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G-Force Test Stand for the Evaluation of Weapon Component Strength

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Abstract. This paper discusses the design of a G-force test stand intended to examine of the effects of mechanical loads present during firing of a weapon and applied to the electronic components contained in the 155 mm calibre guided projectile. The G-force test stand is used to develop and test the effects of using high mechanical loads by decelerating a test specimen through the use of a purpose-designed fender assembly. For the purpose of testing, it is irrelevant whether a load is developed by acceleration or deceleration of the test specimen, as a test result obtained by the deceleration of a test specimen is equivalent to a test result obtained by the acceleration of a test specimen, as used in a 155 mm calibre artillery guided projectile. The G-force test stand was used to test and determine the velocities developed by the test specimens and the G-forces applied to them. The maximum velocity to which a test specimen was accelerated was approx. 72 m/s.

The test stand was able to propel the test specimens to velocities an order of magnitude higher than the velocities obtained with a Kast and Masset ram. The tests were performed with rubber and copper fender assemblies. The effect of the specific fender used was demonstrated on the trend of the generated G-force. The test stand could develop G-forces in excess of 10,000 with a duration of more than 500 μs.

Keywords: G-force, g-load, ammunition components, test stand

1. INTRODUCTION

A constant factor which should be considered in the operation of small arms, artillery, and rocket munitions is the presence of G-forces which vary in value and duration. For small arms and artillery munitions, the projectiles are exposed to G-forces ranging from several hundred to more than 10,000 inside the barrel when fired. In rocket applications, the G-forces during launch, acceleration, and manoeuvring of a rocket missile are much lower and usually below 100. G-force is a dimensionless measure and relative to the Earth's gravitational acceleration. While the mechanical and structural components of munitions are inherently more resistant to G-forces, electronic or electrical modules severely restrict the direct use of the ammunition in which they are contained, especially for precision-guided munitions (PGM). The electronic and electrical modules used in PGM need to be suitably designed and adapted to withstand the high G-forces to which such products are supposed.

The G-force generating equipment used so far uses the gravitational fall effect of the test specimen, which is attached to a ram, on a massive anvil. This paper presents the concept, design, and testing of a new test stand for the generation of short-duration, high G-forces.

2. THE STATE OF THE ART – THE RAM METHOD

The methods used for the generation of high gravitational loads are typically based on the free drop of a mass from a defined height. The Masset ram [1] offers the generation of short-duration, high G-forces. In terms of construction, it is a drop hammer which is propelled along a curved trajectory by a falling load and impacts an anvil. The test specimen is located on the upper face of the ram. Industry standards [2] define the design dimensions and performance of the device (Fig. 1).

The industry standard does not specify any expected G-force value or the duration of its effect on the test specimen. Neither the linear nor the angular velocity of the hammer is specified for the phase directly before the strike against the anvil. From the experimental data developed by users of the Masset ram [3], authors of this paper estimated the maximum possible velocity of the hammer directly before striking the anvil.

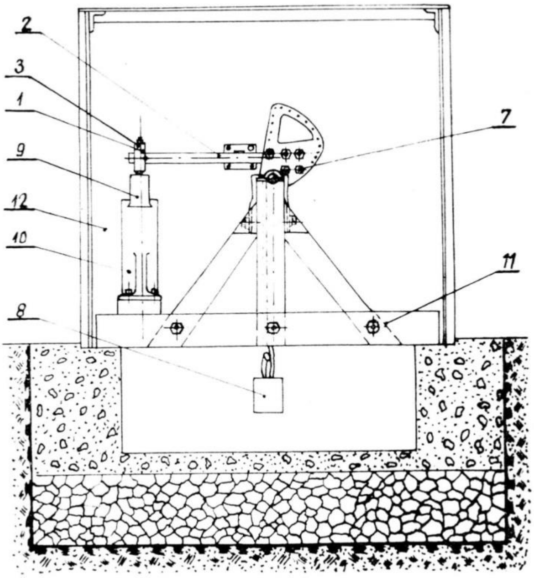


Fig. 1. Masset's ram. Ram elements: 1 – hammer, 2 – hammer handle, 3 – tested sample, 8 – weight, 9 – anvil, 10 – pillar, 11 – base, 12 – casing [2]

If the maximum average G-force was 1796, as found during tests, and the compression ratio of the copper fender was known to be 1.5 mm as generated by the strike of the hammer, then the hammer velocity directly before striking the fender could be estimated as approximately 7.2 m/s. This calculation was made by assuming a constant G-force during the strike of the hammer, although this was only an approximation. Hence, it was sensible to conclude that the maximum hammer velocity generated by the Masset ram was less than 7.2 m/s. The calculated value should be deemed indicative only, as the G-force specified in [3] was measured with a method which could not ensure a high measurement accuracy. Another solution, where the weight is dropped from a defined height onto the test specimen, is the Kast ram (Fig. 2) [4, 5]. For the solution in [5] the maximum possible velocity of the weight was 8 m/s. Knowing this facilitates cross-comparison between the test results.

A Kast ram generates short-duration, high G-forces, not unlike a Masset ram. The difference between the two types of ram is in the mechanical construction. For a Kast ram, the hammer is dropped freely from a defined height onto the test specimen. The G-force when the hammer strikes the test specimen on the anvil can be logged with a G-force sensor. The test stand can be extended with a hammer rebound retarder, which prevents the hammer from striking the test specimen more than once per test run.

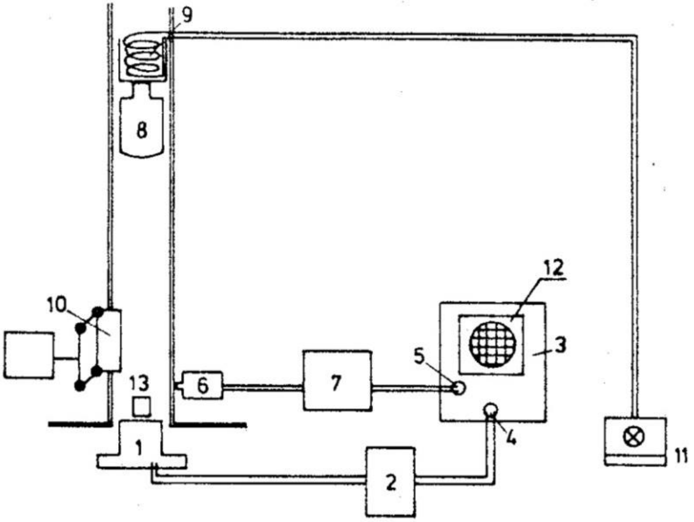


Fig. 2. Ram for G-force tests, where the hammer moves under gravity acceleration [5]. Ram elements: 1 – load cell, 2 – strain gauge amplifier, 3 – recorder, 4 – signal input, 5 – input of the trigger signal, 6 – photocell, 7 – power supply, 8 – weight, 9 – electromagnet, 10 – pneumatic weight catching system, 11 – switch, 12 – photo chamber, 13 – tested sample [5]

The primary parameter which determines the G-force amplitude height and the G-force duration a test stand can generate is the moving element velocity directly before the strike. The higher the velocity is, the higher the G-force amplitude and/or the longer the G-force duration that can be produced, according to Eq. (1).

$$V = \int a(t)dt \tag{1}$$

with: V – velocity; $a(t)$ – instantaneous acceleration; t – time

If the moving element is accelerated by free fall only, as with a Kast ram, the hammer would have to be dropped freely from an approximate height of 3.25 m to produce a terminal velocity of the test specimen of 8 m/s, discounting the drag due to air. Due to the engineering considerations, the construction of such a test stand is not practical. In the classic solution of a Masset ram, where the hammer follows an arced trajectory along with the test specimen, the test specimen is accelerated by the release of the accumulated, mechanical potential energy of a weight. A higher weight mass and a wider range of weight location displacements can accelerate the hammer to a higher velocity. This, however, requires a larger mechanical structure.

The primary guideline for the solution presented in this paper was to produce the highest possible terminal velocity of the test specimen by another method than gravity acting on a mass, while keeping the test stand compact and the test procedure uncomplicated.

3. DESIGN OF THE G-FORCE TEST STAND

The structure of the G-force test stand resembled a cannon, where the projectile propellant was compressed air (Fig. 3). The test specimen in the form of a projectile would first be installed inside the barrel. By opening an electromagnetic valve, compressed air could be released into the barrel, which would then accelerate the projectile. In front of the barrel muzzle was located a suitably specified fender. Upon striking the fender, the projectile was exposed to a high G-force. The G-force generated during the projectile acceleration phase was negligible in comparison to the G-force generated as the projectile struck the fender. The G-force applied to the projectile upon striking the fender was calculated from the data output of a force sensor. The projectile mass was known, and it was possible to precisely calculate the G-force applied to the test specimen housed in the projectile. Recorded imaging from a high-speed camera [6] was used to verify the force sensor output reading during the tests.

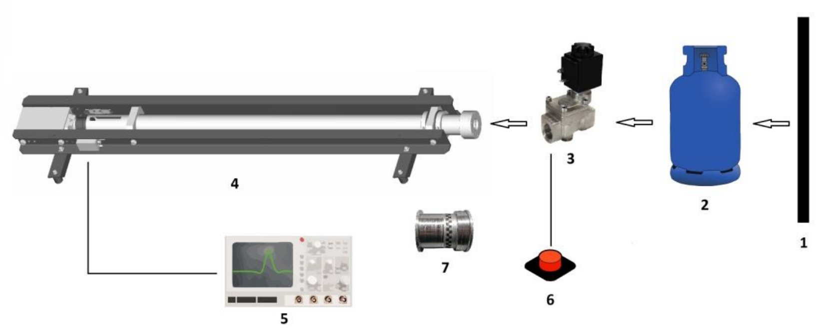


Fig. 3. Diagram of the G-force test stand. Stand elements: 1 – compressed air system, 2 – pressure buffer, 3 – electromagnetic valve, 4 – barrel with position and force sensors, 5 – data logger, 6 – electromagnetic valve trigger, 7 – projectile.

The compressed air system (1) was maintained at a constant pressure. Before the test, the electromagnetic valve on the pressure buffer tank (gas cylinder) (2) inlet was triggered to open. The pressure buffer tank was pressurised to a set value, equal to or lower than the constant pressure of the compressed air system. This facilitated smooth adjustment of the acceleration of the projectile in the barrel.

Aside from the facility for setting a specific pressure, the pressure buffer tank formed a pressure reservoir to reduce the pressure drop as the projectile (7) was being accelerated. The capacity of the pressure buffer tank needs to be specified for the internal volume of the barrel (4) to ensure that the accelerating pressure reduction during the projectile acceleration in the barrel was as low as possible. The buffer tank was depressurised into the barrel by opening the electromagnetic valve (3) using the trigger (6). Directly before striking the fender, the projectile had been accelerated to the maximum velocity feasible with the specific pressure setting. Two beam photocells (4) integrated in the test stand were used to calculate the projectile velocity immediately before the strike on the fender. Once the projectile had struck the fender, the accelerating pressure was relieved by side slots in the barrel tube. The G-force was measured up by a piezoelectric force sensor. The construction of the fender could be varied in terms of thickness, shape, and materials (like rubber or copper). Depending on the specific fender type, it was possible to produce different times, amplitudes, and trends of the G-force for the same projectile velocity. The G-force trend and the output from the beam photocells were recorded by the data logger (5), which could be a standard oscilloscope.

4. EXPERIMENTAL TESTS

The G-force test stand was examined to determine the projectile velocity and G-force which could be generated. For this purpose, a series of test runs was performed with different acceleration pressure settings and different fenders. The conclusions from these tests served to modify the test stand until satisfactory results were achieved. The following shows the permanent deformation of the barrel muzzle (Photo 1), caused by repeated G-force testing.

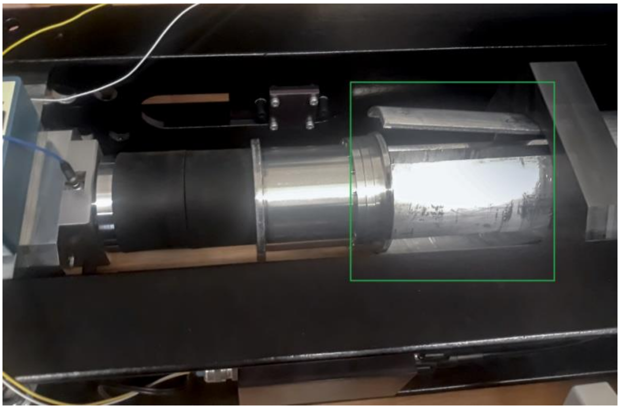


Photo 1. Deformation of the barrel tip (marked with a green frame) caused by multiple G-force tests.

The barrel muzzle was deformed by transient deformation of a rubber fender as it was struck by the projectile. This condition is illustrated well with the high-speed camera imaging (Photo 3). The deformation of the barrel caused the projectile to behave out of specifications upon striking the fender, which made it difficult to remove the barrel from the test stand. To eliminate this issue, a barrel was constructed with a modified muzzle (Photo 2).

The deformation of the barrel following the structural modification and repeated G-force tests was smaller and eliminated the out-of-specification behaviour of the projectile upon striking the fender. It was also easy to remove the modified barrel from the test stand.

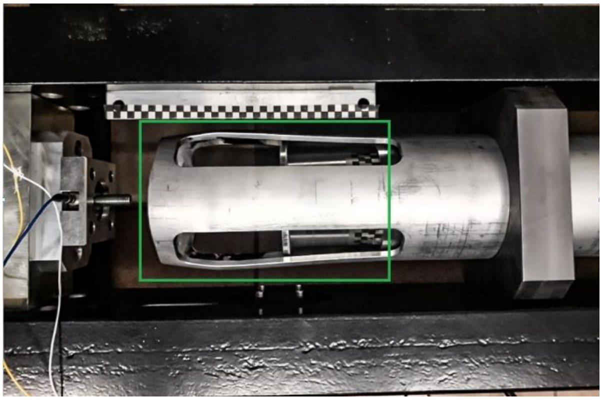
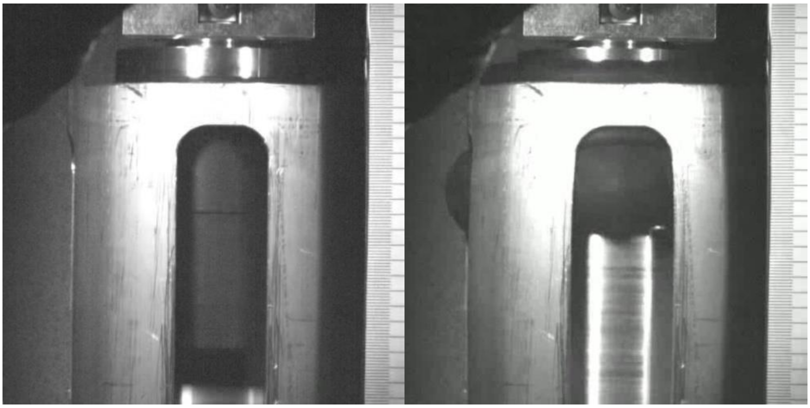


Photo 2. Deformation of the barrel tip (marked with a green frame) after a structural change of the barrel and after multiple G-force tests.



(a) (b)

Photo 3. Pictures from a high-speed camera. Fender before being hit by a projectile (a); fender on impact by a projectile (b).

The moment of striking the fender was imaged with the high-speed camera, capturing the event at approx. 4800 fps (frames per second). During the test shown in Photo 3, the projectile compressed the fender by 40 mm upon impact.

One effect of the impact was that the fender expanded out to the sides, which caused the barrel muzzle to deform, as explained earlier. As a results of the tests, it was decided to increase the inner diameter of the pressure feed line from the pressure buffer tank to the barrel and the inner diameter of the electromagnetic valve in an attempt to increase the attainable projectile velocities.

A test was performed to measure the projectile velocity directly before impact with the fender, as a function of the air pressure setting (Fig. 4). The velocity was usually measured once for each specific pressure, while for selected pressure values (i.e. 0.45 MPa), the measurement tests were repeated. The results allowed the determination of the spread in the time measurements of the displacement of the projectile between the two photocells, which was ±10 μs. This spread was not only caused by a time measurement error. The spread was also driven by the non-uniform behaviour of the projectile inside the barrel between consecutive tests, imprecise pressure settings of the pressure buffer tank, etc.

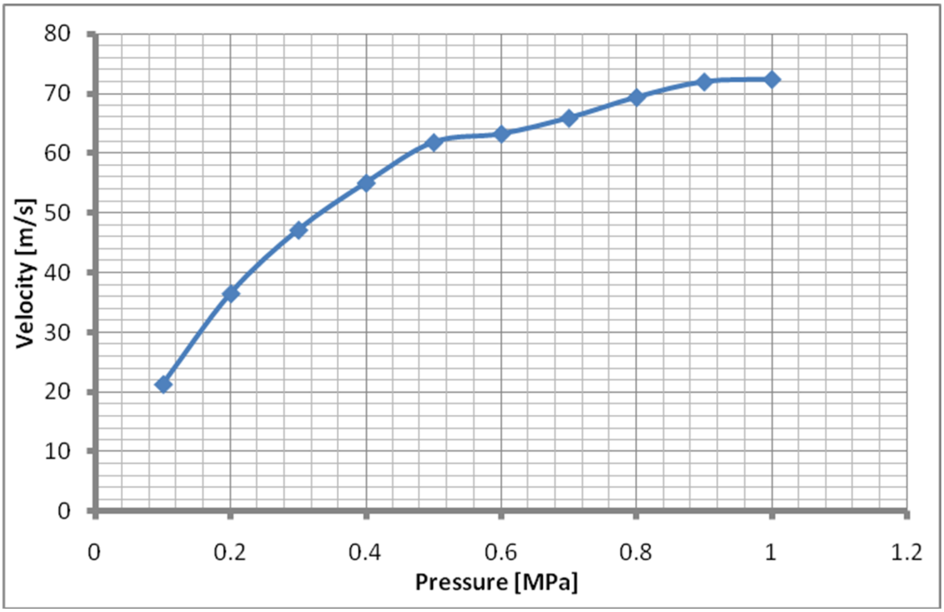


Fig. 4. Graph showing the measured velocity of the projectile just before hitting the fender for different pressures accelerating the projectile

The ±10 μs spread in the time measurements for projectile velocities of approximately 20 m/s and 70 m/s meant that the projectile velocity difference between consecutive test runs was ±0.1 m/s and ±1 m/s, respectively. The projectile velocity difference between the consecutive tests were low enough to deem that the test stands provided sufficiently high repeatability of consecutive testing. This was evident from the force sensor readings, where the G-force trends were very close for the same settings of the test stand. This was very important for the tests, as the test specimen (a telemetry module for a 155 mm calibre guided projectile) must be exposed to and withstand the designed G-forces during the first shot. A test stand not capable of ensuring repeatability of consecutive tests would generate a high risk of exposing the test specimens to G-forces deviating from the assumptions and hence waste the test specimens.

Figure 4 shows that the highest velocity increase occurred for the pressure range 0.1–0.5 MPa. In the 0.5–1 MPa range, the velocity increase of the projectile was considerably lower. This could have been partly due to non-linear phenomena occurring during each test. For example, air drag acting on the projectile inside the barrel is proportional to the square of projectile velocity. The maximum projectile velocity that could be obtained as a result of the tests was approximately 72 m/s. This was nine-fold higher than the velocity achieved in the solution presented in [5].

It was not decided to increase the pressure any further due to the limited ability of the test stand components to withstand higher pressures and the small increase in projectile velocity resulting from an increase in pressure around the pressure of 1 MPa.

Photo 4. General view of the G-force test stand

The G-force test stand (Photo 4) was used to test a telemetry module for a 155 mm calibre artillery projectile.

The test objective was to generate a G-force of 10,000 lasting for as long as possible, up to a maximum of 3 ms. The representation of the whole trend for the G-forces present inside the gun would be technically complex and require the construction of a test stand having a performance similar to that of an artillery piece. It was thus decided to represent only a part of the G-force trend with a maximum amplitude. The measured projectile with telemetry module weight was 723 g (Photo 5).

Photo 5. Projectile with the installed telemetry module of the cal. 155 mm guided ammunition, prepared for acceleration tests

The test involved accelerating a projectile to impact a fender assembly comprising two bonded pieces of an elastomer material with a total thickness of 90 mm. The projectile was accelerated to 57 m/s. The pressure setting and the fender type were specified by experimental testing to produce a G-force amplitude of 10,000 and the maximum possible duration. Assuming that the projectile acceleration was constant inside the barrel tube, the projectile acceleration G-force could be calculated. During the acceleration, the projectile was under a G-force of approximately 83 for approx. 70 ms. This was not the G-force that could cause failure of the test specimen, so it was considered to have a negligible effect on the test result. The G-force of the projectile impact against the fender was recorded by a piezoelectric force sensor. The measurement range and frequency band that the sensor was able to record correctly was sufficient for the proper representation of the G-force trend waveform generated with the test stand. The maximum dynamic G-force the force sensor could properly measure was approx. 12,550 for a 723-gram projectile.

The maximum G-force (Fig. 5) was slightly over 10,000. The pulse FWHM (Full Width at Half Maximum) was 463 μs.

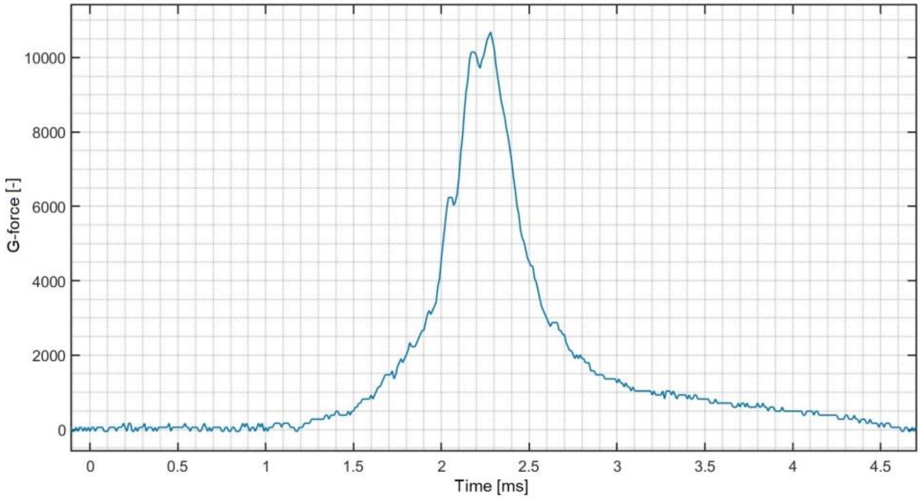


Fig. 5. Graph showing the G-force acting on the projectile when hitting the fender

Testing was performed with the use of copper fender (Photo 6). Copper fender of a suitable shape created a squarer waveform of the G-force trend (Fig. 6). This was the result of the relation between the force and the deformation, dissimilar to the relation for the rubber fenders. For the rubber fenders, the force/deformation relation was similar to a linear function, not unlike a spring. Because of this, the G-force trend during the tests with the rubber were more akin to a Gaussian curve.

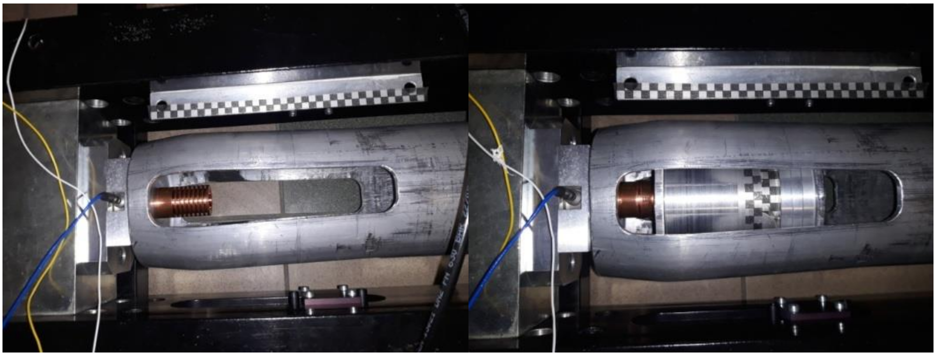

a) b)

Photo 6. G-force tests with the use of a copper fender. Before shot (a); after shot (b)

The copper fenders were non-reusable, only suitable for a single test (Photo 7), which was their main drawback.

Photo 7. Copper fenders. On the left – fender before the G-force test, on the right – fender after the G-force test. As a result of the impact, the fender was shortened by 13 mm

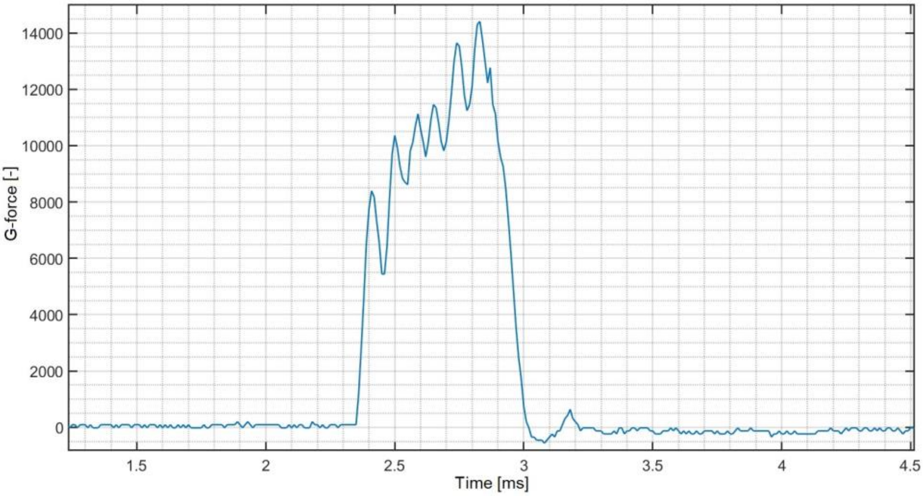


Fig. 6. Graph showing the G-force acting on the projectile when hitting the copper fender

For the copper fender, the G-force chart (Fig. 6) revealed that the acceleration increased faster than with the rubber fenders. The wave shape observed in the trend line was a result of the copper fender shape used. The transient G-force exceeded 10,000 in this test; however, the test was performed without the test specimen in the projectile.

5. CONCLUSIONS

The tests completed on the G-force test stand demonstrated the following:

1. the test stand was suitable for the generation of G-forces over 10,000 and longer than 500 µs FWHM. For the maximum achieved projectile velocity of 72 m/s, the test stand was theoretically capable of generating a G-force with a square trend waveform, of 10,000 and a duration of approximately 730 µs;
2. the test stand provided high repeatability of G-force generation, which was confirmed by repeated testing under the same conditions. The G-force trend waveforms produced in this way featured a high level of correlation;
3. the projectile velocity attainable on the test stand was above 70 m/s, which was one order of magnitude higher than with a Kast ram design. This made it possible to generate G-forces with a higher amplitude and duration (time) than with a Kast or Masset ram;
4. the mechanical and electronic components used in the telemetry module of a 155 mm calibre artillery shell withstood the tests on the G-force test stand, as demonstrated by proving ground tests, where the same type of telemetry module was shot in a 155 mm calibre guided projectile, recovered from the projectile, and found to have retained its full functionality;
5. the test stand was not able to generate the full G-force trend applied to the projectile inside a 155 mm calibre artillery piece.

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Stanowisko do badania odporności elementów uzbrojenia na przeciążenia

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Streszczenie. W niniejszej pracy omówiono konstrukcję stanowiska do badań wpływu przeciążeń występujących podczas wystrzału z armaty na elementy elektroniki umieszczone w pocisku kierowanym kal. 155 mm. Na stanowisku do generacji i badań przeciążeń, wysokie przeciążenie powstaje w wyniku wyhamowania badanej próbki na specjalnie dobranym odbijaczu. Dla celów badawczych nie ma to znaczenia czy przeciążenie powstanie w wyniku rozpędzenia czy też spowolnienia badanej próbki, dlatego wynik badania powstałego na skutek spowolnienia próbki jest tożsamy z wynikiem powstałym na skutek przyśpieszenia próbki, tak jak to ma miejsce w armacie kal. 155 mm. Na stanowisku do generacji i badań przeciążeń przeprowadzono testy, mające na celu zarówno określenie prędkości uzyskiwanych przez badaną próbkę, jak i przeciążeń na nią działających. Maksymalna prędkość do jakiej rozpędzono próbkę wyniosła ok. 72 m/s. Stanowisko pozwala na rozpędzenie badanych elementów do o rząd wyższych prędkości od tych, uzyskiwanych na kafarze Kasta i Masseta. Przeprowadzono badania dla odbijaczy gumowych i miedzianych. Wykazano wpływ zastosowanego odbijacza na kształt charakterystyki uzyskiwanego przeciążenia. Stanowisko pozwala na uzyskiwanie przeciążeń o wartościach powyżej 10000 i czasach trwania powyżej 500 µs.

Słowa kluczowe: przeciążenie, elementy amunicji, stanowisko pomiarowe