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SENSITIVITY OF A BOMB TO WIND TURBULENCE

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This paper presents results of numerical investigations into the bomb release in a turbulent wind field. Short descriptions of mathematical models of both the bomb dynamics and the stochastic wind are shown. The effect of parameters of the turbulent wind field on a random distribution of points of the impact is investigated.

Key words: bomb release, atmospheric turbulence

1. Introduction

The response of a bomb to atmospheric turbulence plays an important role in the process of precise bomb release, i.e. the highest possible degree of accuracy of target hitting, being the main goal of this process. Therefore, the correct prediction of the effects of turbulence on the bomb flight is needed to get some specific point on the Earth's surface. Numerical simulation can be a significant support in this research work. In order to theoretically investigate the bomb response to turbulence, accurate mathematical models of both the bomb and the wind field are required.

Atmospheric conditions can significantly vary during the bomb flight. One of the most important is the structure of a wind field. This field is turbulent, stochastic in nature and is characterised by a set of different parameters. The most essential ones are as follows: power spectral density, standard deviation, and scale of turbulence. The wind changes aerodynamic forces and moments that act on the bomb. It affects the bomb trajectory, and hence, the point of impact. Therefore, different atmospheric conditions force changes in the initial conditions of the bomb release.

The dynamic response of the bomb to external disturbances depends on its physical characteristics. Therefore, one of the problems that arise here is to use a proper and precise description of bomb motion. Only then the results of numerical simulations are reliable and useful.

This paper summarises theoretical research work based on both the 6-DOF model of the bomb flight dynamics and the Shinozuka method that allows simulation of stochastic processes. Sensitivity of the bomb to standard deviation of a wind field has been tested.

2. Mathematical description of bomb dynamics

2.1. Systems of coordinates and equations of motion

A small training bomb was an object under investigation. The flight dynamics model was formulated taking account of what follows (Lebedew and Czernobrowkin, 1973; Ostoslawskij, 1957; Ostoslawskij and Stravewa, 1964, Kowaleczko, 2003; Mnitowski, 2006):

1. the bomb is a rigid body of constant mass, constant moments of inertia, and a constant position of the centre of mass

2. the bomb has two symmetry planes. These are the Oxz and Oxy planes (Fig. 1) that are planes of geometric, mass, and aerodynamic symmetries.

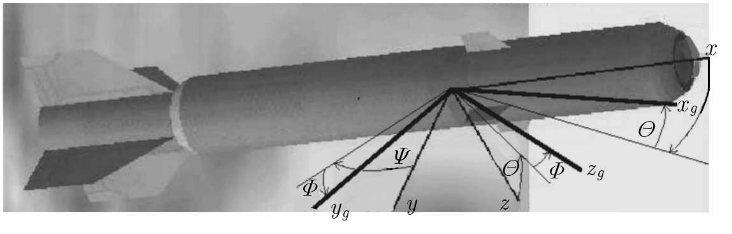

Fig. 1. Systems of coordinates with angles of transition

Three systems of coordinates were used:

$Oxyz$	–	the bomb-fixed system with its origin at the bomb centre of mass
$Ox_ay_az_a$	–	the air-trajectory reference frame
$Ox_gy_gz_g$	–	the Earth-referenced system with its origin at the bomb centre of mass.

Subsequent turns by the following angles: of yaw Ψ, pitch Θ, and roll Φ produce transition of the $Ox_gy_gz_g$ system to the $Oxyz$ system. The transition matrix $\mathbf{L}_{s/g}$ has the following form

$$\mathbf{L}_{s/g} = \tag{2.1}$$
$$= \begin{bmatrix} \cos\Psi\cos\Theta & \sin\Psi\cos\Theta & -\sin\Theta \\ \cos\Psi\sin\Theta\sin\Phi - \sin\Psi\cos\Phi & \sin\Psi\sin\Theta\sin\Phi + \cos\Psi\cos\Phi & \cos\Theta\sin\Phi \\ \cos\Psi\sin\Theta\cos\Phi + \sin\Psi\sin\Phi & \sin\Psi\sin\Theta\cos\Phi - \cos\Psi\sin\Phi & \cos\Theta\cos\Phi \end{bmatrix}$$

Turns by the angles of: sideslip β and attack α result in finding the matrix of transition $\mathbf{L}_{s/a}$ from the $Ox_ay_az_a$ system to the $Oxyz$ system

$$\mathbf{L}_{s/a} = \begin{bmatrix} \cos\alpha\cos\beta & -\cos\alpha\sin\beta & -\sin\alpha \\ \sin\beta & \cos\beta & 0 \\ \sin\alpha\cos\beta & -\sin\alpha\sin\beta & \cos\alpha \end{bmatrix} \tag{2.2}$$

A vector equation of motion of the bomb centre of mass has the following form

$$\frac{d(m\boldsymbol{V})}{dt} = \frac{\partial(m\boldsymbol{V})}{\partial t} + \boldsymbol{\Omega} \times (m\boldsymbol{V}) = \boldsymbol{F} \tag{2.3}$$

where m is the mass of the bomb; $\boldsymbol{V}$ – velocity vector; $\boldsymbol{\Omega}$ – vector of angular velocity of the moving system against the inertial reference frame; $\boldsymbol{F}$ – resultant vector of forces acting on the bomb.

If the system $Ox_ay_az_a$ is assumed to be a moving system, the velocity vector has only one component $U_a = V$. The vector of the angular velocity of the $Ox_ay_az_a$ system against the inertial reference frame can be determined as

$$\boldsymbol{\Omega}_a = \boldsymbol{\Omega}_s + \boldsymbol{\Omega}_{s/a} = \boldsymbol{\Omega}_s + \dot{\boldsymbol{\beta}} - \dot{\boldsymbol{\alpha}} \tag{2.4}$$

The final form of the system of three scalar equations of motion is as follows

$$\begin{gathered} \dot{V} = \frac{1}{m}X_a \qquad \dot{\beta} = \frac{1}{mV}Y_a + P\sin\alpha - R\cos\alpha \\ \dot{\alpha} = \frac{1}{\cos\beta}\Big[\frac{Z_a}{mV} + Q\cos\beta - (P\cos\alpha + R\sin\alpha)\sin\beta\Big] \end{gathered} \tag{2.5}$$

where: P, Q, R denote the roll, pitch and yaw angular velocities of the bomb (components of the vector $\boldsymbol{\Omega}_s$); X_a, Y_a, Z_a – components of the force $\boldsymbol{F}$.

A vector equation of rotational motion of the bomb is as follows

$$\frac{d(\boldsymbol{K})}{dt} = \frac{\partial(\boldsymbol{K})}{\partial t} + \boldsymbol{\Omega} \times \boldsymbol{K} = \boldsymbol{M} \tag{2.6}$$

where: $\boldsymbol{K} = \mathbf{I}\boldsymbol{\Omega}$ is the vector of angular momentum; $\boldsymbol{M}$ – resultant moment of forces acting on the bomb; $\mathbf{I}$ – inertia tensor determined as

$$\mathbf{I} = \begin{bmatrix} I_x & -I_{xy} & -I_{xz} \\ -I_{yx} & I_y & -I_{yz} \\ -I_{zx} & -I_{zx} & I_z \end{bmatrix} \tag{2.7}$$

Taking into account that the following is valid for the bomb

$$I_{xy} = I_{yx} = I_{zy} = I_{yz} = 0 \tag{2.8}$$

one can obtain three scalar equations describing angular motion of the bomb around axes of the $Oxyz$ system

$$\begin{aligned}
\dot{P} &= \frac{1}{I_x}[L + (I_y - I_z)QR] \\
\dot{Q} &= \frac{1}{I_y}[M + (I_z - I_x)RP] \\
\dot{R} &= \frac{1}{I_x I_z}[L + (I_y - I_z)QR]
\end{aligned} \tag{2.9}$$

where L, M, N are components of the vector $\boldsymbol{M}$.

Systems (2.5) and (2.9) are complemented with the following kinematic relations

$$\begin{aligned}
\dot{\varPhi} &= P + (R\cos\varPhi + Q\sin\varPhi)\tan\varTheta \\
\dot{\varTheta} &= Q\cos\varPhi - R\sin\varPhi \\
\dot{\varPsi} &= \frac{1}{\cos\varTheta}(R\cos\varPhi + Q\sin\varPhi)
\end{aligned} \tag{2.10}$$

and

$$\begin{aligned}
\dot{x}_g &= V[\cos\alpha\cos\beta\cos\varTheta\cos\varPsi + \sin\beta(\sin\varPhi\sin\varTheta\cos\varPsi - \cos\varPhi\sin\varPsi) + \\
&\quad + \sin\alpha\cos\beta\cos\varPhi\sin\varTheta\cos\varPsi + \sin\varPhi\sin\varPsi)] \\
\dot{y}_g &= V[\cos\alpha\cos\beta\cos\varTheta\sin\varPsi + \sin\beta(\sin\varPhi\sin\varTheta\sin\varPsi + \cos\varPhi\cos\varPsi) + \\
&\quad + \sin\alpha\cos\beta(\cos\varPhi\sin\varTheta\sin\varPsi + \sin\varPhi\cos\varPsi)] \\
\dot{z}_g &= V[-\cos\alpha\cos\beta\sin\varTheta + \sin\beta\sin\varPhi\cos\varTheta + \sin\alpha\cos\beta\cos\varPhi\sin\varTheta]
\end{aligned} \tag{2.11}$$

Equations (2.5), (2.9), (2.10) and (2.11) compose a system of 12 ordinary differential equations that describe spatial motion of the bomb treated as a rigid body. It can be written down in the following form

$$\frac{d\boldsymbol{X}}{dt} = \boldsymbol{F}(t, \boldsymbol{X}) \tag{2.12}$$

$\boldsymbol{X}$ is a twelve-element vector of the bomb flight parameters

$$\boldsymbol{X} = [V, \alpha, \beta, P, Q, R, \varPhi, \varTheta, \varPsi, x_g, y_g, z_g]^\top$$

2.2. Forces and moments

Aerodynamic and gravitational forces are the only forces that act on the bomb

$$\boldsymbol{F} = \boldsymbol{Q} + \boldsymbol{R} \tag{2.13}$$

Therefore, the resultant force $\boldsymbol{F}$ has the following components in the $Ox_ay_az_a$ system

$$X_a = Q_{x_a} + R_{x_a} \qquad Y_a = Q_{y_a} + R_{y_a} \qquad Z_a = Q_{z_a} + R_{z_a} \tag{2.14}$$

The **weight of the bomb** $\boldsymbol{Q}$ has only one component $\boldsymbol{Q} = [0, 0, mg]^\top$ in the $Ox_gy_gz_g$ system. Using transformation matrices $\mathsf{L}_{s/g}$ and $\mathsf{L}_{s/a}$, one can calculate components of the vector $\boldsymbol{Q}$ in the $Ox_ay_az_a$ system

$$\begin{aligned}
Q_{x_a} &= mg(-\cos\alpha\cos\beta\sin\Theta + \sin\beta\cos\Theta\sin\Phi + \sin\alpha\cos\beta\cos\Theta\cos\Phi)\\
Q_{y_a} &= mg(\cos\alpha\sin\beta\sin\Theta + \cos\beta\cos\Theta\sin\Phi - \sin\alpha\sin\beta\cos\Theta\cos\Phi)\\
Q_{z_a} &= mg(\sin\alpha\sin\Theta + \cos\alpha\cos\Theta\cos\Phi)
\end{aligned} \tag{2.15}$$

The **aerodynamic force** $\boldsymbol{R}$ has the following components in the $Ox_ay_az_a$ system

$$\begin{aligned}
&R_{x_a} = -P_{xa} = -C_{xa}\frac{\rho V^2}{2}S \qquad R_{y_a} = P_{ya} = -C_{ya}\frac{\rho V^2}{2}S\\
&R_{z_a} = -P_{za} = -C_{za}\frac{\rho V^2}{2}S
\end{aligned} \tag{2.16}$$

where: C_{xa}, C_{ya}, C_{za} are coefficients of aerodynamic drag, side and lift forces, respectively; S – cross-sectional area of the bomb; ρ – air density.

The only moments acting on the bomb are moments produced by aerodynamic forces. These moments are usually determined in the $Oxyz$ system. They are as follows:

— rolling moment

$$L = C_l\frac{\rho V^2}{2}Sd \tag{2.17}$$

— pitching moment

$$M = C_m\frac{\rho V^2}{2}Sd \tag{2.18}$$

— yawing moment

$$N = C_n\frac{\rho V^2}{2}Sd \tag{2.19}$$

where: C_l, C_m, C_n are coefficients of rolling, pitching and yawing moments, respectively; d – diameter of the bomb.

3. Mathematical description of a wind field

Generally, a wind field is variable in time and space (Holbit, 1988; Mnitowski, 2006; Shinozuka, 1971; Shinozuka and Jan, 1972; Kowaleczko and Żyluk, 2009)

$$\boldsymbol{V}_w = \boldsymbol{V}_w(t, x_g, y_g, z_g) \tag{3.1}$$

In this work it has been assumed that the wind is independent of time. This assumption proves correct for objects flying at high speeds, e.g. bombs. Because the effect of turbulence on the bomb dynamics is under consideration, the constant component of the wing is omitted.

Wind velocity (3.1) affects angles of both attack and sideslip, which in turn affect aerodynamic forces (2.16) and moments (2.17)-(2.19). The angles mentioned here are as follows

$$\alpha = \arctan\frac{w - w_w}{u - u_w} \qquad \beta = \arctan\frac{v - v_w}{\sqrt{(u - u_w)^2 + (w - w_w)^2}} \tag{3.2}$$

where u, v, w are components of the bomb velocity against the Earth $\boldsymbol{V} = [u, v, w]^\top$; and u_w, v_w, w_w – components of the wind velocity against the Earth $\boldsymbol{V}_w = [u_w, v_w, w_w]^\top$. All these components are determined in the $Oxyz$ system.

Reconstruction of the stochastic structure of the wind field has been based on the Shinozuka method. In this method it is assumed that any stochastic process is a sum of periodic courses, the amplitudes of which depend on the Power Spectral Density $\boldsymbol{\Phi}$ (PSD), and phases are random functions of the "white noise" type. The basic expression to calculate the wind field in terms of a stochastic process takes the following form (see Mnitowski, 2006)

$$v_i(\boldsymbol{r}) = \sum_{j=1}^{i}\sum_{l=1}^{L} |H_{ij}(\boldsymbol{\Omega}_l)|\sqrt{2\Delta\boldsymbol{\Omega}}\cos(\boldsymbol{\Omega}_l'\boldsymbol{r} + \phi_{jl}) \tag{3.3}$$

where: $\boldsymbol{\Omega}$ is a perturbed vector of "spatial" frequency; $\boldsymbol{r}$ – vector that determines the position of point under consideration; ϕ_{jl} – mutually independent and stochastically variable phase displacements of values 0-2π; $\mathbf{H}$ – lower triangular matrix of amplitudes related to the matrix of the Power Spectral Density $\boldsymbol{\Phi}$ by means of the following relationship

$$\boldsymbol{\Phi}(\boldsymbol{\Omega}) = \mathbf{H}(\boldsymbol{\Omega})\mathbf{H}^\top(\boldsymbol{\Omega}) \tag{3.4}$$

In a general case, if components of the matrix $\mathbf{\Phi}(\boldsymbol{\Omega})$ are known, then the non-zero matrix components $\mathbf{H}(\boldsymbol{\Omega})$ can be determined using the following expressions

$$
\begin{aligned}
H_{11} &= \sqrt{\Phi_{11}} & H_{21} &= \frac{\Phi_{21}}{H_{11}} \\
H_{22} &= \sqrt{\Phi_{22} - (H_{21})^2} & H_{31} &= \frac{\Phi_{31}}{H_{11}} \\
H_{32} &= \frac{\Phi_{32} - H_{31}H_{21}}{H_{22}} & H_{33} &= \sqrt{\Phi_{33} - (H_{31})^2 - (H_{32})^2}
\end{aligned}
\tag{3.5}
$$

Expression (3.3) allows us to calculate components of the wind in the Earth-related $Ox_gy_gz_g$ system. Assuming that characteristics of the wind depend on the x_g and y_g coordinates, the expression takes the following form

$$
\begin{aligned}
u_{wg\,t}(x_g, y_g) &= \\
&= \sum_{l_x=1}^{L_x} \sum_{l_y=1}^{L_y} |H_{11}(\Omega_{xl_x}, \Omega_{yl_y})| \sqrt{2\Delta\Omega_x\,\Delta\Omega_y} \cos(\Omega'_{xl_x} x_g + \Omega'_{yl_y} y_g + \phi_{1l_xl_y}) \\
v_{wg\,t}(x_g, y_g) &= \\
&= \sum_{l_x=1}^{L_x} \sum_{l_y=1}^{L_y} |H_{21}(\Omega_{xl_x}, \Omega_{yl_y})| \sqrt{2\Delta\Omega_x\,\Delta\Omega_y} \cos(\Omega'_{xl_x} x_g + \Omega'_{yl_y} y_g + \phi_{1l_xl_y}) + \\
&+ \sum_{l_x=1}^{L_x} \sum_{l_y=1}^{L_y} |H_{22}(\Omega_{xl_x}, \Omega_{yl_y})| \sqrt{2\Delta\Omega_x\,\Delta\Omega_y} \cos(\Omega'_{xl_x} x_g + \Omega'_{yl_y} y_g + \phi_{2l_xl_y}) \\
w_{wg\,t}(x_g, y_g) &= \\
&= \sum_{l_x=1}^{L_x} \sum_{l_y=1}^{L_y} |H_{31}(\Omega_{xl_x}, \Omega_{yl_y})| \sqrt{2\Delta\Omega_x\,\Delta\Omega_y} \cos(\Omega'_{xl_x} x_g + \Omega'_{yl_y} y_g + \phi_{1l_xl_y}) + \\
&+ \sum_{l_x=1}^{L_x} \sum_{l_y=1}^{L_y} |H_{32}(\Omega_{xl_x}, \Omega_{yl_y})| \sqrt{2\Delta\Omega_x\,\Delta\Omega_y} \cos(\Omega'_{xl_x} x_g + \Omega'_{yl_y} y_g + \phi_{2l_xl_y}) + \\
&+ \sum_{l_x=1}^{L_x} \sum_{l_y=1}^{L_y} |H_{33}(\Omega_{xl_x}, \Omega_{yl_y})| \sqrt{2\Delta\Omega_x\,\Delta\Omega_y} \cos(\Omega'_{xl_x} x_g + \Omega'_{yl_y} y_g + \phi_{3l_xl_y})
\end{aligned}
\tag{3.6}
$$

The frequencies Ω are within limited intervals

$$
\Omega_{x\,lower} \leqslant \Omega_x \leqslant \Omega_{x\,upper} \qquad\qquad \Omega_{y\,lower} \leqslant \Omega_y \leqslant \Omega_{y\,upper} \tag{3.7}
$$

Each interval is subdivided into Li of subintervals of the following length

$$\Delta\Omega_x = \frac{\Omega_{x\,upper} - \Omega_{x\,lower}}{L_x} \qquad \Delta\Omega_y = \frac{\Omega_{y\,upper} - \Omega_{y\,lower}}{L_y} \tag{3.8}$$

The arguments of the matrix components $\mathbf{H}(\boldsymbol{\Omega})$ in (3.6) are defined as

$$\begin{aligned} \Omega_{xl_x} &= \Omega_{x\,lower} + (l_x - 1)\Delta\Omega_x \\ \Omega_{yl_y} &= \Omega_{y\,lower} + (l_y - 1)\Delta\Omega_y \end{aligned} \tag{3.9}$$

On the other hand, the frequencies occurring in the arguments of the cosine function are as follows

$$\Omega'_{xl_x} = \Omega_{xl_x} + \delta\Omega_{xl_x} \qquad \Omega'_{yl_y} = \Omega_{yl_y} + \delta\Omega_{yl_y} \tag{3.10}$$

To avoid periodicity of the simulated gust, additional random perturbations $\delta\Omega$ are added to the main frequencies. They satisfy the following inequalities

$$-\frac{\Delta'\Omega_x}{2} \leqslant \delta\Omega_{xl_x} \leqslant \frac{\Delta'\Omega_x}{2} \qquad -\frac{\Delta'\Omega_y}{2} \leqslant \delta\Omega_{yl_y} \leqslant \frac{\Delta'\Omega_y}{2} \tag{3.11}$$

where

$$\Delta'\Omega_x \ll \Delta\Omega_x \qquad \Delta'\Omega_y \ll \Delta\Omega_y \tag{3.12}$$

The phase displacements $\phi_{jl_xl_y}$ $(j = 1,2,3)$ are mutually independent, random, and included in the range of 0-2π.

Formulae (3.4) and (3.5) show that the matrix $\mathbf{H}$ is related to the PSD matrix $\boldsymbol{\Phi}$. In the presented study the Dryden spectrum has been applied. This spectrum is often used to deal with flight dynamics problems. The two-dimensional Dryden spectrum is as follows

$$\begin{aligned} \boldsymbol{\Phi}(\Omega_x,\Omega_y) &= \frac{L_w}{4\pi}\Big(\frac{\sigma}{1 + L_w^2(\Omega_x^2 + \Omega_y^2)}\Big)^2 \cdot \\ &\cdot \begin{bmatrix} 1 + L_w^2(\Omega_x^2 + 4\Omega_y^2) & -3\Omega_x\Omega_y L_w^2 & 0 \\ -3\Omega_x\Omega_y L_w^2 & 1 + L_w^2(4\Omega_x^2 + \Omega_y^2) & 0 \\ 0 & 0 & 3L_w^2(\Omega_x^2 + \Omega_y^2) \end{bmatrix} \end{aligned} \tag{3.13}$$

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

4. Bomb release in atmospheric turbulence

The release of a small training bomb in turbulent atmosphere was simulated. It had been assumed that a bomb of 15 kg was released from the altitude of 1000 metres. The initial speed was 236 m/s (850 km/h). The standard deviation was the same for each wind component. This deviation changed and took the following values: 5 m/s, 10 m/s, 15 m/s, 20 m/s and 25 m/s. For each of these values, a series of 128 simulations were carried out. Next, for each series, stochastic parameters were calculated – variances of coordinates of points of impact of the bomb.

Figures 2-4 show changes in the $\boldsymbol{V}_w$ component versus time gained from three simulations. These results were obtained for the standard deviation of turbulence $\sigma = 10$ m/s. One can see that these wind components are stochastic in nature.

Figures 5-8 present some selected parameters of the bomb flight. Stochastic fluctuations in these parameters are also visible. The amplitude of these fluctuations is closely connected with the deviation of wind σ_{wind}. As described in Kowaleczko and Żyluk (2009), the wind reduces the range of the bomb drop. The reason is that the mean aerodynamic-drag coefficient increases because of the increased angles of attack. This is confirmed by Fig. 9, where the average range of drop as a function of σ_{wind} is shown.

The most important results are to be found in Figs. 10 and 11, which illustrate standard deviations of the x_g and y_g coordinates of the point of impact as functions of σ_{wind}. We can see that these dependences are nonlinear and deviations of coordinates of the point of impact can take very high values. This means that the release/drop of the tested bomb in strong wind is not precise.

5. Conclusions

The conducted analysis has proved that the effect of wind on the accuracy of bomb release is essential and should be taken into account when planning the bombing. Stochastic nature of atmospheric turbulence results in random distribution of points of impact. Gusts increase the angle of attack during the bomb flight and result in reduction of the range of drop. Further studies will cover the question of determining final parameters of the bomb flight in the wind, depending on the bomb release altitude, angle of release, bomb's weight, and parameters that describe the wind field.

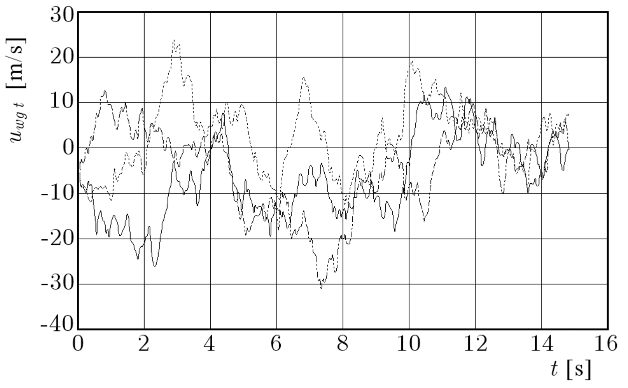

Fig. 2. Diagram of wind component $u_{wg\,t}$ versus time

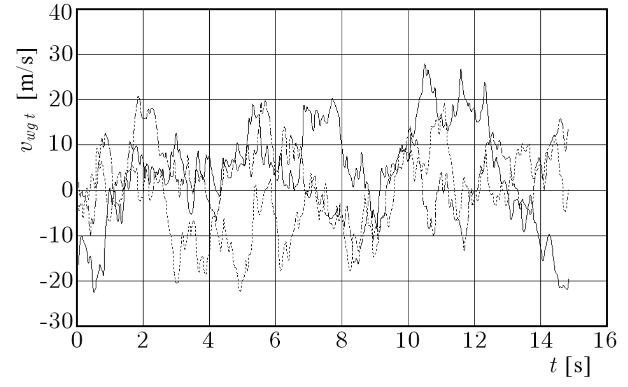

Fig. 3. Diagram of wind component $v_{wg\,t}$ versus time

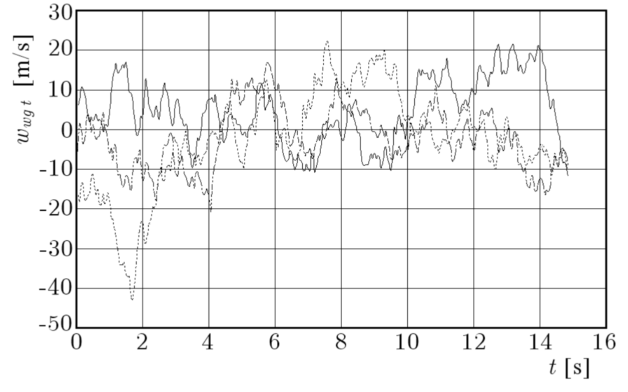

Fig. 4. Diagram of wind component $w_{wg\,t}$ versus time

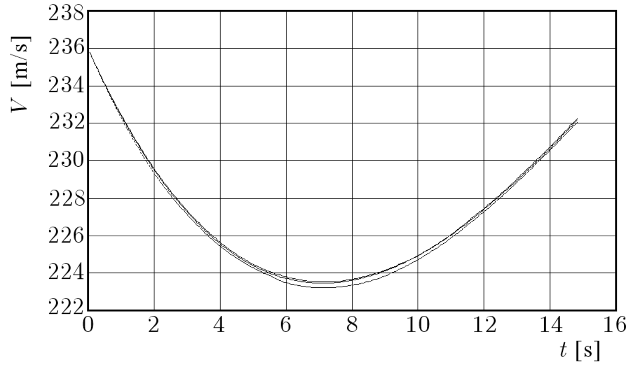

Fig. 5. Speed of the bomb flight

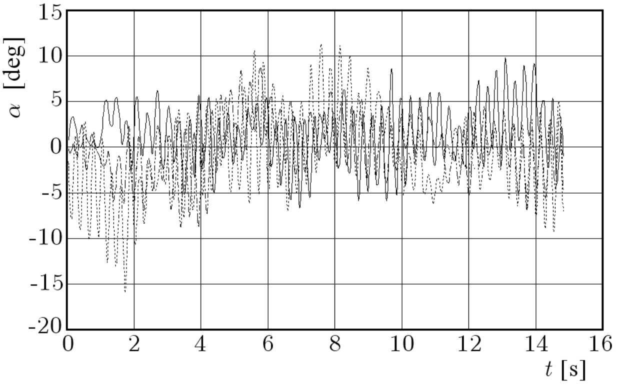

Fig. 6. Angle of attack of the bomb

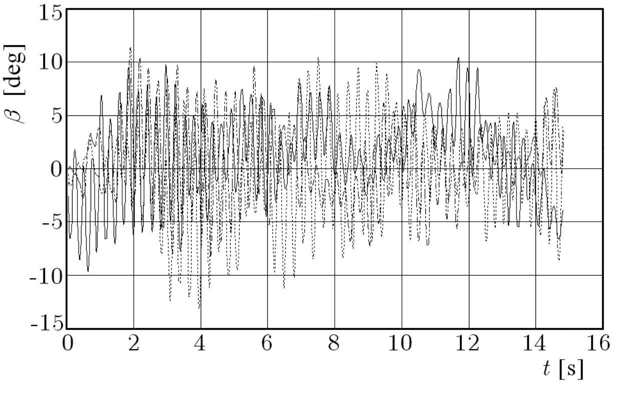

Fig. 7. Angle of sideslip of the bomb

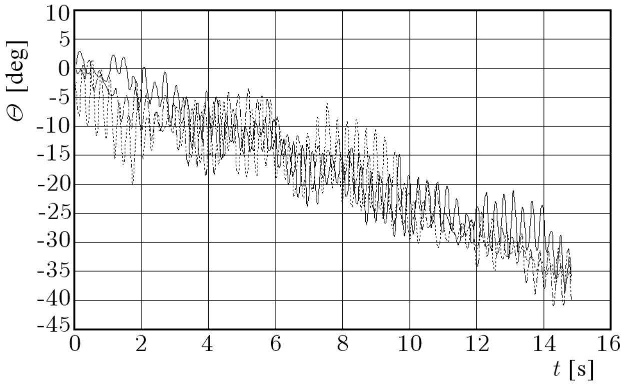

Fig. 8. Angle of pitch of the bomb

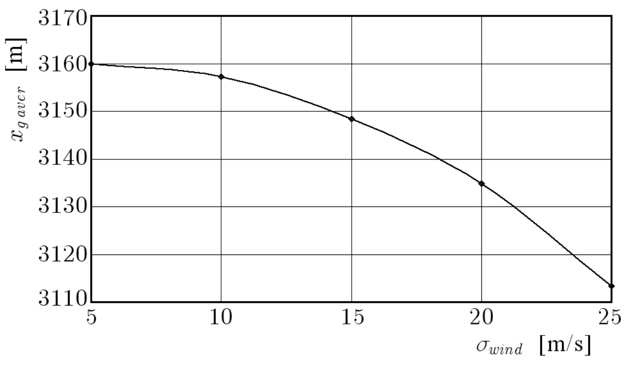

Fig. 9. Average value of x_g coordinate of the point of impact

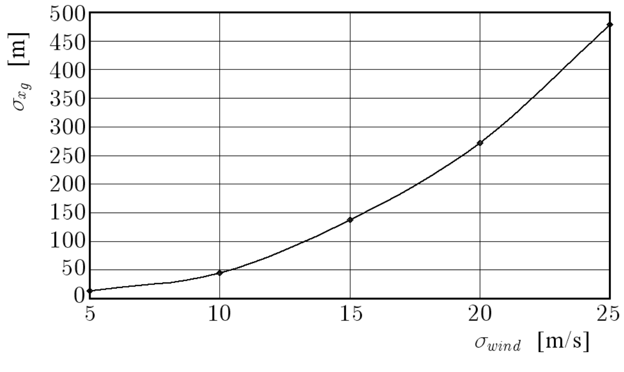

Fig. 10. Standard deviation of x_g coordinate of the point of impact

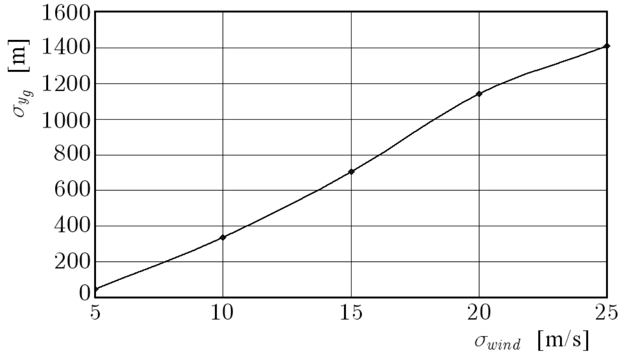

Fig. 11. Standard deviation of y_g coordinate of the point of impact

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Wrażliwość bomby na turbulencje wiatru

Streszczenie

W pracy przedstawiono wyniki numerycznej symulacji wpływu turbulencji wiatru na zrzut bomby. Praca zawiera opis matematyczny dynamiki lotu bomby oraz stochastycznego pola wiatru. Badano zależność pomiędzy parametrami turbulencji i punktem upadku bomby.

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