ZESZYTY NAUKOWE AKADEMII MARYNARKI WOJENNEJ
SCIENTIFIC JOURNAL OF POLISH NAVAL ACADEMY

2017 (LVIII) 2 (209)

DOI: 10.5604/01.3001.0010.4066

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THE CONTROL OF ANTI-AIRCRAFT MISSILE FLIGHT PATH IN ATMOSPHERIC DISTURBANCES

ABSTRACT

The control of homing surface-to-air short-range anti-aircraft missile takes place in the atmosphere, in which there are different types of atmospheric disturbances such as: turbulence, gust and wind shear. The atmospheric disturbances is generated with the Dryden power spectral density model. This paper presents a method for control of flying objects such as anti-aircraft missile moving in a disturbed environment. The method of proportional navigation will be applied for the guidance of missile on the ground target. The research will include the analysis of influence of atmospherics on the hitting the target accuracy, the shape of the flight path and the values of generated control forces. Numerical research will be carried out with use of Matlab/Simulink software. Obtained results will be presented in the graphical form.

Key words:
missile, random disturbances, turbulence, homing.

INTRODUCTION

The system of air defence is to provide effective protection against attack mainly with precision weapon as well as serves to combat manned (aeroplanes, helicopters) and unmanned aerial vehicles. The zone safety, the operation of which includes e.g. air bases, might depend on the effectiveness of the system operation. The planned introduction of anti-aircraft and anti-missile defence systems to the Polish Armed Forces for the years 2013–2022 might indicate the significance of the anti-aircraft defence system in Poland [12].

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The process of anti-aircraft missile (AAM) guidance takes place in the medium called the Earth's atmosphere. When designing control systems for AAM, it is most often assumed that the motion takes place under low wind condition (idealized flight conditions). Actually, AAM is subjected to atmospheric phenomena such as wind, gusts of wind, wind shears, turbulence, which are sudden unpredictable phenomena. The research thereof generally involve demonstrating their influence on: resistance of the flying object construction, performance of control systems as well as permitted flight parameters. Due to the character of such interference, the impact on AAM dynamics, i.e. the flight path of the flying object, will be examined. There are many methods of modelling and analysing random phenomena, which include atmospheric interference. Negative effects of e.g. turbulence as an atmospheric phenomenon, were studied for various types of aircrafts: helicopters [2], guided bomb units [6], aeroplanes [1, 9] and unmanned aircrafts [10].

As a result of the impact of actual flight conditions there is a temporary, but usually sudden change of the AAM flight parameters. In order to prevent the influence of atmospheric interference on the AAM, the automatic missile control system must be designed in a way to ensure its stability. The main element of the system is the controller. In this paper a classic PID controller was applied to determine control force.

$$Q_y = k_p e_S + k_i \int e_S dt + k_d \frac{de_S}{dt}; \qquad (1a)$$

$$e_S = \gamma - \gamma_z, \qquad (1b)$$

where:

Q_y — missile flight control force [N];

γ — achieved flight angle AAM [rad];

γ_z — commanded flight angle [rad].

Setpoint flight angles of AAM were determined from line of sight equations [5]. The controller settings were selected using the metod of numerical optimalization minimum error criteria IAE [11]. Their values are as follows: k_p = 112.4, k_1 = 254.6, k_d = 20.1.

Numerical studies were conducted in Matlab/Simulink. The AAM flight in the vertical plane under the influence of atmospheric turbulence was analysed.

MODELLING ATMOSPHERIC INTERFERENCE

In dynamic systems such as the AAM control system, apart from the determined signals there are as well stochastic signals. In the case of random signals, the homing guidance system is designed in such a way as to additionally counteract the forces generated by the atmospheric interference. An example thereof in this paper will be aerodynamic loads of the AAM caused by the turbulence of the atmosphere.

The Dryden model was chosen out of many methods of turbulence modelling. It constitutes a simplified form of the von Karman model frequently applied in numerical studies.

Modelling atmospheric interference on the basis of the Dryden model assumes turbulence in the form of the power spectral density. As far as the AAM motion in the vertical plane is concerned, the power spectral densities of the turbulence components according to the Dryden model might be recorded in the following way [7]:

$$\Phi_{u_g}(\omega)=\frac{2\sigma_u^2 L_u}{\pi V_p}\frac{1}{1+\left(L_u\frac{\omega}{V_p}\right)^2}; \tag{2a}$$

$$\Phi_{v_g}(\omega)=\frac{\sigma_v^2 L_v}{\pi V_p}\frac{1+3\left(L_v\frac{\omega}{V_p}\right)^2}{\left[1+\left(L_v\frac{\omega}{V_p}\right)^2\right]^2}, \tag{2b}$$

where:

V_p — is the AAM trim velocity [m/s];

L_u, L_v — is the turbulence scale lengths [m];

σ_u, σ_v — is the turbulence intensities [m/s].

Taking into consideration [4] it is assumed that the values for the scale of turbulence wavelength according to the applied Dryden model, are as follows:

$$L_u = L_v = 145\sqrt[3]{h} \text{ for } h < 533.4 \text{ [m]}; \tag{3a}$$

$$L_u = L_v = 533.4 \text{ for } h \geq 533.4 \text{ [m]}. \tag{3b}$$

The turbulence intensity for flying object according to [4] can be determined from equation:

$$\frac{\sigma_u^2}{L_u} = \frac{\sigma_v^2}{L_v}. \tag{4}$$

On the basis of the model described with the dependencies (2) with the accepted length scale (3) and intensity scale (4), a turbulence signal might be generated. It is possible with the use of a white noise generator and a linear filter with appropriate power spectral densities [3]. The dependency of the power spectral density of the output signal and the power spectral density of the input signal takes the following form:

$$\Phi_{u_g,v_g}(\omega) = \left|G_{u_g,v_g}(j\omega)\right|^2 \Phi_n(\omega). \tag{5}$$

Assuming that the power spectral density of Gaussian white noise is $\Phi_n(\omega) = 1$ and using the distribution of the power spectral density $\Phi_{u_g,v_g}(\omega)$ and separating transfer function with zeros and the poles in the left side of the complex plane, transfer function for proper turbulence component is obtained which takes the following form:

$$G_{u_g}(s) = \sigma_u \sqrt{\frac{2L_u}{\pi V_p}} \cdot \frac{1}{1 + \left(\frac{L_u}{V_p}\right)s}; \tag{6a}$$

$$G_{v_g}(s) = \sigma_v \sqrt{\frac{L_v}{\pi V_p}} \cdot \frac{1 + \sqrt{3}\frac{L_v}{V_p}s}{\left(1 + \frac{L_v}{V_p}s\right)^2}. \tag{6b}$$

Figure 1 presents a block diagram of the AAM flight control together with an example of vertical component course of the turbulence velocity.

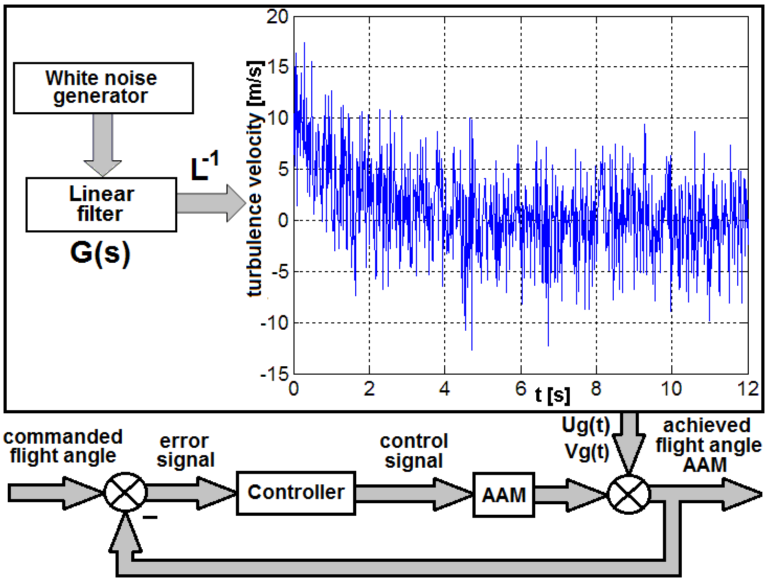

Fig. 1. Block diagram of the AAM flight control under turbulent conditions [own work]

EQUATION OF MISSILE

It was assumed that the missile is a rigid block of constant mass which does not rotate around its own longitudinal axis [5]. The motion of the considered AAM can be written in the form of the following equation:

$$\dot{V} = -g\sin\gamma - \lambda_x V_c^{\,2}\,; \tag{7a}$$

$$\dot{\gamma} = \frac{1}{V_c}\left(\frac{Q_y}{m} - g\cos\gamma\right) + \lambda_y V_c \alpha\,; \tag{7b}$$

$$\ddot{\vartheta} = V_c\left(-D_1\frac{V_c}{l}\alpha - D_2\dot{\alpha} - D_3\dot{\vartheta}\right) + \frac{Q_y e}{J_k}\,; \tag{7c}$$

$$\lambda_x = \frac{c_x S_x \rho}{2m};\ \lambda_y = \frac{c_y S_y \rho}{2m};\ D_{1,2,3} = \frac{C_i l}{J_k}\,; \tag{7d}$$

$$V_c = \sqrt{\left(V - U_g\right)^2 + \left(V - V_g\right)^2}\,. \tag{7e}$$

where:

V — missile velocity [m/s];
l — length of the missile body [m];
ρ — air density [kg/m³];
S_x — cross-sectional area of the missile [m²];
S_y — lifting area [m²];
m — mass of the missile [kg];
J_k — moments of inertia of the missile in relation to its transverse axis [kgm²];
e — distance between control force and aerodynamic pressure centre [m];
g — acceleration of gravity [m/s²];
$\lambda_x, \lambda_y, D_{1,2,3}$ — relative aerodynamic coefficients of aerodynamic forces and moments [1/m] [5];
c_x, c_y, C_i — coefficients of aerodynamic forces and of moments of aerodynamic forces;
U_g, V_g — components of the turbulence velocity [m/s]; ϑ – pitch angle of the missile [rad];
α — attack angle.

The homing guidance algorithm is done with the use of commonly used proportional navigation guidance law [8].

DIGITAL SIMULATION RESULTS AND CONCLUSIONS

Figures 2–11 illustrate automatically guidance the AAM to the air target.

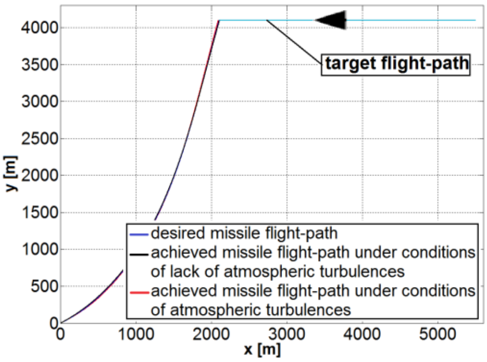

Fig. 2. The AAM and target flight-path [own work]

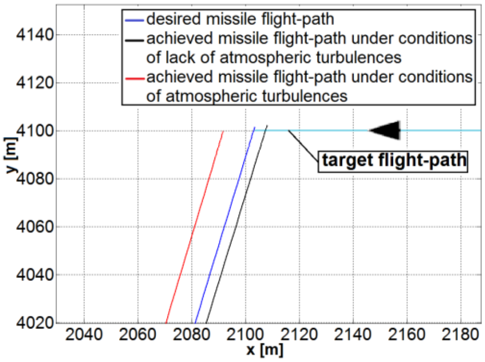

Fig. 3. Zoomed-in part of fig. 2 [own work]

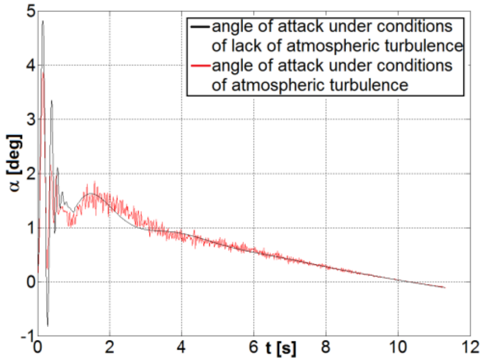

Fig. 4. Realized angle of attack [own work]

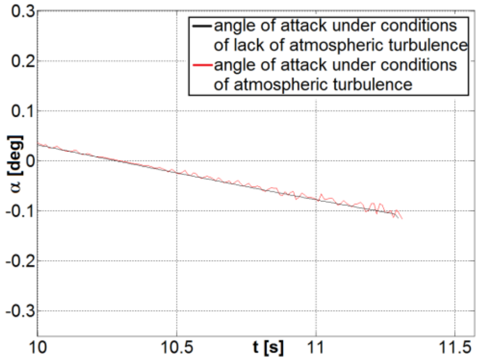

Fig. 5. Zoomed-in part of fig. 4 [own work]

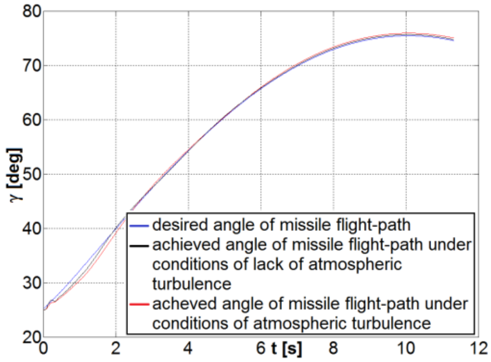

Fig. 6. Angle of missile flight-path [own work]

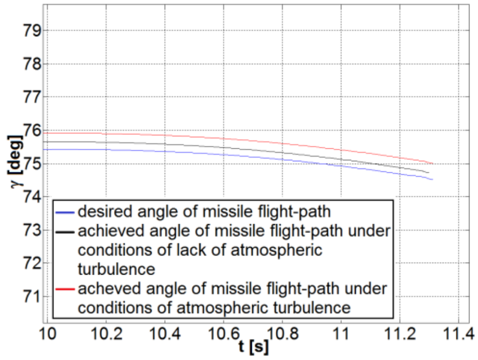

Fig. 7. Zoomed-in part of fig. 6 [own work]

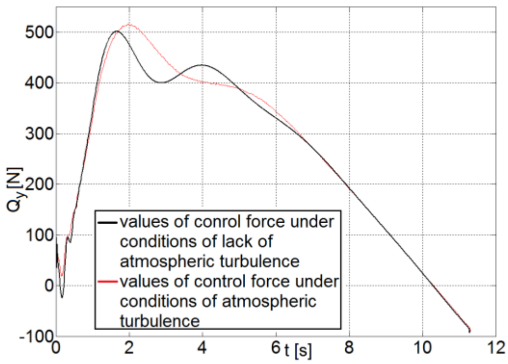

Fig. 8. Control forces of flight AAM [own work]

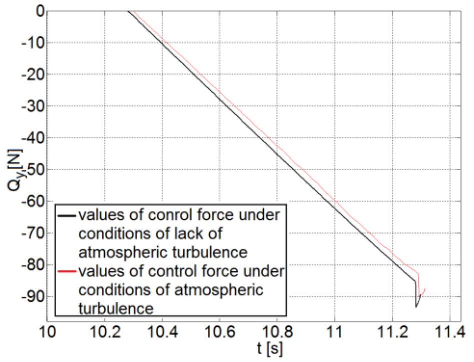

Fig. 9. Zoomed-in part of fig. 8 [own work]

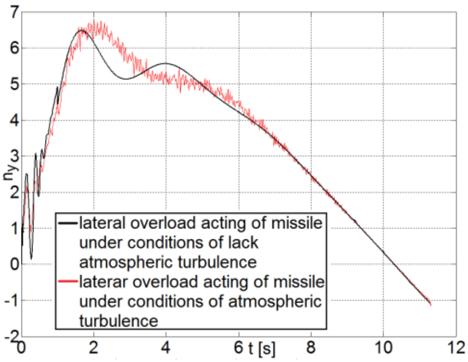

Fig. 10. Kinematic transverse overloads [own work]

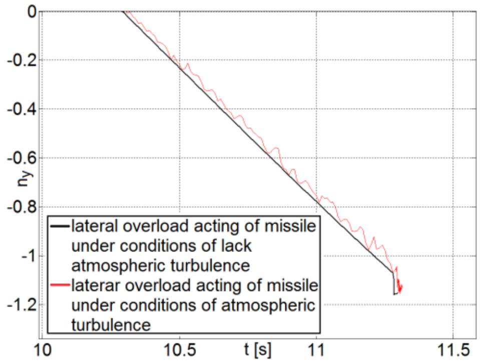

Fig. 11. Zoomed-in part of fig. 10 [own work]

The numerical simulations were conducted for a hypothetical anti-aircraft missile attacking a non-cruise missile from the front hemisphere. The research was carried out for the following data: initial velocity AAM: $V_0 = 20$ [m/s]; target velocity: $V_c = 300$ [m/s]; initial location AAM: $x_0 = 0$ [m/s], $y_0 = 0$ [m]; initial target location: $x_c = 5500$ [m], $y_c = 4000$ [m]; $m = 10{,}8$ [kg]; $l = 1{,}6$ [m]; $J_k = 2{,}304$ [kgm^2]; $\lambda_x = 0{,}000171$ [1/m]; $\lambda_y = 0{,}0051$ [1/m]; $D_1 = 0{,}081$ [1/m]; $D_2 = 0{,}0821$ [1/m]; $D_3 = 0{,}00041$ [1/m].

On the basis of the research conducted, it might be stated that the random interference, i.e. atmospheric turbulence have a significant impact in the initial flight phase of the AAM. The nature of the turbulent atmosphere is visible by changing the overloads affecting the AAM, which results from the changes of the aerodynamic forces. Actual flight conditions resulting from the atmospheric turbulence also influence the angle of attack, where apparent vibrations and control force which is crucial to perform the desired flight path might be observed. Also the graph of performed AAM flight angle deviates from the set course.

All of this phenomena are negative. Tha accuracy of hitting the target for simulation without disturbances amounted 4.51 [m], while In the disturbed conditions it amounted 11.75 [m] — which is over twice smaller value. However in case of use of proximity fuse it should not matter.

The aim of further research should be an analysis of the missile flight control in atmospheric conditions in space, with respect to the turbulence components on all axes. It seems appropriate to verify the impact of the AAM body vibrations on the operation of the scanning and tracking head which was not taken into consideration herein.

REFERENCES

[1] Akmal H., Qu Y., *Estimation of Wind Field Velocity and Aircraft States with an F-16 Lateral Guidance Control System*, Proceeding of the 2015 IEEE International Conference on Information and Automation, China, 2015, pp. 2293–2298.

[2] Alexis K., Nikolakopoulos G., Tzes A., *Switching model predictive attitude control for a quadrotor helicopter subject to atmospheric disturbances*, 'Control Engineering Practice', 2011, 19(10), pp. 1195–1207.

[3] Bociek S., Gruszecki J., *Układy sterowania automatycznego samolotem*, Publ. Politechnika Rzeszowska, Rzeszów 1999 [*The automatic control systems for aircraft* — available in Polish].

[4] Chalk C. R., Neal T. P., Harris T. M., *Background in Formation and User Guide for MIL-F-8785 (ASG)*, Military specification flying qualities of piloted airplanes, AFFDL-TR-69-72, 1969.

[5] Koruba Z., Osiecki J. W., *Budowa, dynamika i nawigacja pocisków rakietowych bliskiego zasięgu*, Part I, script No. 348, Publ. Politechnika Świętokrzyska, Kielce 1999 [*Constructions, Dynamics and Navigation of the Short Range Rocket Missile* — available in Polish].

[6] Kowaleczko G., Żyluk A., *Influence of atmospheric turbulence on bomb release*, 'Journal of Theoretical and Applied Mechanics', 2009, Vol. 41, No. 1, pp. 69–90.

[7] Moorhouse D. J., Woodcock, *Guide for MIL-F-8785C*, Military specification flying qualities of piloted airplanes. U. S. Military Specification MIL-F-8785C, AFWAL-TR-81-3109, 1981.

[8] Solomon Raj D. K., *Performance Evaluation of Proportional Navigation Guidance for Low-Maneuvering Targets*, 'International Journal of Scientific & Engineering Research', 2014, Vol. 5, Issue 9, pp. 93–99.

[9] Stroe G., Andrei I. C., *Analysis Regarding the Effects of Atmospheric Turbulence on Aircraft Dynamics*, 'INCAS Bulletin', 2016, Vol. 8, Issue 2, pp. 123–132.

[10] Sydney N., Smyth B., Paley D. A., *Dynamic Control of Autonomous Quadrotor Flight in an Estimated Wind Field*, Proceeding of the 52nd IEEE Conference on Decision and Control, Italy, 2013, pp. 3609–3616.

[11] Szmidt P., Gapiński D., Koruba Z., *The analysis of selection optimalparameters of PID controllers for a modified artillery-missile system*, Proceeding of the 23rd International Conference Engineering Mechanics, Svratka, Czech Republic, 2017, pp. 970–973.

[12] Zaborowski M., Staniewska K., Ćwiek-Karpowicz J., Gawlikowska-Fyk A., Gradziuk A., Kałan D., Kościński P., Płóciennik S., Sasnal P, Terlikowski M., *Crossing the Vistula River: The Importance of the Air and Missile Defence of Poland*, 'Bulletin. Polish Institute of International Affairs', 2015, No. 44(776), pp. 1–2.

STEROWANIE POCISKIEM PRZECIWLOTNICZYM PODCZAS ZAKŁÓCEŃ ATMOSFERYCZNYCH

STRESZCZENIE

Sterowanie samonaprowadzającym obiektem latającym, jakim jest przeciwlotniczy pocisk rakietowy (PPR), odbywa się w atmosferze ziemskiej, w której zachodzą różnego typu zjawiska atmosferyczne, jak turbulencje, uskoki i podmuchy wiatru. Zakłócenia atmosferyczne przyjęto jako proces stochastyczny w postaci gęstości widmowej mocy (model Drydena). W artykule zaprezentowano metodę sterowania PPR poruszającym się w atmosferze zaburzonej. Do naprowadzania pocisku rakietowego na cel powietrzny wykorzystana została metoda proporcjonalnej nawigacji. Badania obejmują analizę wpływu zakłóceń atmosferycznych na dokładność trafienia w cel, kształt toru lotu oraz wartości generowanych sił sterujących. Symulacje komputerowe przeprowadzone zostały w środowisku Matlab/Simulink, a niektóre wyniki badań przedstawione w postaci graficznej.

Słowa kluczowe:

pocisk przeciwlotniczy, zakłócenia losowe, turbulencja, samonaprowadzanie.