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Evaluation of a Novel Method of Fuze Programming Based on the Number of Projectile Own Revolutions

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Abstract. This paper presents an innovative method of programming fuzes for airburst munitions based on the principle of counting the number of revolutions a projectile makes around its centre line along the flight trajectory in order to determine the distance travelled by the projectile. The proposed innovative method of fuze programming was compared to other known methods of fuze programming based on the results of a computer simulation of firing a 40 mm grenade launcher under near-real conditions. For this purpose, a methodology was developed for external ballistic calculations using a mathematical model of the three-dimensional motion of a non-deformable flying object considered to be a rigid body with six degrees of freedom in an ISO 1151 coordinate system.

Simulations were carried out taking into account real firing conditions for 40 mm grenade launcher ammunition armed with fuzes programmed by each of the methods evaluated. Targets located at various distances were fired upon and the level of dispersion of real fuze action points relative to the expected fuze action point was evaluated for each programming method. It was concluded that the method of determining the distance travelled by the projectile with the principle of counting the projectile's revolutions under real conditions resulted in a dispersion of the fuze action points greater than with the time based methods. In conclusion it was observed that the method of determination for the revolving projectile based on counting the projectile's rotations along the flight trajectory did not guarantee the required precision of the fuze action point locations. This means that the application of the methods to determine the distance of projectile burst along the flight trajectory did not increase the effectiveness of airburst fragmentation munitions.

Keywords: mechanical engineering and operation, ballistics, programmable fuze, turns-counting fuze

1. INTRODUCTION

One method of programming the fuzes of airburst munitions is to set the number of projectile own revolutions along the flight trajectory. The number of revolutions is translated into the distance travelled by the projectile. Fuzes programmed by projectile revolution count are considered in the expert foreign literature [1-7] as one of the most accurate in terms of fuze action. This is understood to mean action at a well-defined point of fuze action above the target, with the smallest dispersion of the fuze action point locations relative to the expected location. Counting projectile revolutions, according to the authors of the above-mentioned references, makes the fuze action point on the flight trajectory independent of the projectile muzzle velocity. Despite the fact that the programming of fuzes with the number of revolutions is considered to be the most accurate method, it has not been widely practised.

The designs for revolution counting fuzes are mainly at the stage of laboratory testing or research and development. The most advanced projects concern fuzes whose operating algorithms are based on programming not by the revolution count alone but by a combination of revolutions and duration with application of a fire control system ('hybrid' fuzes).

In the domestic reference literature, fuzes programmed by the number of projectile revolutions have been presented in [8] and [9]. For example, [9] presents an innovative design solution for a programmable fuze which considers some issues ignored in well-known foreign designs of this type. This design features more favourable structural and ballistic characteristics, compared to the previously known solutions found in fuzes programmed by counting the projectile revolutions. The innovative solution of a fuze counting the projectile revolutions was thoroughly verified in [10].

The results reported in [10] and obtained thanks to the application of the author's research methodology, which reproduced the real firing conditions, suggested the conclusion that programming the fuze action point with a parameter being the number of counted revolutions – whether full or partial – did not guarantee the required precision of fuze action. No reduction in the dispersion of fuze action points along the flight trajectory was achieved in comparison to traditional fuze programming methods.

2. A NEW APPROACH TO THE PROBLEM

The new method of fuze programming and determining the path traveled by the projectile presented in [9] was verified by comparing it to other known methods of fuze programming and determining the path traveled by the projectile, which included:

a) time fuze programming without setting correction;
b) time fuze programming with setting correction;
c) fuze programming with full-revolution count along the trajectory.

Note that the verification of this novel fuze programming method was focused at the stage of work reported here on a single, novel modification of the fuze design. This modification involved counting the half revolutions of the projectile, instead of the traditional full revolutions.

The effects of the applied type of fuze programming on the accuracy of the fuze action point position was made at this stage of the project was verified with a computer simulation of projectile fired with consideration of firing conditions as close to reality as possible.

The methodology included:

a) Development of sets of internal and external ballistic parameters for selected types of munitions (development and summary of numerical values of the sets of characteristics of the physical models of projectiles with fuzes of the considered type, taking into account the disturbances that can occur in real conditions).
b) Adoption, for the process of external ballistic calculations, of a mathematical model of the 3D motion of a non-deformable projectile model formulated in an ISO 1151 coordinate system.
c) Development of a mathematical model for the 3D motion of a sensor detecting the projectile revolutions along the projectile flight trajectory.
d) Development of a basic set of initial conditions assumed for the simulated projectile firing, with the set being identical for all methods of fuze programming included in the comparison.

e) Computer simulation tests (separate for each method of determining the projectile distance travelled along the trajectory) in order to determine the impact of disturbances in the values of the basic characteristics of the physical model (aerodynamic, mass-inertia and geometric characteristics) on the dispersion of fuze action points along the flight trajectory.

Based on the results of the simulation tests, an assessment was made of the accuracy of determination of the fuze action points (the points of projectile burst along the trajectory) for the considered methods of fuze programming.

3. MATHEMATICAL MODEL APPLIED TO THE SIMULATION TESTS

To describe the trajectory of a projectile in the Earth's atmosphere, a full mathematical model of the three-dimensional motion of a non-deformable flying object was adopted using an ISO 1151 coordinate system. This model, detailed in monograph [11], allowed the inclusion of a very large set of variables (geometric characteristics, mass-inertia characteristics and aerodynamic coefficients) in the analysis and evaluation of their influence on the dispersion of projectile fuze action points along the trajectory respectively for each fuze programming method. The mathematical model adopted included: the components of the resultant aerodynamic force vector and the components of the resultant aerodynamic force moment vector, which contained the corresponding aerodynamic coefficients (longitudinal force coefficient for zero nutation angle, longitudinal force coefficient, normal force coefficient, Magnus force coefficient, roll damping moment coefficient, overturning moment coefficient, pitch damping moment coefficient, and Magnus moment coefficient). Changes in the projectile muzzle velocity and projectile mass were also included in the simulation model.

The mathematical model of the 3D motion of a sensor which detects projectile revolutions along the flight trajectory was developed from the mathematical model of the 3D motion of a non-deformable flying object in the ISO 1151 coordinate system and the relation of the electromotive force generated in an induction coil by the effect of a variable electromagnetic field.

In order to test and evaluate the correctness of the mathematical model adopted in the external ballistic calculations, a comparative analysis was performed. M430 ammunition for the Mk 19 automatic grenade launcher was chosen for the analysis, with firing tables according to [12]. The results obtained with the model were compared to the relevant magnitudes specified in the firing tables, see Table 1.

Table 1. Comparison of the ballistic characteristics of the M430 grenade launcher ammunition derived from a computer simulation to the relevant magnitudes summarised in [12]

Elevation [°]	**Flight duration [s]**		**Relative error [%]**	**Remaining velocity [m/s]**		**Relative error [%]**	**Impact angle [°]**		**Relative error [%]**
	Model	**Firing table**		**Model**	**Firing table**		**Model**	**Firing table**	
2.96	2.41	2.40	0.415	182.0	181.7	0.165	3.6	3.6	0
7.42	5.65	5.63	0.351	138.3	138.2	0.072	10.7	10.7	0
14.64	10.19	10.17	0.196	108.6	108.5	0.092	24.5	24.5	0
32.07	18.97	18.97	0	98.3	98.8	0.509	53.6	53.2	0.746
Elevation [°]	**Maximum flight trajectory height [s]**		**Relative error [%]**	**Deviation [m]**		**Relative error [%]**	**Range [m]**		**Relative error [%]**
	Model	**Firing table**		**Model**	**Firing table**		**Model**	**Firing table**	
2.96	7.1	7.1	0	0.8	1.4	75.000	502	500	0.398
7.42	39.4	39.2	0.508	4.2	6.4	52.380	1004	1000	0.398
14.64	129.5	129.1	0.309	13.0	20.6	58.462	1503	1500	0.199
32.07	452.6	453.1	0.110	42.9	65.0	51.515	1984	2000	0.806

4. SAMPLE SIMULATION RESULTS

Two types of 40 mm grenade launcher ammunition (disposable grenade launcher ammunition and automatic grenade launcher ammunition) were selected to verify the proposed fuze programming method presented in [9].

This paper presents examples of the results of simulated projectile firing performed with M383 grenade launcher ammunition, type 40x53 mm HV, and intended for automatic grenade launchers. The fuze used in this ammunition was designed to cause the projectile to burst above a target hidden by a wall, with the burst (detonation) occurring once the fuze action setting counts down (with the setting being time, projectile full revolution count, or projectile half-revolution count).

In the first stage, the firing of projectiles with time fuzes was simulated. Two cases were investigated: programming with time setting without setting correction and programming with time setting with setting correction. Example simulation results were based on the mathematical model described in Section 3 and applicable to the cases of firing at a target hidden behind a wall 101.5 and 501.5 m away, and shown in Figs. 1 and 2.

A result of the firing simulations which followed the adopted methodology was the value of the dispersion of fuze action point locations along the flight trajectory for both time fuze programming methods. Figure 3 shows a chart of the dispersion of fuze action point locations as a function of flight distance for the time fuzes [10].

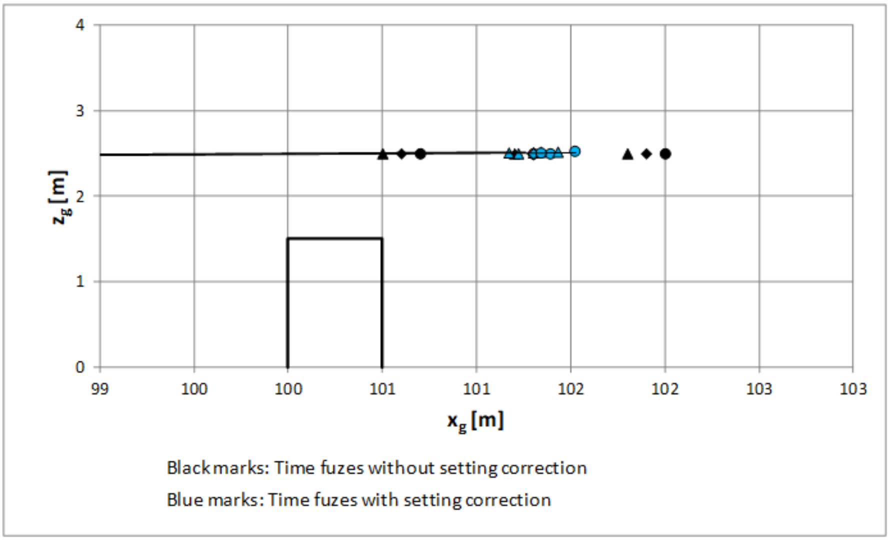


Fig. 1. Dispersion of fuze action point locations along the flight trajectory; required fuze action distance: 101.5 m

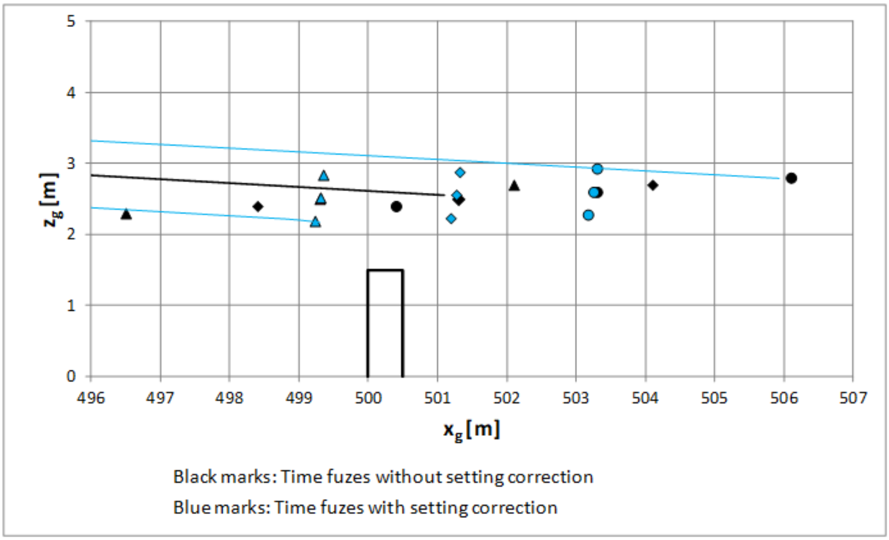


Fig. 2. Dispersion of fuze action point locations along the flight trajectory; required fuze action distance: 501.5 m

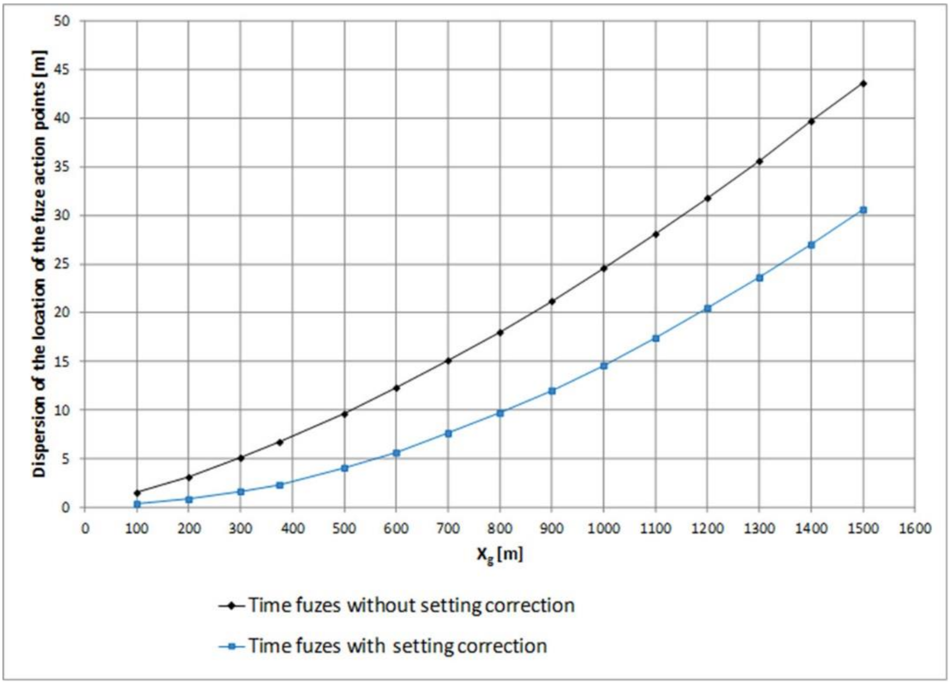


Fig. 3. Dispersion of time fuze action points vs. required fuze action distance

In the next step, firing simulations were carried out with the same projectiles as used to study the time fuze programming method; this time the fuzes were programmed by the full revolution count of the projectiles, that is by a method considered by many researchers so far to be the most accurate. The simulation conditions were the same as for both methods of time fuze programming.

Example simulation results based on the mathematical model described in Section 3 and applicable to the cases of firing at a target hidden behind a wall 101.5 and 501.5 m away, are shown in Figs. 4 and 5 [10].

A result of the firing simulations which followed the adopted methodology was the value of the dispersion of fuze action point locations along the flight trajectory for the known method of fuze programming with the full revolution count of the projectile along the flight trajectory. Figure 6 shows a chart of the dispersion of fuze action points versus the firing distance.

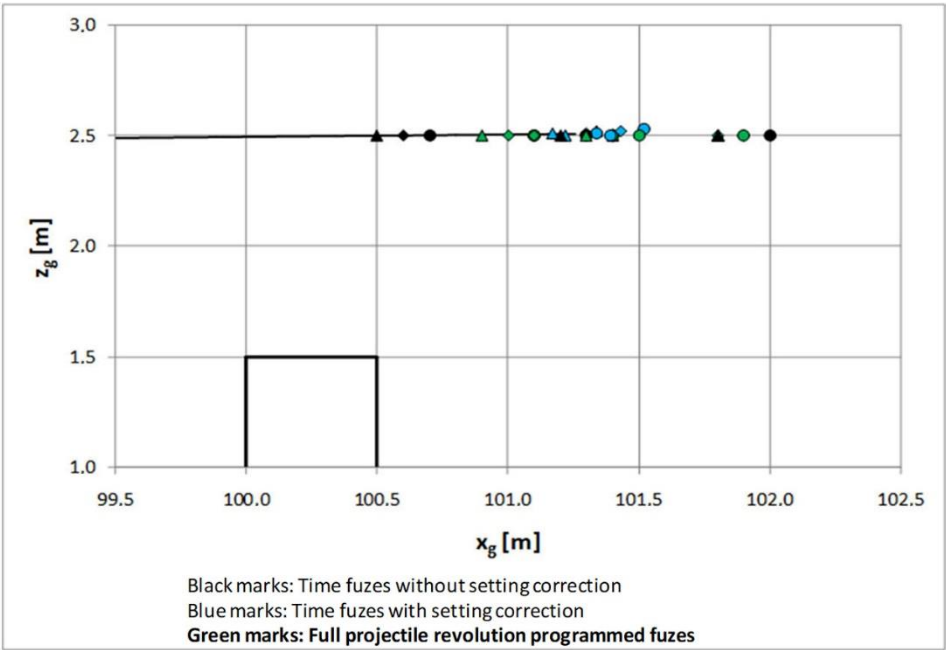


Fig. 4. Dispersion of fuze action point locations along the flight trajectory; required fuze action distance: 101.5 m

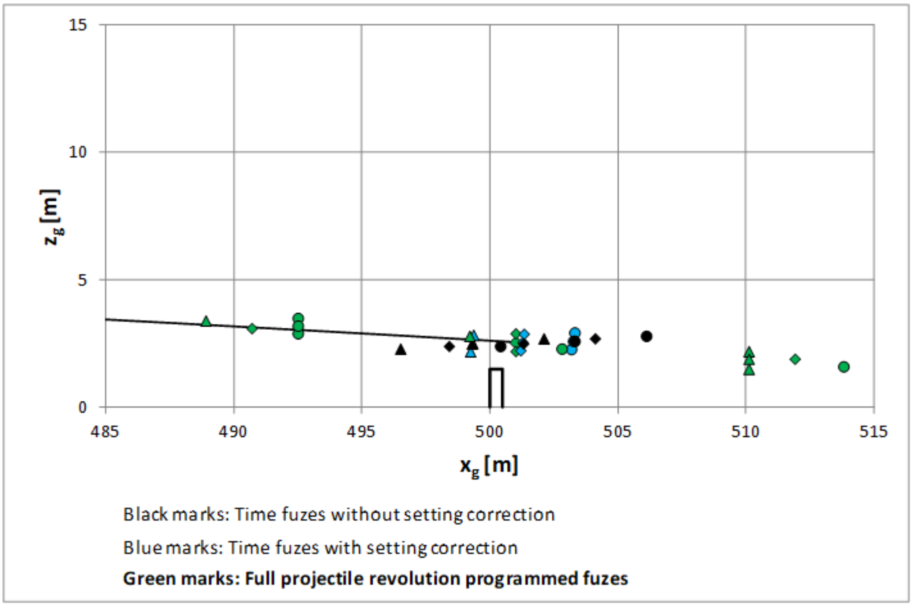


Fig. 5. Dispersion of fuze action point locations along the flight trajectory; required fuze action distance: 501.5 m

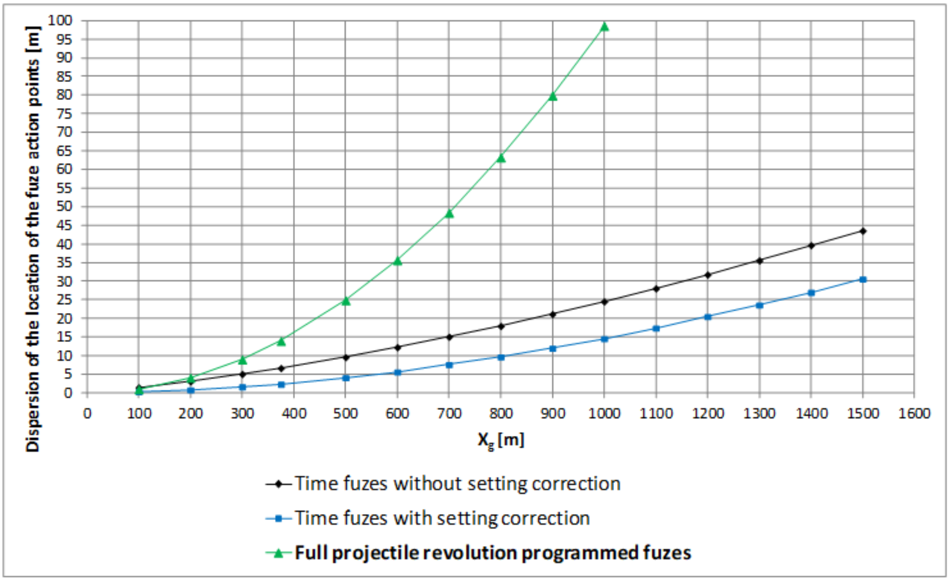


Fig. 6. Dispersion of fuze action point locations along the flight trajectory vs. the required fuze action distance per the evaluated fuze programming method

The results shown in Figs. 4-6 allow the clear conclusion that the method of determining the distance travelled by the projectile along the flight trajectory based on counting the preset count of projectile rotations over the flight trajectory gave a markedly wider dispersion of the fuze action points in comparison to the time fuze programming method. The results were obtained with real firing conditions which included the influence of disturbances in the values of the basic characteristics of the physical model (aerodynamic, mass-inertia, geometric, and medium of motion characteristics). The largest influence on the dispersion of the fuze action point locations was the projectile roll damping moment coefficient and its range of variation.

Further firing simulations with the same projectiles were performed for the same data as in the firing simulation discussed above, but with the fuzes programmed with a half revolution count (a proprietary method presented in [9]).

The examples of results of the simulated firing at a target hidden behind a wall 101.5 and 501.5 m away are shown in Figures 7 and 8 respectively; the charts show a comparison of the results obtained for the fuzes programmed with the half revolution count to the results obtained for the fuzes programmed with the full revolution count. Note the overlap of the fuze action points shown in the graph in Fig. 8. Accordingly, Fig. 9 shows one of the fuze action areas taken from Fig. 8 magnified to improve clarity.

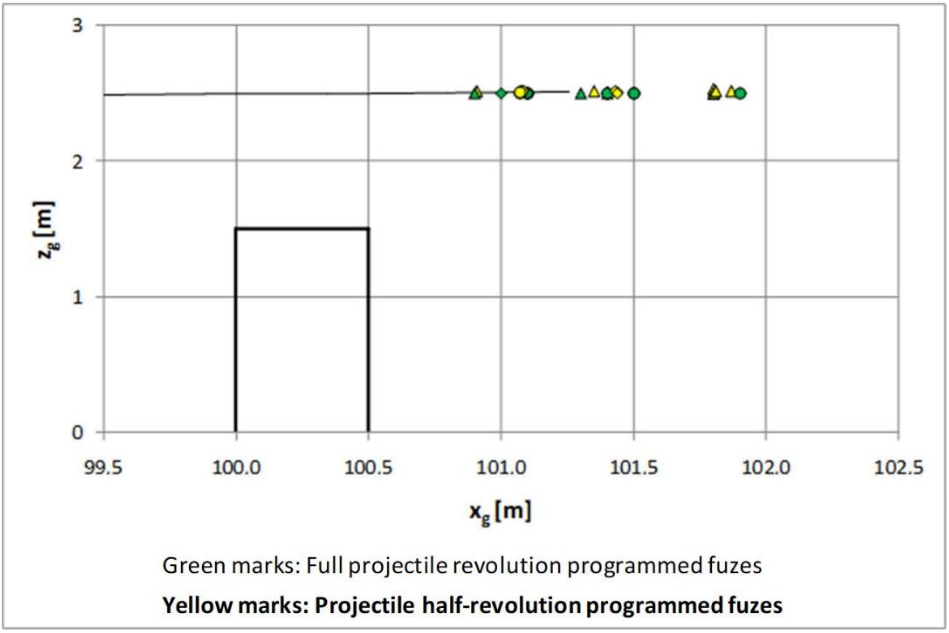


Fig. 7. Dispersion of fuze action point locations along the flight trajectory; required fuze action distance: 101.5 m

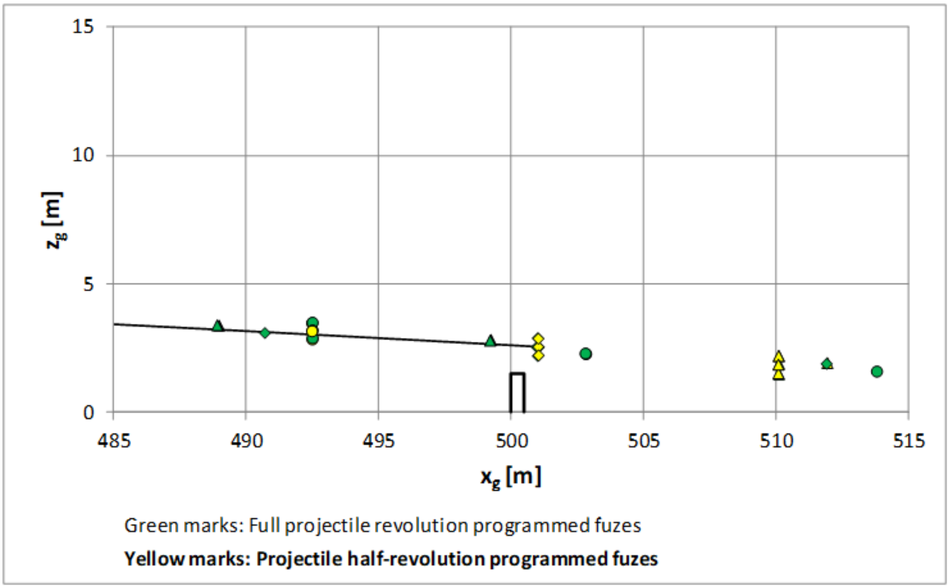


Fig. 8. Dispersion of fuze action point locations along the flight trajectory; required fuze action distance: 501.5 m; the fuze action points coincide

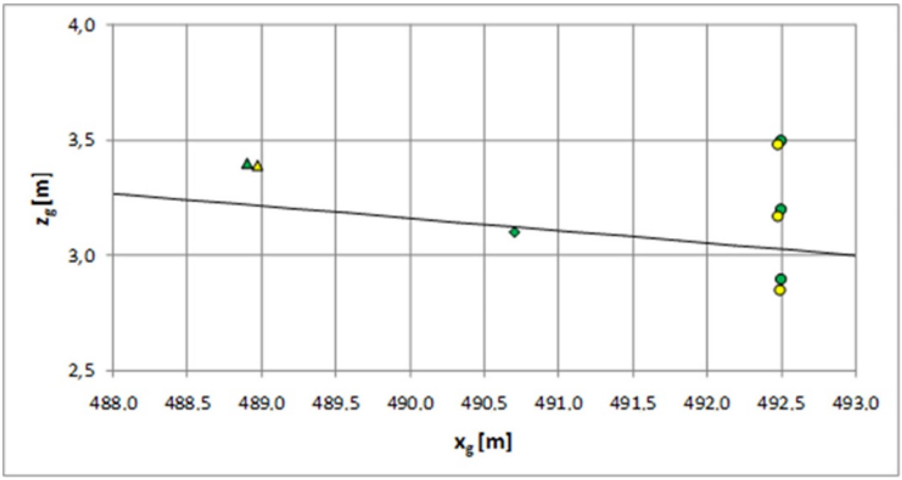


Fig. 9. Dispersion of fuze action point locations along the flight trajectory; Magnification of a selected fuze action area shown in Fig. 8

A result of the firing simulations which followed the adopted methodology was the value of the dispersion of fuze action point locations along the flight trajectory for the novel method of fuze programming with the half revolution count of the projectile along the flight trajectory. Figure 10 presents a graph with the magnitudes of the dispersion of fuze action points along the flight trajectory for the projectile full revolution count programming method and for the projectile half revolution count programming method.

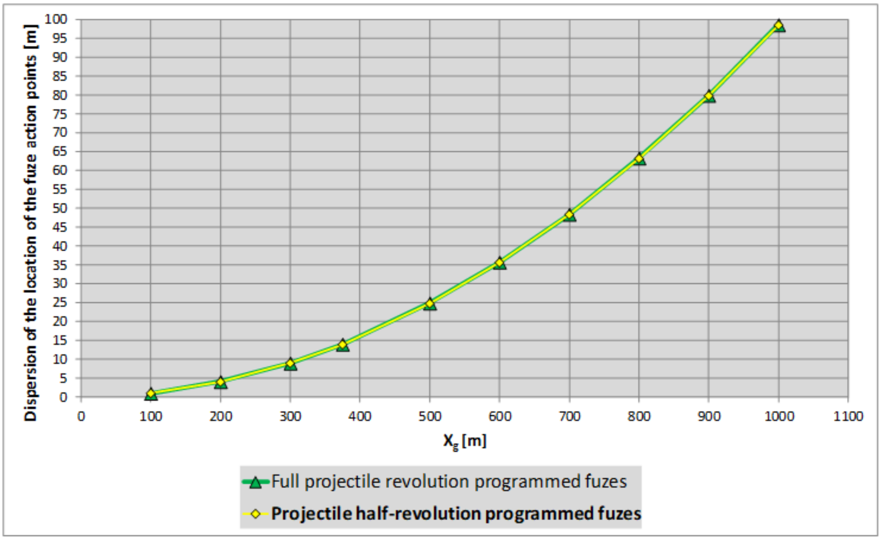
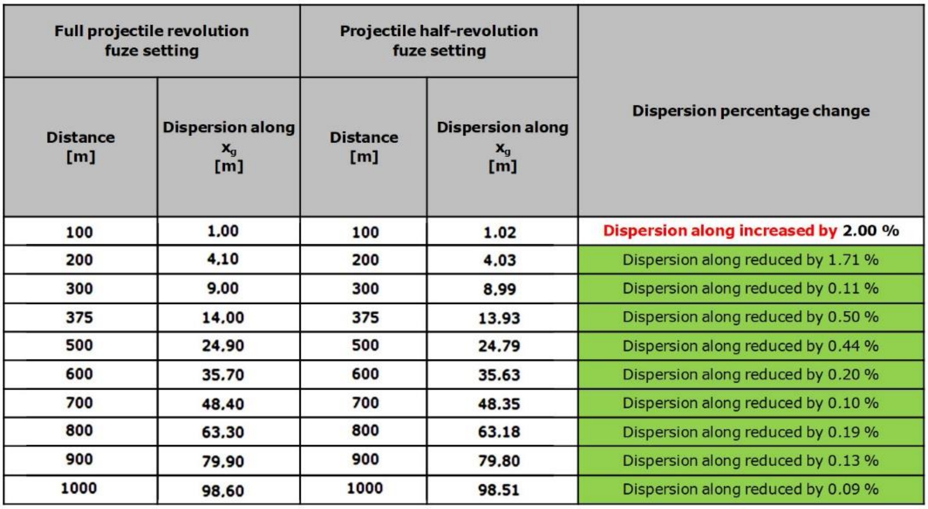


Fig. 10. Dispersion of fuze action point locations along the flight trajectory vs. the required fuze action distance per the evaluated fuze programming method

Note that the two graphs overlap. Again, the largest influence on the dispersion of the fuze action point locations was the projectile roll damping moment coefficient and its range of variation.

The simulation results shown in Fig. 10 prove that the proposed novel method of determining the projectile path on the flight trajectory by counting the half revolutions of the projectile [9] is not a method which would reduce the dispersion of fuze action points along the flight trajectory. When using the half revolution count method, only a slight decrease in the dispersion of fuze action points was observed in comparison to the full revolution count method. The results are shown in Table 2.

Table 2. Comparison of the dispersion of fuze action point locations along the flight path for the method of projectile revolution counting along the flight trajectory [10]



Full projectile revolution fuze setting		**Projectile half-revolution fuze setting**		**Dispersion percentage change**
Distance [m]	**Dispersion along x_g [m]**	**Distance [m]**	**Dispersion along x_g [m]**	
100	1.00	100	1.02	🟥 Dispersion along increased by 2.00 %
200	4.10	200	4.03	🟩 Dispersion along reduced by 1.71 %
300	9.00	300	8.99	🟩 Dispersion along reduced by 0.11 %
375	14.00	375	13.93	🟩 Dispersion along reduced by 0.50 %
500	24.90	500	24.79	🟩 Dispersion along reduced by 0.44 %
600	35.70	600	35.63	🟩 Dispersion along reduced by 0.20 %
700	48.40	700	48.35	🟩 Dispersion along reduced by 0.10 %
800	63.30	800	63.18	🟩 Dispersion along reduced by 0.19 %
900	79.90	900	79.80	🟩 Dispersion along reduced by 0.13 %
1000	98.60	1000	98.51	🟩 Dispersion along reduced by 0.09 %

5. EVALUATION OF THE PROPOSED FUZE PROGRAMMING METHOD

The analyses aimed to evaluate the novel fuze programming method [9] were carried out using proven external ballistic methods with consideration of firing conditions close to real conditions. Therefore, the results obtained vary significantly from those presented by other authors, e.g. in [1-7].

The method of determining the distance travelled by the projectile along the flight trajectory processed by the electronic system of the fuze in question and consisting in counting the set number of half revolutions of the projectile along the flight trajectory gave a definitely wider dispersion of fuze action points when compared to the time fuze programming methods.

It was even less accurate than the method considered to be the worst so far, i.e. the method in which the time setting is not corrected after measuring the projectile flight velocity.

A comparative summary of the analysed fuze programming methods, illustrating the size of the dispersion of fuze action point along the flight trajectory is shown in Fig. 11 in the function of the action distance and the programming method.

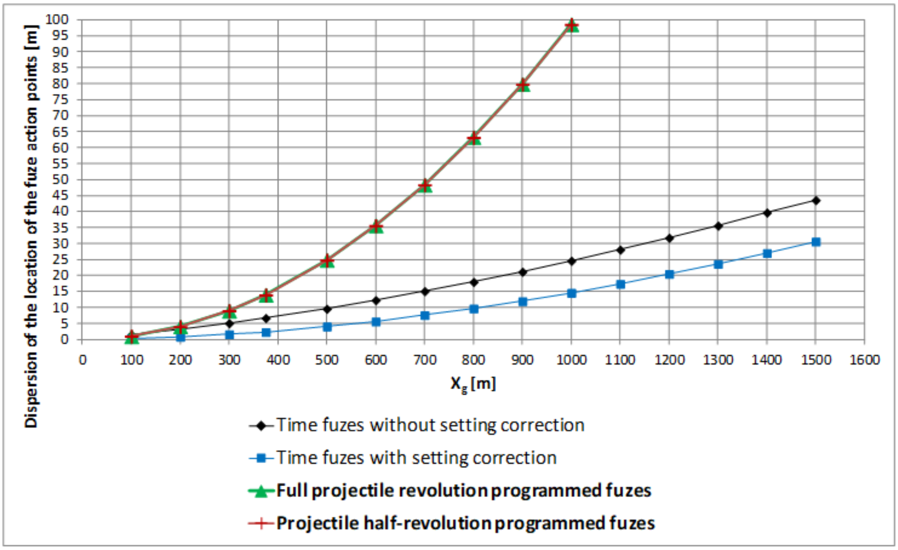


Fig. 11. Comparative summary of the dispersion of fuze action point locations along the flight trajectory vs. the required fuze action distance per the evaluated fuze programming method

6. SUMMARY AND FINAL CONCLUSIONS

Based on the analysis of the results obtained from the firing simulations performed according the adopted investigation methodology, it can be concluded that it is not possible to reduce the dispersion of fuze action points along the flight trajectory if the fuze action algorithm does not consider the interferences of firing conditions. In the case considered here, these interferences are deviations from the values considered to be nominal for the physical model characteristics included in the mathematical model.

After re-examining the reference literature on fuzes programmed with the projectile rotation count, it became evident that in none of the cited papers [1 to 7] did the authors take into account the deviations of the characteristics which affect the behaviour of projectiles along the flight trajectory, in particular the deviations of the values of the aerodynamic, mass-inertia, geometric, or the medium of the motion characteristics.

In the publications referenced above, the projectile's own rotational velocity at the time of exiting the barrel bore was used without any consideration of the reduction of that velocity that occurs along the flight trajectory.

It can therefore be concluded that the positive results presented in the references [1-7] concerning the reduction of the dispersion of fuze action points – in the case of the fuzes programmed with projectile revolution count – were achieved because the tests took place under laboratory conditions or over short firing distances during live test firing in real proving ground conditions, or by using specifically selected ammunition. Testing under these conditions had a considerable effect on the results produced, since the real deviations of the physical model characteristics were characterised by a narrower variation range, unlike in applications with standard ammunition fired over longer distances.

The completed simulation firing tests following the adopted methodology also showed that the novel method of determining the path traveled by the projectile on the flight trajectory in [9], and based on counting the half revolutions of the projectile, did not guarantee a decrease in the dispersion of fuze action points in comparison to the methods of determining the path traveled by the projectile on the flight trajectory by measuring the fuze action time or by counting the full revolutions of the projectile. This method provides results of the dispersion comparable to those produced by the method of projectile path traveled on the flight trajectory determination by counting the projectile full revolutions. Based on the analysis of the firing simulation results it was found that the largest influence on the dispersion of the fuze action point locations along the flight trajectory was the projectile roll damping moment coefficient and its range of variation.

By evaluating the methods of determining the path traveled by the rotating projectile on the flight trajectory by counting its full or half rotations along the flight trajectory, it can be clearly stated that under real firing conditions the methods will be imperfect and they give much worse results of the dispersion of fuze action points along the flight path trajectory compare to methods of projectile path on the flight trajectory determination by time countdown. Both projectile revolution counting methods do not provide the possibility of achieving the required accuracy of the fuze action point on flight trajectory and the effectiveness of the ammunition impacting the target by the projectile airburst over the target.

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Ocena nowatorskiej metody programowania zapalników liczbą obrotów własnych pocisku

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Streszczenie. W pracy przedstawiono nowatorską metodę programowania zapalników amunicji wybuchającej w powietrzu, opartą na zasadzie zliczania obrotów własnych pocisku na torze lotu i określaniu na tej podstawie drogi przebytej przez pocisk. Porównano proponowaną nowatorską metodę programowania zapalników z innymi znanymi metodami programowania zapalników na podstawie wyników symulacji komputerowej strzelania 40 mm granatnikiem, z uwzględnieniem warunków zbliżonych do rzeczywistych. W tym celu opracowano metodykę obliczeń z zakresu balistyki zewnętrznej z wykorzystaniem modelu matematycznego przestrzennego ruchu nieodkształcalnego obiektu latającego traktowanego jako ciało sztywne posiadające sześć stopni swobody, przy zastosowaniu układu współrzędnych wg ISO 1151. Przeprowadzono symulacje, z uwzględnieniem rzeczywistych warunków strzelania pociskami 40 mm amunicji granatnikowej, uzbrojonymi w zapalniki programowane każdą z ocenianych metod. Strzelano do celów usytuowanych na różnych odległościach i oceniano, dla każdej z metod programowania, poziom rozrzutu punktów zadziałania zapalników względem oczekiwanego punktu. We wnioskach stwierdzono, że metoda określania drogi przebytej przez pocisk, opierająca się na zasadzie zliczania obrotów własnych pocisku, po uwzględnieniu warunków rzeczywistych, daje większy rozrzut położenia punktów zadziałania zapalników w porównaniu do metod związanych z odliczaniem czasu.W konkluzji stwierdzono, że metody określania drogi wirującego pocisku oparte na zasadzie zliczania obrotów własnych pocisku na torze lotu, nie gwarantują osiągnięcia wymaganej precyzji odnośnie położenia punktu zadziałania zapalników. To oznacza, że zastosowanie ich do wyznaczania odległości punktu wybuchu pocisków na torze, nie skutkuje zwiększeniem skuteczności amunicji odłamkowej wybuchającej powietrzu.

Słowa kluczowe: budowa i eksploatacja maszyn, balistyka, zapalnik programowalny, zapalnik zliczający obroty.