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THE EVALUATION OF THE EFFICIENCY OF ACTIVE CONTROL SYSTEM FOR AERIAL BOMB

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Abstract

The article presents the results of numerical simulation of a laser-guided bomb, which is dropped in calm weather conditions. The prototype of such a bomb was developed at the Air Force Institute of Technology. It was a result of the modification process of the classical training bomb. The modification consisted of building on the bomb's board a detection system to track targets that are designated by laser and a control system to adjust bomb's glide path to precisely strike the target. In the simulation research, geometric and mass characteristics of the classical training bomb were used. Aerodynamic characteristics of the bomb have been determined using commercial software PRODAS. Using the mathematical model of the bomb spatial motion and model of the laser detection system series of simulations were performed. The main goal was to determine the effectiveness of the adopted construction solution. Therefore, simulations were performed for various initial positions of the bomb and fixed position of the target. It allowed finding the set of control laws coefficients giving the most accuracy of the bomb. The influence of structural modifications of the detection system on the possibility of effective detection and location of the target was also investigated. In the article, exemplary results of numerical calculations performed with the author's software are also shown.

Keywords: *simulation, PID controller, laser-guided bombs*

1. Introduction

Semi-active laser (SAL) detection or tracking systems are used by the military to support precision laser-guided weapons. With a SAL system, a narrow laser beam of energy is produced and transmitted toward a target. The laser radiation is typically generated and transmitted from a laser target designator (LTD) manned by a forward observer, for example. The forward observer directs the laser radiation to the selected target, thereby designating the target. The SAL seeking system of the laser guided bomb, remotely located from the target and designator, can detect the laser radiation reflected as a pulse signal from the target and assists in guiding the weapon to the target.

The Armaments Department of the Air Force Institute of Technology performs theoretical and experimental research works aimed at completing its own construction of this class of munition. As a result of the above research, in the process of modification of the conventional, training bomb, the prototype of the corrected bomb has been designed [6]. The modification consisted of building on board a tracking system, which detects targets pointed by laser. It allows adjusting bomb's glide path to precisely strike the target. The detection system consists of four symmetrically located detectors. The control system is built with two pairs of wings, which allow the bomb to be controlled in two planes.

The theoretical component of this works is focused on computer simulations based on the mathematical model of the bomb spatial motion as well as the model of the laser detection system. The main goal was to determine the effectiveness of the adopted construction solution.

Therefore, simulations were performed for various initial positions of the bomb and fixed position of the target. It allowed finding the set of control laws coefficients giving the most accuracy of the bomb [3, 4]. The influence of structural modifications of the detection system on the possibility of effective detection and location of the target was also investigated. Aerodynamic component of the bomb mathematical model was supported by aerodynamic characteristics calculated theoretically with commercial software Prodas [5] as well as by results of aerodynamic tunnel tests [7].

2. Mathematical model of the bomb motion

Mathematical model of the bomb spatial motion uses the following assumptions:

- it is a rigid body with six degrees of freedom forced by gravitation and aerodynamic impacts,
- the bomb has two surfaces of the mass and aerodynamic symmetry (*Oxy* and *Oxz*) overlapping with the control surfaces,
- control surfaces produce additional forces and moments depending on their deflections.

This model gives the set of 12 differential equations describing bomb spatial motions:

$$\dot{\mathbf{x}} = f(t, \mathbf{x}, \mathbf{u}), \tag{1}$$

where:

t – time,

$\mathbf{x}$ – vector of motion parameters,

$\mathbf{u}$ – vector of control.

This model was presented in details in [2] including aerodynamic aspects. Similar descriptions can be found for instance in [1]. Therefore, it is not repeated in this article. The set (1) is complemented by two control laws based on PID concept.

$$\mathbf{u} = \mu(\mathbf{x}). \tag{2}$$

3. Seeker characteristics

One of the significant problems during the simulation was the correct modelling of the geometry of the tracking system and its characteristics. This system consists of two pairs of identical detectors. They are located symmetrically in relation to the bomb longitudinal axis (Fig. 1). The longitudinal detectors axes of each pair lie in the symmetry planes of the bomb. The receivers were deflected (in the symmetry planes of the bomb) from the longitudinal axis of the bomb by the wedging angle ϕ_{det}. The position of detectors in the coordinate system associated with the bomb is shown in the Tab. 1.

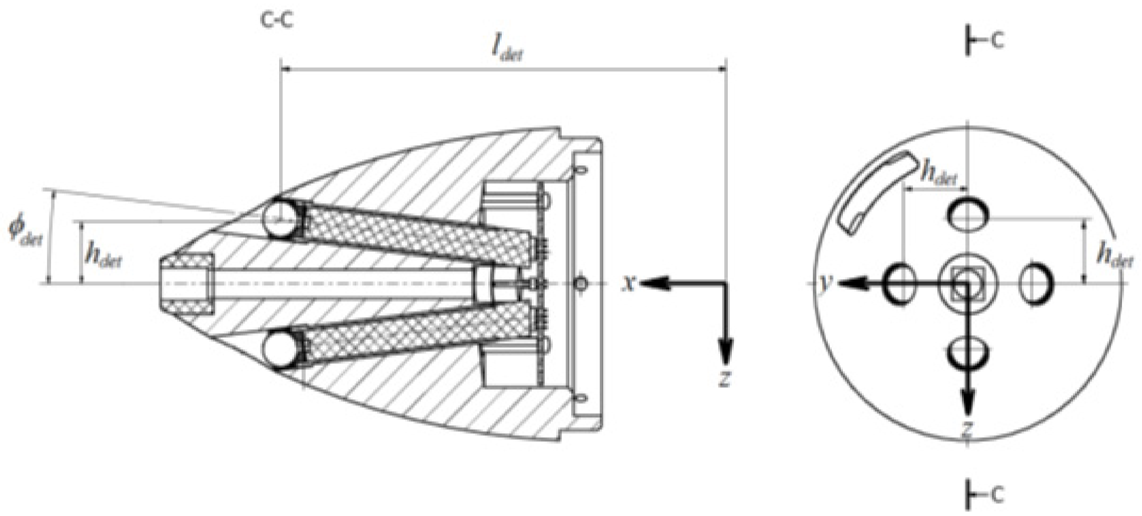

Fig. 1. The model of semi-active laser seeker

Tab. 1. Detectors coordinates and unit vectors

detector	coordinates	unit vector
Up	$\mathbf{r}_g = [l_{det}, 0, -h_{det}]$	$\mathbf{w}_g = [\cos\phi_{det}, 0, -\sin\phi_{det}]$
Down	$\mathbf{r}_d = [l_{det}, 0, h_{det}]$	$\mathbf{w}_d = [\cos\phi_{det}, 0, \sin\phi_{det}]$
Right	$\mathbf{r}_p = [l_{det}, h_{det}, 0]$	$\mathbf{w}_p = [\cos\phi_{det}, \sin\phi_{det}, 0]$
Left	$\mathbf{r}_l = [l_{det}, -h_{det}, 0]$	$\mathbf{w}_l = [\cos\phi_{det}, -\sin\phi_{det}, 0]$

For the simulation reason the detector characteristics were approximated by the function of normal distribution normalized to one with the expected value of $\mu = 0$ and standard deviation $\sigma = 5$ (Fig. 2). It gives always positive signals close to real. The used formula describing detected signal is as follows:

$$\overline{G}_i(\varphi_i) = \frac{G_i(\varphi_i)}{G_0} = e^{-\frac{1}{2}\left(\frac{\varphi_{det\,i}}{\sigma}\right)^2}, \tag{3}$$

where φ_{det} is the angle between the detector unit vector $\mathbf{w}_{det}$ and the line of sight $\mathbf{r}_{LOS}$ (LOS). They are shown in Fig. 3.

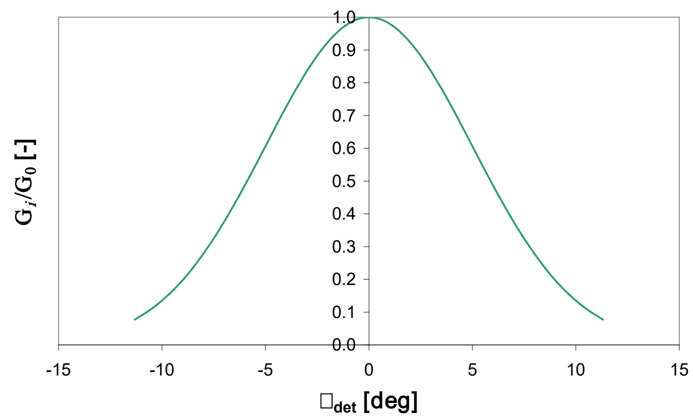

Fig. 2. Normalized detector characteristic

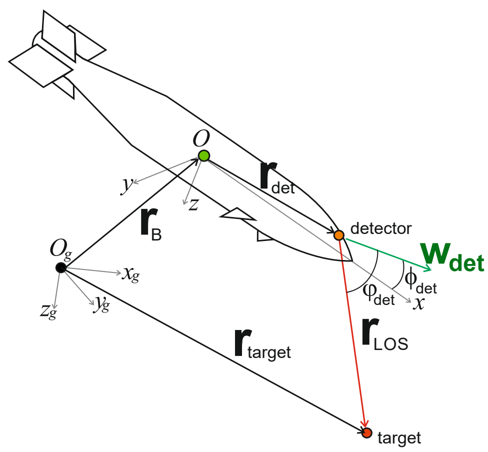

Fig. 3. Line of sight

The presented above arrangement of detectors made it possible to obtain in each of the bomb symmetry planes (corresponding to the control channels in these planes) the differential characteristics presented in red in Fig. 4. If the characteristics of detectors situated in one plane of the symmetry of the bomb are marked in green and blue, we have:

$$(\Delta\overline{G})_{red} = \overline{G}_{blue} - \overline{G}_{green}. \tag{4}$$

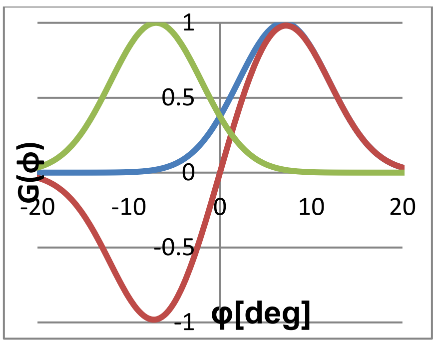

Fig. 4. Characteristic of the pair of detectors

The advantage of this solution is the occurrence of a linear section of the characteristic ΔG in a relatively large range of optical system angle and the point of discriminating the zero crossing with high value.

The choice of laser echo detection system configuration was made based on three assumptions:

- obtaining the widest possible optical system characteristics, maintaining the linear section in the middle part,
- obtaining the highest, maximum amplitude of the differential signal,
- obtaining the optimal characteristic amplitude for the zero angle value of the system target observation (unambiguous point for zero detection).

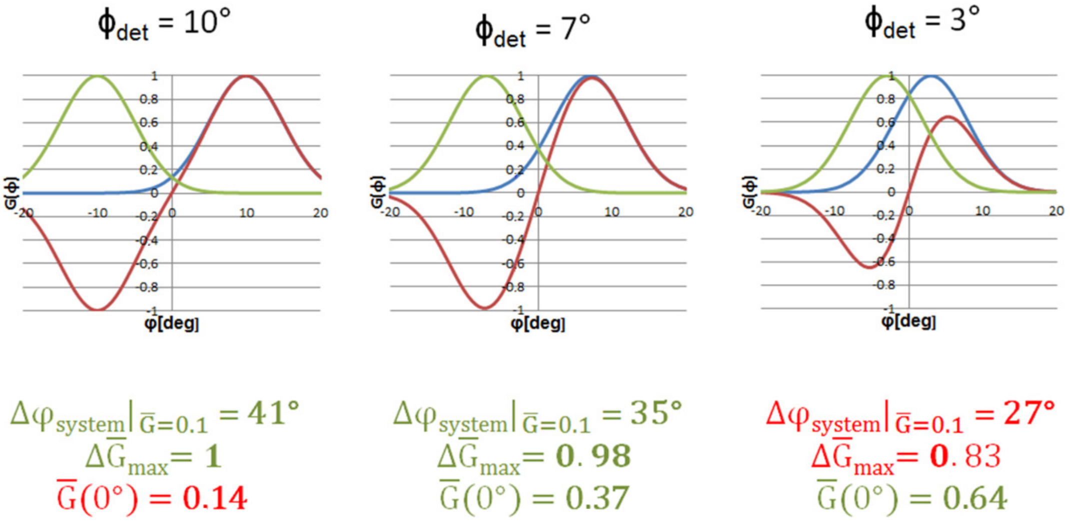

Fig. 5. Characteristic of the pair of detectors for different wedging angles

The analysis was done for three different wedging angles ϕ_{det} (10°, 7°, 3°). Results are shown in Fig. 5. Green and blue lines represent normalized signals of two detectors lying on same plane and the red line is the signal produced by this pair. It was assumed that the boundary value of the signal received by one detector is $\bar{G} = 0.1$.It gives the operational range of the tracking system $\Delta\varphi_{system}$[1], which is presented in this figure. The maximum value of the difference $\Delta\bar{G}$ is also presented as well as the value of the signal $\bar{G}$ (0°) for the case of $\varphi_{system} = 0°$.

At the outset of the analysis, the following conclusions were formulated:

- it should be clarified that the received signal $\bar{G}$ has to be significantly greater than the actual noise level of the receiver ($\bar{G} = 0.1$),
- for the wedging angle of 10 degrees the widest optical system characteristic$\Delta\varphi_{system}$ was obtained, the highest amplitude of the differential signal $\Delta\bar{G}$, but too low value $\bar{G}$ (0°) of the signal for $\varphi_{system} = 0°$,
- for the wedging angle of 3 degrees, both the width of the optical system characteristic $\Delta\varphi_{system}$ and the maximum amplitude of the differential signal $\Delta\bar{G}$ deviates from the limit values,
- the best results were obtained for the wedging angle of 7 degrees and at this angle, the detectors were finally mounted.

4. PID controller

In order to increase the efficiency of the control process and adjust the control system to the process which is the movement of the bomb in space, a control system based on the well-known [9, 10] and commonly used in automation a PID controller has been introduced – see Fig 6.

[1] φ_{system} is the angle between the axis of the bomb and the line directed to the target from the middle point of the seeker.

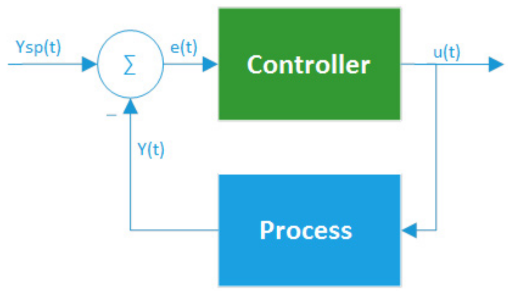

Fig. 6. PID controller

The PID controller continuously calculates an error value e(t) as the difference between a desired set point $Y_{sp}(t)$ and a measured process variable Y(t) and applies a correction based on proportional, integral, and derivative terms (denoted P, I, and D respectively) which give the controller its name. The controller attempts to minimize the error over time by adjustment of a control variable u(t).

The PID controller consists of a combination of proportional, integral and differential term:

$$u(t) = K_p \left[e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau + T_d \frac{de(t)}{dt} \right], \tag{5}$$

$$e(t) = Y_{sp}(t) - Y(t). \tag{6}$$

The term P is proportional to the current value of the error e(t). The term I includes past values of the error and integrates them over time. The term D estimates the future trend of the error e(t).

Although the PID controller has three control terms, some applications use only one or two terms to provide the appropriate control. This is achieved by setting the unused parameters to zero and is called a PI, PD, P or I controller in the absence of the other control actions.

The general principles of choosing the type of regulator for the process are as follows:

- in order to obtain static deviations close to zero, integrator I is necessary,
- PI controller provides good control quality only for low frequency disturbances,
- PD controller provides a wider control band than the PI controller, but with slow-changing disturbances; the values of the control quality indicators are worse,
- PID controller combines the advantages of all previous regulators.

The parameters of the controller are K_p gain, T_i integration time and T_d derivative time. Because the parameters of regulators are very difficult or even impossible to determine in an analytical way, the so-called tuning methods are used. These include, among others:

- impulse response method,
- Ziegler-Nichols method,
- frequency response method.

Two types of controllers were tested during research:

- P type Controller (Kp = 1),
- PI type Controller (Kp = 0.32, Ti = 1.5).

The terms of the controllers were tuned using the Ziegler-Nichols method.

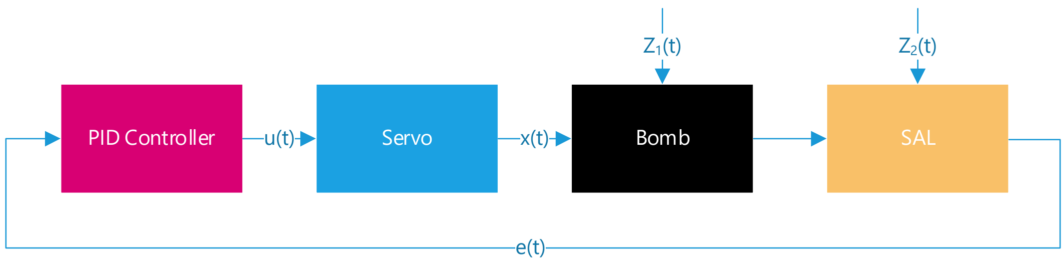

Fig. 7. The workflow of laser-guided system

Ultimately, the laser-guided system operates according to the scheme shown in Fig. 7. The error e(t), which is a function of the difference of the angles of detector sightφ_{det}, goes to the input of the PID controller. The output signal of the regulator u(t) transmits directional command signals to the appropriate pair(s) of canards. The canards deflections interacting with the air cause the bomb motion. Since the seeker is permanently coupled with the bomb, the angles of sight φ_{det} change, and thus the change of error e(t) and the whole process repeat.

5. Results of simulations

Using the described above model of the bomb spatial motion and the model of the laser guided system series of simulations were performed. Simulations were carried out using authors software, which graphical user interface (GUI) was presented at Fig. 8.

On the left side of the GUI, there is a control menu bar. Here one can set the initial parameters for bombing, select the bomb model, choose the model of the detector, set the parameters of the target location, select the parameters of the PID controller and at the end of simulation process, read the bomb parameters at the moment of the bomb's impact.

Simulations were performed assuming that the bomb is released by an aircraft performing steady state horizontal flight, for the following initial conditions [8]: the altitude – 2000 meters, the velocity – 40 m/s, the pitch angle 0.

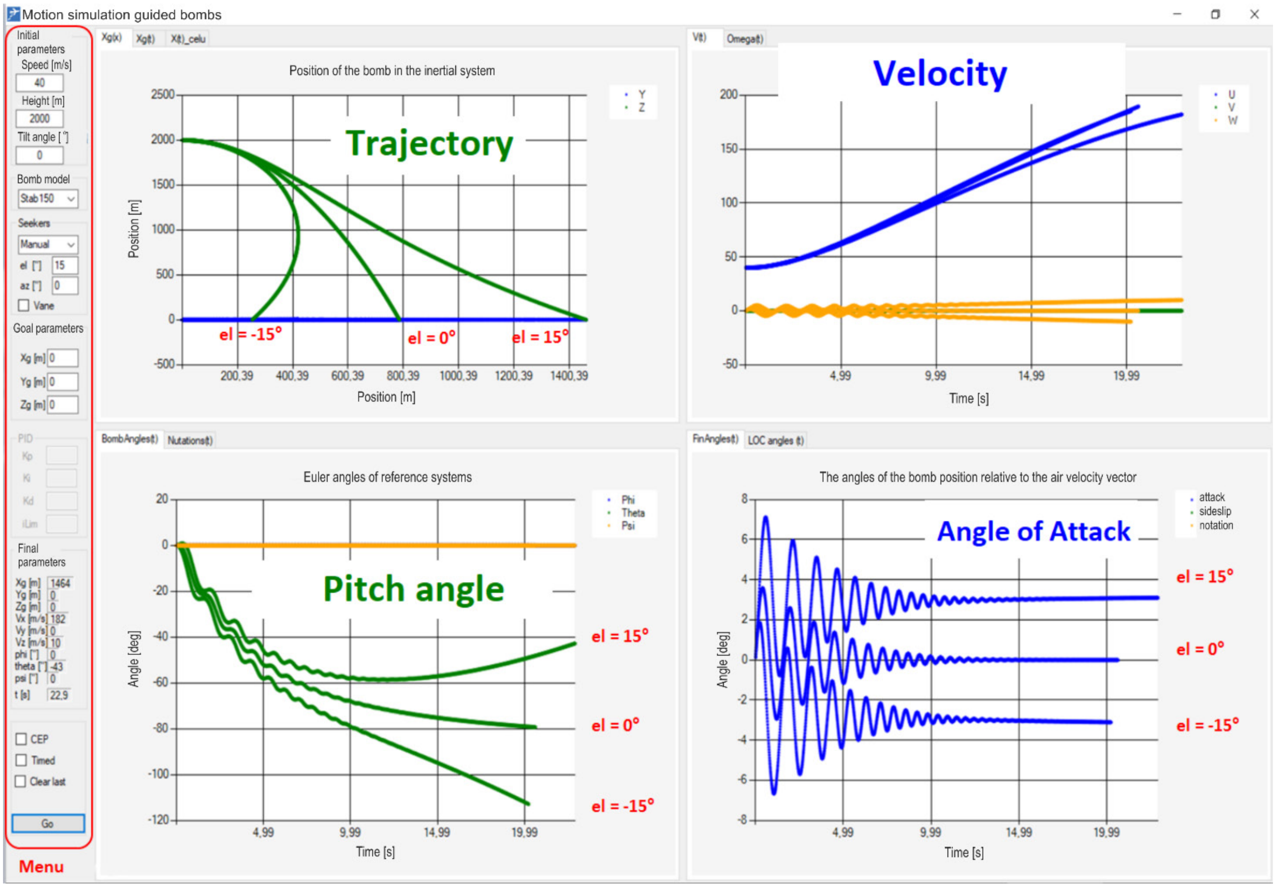

Fig. 8. Graphical user interface of simulation software

5.1. Releases of the unguided bombs

The main goal of releases free-fall bombs was to determine an effectiveness of canards. To achieve this aim three simulations were done for canards deflections: -15º, 0º, +15º.

The results of the simulations are presented in Fig. 9 and Fig. 10. The graph in Fig. 9 shows the trajectories of the bomb (y_g – blue, H – green) as a function of the linear distance x_g and informs about the effectiveness of the control system and the bombing range.

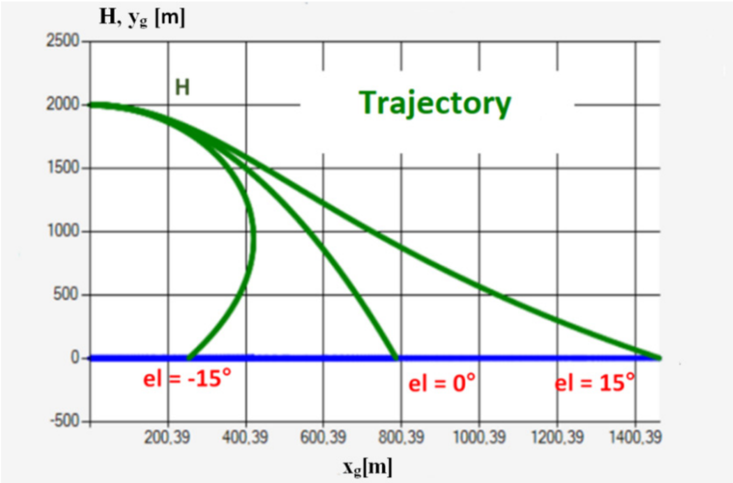

Fig. 9. Vertical trajectory of the bomb – longitudinal control

The graph in Fig. 10 shows the angle of attack changes for different values of canards deflection. The chart shows that despite the extreme deflection of the canards, the angles of attack remain within the range of linear characteristics of the bomb aerodynamic coefficients.

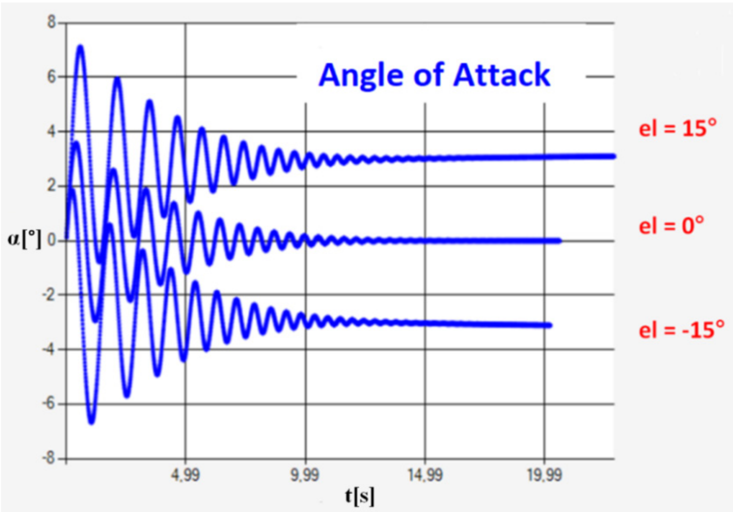

Fig. 10. Angle of attack

5.2. Release of the laser guided bomb

Subsequent simulations consisted of bombing with the guidance system turned on. Simulations were performed for two types of controllers – P and PI. The initial conditions have not been changed, the point of aim (POA) is set to position Xc = [1100, 0, 0].

Figure 11 shows the bomb trajectory with the laser-guided system turned on. Control system in the form of a P-type controller was used. The impact of the bomb (point of impact POI) took place 35 m before the POA. It should be noted here that for the above initial condition of the release with the laser-guided system turned off (canards set in position 0°) the bomb would impact at the point [787, 0, 0]. The simulation shows that the bombing range for guided bomb dramatically increases.

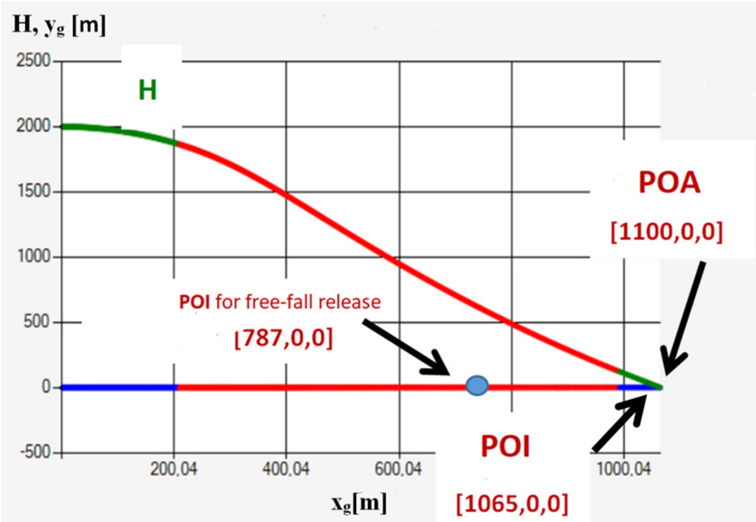

Fig. 11. Vertical trajectory of the bomb – P type controller

Figure 12 shows the canards angles as a function of time for the same simulation. δ_M is the control angle for the longitudinal motion and δ_N for lateral motion. Because the bombing is performed at the horizontal plane the angle δ_N is equal to zero all the time. The influence of changes in the angular position of the bomb on the deflection of the canards is clearly visible.

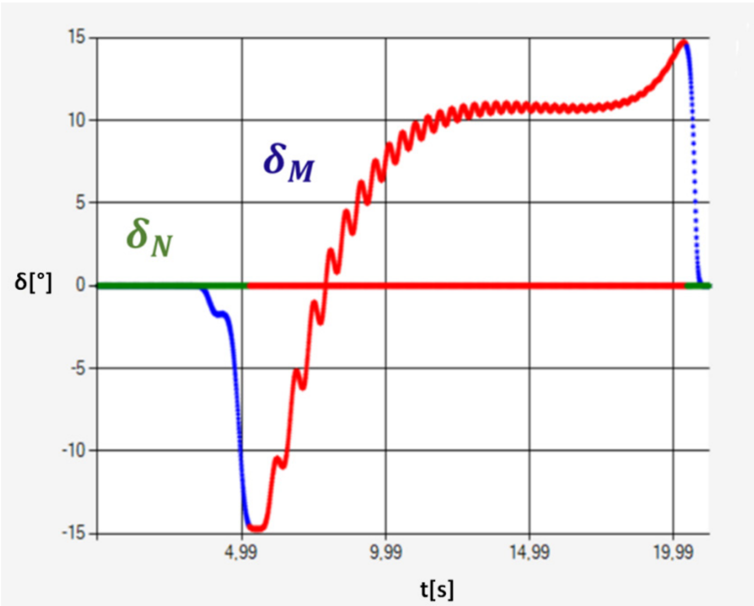

Fig. 12. Cardan's angle – P type controller

Other simulations were performed using a PI type controller. The trajectory of the bomb is shown in Fig. 13. The results of the simulation show that the use of the PI type controller significantly improved bombing precision comparing with the P type one.

As one can see, the term I of the controller has introduced some inertia in the regulator's operation, as a result of which the canards react more slowly to changes of the current φ_{system} angle. This is well illustrated by the graph in Fig. 14. One can also observe a significant reduction in the influence of changes in the angular position of the bomb in reaction to Cardan's deflection.

Additionally, the graph in Fig. 14 shows the specificity of the integral controller's function. The value of canards deflection developed by the term I of the controller was in the short time period so large that it had to be win duped (limited to the maximum value).

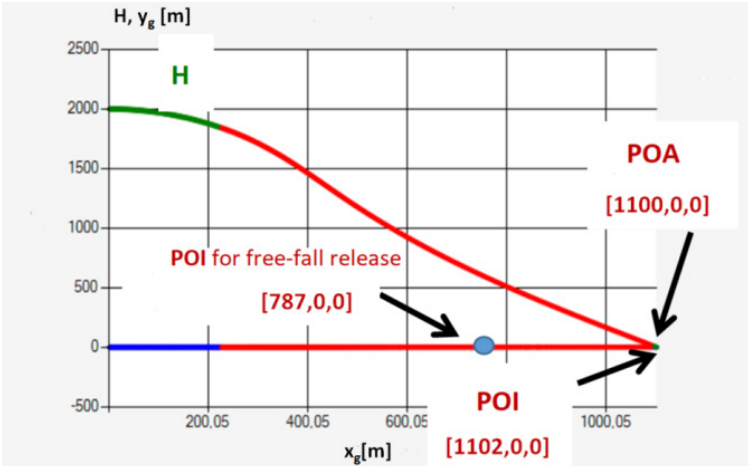

Fig. 13. Vertical trajectory of the bomb – PI type controller

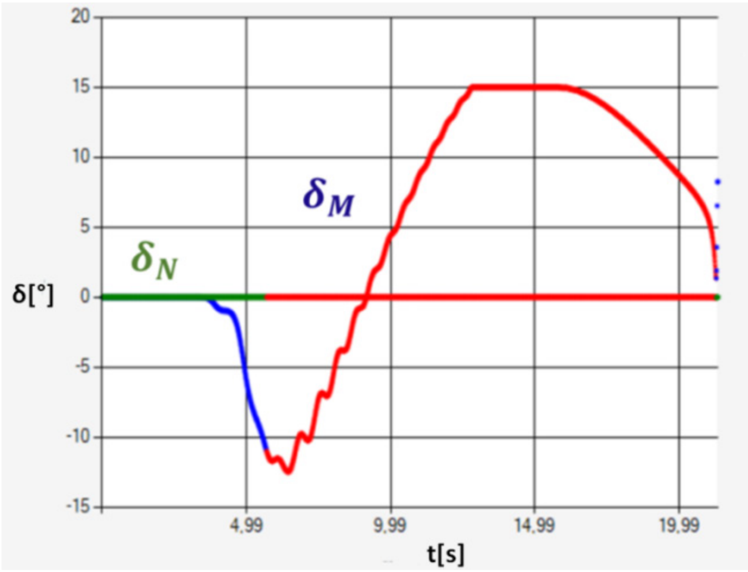

Fig. 14. Cardan's angle – PI type controller

In order to assess bombing precision, simulations were carried out involving the execution of one hundred bomb releases for each of the controller types used. Additionally, the initial conditions for bombing were disturbed using the program's random function. The disturbance was supposed to imitate the pilot error resulting from overtaking or delay of the moment of release in the range of ±2 s. Because the initial velocity was 40 m/s, the change of the point of release in relation to the POA was achieved in the range of ±80 m in the x, y plane. The results of the simulation are shown in Fig. 15.

For a bomb corrected with the P type controller, the average of the POI is about 37 m from the POA. Standard deviations of one hundred bomb's releases in relation to the average of POI are $\sigma_x = 7.2$ m and $\sigma_y = 4.3$ m.

For the case of a bomb corrected with the PI type controller, the bombing precision is significantly improved. The average of the POI is about 2 m from the POA. Standard deviations of one hundred bomb's releases in relation to the average of the POI are $\sigma_x = 2.1$ m and $\sigma_y = 0.5$ m.

6. Conclusions

Based on the performed simulations, it can be concluded that the use of a laser-guided system in aerial bombs significantly increases both the effective of bombing range and the bombing precision. For the initial bombing altitude 2000 m and the initial velocity 80 m/s, the effective bombing range is from about 400 m to about 1200 m from the release point. On the other hand, the bombing precision understood as the minimum distance between the POA and the average of the POI strictly depends on the control laws used, i.e. on the quality of the adjustment of the controller to the model of the bomb spatial motion.

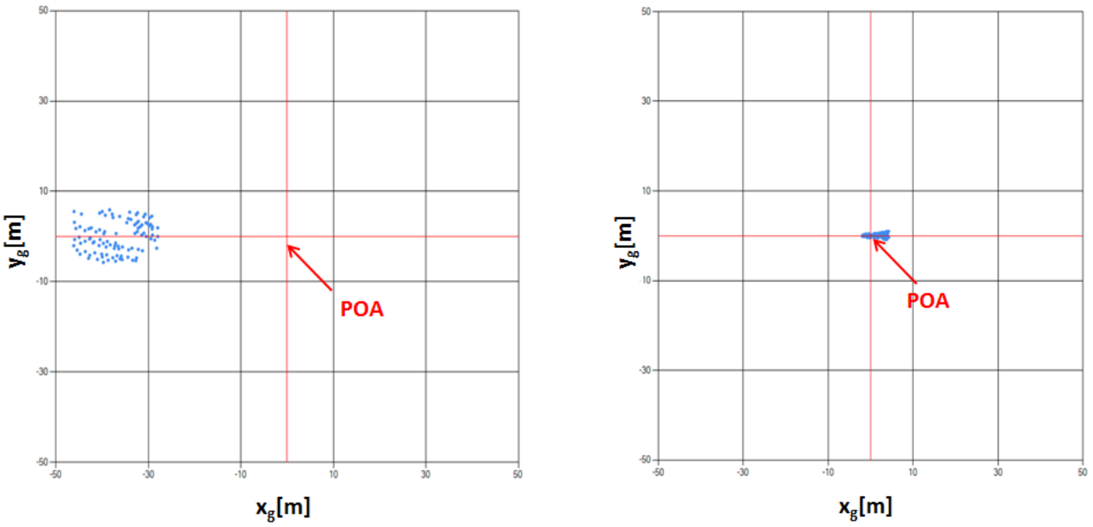

Fig. 15. Results of simulations – P type controller – on the left, PI type controller – on the right

Bearing in mind the above should be stated that the main effort of further work should be focused on the optimization of control laws in terms of bombing precision for various initial bombing condition.

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