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Improving the Spreading Pattern of Precision Rifles by Modelling and Optimising Barrel Harmonics

In the use of precision long guns, there is a continuous effort to improve *accuracy* and *precision,* in other words the *accuracy of the weapons.* These characteristics of the weapons are determined by the consistency of the whole "weapon system".

In this article, we will explore the application of a method that offers a relatively low-cost development opportunity for sport shooters and shooters who use manual ammunition assembly (reloading), which can greatly improve the accuracy of the weapon.

The method described in this article adjusts the time the projectile spends in the barrel to achieve a pre-calculated state of barrel deflection and vibration. To do this, it varies the ammunition assembly parameters (load size, seating depth, neck extraction force, etc.) to tune the internal ballistic processes in the weapon. The procedure is referred to in the literature as "Optimal Barrel Time" (OBT).

Keywords: firing accuracy, internal ballistics, barrel vibrations, modelling, Optimal Barrel Time (OBT)

Introduction

In this paper, the effects of elastic deformation of gun barrels are analysed and modelled with the aim of improving the scattering performance of our weapons.

Analysing the findings and methods described in the technical shooting literature, we have come to the conclusion that while the basic principles of solving the problems identified are generally logical and easy to understand, a number of more difficult questions arise in the course of practical implementation. In order to achieve

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our objective, we need to review the fundamentals of the problem and develop procedures that can be used in practice.

Typical deformation patterns of gun barrels

In gun barrels, the impulse generated by the firing of a shot results in a myriad of different types of movement. The following typical phenomena can be measured with instruments or observed by analysing a slow-motion video: rocking, waving, vibration, twisting, stretching, bulging, pulsation, etc. Moreover, these phenomena appear simultaneously on the gun.

These elastic deformations can be clearly seen in a slow-motion video.[3] The video shows the drastic deformations of the scope, Picatinny rail and barrel of a large-calibre automatic weapon. Narrowing the investigation to the gun barrels, the following characteristic deformations can be distinguished.

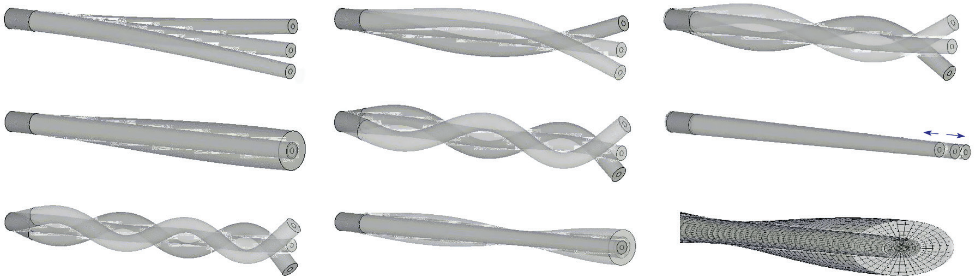

Figure 1: Some typical elastic deformations observed on gun barrels
Source: Compiled by the authors based on Kovács–Béres 2004.

At the varmintal.com website[4] you can see the above elastic deformations in the form of animated GIFs and moving images.

Modelling the vibrations of gun barrels

The calculations and computer modelling are based on harmonic vibrations. It is acknowledged that with this delimitation the generalisability of the model results is impacted, but for reasons of practical feasibility and corroboration of the results, this limit must be made.

3 Future Weapons 2007.
4 For more information see www.varmintal.com/amode.htm

Vibrational reflections

In an infinite rod, vibrations travel at the speed of sound in both directions in response to an impulse. Because of the "finite" nature of a gun barrel, the waves are reflected from both the chambered and muzzle ends and travel to this end until they cease. The vibrations propagate through the material both longitudinally and transversely, which is the reason for the elastic deformations shown in Figure 2, illustrated by strain gauge data.

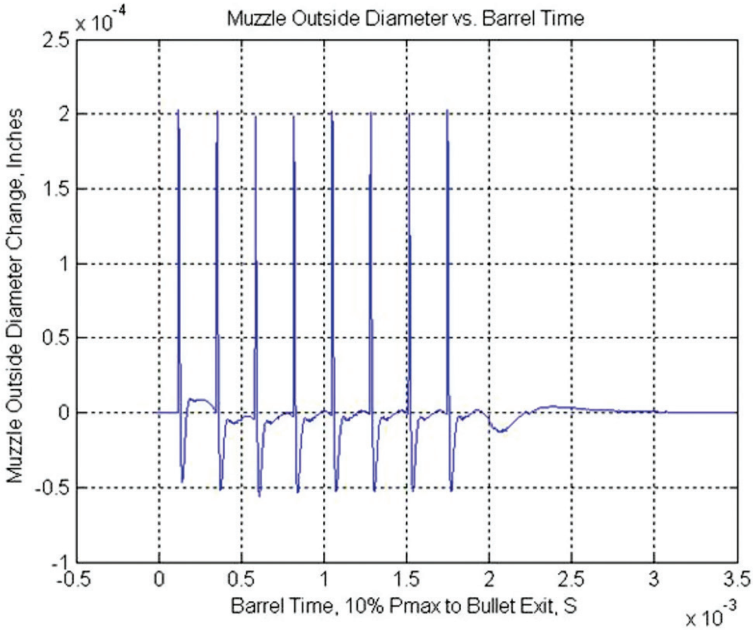

Figure 2: Repetition of vibrations in the gun barrel during the passage of the projectile
Source: Long 2003–2004.

Figure 3 shows an example of how the vibration propagation velocity (Vsteel) and the length of the gun barrel (Lmbarrel length) are used to determine and plot the vibration reflection times. The first complete wave of a vibration wave propagating in steel at a velocity of 5.920 m/s – in this example, a 30-inch (762 mm) path – travels 12 times in the gun barrel.

$Li_{barrel\ lenght}$	30 inch	
$Lm_{barrel\ lenght}$	0.762 m	
V_{steel}	5.920 m/s	
Path of vibration	**Vibration reflection time (T)**	
	ms	*ms*
	odd	*even*
1	0.129	
2		0.257
3	0.386	
4		0.515
5	0.644	
6		0.772
7	0.901	
8		1.030
9	1.158	
10		1.287
11	1.416	
12		1.545

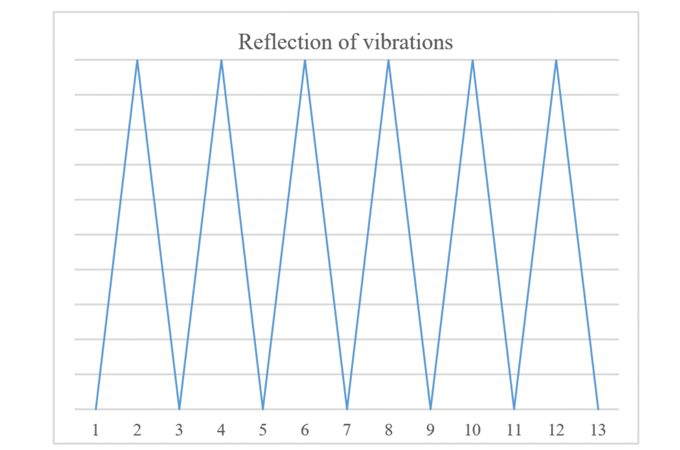

Figure 3: Propagation of barrel vibrations in the gun barrel
Source: Compiled by the author based on www.varmintal.com/amode.htm; https://grtools.de/doku.php

In Figure 4, the results of the *Gordon Reloading Tools* (GRT) internal ballistic planning software are shown in graphical form. The vertical (y) axes represent chamber pressure (bar), projectile velocity (m/s), and projectile energy (J), while the x-axis represents the time the projectile has been in the barrel. In this figure, the time-axis plot is combined with a plot showing the propagation and reflection of vibrations.[5]

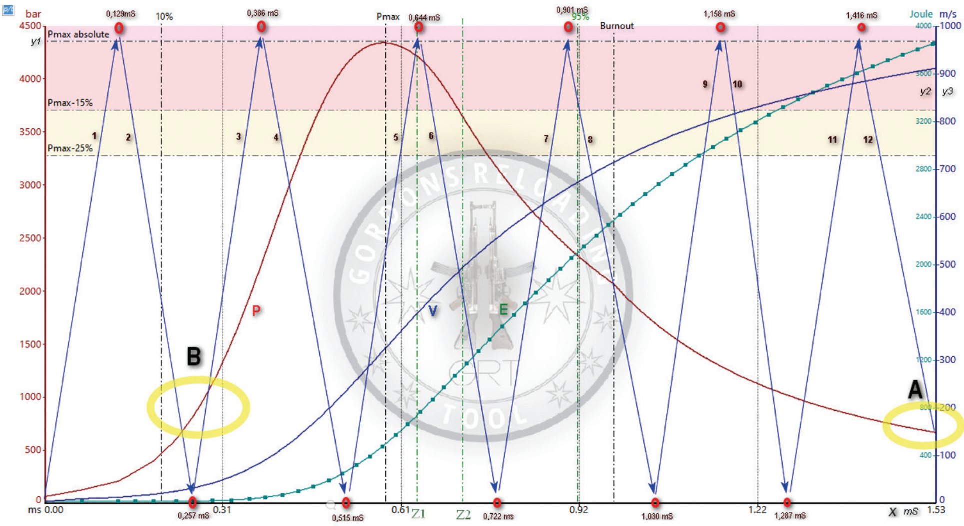

Figure 4: The figure shows the GRT software results for the current charge and the time evolution of the back-and-forth barrel vibrations
Source: Gordon Reloading Tools (GRT) s. a.

[5] Gordon Reloading Tools (GRT) s. a.

See Figure 4 for an explanation of the notations:

- The “P” curve indicates the gas pressure in the space behind the projectile. Its numerical value can be read in the left vertical axis (y1) (bar).
- Curve “V” indicates the current velocity of the projectile. Its numerical value can be read in the right-hand axis (y3) (m/s).
- Curve “E” indicates the energy of the projectile and its numerical value can be read in the inner right axis (y2) (Joule).
- The horizontal (x) axis shows the time the projectile has spent in the barrel, displayed in milliseconds (ms).
- The lines marked with the numbers “1–12” show the path (back and forth) of the vibrations in the barrel (ms).
- The “O” circles indicate each node. This is the time at which the vibration waves reach the end of the gun barrel and propagate back from there. At this point, the end of the barrel is in a “ground state”. If the projectile leaves the muzzle at this time, it will fly in the direction desired by the shooter.
- Point “A” indicates the time at which the projectile leaves the barrel.
- Point “B” marks the beginning of the build-up of gas pressure and the meeting of the vibration waves.
- “10%” – 10% of the powder charge is burnt.
- “Pmax” – maximum gas pressure.
- “Z1” – the limit at which progressive combustion of the gunpowder is transformed into primary-degressive combustion.
- “Z2” – the limit at which primary-degressive combustion of powder becomes secondary-degressive combustion.
- “95%” – the powder charge is 95% burnt.
- “Burnout” – gunpowder charge is completely burnt, no further gas evolution.

Effects of longitudinal vibrations on the scattering pattern – Oscillation, undulation, stretching, etc.

Figure 4 shows the relationship and interaction between the internal ballistic processes calculated by GRT and the harmonics vibrations propagating in the gun barrel, as shown in Figure 3.

Analysing Figure 4, the ideal situation would be to have the last node at 1.53 ms when the projectile leaves the muzzle. At point “A”, it can be observed that the projectile leaves the barrel sooner – i.e. not at the optimal time – thus, it would not pass through its “resting state”. Therefore, the projectile does not travel in the desired direction, but instead in the direction corresponding to the current position of the barrel breech. Since the muzzle “wanders” in a circular pattern due to the vibrations, the scattering pattern also expands in a circular pattern.

The situation can be resolved by *reducing* or *increasing* the projectile velocity. This means varying the powder charge, taking into account the pressure limit of the chamber and, of course, the fulfilment of several pyrotechnical conditions. It can be seen that the nodes are relatively dense, so that a slight shift of the nodes can usually be achieved by changing the charge.

Effect of transverse and longitudinal vibrations on the scattering pattern – Bump, constriction, etc.

The position of point "B" raises an interesting discussion, the pulsating nature of the vibration process propagating in the gun barrel (the contraction and expansion of the barrel bore). As the gun barrel contracts and expands, thus periodically slowing the projectile as it contracts and allowing it to fly more freely due to less friction as it expands, we must infer a motion that is not followed by the internal ballistics modelling programs. The gas pressure is built up in this stage and it is known from István Szajkó's[6] work that the process and conditions of the combustion of gunpowder are crucially impacted by the pressure conditions.

The later "projectile vs. muzzle-bump" encounters are less of a problem, as there is a much larger internal volume behind the projectile, in which the volume change due to pulsation and projectile acceleration has less effect.

Equally important for the accuracy of a weapon is the value of the projectile's *seating depth.* If the projectile is pressed into the transition cone at the end of the rotation-free phase, when the vibration wave is passing around it, the process of press-in may be slowed down, thereby increasing the chamber gas pressure, or, in the case of a muzzle compression, the pressure may be reduced by accelerating. This phenomenon may explain why precision weapons are sensitive to small changes in seating depth, as small as 0.05 mm.

The muzzle-bump migration at the other end of the barrel also raises interesting questions. As shown in the previous sections, the current position and condition of the muzzle of the barrel essentially determines the direction of the projectile's further travel, and therefore it is important to consider whether the muzzle is in a dilated or contracted state when the projectile leaves the barrel.

It can be seen that it is optimal for the muzzle to be in its most narrowed condition when the projectile exits, as this is the best way to control its direction of travel. In an expanded or intermediate state, a poor dispersion pattern similar to that of a fired barrel can be observed.

The principle of optimisation

If the projectile leaves the gun barrel when it is swinging from one phase of vibration to the other and is facing the desired direction of fire, the deflection due to vibrations will be lessened.

[6] István Szajkó (1932–2020) chemical engineer, ballistician. He was one of the leading figures in the production of smokeless gunpowder in Hungary, and was the specialist responsible for gunpowder production at the Nitrochemical Company of Fűzfő (NIKE).

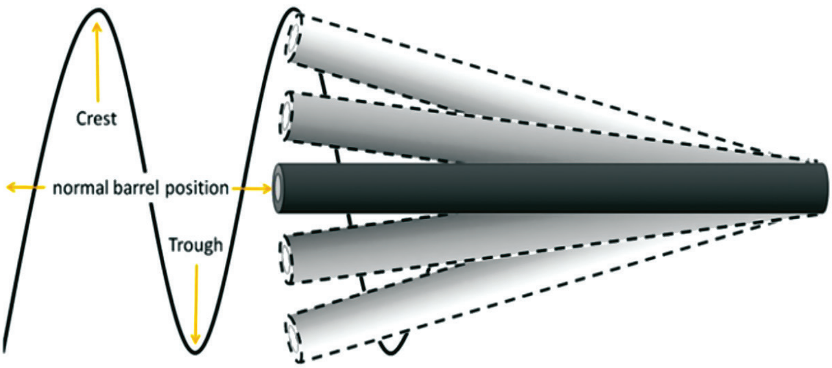

Figure 5: Swings of the gun barrel and change in firing direction
Source: TFB 2021.

In the calculation of the optimal barrel time, these times are determined by calculating the nodes of the harmonic oscillations.

Model for the optimisation of compensator gun barrels

Compensators are becoming more and more common on precision and long-range shooting rifles. These are also referred to as muzzle brakes. However, the term compensator is more appropriate because, in addition to impinging on the outflow of high velocity propellant gases, these devices reduce, or "compensate" for the backward kicking and off-target drift of the weapon by their controlled deflection.

Effect of the compensator on barrel vibrations

When calculating the barrel vibrations, the barrel length determines the temporal "position" of the nodes. In a gun barrel without a compensator, the muzzle is guided by the rifling, determining the direction of travel of the projectile. With a compensator, however, the projectile is flying freely, having already left the muzzle.

If the *Optimum Barrel Time* (OBT) is determined by the original barrel length from the muzzle to the locking plane (cartridge case base), the retrofitted compensator will tune it due to its extra length and weight, as shown in Figure 6.

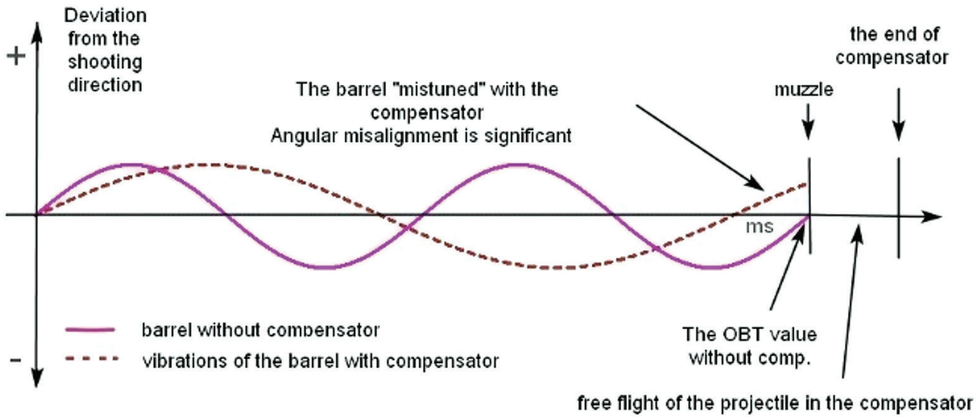

Figure 6: Error of the conventional OBT model for a powder charge optimised for a barrel length without compensator
Source: Compiled by the author based on www.varmintal.com/amode.htm; https://grtools.de/doku.php

If the length of the barrel with the compensator is used as the basis for the calculations, then at the OBT node, the end of the compensator points in the direction of fire, but the projectile is no longer impacted because it has already left the muzzle of the barrel – still inside the compensator, but in the wrong direction. Figure 7 illustrates such a conventional OBT model, where the barrel length is taken as the value plus the compensator, but the calculation is inaccurate due to the "projectile free flight".

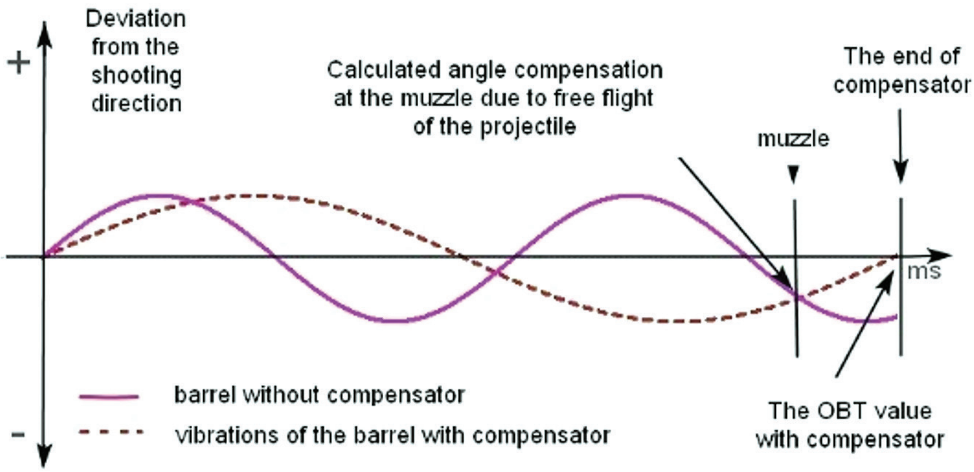

Figure 7: Function of the improved OBT model (barrel with compensator)
Source: Compiled by the author based on www.varmintal.com/amode.htm; https://grtools.de/doku.php

For compensator-equipped barrels, the calculation must be modified by adjusting the OBT. The solution is to increase the value of OBT so that the *compensator end moves over the firing direction allowing the muzzle to point in the correct direction.*

This correction can be determined by calculating the *difference in the period of time between the two vibration waves* and the *time the projectile spends in the compensator.*

The program shown in Figure 8 factors in the effect of the compensator, requires knowing the total length of the barrel with compensator, the internal length of the compensator and the number of the first node as input data for the calculations. In addition, it includes a module for calculating the projectile velocity in relation to the amount of powder used, which is useful for ammunition handloaders.

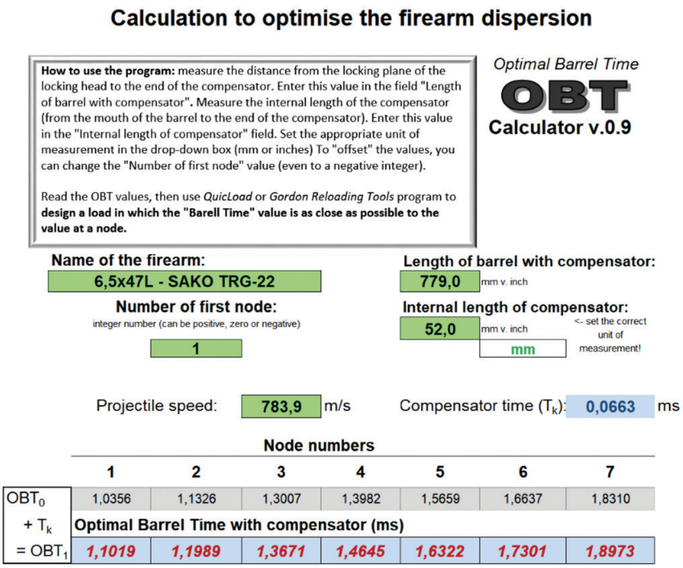

Figure 8: Screenshot of the program which determines the effect of the compensator
Note: Optimal Barrel Time with Compensator (ms) shows the optimal time values for each node.
Source: Compiled by the author based on www.varmintal.com/amode.htm; https://grtools.de/doku.php

Practical validation of the results

We have prepared the shooting control and clarification presented in our study with the above in mind. Using the results of the calculations from the compensator program as a baseline, we prepared some faster loading variations containing more powder and the same number of slower loading variations.

Powder charges were made in 0.2 grain (0.0129 grams) increments, offset in the plus–minus direction from the charge variation calculated by the model. From the resulting ammunition variations, 4 to 4 identical rounds were loaded. Thus, a total of 9 loading variations were produced (–0.8; –0.6; –0.4; –0.2; 0; +0.2; +0.4; +0.6;

+0.8 grains), each with 4 rounds of ammunition. The 36 rounds of ammunition were fired at maximum concentration on a walled range that minimised shooter error and environmental factors, especially wind.

During firing, we attempted to minimise errors due to barrel heating, internal build-up, soiling, and loss of shooter concentration by firing one of each loading variant on each of the bullet plates, with the –4 bullet plate being fired at –0.8 grains, and the –3 bullet plate at –0.6 g (and so on). After one series was completed, the same method as the first was repeated for the second series, and so on.

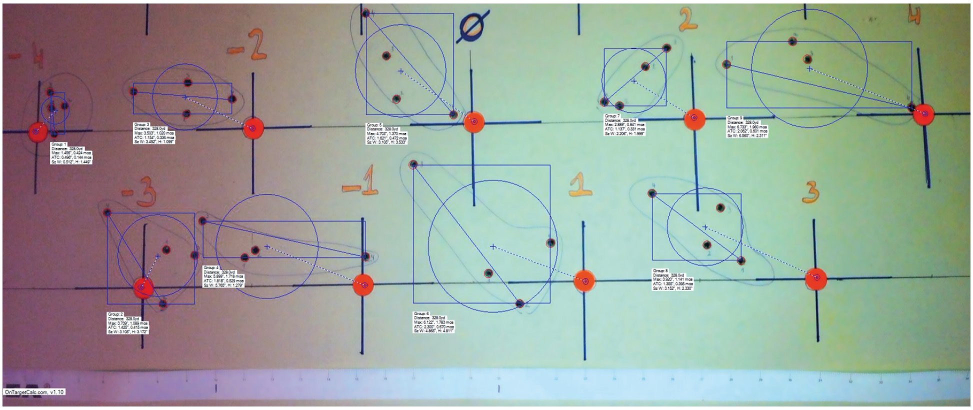

Figure 9: Shooting results

Note: The spread pattern and the graphical and quantified results of the OnTarget scoring software are shown below.

Source: Compiled by the authors based on the OnTarget scoring software.

Figure 9 shows the results of a .308 Winchester rifle fired at 300 meters, evaluated by OnTarget software. In this test, the focus was not on the accuracy of the hits, but on the size of the pattern of dispersion. The ATC (Average to Centre), i.e. the size of the area indicated by the circle, is the most representative indicator of the size of the scatter plot. It can be seen that the gun barrel "throws" the hits associated with each charge at different distances from the target (circle). Characteristic "throw directions" are also observed, indicating the direction of muzzle displacement.

Note that the dispersion plot in the top left of Figure 8 (marked –4) is significantly smaller. Due to the aforementioned limitations of the method, this charge is the guideline for completing the experiments. A further "sensitivity test", possibly in smaller increments, should be carried out around this charge and the subsequent shot charge selected.

Summary

In case of a precision rifle, finding and testing the optimal ammunition load is always very labour-, time- and cost-intensive. Experiments with randomly selected loads would require the selection of hundreds of possible load variations.

The method of calculating the Optimal Barrel Time (OBT) described in our study narrows down the experimental range from hundreds to 8–12 loading variations, which significantly shortens the time required for development. This results in significant resource savings, in addition to firing control.

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