase of flight. The flight trajectory is corrected by an aerodynamic or gasodynamic control system. The Strix missile has very interesting construction. It is guided by a set of impulse engines used one time each. Also in Poland there was the RAD Program carried out in late nineties. The investigations and experimental data described in this paper are based on research program supported by the grant No 0T00A02826 from the Ministry of Science and Information Technology.

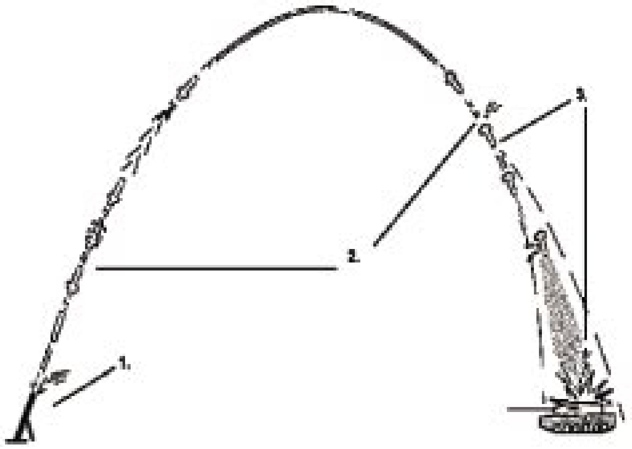

Fig. 1. Phases of flight: 1 – launch, 2 – ballistic phase, 3 – quided phase

2. Problem description

The missile is guided from upper hemisphere. The impulse rocket engines, used only one time each, correct flying trajectory. As it was mentioned before, the projectile is fired from a mortar and 80% of the flight time is ballistic phase. The phases of flight are shown in Figure 1. The aft section is fitted with fins to give the missile aerodynamic stability and spin. The fins are immediately unfolded when the projectile leaves the mortar barrel, and their fixed cant angle gives the projectile a slow spin (about 60 rad/s). The missile is guided at the last phase of flight. This is “fire and forget” projectile. The missile is launched above the targets’ operating area, and at the last steep phase of its flight is automatically guided to the target. The missile must be accurately launched over the targets’ operating area. We make assumption that the seeker has observation angle of 10° and is able to find objects from a distance less than 1000 m. These conditions give an observation area of about 170 m diameter. The first and necessary condition of target interception and successful missile attack is to launch the projectile into such an area.

In the considered kind of projectile, where flight is controlled only at the last phase, the influence exerted on the projectile speed vector must be quick rather than strong. This task can be performed correctly by the use of control system based on rocket correction engines. Small rocket engines have more efficient influence on the speed vector than classic aerodynamic control surfaces. One can expect that this concept of control should give a better guidance of the missile.

Dynamics of control of impulse mortar missile.

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

- steering forces initially change the moment acting on an object (figure 3), than this moment rotates the object around its gravity centre;
- supporting surfaces get necessary angles of attack and produce steering forces.

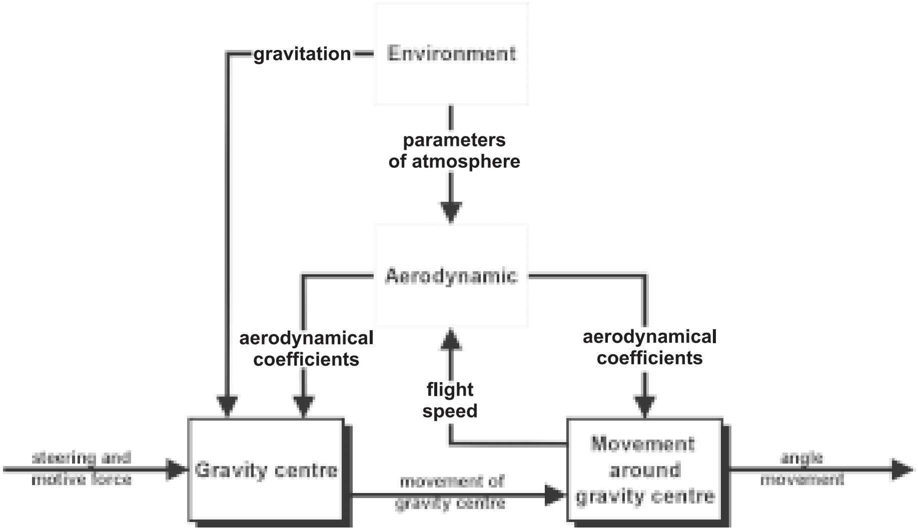

Fig. 2. Block scheme of the object dynamic

This way, the object is turned at first around the mass centre, than this movement effects on the mass centre 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 missile from the seeker. The whole guided phase lasts for about 3 to 5 seconds. This fault can be limited by the direct action on the motion of the gravity centre. 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 centre of the object (Figure 2).

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

- steering forces first exert an influence on the object gravity centre;
- the rotation around the gravity centre is an effect of a gravity centre 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 2.

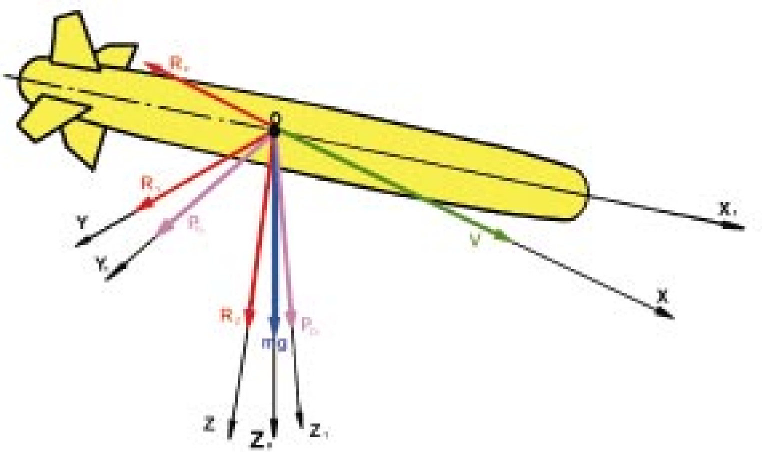

Fig. 3. Forces acting on the missile: mg – gravity force, P – control force from the correcting engine, R – aerodynamic force, V – speed vector

3. 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.

All known control systems of mortar missiles are rather complicated. It especially concerns the seekers. Seekers for this application consist of two-dimensional systems with movable elements. All of them use reference systems based on gyroscopic devices. The presented guided system concept is original and simple. It doesn't use gyroscopic devices and uses only one-dimensional and non-movable seeker. 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.

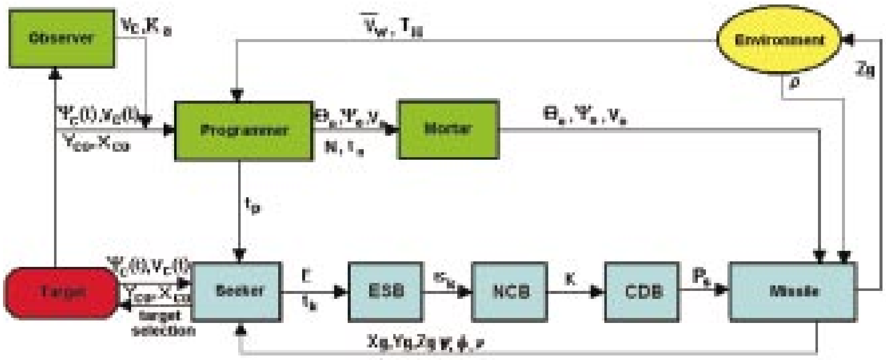

Fig. 4. Block scheme of the missile control system. ESB error signal block, NCB navigation and control block, CDB control devices block

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.

4. Seeker

The one-dimensional linear infrared detector is the measuring sensor of the guidance system. Since the sensor is attached to the rotating missile (Figure 5), the measurement is made in polar coordinates.

For the reason that the seeker detector is spinning with the missile, information about signal E (the angular error between the missile main symmetry axis and the seeker-target axis) appears only once per rotation period, when the detector's line of vision is in the target observation plane. At this moment, the target observation plane is tilt with the angle ϕ_m. The complete image of the scanned area is acquired once per rotation. Therefore, the frequency of acquiring images is strictly related to the angular rate of the missile about its axis of symmetry.

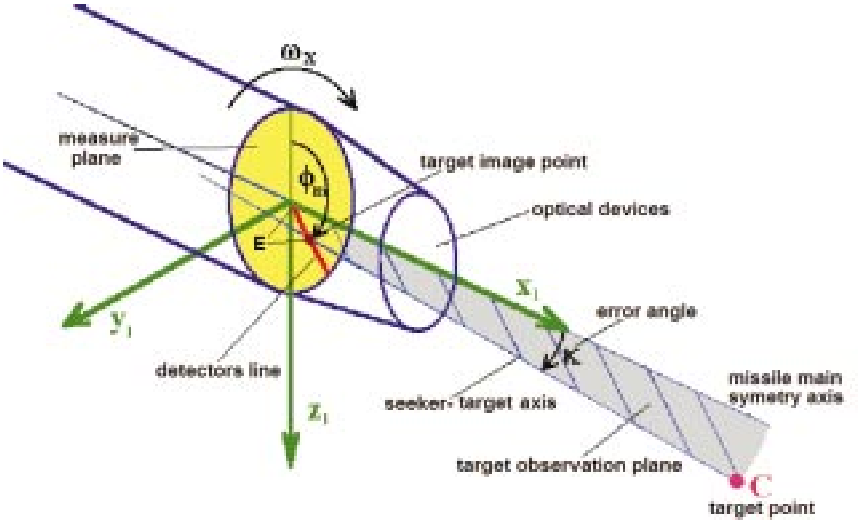

Fig. 5. The overview of Seeker (κ – error angle, ϕ_m – tilt angle of target observation plane)

In effect of that, the error signal E is a discrete one with the sampling time equal to the rotating period of the missile around its longitudinal axis x_1. The detector consists of segments of infrared units, and the value of impulse error signal E has a discrete character and change with the angular error κ (Figure 6).

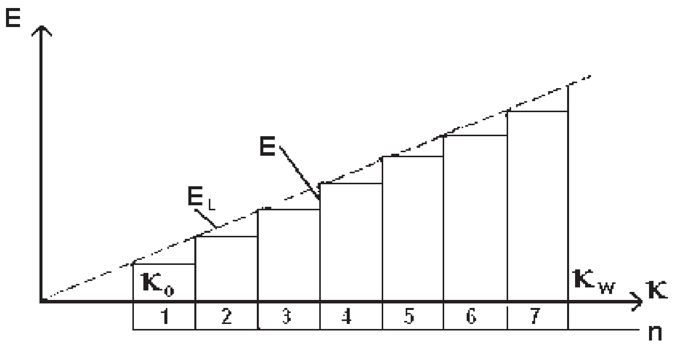

Fig. 6. Characteristics of the impulse error signal: E_L – proportional error signal, E – discrete error signal, κ_o – dead zone, n – element number, κ_w – angular range of the imaging sensor

The rotation of the missile is forced by the skewness of fins, which are located in the rear of the fuselage. The missile (and imaging sensor) angular rate is a function of the speed V. In this study it is assumed that this function is linear. Such simplification does not have any significant influence on the calculation accuracy. The time range of this sample measurement is from launch to the impact on ground. The control and guidance systems operate only in the final five seconds of the flight (in the descent phase). Due to the gravity force, this is the phase of a continuous acceleration. Consequently, it increases the scanning frequency.

The linear detector of the seeker is located on the radius of a measurement disk. It consists of up to several hundreds photosensitive segments. The axis of the disk coincides with the missile longitudinal axis x_1 what means that the disk is located in the y_1, z_1 plane. It is assumed that the detector axis is consistent with the axis z1. This kind of detector gives us only one measure of the error angle per a whole projectile rotation, at the moment when the detector is in the target observation plane. The target observation plane is determined by the seeker-target line and the main symmetry axis of the missile. At the rest of the rotation time, the signal of error E is equal to zero. The signal of error E is detected as an impulse with amplitude proportional to the angle κ at the moment when the missile angle ϕ is equal to the angle ϕ_m of the target observation plane (Figure 5).

5. Description of control devices and realization method

In presented method, the control is realized by one-time-used correction engines located around the flying object's centre of gravity (Figure 7). 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 (Figure 8). 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.

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

K – control signal from NCB navigation and control block;
e – 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 missile can be used against both stationary and moving targets.

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.

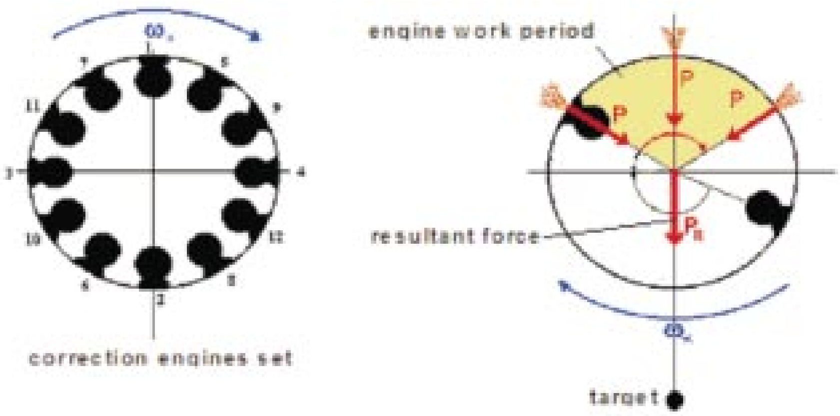

Fig. 7. Control rocket engines

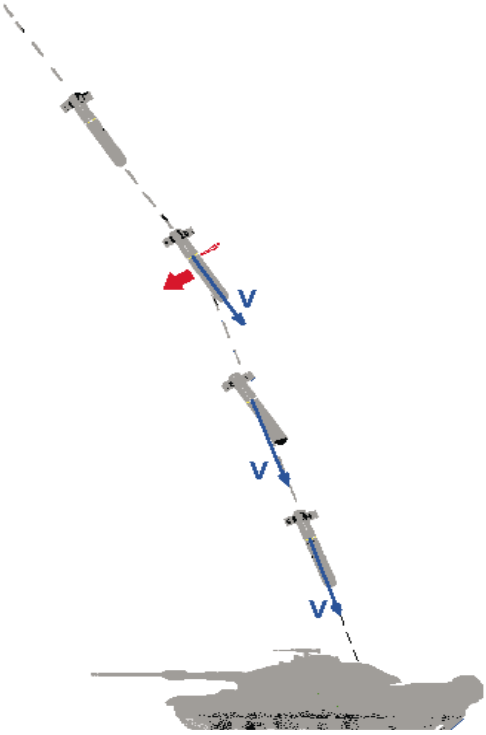

Fig. 8. Control system, method of realizing

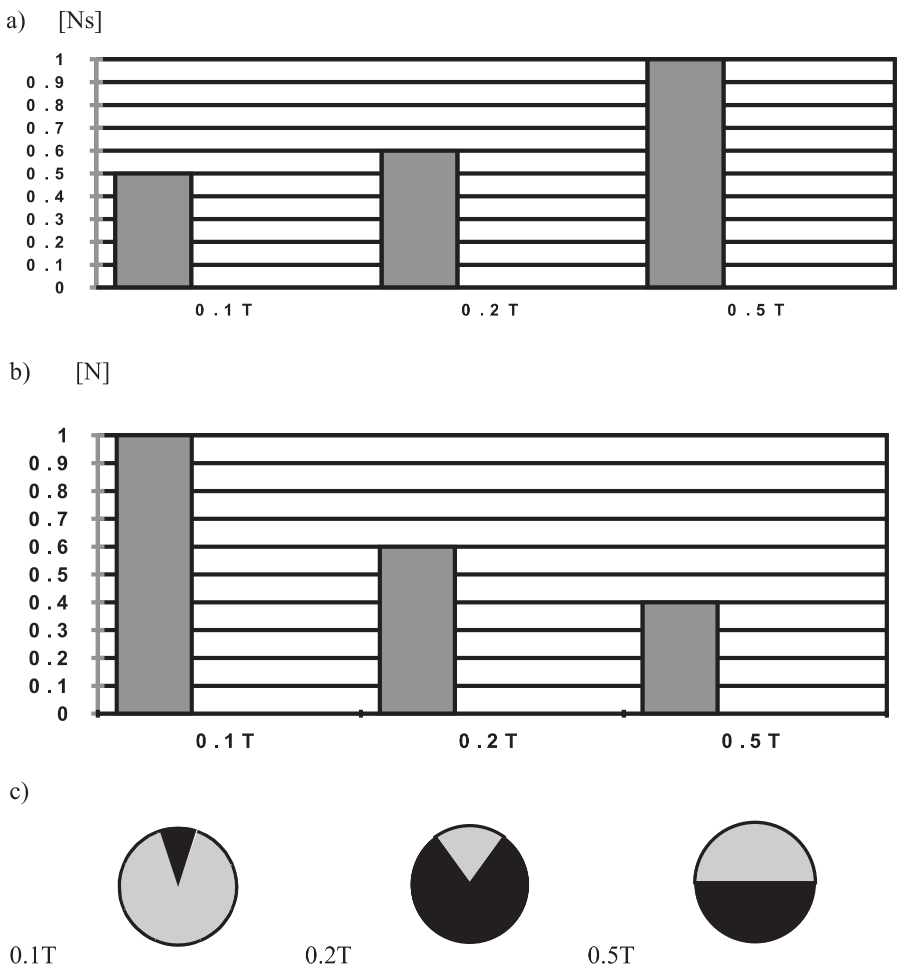

Fig. 9. Change of value of: a) The control impulse, b) The control force dependence on the correcting engine work time, c) The work time (black colour) in proportion to the single rotation time.

The task of the rocket engines set is to correct the course of the projectile in the last phase of the trajectory, homing it to the target, to achieve a direct hit (Figure 8). Correcting rocket engines are located in a cylindrical unit, arranged radially around the periphery. Each one of correction rocket engines can be fired individually only once in a selected radial direction.

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. The way of the course change is shown in Figure 8. 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.

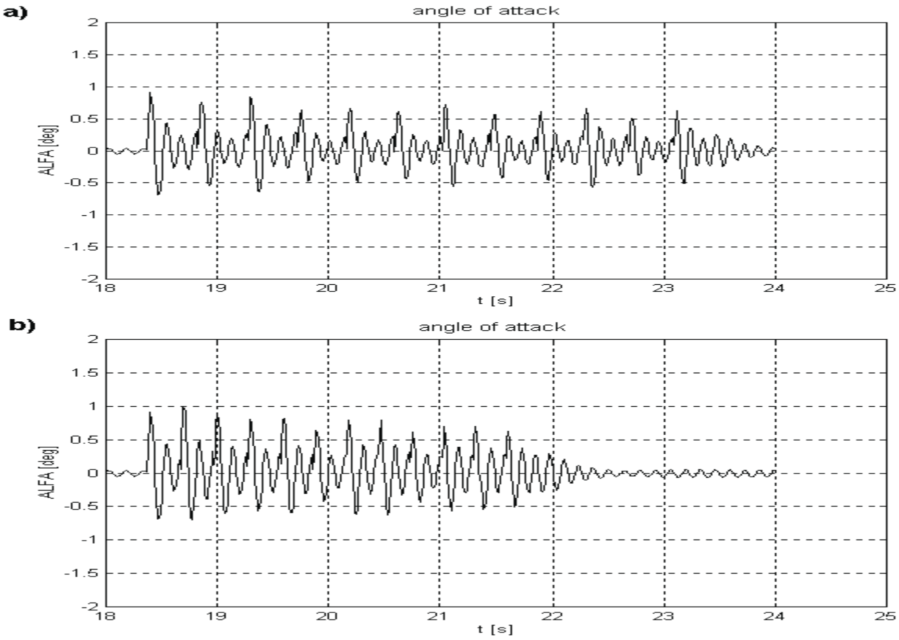

Fig. 10. The angle of attack during the control phase of flight. Case a) N=3, case b) N=2

The time of the correction engine work t_k should be as short as possible (Figure 9). Tests have shown that this time shouldn't be longer than ¼ time of a mortar missile turn. During this time, the impulse of the correction engine changes the mortar missile course, which leads the missile main symmetry axis. The angles of attack and of side-slip increase. These angles generate lateral oscillations. The time of suppression of these oscillations depends on the frequency of the correcting engines firing N (Figure 10) and the missile angular velocity along the x axis ω_x. The shortest time of oscillations suppression is observed when N is equal 1. The amplitudes of the angle of attack and the angle of side-slip don't generate significant disturbances of the target detection. However, some combinations of N, ω_x, and of the flying speed can lead to a resonance. The angle of attack and the angle of side-slip may considerably increase.

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, doesn't require any compromise between stability and controllability, because the stability value of the projectile isn't limited. However, this method makes the algorithms of the correcting engines firing more complicated. The sequence of the correcting engines firing should be such that the unbalance of the projectile is minimal. This algorithm should give the value of the mean effect of control proportional to the control signal value.

6. Results

The aim of the study was to find algorithms and dynamic properties 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 missile in all phases of the flight, from the launch till the impact to the target or to the ground. The description of movement is sufficiently general for the investigation (analysis) of the control process with differential guided methods.

Some simulation results of control process are shown in Figure 11. The target is 5000 m far from the launcher, the missile initial speed 170 m/s. The error angle between the seeker-target line and the main symmetry axis of the object oscillates in the short range. The control system shows good results of the control process. The huge errors at the last milliseconds of the flight are the effect of assumption that the target is modelled as a point. Case a) presents the simulation with the target velocity $V_c = 0$ and the case b) presents the simulation with the target velocity $V_c = 4$ m/s. The presented method of control gives good results (the final error is less than 2 m from the point treated as a centre of the target) when the target velocity is less than $V_c = 5$ m/s. With V_c higher than 5 m/s, the missile has a problem with reaching the target. Final errors are: case a) 1.1 m, case b) 1.5 m.

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 3500 m far from the launcher and the missile initial speed is 170 m/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 les 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 1.2 m from the target point. For a typical tank size, the results like these can be recognized as satisfactory. Figures 13.a,b,c show another parameters of the flight for the case from Figure 12.

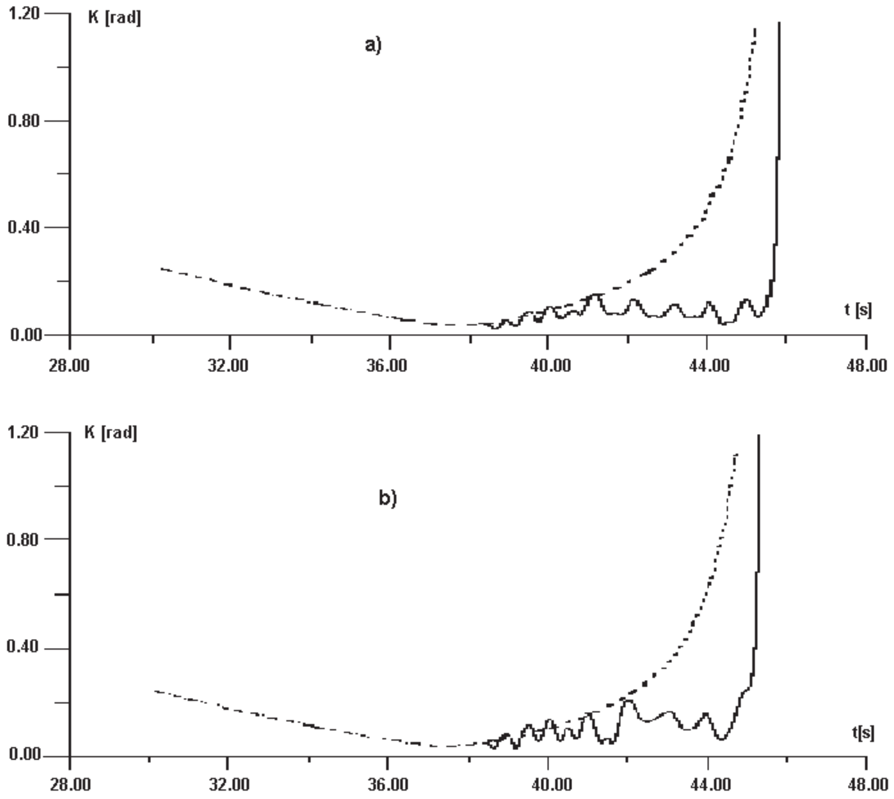

Fig. 11. The angular error between the seeker-target line and the main symmetry axis of the missile from a numerical experiment. Solid line – controlled missile, dash line – ballistic flight without control. Case a) target velocity $V_c = 0$, case b) target velocity $V_c = 4$ m/s

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 les than 0.5°. The final result is the hit with an error of 0.8 m 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.

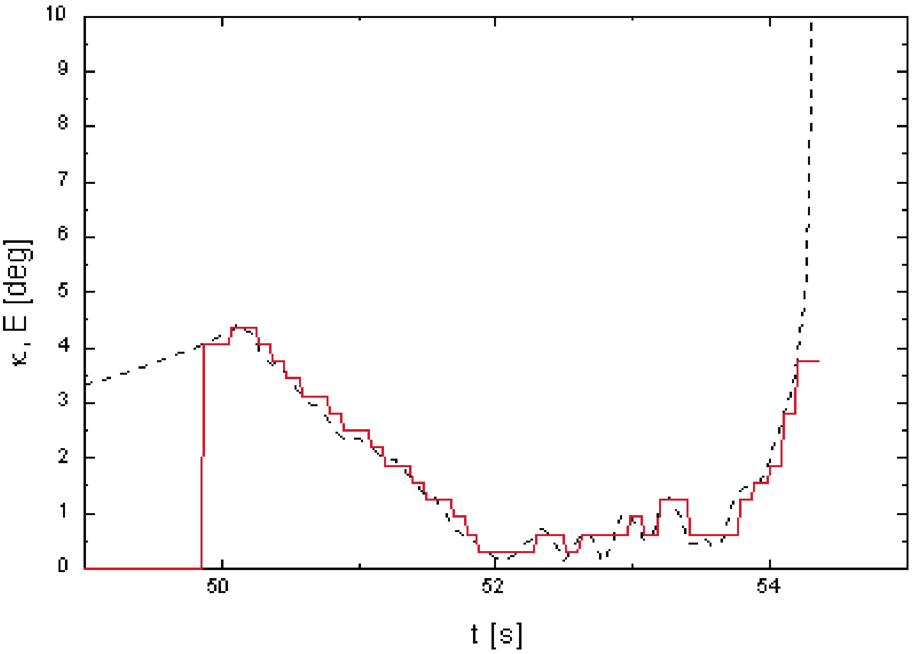

Fig. 12. The angular error κ (dash line) and the error value E measured by the Seeker (solid line) during the guidance phase of the missile motion (flight). The error is measured as an angle between the main symmetry axis and the seeker-target axis. The attack from 1000 m with the initial speed V = 160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

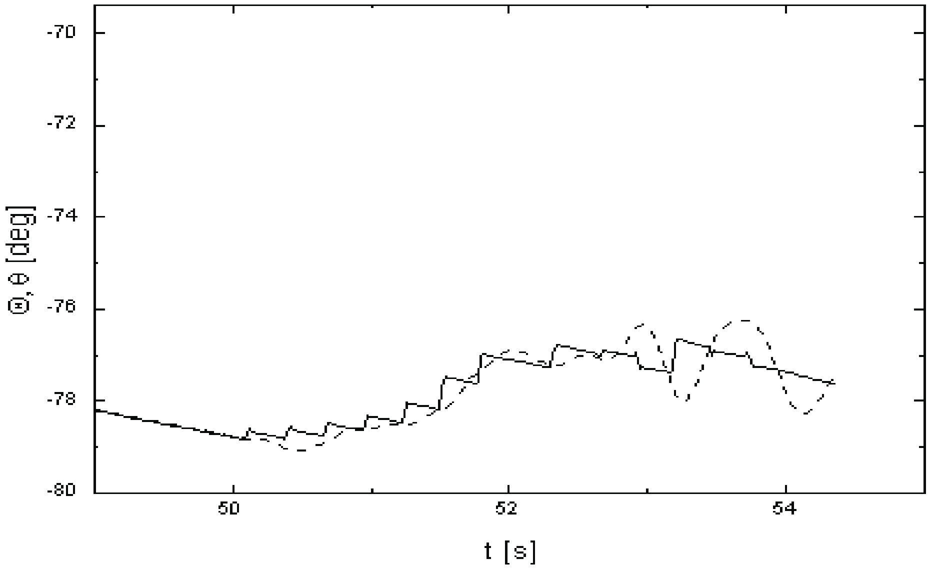

Fig. 13a.

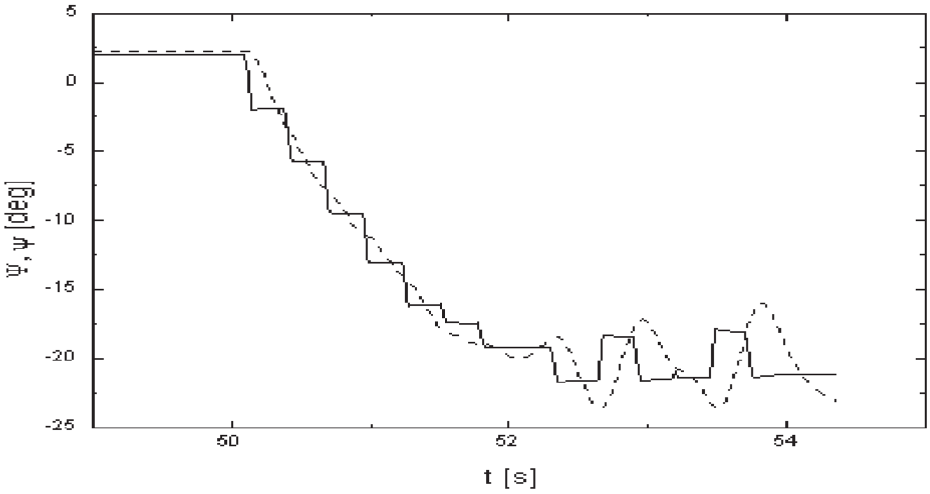

Fig. 13b.

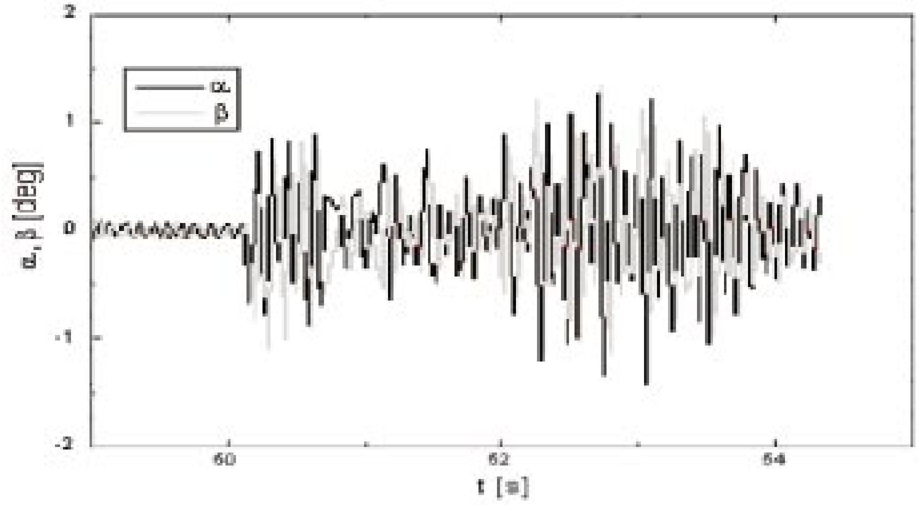

Fig. 13c.

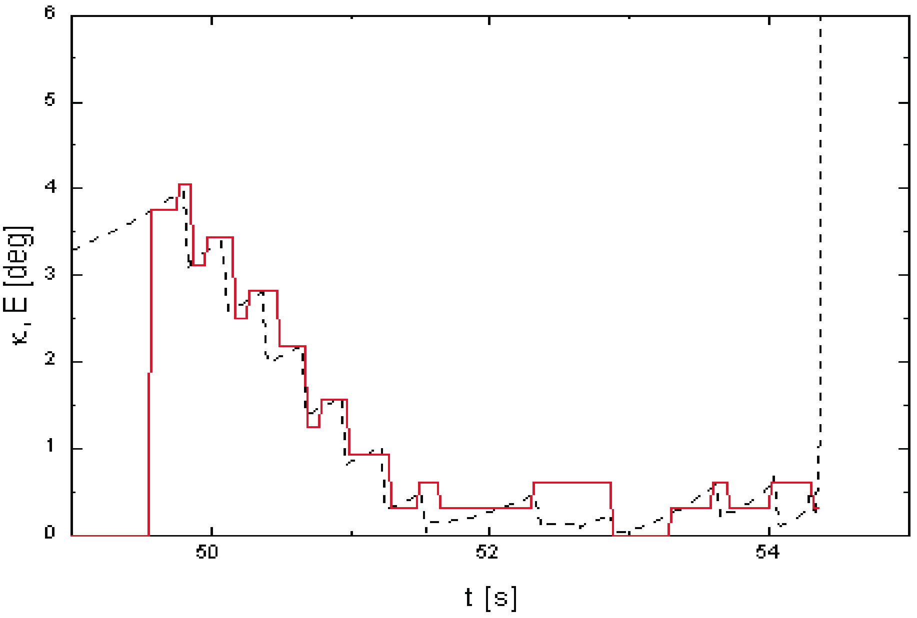

Fig. 14. The angular error κ (dash line) and the error value E measured by the Seeker (solid line) during the guidance phase of the missile. The error is measured as an angle between the speed vector axis and the seeker-target axis. The attack at the same conditions like in Figure 12

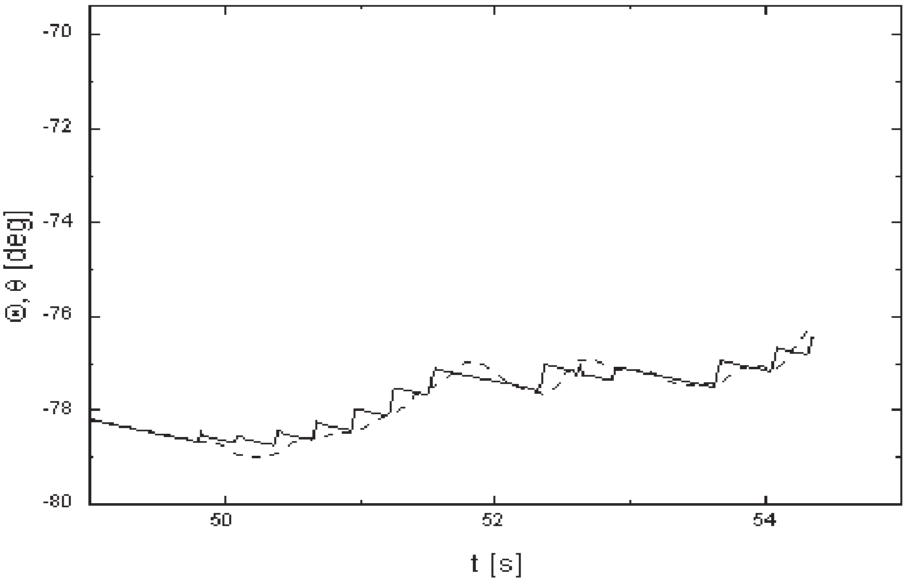

Fig. 15a.

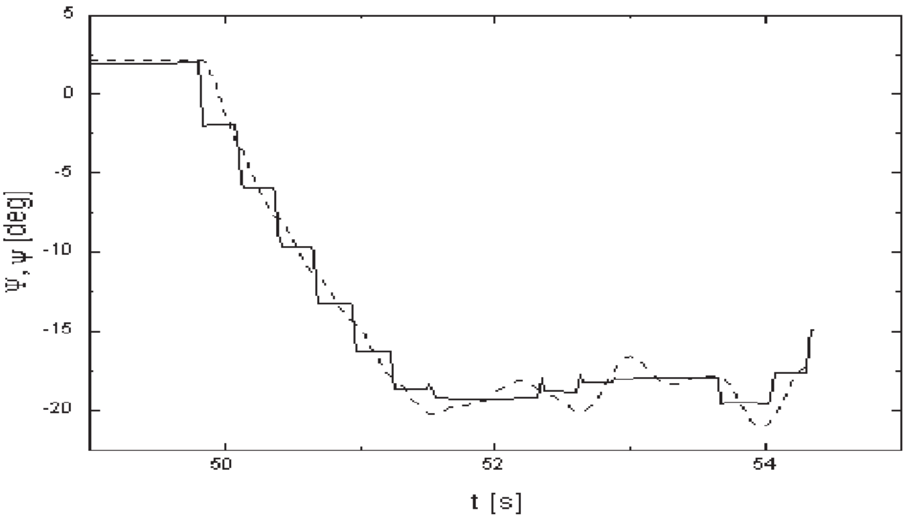

Fig. 15b.

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.

The investigation shows that for successful control the missile needs a proper energy capability in the potential of correction rocket engines. The amount of energy depends on mass of the missile. The division of energy between rocket engines and the engines' times of work are up to designer's decision.

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System sterowania inteligentnych pocisków moździerzowych

Streszczenie

W pracy przedstawiono doświadczenia z badań nad małymi inteligentnymi pociskami moździerzowymi. Prezentowany system jest prosty i niedrogi. Oparty jest na zestawie jednorazowych impulsowych silników korekcyjnych oraz linijkowym koordynatorze związanym na stałe z pociskiem i wirującym wraz z nim. Taki układ sterowania nie posiada części ruchomych. Impulsy sterujące od silników korekcyjnych są skierowane prostopadle do osi głównej symetrii pocisku i przechodzą przez środek ciężkości pocisku. W artykule opisano system sterowania. Szczególną uwagę zwrócono na głowicę śledzącą i układ wykonawczy sterowania. Zaprezentowano kilka wyników symulacji numerycznych lotu sterowanego pocisku.