

Design of experiments analysis of a gas-delayed blowback system of operation

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Abstract. The paper presents results of an investigation into a gas-delayed blowback operation firearm system. A recently developed experimental stand was used to this end. In this article, the results are subjected to statistical analysis using design of experiments methods, including response surface methodology (RSM). This analysis facilitates the determination of the significance and nature of parameters such as distance of the gas port from the breech end of the barrel, diameter of the gas port, mass of the recoiling assembly, diameter of the gas piston rod and length of the gas chamber that influence the operation of such systems. The results of the research can be used to validate a mathematical model of a weapon operating on this principle and serve as the starting point for the optimization process of this type of design.

Keywords: internal ballistic; design of experiment; response surface; firearm, numerical simulations.

1. INTRODUCTION

The analysis of the current state of firearms technology operating on the principle of delayed blowback [1] has revealed a scarcity of research specifically addressing weapons functioning based on gas-delayed blowback. This gap in research may stem from the significant limitations on the applicability of this type of system in small arms. However, the authors propose a design solution that addresses many of these limitations. The core mechanism of gas-delayed blowback involves propellant gases entering a gas chamber through a vent in the barrel during firing, and they act on a gas piston to delay the movement of the breech. Figure 1a illustrates an alternative configuration of this system, proposed by the authors, where the propellant gases exert force on the rear surface of the piston. In conventional designs (e.g. the HK P7 pistol, shown in Fig. 1b), propellant gases act on the front face of the gas piston during firing, limiting this design primarily to firearms where the bolt overlaps the barrel. In such designs, a short recoil is usually used, which is easy to implement there. The new approach presented by the authors potentially broadens the applicability of this system to various types of firearms, such as submachine guns, rifles and machine guns.

In this study, a mathematical model for the proposed system was developed [2]. Utilizing this model, theoretical research were carried out [3]. This research was conducted in order to select the input parameters of the object, to establish the nature of this influence (linear, non-linear) and to select the appropriate experimental plan. The insights gained from these studies be-

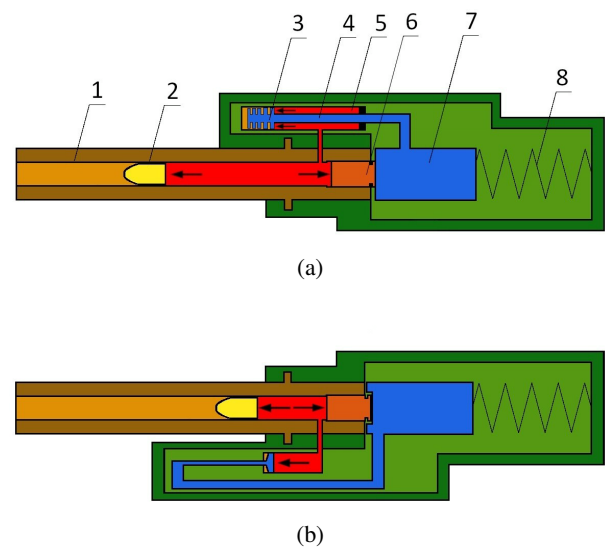


Fig. 1. Scheme of gas-delayed blowback operation firearm: (a) alternative configuration (proposed by the authors), (b) conventional design; 1 – barrel, 2 – projectile, 3 – gas piston 4 – gas piston rod, 5 – gas chamber, 6 – cartridge case, 7 – bolt (recoiling assembly), 8 – recoil spring

came the basis for designing a laboratory stand [4], which was intended to validate the model developed (see Fig. 2). Conference paper [5] presents results for selected configurations from the core of the experimental plan.

This work serves as an extension of that research and includes experimental results for the entire experimental plan and statistical analysis performed based on response surface methodology (RSM) involving the determination of approximating functions for the maximum velocity of the recoiling assembly and the de-

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Manuscript submitted 2025-09-18, revised 2026-01-21, initially accepted for publication 2026-02-04, published in May 2026.

termination of the significance of the coefficients of this function. This study aims to utilize the design of experiments (DoE) and RSM to optimize the performance of a gas-delayed blowback firearm system.

The authors of this article aim to utilize the DoE and RSM methods. An analysis of the latest knowledge in this field has revealed a number of works in this area. Study [6] proposed methodologies for optimizing 3D printing parameters for the extrusion of soft materials in the field of biomedicine. It was hypothesized that combining image processing with the analysis of experiment design and machine learning could aid in obtaining useful information from a project quality perspective. In recent years, the use of DoE and RSM tools in forensic analysis has also increased. Review [7] presents findings from forty peer-reviewed articles that utilized DoE in forensics. The authors of [8] focus on the application of DoE and the benefits derived from it in quality control issues. They emphasize the multitude of fields in which DoE is applicable.

Work [9] demonstrates the use of DoE and RSM to optimize the dynamic and thermal behavior of a synthetic jet in a symmetric two-dimensional configuration composed of the surrounding air.

Despite the wide application of DoE and RSM in various fields of science and engineering, often combined recently with machine learning methods, the authors noted a lack of such publications in the field of weapon design and research. However, a significant potential of these methods was recognized, and it was decided to utilize them.

2. METHODS

The laboratory stand was designed to conduct research based on standardized experimental plans. The Bi plan design for experimental planning, consisting of a core and star points, was employed to conduct the experiment [10–15]. The selection of the plan was based on the conclusions drawn from the work included in paper [4]. The core of the plan is constructed based on a two-level fractional factorial design. In order to reduce the number of experimental plan combinations values X_5 in the core of the plan were calculated from the generating relationship (variables are described in Table 1):

$$X_1 X_2 X_3 X_4 = X_5. \tag{1}$$

Star points of the plan are responsible for the ability to determine the nonlinear influence of parameters on the object. The star arm of the Bi based experimental plan has a value of 1. Therefore, the star points created for normalized (coded) quantities are: -1, 0 and 1. The value of the star arm was one of the crucial reason to choose a Bi based plan due to the structural limitations of the laboratory stand. The resulting experimental design plan includes 26 configurations.

Table 1 lists the values of adjustable parameters of the experimental stand. Parameters and their scope were selected based on theoretical studies described in paper [4].

The experiment plan for normalized quantities is shown in Table 2.

Table 1

Values of changeable parameters of the experimental stand

Label	Name of the parameter	Value		
		-1	0	1
X_1	Distance of the gas port from the breech end of the barrel [mm]	21.5	36.5	51.5
X_2	Diameter of the gas port [mm]	1.0	1.4	1.8
X_3	Mass of the recoiling assembly [g]	360	390	420
X_4	Diameter of the gas piston rod [mm]	4	5	6
X_5	Length of the gas chamber [mm]	91	96	101

Table 2

Experimental plan for normalized values of the factors

Configuration	X_1	X_2	X_3	X_4	X_5
1	-1	-1	-1	-1	1
2	1	-1	-1	-1	-1
3	-1	1	-1	-1	-1
4	1	1	-1	-1	1
5	-1	-1	1	-1	-1
6	1	-1	1	-1	1
7	-1	1	1	-1	1
8	1	1	1	-1	-1
9	-1	-1	-1	1	-1
10	1	-1	-1	1	1
11	-1	1	-1	1	1
12	1	1	-1	1	-1
13	-1	-1	1	1	1
14	1	-1	1	1	-1
15	-1	1	1	1	-1
16	1	1	1	1	1
17	-1	0	0	0	0
18	1	0	0	0	0
19	0	-1	0	0	0
20	0	1	0	0	0
21	0	0	-1	0	0
22	0	0	1	0	0
23	0	0	0	-1	0
24	0	0	0	1	0
25	0	0	0	0	-1
26	0	0	0	0	1

Seven trials were conducted for each configuration, and the order of testing these configurations was randomized. The tests utilized GECO's 9×19 mm PARA FMJ ammunition with an 8 g bullet, all sourced from a single batch. The key parameter identified as having the most significant impact on the operation of a weapon functioning on the principle of gas-delayed blowback

was the velocity of the recoiling assembly. The displacement of the recoiling assembly was measured using a laser displacement sensor Micro-Epsilon IDL 1750-750 connected to a Kistler 2519 transient recorder. Velocity was determined by differentiating displacement using the LOESS algorithm [16] modified in work [17]. Pressure in the gas chamber was measured with a Kistler 6215 sensor connected to the same recorder.

3. RESULTS

Throughout the research conducted, significant data were collected, enabling the verification of some established assumptions. Notably, the results of the study confirmed the effectiveness of the proposed new design of the gas-delayed blowback system. In the evaluated cases, a reduction in the maximum velocity of the recoiling assembly was observed, with a maximum decrease of approximately 21% for the component's largest assumed mass and about 31% for its smallest assumed mass. Figure 2 and Table 3 together present the average maximum velocities of the recoiling assembly for each configuration. Additionally, Figure 3 and Table 3 display results for configurations 27–29. In these configurations, the gas system was deactivated, leaving the mass of the recoiling assembly as the sole variable. Specifically, the masses of the recoiling assembly were 360 g in configuration 27, 390 g in configuration 28, and 420 g in configuration 29. These configurations, representative of the simple blowback system, were included for comparative analysis. And to compare, the maximum velocity of the recoiling assembly for the HK P7 pistol, depending on the ammunition used, is 9.30–9.65 m/s.

Table 3

Summary of average maximum velocities of the recoiling assembly (where: CN – configuration number, V_{RA} – average maximum velocity of the recoiling assembly, $S(z)$ – standard deviation)

CN	V_{RA} [m/s]	$S(z)$ [m/s]	CN	V_{RA} [m/s]	$S(z)$ [m/s]
1	8.52	0.27	16	7.19	0.31
2	8.48	0.31	17	7.17	0.21
3	7.68	0.38	18	7.73	0.27
4	8.46	0.55	19	7.79	0.26
5	7.07	0.22	20	7.30	0.25
6	7.45	0.16	21	8.34	0.07
7	6.78	0.33	22	7.07	0.14
8	7.10	0.37	23	7.61	0.15
9	9.07	0.38	24	7.48	0.16
10	8.87	0.19	25	7.56	0.16
11	7.42	0.50	26	7.64	0.20
12	8.36	0.20	27	9.20	0.14
13	7.59	0.18	28	8.18	0.26
14	7.68	0.14	29	7.63	0.31
15	6.84	0.26			

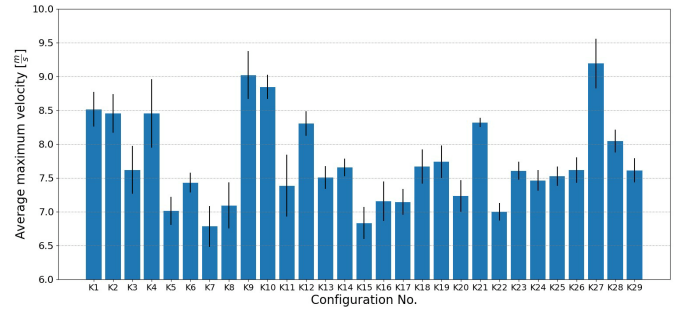


Fig. 2. Results of average maximum velocities of the recoiling assembly

The analysis of the research results for average maximum velocities of the recoiling assembly, based on the lowest standard deviations $S(z)$, suggests that the system operated most stably in the intermediate configurations 21–26. The results for configurations 6 and 14 also are characterized by high repeatability. These are configurations in which there is a combination of the smallest gas port placed furthest from the breech end of the barrel. Taking into account the results of the gas chamber pressure measurement (Table 4), it can be concluded that the high repeatability is due to the limited gas-delay action in these configurations.

Significant issues were noted during the study. A notable problem involved fragments of projectile jackets entering the gas chamber. This issue was specific to configurations where the gas port was located 21.5 mm from the breech end of the barrel, with the port situated 0.5 mm from the edge of the cartridge case, measured tangentially. Pistol propellant is known for its rapid attainment of maximum pressure, which can lead to significant deformation of the bullet jacket in the initial phase of movement.

While this deformation may positively interact with the barrel's grooves, the presence of a hole in the barrel at this distance leads to the jacket being cut and its fragments being pushed into the gas chamber. In configurations with the gas port placed at 36.5 mm and 51.5 mm from the breech end of the barrel, this problem was not observed. Results analysis indicates that this issue does not have a statistically significant impact on the repeatability of the weapon's automatic operation. However, it is important to highlight that the entry of projectile jacket fragments into the gas chamber is highly undesirable in firearm applications.

Figure 3 and Table 4 present the measurements of the average maximum pressures in the gas chamber for each configuration.

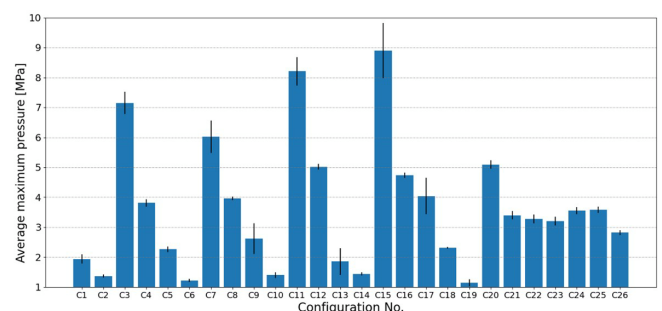


Fig. 3. Results of average maximum pressures in the gas chamber

Table 4

Summary of average maximum pressures in the gas chamber (where: CN – configuration number, P_{GC} – average maximum pressure in the gas chamber, $S(z)$ – standard deviation)

CN	P_{GC} [MPa]	$S(z)$ [MPa]	CN	P_{GC} [MPa]	$S(z)$ [MPa]
1	1.94	0.17	14	1.44	0.06
2	1.37	0.06	15	8.95	1.00
3	7.16	0.41	16	4.74	0.10
4	3.81	0.13	17	4.07	0.65
5	2.27	0.10	18	2.32	0.03
6	1.22	0.06	19	1.15	0.12
7	6.07	0.58	20	5.09	0.15
8	3.96	0.06	21	3.40	0.15
9	2.64	0.55	22	3.28	0.16
10	1.40	0.10	23	3.20	0.16
11	8.21	0.51	24	3.55	0.12
12	5.02	0.11	25	3.58	0.11
13	1.86	0.48	26	2.82	0.09

The analysis of the research results for average maximum pressure, based on the standard deviations $S(z)$, shows that results for configurations where the gas port is located closest to the breech end of the barrel (C3, C7, C9, C11, C13, C15 and C17) are characterized by the greatest uniqueness. Taking this into account, the authors conclude that the reason for the relatively high non-repeatability of maximum pressure in the gas chamber, significantly higher than in other cases, was the previously mentioned fragments of the projectile jacket entering the gas chamber. It can be observed that the spread of pressures in the gas chamber does not significantly translate into the non-repeatability of the maximum velocity of the recoiling assembly. This is particularly evident in configurations where the port is closest to the breech end of the barrel. The most representative example is evident in the results for configuration No. 15. This may indicate the system's resistance to non-repeatable shooting conditions caused, for example, by the ammunition.

4. STATISTICAL ANALISYS

The study analyses a method for assessing the significance of coefficients in an approximating function. This function represents the response surface of an object determined experimentally. In our factor analysis, which considers five factors, we utilized a quadratic function to approximate the experimental results. The use of the "Bi Plan" approach enabled this specific method of approximation. Table 5 presents the characteristics of the experimental research object along with the statistical parameters.

Based on the experimental results, coefficients of the approximating function were determined, as shown in Table 6. The approximation was based on the least squares method.

Table 5

Characteristics of the research object

Parameter	Symbol	Value
number of repetitions	r	7
number of treatments	n	26
frequency	f	156
significance level	α	0.05
variance of the object	$S^2(z)$	0.076
standard deviation of the object	$S(z)$	0.277
limiting error of the object	e	0.547

Table 6

Matrix of coefficients of the function of the object

Coefficient label	Coefficient matrix (value)	The parameter to which the coefficient applies
b_0	7.515	b_0
b_1	0.177	X_1
b_2	-0.299	X_2
b_3	-0.580	X_3
b_4	0.075	X_4
b_5	0.006	X_5
b_6	-0.064	X_1^2
b_7	0.028	X_2^2
b_8	0.194	X_3^2
b_9	0.031	X_4^2
b_{10}	0.082	X_5^2
b_{11}	0.135	$X_1 X_2$
b_{12}	-0.021	$X_1 X_3$
b_{13}	-0.017	$X_1 X_4$
b_{14}	0.044	$X_1 X_5$
b_{15}	0.071	$X_2 X_3$
b_{16}	-0.119	$X_2 X_4$
b_{17}	-0.016	$X_2 X_5$
b_{18}	0.020	$X_3 X_4$
b_{19}	0.042	$X_3 X_5$
b_{20}	-0.111	$X_4 X_5$

Accordingly, the approximating function is of the following form:

$$\begin{aligned}
 f_A(X_1, X_2, X_3, X_4, X_5) = & 7.515 + 0.177X_1 - 0.299X_2 \\
 & - 0.580X_3 + 0.075X_4 + 0.006X_5 - 0.064X_1^2 \\
 & + 0.028X_2^2 + 0.194X_3^2 + 0.031X_4^2 + 0.082X_5^2 \\
 & + 0.135X_1X_2 - 0.021X_1X_3 - 0.017X_1X_4 + 0.044X_1X_5 \\
 & + 0.071X_2X_3 - 0.119X_2X_4 - 0.016X_2X_5 + 0.020X_3X_4 \\
 & + 0.042X_3X_5 - 0.111X_4X_5.
 \end{aligned} \quad (2)$$

In the next step of the analysis, the adequacy of the function of the object will be assessed. Checking the adequacy of the function was carried out based on the 3 tests outlined below.

Fisher-Snedecor test

Firstly, the Fisher-Snedecor test was applied. Using the previously determined coefficients of the object function, the approximated values of the output were calculated. Based on them, the adequacy variance $S^2(z)_a = 0.12058$ and frequency $f_a = 5$ were calculated. In the next step, the random variable $F = 1.56686$ could be identified. Comparing the obtained F value to the critical $F_{kr} = F_{\alpha, f, f_a} = 2.27214$ value, calculated for the adopted significance level α , with the values of f_a and f , it was found that the condition $F \leq F_{\alpha, f, f_a}$ is satisfied, which in turn proves that the function is adequate.

Multiple correlation coefficient

The second method used to assess the adequacy of the function was the multiple correlation coefficient. The calculated R -coefficient can take values in the range of $[0, 1]$. As it approaches 1, the correlation improves, and conversely, the closer the R value is to 0, the worse the correlation is. In this case the obtained value of $R=0.9956$ can be considered as a very good correlation.

Estimation of the approximation error and comparison with the assumed acceptable value of this error

The third method was to assume an acceptable value of approximation error and to compare the estimated approximation error with this value. According to this criterion, an approximation is adequate if the approximation error does not exceed the assumed value. The acceptable value of the approximation error can be the same as the standard deviation of the object or limiting error of the object. The approximation error can be defined in various ways. Since the object function approximation procedure used was the least squares method, the mean square error of the approximation was used as an estimation of the approximation error. In this case, the mean square error of the approximation was $M = 0.05756$, and it was compared with the standard deviation of the object $S(z) = 0.27741$. The mean square error of the approximation is distinctly lower than the standard deviation of the object, which is a condition to consider the function as adequate. To make the criterion more reliable, the maximum absolute error of the approximation $\Delta_{z_{\max}} = 0.14343$ was compared to the limiting error of the object $e = 0.54797$. In this case, the error which describes approximation was also lower than the error from the object, which also indicates the adequacy of the function.

Verification of the significance of the coefficients of the object function

In many cases, the coefficients of the object function take small values. To assess whether a parameter significantly influences the output quantity – as opposed to being a result of random disturbances and measurement errors – it is necessary to verify the significance of these coefficient values using the Student's

t-test. This analysis requires fulfilling certain conditions: the coefficients should be based on normalized values of input parameters and set within a symmetric and identical interval for each parameter. Additionally, the variance of the object's imprecision and the degrees of freedom should either be determinable or already known.

Therefore, it is necessary to determine the value of the random variable t :

$$t = t(b_m) = \frac{|b_m|}{S(b_m)}, \quad (3)$$

where: b_m – value of the m -th coefficient of the object function, $S(b_m)$ – standard deviation of the verified coefficient:

$$S(b_m) = \sqrt{M_{mm}^{-1} S^2(z)}, \quad (4)$$

where: M_{mm}^{-1} – diagonal element of the inverse matrix of the information matrix (suitable for a given verified coefficient).

Comparing the value of variable t to the critical value (for frequency f and the assumed level of significance α), it is verified whether the coefficient is significant. The calculated critical value is 1.975.

In addition, significance level values were determined, using a two-sided Student's t-distribution. The significance level is usually taken to be within the $[0.01, 0.1]$ bracket.

Based on the above, it was determined that the simplified function containing only significant coefficients has the following form:

$$f_A(X_1, X_2, X_3, X_4, X_5) = 7.702 + 0.177X_1 - 0.299X_2 - 0.580X_3 + 0.135X_1X_2 - 0.119X_2X_4. \quad (5)$$

Please note that none of the X_i^2 parameters (quadratic) is included in the simplified object function.

Checking the adequacy of the new function was conducted again based on the 3 tests outlined below.

Fisher-Snedecor test

The adequacy variance in this case $S^2(z)_a = 0.31705$ and frequency $f_a = 20$ were calculated. In the next step the random variable $F = 4.11978$ was identified. Comparing the obtained F value to the critical $F_{kr} = F_{\alpha, f, f_a} = 1.63825$ value, the condition $F \leq F_{\alpha, f, f_a}$ is not fulfilled, which indicates that the function is not adequate.

Multiple correlation coefficient

The calculated multiple correlation coefficient was $R = 0.95191$, which indicates a relatively weak fit of the approximating function.

Estimation of the approximation error and comparison with the assumed acceptable value of this error

For approximating function (5) the mean square error of the approximation was $M = 0.18666$, i.e. a value lower than the standard deviation of the object. Maximum absolute error of the approximation $\Delta_{z_{\max}} = 0.44631$ was also lower than the limiting

error of the object. This results can indicate that the function is adequate.

Analysis of the correctness of the method of assessing the significance of the coefficients and the search for an alternative method

The values of the coefficients of the approximating function are calculated by multiplying the inverse information matrix by the one-column right-hand side matrix:

$$b_i = \sum_{j=1}^{N_b+1} M_{ij}^{-1} c_j. \quad (6)$$

The right-hand side matrix is obtained by multiplying the transposed experiment plan matrix by the one-column average value matrix:

$$c_j = \sum_{k=1}^n X_{jk}^T \bar{z}_k. \quad (7)$$

The values of the elements of the transposed experiment plan matrix for plans with a star arm equal to 1 are of the order of magnitude of unity. Thus, it can be assumed that the uncertainty of the mean values is transferred to the c_j values. This means that the average variance of the c_j values is equal to the variance of object S^2 .

In the case of a linear function, the inverse information matrix is a diagonal matrix. Therefore:

$$b_i = M_{ii}^{-1} c_i. \quad (8)$$

In the literature [8, 10] it is assumed that the variance of the b_i coefficient is proportional to the corresponding diagonal element of the M^{-1} matrix. This is the basis for evaluating the standard deviation of the b_i coefficient:

$$S_{b_i} = \sqrt{S^2 M_{ii}^{-1}}. \quad (9)$$

Thus, the statistic for the Student's t-test can be defined as follows:

$$t = \frac{|b_i|}{\sqrt{S^2 M_{ii}^{-1}}}. \quad (10)$$

Determining the critical value of t enables the assessment of a given coefficient's significance. However, when evaluating the coefficients using the Student's t-test, it was found that only some coefficients met the significance condition at the specified significance level. Furthermore, the simplified function failed to meet the adequacy condition.

The inadequacy of the method for assessing coefficient significance in a nonlinear function becomes evident in Fig. 4, which displays a comparison of the coefficients absolute values. Bars indicating the coefficients that meet the significance condition (from the first simplification, excluding parameters whose significance level values, as determined by a two-sided Student's t-distribution, were below 0.1) are highlighted in red.

Comparing these values with those of other coefficients suggests that the influence of some additional coefficients cannot be disregarded. This observation necessitates a reevaluation of the current method for assessing coefficient significance and prompts the exploration of alternative approaches.

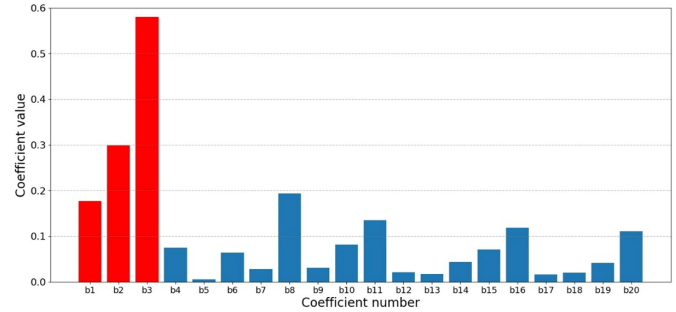


Fig. 4. Comparison of the coefficients absolute values

The method for assessing coefficient significance, as developed in the literature, is primarily designed for linear regression. In light of this, the authors of this paper have endeavored to extend this method to approximate using a linear combination of arbitrary functions. In this approach, individual functions are considered explanatory variables, and the accompanying coefficients represent the impact of each function. However, this methodology yields accurate results only if all functions vary within the same range.

This uniformity is absent in the case of the quadratic function. Expressions containing a quadratic term vary within the range of $[0, 1]$, while others fluctuate within the range of $[-1, 1]$. This discrepancy results in the inverse information matrix being non-diagonal, with the matrix being diagonal for linear terms and for products of input quantities, but not for quadratic terms and the constant term b_0 . Consequently, this discrepancy renders the method unsuitable for assessing the significance of coefficients in this context.

Based on (6), we can estimate the variance of the b_i coefficient as:

$$S_{b_i}^2 = \sum_{j=1}^{N_b+1} M_{ij}^{-1} S^2 = S^2 \sum_{j=1}^{N_b+1} M_{ij}^{-1}. \quad (11)$$

Since the sum occurring in the formula can have a negative value, it is possible to assume its absolute value in the following formula:

$$S_{b_i}^2 = S^2 \left| \sum_{j=1}^{N_b+1} M_{ij}^{-1} \right|. \quad (12)$$

Thus, the standard deviation of the coefficient from the formula was calculated:

$$S_{b_i} = \sqrt{S^2 \left| \sum_{j=1}^{N_b+1} M_{ij}^{-1} \right|}. \quad (13)$$

For a diagonal matrix, (13) is equivalent to (8). With regard to the inverse information matrix, the non-diagonal members ap-

pear in the row referring to the coefficient b_0 and the coefficients: b_6 to b_{10} . Using (13), the results were obtained. Compared to the previous assessment, the coefficients at X_3^2 and X_5^2 were also assessed as significant. Thus, we can simplify the approximating function to the form below:

$$f_A(X_1, X_2, X_3, X_4, X_5) = 7.514 + 0.177X_1 - 0.299X_2 - 0.580X_3 + 0.192X_3^2 + 0.080X_5^2. \quad (14)$$

The F-test for the adequacy of the simplified function was negative. Some of the approximated $f_A(X_1, X_2, X_3, X_4, X_5)$ values differed significantly from the measured values. This indicates that the attempt to modify the method of assessing the significance of coefficients fails. This raises the question regarding the applicability of the F-test for adequacy assessment. This test has also been adapted from linear regression methods. Let us then consider other tests.

The mean squared error of approximation was 0.20, and it is lower than the standard deviation of the object, which is 0.28. Maximum absolute error of approximation in this case was 0.59 and it's of a higher value than the limiting error of the object, which is 0.55. This results may indicate inadequacy of the function.

The assessment of the significance of the coefficient values aims to eliminate those coefficients whose values affect the values of the approximating function at the level of random disturbances. In the case of coefficients at linear terms, the evaluation of standard deviation can be made using (9). For all these coefficients, the value of standard deviation is the same and can be taken as a measure of the impact of random disturbances on all other coefficients. It amounts to 0.065. To take into account the impact of randomness, similarly to the Student's t criterion, we multiply it by the critical value of the variable $t = 1.975$. The obtained value of 0.128 can be adopted as a measure of the impact of random disturbances on the values of coefficients.

Based on the values of the coefficients, we can conclude that the approximating function should include coefficients b_1 , b_2 , b_3 , b_8 , and b_{11} . Additionally, coefficients b_{16} and b_{20} , which are close to the threshold value, can be included. Let us then adopt the approximating function in the following form:

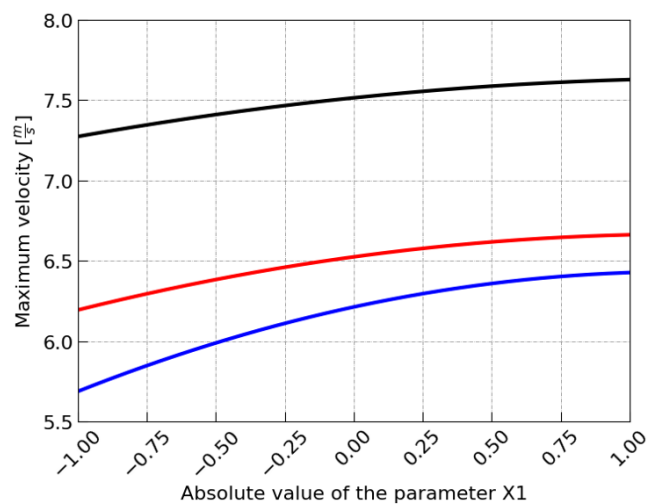
$$f_A(X_1, X_2, X_3, X_4, X_5) = 7.534 + 0.177X_1 - 0.299X_2 - 0.580X_3 + 0.243X_3^2 + 0.135X_1X_2 - 0.119X_2X_4 - 0.111X_4X_5. \quad (15)$$

The F value of 1.93 is higher than the critical value of 1.67, and the multiple correlation coefficient of 0.98. This suggests that the function may be inadequate. The mean squared error of approximation is equal to 0.121, which is lower than the standard deviation of the object. The maximum absolute error of approximation was also lower than the limiting error of the object. Based on the error method, it can be concluded that the function is adequate. This implies that the simplest criteria provide the best assessment of the function's adequacy in this case. These criteria are not based on those used in linear regression methods.

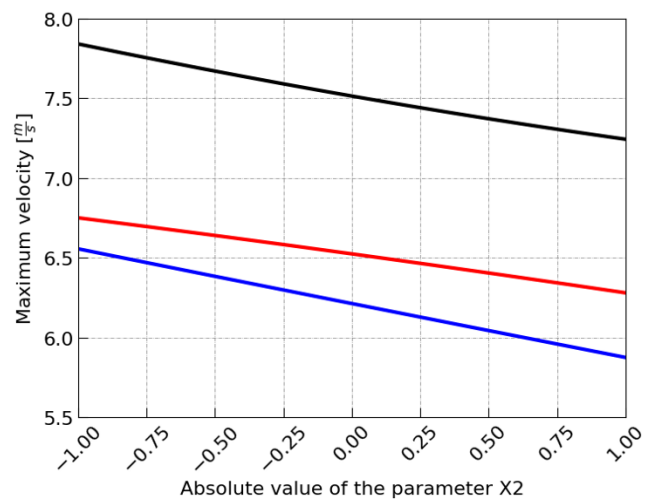
Certain conclusions can be drawn from the analysis of the significance of coefficients. The dependence on the variable X_3 is clearly non-linear. The dependence on parameters X_1 and X_2 can be considered linear against random dispersion. However, these parameters have an influence through their interaction. This means that changes in the value of one parameter affect the dependence on the other parameter. The dependence on factor X_4 and X_5 occurs only by their interaction. Since the product of these parameters defines the volume of the gas chamber, this may indicate a linear dependence on the gas chamber's volume rather than on each of the parameters separately. Of course, such a dependence may occur, but it is insignificant against random disturbances.

Comparison of experimental results with theoretical model

In the studies referenced in [3], efforts were made to simulate phenomena and establish their parameter relationships. Figure 5, displayed below, offers a comparison between experimental results and simulation outcomes. These graphs illustrate how the output parameter (maximum velocity of the recoiling

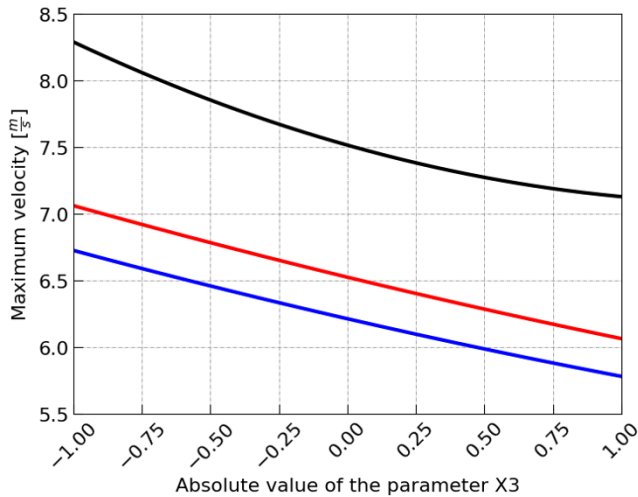


(a)

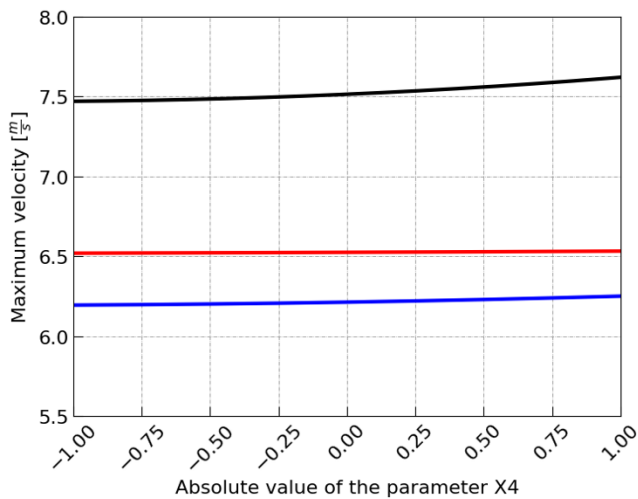


(b)

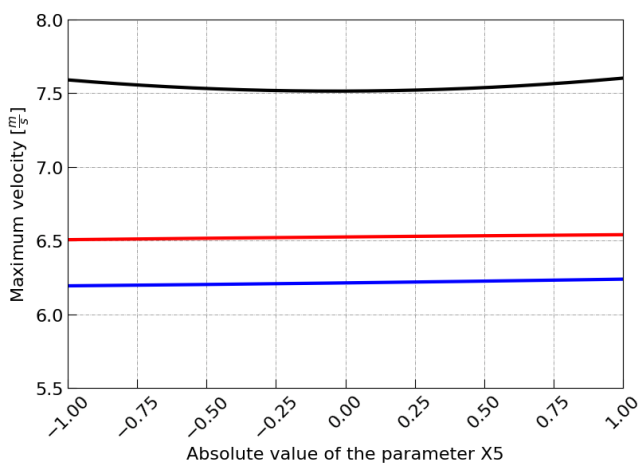
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(c)



(d)



(e)

Fig. 5. Maximum recoiling assembly velocity as a function of parameter X_1 – X_5 : black line – experiment, red line – simulation (gas flow coefficient value of 0.5), blue line – simulation (gas flow coefficient value of 1)

assembly) varies with changes in one input parameter, while keeping the other input parameters constant at their central values. Simulations were conducted with the coefficient of gas flow loss from the barrel to the gas chamber set at 1 (represented by the blue line) and 0.5 (represented by the red line).

The adequacy of the functions derived from the simulation model, in comparison to those obtained from experimental results, was evaluated using the multiple correlation coefficient. The results fall within the range of 0.789–0.829 for the gas flow coefficient equal to 1, and 0.854–0.872 for 0.5.

The multiple correlation coefficient does not exceed 0.87, indicating that the function inadequately mirrors the required level. This suggests that the simulation model needs refinement due to significant discrepancies when compared to experimental results. Nevertheless, the qualitative dependence of the recoiling assembly maximum velocity on the parameters is reflected properly by the theoretical model. This confirms that the approach applied to designing the experimental stand, based on the results of a not fully identified theoretical model, was correct. Now, the experimental results can be used to improve the theoretical model. The discrepancies between the experimental results and the results of the theoretical model are likely to be caused by the choice of the characteristics of the propellant. The model utilizes data from other studies, while the characterization of the propellant used in the experimental studies has not yet been completed.

It is noteworthy that for a gas flow coefficient of 0.5, the correlation is consistently better across all parameters as compared to a coefficient of 1. This observation implies that the initially assumed value of 1 may be too high. Consequently, a thorough analysis of the model is necessary to establish a coefficient value that more accurately reflects the actual phenomena.

5. CONCLUSIONS

- The study results confirmed the effectiveness of the proposed new design of the gas-delayed blowback system. In the evaluated scenarios, a notable reduction in the maximum velocity of the recoiling assembly was observed. Specifically, there was a maximum decrease of approximately 21% for the component's largest assumed mass, and around 31% for its smallest assumed mass.
- The study revealed significant issues, particularly the entry of projectile jacket fragments into the gas chamber. This problem was specific to configurations with the gas port located 21.5 mm from the breech end of the barrel. Despite not having a statistically significant impact on the maximum velocity of the recoiling assembly, the presence of jacket fragments in the gas chamber is highly undesirable for maintenance. Notably, this issue was absent from the configurations in which the gas port was placed at 36.5 mm and 51.5 mm from the breech end.
- The research indicates that greater distance of the gas port from the breech end of the barrel enhances the repeatability of pressure in the gas chamber, with maximum pressure variations within 4%. The high non-repeatability of cham-

ber pressure is mainly attributed to the entry of projectile jacket fragments. However, this pressure variability does not significantly impact the velocity of the recoiling assembly, highlighting the system's resilience to inconsistent firing conditions.

- The method of assessing the significance of coefficients' values for the approximating function based on the Student's t-test cannot be applied in the case of a quadratic function. This is due to the way standard deviation of the coefficients is estimated.
- The mass of the recoiling assembly (X_3) has the greatest impact on the gas delayed blowback system's operation. Additionally, the analysis showed that this impact is nonlinear.
- The dependence on distance of the gas port from the breech end of the barrel (X_1) and diameter of the gas port (X_2) can be considered linear against random dispersion. Moreover, these parameters have an influence through their interaction.
- The dependence on diameter of the gas piston rod (X_4) and length of the gas chamber (X_5) occurs by their interaction. Since the product of these parameters defines the volume of the gas chamber, this may indicate a linear dependence on the gas chamber's volume rather than on each of the parameters separately.
- The interaction between the diameter of the gas port (X_2) and the diameter of the gas piston rod (X_4) also affects the system. This is likely due to a change in the nature of the flow of propellant gases into the gas chamber when these parameters are altered.

The article confirms the feasibility of using DOE and RSM in the field of automatic firearm design. Additionally, the obtained data can serve as a basis for the validation of mathematical models and for conducting the optimization process of such designs. The tools developed in this way can be used in the process of designing new types of weapons, accelerating and reducing the cost of this process.

However, this approach is not without its drawbacks. Firstly, the object's function is validated only within a specific range of input parameters for which the experimental studies were conducted. Additionally, such methods can be applied to objects that allow for the adjustment of input parameters, which in the examined field necessitates the creation of specialized testing facilities.

In addition, the effectiveness of the modified automatic operation system of the firearm with a delayed blowback with gas-delay was confirmed. This creates opportunities to use this type of system in practically any type of firearm.

Based on the results obtained, the authors intend to modify and validate the developed mathematical model. They also plan to analyze issues related to the flow loss coefficient, focusing on its determination and its dependence on the design parameters of the system.

ACKNOWLEDGEMENTS

This work was financed by Military University of Technology under research project UGB/829/WAT.

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