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Measurement Analysis of Physical Quantities for Ballistic Tests using Different Sensors

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Measurements of recoil and counter-recoil movement in weapons are essential in order to optimize ballistic performances, to ensure safety during firing, to improve the accuracy and the effectiveness of the weapon during its life cycle and to guide design and development work. From this, the present work focuses on contact-based measurements of the counter-recoil movement of the D30J 122 mm howitzer using two inductive sensors, namely, displacement sensor and acceleration sensor. The measurements from the displacement sensor were used to calculate the velocity and acceleration of the counter-recoil by derivation and those of the acceleration sensors were used to calculate the velocity and displacement of the counter-recoil by integration. The comparison between the measured and calculated results obtained from the two sensors shows a very good similarity in form of variation and in values, which validates the applied experimental approach in this work and confirms the accuracy of both measurement methods

Key words: **Howitzer, counter-recoil measurement, inductive sensors, measurement uncertainty.**

Introduction

IN order to ensure the safety and effectiveness of artillery fire, the physical quantities characterizing the movement of the recoil mass of artillery weapons must be analyzed in the design phases and in the exploitation phase of these weapons. Artillery weapons are considered stable if the main support of the carriage or mounting remains stationary during both recoil and counter-recoil. Excessive movement while firing will affect the accuracy of the weapon, and will require it to be repositioned or rested, which in turn also affects rate of fire on the battlefield. Experimental measurements of displacement, velocity and acceleration of recoil and counter-recoil are indispensable in the design and development phase of artillery weapons or in the control of the operational level of weapons that are in service. There are mainly two types of measurement methods which are: (I) contact-based methods and (II) non-contact-based methods, which are based on an optical instrument. In contrast to contact-based methods, measurements in this research are completed by different types of sensors placed in contact with different parts of the weapon.

Tiwari et al. [1] modelled a rigid body dynamic of a howitzer with experimental characterization and performance analysis in which acceleration of the counter-recoiling barrel was measured using the accelerometer B&K 4517, with sensitivity of 10 mV/g and data acquisition was done using 24-bit resolution NI 9234 DAQ card, with voltage range of -5 V to +5 V. These acceleration data of the counter-recoiling barrel were integrated over time to get velocity and displacement. Jia et al. [2] analyzed the recoil movement characteristics of artillery firing based on Symlet Wavelet Filtering technique whose recoil acceleration was measured by piezoelectric acceleration sensor YD-PC. Sampling frequency was 5 kHz and then the recoil velocity and the recoil displacement were calculated by integrating in time the acceleration signal, filtered by the above-mentioned technique. Alam et al. [3] presented a non-contact method for measuring the recoil displacement and recoil velocity of an artillery gun, in which a Photron FASTCAM SA5 high-speed video camera (HSV) is used for data acquisition and MATLAB is used as the tool image processing to analyze the acquired data. The firing event and high-speed camera were synchronized using a muzzle flash detector (FD). The camera frame rate was set at 1000 frame per second. Li et al. [4] studied a failure mechanism of the recoil device of the 125 mm tank gun based on technical test platform, for this a steel wire tachometer was used for the measurement of the displacement and velocity in the process of recoil. A three-axis accelerometer was used for the measurement of the recoil acceleration. Bin Hussain et al. [5] performed a characterization of a gun recoil resistance model of a 40 mm proof weapon for use in internal ballistic modelling in which two methods were used for the measurement of recoil parameters. The first is a non-contact method which consists of using a high-speed video camera (HSV) for the measurement of the recoil displacement and the recoil velocity. As for the second method, it is with contact and consists in using a piezo resistive accelerometer for the

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measurement of the recoil acceleration, then the calculation of recoil velocity through the integration of the signal of the measured acceleration. This recoil velocity calculated by integration was compared with that obtained by measurement using the high-speed video camera (HSV). Badurowicz et al. [6] realized numerical and experimental investigation of a short-recoil-operated weapon and impact of construction characteristics on its operation cycle. A non-contact measurement method was used based on the use of the triangulation laser displacement sensor (Micro-Epsilon opto NCDT 2300-200) which has a maximum frequency of 49.14 kHz and a resolution of 3 µm. Lonzi et al. [7] developed an experimental setup to determine the impulsive force exerted on the shoulder of the shooter during the firing action. For the recoil force measurement, they used a PCB Piezotronics 208C05 piezoelectric load cell and a PCB Piezotronics 350C02 accelerometer.

The aim of this work is to improve the monitoring of artillery weapon assemblies during exploitation. In practice, only the length of the recoil is monitored, while the recoil and counter-recoil velocities give us indications about the way that the recoil device works. On the basis of the counter-recoil velocity elements, it is possible to identify potential sealing elements problems (state of sealing rings, quantity and viscosity of hydraulic oils, etc.), which, if not repaired, can cause bigger damage. For that, contact-based measurements of the counter-recoil movement of the howitzer 122 mm D30J were carried out through the use of two inductive sensors, namely (I) displacement measurement sensor HBM WA300 and (II) acceleration measurement sensor HBM B12. The first sensor measurements were used to calculate the velocity and acceleration of the counter-recoil through a derivation approach. Additionally, the displacement and velocity of the counter-recoil were calculated from the second sensor measurements using an integration approach. Following this, the results obtained from the two sensors were analyzed and compared with each other and at the end the two types of uncertainties A, B and *combined uncertainty* were determined for the maximum counter-recoil velocity.

Howitzer stability during the counter-recoil movement

When firing a projectile and during both phases, recoil and counter-recoil, the howitzer must be stably supported in all support points without moving in the horizontal and vertical plane of fire and ensure the continuity of the firing sight. In wheeled towed artillery weapons, the horizontal components of the braking force are supported by a trail (point C, Fig. 1). In order to consider the stability conditions during the counter-recoil, the starting hypotheses are: the howitzer parts and the ground are absolutely rigid, the weapon fires from a horizontal surface and with a barrel elevation $\varphi > 0$, the trail (point C) does not allow the weapon to recoil and all the forces act in the plane of symmetry of the weapon. The forces on the howitzer and the geometric quantities of Fig. 1 mean:

- The forces: $\vec{I_v}$ the counter-recoil inertial force, $\vec{Q_b}$ the howitzer's weight in the combat position when firing, $\vec{N_A}$, $\vec{N_C}$, $\overrightarrow{T_A}$ and $\overrightarrow{T_C}$ reaction forces of howitzer at points A and C.
- The geometric quantities: G the center of mass of the howitzer, O the center of mass of the recoil parts, D the distance from center of mass of the howitzer to point C (variable), L the normal distance between points A and C (carriage length), h the normal distance between point A and the longitudinal axis of inertia of the mass of the recoil parts and φ the barrel elevation angle.

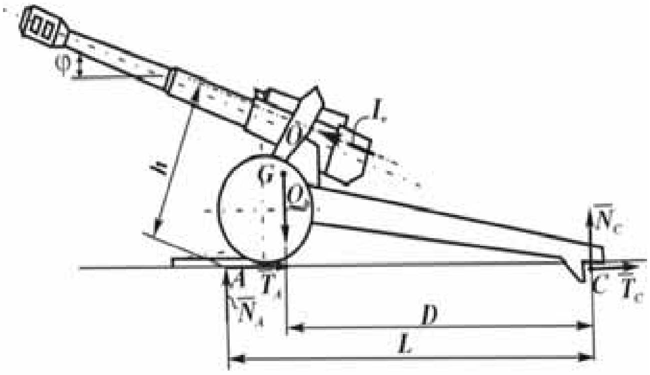

Figure 1. Forces on the howitzer during movement of the counter-recoil [8]

When moving the recoil parts to their original position, the movement of the howitzer on the ground is prevented by the friction forces between the carriage and the ground. The return of the recoil parts is carried out by the energy accumulated at the counter-recoil mechanism at the end of the recoil, that is, the force of the counter-recoil [8]. The force of inertia, according to the equation of motion of the counter-recoil, is:

$$\overrightarrow{I_v} = m_t \frac{d\vec{u}}{dt} = \overrightarrow{F_v} \tag{1}$$

Where: u – the counter-recoil velocity, m_t – the mass of the recoil parts and F_v – the resultant force on the recoil parts during counter-recoil.

From the conditions of balance of forces and moments around point A (Fig.1), the reaction forces of the ground on the carriage are as follows:

$$T_A + T_C = F_v \cdot \cos\varphi \tag{2}$$

$$N_A = Q_b - F_v \cdot \sin\varphi - N_C \tag{3}$$

$$N_C = \frac{Q_b\left(L-D\right) - h \cdot F_v}{L} \tag{4}$$

In practice, the resolution of this system of equations by analytical or numerical methods enables determining the physical quantities which define the counter-recoil movement, namely the force, the acceleration, the velocity and the displacement.

Depending on the form of the force change F_v, practically the counter-recoil motion can be performed in at least three steps or periods, shown in Fig.2 (the curve is read from right to left):

- When $F_v > 0$, the counter-recoil movement in the first period is of the accelerated type (increasing velocity);
- When $F_v = 0$, the counter-recoil movement in the second period is of the uniform type (constant velocity);
- When $F_v < 0$, the counter-recoil movement in the third period is of the decelerated type (decreasing velocity).

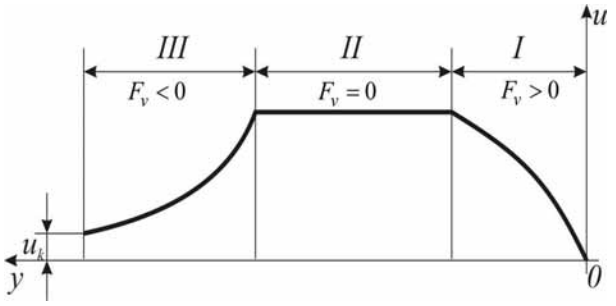

Figure 2. Velocity change of the counter-recoil [8]

The safe and reassured contact of the recoil parts at the end of the counter-return is ensured by a velocity $u_k \leq 0.2$ m/s, which is damped by hitting the rear part of the cradle.

Experiment

The experiment consists in carrying out an artificial recoil of the moving parts of the howitzer 122 mm D30J using a hydraulic device in order to measure the counter-recoil displacement and the counter-recoil acceleration in a synchronized manner. This was done by employing two inductive sensors (synchronized measurement). A measurement system has been set up, consisting of: howitzer 122 mm D30J, hydraulic device, displacement measurement sensor HBM WA300, acceleration measurement sensor HBM B12, data acquisition system HBM Quantum MX840B (8-channels) and computer software. A schematic diagram of the measurement system is shown in Fig.3 and the installation of the two sensors is shown in Fig.4.

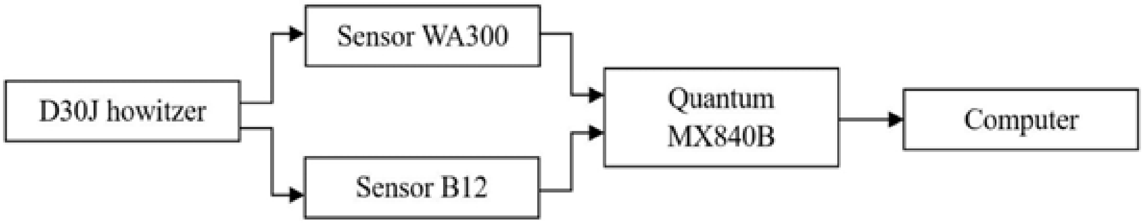

Figure 3. Schematic diagram of the measurement system

Figure 4. Installation of the two sensors (left sensor WA300, right sensor B12)

The measurement tests were carried out by moving the recoil mass of the 122 mm D30J howitzer by 280 mm in the direction of recoil, using the hydraulic artificial recoil device. The recoil mass was then allowed to self-return to its initial position under the action of gas pressure in the counter recoil mechanism, at which moment data recording began. The sampling rate in the two data acquisition channels was set for 50 Hz. For the defined measurement system, twelve (12) tests were completed.

The working of inductive sensors is based on the variation of the inductance of the coil according to the resistance variations of the electromagnetic circuit or of the electromagnetic inductance. Inductive sensors of the differential type with a moving core are most often used. Fig. 5 shows the characteristics of such a sensor in use.

The inductive displacement sensor HBM WA300 can measure displacements up to 300 mm. When the sensor is moved as far as possible from the neutral position, the sensor output signal is 80 mV/V with a linearity deviation less than or equal to ±0,2% including hysteresis [9]. As for the inductive acceleration sensor HBM B12, it is used to measure acceleration in the range of ±200 m/s^2 at a frequency of 100 Hz, as well as to measure acceleration in the range of ±1000 m/s^2 at a frequency of 250 Hz. In both cases, the output signal of the sensor is ±80 mV/V for the whole measurement range of the sensor with a linearity deviation less than or equal to ±2% including hysteresis [10].

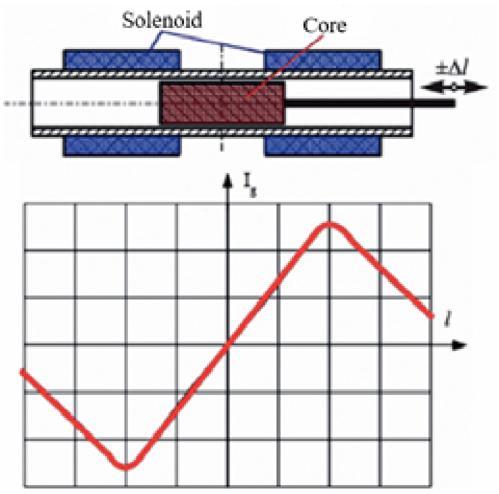

Figure 5. Differential type inductive sensor and its characteristics [11]

Although the characteristic of the sensor shown may be highly non-linear, these sensors are often used for measurement because they have a portion of the characteristic that is linear. Because of this linear region, moving core differential type inductive sensors can have high accuracy and sensitivity [11].

The data acquisition system HBM Quantum MX840B is a high-precision data acquisition system designed for use in various testing and measurement applications. It has eight (8) individually configurable measurement channels (electrically isolated). It has the ability to connect more than sixteen (16) transducer technologies per channel and its individual sampling rates can go up to 40 kS/s per channel, active low-pass filter. In each channel of the HBM Quantum MX840B there is a 24-bit A/D converter. Its linearity deviation is less than or equal to ±0,02 % [12].

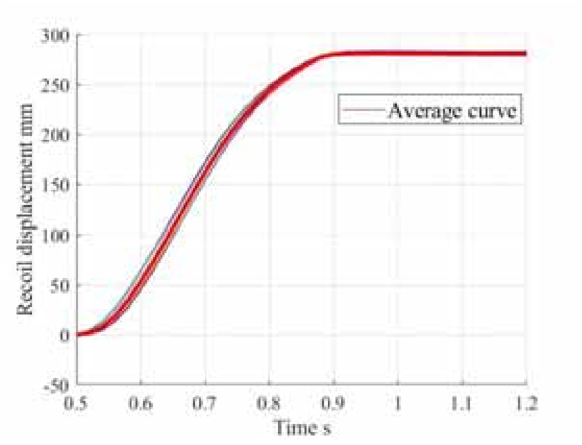

Figure 6. The average curve of counter-recoil displacement

The measured acceleration is integrated in time to get velocity and displacement as a function of time, then measured displacement is derivated in time to get velocity and acceleration as a function of time. In Fig.8 a comparison between the measured and the integrated counter-recoil displacement is shown.

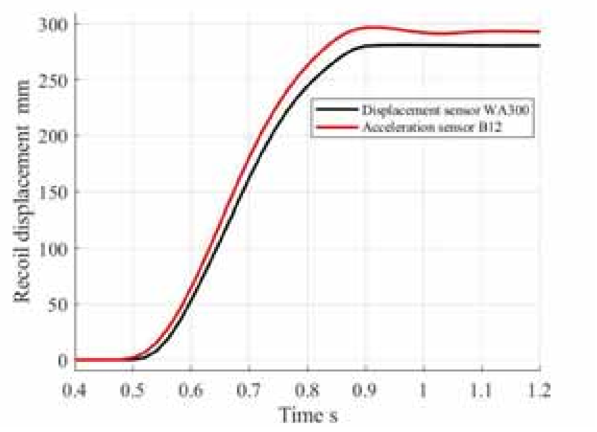

Figure 8. Counter-recoil displacement comparison

Fig.9 shows a comparison between the measured and the derivated counter-recoil acceleration.

Results and discussion

In this chapter, the experimental results are presented and discussed. Results obtained using the acceleration sensor B12 are compared with the results obtained using the displacement sensor WA300. Based on the results derived from 12 tests, it is possible to determine the average curve of counter-recoil displacement and the average curve of counter-recoil acceleration, shown in Fig.6 and Fig.7.

Fig.6 shows a counter-recoil time of about 0.42 s and a maximum counter-recoil displacement of approximately 280 mm which corresponds to the length at which the recoil mass was pulled at the start position of the tests. This movement is due to the counter-recoil device already loaded in the first phase of the recoil which returns the recoil mass to its initial position. The acceleration shows a peak of 11 m/s². The graphs show only the counter-recoil phase of the recoil movement.

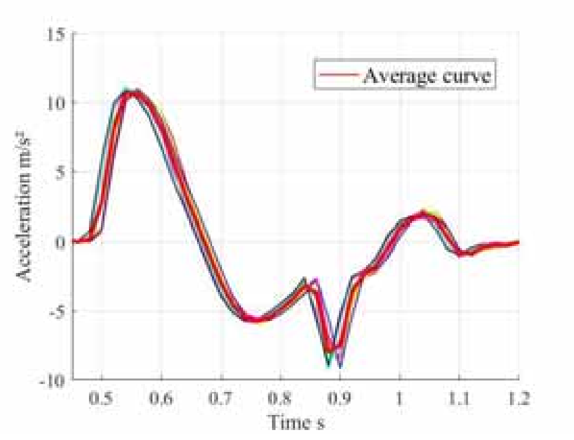

Figure 7. The average curve of counter-recoil acceleration

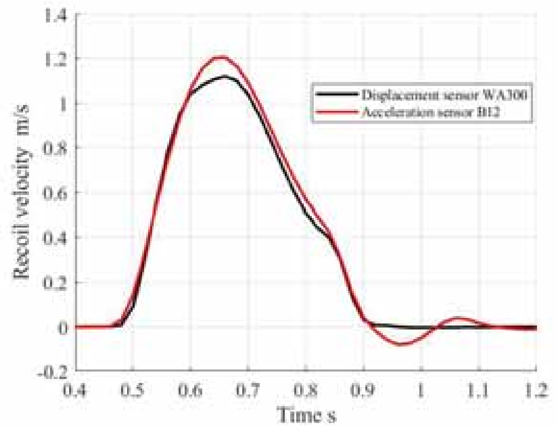

Figure 9. Counter-recoil acceleration comparison

Fig.10 shows a comparison between the counter-recoil velocity obtained by integration and that obtained by derivation.

It seems from the graphs in Fig.8 to Fig.10 that the results obtained by both inductive sensors are very close to each other. According to the curve in Fig.10 in the counter - recoil movement, there are two phases of velocity. In the first phase the velocity increases until the maximum value (1.12 m/s for displacement sensor, 1.2 m/s for acceleration sensor), then it decreases to zero.

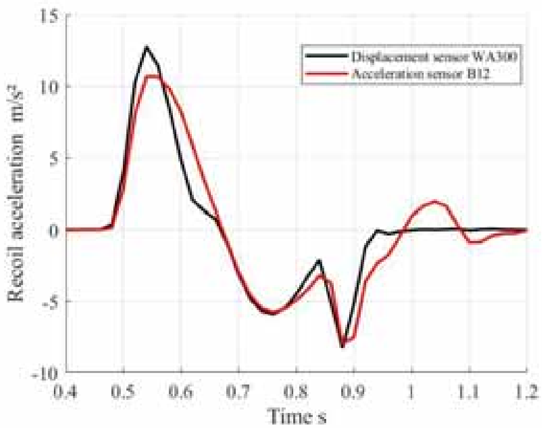

Figure 10. Counter-recoil velocity comparison

In the first phase when $F_v > 0$, the counter-recoil movement is accelerated. At the beginning of the counter-recoil movement, the stored force in the pneumatic system moves the recoiling parts forward which increases the counter-recoil velocity. In the second phase, since the restoring force is much less than the resistance force, then the counter-recoil movement is decelerated which decreases velocity.

The results in Table 1 show that the mean value (of all 12 tests) of the maximum counter-recoil velocity obtained using the displacement sensor and that obtained using acceleration sensor are almost equal. The uncertainties type A, type B and combined uncertainty of maximum counter-recoil velocity obtained using the displacement sensor are smaller than that using the acceleration sensor, thus the displacement sensor is more precise.

Table 1. Mean value and uncertainties of maximum counter-recoil velocity

	Displacement sensor	Acceleration sensor
Mean value of maximum counter-recoil velocity [m/s]	1.120	1.200
Uncertainty type A (u_A) [%]	±0.357	±0.667
Uncertainty type A (u_B) [%]	±0.215	±2
Combined uncertainty (u_c) [%]	±0.417	±2.108

Conclusion

In the field of firearms, particularly in artillery, recoil movement is an inevitable consequence when firing. The measurement of its characteristics can be done in several ways. In this paper, a contact-based measurement of howitzer counter-recoil movement characteristics was proposed based on the inductive sensors. The characteristics of the counter-recoil were determined using the above-mentioned experimental device set up. The results obtained by two different sensors are very close to each other in terms of variations and values.

The use of the WA300 inductive displacement sensor presents advantages such as: high speed measurement, high durability, real-time monitoring and a high precision. On the other side, it also has disadvantages such as: sensitivity to the environment (temperature, humidity and electromagnetic interference), it requires complex and careful assembly, low range recoil, it requires calibration and maintenance. To avoid these disadvantages, another sensor can be used. The draw wire position sensors present the same advantages as inductive displacement sensors in addition to other advantages such as: extended measuring range, insensitivity to the electromagnetic fields.

The use of the inductive acceleration sensor B12 presents the advantages such as: high sensitivity, high durability, fast-response time, insensitivity to contamination, compact and light weight, easy installation and long service life. However, it presents disadvantages such as: limited measurement range, sensitivity to magnetic fields, non-linearity at the extreme ends of measurement range. As an alternative for this sensor, piezoelectric accelerometers can be used, since this type of sensors presents less disadvantages such as: extended measurement range, higher frequency measurement and insensitivity to electromagnetic fields.

As a continuance to this paper or a perspective, the proposed experimental method can be used on a real howitzer firing at a firing range in order to measure the real characteristics of the recoil and the counter-recoil movement, namely: displacement, velocity and acceleration.

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Analiza merenja fizičkih veličina kod balističkih ispitivanja primenom različitih tipova senzora

Merenje parametara trzanja i vraćanja kod sistema oružja su od suštinskog značaja da bi se optimizovale balističke performanse, obezbedila stabilnost tokom opaljenja, povećala tačnost i preciznost oružja tokom njegovog životnog ciklusa i da bi se unapredio proces projektovanja i razvoja naoružanja. Na osnovu navedenog rad se fokusira na realna merenja procesa vraćanja trzajućih delova haubice 122 mm D30J pomoću dva induktivna senzora, odnosno senzora za merenje pomeranja i senzora za merenje ubrzanja. Merenja senzorom pomeranja su korišćena za izračunavanje brzine i ubrzanja vraćanja derivacijom, a merenja senzora ubrzanja su korišćena za izračunavanje brzine i pomeranja integracijom. Poređenje izmerenih i izračunatih rezultata dobijenih primenom ova dva senzora daje veoma dobro podudaranje po načinu promene i odstupanjima, što potvrđuje primenjen eksperimentalni pristup u ovom radu i tačnost obe metode merenja.

Ključne reči: **haubica, merenje parametara vraćanja, induktivni senzori, merna nesigurnost.**