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DESIGN PRINCIPLES FOR A STANDARDIZED MUZZLE RISE TEST RIG

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Abstract: Muzzle rise is a critical factor affecting firearm accuracy, controllability, and hit rate, with its magnitude being highly dependent on weapon geometry. Improving the management of muzzle rise is, therefore, a key objective for arms manufacturers seeking to enhance weapon performance. This study addresses the need for standardized measurement by outlining the fundamental design principles and essential parameters for an effective muzzle rise test apparatus. It proposes a framework for a rig capable of providing reliable, quantitative data on muzzle dynamics to aid in future weapon design and evaluation.
Key words: firearms, muzzle rise, hit rate, accuracy, test rig

INTRODUCTION

The reliability and effectiveness of equipment used in infantry rifles are fundamental elements of operational success on the modern battlefield. Therefore, multi-dimensional testing processes are conducted to demonstrate the military standard compliance, durability, and functional adequacy of such equipment. These tests aim to measure the performance of equipment under harsh environmental and operational conditions, covering not only laboratory conditions but also realistic combat scenarios [1, 2].
Weapon accessories (optical systems, night vision devices, laser designators, holographic and red-dot sights) enhance the user's target acquisition capability and firing accuracy, while stocks and ergonomically designed support equipment improve weapon control and user comfort. Barrel-mounted accessories such as compensators, flash hiders, suppressors, muzzle brakes, and similar devices play a critical role in reducing recoil, concealing the shooter's position, and optimizing range/accuracy characteristics. This diversity demonstrates that equipment selection directly determines the user's effectiveness, safety, and operational efficiency [3].
Equipment evaluation can be grouped under three main categories, which can be listed as environmental, mechanical and functional tests. Environmental Tests measure the functionality of equipment under harsh conditions such as extreme temperatures, humidity, condensation, dust and sand. Conducted using MIL-STD-810 standards, IP codes and similar methods, these tests aim to prove the product's reliability and durability in the field. Mechanical Tests evaluate the structural integrity and endurance limits of equipment through vibration, impact, shock and drop tests. Methods such as sinusoidal and random vibration tests reveal potential resonance issues and deformations that may occur during prolonged use. Functional Tests: Equipment technical specifications are examined through ballistic, metallurgical, electrical, and optical tests. The zeroing consistency of sights, illumination, and the functionality of electronic components are also evaluated within this scope [4].
This multi-layered testing process ensures not only the reliability of the equipment but also its adaptability to technological developments, quality control, and standardization. Consequently, the meticulous selection and comprehensive testing of all equipment used in infantry rifles is critical for both the safety of military personnel and the sustainable success of operations [5].
Small arms is a term that encompasses both pistols and rifles, where barrel retraction is a critical factor influencing weapon controllability and the accuracy of successive shots. Despite its significance, no standardized metric currently exists to quantify this phenomenon. Barrel retraction is intrinsically linked to the weapon's internal design, meaning that even firearms with comparable calibers, weights, and external geometries can demonstrate markedly different retraction characteristics. This variability underscores the necessity of standardizing its measurement and incorporating it into formal technical specifications [6, 7].

This study presents a design framework for a test apparatus intended to integrate the assessment of barrel retraction into the weapon selection protocols used by national agencies. For such a standard to be internationally viable, the defined criteria must be objectively measurable and repeatable across different testing environments. The proposed system was developed with a focus on its core functional elements, operational principles, and overall suitability for providing reliable, quantitative data on retraction dynamics.

MATERIAL AND METHODS

The physical cause of muzzle rise is torque and the resulting imbalance. When the line of action of the recoil force generated by the firing of the bullet remains above the weapon's center of gravity or grip line, it causes the barrel to rotate upwards (pitch/muzzle rise). In addition, the flow of gas at the muzzle and the direction of the gas can also generate additional torque. The recoil impulse and peak force are fundamental parameters related to muzzle rise.

Military Equipment Standardization

Within the international defense industry, countries shape their procurement preferences based on operational requirements, geographical conditions and climatic factors. However, despite this diversity in preferences, the production and testing of military equipment is carried out within the framework of universal standards that guarantee reliability, interoperability and operational effectiveness. The testing processes for military equipment, including infantry rifles, are generally subject to strict protocols established by internationally recognized military institutions and standardization organizations. These military standards can generally be examined under three main categories: NATO Standards, American Standards (USA) and International Standards.

NATO Standards (STANAG)

NATO (North Atlantic Treaty Organization) standards consist of Standardization Agreement (STANAG) documents that aim to enhance the interoperability and operational effectiveness of allied member countries' military equipment. These standards contain comprehensive rules and requirements established to ensure the compatibility, reliability, and performance of equipment. Some of the prominent NATO standards in the context of infantry rifles are as follows:
STANAG 4172: Defines the technical specifications for Standard 5.56x45mm ammunition and the performance and durability test criteria for infantry rifles using this ammunition.
STANAG 4218/4219: This standard defined as Accelerometer Test Procedure for an Aircraft Inertial Navigation System which was renewed.
STANAG 4366/2333: Covers standards for combat clothing and their testing conditions.
STANAG 4375/4757/AOP 4157: NATO's test standards for weapons and ammunition
STANAG 4509: Technical Performance Specification Providing for the Interchangeability of 5.7 Mm X 28 Ammunition - Aop-4509 Edition A [8].

American Military Standards (MIL-STD)

American military standards (Military Standard - MIL-STD) are a comprehensive set of criteria established by the US Department of Defense (DoD) for the design, production, testing and evaluation of all military equipment. These standards were developed to meet the needs of US military units and to ensure that equipment used in operations is highly reliable. The basic MIL-STDs related to infantry rifles are as follows:
MIL-STD-810G: Provides a series of methods for testing the equipment's resistance to various environmental conditions such as extreme heat/cold, humidity, vibration, shock, dust, salt fog, etc. [9].

MIL-STD-1911: Standardizes safety and functional tests for firearms for example, trigger pull test, drop test [10]
MIL-STD-461: Ensures that weapon systems carrying electronic equipment do not experience problems interacting with other devices by specifying test requirements for electromagnetic interference (EMI) and electromagnetic compatibility (EMC) [11].

International Standards

This category includes standards published by various international standards organizations that broadly define the quality, reliability, and performance of military equipment. These standards are vital for facilitating international cooperation and ensuring the global compatibility of equipment. The relevant organizations and standards are as follows:

International Organization for Standardization (ISO) [12]:
ISO 9001: A quality management system standard that provides the basic framework for quality management of production and testing processes.
ISO 12232: Contains standards for measuring and evaluating the performance of optical and imaging systems (night vision goggles, laser pointers, etc.).
ISO 9227: Aims to measure the corrosion resistance of materials by standardizing the neutral salt spray (salt mist) test method.
In summary, modern military equipment, including infantry rifles, undergoes rigorous testing and quality control processes defined by established standards such as NATO, MIL-STD and ISO/IEC to ensure the successful execution of operational tasks. These standards form the basis for forces in different geographical locations to conduct joint operations with confidence in the performance and reliability of their equipment.

RESULTS AND DISCUSSION

Standards such as STANAG 4366 and MIL-STD-1911 detail the current methodologies for testing recoil, muzzle rise, and firing stability. These phenomena are primarily addressed within the context of shooting safety or functional performance testing. In contrast, academic literature provides a broader examination of weapon dynamics, ballistics, control systems, and measurement techniques. While tools like high-speed cameras, laser sensors, and accelerometers are commonly employed to quantify recoil, existing standards lack a comprehensive and detailed definition of the recoil phenomenon itself. Consequently, these standards may require revision to keep pace with technological advancements.
The foundation of any effective standard lies in its use of measurable metrics that yield consistent and repeatable results. Key metrics for quantifying recoil include angular displacement, angular velocity, stabilization time, vibration spectrum, and the establishment of repeatable test conditions.
Angular displacement is the maximum vertical angle the barrel reaches from its initial position that can be measured in degrees or milliradians. Angular velocity is the rate at which the barrel moves upward. Stabilization time is the duration required for the weapon to return consistently to its original target position after firing. Lastly repeatable conditions mean the test setup which must maintain constant parameters, such as locking torque, trigger pull force, and buttstock weight across all tests.
In aim to define more sophisticated engineering parameters, the concept of Degrees of Freedom (DoF) is critical. A test setup allowing rotation along the horizontal axis enables a more realistic analysis of recoil dynamics during firing. Inertial Measurement Units (IMUs) is one the sophisticated engineering parameters in which sensors such as accelerometers and gyroscopes were integrated onto the weapon or fixture are essential for high-precision measurement of angular velocity and acceleration. High-Speed Cameras are in common usage for ultimate fast action like gun firing. These systems visually record motion for subsequent analysis with motion-tracking software. Laser and Optical Sensors can track the displacement of a reference point on the weapon or a target at a distance. The weapon should

be stabilized either by a robotic arm that simulates a human grip or by being secured in a rigid vise. A significant design challenge involves developing an automatic trigger pull mechanism that applies a consistent force and speed for every test.

Following the setup's completion, data must be collected over several hundred shots to ensure statistical significance. The mean, standard deviation, and confidence intervals of this data should be analyzed to guide necessary optimizations to the apparatus. This process of firing tests and data collection is iterative, repeated until the setup is fully optimized. Throughout this phase, comparing experimental data with existing literature is crucial for the academic validation of the methodology.

The setup's validity will be demonstrated by its consistent ability to differentiate between weapon classes, specifically defined here as high muzzle-rise and low muzzle-rise weapons and to produce results that represent the behavioral extremes of these classes.

Once the method and experimental setup are matured, it would be advantageous to engage with standardization bodies (e.g., NATO, ISO, TSE) to develop formal technical proposals for new test standards.

Given that the apparatus contains high-energy moving parts and a live firearm, operational safety is paramount. The entire system must be designed to be remotely controlled and operated. Furthermore, to ensure widespread adoption, the setup must be cost-effective and easily repeatable by other testing laboratories.

Recoil and muzzle motion dynamics within this new setup can be modeled using physical numerical analyses, such as multi-body dynamics and elastic structural modeling. While these numerical models ultimately require validation against live-fire data, they are invaluable during the initial design phase. They provide powerful predictive capabilities and yield critical approximate results, especially when experimental testing is prohibitively expensive, dangerous, or logistically challenging. Such analyses allow for the examination of key parameters like mass, moments of inertia, and recoil forces through dynamic, static, rigid, and rigid-elastic simulations [13, 14].

Subsequent to numerical modeling, controlled studies can be conducted using safe propulsion sources, such as gas injection or thrust mechanisms, instead of live ammunition to examine the setup's behavior further.

Throughout this design process, factors of safety, ethical responsibility, and production quality control must be prioritized above all else.

CONCLUSION

In order to increase firing accuracy in firearms, the following points should be considered when designing an experimental setup aimed at reducing recoil.

1- In a recoil test setup, multiple metric values such as acceleration, angular displacement, and impulse should be measured; relying on a single value could lead to misleading results.

2- The setup should be suitable for different firearms, using the same ammunition, identical firing conditions, and a sufficient number of repetitions, with calibration of measurements documented.

3- Both shooter ergonomics and barrel gas behaviour should be examined together. Factors such as noise should be measured if necessary — some solutions (muzzle brakes) may be very good on their own but can create disadvantages in practical use (side gas, noise, side effects).

4- International safety criteria must be met.

5- Operating costs should be kept low, as the cost per shot becomes a significant parameter in scenarios involving numerous repeated firings.

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