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Kinematic analysis of small arms systems with the help of high-speed camera

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Abstract. This paper presents a method of recording and analyzing the nonlinear behavior of a vibrating weapon system, especially the barrel with the help of high-speed camera and specialized software. High-speed cameras use high-speed digital video files to extract motion and measure moving objects, gaining a qualitative and quantitative perspective of the experiment. The technique used allows us to visualize and analyze the movement, especially the movement that is too fast for the human eye or which is not perceived by ordinary cameras. The user can make measurements of synchronicity, positioning, distance, speed, angle, and angular velocity, and can track multiple points or objects to calculate and find the two-dimensional coordinates, speed or acceleration. Variation of the kinematic parameters of the weapon is determined by delimiting the regions of interest with markers and analyzing them with Photron Motion Tools. In semi-automatic and automatic firings, as a result of the remaining vibration, recoil and torque, the displacement of the barrel increases, the shooter having no control over the line of sight and the accuracy of the shooting decreases depending on their experience.

1. Introduction

The interaction of a moving mass (cartridge) with the interior of the muzzle during shootings is an actual and important issue for the defense industries due to the influence of accuracy and precision factors when firing available weapons. Such a study is valuable due to the effects of the unbalanced mass of the projectile on the muzzle vibrations.

Due to the complexity of the firing phenomenon, attempts to accurately determine the influence of barrel and projectile interaction and gases flow are still underway.

Barrel oscillations are determined by the variation of gas pressure and velocity of the projectile inside the barrel [1].

When the projectile leaves the muzzle, disturbing factors act upon it - the most important of which are the barrel oscillations and the special gas dynamics conditions generated by the gases accompanying the projectile, the effect of which is the jump and the deviation due to jump, where the jump angle the angle between a reference line connected to the initial position of the barrel and the actual trajectory direction (direction of the velocity vector). Therefore, the jump is the result and extent of the initial disturbances applied to the projectile.

Barrel oscillations are determined by interior ballistic processes: gas pressure variation and projectile velocity inside the barrel.

The barrel is an elastic system which, under the action of external forces, performs complex vibrations resulting from the composition of radial vibrations, bending transverse vibrations, longitudinal vibrations and torsional vibrations.

The greatest influence on precision is given by transverse vibrations, which depend on the constructive characteristics of the barrel.

In order to find out the resultant oscillatory movement, there are simplifications made such as: neglecting the influence of shear forces, rotation inertia, dissipative forces, considering the barrel as a prismatic bar with its own mass embedded at one end [2].

Transverse vibrations are represented by:

$$M_x \frac{\partial^2 y}{\partial t^2} + \frac{\partial}{\partial x}\left[E \cdot I_x \cdot \frac{\partial^2 y}{\partial x^2}\right] = 0 \tag{1}$$

where: M_x is the mass of the barrel; I_x is the moment of inertia for the barrel cross section**;** EI_x – barrel rigidity to bending; E is the modulus of elasticity; y is the transversal deviation, x is the cross-section abscissa from the barrel reference plane to the receiver.

For the inner diameter of the barrel d_1 and the outer diameter d_2, the moment of inertia I is determined with:

$$I = \frac{\pi d_2^4}{64}\left[1 - \left(\frac{d_1}{d_2}\right)^4\right] \tag{2}$$

If the rigidity of the barrel is constant (EI_x = const.), the solution of the differential equation (2) gives the following values for the transverse vibrations of the barrel.

The frequency of the fundamental vibration mode is:

$$\nu = \frac{1}{2\pi} \cdot \frac{c^2}{l^2}\sqrt{\frac{E \cdot g \cdot I}{\rho \cdot A}} \tag{3}$$

where: l is the barrel length, A is the area of the barrel cross section; ρ is the density of barrel material; c is the first root of the transcendent equation: $\cos c \ \cdot \cos h\, c + l = 0$

The frequency of the first vibration mode:

$$\nu_1 = \frac{c_1^2}{c^2} \cdot \nu \tag{4}$$

By continuing the mathematical model, one can observe that the real vibrations of the barrel are dampened vibrations. This is an important aspect, mainly in the case of automatic weapon systems, in which vibration damping may not end in the time interval following two consecutive shots.

To control and reduce muzzle vibrations and to provide better firing accuracy, it is necessary to predict the nonlinear muzzle behavior [3]. In fact, determining the non-linear dynamic behavior of a muzzle is very difficult because there are many interdependent parameters such as the projectile velocity and mass, the nonlinear geometry of the interior of the muzzle, damping, etc. For this reason, a more precise and simpler method is needed to define the nonlinear behavior of a kinematic system.

High-speed cameras use high-speed digital video files to observe motion pattern and measure moving objects, gaining a qualitative and quantitative perspective of the experiment. This technique allows us to visualize and analyze movement, especially the movement that is too fast for the human eye or which is not perceived by ordinary cameras. The user can make measurements of synchronicity, positioning, distance, speed, angle, angular velocity, and can track multiple points or objects in order to calculate and establish the two-dimensional coordinates, speed or acceleration.

During shootings with different caliber weapons, performance appreciation is mainly based on the target score, which is clear and useful but also a relative indicator for evaluating performance. However, when performance has to be analyzed at a more specific level, the emphasis should be on the description of the movement pattern itself. In this context, motion kinematics can be introduced through behavioral performance of a shooter, namely postural balance and muzzle stability.

2. Equipment setup and description

In order to understand and observe the barrel stability, vibrations and motion tracking, an equipment system as shown in figure 1 was set up, using high-performing modern technology.

The equipment used for shootings and measurements is part of the Accredited Ballistic Applications Laboratory of the Royal Military Academy in Brussels.

The equipment setup used for motion tracking and stability analysis is comprised of:

- Photron FASTCAM SA-3 high speed camera;
- Data acquisition and processing system with specialized software (Photron Motion Tools, LabView, Microsoft Excel);
- High luminosity spotlights focused on the interest area - High Power Light ARRI 1K.

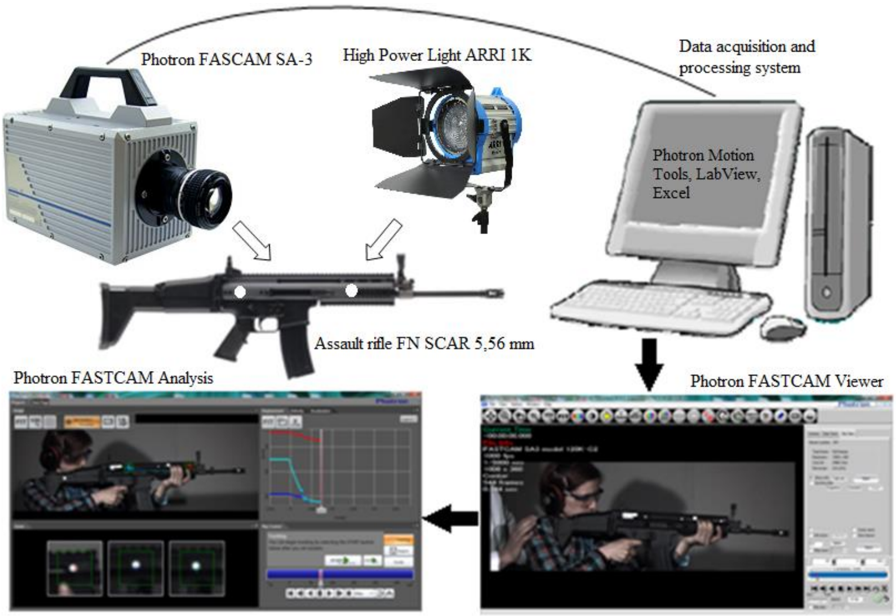

Figure 1. Experimental setup.

The weapon used for the experimental tests was FN SCAR (Fabrique Nationale Special Forces Combat Assault Rifle), which is an assault weapon produced by the FN Herstal Company in Belgium with a caliber of 5.56x45mm NATO and it is used by the special forces of the United States of America.

The firearm was firmly held by a shooter in standing position and it was fired in burst mode, so the vertical and horizontal of the weapon itself and the shooter's position could be observed and analyzed.

Experimental tests were started by controlling the high-speed camera with Photron FASTCAM Viewer, meaning shot and display settings, trigger mode, shutter etc. After shooting and recording images from the camera's memory, they are saved as files on the specialized computer. The records were then processed with Photron Motion Tools (Photron FASTCAM Viewer – PFV și Photron FASTCAM Analysis – PFA), an automated slow-motion-analysis camera control software for use with computer-based high-speed video cameras developed by Photron.

Figure 2. Assault rifle FN SCAR 5,56 mm [4].

PFV software has been designed to provide control of Photron high-speed cameras, data saving, image replay and simple motion analysis. Advanced operation menus provide access to features for enhanced camera operation and image enhancement. Tools are provided to allow image calibration and easy measurement of angles and distances from image data. PFV software allows image sequences to be exported directly to optional PFA software. This motion analysis software is launched automatically from PFV software, and provides automated tracking of up to five points using a correlation or centre of gravity tracking algorithm provides 2D analysis of motion within an image sequence. X, Y and absolute values of displacement, velocity and acceleration are automatically calculated and displayed in graphical form. Data may be exported as a comma separated value file [5].

3. Method and measurements

For the experimental tests, an optical method was used. The variation of the kinematic parameters of specific chosen points on the barrel and the recording of its movements has been done with the help of a high-speed camera. This procedure allows the visualization and analysis of the vibrational phenomenon and displacement of the whole weapon and the shooter's posture.

3.1. Camera calibration

Variation of the kinematic parameters of certain parts of the weapon (barrel, recoil parts, etc.) was determined by delimiting the regions of interest by means of contrasting white markers.

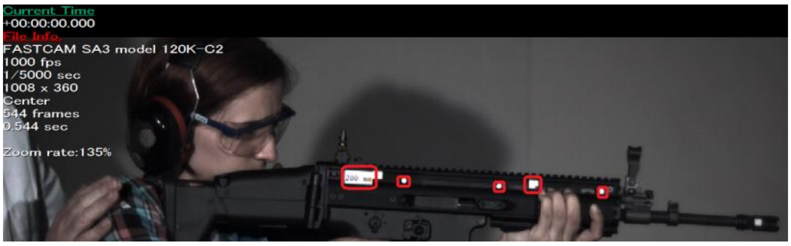

Figure 3. Points of interest outlined by reflective markers.

The high-speed camera Photron FASTCAM SA-3 has been set to:
- recording speed: 1.000 frames per second;
- resolution: 1008x360;
- scale: 0,093 pixels/mm.

The calibration process was done with the help of a grid (marker) of calibration to determine the real distances and displacements. The tracking software requires calibration and determination of a coordinate system defined by locations with known coordinates in the acquisition area, in this case the 200 mm marker provides accurate and real measurements.

3.2. Experimental tests

With the help of PFA software, it was possible to analyze the motion in an image sequence imported directly from the PFV software in order to measure movement, velocity and acceleration, which could then be exported to a value file (csv) in Microsoft Excel or similar. The resulting graphs could be viewed in sync with the recorded high-speed images.

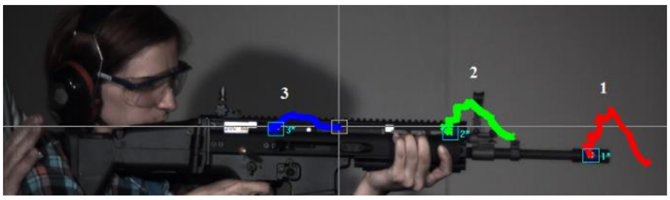

Figure 4. Stability Analysis for 5.56 mm FN SCAR Assault Rifle.

Thus, we could observe the movement of the firing weapon according to three points chosen as a reference system. Motion analysis results are directly exported by the software to Excel, so they can be processed and can be used to evaluate the weapon's return rate.

During filming, it was found that with the tremendous power released when firing with the FN SCAR rifle, the return does not always seem sufficiently precise and its effects on the shooter-gun assembly can thus be calculated and analyzed. The PFA software follows specific weapon characteristics, namely the three selected areas, to quantify the effects of recoil when the trigger is struck.

4. Results

The indicators used to determine successive positions during shots were analyzed using the PFA analysis software. This allows the determination of the speed and acceleration of each point to then calculate the average and determine a general rate of return of the weapon.

As it can be observed in figure 5, the gun moves forward and upward and then forward and downward after the bullet exits the muzzle.

Initially, an image of the behavior of the different contrast points chosen is shown. This is to assess whether there are points that have a specific or deviant behavior and cannot be included in the calculation of the average speed and acceleration of the weapon. Point tracking begins when the cartridge starts to move inside the barrel, the negative time in the graph is due to the settings of the PFV software, starting from -0.05 seconds before the trigger firing, so that one can observe the full movement.

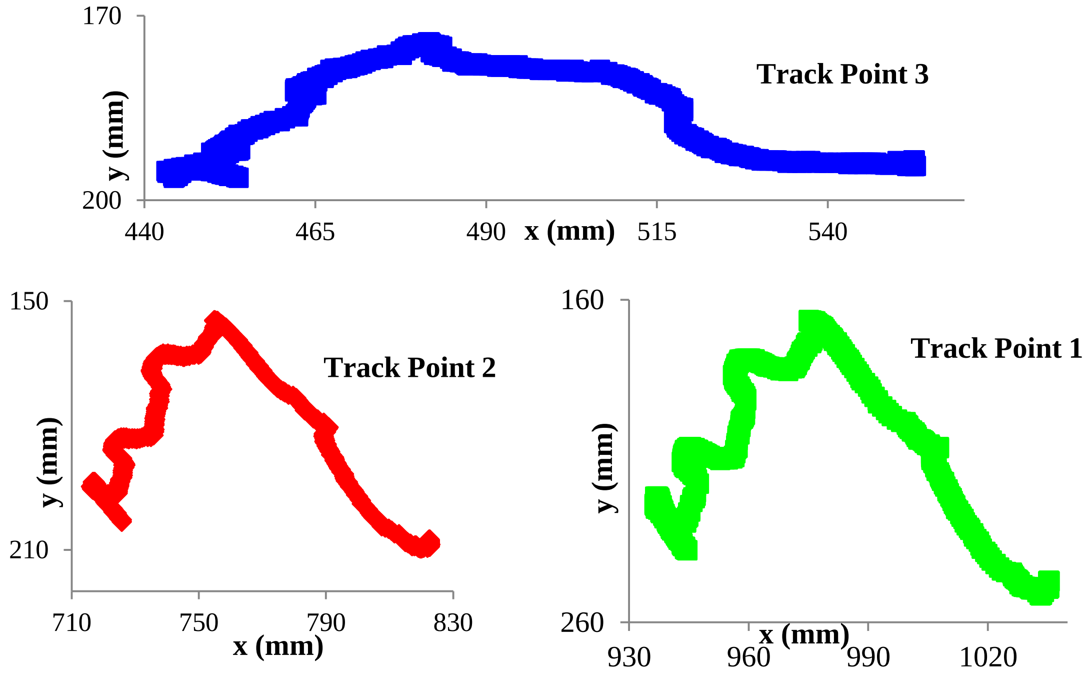

Figure 5. XY Coordinates for the selected track points.

The reference axis X is positive towards the muzzle and the Y axis is positive, being downwardly, as in the previous figure. This explains the negative values for the evolution of weapon positions and components. The Track point 1, 2 and 3 have the same coordinates in figures 4 and 5 because the values acquired with PFA are then exported directly to Excel, thus calculating exactly the maximum and minimum points, speed, return rate, etc.

The same procedure is used for all selected track points, knowing that up to five markers for an experiment can be selected in the PFA.

5. Conclusions

The method of measuring and recording the kinematics of a firearm with the help of a high-speed camera is efficient because it provides us with the possibility of obtaining accurate and detailed motion measurements of a chosen point from the weapon body during firings, in our case the measurement error being 0,93 pixels/mm. High-frequency recordings (1.000 frames per second) allow the user to study in detail the general behavior of the weapon during shooting as well as its posture at that time.

The recorded results indicate that the shooter-firearm assembly has a vibratory and recoil motion that starts from the moment of propellant's ignition until the projectile exits the gun barrel, a movement that repeats itself according to a particular pattern depending on the shooter and its experience, hence the fact that this movement occurs after a certain law.

In semi-automatic and automatic shootings, as a result of the remnant vibration, recoil and firearm rotation due to the rotational torque (couple), the elevation of the muzzle increases, the shooter having no control over the line of sight, the accuracy of the shooter decreases depending on his/her experience.

In this case, there was no detailed analysis of the different results due to the limited number of frames and the limited scope of the initial investigation. Tests still provide sufficient information to gain a first insight into the investigated phenomena of the muzzle rise and implicitly the recoiling parts.

6. References

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