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Effect of Atmospheric Turbulence on the Striking Accuracy of Guided Bombs

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Abstract. This paper presents the test results of a simulation of an air-to-surface guided bomb drop in a turbulent atmosphere. The guided bomb was developed from a practice bomb built and upgraded by the Air Force Institute of Technology. The paper presents the test results of a numerical simulation of an air-to-surface guided bomb drop ran in a proprietary software environment. The numerical simulation inputs included aerodynamic characteristics calculated with PRODAS software and verified by wind tunnel tests. The stochastic components of atmospheric turbulence were simulated with a stochastic process model proposed by Shinozuki. Examples of the guided bomb drop simulation results are given in the paper. The effect of atmospheric turbulence parameters, i.e. standard deviation, σ and turbulence scale, L_w on the striking accuracy and ground impact scatter, are also shown.
Keywords: guided bomb, numerical simulation, atmospheric turbulence

1. INTRODUCTION

Aircraft munitions are among the critical defining factors of aircraft combat worthiness. The dynamics of modern combat operations and the operating conditions of the future combat theatre continuously require improvement in the performance and application methods of aircraft munitions. Precision-guided munitions have become indispensable in modern combat. The design of precision munitions, which include air-to-surface guided bombs, is inextricable to theoretical and experimental research. Theoretical research comes before experimental proving ground tests. Simulation results developed by theoretical research are the inputs required to enable the definition of various characteristics of tested munitions. For example, these characteristics enable an estimation of a guided bomb combat and dynamic performance. If the tactical and technical requirements of a munition project are not met, design modifications can be implemented before the final design solution is approved. Simulation software enables analysis of the effects of many factors which affect test objects. The factors can include atmospheric turbulence, targeting system errors, instability of flight of the munition carrier, or human factors. The implementation of design modifications dictated by simulation results helps markedly reduce the costs of the next research and development stage, namely proving ground tests; simulation results help define the scope of in-flight testing of munitions (and the scope might include the munition release initial parameters and permissible atmospheric conditions).

The simulation results presented in this paper were derived by applying proprietary software based on a traditional mathematical model of motion of a rigid body exposed to the forces of inertia, aerodynamic phenomena, and gravity. [3, 5–7]. The model specified a motion in three-dimensional space, and the modelled guided bomb had six degrees of freedom [1, 2, 12–15, 19, 20]. Twelve ODEs (ordinary differential equations) were solved that comprised:

- equations of translation of the guided bomb's centre of inertia, expressed in a non-inertial system of the guided bomb;
- equations of rotation of the guided bomb, expressed in a non-inertial system of the guided bomb;
- the kinematic relationships which enabled the determination of the guided bomb's position angles in three-dimensional space;
- the kinematic relationships which enabled the determination of the guided bomb's trajectory in the inertial system of the Earth.

The research contemplated in this paper used the characteristics of the guided bomb calculated with PRODAS, a commercially available software environment [16]. The characteristics enabled consideration of the effect of the Mach number. Only incompressible characteristics determined by wind tunnel tests were considered in this research.

The results shown herein apply to a simulation of a guided bomb drop in a turbulent atmosphere. Turbulence of the atmosphere which is crossed by a falling guided bomb adds aerodynamic effects which disturb the flight trajectory. This is directly translated to the ground impact scatter and striking accuracy of guided bombs. The determination of the effect of atmospheric turbulence requires the application of a reliable and efficient turbulence model. The simulation was calculated with a Shinozuki model [8, 9, 10, 17, 18]. The Shinozuki model enables simulations of wind gusts the stochastic characteristics (standard deviation, power spectrum, and turbulence scale) of which correspond to the characteristics of real-life wind gusts recoded during multi-annual weather measurements conducted by different research units specialized in studies of the Earth's atmosphere. The models of guided bomb motion and atmospheric turbulences are specified in [7].

According to the Shinozuki model, the wind turbulence components could be expressed as a harmonic series with random parameters:

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

with:

$\boldsymbol{V}_{turb\_i}(\boldsymbol{r})$ – turbulence vector component number i at a point determined by vector $\mathbf{r} = [x_g, y_g, z_g]^T$;

H_{ij} – elements of matrix $\mathbf{H}$, which defines the oscillation amplitudes;

$\mathbf{\Omega}_l = \left[\Omega_{lx}, \Omega_{ly}, \Omega_{lz}\right]^T$ – spatial frequency vector;

$\mathbf{\Omega}_l'$ – randomly disturbed vector $\mathbf{\Omega}_l$; φ_{jl} – random phase of oscillation.

Matrix $\mathbf{H}$ was related to the spectral density matrix of power (the power spectrum) as follows:

$$\mathbf{\Phi}(\mathbf{\Omega})=\mathbf{H}(\mathbf{\Omega})\cdot\mathbf{H}^T(\mathbf{\Omega}) \quad (2)$$

The power spectrum depended on standard deviation, σ and turbulence scale, L_w. The standard deviation was the basis for the assessment of the wind force. The turbulence scale defined the distance of correlation between the wind gusts. The simulation research was based on the following classification of wind force:

- still air: $\sigma = 0$ m/s;
- negligible wind: $\sigma = 0$ to 2 m/s;
- moderate wind: $\sigma = 2$ to 4 m/s;
- strong wind: $\sigma = 4$ to 6 m/s;
- extremely strong wind: $\sigma > 6$ m/s.

The typical turbulence scale value was 400 m. To test the effect of the turbulence scale on the guided bomb's behaviour in flight, four additional values of L_w were considered: 300 m, 500 m, 600 m, and 700 m.

2. BASIC TECHNICAL DATA OF THE GUIDED BOMB

The tested practice guided bomb (Fig. 1) is intended to train flight personnel in air bombardment with laser-guided munitions.

The guided bomb was developed by modification of an existing practice bomb. The modification comprised the installation of two control rudders on the bomb body for active flight trajectory correction. The front section of the guided bomb housed four detection modules intended for the detection of laser-painted targets. The bomb's front section enclosure houses computing and actuator systems which developed the control signals of the control rudder angles. The tactical and technical specifications of the guided bomb follow:

- Length overall 850 mm
- Body diameter 109.7 mm
- Control rudder span 212 mm
- Weight 15.5 kg
- Max rate of descent 329 m/s
- Specific time, [1] 20.8 s

Fig. 1. Overview of the test guided bomb

3. GROUND IMPACT SCATTER AND STRIKING ACCURACY OF THE GUIDED BOMB

If the guided bomb was dropped in still wind, the ground impact location depended only on the bomb release initial conditions (i.e. altitude, air speed and angle of release). The ground impact location will vary with the effect of wind. The variation of wind made the ground impact locations form an area called the 'ground impact scatter ellipse'. The ground impact scatter could be described with these parameters [4, 11]:

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[1] The specific time is the duration of descent of the guided bomb released in specific reference atmosphere at 40 m/s, at the altitude of 2000 m with the carrier aircraft flying along a horizontal plane.

- average striking location;
- probable offsets, U_x, U_y;
- Circular Error Probability (*CEP*);
- striking error *R;*
- striking range and deviation of the guided bomb.

The parameters were applied in the analysis of the results provided by the simulated drops of the guided bombs in a turbulent atmosphere and are explained below.

3.1. Average striking location

The average striking location was a point in space the coordinates of which were the arithmetic mean values of the coordinates of the ground impact locations in the successive (simulated) guided bomb drops [4, 8, 11]:

$$\bar{x} = \frac{\sum_{i=1}^{n} x_{gi}}{n} \tag{3}$$

$$\bar{y} = \frac{\sum_{i=1}^{n} y_{gi}}{n} \tag{4}$$

with:

x_{gi} – coordinate along the striking range direction axis for the ground impact location number *i*;

y_{gi} – coordinate along the striking range transverse axis for the ground impact location number *i*;

n – number of the ground impact locations.

3.2. Probable offsets

A rectangular area which contained 50% of the total number of ground impacts was determined on the plane of the ground impact scatter. The area boundaries were determined by the so-called probable offsets. The probable offsets were defined along and transverse to the striking range direction [4, 8, 11]. The probable offsets were equal to the following, respectively:

$$U_x = 0{,}6745 \sqrt{\frac{\sum_{i=1}^{n} (x_{gi} - \bar{x})^2}{n-1}} = 0{,}6745\ \delta_x \tag{5}$$

$$U_y = 0{,}6745 \sqrt{\frac{\sum_{i=1}^{n} (y_{gi} - \bar{y})^2}{n-1}} = 0{,}6745\ \delta_y \tag{6}$$

where standard deviation δ_x and δ_y were applied:

$$\delta_x = \sqrt{\frac{\sum_{i=1}^{n}(x_{gi} + \bar{x})^2}{n-1}} \tag{7}$$

$$\delta_y = \sqrt{\frac{\sum_{i=1}^{n}(y_{gi} + \bar{y})^2}{n-1}} \tag{8}$$

3.3. CEP (Circular Error Probability)

The plane of the ground impact locations had a circle determined with the origin coinciding with the average striking location and circumscribing 50% of the ground impact locations. The radius of the circle was CEP (circular error probability) [4, 8]. CEP was calculated with this relationship:

$$CEP = 1{,}177 \left(\frac{\delta_x + \delta_y}{2}\right) \tag{9}$$

3.4. Striking error

The striking error, denoted with R, was the distance between the target location and the average ground impact location. Here, the target location was the ground impact (striking) location in still wind [8, 6]. It was calculated with this expression:

$$R = \sqrt{(\bar{x} - x_c)^2 + (\bar{y} - y_c)^2)} \tag{10}$$

with:

x_c, y_c – target location coordinates

3.5. Average striking range

The average striking range, X_{dg}, was the difference of the x coordinates between the release location and the average ground impact location of the guided bomb.

The average deviation, Y_{og} was the difference of the y coordinates between the release location and the average ground impact location of the guided bomb [6, 11]. These concepts are illustrated in Fig. 2.

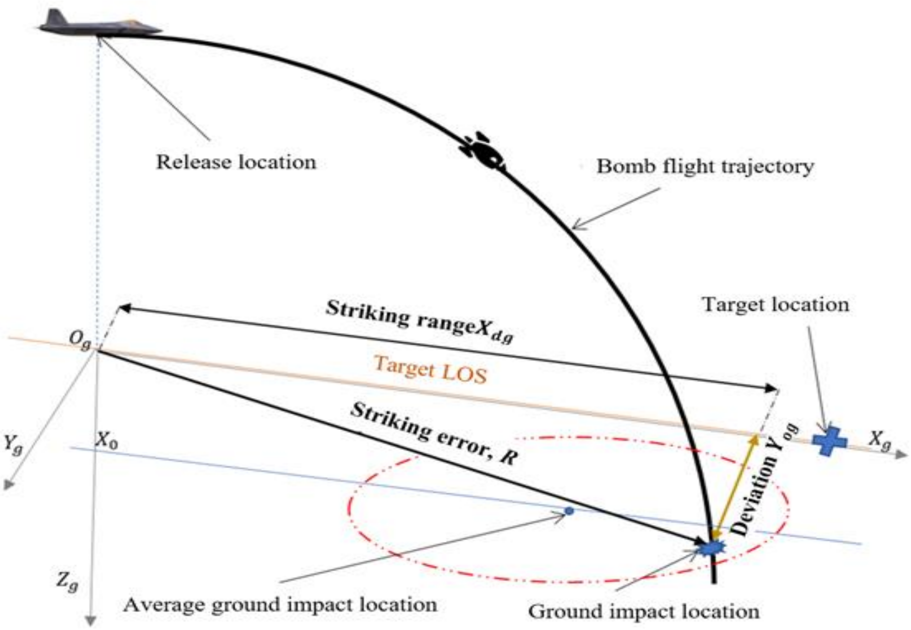

Fig. 2. Striking range and deviation of the guided bomb

4. SIMULATION RESULTS

The relationships defined above were applied to analyse the results of simulated guided bomb drops in a turbulent atmosphere. The bomb release initial conditions were constant in all simulation runs. The variables were the atmospheric turbulence parameters. The simulation results were compared to the simulated zero-turbulence bomb drop parameters.

The bomb release initial conditions (parameters) in the simulations follow:

- bomb release location coordinates: $x_{zrz} = 0$ m, $y_{zrz} = 0$ m;
- bomb release altitude: $H_p = 3000$ m;
- bomb release air speed: $V_p = 55$ m/s and 139 m/s;
- bomb release angle: $\Theta_p = 0°$ (horizontal carrier aircraft flight path).

These values were adopted from analyses of air to surface bombardment by combat helicopters, training and combat airplanes and drones. The values conformed to the design inputs for the proving ground tests with Mi-24 helicopters as the guided bomb carriers (and with the bomb release initial parameters of: $H_p = 3000$ m, $V_p = 55$ m/s, and $\Theta_p = 0°$). A comparison of the proving ground test results with the simulated guided bomb drop results will help develop charts of bombardment parameter corrections and the definition of the so-called bomb release parameter limits.

The analytical results below apply to the following simulation options:

I. bomb release along a horizontal flight trajectory ($\Theta_p = 0°$) at 55 m/s and from 3000 m with a constant turbulence scale of $L_w = 400$ m and standard deviation values, σ, equal to the following, respectively: 0.5 m/s, 2 m/s, 3 m/s, 4 m/s, 5 m/s, 6 m/s, 7 m/s, 10 m/s, and 12 m/s;

II. bomb release along a horizontal flight trajectory ($\Theta_p = 0°$) at 139 m/s and from 3000 m with a standard deviation equal to $\sigma = 4$ m/s and wind turbulence scale values, L_w, equal to the following, respectively: 300 m, 400 m, 500 m, 600 m, and 700 m.

For each simulation option, tests with $n \geq 30$ of bomb releases were performed. This number of bomb releases enabled a correct determination of the behaviour of the guided bomb along its flight trajectory [8].

Option I. Figure 3 shows the ground impact locations of the guided bomb in Option I. The largest and lowest ground impact scatter was found with the turbulence standard deviation of $\sigma = 12$ m/s and $\sigma = 0.5$ m/s, respectively. The major axis length of the ground impact scatter ellipse along the striking range axis was 167.96 m at $\sigma = 12$ m/s and 3.03 m at $\sigma = 0.5$ m/s. The maximum and minimum length of the ground impact scatter ellipse along the striking range transverse was 111.93 m and 2.33 m, respectively.

Figure 4 shows the average ground impact locations for each of the tested standard deviation values. The maximum deviation of the average ground impact location along axis Y_g was 0.83 m at $\sigma = 5$ m/s; along the striking range axis, X_g, it was 6.86 m at $\sigma = 12$ m/s. The average ground impact locations were confined to a strip running in parallel to the striking range axis. The strip width was $\Delta S_{szer} = 1.61$ m. The strip width was defined by the average ground impact locations that corresponded to the maximum deviation values along axis Y_g.

The maximum striking range was found for the following turbulence parameters: $L_w = 400$ m and $\sigma = 5$ m/s; it was equal to $X_{dg\,max} = 1316.16$ m. The minimum striking range of $X_{dg\,min} = 1239.81$ m was at the average ground impact location with a standard deviation of $\sigma = 12$ m/s. The same figure shows the ground impact location the coordinates of which were the average values of the average ground impact locations. It is termed the ‘average striking location’. The average striking location coordinates were $\bar{x} = 1292.64$ m and $\bar{y} = -0.03$ m, respectively. A comparison between the average striking location coordinates and the still-wind ground impact location revealed that atmospheric turbulence significantly reduced the striking range of the guided bomb.

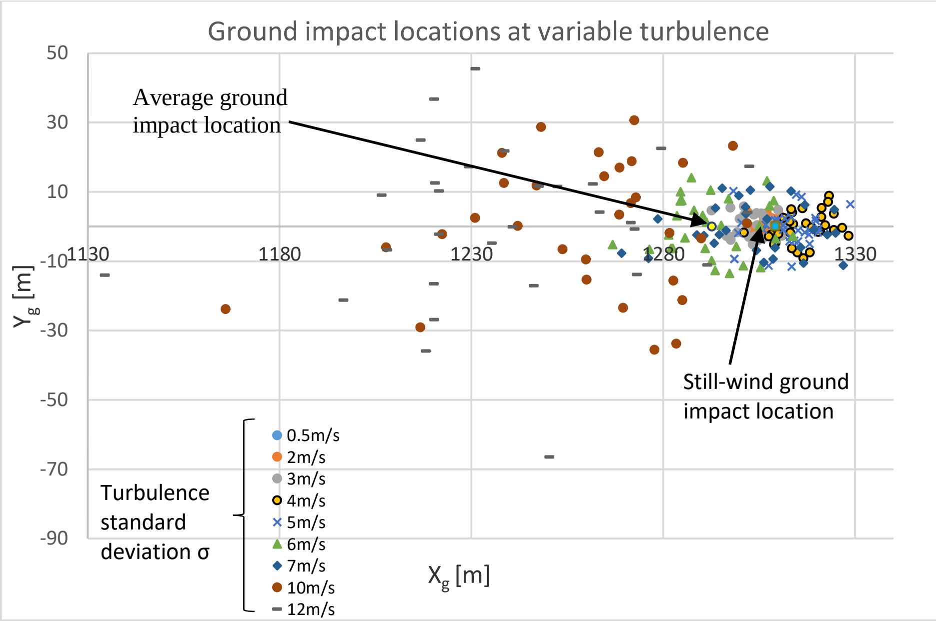

Fig. 3. Ground impact locations of the guided bomb with various standard deviations of the wind

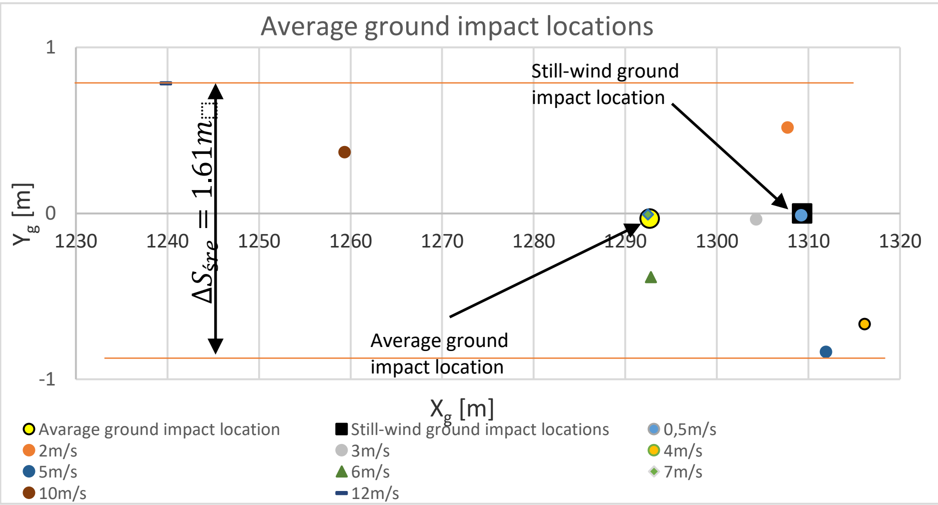

Fig. 4. Average ground impact locations for variable standard deviation of the wind

The striking range of the guided bomb was found to increase from the striking range of the still-wind bomb drop with the following two standard deviation values: $\sigma = 4$ m/s and 5 m/s.

For all other tested standard deviation values, the striking range was reduced from the still-wind bomb drop conditions. The maximum to minimum differential striking range was ΔX_g = 66.35 m.

Figure 5 shows the striking error for the various standard deviation values tested. The lowest and highest striking errors were, respectively: at σ = 0.5 m/s and equal to R = 0.06 m and at σ = 12 m/s and equal to R = 69.48 m. A trend line was plotted for the results. The trend line was a second degree polynomial which follows:

$$y = 0.6342\, x^2 + 1.8959\, x + 2.2104 \qquad (11)$$

The reliability of the trend line was defined by the so-called determination factor, [2] R^2. The determination factor told which part of the explained variable was explained by the applied model. The trend line was most reliable for R^2 = 1 or approximate to 1. Here, R^2 = 0.9834, which means that the trend line had a high reliability.

Figure 6 shows the CEP (Circular Error Probability) values for various standard deviation values. CEP ranges from 0.64 m at the minimum turbulence (the wind standard deviation at σ = 0.5 m/s) to 31.88 m (at σ = 12 m/s).

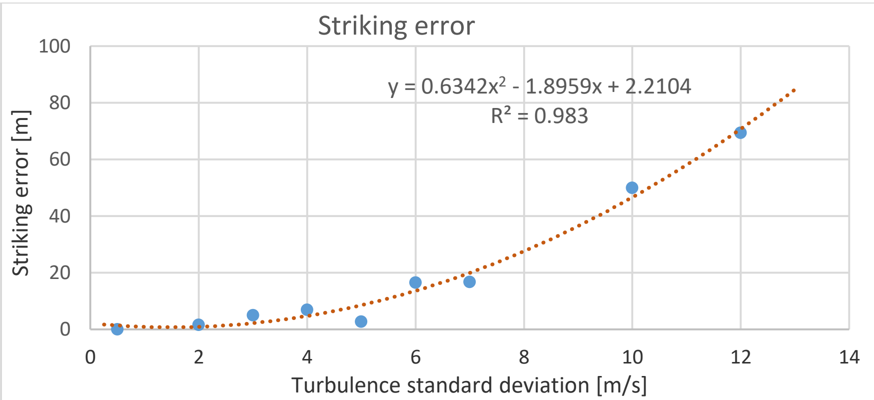

Fig. 5. Striking error for variable wind standard deviation values

[2] $R^2 = \frac{\sum_{t=1}^{n}(\hat{y}_t - \bar{y})^2}{\sum_{t-1}^{n}(y_t - \bar{y})^2}$ with: y_t – actual value of the dependent variable; $\hat{y}_t$ – forecast value of the dependent variable; $\bar{y}$ – mean value of the actual dependent variable.

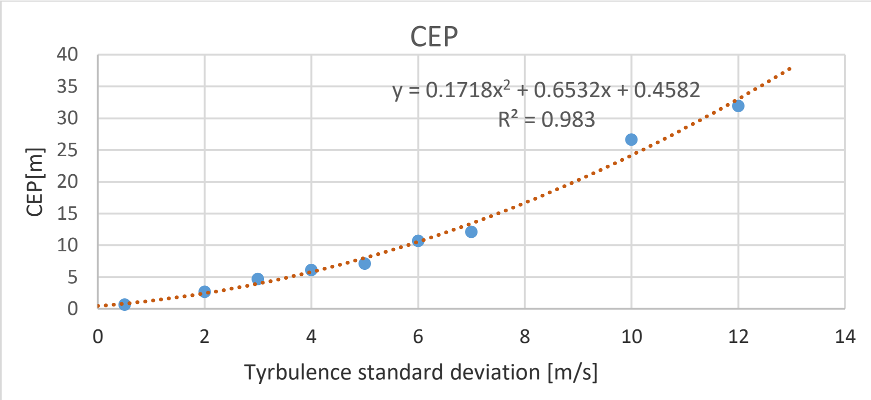

Fig. 6. CEP for variable wind standard deviation values

The plotted trend line for the CEP variation with the variable standard deviation of the wind was a second degree polynomial which follows:

$$y = 0.1718\ x^2 + 0.6532\ x + 0.4582 \tag{12}$$

The calculated determination factor was $R^2 = 0.9887$.

The probable offsets, U_x and U_y, were among the parameters which determined the ground impact location scatter. The determination of the probable offsets is shown below for one of the sub options. The respective bomb release initial parameters and turbulence parameters were: $V_p = 55$ m/s, $H_p = 3000$ m and Θ_p=0°; with the turbulence scale, $L_w = 400$ m at the standard deviation, $\sigma = 4$ m/s. The results are shown in Fig. 7. Here, the probable offset, U_x, which enabled the definition of a 2 U_x - wide strip in parallel to axis OY_g and circumscribing 50% of the ground impact locations, was $U_x = 4.31$ m. The probable offset, U_y, which enabled the definition of a $2U_y$ - wide strip in parallel to axis OX_g and circumscribing 50% of the ground impact locations, was $U_y = 3.01$ m. The boundaries of the strips were determined with the following coordinates: $X_{g1} = 1320.47$ m, $X_{g2} = 1311.85$ m (for the striking range) $Y_{g1} = 2.35$ m, $Y_{g2} = -3.67$ m (for the deviation). In this case of the simulation, the result revealed an increase of the striking range by $\Delta X_g = 6.87$ m. It was not typical, since in most options, the striking distance was reduced as shown in the discussion of Fig. 4. A slight deviation of the average ground impact location was obtained and equal to $\Delta Y_g = -0.66$ m.

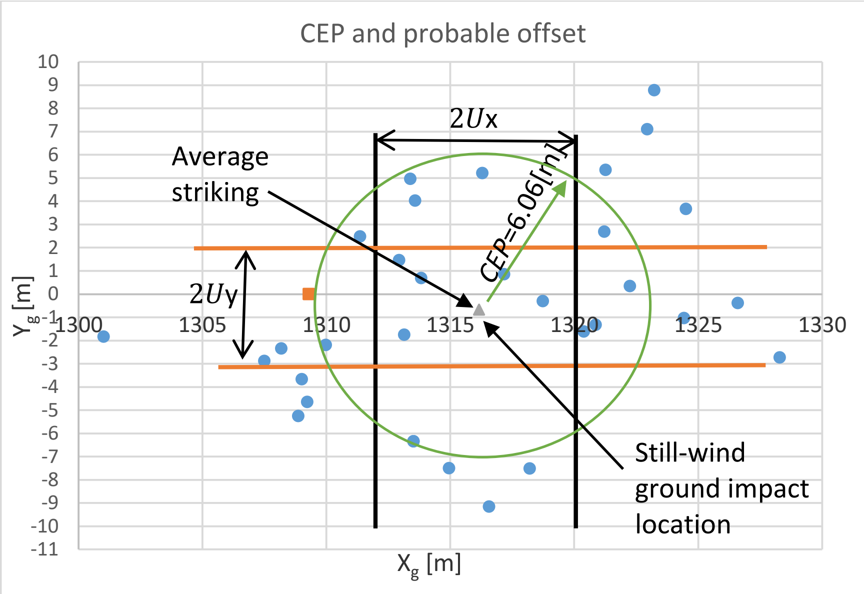

Fig. 7. CEP and probable offset for the guided bomb released at V_p = 55 m/s, H_p = 3000 m and Θ_p = 0°, and L_w = 400 m, σ = 4 m/s

Option II. The second option of the guided bomb drop simulation concerned the effect of the turbulence scale on the in-flight behaviour of the guided bomb. The ground impact locations of the guided bomb released at H_p = 3000 m, V_p = 139 m/s and Θ_p = 0°, given the standard deviation of the wind at 4 m/s and the turbulence scales of 300 m, 400 m, 500 m, 600 m, and 700 m are shown in Fig. 8.

The major axis length of the ground impact scatter ellipse along the striking range axis was defined by the ground impact location coordinates which reached the maximum and minimum striking ranges. The length was ΔX_{dg} = 37.24 m. The minor axis length of the ground impact scatter ellipse which was transverse to the striking range axis was limited by the ground impact location coordinates at the maximum deviation from the target LOS (line of sight). It was ΔY_{og} = 24.36 m. Table 1 lists the individual axes of the ground impact scatter ellipses for the considered turbulence scales.

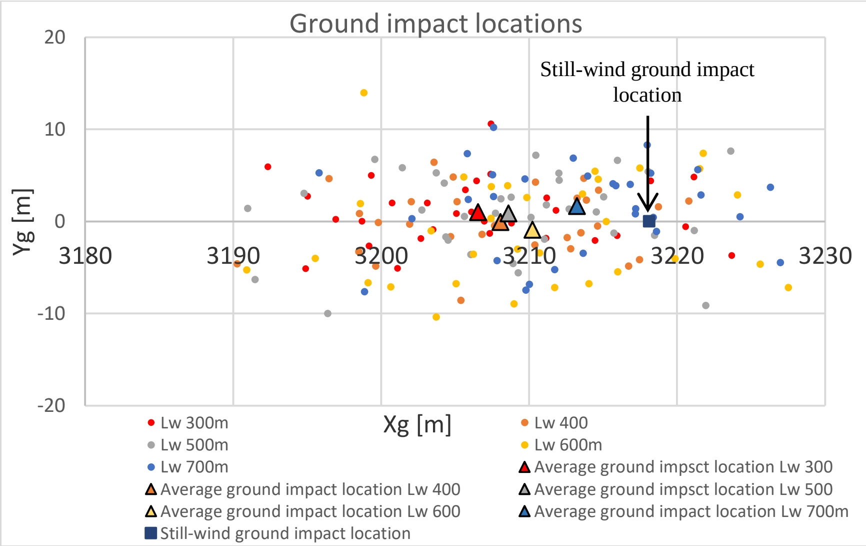

Fig. 8. Ground impact locations at variable turbulence scales

Table 1. Axis length of the ground impact scatter ellipse

	Turbulence scale at constant wind standard deviation of 4 m/s				
	300 m	400 m	500 m	600 m	700 m
Ground impact scatter ellipse axis length along axis X_g	31.35	30.52	32.65	36.61	31.18
Ground impact scatter ellipse axis length transverse to axis X_g	15.73	15.01	17.65	24.37	17.86

The maximum length difference for the ground impact scatter ellipse axis along and transverse to the striking range axis was 5.43 m and 9.34 m, respectively. Figure 9 shows the average ground impact locations for different wind turbulence scales.

The maximum striking error, $R = 11.6$ m was found for the turbulence scale of $L_w = 300$ m. The minimum striking error, $R = 5.16$ m was found for the turbulence scale of 700 m. The maximum to minimum striking error differential was $\Delta R = 6.44$ m.

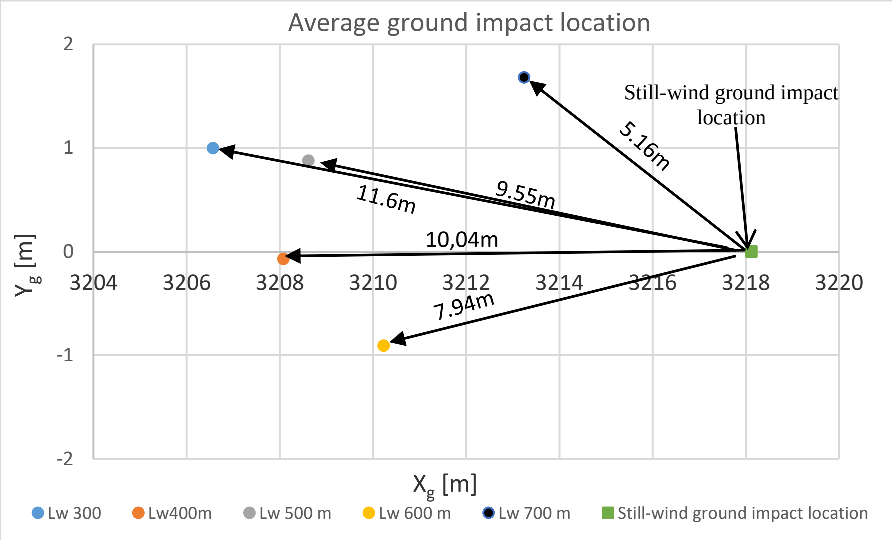

Fig. 9. Average ground impact locations at variable turbulence scales

The distribution of the ground impact locations revealed that the striking error reduction was inversely proportional to the turbulence scale (see Fig. 10) and that the striking range of the guided bomb was lower than in still wind conditions.

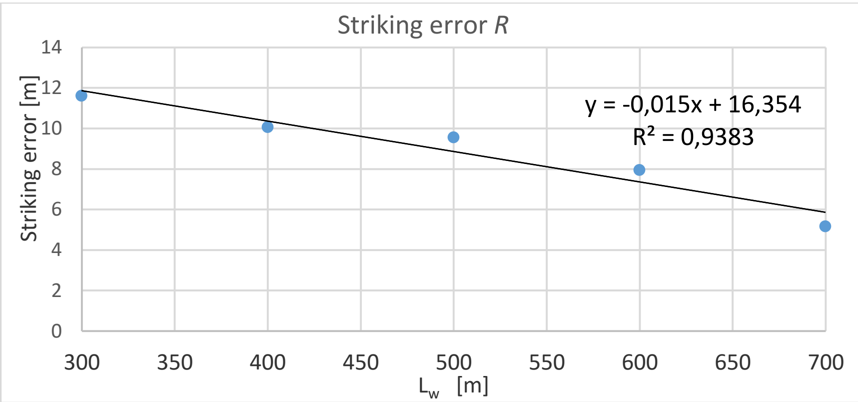

Fig. 10. Striking error at variable turbulence scale

The CEP change is shown in Fig. 11. The CEP radius varied within 2.19 m. The minimum CEP radius was at the turbulence scale of L_w = 300 m and equal to 6.5 m. The maximum CEP radius (8.7 m) was at the turbulence scale of L_w = 600 m and equal to 6.5 m.

The trend line plotted for this option revealed that the ground impact location scatter increased slightly with the turbulence scale.

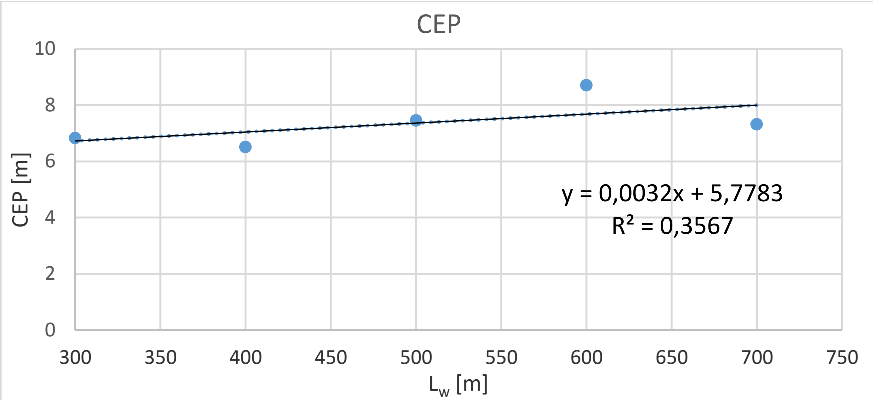

Fig. 11. CEP at variable turbulence scale

5. CONCLUSION

The analytical results determined so far confirmed that atmospheric turbulence largely affects the scatter (or distribution) of ground impact locations of the guided bomb. On plane OX_gY_g, the ground impact locations formed the so-called ground impact scatter ellipse. The major axis length of the ground impact scatter ellipse along the striking range axis was defined by the ground impact location coordinates which reached the maximum and minimum striking ranges. The minor axis length of the ground impact scatter ellipse which was transverse to the striking range axis and crossed the average ground impact location was limited by the ground impact location coordinates at the maximum deviation from the target LOS (line of sight).

The results indicated that the striking error and the ground impact location scatter increased with the standard deviation of the wind. A comparison of the surface area between the generated ground impact scatter ellipses revealed it grew considerably with the values of σ. When the turbulence scale was changed, the ground impact scatter ellipse axis along and transverse to the striking range axis varied by 5.43 m and 9.34 m, respectively. When the turbulence scale was changed while maintaining the standard deviation at 4 m/s, the striking error decreased while L_w increased, whereas CEP revealed a poorly increasing trend.

The completed simulations revealed that the scatter (or distribution) of ground impact locations was affected more by the standard deviation variations than the turbulence scale changes. The variation of the standard deviation in an interval of 0.5÷12 m/s at L_w = 400 m increased the striking error from $R_{\sigma0,5}$ = 0.06 m to $R_{\sigma12}$ = 69.48 m.

The effect of changes in the turbulence scale, L_w, was lower. The change of the turbulence scale from 300 m to 700 m changed the striking error within an interval of 5.16÷11.6 m.

The calculation results developed to date indicated that standard deviation was a critical parameter to the effect of atmospheric turbulence on the guided bomb drop. This will determine the objective of future calculations under this research accordingly. Future calculations will be carried out to study the effect of σ on the striking accuracy with varying initial conditions of guided bomb release (i.e. the carrier aircraft angle and the release angle).

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Wpływ parametrów atmosfery na dokładność trafienia bomby w cel

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Streszczenie. W artykule przedstawiono wyniki przeprowadzonych symulacji zrzutu bomby w turbulentnej atmosferze. Bomba ta powstała na bazie bomby ćwiczebnej zbudowanej i zmodernizowanej w Instytucie Technicznym Wojsk Lotniczych. W artykule przedstawiono wyniki numerycznej symulacji z wykorzystaniem autorskiego oprogramowania. W obliczeniach użyto charakterystyki aerodynamiczne wyliczone programem PRODAS, które weryfikowano badaniami w tunelu aerodynamicznym. Do opisu składowej turbulencji wykorzystano model procesów stochastycznych zaproponowany przez Shinozukiego. Przedstawiono przykładowe wyniki symulacji zrzutu bomby. Pokazano wpływ parametrów turbulencji atmosfery - odchylenia standardowego i skali turbulencji σ, L_w, na celność i rozrzut.

Słowa kluczowe: bomba korygowana, symulacja numeryczna, turbulencja atmosfery