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Experimental Study of Automatic Weapon Vibrations when Burst Firing

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Abstract. The article presents a new approach to finding the dynamic characteristics of automatic weapons, mainly in case of burst firing. The experiments were tested out on a 30 mm AGS-17 grenade launcher mounted on a tripod in the event of a shot. The obtained results are the basis for evaluating the firing stability of an automatic weapon when burst firing, which allows modernising the existing weapons and evaluating similar weapon systems. Furthermore, the outputs can be used to validate a dynamic model of an automatic weapon system mounted on the tripod. The procedure can be used as an example of practical technique and methodology for other weapon systems.
Keywords: vibration, weapon system, burst firing, firing stability, tripod

1. INTRODUCTION

For each automatic weapon, determination of the dynamics is an essential task. The dynamics must be considered to evaluate the firing stability as well as the firing efficiency of the weapon. Currently, there are three ways of determining weapon system's vibrations. One of them is a pure calculation method of the movement of the main parts using mathematical models [1]. The second technique is a pure experimental investigation of oscillations of the weapon system. The last technique is a combination of both previous techniques while adding all of the forces and torques acting on the weapon system. Among them, experimental research plays an important role in calculating new designs, manufacturing, and improving current weapon models. The experimental data accurately reflect the properties of the object and can be considered as a standard to evaluate the accuracy of theoretical computational models. Nowadays, to measure the dynamic parameters of an automatic weapon on the mount, the following two main methods were often selected:

1.1. Use of optical laser gauges or displacement transducers

For this method, to measure basic kinematic parameters of a weapon, we need to:

- examine the actual structure of the weapon to be measured,
- determine the positions that need to be measured on the weapon,
- design the special frame system where the gauges are fixed and the weapon can move, as it is shown in Fig. 1, see [2].

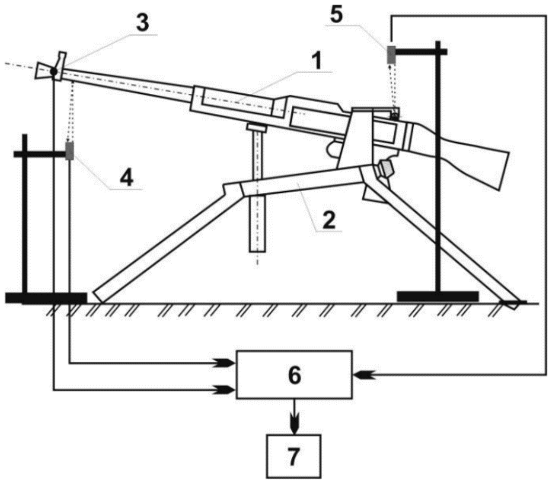


Fig. 1. Weapon and laser gauges [2]: 1 – weapon; 2 – tripod; 3 – strain gauge; 4, 5 – laser gauges, 6 – measuring system DEWE; 7 – computer.

For optical laser gauges, it is necessary to create reflective surfaces suitable for reflecting the high-frequency light pulses produced by the gauges when performing measurements.

The main advantage of this method is its simplicity with low preparation requirements. Furthermore, it is relatively inexpensive compared to using a high-speed camera. However, due to that, the number of scanned points per measuring object is proportional to the number of gauges, more gauges and more scanned points are required to obtain more accurate results. Besides, using a cable to connect the gauges and the amplifier in the device causes unforeseeable changes of electrical characteristics when they must be longer in length for protection and security of the measuring team.

1.2. Use of a high-speed camera

This is a contactless optical method, that cannot affect the weapon during the experimental firing, and overcoming the limitations of the method using optical laser gauges or displacement transducers, see Fig. 2 and Fig. 3.

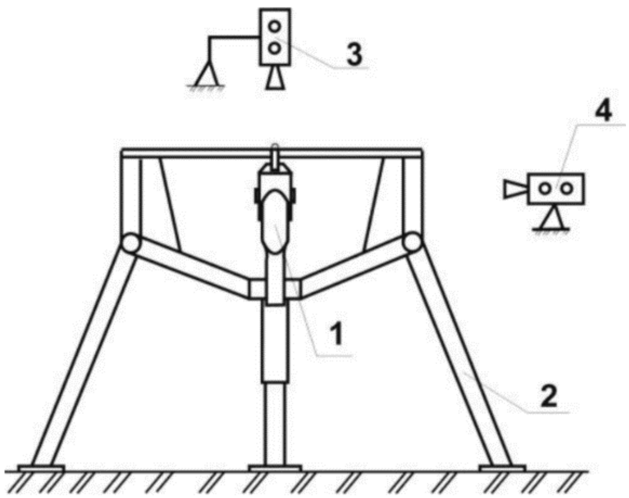


Fig.2. Weapon and cameras – rear view [2]:
1 – weapon; 2 – tripod; 3, 4 – high-speed cameras

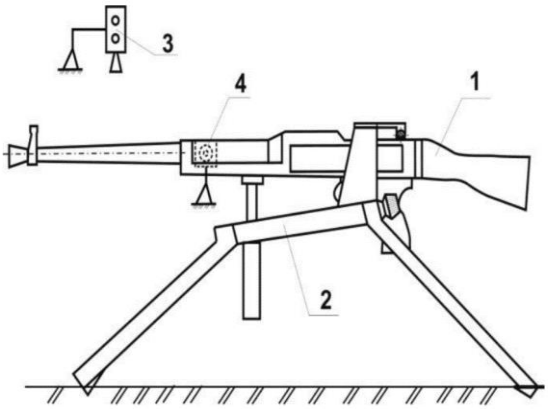


Fig.3. Weapon and cameras – side view [2]:
1 – weapon; 2 – tripod; 3, 4 – high-speed cameras

The most outstanding advantage of using a high-speed camera is that it is simple to use and quick to prepare. With this method, we can measure the displacement of any position on the weapon. The main disadvantage of this method is high cost of the high-speed camera.

2. SET UP OF A MEASUREMENT SYSTEM AND A METHOD FOR PROCESSING MEASUREMENT RESULTS

2.1. Set up of a measurement system

A measuring system is a set of devices that have the ability to connect, receive, and convert signals of physical quantities of the measured object. The measuring system used in this experiment includes: the measuring system DEWETRON 3000; displacement transducers DHT – A -100; high-speed camera system FASTCAM SA1.1 model 675K - C1; and the computer with data acquisition software. The arrangement of the technical experiment is shown in Fig. 4.

Figure 4 shows positions of gauges and the high-speed camera used for identification of the main parameters of the weapon system. The following indicators were measured on the weapon system:

- the linear displacement of the weapon along the X-axis,
- the linear displacement of the gun barrel in the horizontal plane (OXY),
- the linear displacement of the gun barrel in the vertical plane (OXZ).

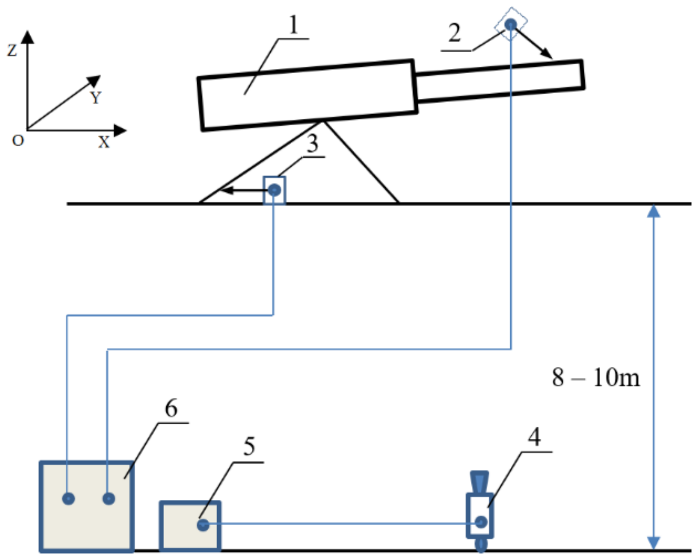


Fig. 4. Arrangement of technical experiment: 1 – weapon; 2, 3 – displacement transducers; 4 – high-speed camera; 5 – computer with data acquisition software; 6 – measuring system DEWETRON 3000.

The experiment consisted of three independent but simultaneous experimental measurements. The linear displacement of the weapon along the X-axis and the horizontal movement of the gun barrel was determined using the displacement transducers DHT – A -100. The vertical displacement of the gun barrel was determined using the high-speed camera system FASTCAM SA1.1 model 675K - C1.

- **Measuring system DEWETRON 3000**

The measuring system DEWETRON 3000 is an industrial computer combined with a set of measuring channels, produced by the Republic of Austria. This device allows us to receive and to convert analogue signals into digital ones. The basic parameters of the measuring system DEWETRON 3000 are shown in Table 1.

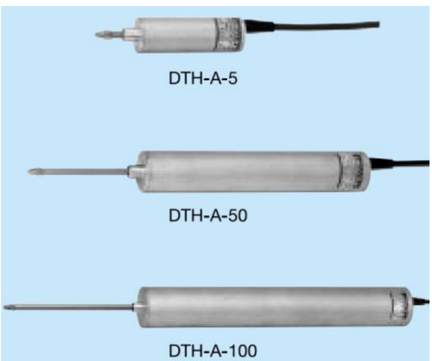
Table 1. Basic parameters of the measuring system DEWETRON 3000

DEWETRON 3000	Description
	- Power supply, wide input range: (85÷265 VAC, 40÷400 Hz).
	- Operating temperature: 0 to 50°C.
	- DC Volts Range: 100 mV.
	- Frequency: 7÷92 Hz.
	- Weight: 5.5 kg.
	- Conversion card A/D (AT-MIO-16E-10): + No. of channels: 16. + Maximum sampling rate: 50 kHz.

- **Displacement Transducers DHT – A -100**

The DTH-A series displacement transducers adopt a strain gauge for the sensing element to ensure a long-term, stable measurement. They can be widely used for the measurement of a structural relative displacement or an absolute displacement from a steady point. The DTH-A is a high accuracy, compact, and lightweight displacement transducer. The basic parameters of the DTH-A are shown in Table 2.

Table 2. Basic parameters of displacement transducers

Displacement transducers	Description
	- Nonlinearity: within ±0.1% RO
	- Rated output: 5 mV/V (10000 μm/m) ±0.1%
	- Measuring force: Approx. 1.5 to 4 N
	- Safe temperature range: -10÷70°C (noncondensing)
	- Safe excitation voltage: 6 VAC or DC
	- Frequency response range: DC to approx. 2 Hz
	- Rated capacity: 5 to 100 mm
	- Power supply: 10÷30 (57) V (W)

- **The high-speed camera system FASTCAM SA1.1 model 675K - C1**

The basic system's components, when using a FASTCAM series high-speed camera, are shown in Fig. 5.

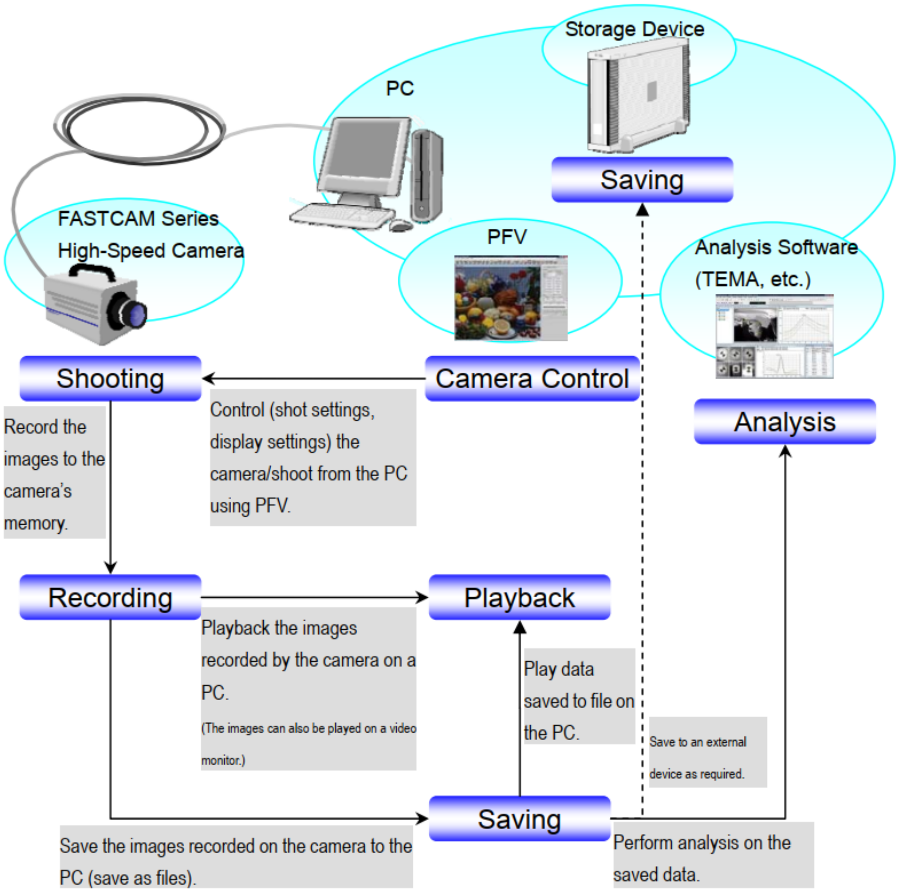


Fig. 5. Structure diagram of the system Camera FASTCAM SA1.1

The camera system consists of one high-speed camera Fastcam SA1.1 with basic parameters shown in Table 3; a computer SONY VAIO used to install software PFV and store information; a lighting system; cable connection and tripods. PFV is the software used to control the Photron FASTCAM series high-speed cameras from the PC. Operations such as setting camera options, shooting, and saving recorded data to the PC can be accomplished with PFV. The TEMA software was applied on the SONY VAIO computer to process the recordings as well as to collect the required data.

From the experience, the estimated maximum frequency of the mechanical system was set at 300 Hz and so, a 50 000 Hz sampling frequency was sufficient for signal digitalisation. Before digitalisation, the signals were filtered by low-frequency filters with a low-pass filter at 120 Hz. For high-speed cameras, with the reference to assumed weapon movement velocity, weapon dimension, and required image quality, the recording frequency was chosen as 5400 frames per second, which made it possible to obtain the record with the resolution of 1024x1024 pixels.

The weapon is mounted on the tripod with a special frame, where the fixed parts of the gauges are mounted, and the weapon can move inside the frame. The gauges are used to determine the horizontal movement of the barrel and the linear displacement of the weapon along the X-axis. The two signals are processed by the DEWETRON 3000 measuring system and fed to a computer.

Table 3. The basic parameters of the high-speed Fastcam SA1.1 cameras

Cameras Fast-cam SA1.1	**Description**
	The maximum frame rate 675000 frames per second.
	Data memory: 8 GB equivalent to 5457 frame 64x16 pixels or 5400 frame 1024x1024 pixels.
	Sensor: 12 bit DAC.

The high-speed camera was placed on a horizontal plane, perpendicular to the firing plane of the weapon, to determine the vertical displacement of the barrel, see [3]. These devices are connected to the computer. Some experimental pictures of the AGS-17 grenade launcher at the shooting range are in Fig. 6 and Fig. 7.

Experimental conditions: temperature 25°C÷31°C and humidity 75%. The shooter selected for the experiment has a height of 1.65 m and a weight of 66 kg; The experiment was performed with 5 identical measurements. For each measurement, we fired at bursts of three rounds with the elevation and azimuth angle of the gun of zero degrees.

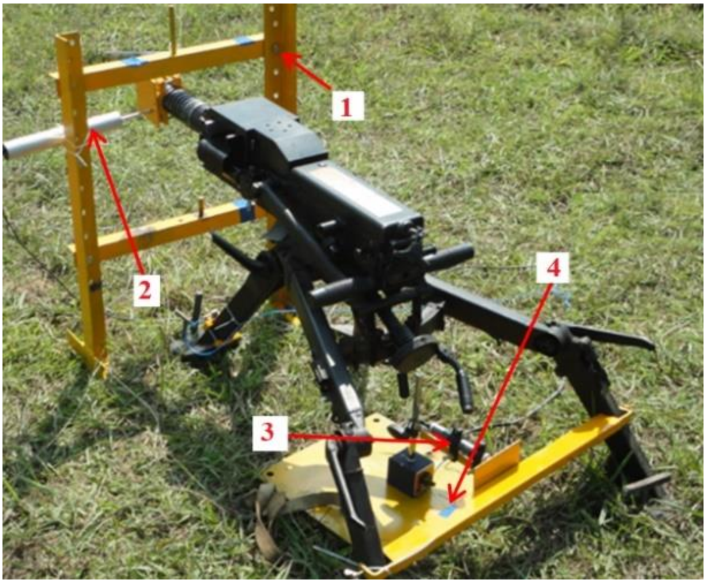


Fig. 6. Experimental way of stability investigation: 1 – special frame system; 2, 3 – displacement transducers DTH-A-100; 4 – measuring mount.

Fig. 7. Deployment of an experiment

When the measurements are finished, the data files, received from the measuring devices, are represented as a displacement of the weapon with respect to time. The data file of the linear displacement of the gun barrel in the vertical plane was taken from the computer which was connected to the high-speed camera. The data file of the linear displacement of the gun barrel in the horizontal plane and the linear displacement of the weapon along the X-axis were taken from the computer which was connected to the measuring system DEWETRON 3000. The output signals were filtered and converted into a digital form using an analogue-to-digital converter for computer processing.

The measured results after 5 measurements are shown in Fig. 8 to Fig. 13. The graphs in Fig. 8 - Fig. 12 show the gun barrel's displacement in the vertical and horizontal plane after each measurement. The graph in Fig. 13 shows the linear displacement of the gun after five measurements. The measurement results show that the gun was moved from its original position after each shot. This makes the gun unstable, reducing the firing accuracy.

The first measurement:

(a)

(b)

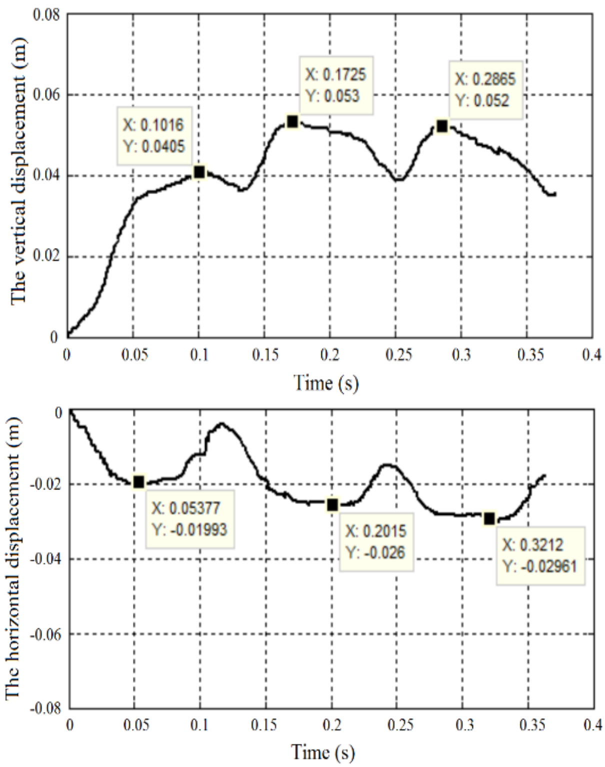
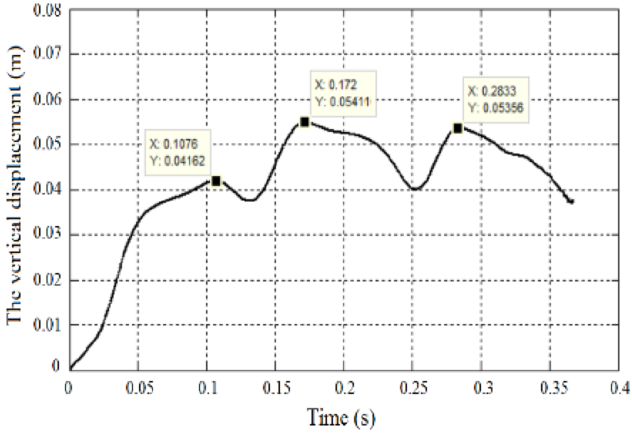


Fig. 8. The gun barrel's displacement in the vertical (a) and horizontal plane (b)

(a)



(b)

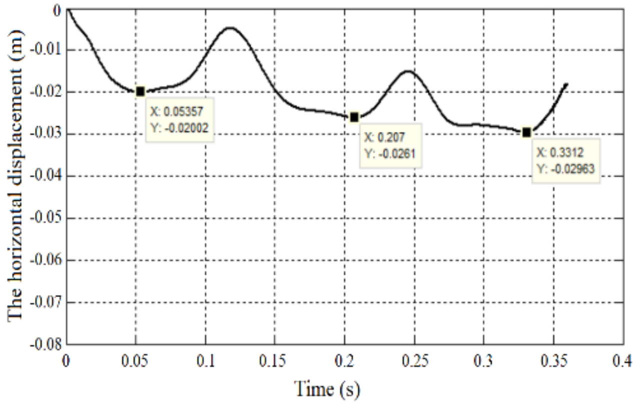


Fig. 9. The gun barrel's displacement in the vertical (a) and horizontal plane (b)

The third measurement:

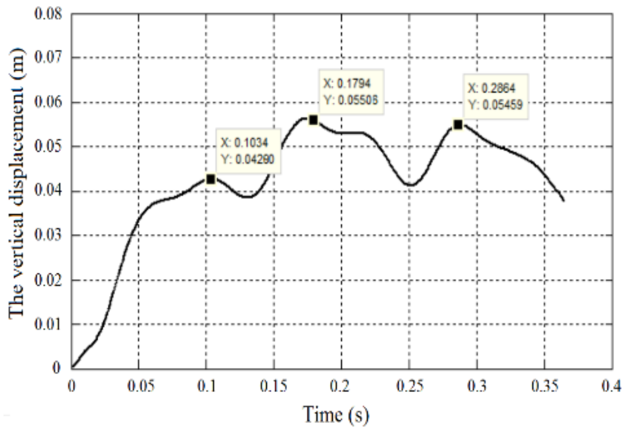


Fig. 10a. The gun barrel's displacement in the vertical plane

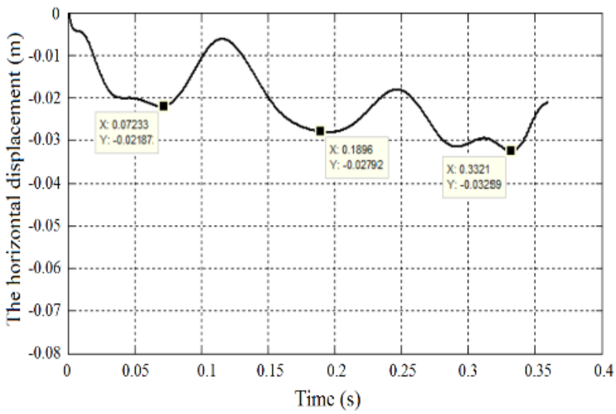


Fig. 10b. The gun barrel's displacement in the horizontal plane

The fourth measurement:

(a)

(b)

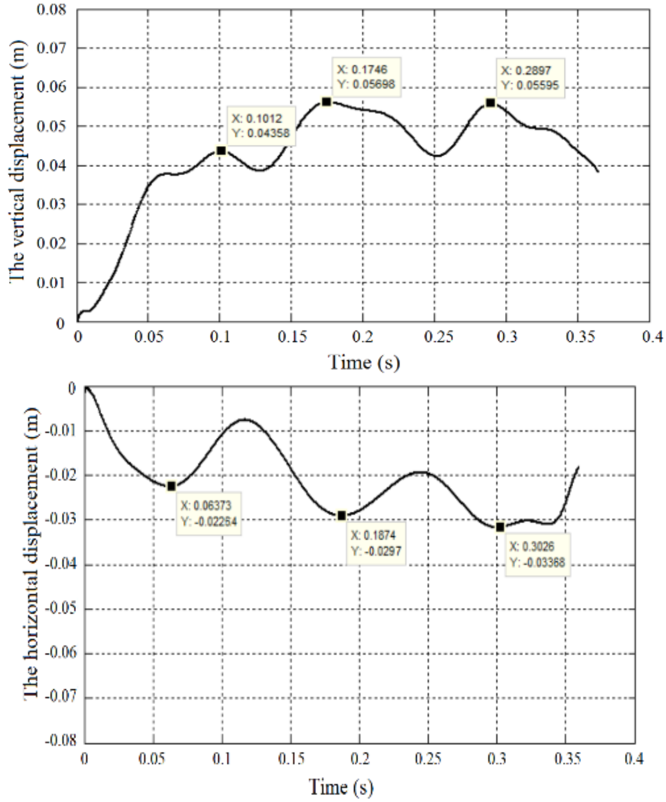


Fig. 11. The gun barrel's displacement in the vertical (a) and horizontal plane (b)

The fifth measurement:

(a)

(b)

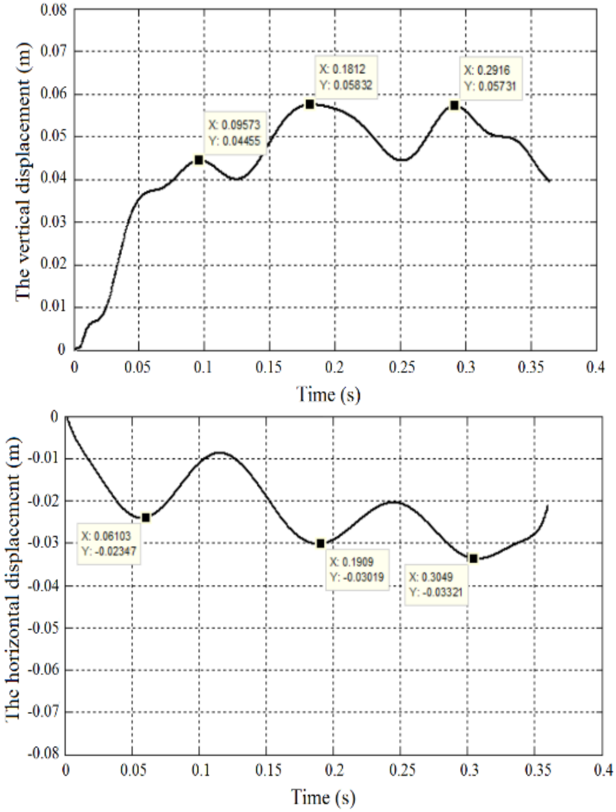


Fig. 12. The gun barrel's displacement in the vertical (a) and horizontal plane (b)

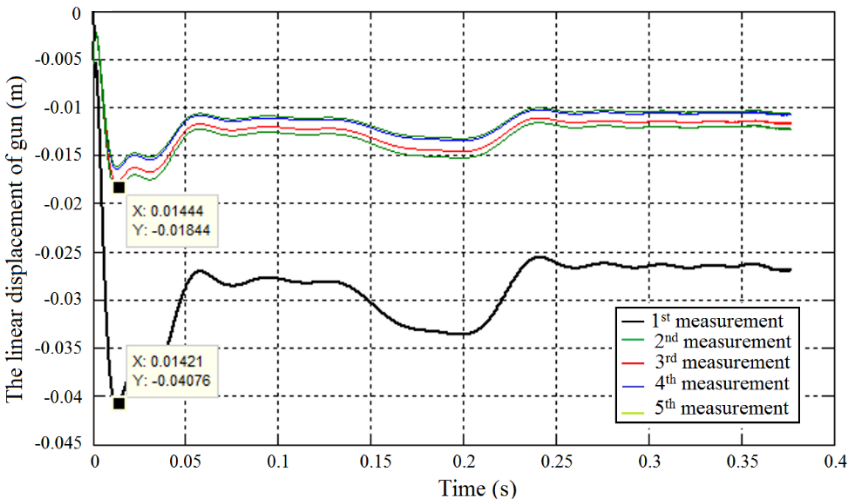


Fig. 13. The linear displacement of the weapon along the X-axis

2.2. Determination of the bounce angle of the weapon for each measurement

After determining the displacement of the gun barrel compared to the initial position, we proceed to determine the bounce angle of the gun according to the formula:

$$\alpha_z = arctg\frac{z_n}{l}, \qquad \alpha_y = arctg\frac{y_n}{l} \qquad (1)$$

where z_n and y_n are displacements of the muzzle of the barrel in the vertical and horizontal plane from the original position; $l = 0.838$ m is the length from the muzzle of the barrel to the position of the armrests; α_z is the change of the angle of elevation of the weapon in the vertical plane, and α_y is the change of the angle of traverse of the weapon in the horizontal plane.

After processing the experimental data, we have obtained the maximum bounce angle of the weapon in the vertical plane (Tab. 4), the maximum bounce angle of the weapon in the horizontal plane (Tab. 5) after each shot, and the maximum linear displacement of the weapon on the tripod over the terrain (Tab. 6) after five measurements.

Table 4. The maximum bounce angle of the gun in the vertical plane

	The 1st shot	The 2nd shot	The 3rd shot
First measurement	$4.83\cdot10^{-2}$ rad	$6.32\cdot10^{-2}$ rad	$6.20\cdot10^{-2}$ rad
Second measurement	$4.96\cdot10^{-2}$ rad	$6.45\cdot10^{-2}$ rad	$6.36\cdot10^{-2}$ rad
Third measurement	$5.11\cdot10^{-2}$ rad	$6.55\cdot10^{-2}$ rad	$6.51\cdot10^{-2}$ rad
Fourth measurement	$5.20\cdot10^{-2}$ rad	$6.91\cdot10^{-2}$ rad	$6.67\cdot10^{-2}$ rad
Fifth measurement	$5.32\cdot10^{-2}$ rad	$6.95\cdot10^{-2}$ rad	$6.83\cdot10^{-2}$ rad

Table 5. The maximum bounce angle of the gun in the horizontal plane

	The 1st shot	The 2nd shot	The 3rd shot
First measurement	$-2.37\cdot10^{-2}$ rad	$-3.10\cdot10^{-2}$ rad	$-3.53\cdot10^{-2}$ rad
Second measurement	$-2.47\cdot10^{-2}$ rad	$-3.27\cdot10^{-2}$ rad	$-3.72\cdot10^{-2}$ rad
Third measurement	$-2.61\cdot10^{-2}$ rad	$-3.33\cdot10^{-2}$ rad	$-3.92\cdot10^{-2}$ rad
Fourth measurement	$-2.70\cdot10^{-2}$ rad	$-3.58\cdot10^{-2}$ rad	$-4.03\cdot10^{-2}$ rad
Fifth measurement	$-2.80\cdot10^{-2}$ rad	$-3.61\cdot10^{-2}$ rad	$-4.19\cdot10^{-2}$ rad

Table 6. The maximum linear displacement of the weapon along the X-axis

First measurement	$-4.076 \cdot 10^{-2}$ m
Second measurement	$-1.84 \cdot 10^{-2}$ m
Third measurement	$-1.76 \cdot 10^{-2}$ m
Fourth measurement	$-1.72 \cdot 10^{-2}$ m
Fifth measurement	$-1.70 \cdot 10^{-2}$ m

Because during the first shot, the terrain was still not tight, the linear displacement of the weapon was large.

2.3. Method of processing measurement results

When calculating random errors, we use their numerical properties, that are the expected mean value and the sample standard deviation. These statistical features are sufficient to evaluate the error of the measurement results. To accurately define these statistical features, we need a large number of measurements ($n > 30$). However, the number of measurements is limited ($n < 30$). Therefore, the quantities to be measured belong to the Student's distribution, including the sample mean ($\bar{X}$) and the sample standard deviation (S_x). They are determined by the following formulas, see [4]:

$$\bar{X} = \left(x_1 + x_2 + x_3 + \ldots + x_i + x_n\right) / n = \sum_{i=1}^{n} \frac{x_i}{n}. \tag{2}$$

$$S_x = \sqrt{\frac{\sum_{i=1}^{n}\left(x_i - \bar{X}\right)^2}{(n-1)}}. \tag{3}$$

where x_i is the sample data set and n is the sample size.

For P confidence, we can estimate the confidence interval using the following formula:

$$\bar{X} - t_{\alpha/2}^{(n-1)} \cdot \frac{S_x}{\sqrt{n}} < X_0 < \bar{X} + t_{\alpha/2}^{(n-1)} \cdot \frac{S_x}{\sqrt{n}}. \tag{4}$$

where $t_{\alpha/2}^{(n-1)}$ is the Student's distribution coefficient, it depends on the given probability P and the number of measurements n, and it is determined according to the lookup table, [5].

Equation (4) can be abbreviated as follows:

$$\left(\bar{X}-\Delta\right)<X_o<\left(\bar{X}+\Delta\right). \quad (5)$$

where $\Delta = t_{\alpha/2}^{(n-1)} \cdot \frac{S}{\sqrt{n}}$ is the accuracy of the estimate.

In addition, we can also determine the relative error of measurement:

$$\varepsilon\% = \frac{x_i - \bar{X}}{\bar{X}} \cdot 100. \quad (6)$$

The above error's assessment method has been applied to evaluate the error of the vertical bounce angle, horizontal bounce angle, and backward displacement of the gun when testing for each shot. The results are shown in Tab. 7 to Tab. 13.

Table 7. Result of calculating the error of the vertical bounce angle (the first shot)

Ordinal number	x_i [rad]	$\bar{X}$ [rad]	$(x_i - \bar{X})$ [rad]	S [rad]	Δ [rad]	ε (%)
1	$4.83\cdot10^{-2}$	$5.08\cdot10^{-2}$	$-2.5\cdot10^{-3}$	$1.94\cdot10^{-3}$	$2.41\cdot10^{-3}$	-4.92
2	$4.96\cdot10^{-2}$		$-1.2\cdot10^{-3}$			-2.36
3	$5.11\cdot10^{-2}$		$3.0\cdot10^{-4}$			0.591
4	$5.20\cdot10^{-2}$		$1.2\cdot10^{-3}$			2.36
5	$5.32\cdot10^{-2}$		$2.4\cdot10^{-3}$			4.72
The confidence interval to look for is 0.0508 $\pm$0.00241 rad						

Table 8. Result of calculating the error of the vertical bounce angle (the second shot)

Ordinal number	x_i [rad]	$\bar{X}$ [rad]	$(x_i - \bar{X})$ [rad]	S [rad]	Δ [rad]	ε (%)
1	$6.32\cdot10^{-2}$	$6.64\cdot10^{-2}$	$-3.2\cdot10^{-3}$	$2.81\cdot10^{-3}$	$3.49\cdot10^{-3}$	-4.82
2	$6.45\cdot10^{-2}$		$-1.9\cdot10^{-3}$			-2.86
3	$6.55\cdot10^{-2}$		$-9.0\cdot10^{-4}$			-1.36
4	$6.91\cdot10^{-2}$		$2.7\cdot10^{-3}$			4.07
5	$6.95\cdot10^{-2}$		$3.1\cdot10^{-3}$			4.67
The confidence interval to look for is 0.0664 $\pm$0.00349 rad						

Table 9. Result of calculating the error of the vertical bounce angle (the third shot)

Ordinal number	x_i [rad]	$\bar{X}$ [rad]	$(x_i - \bar{X})$ [rad]	S [rad]	Δ [rad]	ε (%)
1	$6.20 \cdot 10^{-2}$	$6.51 \cdot 10^{-2}$	$-3.1 \cdot 10^{-3}$	$2.48 \cdot 10^{-3}$	$3.09 \cdot 10^{-3}$	-4.76
2	$6.36 \cdot 10^{-2}$		$-1.5 \cdot 10^{-3}$			-2.30
3	$6.51 \cdot 10^{-2}$		0.0			0.00
4	$6.67 \cdot 10^{-2}$		$1.6 \cdot 10^{-3}$			2.46
5	$6.83 \cdot 10^{-2}$		$3.2 \cdot 10^{-3}$			4.92
The confidence interval to look for is 0.0651 $\pm$0.00309 rad						

Table 10. Result of calculating the error of the horizontal bounce angle (the first shot)

Ordinal number	x_i [rad]	$\bar{X}$ [rad]	$(x_i - \bar{X})$ [rad]	S [rad]	Δ [rad]	ε (%)
1	$-2.37 \cdot 10^{-2}$	$-2.59 \cdot 10^{-2}$	$2.2 \cdot 10^{-3}$	$1.73 \cdot 10^{-3}$	$2.15 \cdot 10^{-3}$	-8.49
2	$-2.47 \cdot 10^{-2}$		$1.2 \cdot 10^{-3}$			-4.63
3	$-2.61 \cdot 10^{-2}$		$-2.0 \cdot 10^{-4}$			0.772
4	$-2.70 \cdot 10^{-2}$		$-1.1 \cdot 10^{-3}$			4.25
5	$-2.80 \cdot 10^{-2}$		$-2.1 \cdot 10^{-3}$			8.11
The confidence interval to look for is -0.0259 $\pm$0.00215 rad						

Table 11. Result of calculating the error of the horizontal bounce angle (the second shot)

Ordinal number	x_i [rad]	$\bar{X}$ [rad]	$(x_i - \bar{X})$ [rad]	S [rad]	Δ [rad]	ε (%)
1	$-3.10 \cdot 10^{-2}$	$-3.38 \cdot 10^{-2}$	$2.8 \cdot 10^{-3}$	$2.16 \cdot 10^{-3}$	$2.68 \cdot 10^{-3}$	-8.28
2	$-3.27 \cdot 10^{-2}$		$1.1 \cdot 10^{-3}$			-3.25
3	$-3.33 \cdot 10^{-2}$		$5.0 \cdot 10^{-4}$			-1.48
4	$-3.58 \cdot 10^{-2}$		$-2.0 \cdot 10^{-3}$			5.92
5	$-3.61 \cdot 10^{-2}$		$-2.3 \cdot 10^{-3}$			6.80
The confidence interval to look for is -0.0338 $\pm$0.00268 rad						

Table 12. Result of calculating the error of the horizontal bounce angle (the third shot)

Ordinal number	x_i [rad]	$\bar{X}$ [rad]	$(x_i - \bar{X})$ [rad]	S [rad]	Δ [rad]	ε (%)
1	$-3.53 \cdot 10^{-2}$	$-3.88 \cdot 10^{-2}$	$3.5 \cdot 10^{-3}$	$2.59 \cdot 10^{-3}$	$3.22 \cdot 10^{-3}$	-9.02
2	$-3.72 \cdot 10^{-2}$		$1.6 \cdot 10^{-3}$			-4.12
3	$-3.92 \cdot 10^{-2}$		$-4.0 \cdot 10^{-4}$			1.03
4	$-4.03 \cdot 10^{-2}$		$-1.5 \cdot 10^{-3}$			3.87
5	$-4.19 \cdot 10^{-2}$		$-3.1 \cdot 10^{-3}$			7.99
The confidence interval to look for is -0.0388 ± 0.00322 rad						

Table 13. Result of calculating the error of the backward displacement of the gun

Ordinal number	x_i [m]	$\bar{X}$ [m]	$(x_i - \bar{X})$ [m]	S [m]	Δ [m]	ε (%)
2	$-1.84 \cdot 10^{-2}$	$-1.755 \cdot 10^{-2}$	$-8.50 \cdot 10^{-4}$	$6.19 \cdot 10^{-4}$	$7.27 \cdot 10^{-4}$	4.84
3	$-1.76 \cdot 10^{-2}$		$-5.00 \cdot 10^{-5}$			0.285
4	$-1.72 \cdot 10^{-2}$		$3.5 \cdot 10^{-4}$			-1.99
5	$-1.7 \cdot 10^{-2}$		$5.5 \cdot 10^{-4}$			-3.13
The confidence interval to look for is -0.01755 ± 0.000727 m						

The obtained results can be commented on as follows:

- The relative error ε% of the vertical bounce angle of the shots was in the range of 0% to 4.92% and the horizontal bounce angle of the shots was in the range from 0% to 9.02%. These errors are within acceptable limits (< 10%).
- When skipping the first measurement (due to the unstable ground when firing), the relative error ε% of the backward displacement of the weapon of the shots is in the range of 0% to 4.84%.
- An absolutely larger deviation in the traverse is due to the lateral location of the magazine with belt and rounds, which creates a larger arm of the acting forces due to the transverse displacement of the centre of gravity of the whole system.
- Some causes of experimental errors: Guns are not new, experimental guns are level 2 guns. Errors due to the measuring equipment and the measuring conditions, see [3], [6].

3. CONCLUSIONS

This experiment presents a method for determining some parameters for evaluating the firing stability of automatic weapons mounted on tripods. The obtained test results confirm the accuracy of the measurement plans. The relative errors of the measurement plans do not exceed 10%. The equipment used in the tests are of high precision, dedicated, and suitable for the physical quantities of the measured object. The method of determining the kinetic parameters of weapons is reasonable, suitable for actual conditions, and it can be applied to similar automatic weapons mounted on tripods, always with a specific automation drive system. The results obtained can be used in design calculations, as well as input to determine gun firing accuracy and to optimise the overall structure of mounted automatic weapons.

Furthermore, the outputs can be used for validation of a dynamic model of an automatic weapon system mounted on the tripod and the procedure can be used as an example of a practical technique and methodology for other weapon systems.

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