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Research paper

Hybrid Control System for a Vertically Guided Bomb During Self-guidance in Turbulent Conditions

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Abstract. The article presents a mathematical model and an algorithm for hybrid control of a bomb aimed at a moving ground target. The guided bomb flight control system subject to the study combines a conventional PD controller and a quasi-sliding mode (QSM) controller. The target trajectory was determined based on the kinematic relations of the mutual motion of the bomb and the ground target using the proportional approach method. The main aim of the article is to analyse the impact of atmospheric turbulence on the flight of a guided bomb, and then to determine its impact on homing parameters, such as homing time and accuracy of hitting a ground target. The numerical studies covered three types of controllers: conventional PID, quasi-sliding and hybrid. The effectiveness of the proposed control system was analysed without and during random atmospheric turbulence. The article examines the hybrid system's properties for controlling guided bombs. Numerical studies were performed using the Matlab/Simulink software suite. The article presents selected results of this computer simulation.
Keywords: guidance / homing, guided bomb, hybrid control system, sliding mode control, atmospheric turbulence

1. INTRODUCTION

Today's warfare requires air-to-ground flying objects (guided bombs, rocket missiles) to strike precisely against detected ground targets. The authors [1] point out that precision-guided airborne munitions are gradually gaining importance at the cost of conventional "nonselective" means of destroying targets in modern armed conflicts. Launching an attack even from a great distance should be possible while minimising collateral damage [2]. This type of munitions can be used, for example, during a precise strike against a selected combat vehicle moving in a military column. Such tasks require well-planned and accurate action. The article assumes that the inaccuracy of a guided bomb hitting a moving ground target is to be less than 7 metres. It is therefore essential that a guided bomb flight control system is adequately designed to meet this requirement. Among the many control methods described in the literature, the most popular are still conventional PID controllers [3], [4], [5]. However, the authors have proven in their work [6] that using a conventional controller for adjusting the angular deviation alone did not allow the ground target to be hit with the required precision. The hybrid algorithm has changed this. Going a step further, this paper offers another type of hybrid algorithm. The authors suggest combining a conventional PD controller with a quasi-sliding mode (QSM) controller, but in parallel. The occurrence of disturbances and uncertainties in the control and guidance systems of a guided bomb is natural, and it is necessary to consider these factors when designing this type of system. When considering flying objects, including a guided bomb, atmospheric turbulence can significantly impact the flight trajectory. That is why the authors decided to examine the impact of a random atmospheric turbulence on the guided bomb flight control system of their design. For this purpose, the random nature of turbulence velocities was modelled using preset parameters.

To sum up, the making of this control system consisted of the following steps, according to [7]:

1) Create a model of the kinematics and dynamics of the guided bomb.
2) Design a hybrid control algorithm.
3) Implement the control algorithm – this step consisted of the algorithm's numerical implementation in the Matlab/Simulink environment, during which a simulation application was developed to verify the behaviour of the kinematics and dynamics model of the guided bomb and the operation of the proposed control algorithm.

The main subject of this article is the analysis of the effectiveness of the guided bomb control system during the occurrence of random atmospheric turbulence.

2. FLAT MATHEMATICAL MODEL OF GUIDING A BOMB TO A GROUND TARGET

2.1. Equations of motion of the bomb in the vertical plane

The bomb is assumed to move only in the vertical plane. For this scenario, the nonlinear equations of motion of the bomb can be written as follows [8]:

$$m\left[\dot{U} + QW + g\sin\Theta\right] = F_x \tag{1}$$

$$m\left[\dot{W} - QU + g\cos\Theta\right] = F_z \tag{2}$$

$$\dot{Q} = \frac{1}{I_y}\left[M_y + \left(I_z - I_x\right)PR\right] \tag{3}$$

$$\dot{\Theta} = Q \tag{4}$$

The forces F_x and F_z, and the moment M_y acting on the bomb, appearing in relations (1)-(3), can take this form:

$$F_x = -mg\sin\Theta - C_{aX}\frac{\rho\left|\mathbf{V}_a\right|^2}{2}S_b \tag{5}$$

$$F_z = mg\cos\Theta + \frac{\rho\left|\mathbf{V_a}\right|^2}{2}S_b\left(-C_{aN}\left(\frac{W}{\left|\mathbf{V_a}\right|}\right) - C_{aNr}\left(\frac{Qd}{2\left|\mathbf{V_a}\right|}\right) - C_{Nd}\delta_w\right) \tag{6}$$

$$M_y = \frac{\rho\left|\mathbf{V_a}\right|^2}{2}S_b\left(dC_m\left(\frac{W}{\left|\mathbf{V_a}\right|}\right) + dC_q\left(\frac{Qd}{2\left|\mathbf{V_a}\right|}\right) - l_d C_{Nd}\delta_w\right) \tag{7}$$

where: m – mass of the bomb, g – gravitational acceleration, U, W – components of the velocity vector of the bomb relative to air in the frame of reference S_{xyz}, Q – component of the angular velocity vector of the bomb in the frame of reference, Θ – quasi-Eulerian tilt angle, ρ – air density, d – diameter of the bomb body, S_b – characteristic surface (cross-sectional area) of the bomb, l_d – distance between the rudder thrust centre and the centre of mass of the bomb, V_a – vector of velocity of the centre of mass of the bomb relative to air, δ_w – elevator deflection angle, C_{aX} – aerodynamic axial force coefficient, C_{aN} – aerodynamic normal force coefficient, C_{aNr} – aerodynamic damping force coefficient, C_m – aerodynamic pitching moment coefficient, C_q – coefficient of damping pitching moment, C_{Nd} – aerodynamic control force coefficient.

Aerodynamic forces and moments are the most important external factors acting on the bomb. Their value is estimated by determining the aerodynamic characteristics of the bomb. The aerodynamic coefficients appearing in equations (5)-(7) were taken from a doctoral dissertation [9].

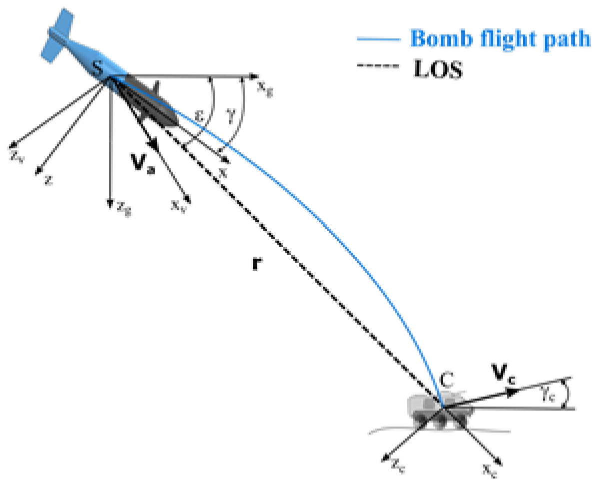

Fig. 1. Overview of the bomb's self-guidance towards a ground target

Taking into account Fig. 1, the equations of the kinematics of the mutual motion of the bomb and the ground target, in the case of the vertical plane, can be written as follows:

$$\frac{dr}{dt} = V_c\left(\cos\gamma_c\cos\varepsilon + \sin\varepsilon\sin\gamma_c\right) - V_a\left(\cos\gamma\cos\varepsilon + \sin\varepsilon\sin\gamma\right) \quad (8)$$

$$-\frac{d\varepsilon}{dt}r = V_c\left(\cos\gamma_c\sin\varepsilon - \cos\varepsilon\sin\gamma_c\right) - V_a\left(\cos\gamma\sin\varepsilon - \cos\varepsilon\sin\gamma\right) \quad (9)$$

where: r – distance of the bomb from the ground target, V_c – velocity of the target, γ_c – tilt angle of the target's velocity vector, γ – tilt angle of the bomb's velocity vector, ε – tilt angle of the target line of sight (TLS).

The trajectory of the bomb's centre of mass in the earth-related coordinate system is obtained using appropriate transformations presented in the work [10]. Finally, in the case of the bomb moving in the vertical plane, we get:

$$\begin{aligned} \frac{dx_g}{dt} &= U\cos\Theta + W\sin\Theta \\ \frac{dz_g}{dt} &= -U\sin\Theta + W\cos\Theta \end{aligned} \tag{10}$$

Equations of motion of the centre of mass of the target in the system related to the flight trajectory for the vertical plane:

$$\begin{aligned} \frac{dx_c}{dt} &= V_c\cos\gamma_c \\ \frac{dz_c}{dt} &= -V_c\sin\gamma_c \end{aligned} \tag{11}$$

In this article, we consider the case for which V_c = const. and $\gamma_c = 0$, so the target moves in a straight line.

3. HYBRID GUIDED BOMB CONTROL SYSTEM

The primary device of the guided bomb flight control system is the autopilot, which executes the object-guiding algorithm using the control actuator system. In the case under consideration, the control actuator system is the elevator. The proposed structure of the hybrid controller combines a conventional PD controller with a QSM controller that is connected in parallel. The block diagram of the hybrid guided bomb control system is shown in Fig. 2. Such solutions are successfully used to control various types of objects including rocket missiles [11] and hypersonic flying objects [12]. The task of the autopilot is to continuously calculate control errors (deviations) e_w and, based on this, generate appropriate control signals in the case under consideration u_w. The law of control is therefore given in this form:

$$u_w = u_{PD} + u_{QSM} \tag{12}$$

In the case of the PD controller, the control signal takes the following form:

$$u_{PD} = k_{pw}e_w + k_{dw}\frac{de_w}{dt} \tag{13}$$

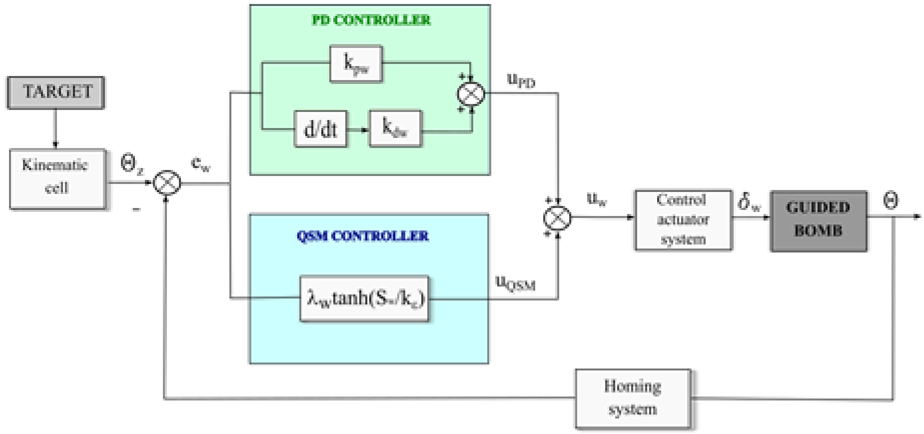

Fig. 2. Block diagram of the hybrid guided bomb control system

In this paper, we consider a QSM controller for which the sliding plane takes the form expressed by the equation:

$$S_w\left(e_w,t\right)=\frac{de_w}{dt}+c_c\cdot e_w,\quad c_c>0 \tag{14}$$

where: c_c – controller parameter (constant).

The control signal from the QSM controller takes the following form:

$$\delta_w=\lambda_w\cdot\tanh\left(\frac{S_w}{k_\varepsilon}\right) \tag{15}$$

where: k_g – coefficient that determines the slope of the signum function, λ_w – constant with a positive value (controller's parameter)

Due to the omission of the dynamics of the control actuator system (elevator) for the flight of the bomb, it was assumed that $u_w = \delta_w$. For the proposed structure, the control error depends only on the guided bomb tilt angle:

$$e_w=\Theta_z-\Theta \tag{16}$$

The bomb directed at a ground target guides itself according to the proportional navigation algorithm (see [6]):

$$\frac{d\gamma}{dt}=a_\varepsilon\frac{d\varepsilon}{dt} \tag{17}$$

4. MODELING ATMOSPHERIC TURBULENCE

Atmospheric turbulence is modelled in this paper as a stationary random Gaussian process [13]. The term “stationary” means that the profile is considered infinite, with constant statistical properties. The turbulence profile is random and can only be defined by its statistical characteristics [14]. The Dryden and von Karman models are generally used today to calculate spectral densities of the power of turbulence velocities. According to [15], the von Karman model is based on theoretical and experimental measurements, while the Dryden turbulence model is a simplified version. Although the velocity profiles obtained from both models are comparable, the Dryden model was used in this study because it is more convenient in numerical research.

According to the recommendations of military specifications [16], [17], the power spectral density functions of the Dryden model for the linear components of turbulence velocities can be written as follows

$$\Phi_{u_t}(\omega) = \frac{2\sigma_u^2 L_u}{\pi V} \frac{1}{1+\left(L_u \frac{\omega}{V}\right)^2} \tag{18}$$

$$\Phi_{w_t}(\omega) = \frac{\sigma_w^2 L_w}{\pi V} \frac{1+3\left(L_w \frac{\omega}{V}\right)^2}{\left[1+\left(L_w \frac{\omega}{V}\right)^2\right]^2} \tag{19}$$

where: σ_u, σ_w, – standard deviation of atmospheric turbulence components, L_u, L_w – scales of appropriate atmospheric turbulence components, V – average flight speed of the bomb, ω - frequency

Additionally, the analysis covered the impact of conditions similar to real ones (the bomb moves in the Earth’s atmosphere) on the accuracy of hitting the ground target, the shape of the flight trajectory and the values of the generated control forces. Numerical methods were used to generate linear velocities of atmospheric turbulences to perform numerical simulations. An analysis of the effectiveness of the bomb control system during this type of turbulence is required. A random course of the atmospheric turbulence velocity components was generated for the initial data: $\sigma_u = \sigma_w = 15$ m/s and $L_u = L_w = 650$ m.

5. RESULTS OF THE SIMULATION STUDIES

As part of the research, an analysis of the effectiveness of the hybrid control system was carried out for the scenario involving the influence of atmospheric turbulence.

For each of the considered cases, a numerical simulation was performed in the Matlab software suite for identical initial conditions, namely:

- starting position of the bomb: $x_{g0} = 0$ m, $z_{g0} = 3000$ m;
- initial components of the drop velocity: $U_0 = 120$ m/s, $W_0 = 0$ m/s;
- initial position of the ground target: $x_{c0} = 2000$ m, $z_{c0} = 0$ m;
- initial velocity of the ground target: we assume $V_{c0} = 0$ m/s, for the stationary target, while the moving target moves in a straight line with a constant speed of $V_{c0} = 5$ m/s;
- initial bomb tilt angle: $\Theta_0 = 0^o$;
- initial flight trajectory tilt angle: $\gamma_0 = 0^o$;
- the remaining parameters are null.

The bomb was guided using the proportional navigation algorithm with the coefficient $a_\varepsilon = 3.5$. Additionally, in the case of the QSM controller, it was assumed that $\lambda_w = \delta_{max}$, i.e. $\lambda_w = 20^o$. The results of the numerical simulation of the bomb self-guidance to the moving ground target are shown in Figures 3-8.

As part of the simulation studies, the values of self-guidance parameters, such as the homing time and the accuracy of hitting the ground target, were determined. The resulting values of the parameters are listed in Table 1.

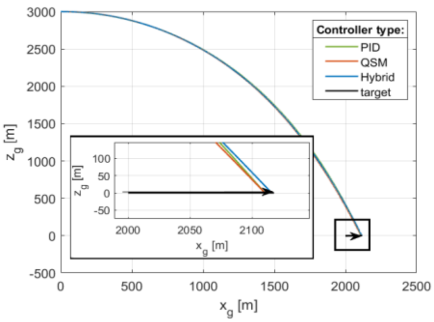

Fig. 3. Flight trajectories of the bomb heading to the moving target

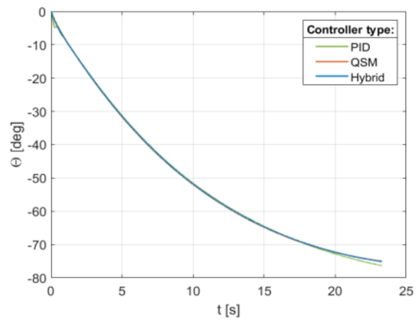

Fig. 4. Bomb tilt angles as a function of time

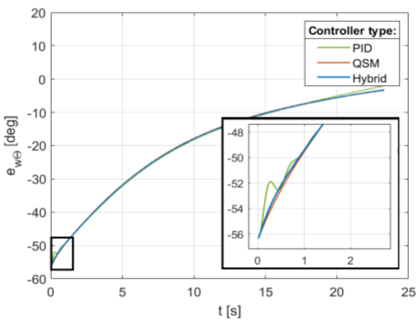

Fig. 5. Angular deviations of the bomb flight as a function of time

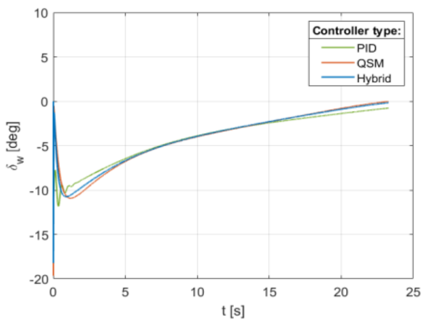

Fig. 6. Elevator deflection angles as a function of time

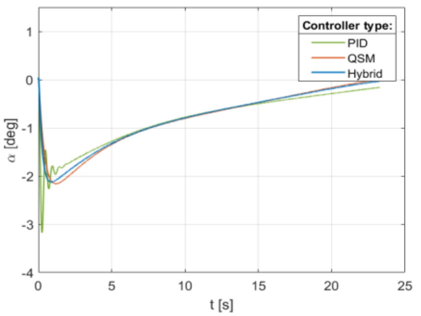

Fig. 7. Bomb angles of attack as a function of time

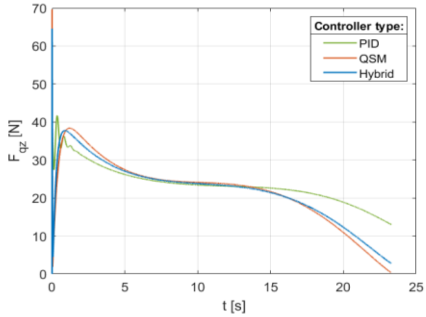

Fig. 8. Control forces as a function of time

Table 1: List of parameters of the bomb self-guidance to the moving target

Moving target: $V_c = 5$ m/s		
Controller type	**Homing time [s]**	**Hit accuracy [m]**
PID	23.30	7.30
QSM	23.27	7.26
Hybrid	23.29	1.86

Table 2 shows selected values of the amplification factors for all the types of controllers tested.

Table 2: List of controller gain factors: PID, QSM and Hybrid for the moving target

Moving target: $V_c = 5$ m/s				
PID	k_{pw}	k_{iw}	k_{dw}	
	0.21	0.001	0.135	
QSM	c_c		k_ε	
	0.167		0.081	
Hybrid	k_{pw}	k_{dw}	c_c	k_ε
	0.0025	0.055	0.22	0.165

The numerical studies made it possible to assess the effectiveness of the proposed guided bomb control algorithms, mainly those of the hybrid control system. The main criterion was the minimum distance of the spot of the bomb landing, i.e. the accuracy of the hit. The self-guiding of the bomb aimed at the moving ground target was correct. Of the three types of algorithms considered, the most effective was the Hybrid algorithm, which was a combination of the PD control and the QSM control (the accuracy was 1.86 metres).

It should be emphasised that both the PID controller and the QSM controller, used separately, fell slightly short the required homing accuracy. However, if we take into account the precision of hitting the ground target, it is the Hybrid controller that should be used for the guided bomb flight control system. The remaining flight parameters of the guided bomb (angle of attack and pitch angle) showed a similar nature of changes for all the controllers tested. The elevator angle was at its highest in the initial phase of the guided bomb's flight, but it did not exceed the permissible value anyway $\lambda_w = 20^o$.

The results of the numerical simulation of the bomb homing towards the moving ground target during atmospheric turbulence are shown in Figs. 9-14.

As part of the simulation studies, the values of self-guidance parameters, such as the homing time and the accuracy of hitting the ground target, were determined. The values of the parameters are listed in Table 3.

Table 4 shows selected values of the amplification factors for all the tested types of controllers that were subjected to atmospheric turbulence.

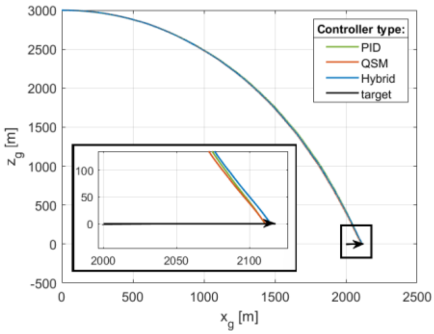

Fig. 9. Bomb flight trajectories to the moving target

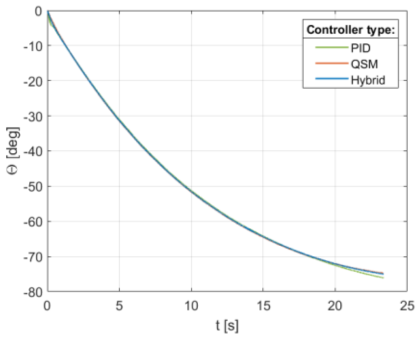

Fig. 10. Bomb tilt angles as a function of time

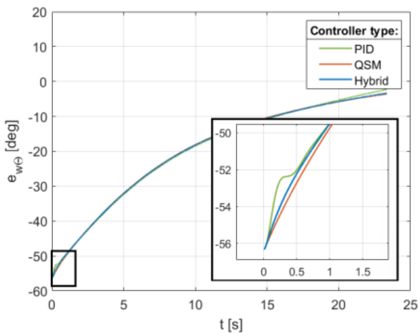

Fig. 11. Angular deviations of the bomb flight as a function of time

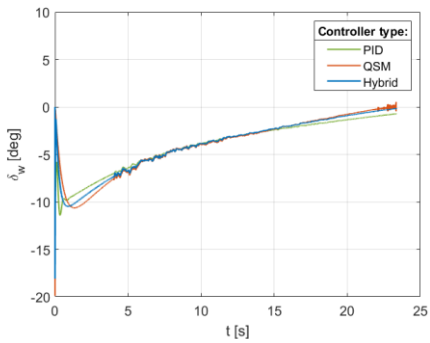

Fig. 12. Elevator deflection angles as a function of time

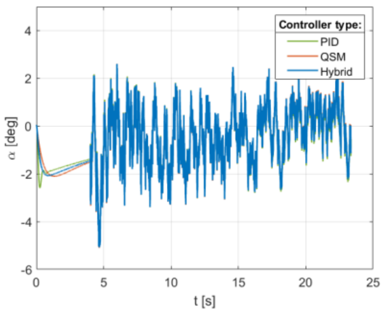

Fig. 13. Bomb angles of attack as a function of time

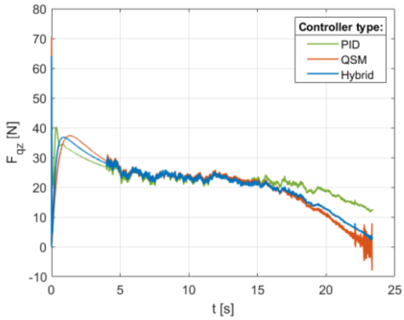

Fig. 14. Control forces as a function of time

Table 3. List of parameters for the bomb self-guidance to the moving target during atmospheric turbulence

Moving target: V_c = 5 m/s		
Controller type	**Homing time [s]**	**Hit accuracy [m]**
PID	23.37	7.37
QSM	23.35	7.05
Hybrid	23.34	3.45

Table 4. List of controller gain factors for the moving target: PID, QSM and Hybrid for the moving target

<table>
<tr><th colspan="13">Moving target: V_c = 5 m/s</th></tr>
<tr><td rowspan="2">PID</td><td colspan="4">k_{pw}</td><td colspan="4">k_{iw}</td><td colspan="4">k_{dw}</td></tr>
<tr><td colspan="4">0.22</td><td colspan="4">0.001</td><td colspan="4">0.28</td></tr>
<tr><td rowspan="2">QSM</td><td colspan="6">c_c</td><td colspan="6">$k_ε$</td></tr>
<tr><td colspan="6">0.15</td><td colspan="6">0.059</td></tr>
<tr><td rowspan="2">Hybrid</td><td colspan="3">k_{pw}</td><td colspan="3">k_{dw}</td><td colspan="3">c_c</td><td colspan="3">$k_ε$</td></tr>
<tr><td colspan="3">0.0025</td><td colspan="3">0.079</td><td colspan="3">0.22</td><td colspan="3">0.17</td></tr>
</table>

The research results show an evident influence of atmospheric turbulence on the dynamics and trajectory of the guided bomb. At the same time, the diagrams of the bomb's flight state variables entering the area of atmospheric turbulence in the fourth second of flight confirm the correctness of the proposed model. Based on the study results, it is possible to notice differences in the operation of the elevator when atmospheric turbulences affect the bomb. The Hybrid controller provided the best accuracy of hitting the ground target (3.45 meters), although this accuracy changed minimally for the PID and QSM controllers in the case of self-guidance without atmospheric turbulence.

All the tested variables of the guided bomb flight status (pitch angle, attack angle, elevator deflection angle) and the control force for all the analysed controllers show a similar nature of changes, and change their values randomly in the presence of turbulence.

It is also important to determine the impact of individual types of control signals of the Hybrid controller on the effectiveness of its operation.

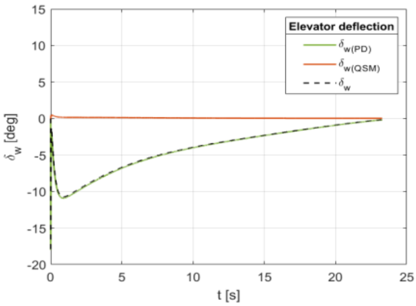

Fig. 15. Elevator deflection angles as a function of time

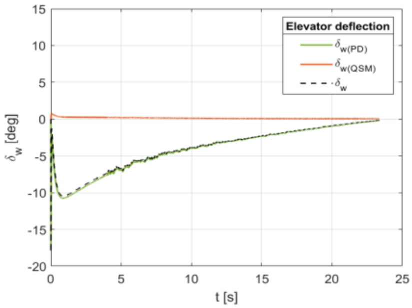

Fig. 16. Elevator deflection angles as a function of time

Figures 15 and 16 show the deflection angles generated by the PD and QSM controllers. Despite the insignificant value of the control signal generated by the conventional PD controller, we obtain an object precisely guided to the ground target (hit accuracy of about 2 metres). It is not possible to achieve such accuracy with the conventional PID and QSM controllers working independently.

6. CONCLUSIONS

Theoretical considerations and simulation studies made it possible to assess the effectiveness of the guided bomb control algorithms proposed in this work.

It has been demonstrated that the flight control system proposed for guided bombs allows them to be successfully delivered to the target area and precisely reach it with high accuracy of even less than two metres. Such high accuracy allows for point-to-point destruction of heavily armoured targets such as tanks, combat vehicles, artillery and missile systems, bunkers, fortifications and command posts. However, such high accuracy requires a more complex and expensive controller: the Hybrid one consisting of PID and QSM working in parallel. In the case of targets that can be destroyed with fragmentation-demolition warheads that do not require high homing precision, sufficient for a range of several metres, a slightly simpler conventional PID or QSM controller can be used. It should be emphasised that the study results have clearly shown that the proposed Hybrid controller is resistant to the impact of random atmospheric turbulence.

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Hybrydowy system sterowania bombą kierowaną w płaszczyźnie pionowej podczas samonaprowadzania w warunkach działania turbulencji

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Streszczenie. W artykule przedstawiony został model matematyczny oraz algorytm hybrydowego sterowania bombą kierowaną na ruchomy cel naziemny. Analizowany system sterowania lotem bomby kierowanej stanowi połączenie regulatora klasycznego PD oraz regulatora quasi–ślizgowego. Tor zadany wyznaczono ze związków kinematycznych ruchu wzajemnego bomby i celu naziemnego z wykorzystaniem metody proporcjonalnego zbliżania. Głównym celem artykułu jest analiza wpływu zakłóceń atmosferycznych na lot bomby kierowanej, a następnie określenie ich wpływu na parametry samonaprowadzania takie jak: czas naprowadzania oraz dokładność trafienia w cel naziemny. Badania numeryczne obejmowały trzy typy regulatorów: klasycznego PID, quasi–ślizgowego oraz hybrydowego. Dokonano analizy skuteczności działania zaproponowanego systemu sterowania bez i podczas działania losowych zakłóceń atmosferycznych (turbulencji).

Słowa kluczowe: naprowadzanie, bomba kierowana, hybrydowy system sterowania, sterowanie ślizgowe, turbulencja atmosferyczna