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Numerical Analysis of the Effects of the Geometric and Weight Parameters on the Exterior Ballistics of a Designed Counterprojectile

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Abstract. This paper presents a selection of deliverables of a research project intended to develop a technology demonstrator for an active protection system smart counterprojectile. Numerical simulations were completed to analyse the effects of geometry and weight of the counterprojectile warhead on the counterprojectile flight (motion) parameters. This paper investigates four variants of the counterprojectile warhead shape and three variants of the counterprojectile warhead weight. Given the investigated geometric and weight variants, the PRODAS software environment was used to develop geometric models of the counterprojectile warhead, followed by the determination of the model aerodynamic characteristics. The final deliverable of this work are the results of the numerical simulation of the counterprojectile motion along the initial flight path length.

This work has been compiled from the paper presented during the 11th International Armament Conference on Scientific Aspects of Armament and Safety Technology, Ryn, Poland, 19 to 22 September 2016

Given the required activation of the active protection system in direct proximity of the protected object, the analyses of counterprojectile motion parameters were restricted to a distance of ten-odd metres from the counterprojectile launching system.
Keywords: mechanics, exterior ballistics, numerical analysis

1. INTRODUCTION

A smart counterprojectile is a key component of an active protection system being developed at the Military University of Technology under an R&D project co-financed by the Polish National Centre for Research and Development. The smart counterprojectile has two basic components: a rocket propulsion system, and a warhead with detection, decision, resolving, safety and actuation (combat) systems. The results of the work on the design engineering of the rocket propulsion system are covered in [1, 2]. The rocket propulsion system manufactured by Zakłady Metalowe DEZMET S.A. (Nowa Dęba, Poland) was tested with a warhead mock-up of the counterprojectile at a proving ground [3]. The warhead mock-up (see Image 1) was only intended to represent the foreseen and finished warhead weight.

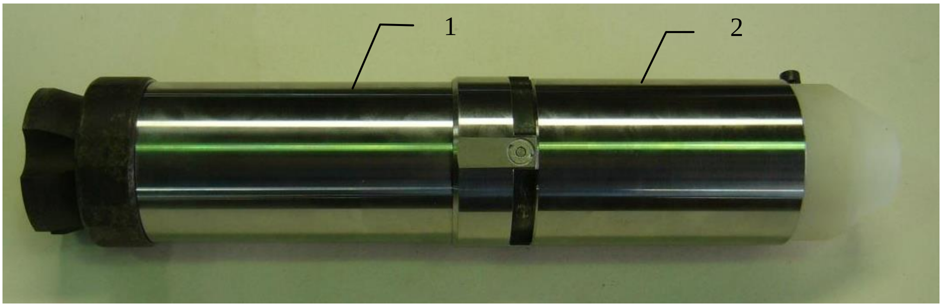

Image 1. Counterprojectile: 1 – rocket propulsion system, 2 – warhead

To test the behaviour of the counterprojectile along a distance of the first ten-odd metres after clearing its launching system, numerical analyses were carried out on the effect of the warhead weight and geometry on the counterprojectile motion parameters. The numerical simulations for the analyses were ran in a dedicated software suite, PRODAS v. 3.5 [4]. Four various warhead models were investigated, each with a different nose tip geometry: trapezoidal, conical, hemispherical, and parabolic. Moreover, each geometric model had three different weight variants. Each model had different centres of gravity and aerodynamic pressure, depending on the warhead weight and geometry variant; as a result, the aerodynamic characteristics of each model were also different.

Figure 1 shows a diagram which explains the basic components of the counterprojectile analysed as presented in this paper.

The weight values of the counterprojectile components are listed for the reference configuration in Table 1.

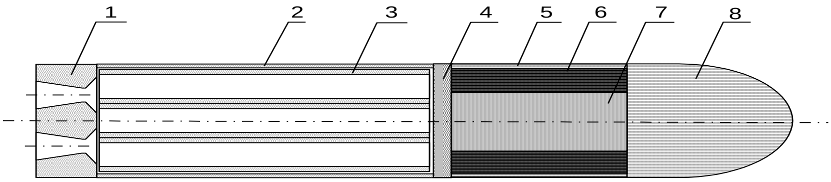

Fig. 1. Sectional view of the counterprojectile:
1 – jet nozzle block, 2 – rocket engine chamber, 3 – propellant charge, 4 – head,
5 – warhead casing, 6 – fragmentation liner, 7 – explosive charge, 8 – detonator
(component systems: detection, resolving, safety)

Table 1. Counterprojectile component weight values

Component	**Weight (kg)**
Jet nozzle block	0.632
Head	0.398
Rocket engine chamber	1.266
Propellant charge	0.385
Warhead casing	0.613
Fragmentation liner	0.890
Explosive charge	0.330
Detonator	1.116
Total	**5.630**

2. PHYSICAL MODELS OF THE ANTI-MISSILE

The PRODAS v. 3.5 software suite was used to develop models representing the geometric shape and dimensions of the counterprojectile with the warhead in the four variants specified herein. The models shown in Figs. 2-5 served as input data for the calculation of the aerodynamic factors (characteristics) of the counterprojectile and the simulation of its motion (flight). The models show the location of the centre of gravity (CG) and the centre of pressure (CP).

Given the subsonic-only velocity range of the counterprojectile, its aerodynamic characteristics with the investigated warhead geometries were determined at a Mach number of Ma = 0-1 (see Tables 2 to 5). The specific table columns read as follows:

- Mach – Mach number
- CX0 – drag factor at zero attack angle
- CX2 – drag factor

- CNa – normal force factor
- CYpa – Magnus force factor
- Cma – overturning momentum factor
- Cma – aerodynamic damping momentum factor
- Clp – banking moment aerodynamic damping factor
- CXf – frontal drag factor.

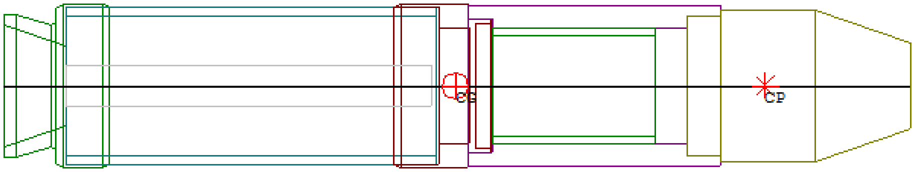

Fig. 2. Counterprojectile model with the trapezoidal warhead geometry

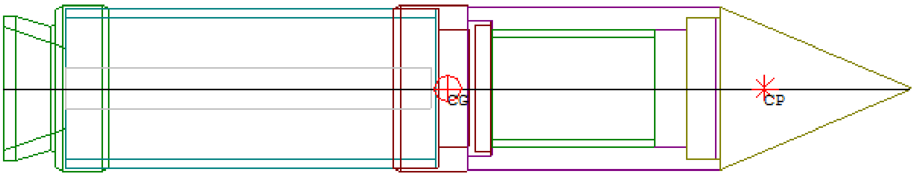

Fig. 3. Counterprojectile model with the conical warhead geometry

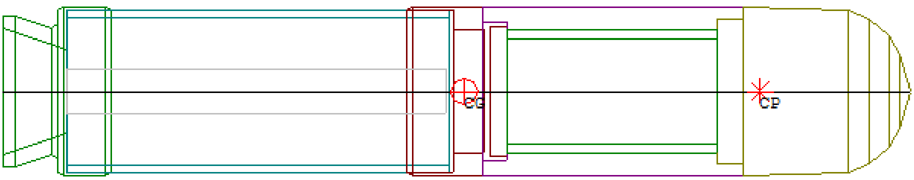

Fig. 4. Counterprojectile model with the hemispherical warhead geometry

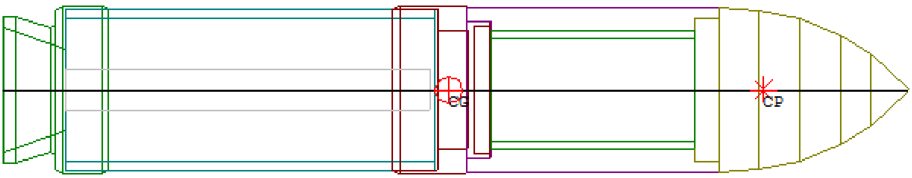

Fig. 5. Counterprojectile model with the parabolic warhead geometry

Table 2. Counterprojectile aerodynamic characteristics, trapezoid warhead geometry

Mach	CX0	CX2	CNa	CYpa	Cma	Cmq	Clp	CXf
0.01	0.2719	2.54	2.238	-0.84	3.935	9.9	-0.03681	0.1258
0.40	0.2673	2.54	2.232	-0.84	3.953	10.6	-0.03701	0.1196
0.60	0.2782	2.55	2.218	-0.84	3.897	9.7	-0.03664	0.1223
0.70	0.2871	2.80	2.209	-0.85	3.852	9.0	-0.03633	0.1265
0.75	0.2976	2.89	2.214	-0.86	3.777	8.2	-0.03607	0.1347
0.80	0.3183	2.97	2.265	-0.88	3.690	6.4	-0.03569	0.1529
0.85	0.3643	3.05	2.304	-0.91	3.571	5.8	-0.03515	0.1966
0.875	0.4055	3.14	2.347	-0.92	3.521	3.8	-0.03535	0.2367
0.90	0.4531	3.24	2.394	-0.95	3.504	0.7	-0.03592	0.2832
0.925	0.509	3.36	2.452	-1.07	3.538	-3.3	-0.03712	0.338
0.95	0.5667	3.49	2.522	-1.22	3.563	-8.7	-0.03823	0.3946
0.975	0.6435	3.72	2.559	-1.08	3.695	-14.3	-0.0390	0.4703
1	0.7415	4.03	2.566	-0.99	3.887	-18.9	-0.03934	0.5267

Table 3. Counterprojectile aerodynamic characteristics, conical warhead geometry

Mach	CX0	CX2	CNa	CYpa	Cma	Cmq	Clp	CXf
0.01	0.2282	2.38	2.247	-0.84	3.649	4.8	-0.04030	0.0814
0.40	0.2282	2.38	2.561	-0.84	3.518	6.1	-0.04513	0.0798
0.60	0.2355	2.39	2.501	-0.84	3.495	5.2	-0.04426	0.0789
0.70	0.2409	2.61	2.415	-0.85	3.493	4.3	-0.04298	0.0797
0.75	0.2453	2.71	2.361	-0.86	3.489	3.5	-0.04215	0.0817
0.80	0.2616	2.8	2.339	-0.88	3.553	1.9	-0.03988	0.0957
0.85	0.2822	2.87	2.355	-0.91	3.599	1.4	-0.03834	0.1139
0.875	0.305	2.94	2.416	-0.92	3.612	-0.1	-0.03844	0.1356
0.9	0.3358	3.00	2.482	-0.95	3.630	-2.7	-0.03887	0.1652
0.925	0.3763	3.10	2.557	-1.07	3.658	-5.8	-0.03984	0.2047
0.95	0.4256	3.22	2.636	-1.22	3.677	-10.3	-0.04075	0.2529
0.975	0.4881	3.45	2.694	-1.08	3.756	-15.1	-0.04138	0.3143
1	0.5591	3.68	2.734	-0.99	3.863	-19.4	-0.04166	0.3437

Table 4. Counterprojectile aerodynamic characteristics, hemispherical warhead geometry

Mach	**CX0**	**CX2**	**CNa**	**CYpa**	**Cma**	**Cmq**	**Clp**	**CXf**
0.01	0.2292	2.69	2.236	-0.82	3.548	-3.4	-0.03249	0.0824
0.40	0.2180	2.69	2.553	-0.82	3.431	-2.2	-0.03721	0.0695
0.60	0.2287	2.70	2.487	-0.82	3.385	-2.6	-0.03647	0.0721
0.70	0.2383	2.97	2.397	-0.83	3.366	-3.2	-0.03530	0.0771
0.75	0.2447	3.10	2.337	-0.84	3.341	-3.7	-0.03455	0.0811
0.80	0.2648	3.22	2.310	-0.86	3.378	-5.0	-0.03247	0.0988
0.85	0.3027	3.36	2.315	-0.88	3.463	-5.3	-0.03106	0.1344
0.875	0.3329	3.46	2.370	-0.90	3.495	-6.4	-0.03120	0.1635
0.90	0.3696	3.55	2.432	-0.92	3.529	-8.3	-0.03165	0.1991
0.925	0.4160	3.69	2.511	-1.04	3.584	-10.3	-0.03262	0.2444
0.95	0.4625	3.88	2.588	-1.19	3.606	-14.0	-0.03359	0.2898
0.975	0.5294	4.16	2.631	-1.05	3.691	-18.4	-0.03431	0.3556
1	0.6109	4.47	2.650	-0.97	3.820	-22.5	-0.03477	0.3954

Table 5. Counterprojectile aerodynamic characteristics, parabolic warhead geometry

Mach	**CX0**	**CX2**	**CNa**	**CYpa**	**Cma**	**Cmq**	**Clp**	**CXf**
0.01	0.2497	2.80	2.106	-0.84	4.009	1.0	-0.02951	0.1033
0.40	0.2381	2.80	2.104	-0.84	4.020	1.7	-0.02962	0.0900
0.60	0.2506	2.80	2.092	-0.84	3.976	1.2	-0.02935	0.0943
0.70	0.2616	3.07	2.084	-0.85	3.941	0.7	-0.02914	0.1007
0.75	0.2693	3.19	2.092	-0.86	3.890	0.2	-0.02896	0.1060
0.80	0.2864	3.30	2.134	-0.88	3.841	-1.2	-0.02875	0.1207
0.85	0.3214	3.42	2.165	-0.91	3.782	-1.6	-0.02836	0.1534
0.875	0.3495	3.53	2.207	-0.92	3.769	-3.1	-0.02855	0.1804
0.90	0.3833	3.65	2.255	-0.95	3.781	-5.5	-0.02905	0.2131
0.925	0.4242	3.80	2.315	-1.07	3.837	-8.1	-0.03007	0.2528
0.95	0.4685	3.96	2.390	-1.22	3.894	-12.3	-0.03105	0.2961
0.975	0.5370	4.22	2.427	-1.08	4.028	-17.2	-0.03174	0.3635
1	0.6239	4.55	2.434	-0.99	4.212	-21.6	-0.03212	0.4087

3. NUMERICAL SIMULATIONS OF THE COUNTERPROJECTILE FLIGHT

The 6DOF Body Fixed model available in PRODAS [4] was applied to determine the significant flight parameters of the counterprojectile's four warhead geometry variants. Given the required activation of the active protection system in direct proximity of the protected object, the numerical simulations of counterprojectile motion parameters were restricted to a distance of 15 metres away from the counterprojectile launching system.

The numerical simulation parameters included the rocket engine thrust *R* versus time *t* (see Fig. 6), which was determined theoretically by solving equations of a mathematical model of the rocket engine burn [3].

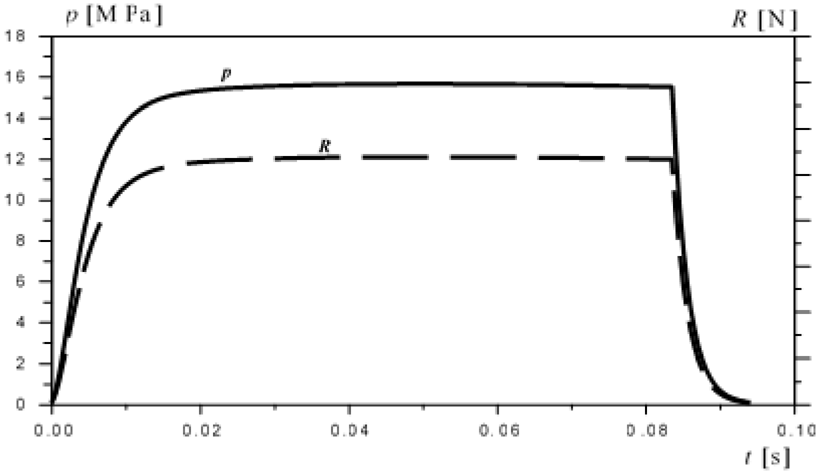

Fig. 6. Pressure and rocket engine thrust charts

The following initial input data were used in the calculations:

- counterprojectile initial velocity v_0 = 4 m/s,
- angle of departure 0°.

Tables 6-9 show the specific numerical simulation results for the four warhead geometry variants, each 2.949 kg in weight.

The individual table columns read as follows:

- Time
- X, Y, Z – counterprojectile linear coordinates
- Slant – range (flight trajectory projection length over an XY plane)
- Velocity of the counterprojectile
- Alpha – attack angle
- Mach
- Drop – counterprojectile descent

- KineticEnergy – counterprojectile kinetic energy
- SpinDegM – counterprojectile rotation angle vs. distance covered
- DvDx – counterprojectile velocity reduction.

Table 6. Flight parameters of the counterprojectile with the trapezoidal warhead

Time	X	Y	Z	Slant	Velocity	Alpha	Mach	Drop	Kinetic Energy	SpinDegM	DvDx
s	m	m	m	m	m/s	deg	-	millrad	kJ	deg/m	m/s/1000m
0	0	0	0	0	4	0	0.012	0	0	44.89	-0.001
0.025	0.46	0	0	0.46	39.82	0.35	0.117	6.72	4.4	4.51	47.924
0.050	2.06	0	-0.01	2.06	88.54	0.32	0.260	5.95	21.3	2.03	22.346
0.075	4.89	0	-0.03	4.89	138.44	0.33	0.407	5.59	50.9	1.30	14.527
0.100	8.72	0	-0.05	8.72	156.00	0.45	0.458	5.51	64.1	1.15	-0.025
0.125	12.61	0	-0.07	12.61	155.87	0.69	0.458	5.92	64.0	1.15	-0.025
0.140	14.95	0	-0.09	14.95	155.80	0.88	0.458	6.25	64.0	1.15	- 0.025

Table 7. Flight parameters of the counterprojectile with the conical warhead

Time	X	Y	Z	Slant	Velocity	Alpha	Mach	Drop	Kinetic Energy	SpinDegM	DvDx
s	m	m	m	m	m/s	deg	-	millrad	kJ	deg/m	m/s/1000m
0	0	0	0	0	4	0	0.012	0	0	44.89	-0.001
0.025	0.46	0	0	0.46	39.81	0.35	0.117	6.72	4.4	4.51	47.924
0.050	2.06	0	-0.01	2.06	88.53	0.32	0.260	5.95	21.3	2.03	22.347
0.075	4.89	0	-0.03	4.89	138.43	0.33	0.407	5.59	50.9	1.30	14.529
0.100	8.72	0	-0.05	8.72	156.03	0.44	0.459	5.51	64.2	1.15	-0.021
0.125	12.61	0	-0.07	12.61	155.96	0.67	0.458	5.92	64.1	1.15	-0.021
0.140	14.95	0	-0.09	14.95	155.93	0.86	0.458	6.25	64.1	1.15	-0.021

Table 8. Flight parameters of the counterprojectile with the hemispherical warhead

Time	X	Y	Z	Slant	Velocity	Alpha	Mach	Drop	Kinetic Energy	SpinDegM	DvDx
s	m	m	m	m	m/s	deg	-	millrad	kJ	deg/m	m/s/1000m
0	0	0	0	0	4	0	0.012	0	0	44.89	-0.001
0.025	0.46	0	0	0.46	39.81	0.35	0.117	6.72	4.4	4.51	47.924
0.050	2.06	0	-0.01	2.06	88.53	0.32	0.260	5.95	21.3	2.03	22.347
0.075	4.89	0	-0.03	4.89	138.44	0.33	0.407	5.59	50.9	1.30	14.530
0.100	8.72	0	-0.05	8.72	156.04	0.44	0.459	5.51	64.2	1.15	-0.020
0.125	12.62	0	-0.07	12.62	155.98	0.67	0.458	5.92	64.1	1.15	-0.020
0.140	14.96	0	-0.09	14.96	155.95	0.85	0.458	6.25	64.1	1.15	-0.020

Table 9. Flight parameters of the counterprojectile with the parabolic warhead

Time	X	Y	Z	Slant	Velocity	Alpha	Mach	Drop	Kinetic Energy	SpinDegM	DvDx
s	m	m	m	m	m/s	deg	-	millrad	kJ	deg/m	m/s/1000m
0	0	0	0	0	4	0	0.012	0	0	44.89	-0.001
0.025	0.46	0	0	0.46	39.81	0.35	0.117	6.72	4.4	4.51	47.924
0.05	2.06	0	-0.01	2.06	88.52	0.32	0.260	5.95	21.3	2.03	22.346
0.075	4.89	0	-0.03	4.89	138.43	0.33	0.407	5.59	50.9	1.30	14.529
0.100	8.72	0	-0.05	8.72	156.02	0.46	0.458	5.50	64.2	1.15	-0.022
0.125	12.62	0	-0.07	12.62	155.95	0.72	0.458	5.91	64.1	1.15	-0.022
0.140	14.96	0	-0.09	14.96	155.88	0.94	0.458	6.24	64.0	1.15	-0.022

The numerical analysis also involved a numerical simulation of the counterprojectile with the warhead weight reduced by 0.2 and 0.4 kg, respectively. The calculation results for the three trapezoidal warhead weight values are shown in Figs. 7 to 9.

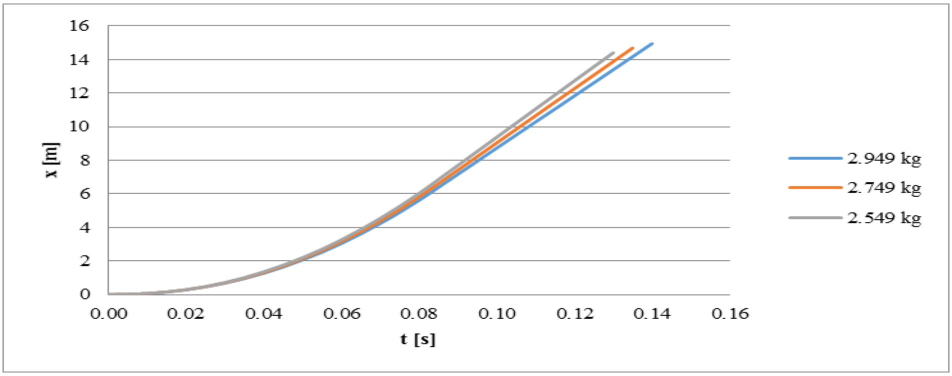

Fig. 7. Coordinate *x* vs. time *t*

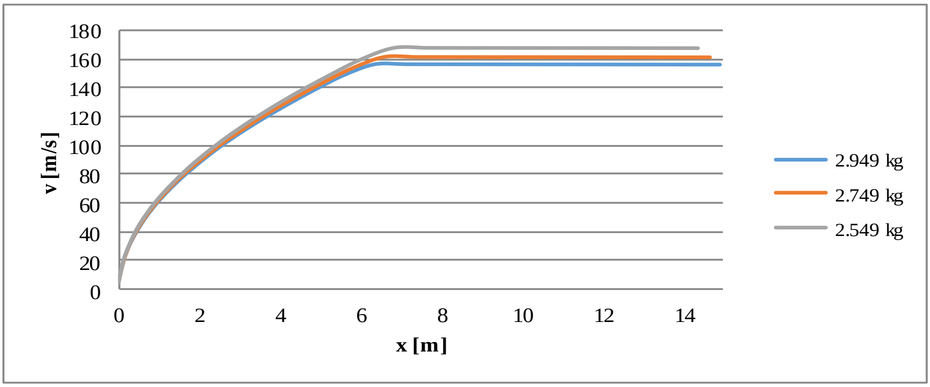

Fig. 8. Chart plots of the counterprojectile velocity *v* vs. counterprojectile displacement *x*

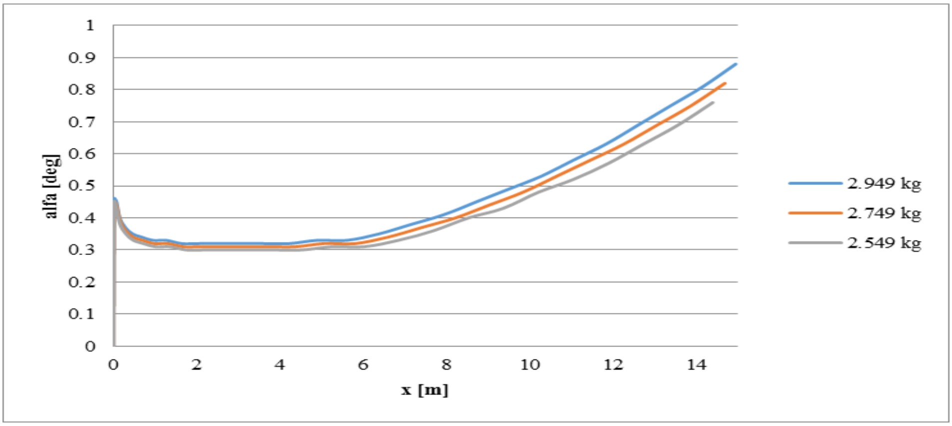

Fig. 9. Chart plots of the attack angle α vs. counterprojectile displacement x

4. SUMMARY

The critical factors at the stages of design, fabrication and testing of the technology demonstrator of the active protection system smart counterprojectile, the results of tests and theoretical analyses, inclusive of the counterprojectile behaviour between its launch and activation of the warhead. This paper presents the results of the flight (motion) simulations of the counterprojectile carried out in PRODAS. The simulation was run for four specific geometries of the counterprojectile nose tip.

The simulations suggest that the counterprojectile warhead geometry has a negligible effect on the flight parameters along the initial flight distance (within 15 m from the launching system).

It would seem to be obvious that the effect of the same would be more pronounced over a longer distance from the launching system. However, the counterprojectile is expected to detonate within 15 m from launch and destroy the target; hence no such analysis was carried out.

The counterprojectile weight seems to have had a more pronounced effect on the flight parameters. Reduction of this weight by 0.2 and 0.4 kg increased the counterprojectile velocity by 3.7% and 7.7%, respectively.

Given the counterprojectile distance of 15 m from the launching system investigated herein, the change of the coordinate z (altitude) of the counterprojectile was ca. 0.09 m, which should have no noticeable effect on the active protection system performance. The counterprojectile flight trajectory corrections (if any) could be modified by changing the angle of departure.

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Analiza numeryczna wpływu parametrów geometryczno -masowych projektowanego antypocisku na jego balistykę zewnętrzną

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Streszczenie. W pracy przedstawiono niektóre wyniki realizacji projektu badawczego, którego celem jest opracowanie demonstratora technologii inteligentnego antypocisku systemu ochrony aktywnej. Przeanalizowano, na drodze symulacji numerycznych, wpływ geometrii oraz masy głowicy bojowej antypocisku na parametry jego ruchu (lotu). W artykule rozpatrzono cztery warianty kształtu głowicy antypocisku oraz trzy warianty masowe. Dla rozpatrywanych wariantów geometryczno-masowych opracowano w środowisku PRODAS modele geometryczne głowicy antypocisku, a następnie wyznaczono ich charakterystyki aerodynamiczne. Ostatecznym rezultatem pracy są wyniki symulacji numerycznych ruchu antypocisku na początkowym odcinku toru lotu. Ze względu na wymagane działanie systemu ochrony aktywnej w bezpośredniej odległości od ochranianego obiektu, analizy parametrów ruchu antypocisku ograniczono do kilkunastu metrów od wyrzutni.

Słowa kluczowe: mechanika, balistyka zewnętrzna, analiza numeryczna