PROBLEMY MECHATRONIKI
UZBROJENIE, LOTNICTWO, INŻYNIERIA BEZPIECZEŃSTWA

ISSN 2081-5891 **9, 2 (32), 2018, 85-98**

PROBLEMS OF MECHATRONICS
ARMAMENT, AVIATION, SAFETY ENGINEERING

Analysis of Results of Empirical Investigations of Launcher-Missile System Using TEMA Motion Program Environment

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Received by the editorial staff on 8 June 2016 r.
Reviewed and verified version received on 8 June 2018 r.

DOI 10.5604/01.3001.0012.1103

Abstract. The paper presents an analysis of the pictures, recorded from the testing ground investigations, obtained with application of the fast-digital camera Phantom v9.1. The analysis was focused on determination of the kinematics of motion of the launcher-missile system. TEMA Motion program was used for motion analysis of the investigated system. The courses of variability of kinematic values characterising motion of the selected points of the launcher were determined. The results analysis showed that the launcher undergoes the linear displacement (X, Y) and angular one (α) that cause significant differences in the flight trajectory of the successively launched missiles.
Keywords: mechanics, kinematics of motion, picture analysis, missile start recording, missiles launcher

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, 19-22 September 2016.

1. INTRODUCTION

The object that is considered in the paper is the Remote-Controlled Weapon Station ZSMU-70. The ZSMU-70 Weapon Station, as it is given by the manufacturer – the Polish Defence Holding, is intended for destruction (immobilisation or significant damage) of ground-based point targets of various resistance characteristics. The station is equipped with WW-4 launcher, consisting of a platform and four tubular guides, in which unguided short-range NLPR-70 missiles are situated. NLPR-70 missiles are devoted to destruct various floating targets and ground-based ones, including warships, light armoured vehicles and infrastructure. The WW-4 launcher together with the platform and missiles is mounted on the armoured TUR-2 vehicle. Figure 1 shows a picture of the considered object of investigations [1].

Fig. 1. ZSMU-70 station equipped with the WW-4 launcher and NLPR-70 missiles

In the presented weapon station, two main objects should be distinguished: a launcher and an armoured vehicle [2.3]. Start of unguided NLPR-70 missiles from the WW-4 launcher, mounted on the TUR-2 vehicle, has been recorded with the fast-digital Phantom v9.1 camera on the testing ground in Nowa Dęba (Poland).

The hitherto work presents the analysis of the recorded results of empirical investigations aimed at determination of the kinematics of the launcher-missile system. The motion of this system was analysed using special TEMA Motion program which converts the pictures recorded by means of the fast-digital camera Phantom v9.1. Due to application of TEMA Motion program, the courses of variability of kinematic values, characterising the motion of selected points of the launcher, could be determined.

The aim of this work is to determine characteristics of displacement, velocity, and acceleration in time. On the basis of these characteristics, initial estimation of the launcher motion during missiles launching can be possible and univocal indication that the launcher undergoes significant linear and angular displacements (X, Y) and (α), respectively.

2. EMPIRICAL INVESTIGATION

2.1. Recording the missiles start

The unguided missiles were launched on the testing ground in Nowa Dęba from the presented system, located on the stationary vehicle. Start of the unguided NLPR-70 missiles from the WW-4 launcher, situated on the armoured vehicle TUR-2, has been recorded using the fast, digital camera Phantom v9.1 of the Vision Research firm. Within the frame of investigations, over 20 similar recordings of missiles start were obtained. Significant parameters for proper recording with a fast camera are: well illuminated investigated object (the best is cloudless, sunny day), background for the object, stable surface for tripod of the camera, directed perpendicularly to the investigated object, camera situated the possibly close to the object, adequate choice of a focal length and a value of a lens shutter, application of a camera's trigger. Moreover, if it is possible, very helpful are markers that are stacked to the investigated object.

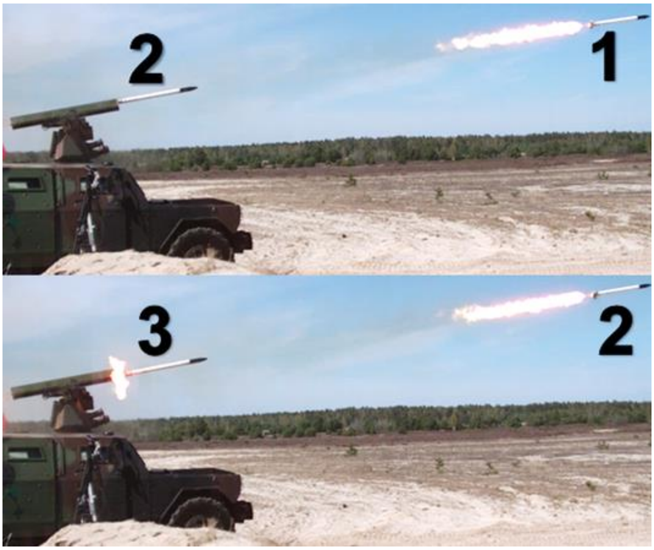

Fig. 2. ZSMU-70 station during the launch of unguided missiles. (Digits in the figure denote successively launched missiles: 1 – the first missile, 2 – the second missile, 3 – the third missile)

Figure 2 shows the start of an unguided missile that was launched from the investigated ZSMU-70 station.

Generally, the start process of the launched unguided missile can be divided into six stages: 1 – target recognition and aiming, 2 – start/marching engine activation, 3 – missile motion along the launcher, 4 – missile leaving the launcher, 5 – missile flight, 6 – reaching the goal – hit in the target (immobilization, significant damage or possible destruction of the target.

Launching the unguided NLPR-70 missiles has been performed from a stationary vehicle. Thus, enforcements that are generated in the launcher-missile system are caused only by the missile launch from the launcher. As it was mentioned previously, the missile start is initiated by activation the start engine that operates during the whole motion of the missile along the launcher. At the moment when the missile leaves the launcher, the force P_w acts on the launcher (Fig. 3) that results from interaction of exhausted gases of the missile [5].

Fig. 3. Extortions originating from exhausted gases

Disturbances, occurred in this way, can cause high inefficiency in missiles accuracy – having in view increase in missiles spread – in case of ground-based point target destruction. Thus, in this work, the investigations will be presented that are aimed at the statement which phenomena, and how much, they affect the scatter of ZSMU-70 station operation.

2.2. Analysis of the recorded picture

As it was mentioned previously, the missiles start has been recorded with the fast-digital Phantom v9.1 camera of the Vision Research firm.

Due to the obtained camera films, this paper presents the analysis of results of empirical investigations aimed at determination of the kinematics of the launcher-missile system. Both, initial analysis and detailed one have been carried out in the vertical-transversal plane (X-Y) of the launcher-missile system (Fig. 12). The investigations performed on testing ground showed that successively launched missiles had not the same trajectory as the first launched projectile.

After initial analysis of the recorded films, one can see differences in missiles trajectories, just in the first phase of their flight – Fig. 4. The occurred disturbances in the launcher-missile system are so high that, in practice, hit in a point target is impossible with NLPR missiles because they are unguided and do not have enough big explosive charge in their constructions that could cover with fire the area sufficient to achieve a goal. In general, negative effect of the occurred disturbances is large scatter of the launched missiles.

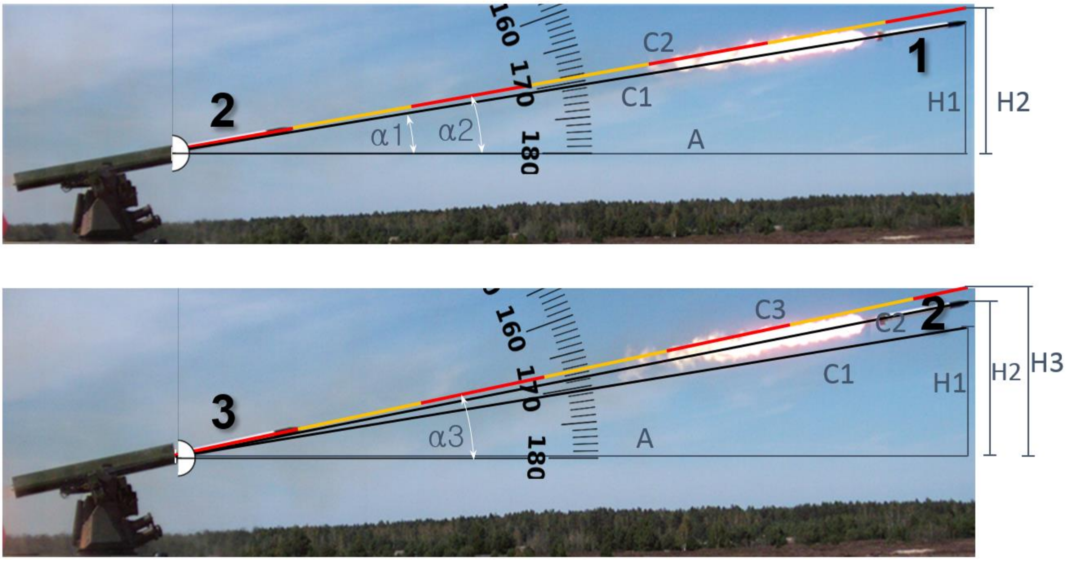

Fig. 4. Differences in trajectories of NLPR-70 missiles

The symbols C1, C2, and C3 in Fig 4 denote the trajectories and distances travelled in the initial phase of the flight of successively launched missiles, C1 – the first missile, C2 – the second missile, and C3 – the third missile. The symbol A – it is projection of the values C1, C2, and C3 on the horizontal axis. The symbols H1, H2, and H3 are the heights at which is the front part of a missile head after the travelled distances of flight C1, C2, and C3, respectively.

Table 1 presents characteristic dimensions and results in trajectories obtained from the carried-out analysis of the pictures of three launched one by one missiles.

Detailed motion analysis of the investigated system launcher-missile was carried-out using special TEMA Motion program which converts the recorded picture by means of the fast-digital camera Phantom v9.1. This program determines, on the basis of a position of the investigated object in the subsequent frames of the film, its displacement, velocity, and acceleration. The displacement, velocity, and acceleration values are determined due to tracking the point chosen by the user [4]. Application of TEMA Motion program allowed for precise determination of the courses of variability of kinematic values characterising motion of the selected points of the launcher.

Table 1. Characteristic dimensions and differences in trajectories

Characteristic dimensions [mm]	Estimated difference in vertical trajectory at the distance A ≈ 8840 [mm]:	
	between missiles #1 and #2	between missiles #1 and #3
A ≈ 8840	Delta_2 = H2-H1 ≈ 210 [mm]	Delta_3 = H3-H1 ≈ 370 [mm]
C1 ≈ 8970		
C2 ≈ 9010		
C3 ≈ 9040		
H1 ≈ 1530		
H2 ≈ 1740		
H3 ≈ 1900		
$\alpha 1 \approx 10^{\circ}$	Estimated difference in vertical trajectory at the distance A’ ≈ 2000 [m]:	
$\alpha 2 \approx 11^{\circ}$	between missiles #1 and #2	between missiles #1 and #3
$\alpha 3 \approx 12^{\circ}$	Delta_2’ ≈ 40 [m]	Delta_3’ ≈ 70 [m]

Among all the recorded films, only representative one is shown here. 253 frames have been recorded with the velocity of 1700 (fps) (frames per second) what gives t = 148.764 ms of the recording time. It should be mentioned, that $t0$ means $t0$ = 0 ms, i.e., the start of the film recording and t denotes the total time of the film. Each next denotation $t1$, $t2$, etc. will denote the defined moment of the being analysed recording.

Figures 5, 8, and 9 present the chosen characteristic moments of the missile start that have the highest influence on efficiency of the investigated weapon station. It can be seen, that at the moment $t1$ = 5.292 ms, the missile’s engine has been activated. During the period from $t1$ = 5.292 ms up to $t3$ = 80.556 ms, the missile moves inside the launcher. It lasted ($t3$-$t1$) = 75.264 ms.

It should be noticed that at the moment $t2$ = 33.5 ms, the missile dislocated and simultaneously the centre of gravity of the launcher-missile system moved forwards. Next, the displacement of the centre of gravity has caused inclination of the front part of the launcher downwards of about 1-2 mm (adequately, the rear part of the launcher moved upwards of about 1-2 mm) and rotation of the launcher by the small angle $\alpha \leq -1^{\circ}$. At the moment $t4$ = 81.144 ms, the missile has left the launcher. Since that moment, the launcher is affected by exhausted gases, influence of this effect can be clearly seen at the time from $t4$ = 81.144 ms to $t6$ = 125.244 ms. Important and clear change, that has been observed, was vertical displacement of the frontal part of the launcher upwards, changing from the value y = 1020 mm up to the value y = 1036 mm, and vertical displacement of the rear part of the launcher downwards, from y = 1016 mm up to y = 996 mm. Moreover, the launcher is tilted (deviated) from a balance position by the angle α that changes during missile launching from the launcher.

Fig. 5. Start of the missile's engine ($t1$ = 5.292 ms)

Fig. 6. Change in the centre of gravity of the launcher-missile system ($t2$ = 33.5 ms)

Fig. 7. Displacement of the missile inside the launcher
(from $t1$ = 5.292 ms up to $t3$ = 80.556 ms)

Fig. 8. Missile leaves the launcher ($t4$ = 81.144 ms)

Fig. 9. Impact of exhausted gases on the launcher
(from $t4$ = 81.144 ms to $t6$ = 125.244 ms)

2.2.1. Determination of characteristic points of the object

As characteristic points, that were tracked by the TEMA Motion program, Point 3 – located on the rear part of the launcher and Point 4 – located on the front part of the launcher were chosen (Fig. 10). Both these points are at the possibly far distance from the rotation axis of the launcher, so that, the calculations of the α angle were vitiated by the lowest possible error, the lower error, the larger is the measuring basis (distance between Points 3 and 4 on the launcher)

Fig. 10. Location of points chosen for analysis: Point 3 and Point 4 and points for check analysis: Points 1, 2, 5, 6

Impact of exhausted gases, made difficult to track the point, because they partially cover the front part of the launcher what can be clearly seen in Fig. 11 at the moment $t5$ = 117.6 ms of the performed analysis of the picture.

Fig. 11. Impact of exhausted gases on the point tracking

For tracking the launcher points, with the TEMA Motion program, a correlation option was used which, due to matching the shades of pixels of the picture fragment, allows for tracking the chosen point. For elaboration of the recorded results of empirical investigations, the picture filters were helpful (application of grey shadows, change in colours intensity, and the like) increasing contrast of the investigated point and facilitating its tracking.

2.2.2. Dimensions / Scaling

For definition of reference dimension (scale), the distance length of the caisson L of the launcher between two points denoted in TEMA Motion program, Fig. 12 was used.

Fig. 12. Dimension of the launcher length (L) with the denoted reference points in TEMA Motion program

2.2.3. Characteristics of $Y_3(t)$ and $Y_4(t)$ displacements of points 3 and 4

Figures 13 and 14 show characteristics of displacements of the interesting points of the launcher.

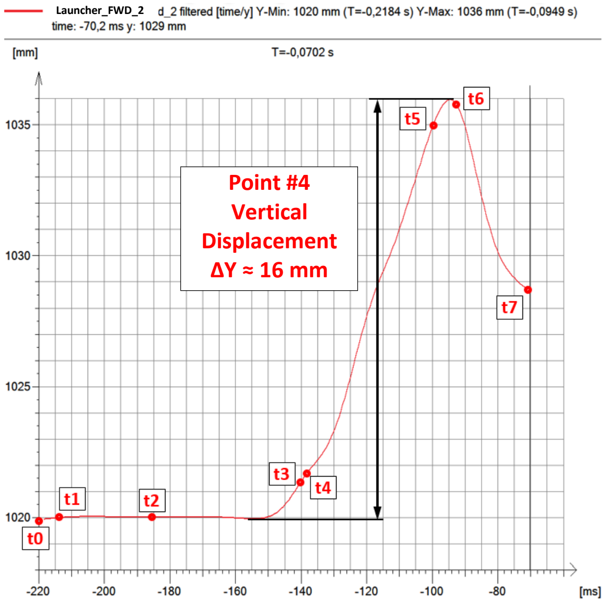

Fig. 13. Characteristic of displacements in the time domain $Y_4(t)$ – the launcher's front

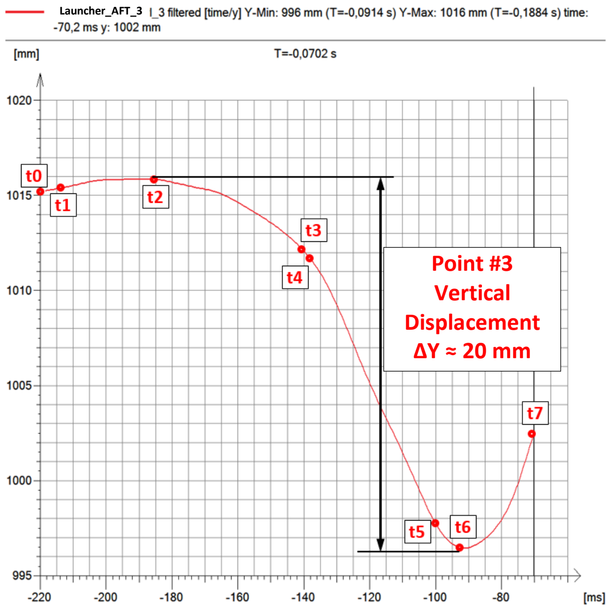

Fig. 14. Characteristic of displacement in the time domain $Y_3(t)$ – the launcher's rear part

2.2.4. Characteristics of the displacement $X_3(t)$ of point 3

Figures 15 and 16 present the characteristics of the interesting points of the launcher.

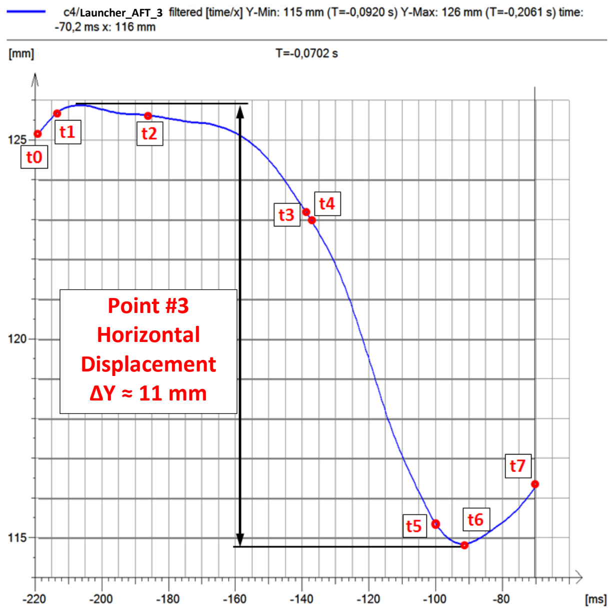

Fig. 15. Displacement's characteristic in the time domain $Y_3(t)$ – the launcher's rear part

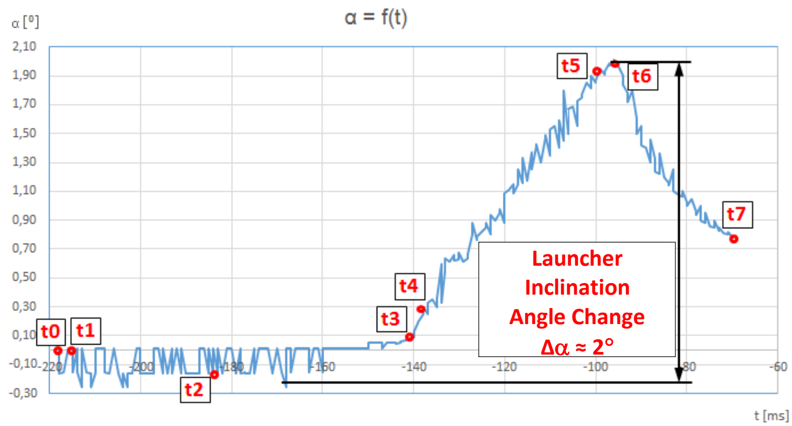

Fig. 16. Characteristic of change of the angle of launcher inclination α in the time domain $\alpha(t)$

The obtained values of displacements, velocity, and acceleration of the launcher, for selected characteristic time points are listed in Table 2.

Table 2. List of the obtained values of displacement, velocity, and acceleration of the launcher for selected characteristic time points

ti	*t* [ms]	α [°]	Y_3 [mm]	Vy_3 [mm/s]	ay_3 [m/s2]	X_3 [mm]	Vx_3 [mm/s]	ax_3 [m/s2]	Y_4 [mm]	Vy_4 [mm/s]	ay_4 [m/s2]
t0	0.0	0.0	1015.0	0.0	0.0	125.0	0.0	0.0	1020.0	0.0	0.0
t1	5.295	-0.16	1015.5	30.651	1.7835	126.0	82.096	-9.4452	1020.0	9.1585	-1.5032
t2	33.5	0.03	1016.0	-8.953	-4.126	126.0	-8.617	-1.1783	1020.0	-0.2687	-0.0687
t3	80.556	0.09	1012.0	-226.36	-16.978	123.0	-132.23	-3.5704	1022.0	169.29	0.0886
t4	81.144	0.25	1012.0	-216.45	-15.025	123.0	-128.45	-2.7697	1022.0	167.19	1.6138
t5	117.6	1.85	998.0	-313.55	24.575	115.5	-137.1	11.974	1035.0	343.52	-29.092
t6	125.144	1.96	996.0	0.0	33.822	115.0	0.0	15.49	1036.0	-143.01	-81.616
t7	148.764	0.80	1002.0	568.32	10.339	116.0	113.83	3.2918	1029.0	-116.04	-2.184

3. CONCLUSIONS

Initial and detailed analyses of the recorded pictures from previously performed tests on the testing ground were made. The characteristics in time domain of kinematic values, characterising the launcher movement during missiles launching were obtained. The characteristics of displacements, velocity, and acceleration in time domain allowed for initial estimation of the launcher motion during the missiles launching. They showed univocally the reason of inefficiency of the investigated weapon station. From the carried-out analysis, the results were obtained that can be used for validation of theoretical models. Impact of six characteristic points of the launcher behaviour, during the missiles launching, has been determined.

It was noticed, that essential and clear change is vertical displacement of the front's part of the launcher upwards (rear part downwards) because of the change of the centre of gravity causing that even the first missile at the moment of the launcher leave, moves along the wrong flight trajectory. Moreover, an absolute value of the vertical displacement of the launcher, since the moment of the start of the first missile up to the moment of maximum impact of exhausted gases on the launcher can amount even 20 mm. The investigated system launcher-missile, during the missiles launching, undergoes significant linear displacement (X, Y) and angular displacement (α). It causes significant differences in the flight trajectory.

It was estimated that at the distance of about 10 m, vertical change in trajectory for missile no. 2 is about 210 mm and for missile no. 3 is about 370 mm.

The estimated vertical change in trajectory, at the distance of 2000 m for missile no. 2 is about 40 m and for missile no. 3 is about 70 m.

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Analiza wyników badań empirycznych układu wyrzutnia – pocisk rakietowy z wykorzystaniem środowiska programu TEMA Motion

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Streszczenie. W pracy przedstawiono analizę zarejestrowanych obrazów z badań poligonowych przy użyciu szybkiej kamery cyfrowej Phantom v9.1. Celem analizy jest określenie kinematyki ruchu układu wyrzutnia – pocisk rakietowy. Do analizy ruchu badanego układu użyto programu TEMA Motion. Określono przebiegi zmienności wielkości kinematycznych charakteryzujących ruch wybranych punktów wyrzutni. Analiza wyników wykazała, że wyrzutnia ulega przemieszczeniu liniowemu (X, Y) oraz kątowemu (α), które prowadzą do istotnych różnic w trajektorii lotu wystrzeliwanych po sobie pocisków rakietowych.

Słowa kluczowe: mechanika, kinematyka ruchu, analiza obrazu, rejestracja startu pocisku rakietowego, wyrzutnia rakiet