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INFLUENCE OF THE ATMOSPHERIC TURBULENCE ON THE ACCURACY OF THE MISSILE TARGETING

Grzegorz Kowaleczko

Polish Air Force Academy
Dywizjonu 303 Street 35, 08-521 Deblin, Poland
tel.: +48 261851330, fax*: +48 815517417*
e-mail: g.kowaleczko@chello.pl

[1]Romuald Kaźmierczak, [2]Andrzej Zyluk

Air Force Institute of Technology
Ksiecia Boleslawa Street 6, 01-494 Warsaw, Poland
tel.: +48 261851401, 48 261851302
e-mail: romuald.kazmierczak@itwl.pl,[1] andrzej.zyluk@itwl.pl [2]

Abstract

The article presents results of simulation of six-degrees of freedom motion for a missile subjected to atmospheric turbulences. Therefore, an applied mathematical model of motion includes description of stochastic turbulences influencing on missile flight. Both models of the motion as well as of turbulences are shortly presented. The motion model is typical for exterior ballistic problems – the spatial motion of the rigid body is described. Detailed formulas for aerodynamic forces and moments acting on the missile are presented. The much attention has been paid to the model of turbulence. This is the stochastic model based on the Power Spectral Densities and the Shinozuka's method of stochastic processes simulations. They allow reconstructing a spatial structure of the wind field.

Model validity was assessed by comparing the calculation results with the data recorded during shooting on the range. Result of series of simulations allows determining the missile sensitivity to this case of disturbances. Exemplary results of simulations are shown. The main important of them allow determining an influence of the turbulence on a point of the missile fall.

Keywords: *missile dynamics, stochastic turbulences, numerical simulations.*

1. Introduction

A maximum accuracy and precision are the main goal during missile shooting, which can be performed in various atmospheric conditions. Aerodynamic forces are the main forces acting on the missiles. They directly depend on the missile velocity relative to the air. Therefore, atmospheric turbulences may be a significant factor affecting the missile motion. Depending on them a different point on the Earth's surface can be reached. This means that turbulences influence on the accuracy and precision of the missile. The main problem is to determine the sensitivity of the missile to this kind of disturbances. This problem can be resolved experimentally or in the way of theoretical investigations.

To resolve this problem theoretically the 6-DOF mathematical model of missile motion has to be applied. We can find a lot of similar each other models in the literature [1-4, 6, 12, 15-17, 20]. In this article, a model of the missile with variable mass is used. It is described in details in [8]. This model includes changes of missile mass characteristics during burning process. Thrust is not treated as the external force and is calculated on the basis of a solution of inner ballistic problems [8, 10, 11, 23, 24]. The used model also describes the jet damping effect [21], but this effect is the second of importance, as it is shown in [8].

Applied in this article description of atmospheric turbulences takes into account stochastic character of the wind field. To determine this field, the Shinozuka's method was applied, which was translator used to model earthquakes [18, 19] and is adopted to simulate turbulences treated as the stochastic processed [9, 13].

2. Mathematical description of the missile motion

Coordinate systems

The following orthogonal coordinate systems were used to determine motion equations of the missile: $Ox_gy_gz_g$ – the Earth-referenced system with its origin O at any fixed point of the missile, $Oxyz$ – the missile-fixed system with the origin at point O, $Ox_ay_az_a$ – the air trajectory reference frame. The origin O is the centre of mass of the missile after the combustion process.

These systems are related to each other by means of the following angles: (Ψ – yaw, Θ – pitch, Φ – roll) for systems $O_gx_gy_gz_g$ and $Oxyz$ and (α – angle of attack, β – sideslip angle) for systems $O_gx_gy_gz_g$ and $Oxyz$. The transformation matrices between systems /from $Ox_gy_gz_g$ to $Oxyz$ and from $Ox_ay_az_a$ to $Oxyz$/ are as follows:

$$\mathbf{L}_{m/g}=\begin{bmatrix} cP\cdot cT & sP\cdot cT & -sT \\ cP\cdot sT\cdot sF-sP\cdot cF & sP\cdot sT\cdot sF+cP\cdot cF & cT\cdot sF \\ cP\cdot sT\cdot cF+sP\cdot sF & sP\cdot sT\cdot cF-cP\cdot sF & cT\cdot cF \end{bmatrix},\ \mathbf{L}_{m/a}=\begin{bmatrix} cA\cdot cB & -cA\cdot sB & -sA \\ sB & cB & 0 \\ sA\cdot cB & -sA\cdot sB & cA \end{bmatrix}, \tag{1}$$

where: cP=cosΨ, sP=sinΨ, cT=cosΘ, sT=sinΘ, cF=cosΦ, sF=sinΦ, cA=cosα, sA=sinα, cB=cosβ, sB=sinβ.

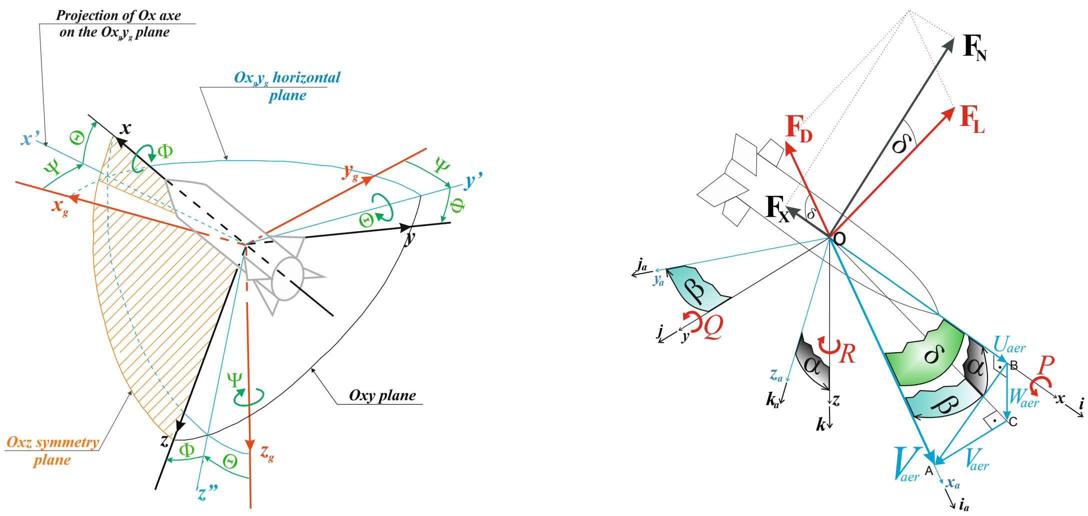

Fig. 1. Coordinate systems, static aerodynamic forces, angles and velocities

Equations of translator motion

In $Oxyz$ system six scalar equations of translatory and rotational motions taken from [8] are as follows:

$$m\left(\dot{U}+QW-RV\right)-S_x\left(Q^2+R^2\right)+ma_{x\_rel\_C}+\ddot{m}(x_C-x_E)+2\dot{m}U_{rel\_C}=F_x+T, \tag{2a}$$

$$m\left(\dot{V}+RU-PW\right)+S_x(PQ+\dot{R})+2mRU_{rel\_C}+2\dot{m}R(x_C-x_E)=F_y, \tag{2b}$$

$$m\left(\dot{W}+PV-QU\right)+S_x(PR-\dot{Q})-2mQU_{rel\_C}-2\dot{m}Q(x_C-x_E)=F_z, \tag{2c}$$

$$I_x \dot{P} = L\,, \tag{2d}$$

$$I_y \dot{Q} + PR(I_x - I) - S_x(\dot{W} + PV - QU) + 2Q\sum_i m_i x_i U_{rel\_i} = M\,, \tag{2e}$$

$$I_z \dot{R} + PQ(I - I_x) + S_x(\dot{V} + RU - PW) + 2R\sum_i m_i x_i U_{rel\_i} = N\,, \tag{2f}$$

where we have: $m = m_{fuselage} + m_{fuel} + m_{chamber} + m_{nozzle}$ – missile mass, $\dot{m} = \dot{m}_{fuel}$ – mass flow rate, $\ddot{m} = \ddot{m}_{fuel}$ – acceleration of mass change, (I_x, I_y, I_z) – inertia moments, (m_i, x_i) – mass and coordinate of i-th elementary mass of the combustion – products inside the missile, $\mathbf{V}_O = [U, V, W]^T$ – the velocity of the pole O relative to the Earth, $\boldsymbol{\omega} = [P, Q, R]^T$ – the angular velocity of the missile, – $S_x = \sum_i x_i m_i$ – the static moment of the missile, $x_C = S_x / m$ – the coordinate of the mass centre, x_E – the coordinate of the nozzle exit, $U_{rel\_C} = \dot{m} \cdot \dfrac{x_{fuel} - x_C}{m}$ – the relative velocity of the mass centre, $a_{x\_rel\_C} = -2\dfrac{\dot{m}}{m} U_{rel\_C}$ – the relative velocity of the mass centre, $\mathbf{F} = [F_x, F_y, F_z]^T$ – the sum of aerodynamic and gravitational forces, T – the thrust, $\mathbf{M}_O = [L_O, M_O, N_O]^T$ – moments relative to the pole O.

Equations (2) are obtained assuming that the missile has two symmetry planes. They are complemented by kinematic relations for rates of roll, pitch and yaw and for components of velocities in relation to the Earth:

$$\dot{\Phi} = P + (R\cos\Phi + Q\sin\Phi)tg\Theta\,, \tag{3a}$$

$$\dot{\Theta} = Q\cos\Phi - R\sin\Phi\,, \tag{3b}$$

$$\dot{\Psi} = (R\cos\Phi + Q\sin\Phi)/\cos\Theta\,, \tag{3c}$$

$$\begin{bmatrix} \dot{x}_g \\ \dot{y}_g \\ \dot{z}_g \end{bmatrix} = \mathbf{L}_{m/g}^{-1} \begin{bmatrix} U \\ V \\ W \end{bmatrix}. \tag{4}$$

3. External forces end moments

The external force $\mathbf{F}$ is the sum of the weight $\mathbf{Q}$ and the aerodynamic force $\mathbf{F}_{aer}$. Whereas, the aerodynamic moment $\mathbf{M}_O$ relative to the pole O is the sum of the moments generated by the weight $\mathbf{M}_Q$ and the aerodynamic moment $\mathbf{M}_{aer}$:

$$\mathbf{F} = \mathbf{Q} + \mathbf{F}_{aer}\,,\ \mathbf{M}_O = \mathbf{M}_Q + \mathbf{M}_{aer}\,. \tag{5}$$

In $Oxyz$ system, the weight has following components $\mathbf{Q} = mg[-sT,\ \ cT \cdot sF,\ \ cT \cdot cF]^T$. It produces moment $\mathbf{M}_Q = mg[0,\ \ -x_C \cdot cT \cdot cF,\ \ x_C \cdot cT \cdot sF]^T$.

To calculate aerodynamic forces and moments one has to know the missile velocity relative to air $\mathbf{V}_{aer} = \mathbf{V}_O - \mathbf{V}_w$ where $\mathbf{V}_w$ is the wind (turbulence) velocity.

The aerodynamic forces and moments can be divided into static and dynamic. Static forces and moments are determined on the basis of the nutation angle, which is calculated on the basis of angle of attack α and sideslip angle β:

$$\alpha = \arctan\frac{W-W_w}{U-U_w}, \qquad \beta = \arctan\frac{V-V_w}{\sqrt{(U-U_w)^2+(W-W_w)^2}}, \qquad \delta = \arcsin\left(\sqrt{\sin^2\beta + \cos^2\beta\sin^2\alpha}\right).$$

While, the dynamic forces and moments are created when the missile is rotating. The resultant aerodynamic force $\mathbf{F}_{aer}$ is equal to the sum of forces set out below:

$$\mathbf{F}_{aer} = \mathbf{F}_D + \mathbf{F}_L + \mathbf{F}_M + \mathbf{F}_{pdf} \text{ or } \mathbf{F}_{aer} = \mathbf{F}_X + \mathbf{F}_N + \mathbf{F}_M + \mathbf{F}_{pdf}. \tag{6}$$

To determine aerodynamic forces and moments acting on the missile the following unit vectors of coordinate systems have to be used: unit vectors $\boldsymbol{i}$, $\boldsymbol{j}$, $\boldsymbol{k}$ of the system $Oxyz$ and unit vectors $\boldsymbol{i_a}$, $\boldsymbol{j_a}$, $\boldsymbol{k_a}$ of the aerodynamic system $Ox_ay_az_a$. Summary expressions for these forces and moments are shown in the table below.

Forces & Moments	General formula	Components in *Oxyz* system	Scalar value	Coefficient & Comments
Aerodynamic forces: $\mathbf{F}_{aer} = \mathbf{F}_D + \mathbf{F}_L + \mathbf{F}_M + \mathbf{F}_{pdf}$ **or** $\mathbf{F}_{aer} = \mathbf{F}_X + \mathbf{F}_N + \mathbf{F}_M + \mathbf{F}_{pdf}$				
Static aerodynamic forces				
Drag force $\mathbf{F}_D$	$\mathbf{F}_D = -C_D\frac{\rho V_{aer}^2}{2}S\cdot\boldsymbol{i_a}$	$\mathbf{F}_D = -C_D\frac{\rho V_{aer}^2}{2}S\cdot \left[\frac{U}{V_{pow}},\ \frac{V}{V_{pow}},\ \frac{W}{V_{pow}}\right]^T$	$F_D = C_D\frac{\rho V_{aer}^2}{2}S$	$C_D = C_{D0} + C_{D\delta 2}\delta^2$ $C_D>0$ This force is parallel to the trajectory, and is directed opposite to the velocity vector of the missile.
Lift force $\mathbf{F}_L$	$\mathbf{F}_L = \frac{\rho V_{aer}^2}{2}S\cdot C_{L\delta}\cdot [\boldsymbol{i_a}\times(\boldsymbol{i}\times\boldsymbol{i_a})]$	$\mathbf{F}_L = \frac{\rho V_{aer}^2}{2}S\cdot C_{L\delta}\cdot \left[\left(\frac{V^2+W^2}{V_{aer}^2}\right),\ \left(\frac{-UV}{V_{aer}^2}\right),\ \left(\frac{-UW}{V_{aer}^2}\right)\right]$	$F_L = C_L\frac{\rho V_{aer}^2}{2}S$	$C_L = C_{L\delta}\delta = C_{L\delta 0}\delta + C_{L\delta 2}\delta^3$ $C_{L\delta} = C_{L\delta 0} + C_{L\delta 2}\delta^2$ This force lies in the drag plane and is perpendicular to the trajectory and hence to the velocity of the missile.
Axial force $\mathbf{F}_X$	$\mathbf{F}_X = -C_x\frac{\rho V_{aer}^2}{2}S\cdot\boldsymbol{i}$	$\mathbf{F}_X = -C_x\frac{\rho V_{aer}^2}{2}S[1,\ 0,\ 0]^T$	$F_X = C_x\frac{\rho V_{aer}^2}{2}S$	$C_x = C_{x0} + C_{x\delta 2}\delta^2 + C_{x\delta 4}\delta^4$ $C_x>0$ This force is parallel to the longitudinal axis of the projectile and has opposite sense.
Normal force $\mathbf{F}_N$	$\mathbf{F}_N = \frac{\rho V_{aer}^2}{2}S\cdot C_{N\delta}\cdot [\boldsymbol{i}\times(\boldsymbol{i}\times\boldsymbol{i_a})]$	$\mathbf{F}_N = -\frac{\rho V_{aer}^2}{2}S\cdot C_{N\delta}\cdot \left[0,\ \frac{V}{V_{aer}},\ \frac{W}{V_{aer}}\right]^T$	$F_N = C_N\frac{\rho V_{aer}^2}{2}S$	$C_N = C_{N\delta}\delta = C_{N\delta 0}\delta + C_{N\delta 2}\delta^3$ $C_{N\delta} = C_{N\delta 0} + C_{N\delta 2}\delta^2$ This force is perpendicular to the longitudinal axis of the missile and lies in the drag plane.
Dynamic aerodynamic forces				
Magnus force $\mathbf{F}_M$	$\mathbf{F}_M = \frac{\rho V_{aer}^2}{2}S\left(\frac{Pd}{V_{aer}}\right)C_{N_{p\delta}}\cdot(\boldsymbol{i_a}\times\boldsymbol{i})$	$\mathbf{F}_M = \frac{\rho V_{aer}^2}{2}S\left(\frac{Pd}{V_{aer}}\right)C_{N_{p\delta}}\cdot \left[0,\ \frac{W}{V_{aer}},\ \frac{-V}{V_{aer}}\right]^T$	$F_M = \frac{\rho V_{aer}^2}{2}S\left(\frac{Pd}{V_{aer}}\right)C_{N_p}$	$C_{N_p} = C_{N_{p\delta}}\delta = C_{N_{p\delta 0}}\delta + C_{N_{p\delta 2}}\delta^3$ $C_{N_{p\delta}} = C_{N_{p\delta 0}} + C_{N_{p\delta 2}}\delta^2$ $C_{N_p} < 0$ This force arises when the missile rotates with the angular velocity P about the longitudinal Ox. It is

				perpendicular to the drag plane.
Pitch damping force $\mathbf{F}_{pdf}$	$\mathbf{F}_{pdf} = \frac{\rho V_{aer}^2}{2} Sd \cdot \cdot (C_{Nq} + C_{N\dot{\alpha}}) \left(\frac{d\boldsymbol{i}}{dt}\right)$	$\mathbf{F}_{pdf} = \frac{\rho V_{aer}^2}{2} S(C_{Nq} + C_{N\dot{\alpha}}) \cdot \cdot \left[0, \quad \frac{Rd}{V_{aer}}, \quad \frac{-Qd}{V_{aer}}\right]$	$F_{pdf} = \frac{\rho V_{aer}^2}{2} S\left(\frac{Q_t d}{V_{aer}}\right) \cdot \cdot (C_{Nq} + C_{N\dot{\delta}})$	$Q_t = \sqrt{Q^2 + R^2}$ The angular velocities Q and R and the rate of change of the nutation angle δ generate additional dynamic force, which also produce damping moment.
Aerodynamic moments $\mathbf{M}_{aer} = \mathbf{M}_{om} + \mathbf{M}_{pdm} + \mathbf{M}_{sdm} + \mathbf{M}_{M}$				
Static aerodynamic moment				
Over-turning moment $\mathbf{M}_{om}$	$\mathbf{M}_{om} = \frac{\rho V_{aer}^2}{2} Sd \cdot \cdot C_{M\delta} (\boldsymbol{i}_a \times \boldsymbol{i})$	$\mathbf{M}_{om} = \frac{\rho V_{aer}^2}{2} Sd \cdot C_{M\delta} \cdot \cdot \left[0, \quad \frac{W}{V_{aer}}, \quad \frac{-V}{V_{aer}}\right]^T$	$M_{om} = \frac{\rho V_{aer}^2}{2} Sd \cdot C_M$	$C_M = C_{M\delta}\delta = C_{M\delta 0}\delta + C_{M\delta 2}\delta^3$ $C_{M\delta} = C_{M\delta 0} + C_{M\delta 2}\delta^2$ This moment arises because the centre of pressure does not coincide with the mass centre of missile as well as with the pole O.
Dynamic aerodynamic moment				
Pitch damping moment $\mathbf{M}_{pdm}$	$\mathbf{M}_{pdm} = \frac{\rho V_{aer}^2}{2} Sd^2 \cdot \cdot (C_{Mq} + C_{M\dot{\alpha}}) \left(\boldsymbol{i} \times \frac{d\boldsymbol{i}}{dt}\right)$	$\mathbf{M}_{pdm} = \frac{\rho V_{aer}^2}{2} Sd(C_{Mq} + C_{M\dot{\alpha}}) \cdot \cdot \left[0, \quad \frac{Qd}{V_{aer}}, \quad \frac{Rd}{V_{aer}}\right]$	$M_{pdm} = \frac{\rho V_{aer}^2}{2} Sd\left(\frac{Q_t d}{V_{pow}}\right) \cdot \cdot (C_{Mq} + C_{M\dot{\delta}})$	This moment arises if the missile has angular velocities Q and R and if there is a rate of change of the nutation angle δ.
Spin damping moment $\mathbf{M}_{sdm}$	$\mathbf{M}_{sdm} = \frac{\rho V_{aer}^2}{2} SdC_{lp} \cdot \cdot \left(\frac{Pd}{V_{aer}}\right)\boldsymbol{i}$	$\mathbf{M}_{sdm} = \frac{\rho V_{aer}^2}{2} SdC_{lp}\left(\frac{Pd}{V_{aer}}\right) \cdot \cdot [1, \quad 0, \quad 0]$	$M_{sdm} = \frac{\rho V_{aer}^2}{2} SdC_{lp}\left(\frac{Pd}{V_{aer}}\right)$	$C_{lp} < 0$ If the missile is rotated about the longitudinal axis, the rotation is decelerated due to air viscosity.
Magnus moment $\mathbf{M}_{pdm}$	$\mathbf{M}_{M} = \frac{\rho V_{aer}^2}{2} Sd\left(\frac{Pd}{V_{aer}}\right) C_M \cdot [\boldsymbol{i} \times (\boldsymbol{i}_a \times \boldsymbol{i})]$	$\mathbf{M}_{M} = \frac{\rho V_{aer}^2}{2} Sd\left(\frac{Pd}{V_{aer}}\right) C_{M_{p\delta}} \cdot \cdot \left[0, \quad \frac{V}{V_{aer}}, \quad \frac{W}{V_{aer}}\right]^T$	$M_{M} = \frac{\rho V_{aer}^2}{2} Sd\left(\frac{Pd}{V_{aer}}\right) C_M$	$C_{M_p} = C_{M_{p\delta}}\delta = C_{M_{p\alpha 0}}\delta + C_{M_{p\delta 2}}\delta^3$ $C_{M_{p\delta}} = C_{M_{p\delta 0}} + C_{M_{p\delta 2}}\delta^2$ This moment arises because the Magnus force is applied outside of the centre of mass.

ρ – air density, C_i – coefficients of aerodynamic forces and moments, d – diameter of the missile, S – reference area.

Aerodynamic coefficients are determined using PRODAS software [14], which theoretical base can be found in [5]. Exemplary courses are shown in Fig. 2 and 3.

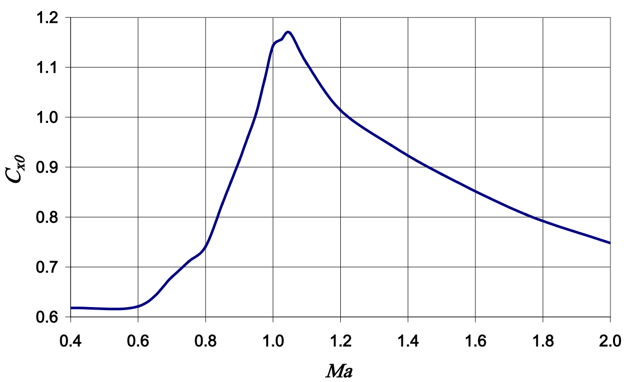

Fig. 2. Drag coefficient C_{x0}

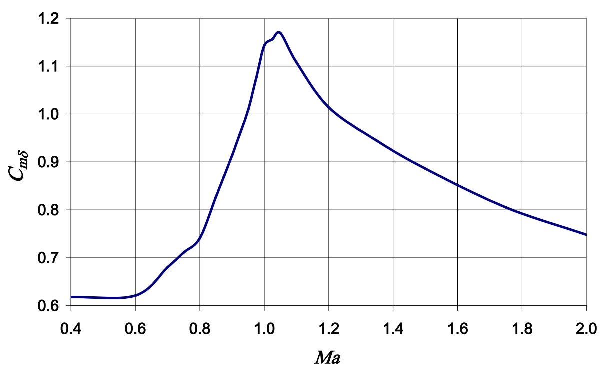

Fig. 3. Pitch moment coefficient $C_{m\delta}$

4. Model of the turbulence

The wind is dependent on time and space, but very often, it is assumed that it is only function of space $\mathbf{V}_w = \mathbf{V}_w(x_g, y_g, z_g)$. This assumption is based on the Taylor's "frozen turbulence" hypothesis. According to this hypothesis, the advection velocity of the turbulence is much greater than the velocity scale of the turbulence itself. The velocity $\mathbf{V}_w$ has two component – one with the constant value and direction and the second, which is various. In this article, the first component is omitted and the second is treated as the stochastic process representing atmospheric turbulence. To describe this turbulence Shinozuka's method was applied [9, 13, 19, 20]. This method is very useful to numerical simulation of stochastic processes. Originally, it was dedicated to simulate earthquakes. In this method, any stochastic process is written as a sum of periodic functions, amplitudes of which depend on the so-called Power Spectral Density Φ (PSD). Phases of these functions are random "white noise". The formula for *i*-th component of $\mathbf{V}_w$ is as follows:

$$\mathbf{V}_{w\_i}(\mathbf{r}) = \sum_{j=1}^{i}\sum_{l=1}^{L}\left|H_{ij}\left(\mathbf{\Omega}_l\right)\right|\sqrt{2\Delta\mathbf{\Omega}}\cos\left(\mathbf{\Omega}_l^{'}\mathbf{r} + \phi_{jl}\right), \tag{7}$$

where: $\mathbf{\Omega}_l$ – the vector of „spatial" frequency, $\mathbf{\Omega}_l^{'}$ – the perturbed vector of „spatial" frequency; $\mathbf{r}=[x_g, y_g, z_g]$ – the vector determining position of the point under consideration; ϕ_{jl} – the mutually independent and stochastically variable phase displacements of values 0-2π; **H** – the lower triangular matrix of amplitudes related to the matrix of Power Spectral Density **Φ** by means of the following dependence:

$$\mathbf{\Phi}(\mathbf{\Omega}) = \mathbf{H}(\mathbf{\Omega}) \cdot \mathbf{H}^T(\mathbf{\Omega}). \tag{8}$$

Nonzero components of matrix **H**(**Ω**) can be determined if PSD is known:

$$H_{11} = \sqrt{\Phi_{11}}, \qquad H_{21} = \Phi_{21}/H_{11}, \qquad H_{22} = \sqrt{\Phi_{22} - \left(H_{21}\right)^2},$$

$$H_{31} = \Phi_{31}/H_{11}, \qquad H_{32} = (\Phi_{32} - H_{31}H_{21})/H_{22}, \qquad H_{33} = \sqrt{\Phi_{33} - \left(H_{31}\right)^2 - \left(H_{32}\right)^2}.$$

As it is above visible, to determine matrix **H** the Power Spectral Density **Φ** must be known. It can be determined on the basis of available measurements of wind field fluctuations, or using specific expressions presented in the literature. One of the most popular is the Dryden's spectrum used in flight mechanics [7, 9, 13]. We can find three variants of spectrums:

– one dimensional spectrum:

$$\mathbf{\Phi}(\Omega_x) = \frac{L_w}{2\pi}\frac{\sigma^2}{\left[1 + L_w^2\Omega_x^2\right]^2}\begin{bmatrix} 2\left(1 + L_w^2\Omega_x^2\right) & 0 & 0, \\ 0 & 1 + 3L_w^2\Omega_x^2 & 0, \\ 0 & 0 & 1 + 3L_w^2\Omega_x^2, \end{bmatrix} \tag{9a}$$

– two dimensional spectrum:

$$\mathbf{\Phi}(\Omega_x, \Omega_y) = \frac{L_w^2}{4\pi}\frac{\sigma^2}{\left[1 + L_w^2\left(\Omega_x^2 + \Omega_y^2\right)\right]^{\frac{5}{2}}}\begin{bmatrix} 1 + L_w^2\left(\Omega_x^2 + 4\Omega_y^2\right) & -3\Omega_x\Omega_y L_w^2 & 0, \\ -3\Omega_x\Omega_y L_w^2 & 1 + L_w^2\left(4\Omega_x^2 + \Omega_y^2\right) & 0, \\ 0 & 0 & 3L_w^2\left(\Omega_x^2 + \Omega_y^2\right), \end{bmatrix} \tag{9b}$$

– three dimensional spectrum:

$$\mathbf{\Phi}(\Omega_x,\Omega_y,\Omega_z)=\frac{2L_w^3}{\pi^2}\frac{\sigma^2}{\left[1+L_w^2\left(\Omega_x^2+\Omega_y^2+\Omega_z\right)\right]^3}\begin{bmatrix} L_w^2\left(\Omega_y^2+\Omega_z^2\right) & -\Omega_x\Omega_y L_w^2 & -\Omega_x\Omega_z L_w^2 \\ -\Omega_y\Omega_x L_w^2 & L_w^2\left(\Omega_x^2+\Omega_z^2\right) & -\Omega_y\Omega_z L_w^2 \\ -\Omega_z\Omega_x L_w^2 & -\Omega_z\Omega_y L_w^2 & L_w^2\left(\Omega_x^2+\Omega_y^2\right)\end{bmatrix} \tag{9c}$$

where: L_w – the scale of turbulence, σ – the standard deviation of turbulence.

On the basis of (7) components of the turbulence in $Ox_gy_gz_g$ system can be calculated as follows:

– for one dimensional spectrum ($y_g=const,\ z_g=const$):

$$U_{wg}(x_g)=\sum_{l_x=1}^{L_x}\sum_{l_y=1}^{L_y}\left|H_{11}\left(\Omega_{xl_x}\right)\right|\sqrt{2\cdot\Delta\Omega_x}\cos\left[\Omega'_{xl_x}x_g+\phi_{1l_x}\right], \tag{10a}$$

$$V_{wg}(x_g)=\sum_{l_x=1}^{L_x}\sum_{l_y=1}^{L_y}\left|H_{21}\left(\Omega_{xl_x}\right)\right|\sqrt{2\cdot\Delta\Omega_x}\cos\left[\Omega'_{xl_x}x_g+\phi_{1l_x}\right]+\sum_{l_x=1}^{L_x}\sum_{l_y=1}^{L_y}\left|H_{22}\left(\Omega_{xl_x}\right)\right|\sqrt{2\cdot\Delta\Omega_x}\cos\left[\Omega'_{xl_x}x_g+\phi_{2l_x}\right], \tag{10b}$$

$$\begin{aligned}W_{wg}(x_g)=&\sum_{l_x=1}^{L_x}\sum_{l_y=1}^{L_y}\left|H_{31}\left(\Omega_{xl_x}\right)\right|\sqrt{2\cdot\Delta\Omega_x}\cos\left[\Omega'_{xl_x}x_g+\varphi_{1l_x}\right]+\sum_{l_x=1}^{L_x}\sum_{l_y=1}^{L_y}\left|H_{32}\left(\Omega_{xl_x}\right)\right|\sqrt{2\cdot\Delta\Omega_x}\cos\left[\Omega'_{xl_x}x_g+\varphi_{2l_x}\right]\\&+\sum_{l_x=1}^{L_x}\sum_{l_y=1}^{L_y}\left|H_{33}\left(\Omega_{xl_x}\right)\right|\sqrt{2\cdot\Delta\Omega_x}\cos\left[\Omega'_{xl_x}x_g+\varphi_{3l_x}\right],\end{aligned} \tag{10c}$$

– for two dimensional spectrum ($z_g=const$):

$$U_{wg}(x_g,y_g)=\sum_{l_x=1}^{L_x}\sum_{l_y=1}^{L_y}\left|H_{11}\left(\Omega_{xl_x},\Omega_{yl_y}\right)\right|\sqrt{2\cdot\Delta\Omega_x\cdot\Delta\Omega_y}\cos\left[\Omega'_{xl_x}x_g+\Omega'_{yl_y}y_g+\phi_{1l_xl_y}\right], \tag{11a}$$

$$\begin{aligned}V_{wg}(x_g,y_g)=&\sum_{l_x=1}^{L_x}\sum_{l_y=1}^{L_y}\left|H_{21}\left(\Omega_{xl_x},\Omega_{yl_y}\right)\right|\sqrt{2\cdot\Delta\Omega_x\cdot\Delta\Omega_y}\cos\left[\Omega'_{xl_x}x_g+\Omega'_{yl_y}y_g+\varphi_{1l_xl_y}\right]\\&+\sum_{l_x=1}^{L_x}\sum_{l_y=1}^{L_y}\left|H_{22}\left(\Omega_{xl_x},\Omega_{yl_y}\right)\right|\sqrt{2\cdot\Delta\Omega_x\cdot\Delta\Omega_y}\cos\left[\Omega'_{xl_x}x_g+\Omega'_{yl_y}y_g+\varphi_{2l_xl_y}\right],\end{aligned} \tag{11b}$$

$$\begin{aligned}W_{wg}(x_g,y_g)=&\sum_{l_x=1}^{L_x}\sum_{l_y=1}^{L_y}\left|H_{31}\left(\Omega_{xl_x},\Omega_{yl_y}\right)\right|\sqrt{2\cdot\Delta\Omega_x\cdot\Delta\Omega_y}\cos\left[\Omega'_{xl_x}x_g+\Omega'_{yl_y}y_g+\varphi_{1l_xl_y}\right]\\&+\sum_{l_x=1}^{L_x}\sum_{l_y=1}^{L_y}\left|H_{32}\left(\Omega_{xl_x},\Omega_{yl_y}\right)\right|\sqrt{2\cdot\Delta\Omega_x\cdot\Delta\Omega_y}\cos\left[\Omega'_{xl_x}x_g+\Omega'_{yl_y}y_g+\varphi_{2l_xl_y}\right]\\&+\sum_{l_x=1}^{L_x}\sum_{l_y=1}^{L_y}\left|H_{33}\left(\Omega_{xl_x},\Omega_{yl_y}\right)\right|\sqrt{2\cdot\Delta\Omega_x\cdot\Delta\Omega_y}\cos\left[\Omega'_{xl_x}x_g+\Omega'_{yl_y}y_g+\varphi_{3l_xl_y}\right],\end{aligned} \tag{11c}$$

– for three dimensional spectrum:

$$\begin{aligned}&U_{wg}(x_g,y_g,z_g)=\\&=\sum_{l_x=1}^{L_x}\sum_{l_y=1}^{L_y}\sum_{l_z=1}^{L_z}\left|H_{11}\left(\Omega_{xl_x},\Omega_{yl_y},\Omega_{zl_z}\right)\right|\sqrt{2\cdot\Delta\Omega_x\cdot\Delta\Omega_y\cdot\Delta\Omega_z}\cos\left[\Omega'_{xl_x}x_g+\Omega'_{yl_y}y_g+\Omega'_{zl_z}z_g+\varphi_{1l_xl_yl_z}\right]\end{aligned} \tag{12a}$$

$$\begin{aligned}&V_{wg}(x_g,y_g,z_g)=\\&=\sum_{l_x=1}^{L_x}\sum_{l_y=1}^{L_y}\sum_{l_z=1}^{L_z}\left|H_{21}\left(\Omega_{xl_x},\Omega_{yl_y},\Omega_{zl_z}\right)\right|\sqrt{2\cdot\Delta\Omega_x\cdot\Delta\Omega_y\cdot\Delta\Omega_z}\cos\left[\Omega'_{xl_x}x_g+\Omega'_{yl_y}y_g+\Omega'_{zl_z}z_g+\varphi_{1l_xl_yl_z}\right]+\\&+\sum_{l_x=1}^{L_x}\sum_{l_y=1}^{L_y}\sum_{l_z=1}^{L_z}\left|H_{22}\left(\Omega_{xl_x},\Omega_{yl_y},\Omega_{zl_z}\right)\right|\sqrt{2\cdot\Delta\Omega_x\cdot\Delta\Omega_y\cdot\Delta\Omega_z}\cos\left[\Omega'_{xl_x}x_g+\Omega'_{yl_y}y_g+\Omega'_{zl_z}z_g+\varphi_{2l_xl_yl_z}\right],\end{aligned} \tag{12b}$$

$$
\begin{aligned}
&W_{wg}(x_g, y_g, z_g) = \\
&= \sum_{l_x=1}^{L_x}\sum_{l_y=1}^{L_y}\sum_{l_z=1}^{L_z} \left| H_{31}\left(\Omega_{xl_x}, \Omega_{yl_y}, \Omega_{zl_z}\right)\right| \sqrt{2\cdot\Delta\Omega_x\cdot\Delta\Omega_y\cdot\Delta\Omega_z}\cos\left[\Omega'_{xl_x}x_g + \Omega'_{yl_y}y_g + \Omega'_{zl_z}z_g + \varphi_{1l_xl_yl_z}\right] + \\
&+ \sum_{l_x=1}^{L_x}\sum_{l_y=1}^{L_y}\sum_{l_z=1}^{L_z} \left| H_{32}\left(\Omega_{xl_x}, \Omega_{yl_y}, \Omega_{zl_z}\right)\right| \sqrt{2\cdot\Delta\Omega_x\cdot\Delta\Omega_y\cdot\Delta\Omega_z}\cos\left[\Omega'_{xl_x}x_g + \Omega'_{yl_y}y_g + \Omega'_{zl_z}z_g + \varphi_{2l_xl_yl_z}\right] + \\
&+ \sum_{l_x=1}^{L_x}\sum_{l_y=1}^{L_y}\sum_{l_z=1}^{L_z} \left| H_{33}\left(\Omega_{xl_x}, \Omega_{yl_y}, \Omega_{zl_z}\right)\right| \sqrt{2\cdot\Delta\Omega_x\cdot\Delta\Omega_y\cdot\Delta\Omega_z}\cos\left[\Omega'_{xl_x}x_g + \Omega'_{yl_y}y_g + \Omega'_{zl_z}z_g + \varphi_{3l_xl_yl_z}\right],
\end{aligned}
\tag{12c}
$$

Additional subscript "g" shows that velocity components are determined in $Ox_gy_gz_g$ coordinate system.

For calculations boundary values of „spatial" frequency, must be defined:

$$\Omega_{x\,\mathrm{lower}} \le \Omega_x \le \Omega_{x\,\mathrm{upper}},\ \Omega_{y\,\mathrm{lower}} \le \Omega_y \le \Omega_{y\,\mathrm{upper}},\ \Omega_{z\,\mathrm{lower}} \le \Omega_z \le \Omega_{z\,\mathrm{upper}} \tag{13}$$

and next ranges of frequencies are respectively divided into L_x, L_y and L – subintervals in the manner:

$$\Delta\Omega_x = (\Omega_{x\,\mathrm{upper}} - \Omega_{x\,\mathrm{lower}})/L_x,\ \Delta\Omega_y = (\Omega_{y\,\mathrm{upper}} - \Omega_{y\,\mathrm{lower}})/L_x,\ \Delta\Omega_z = (\Omega_{z\,\mathrm{upper}} - \Omega_{z\,\mathrm{lower}})/L_x. \tag{14}$$

The subsequent values of frequencies in (10) are calculated with formulas:

$$\Omega_{xl_x} = \Omega_{x\,\mathrm{lower}} + (l_x - 1)\Delta\Omega_x,\ \Omega_{yl_y} = \Omega_{y\,\mathrm{lower}} + (l_y - 1)\Delta\Omega_y,\ \Omega_{zl_z} = \Omega_{z\,\mathrm{lower}} + (l_z - 1)\Delta\Omega_z. \tag{15}$$

The perturbed vector of „spatial" frequency $\mathbf{\Omega}'_l$ in (7) is randomly perturbed vector $\mathbf{\Omega}_l$, which is determined to avoid periodicity of the simulated turbulence. It has following components:

$$\Omega'_{xl_x} = \Omega_{xl_x} + \delta\Omega_{xl_x},\ \Omega'_{yl_y} = \Omega_{yl_y} + \delta\Omega_{yl_y},\ \Omega'_{zl_z} = \Omega_{zl_z} + \delta\Omega_{zl_z}. \tag{16}$$

Each perturbation must satisfy the condition which e.g. for x component has the form:

$$\left|\delta\Omega_{xl_x}\right| << 0.5\cdot\Delta\Omega_x,\ \left|\delta\Omega_{yl_y}\right| << 0.5\cdot\Delta\Omega_y,\ \left|\delta\Omega_{zl_z}\right| << 0.5\cdot\Delta\Omega_z. \tag{17}$$

Phase displacements ϕ_{jl_x}, $\phi_{jl_xl_y}$, $\phi_{jl_xl_yl_z}$ ($j = 1, 2, 3$) are mutually independent, randomly variable, and included in the range of 0-2π.

5. Results of simulations

Simulations were performed for the missile ICP-1 which is used by Polish Military Forces as a target for antiaircraft training reason /see Fig. 4/. The basic data of the missile are as follows: initial mas 5.36 kg, fuel mass 1.13 kg, diameter 57 mm, length 1100 mm, engine-working time 0.7 s.

At the beginning of simulations, the described above model of missile motion was tested by comparing its results with data recorder during real firing tests. In Fig. 5 and 6, we can see comparison for flight velocity and trajectory for the initial conditions: the pitch angle Θ=45^0, the initial velocity V_{aer}=40 m/s. We can see good comparison between theoretical calculations and real data despite of differences between theoretically calculated and measured thrust – Fig. 7.

Fig. 4. ICP-1 missile

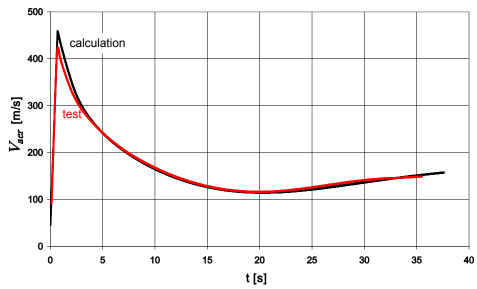

Fig. 5. Flight velocity of the missile

Next simulations were performed including shown above stochastic description of the turbulence. The two dimensional PSD were used. Components of the PSD are presented in Fig. 8−10. Parameters of turbulence were as follows: the scale of turbulence L_w =400 m, the standard deviation of turbulence σ =5 m/s. During each simulation, different profile of turbulence was obtained. It is shown in Fig. 11 where exemplary courses of $W_{wg\,t}(t)$ turbulence component for two simulations are presented. As it was assumed, we can see that the courses are different each other although they both have the same parameters of stochastic description.

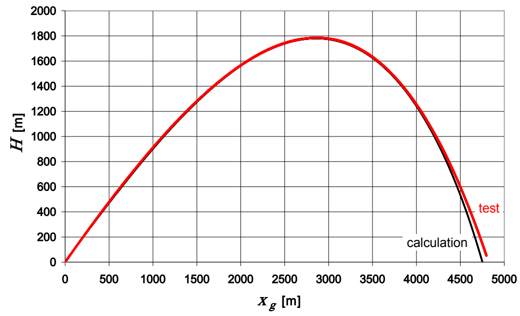

Fig. 6. Trajectory of the missile

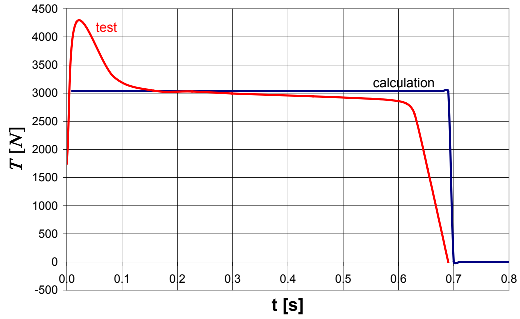

Fig. 7. Theoretical and measured thrust

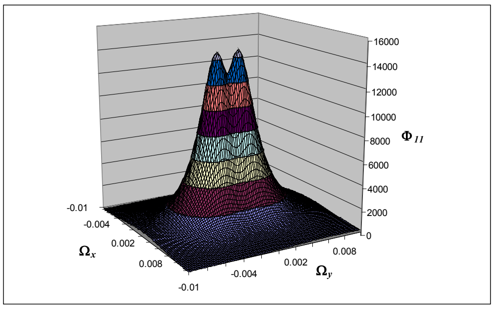

Fig. 8. PSD Φ_{11} component

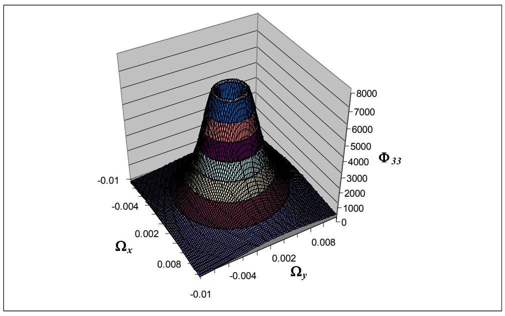

Fig. 9. PSD Φ_{33} component

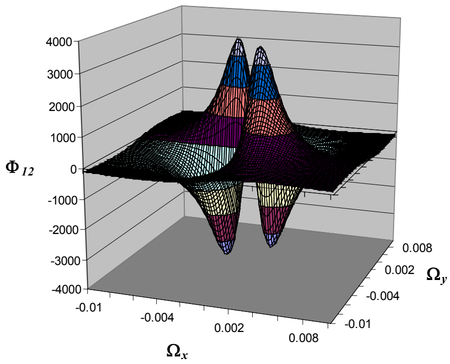

Fig. 10. PSD Φ_{12} component

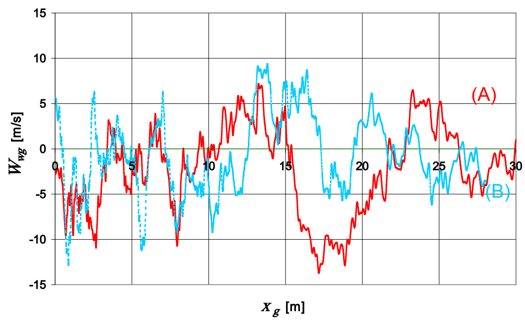

Fig. 11. W_{wg} component of turbulence

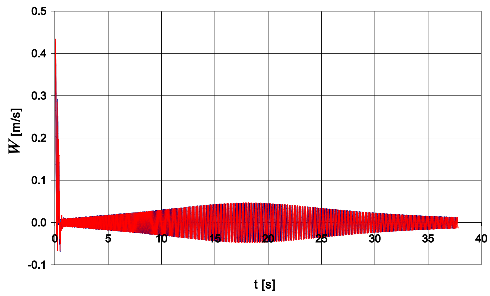

Fig. 12. W component of linear velocity

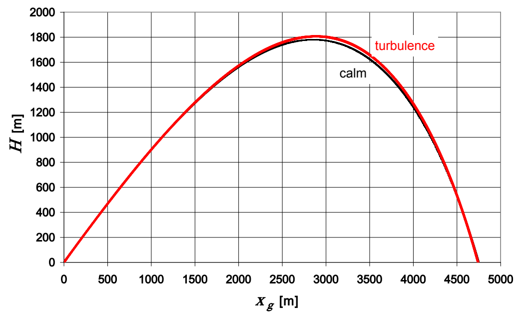

Fig. 13 Vertical trajectory

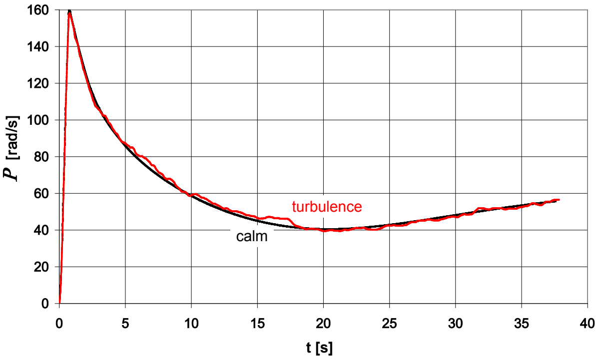

Fig. 14. Rolling angular velocity P

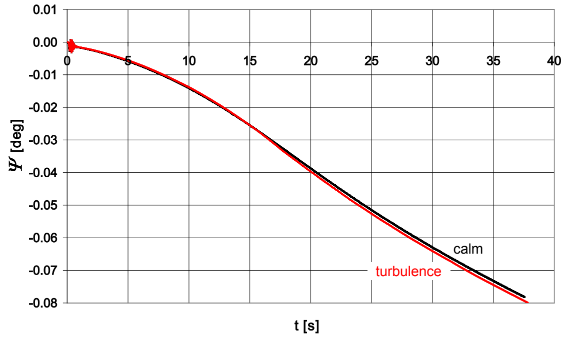

Fig. 15. Yaw angle Ψ

Figures 12-15 show courses of a few flight parameters for calm and turbulent atmosphere versus time. They were obtained for the same initial conditions as above i.e. Θ=45°, V_{aer}=40 m/s. For the sake of comparison, each diagram also shows results for the case of calm atmosphere. They are represented with a black dotted line. We can find only small influence of turbulence on some courses. The most visible effect is for the rolling angular velocity P /Fig. 14/ and for the yaw angle Ψ /Fig. 15/. However, detailed analysis shows that even small disturbances of the flight parameters cause important influence on the point of missile fall. Fig. presents these points obtained for twenty-four simulations for the pitch angle equal to 40^0. The coordinates of the fall point without turbulence are respectively m_g=4407.6 m and y_g=-1.752 m. It means that the trajectory of the missile deviates to the left. In the case of turbulence, the average values of coordinates are as follows: $x_{g\ av}$=4362.75 m and $y_{g\ av}$=-1.74 m. Their standard deviations are equal to: σ_x=58.47 m and σ_y =0.015 m. It shows that turbulence strongly impacts on the firing range of missile. It is important if the high precision is required. Comparing shown above x_g coordinates we can see that the turbulence reduces the range of the missile. The reason is that the mean aerodynamic-drag coefficient increases because of the increased nutation angle (Fig. 17).

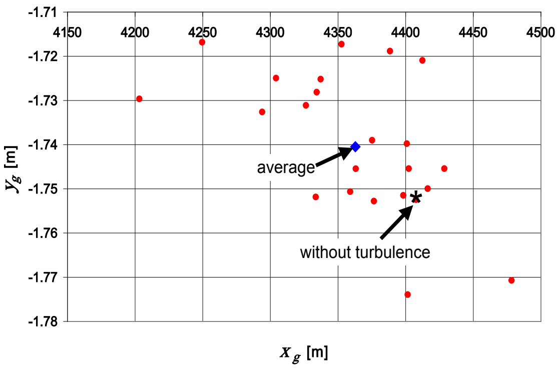

Fig. 16. Points of the missile fall on the horizontal plane Ox_gy_g

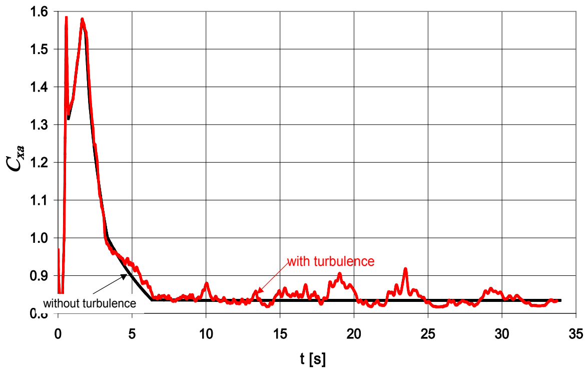

Fig. 17. Aerodynamic drag coefficient during missile flight

6. Conclusions

The conducted analysis has proved that the effect of turbulence on the missile accuracy may be essential and should be taken into account when planning the precise firing. Stochastic nature of the atmospheric turbulence results in the random distribution of points of fall. Turbulences increase the nutation angle during the missile flight and result in the reduction of the range of firing. Further studies will cover the question of determining final parameters of the missile flight in the wind, depending on initial pitch angle and parameters that describe the wind field.

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