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DEVELOPMENT OF A METHOD FOR DETERMINING THE WEAR OF AN ARTILLERY MOUNT BARREL UNDER CONDITIONS OF UNCERTAIN DISTURBANCES BASED ON FUZZY LOGIC AND STOCHASTIC MODELING

The object of research is the processes of determining the wear of gun barrels and controlling the firing of artillery mounts under conditions of uncertain disturbances. This work addresses the problem of ensuring the adequacy of determining the current wear of the barrel and adaptive adjustment of the settings of the artillery mount when firing in short series from different positions. At the same time, the research considered the effect of random disturbing influences on the mount, including the failure of the projectile leading belt and the low quality of the powder charge.

The research used fuzzy logic methods to calculate the current value of barrel wear based on the parameters of the ballistic wave of the shot and taking into account the total gun firing. Also, stochastic modeling methods, in particular, Markov chains, were used to simulate the processes of firing under conditions of random disturbances.

A method for determining the current barrel wear based on fuzzy logic has been developed and investigated, which allows for adaptive adjustment of artillery mount settings when firing in short bursts under conditions of uncertain disturbances. To correctly determine wear, the proposed method uses three information channels, including the dominant frequency and depth of frequency modulation of the ballistic wave, as well as the total gun firing rate.

The results of computational experiments were obtained, confirming the high efficiency of the developed method in comparison with other known methods. In particular, an increase in firing efficiency by 14.5% and a reduction in the time spent at firing positions by 3 min. were achieved when compared with the most effective method using measurements of the dominant frequency of the ballistic wave.

The developed method can be used for diagnostics and control of modern artillery systems to increase firing efficiency and reduce the time spent at firing positions.

Keywords: *artillery firing, barrel wear determination, fuzzy logic, rule base, stochastic modeling.*

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1. Introduction

The combat operations of military conflicts of the last decade are characterized by the widespread use of the latest technologies, ranging from tactical-level strike drones to intelligent systems of automated command and control of troops in real time. However, along with unmanned systems and other types of high-precision weapons, barreled field and long-range artillery still remains a fairly effective means of fire destruction [1]. Modern approaches to the use of artillery mounts and complexes involve the transition from massive fire over areas to pinpoint strikes on targets in the near rear. At the same time, such use of artillery requires constant improvement of laying, control and correction systems.

Modern research in this area is conducted both to improve individual indicators and to generally increase the effectiveness of artillery mounts and systems [2]. One of the most promising areas is the improvement of mathematical support, which allows taking into account an increasing number of external factors to improve the accuracy and range of fire. In particular, mathematical and simulation models have been developed that allow taking into account various meteorological conditions [3], as well as rounding errors of aiming angles and the influence of the Coriolis effect when calculating projectile flight trajectories [4]. Also, a significant increase in accuracy can be achieved when using a modified projectile model with five degrees of freedom [5].

Special attention is paid to research aimed at developing new tactical techniques and approaches to the use of artillery, including integration with other types of modern weapons [6]. Thus, in the works [7, 8] new methods for solving counter-battery combat problems using UAVs and radar networks, respectively, are considered.

Also, a general increase in the efficiency of artillery systems can be achieved by improving intelligent methods for optimizing and controlling individual mechanisms of mounts. Namely, in [9] a hybrid approach based on a neural network with radial basis functions and a genetic algorithm was proposed for finding the optimal design parameters of an artillery mount in order to increase the accuracy of fire. In [10] an improved heuristic multi-agent method was developed for optimizing the parameters of the control system for the mechanisms of raising and rotating the gun barrel.

However, the vast majority of the considered methods and approaches have significant limitations when applied in conditions of large-scale and protracted high-intensity war [11]. The above conditions are primarily characterized by a shortage of serviceable guns and a large number of assigned fire missions, a shortage and low quality of ammunition, as well as a counter-battery factor and a large number of enemy unmanned surveillance vehicles. These factors significantly reduce the overall effectiveness of artillery use, and in some cases completely make it impossible to perform the assigned fire missions [12]. In turn, the first two factors lead to the need to fire an excessive number of shots per gun in a short period of time, which causes the most undesirable disturbance – barrel wear. This disturbance significantly reduces the initial velocity of the projectile and, accordingly, the probability of an accurate shot even at the nominal values of all other parameters and settings [13]. The third factor significantly increases the requirements for the consumption of ammunition allocated for the destruction or defeat of one target. The fourth factor creates additional uncertain disturbances, which also reduce the accuracy and range of fire. Thus, if low-quality ammunition accidentally gets into the gun's ammunition and is subsequently used, the current shot will most likely be ineffective. Accordingly, the last two factors significantly reduce the permissible safe time for the gun to stay in the firing position and increase the risk of it being hit by the enemy after the first shot. This, in turn, further increases the requirements for the time of execution of the assigned fire tasks.

Thus, for the effective execution of fire tasks by artillery systems under the above conditions, it is necessary to assess the wear of the barrels and constantly make adjustments in real time, taking into account all the above factors. In [14], a method for determining the wear of the gun barrel by measuring the projectile's departure speed by an acoustic signal has already been developed. However, under the influence of random disturbances in the form of low quality of the ammunition used, the presented method may incorrectly estimate the current wear, since it does not allow to determine the cause of the decrease in the initial velocity of the projectile. Therefore, there is a need to create an improved method that will correctly determine the current wear of the gun barrel under the influence of uncertain disturbances and will allow to adjust the settings in the presence of other complicating factors. To establish the cause of the decrease in the velocity of the projectile in the specified method, it is advisable to use several input channels of heterogeneous information. Therefore, this method should be based on a mathematical apparatus that will allow to effectively formalize heterogeneous input data in conditions of uncertainty and incomplete or inaccurate information. Also, the main calculations performed should be logically transparent and easily interpreted so that artillery system operators can monitor the correctness of the work. From this point of view, the use of fuzzy logic looks quite promising in this case [15]. Fuzzy logic models make it possible to perform calculations with heterogeneous data, given with errors or with the presence of noise, quite easily [16]. The use of linguistic terms and membership functions of various types allows to operate with qualitative estimates and to approximate complex multidimensional nonlinear dependencies [17]. In turn, the representation of these dependencies in the form of sets of relatively simple and intuitive rules gives these models logical transparency [18]. In addition, the use of human knowledge and accumulated experience of operators makes systems based on fuzzy logic intelligent [19].

To study the effectiveness of the proposed method, it is also necessary to develop a simulation model of artillery firing under conditions of uncertain disturbances and the above-mentioned limitations. For this purpose, it is advisable to apply stochastic modeling methods, which will allow evaluating the main indicators of firing quality in different scenarios and with different initial data [20].

The object of research is the processes of determining the wear of gun barrels and controlling the firing of artillery mounts under conditions of uncertain disturbances.

The aim of research is to increase the efficiency of artillery firing and reduce the time the gun stays at firing positions by developing a method for determining the current wear of the barrel and adaptively adjusting the settings under conditions of uncertain disturbances based on fuzzy logic and stochastic modeling.

To achieve the aim, it is necessary to solve the following objectives:

1. To form a step-by-step structure of the method for determining the current barrel wear and adaptive adjustment of the artillery mount settings under conditions of uncertain disturbances.
2. To synthesize a fuzzy model for calculating the current barrel wear of a gun.
3. To develop a stochastic simulation model of artillery mount firing under conditions of uncertain disturbances.
4. To conduct a series of computational experiments based on the simulation model of firing to study the effectiveness of the developed method.

2. Materials and Methods

The research used fuzzy logic methods to calculate the current barrel wear value based on the parameters of the ballistic wave of the shot and taking into account the total gun firing. Also, in the process of studying the effectiveness of the proposed method for determining barrel wear, stochastic modeling methods were used. In particular, Markov chains and a probabilistic-analytical approach to modeling random processes were implemented to simulate series of artillery shots under conditions of uncertain disturbances.

This work considers the artillery fire tactics "shoot-and-scoot" [21], which is one of the most effective in conditions of counter-battery factor and the presence of a large number of unmanned enemy observation vehicles. This tactic involves cyclic firing by an artillery mount in short series of shots alternately from different pre-prepared positions. Fig. 1 shows a schematic representation of the mount's action cycle when implementing the considered tactic.

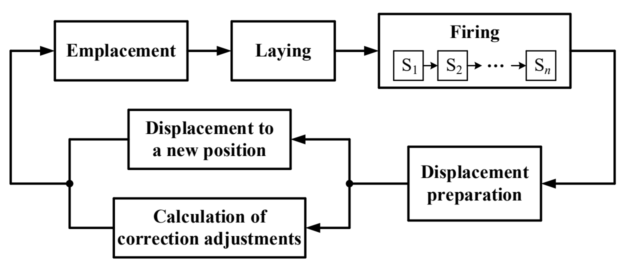

Fig. 1. Schematic of the artillery firing cycle when implementing the "shoot-and-scoot" tactic

In particular, after emplacement at one firing position, the mount carries out laying according to pre-calculated settings and performs a short firing series (firing) of several shots ($S_1, S_2, ..., S_n$) with the minimum possible time between shots. In this case, a series of 3–5 shots is optimal. Next, the artillery mount is immediately rolled up (displacement preparation) and moved to another position (displacement to a new position), after which this cycle is repeated again. Also, during the movement, the computing module calculates correction adjustments to laying the mount to a new position and execute effective shots. The mount exits the above cycle and moves to a safe place of long-term basing can be implemented upon receipt of information about the destruction of the target or after executing the maximum, previously specified, number of shots. Moreover, in the first case, the exit can be carried out after executing any of the considered in Fig. 1 operations, and in the second – after the firing series.

The main advantage of using the considered tactics is that the calculation of correction adjustments for laying before the next series is carried out during the movement, and not at the firing position. This allows to minimize the time spent at the firing positions and, accordingly, reduce the risk of the artillery mount being hit by enemy counter-battery fire.

The calculation of the correction parameters of the firing during the movement of the mount is carried out on the basis of the built-in ballistic models, taking into account the topographic reference of the next position, current weather data and other available information. To increase the accuracy of the calculations, a modified model with five degrees of freedom of the projectile can be used as a ballistic model [5]. However, regardless of the accuracy of the ballistic model used, a fairly significant permanent disturbance that can significantly worsen the accuracy of firing or even make it ineffective is the wear of the gun barrel [22]. In turn, the current value of barrel wear W_b gradually increases with the increase in the total number of shots fired N_{sh} by a given gun [23]. As expression (1) [14] shows, the existing non-zero value of barrel wear W_b primarily reduces the initial projectile departure velocity υ_0

$$\upsilon_0 = \upsilon_{0n} F_w \left(1 - W_b\right), \tag{1}$$

where υ_{0n} – the nominal value of the initial velocity of the projectile; F_w – some empirical function.

This does not allow an effective shot to be made even with the nominal values of all other parameters and high accuracy of ballistic calculations. In this case, a shot is considered effective if the fired projectile lands within the given permissible dispersion ellipse [24].

Thus, regardless of the available ballistic model, when calculating adjustments during the movement of the mount, it is necessary to have reliable information about the current barrel wear and make appropriate corrections to the initial velocity of the projectile. At the same time, to achieve the highest accuracy of adjustments for the next series of shots, it is advisable to determine the current value of wear on the last shot of the previous series. The simplest solution is to use a model approach that involves determining the wear W_b by the value of the total barrel shot N_{sh} based on a certain empirical dependence. For example, the dependence can be used for this

$$W_b = \frac{1}{1 + e^{-\frac{k_r}{N_{sh0.5}}\left(N_{sh} - N_{sh0.5}\right)}}, \tag{2}$$

where $N_{sh0.5}$ – the value of the shot at which the gun barrel is worn out by 50% ($W_b = 0.5$); k_r – an empirical coefficient.

When applying this dependence, the values of $N_{sh0.5}$ and k_r are set for each specific type of artillery system. However, a significant drawback of this approach is that it does not take into account the operating conditions of the artillery mount, the quality of the shells and charges used, as well as other factors that can significantly accelerate barrel wear. Also, in addition to the slow gradual accumulation of wear during normal shots, a random stepwise disturbance may occur during an abnormal shot, which will cause a one-time jump-like increase in the wear value W_b. Such a disturbance is the disruption of the projectile leading belt, which causes some damage to the barrel rifling. If a disturbance (anomaly) of this type appears in a certain shot of the current series, it will not be taken into account using expression (2) during the adjustments made after this series during the movement process. This will lead to the fact that all subsequent series of shots from new firing positions will be ineffective with a high probability.

The method given in [14] is devoid of these shortcomings, which allows experimentally determining the projectile departure velocity υ_0 for each current shot with its subsequent conversion into the corresponding value of barrel wear W_b. In this method, the initial projectile velocity υ_0 is determined by the dominant frequency of the ballistic wave spectrum f_{dom} formed during its departure, using a set of acoustic sensors installed next to the gun. In turn

$$f_{dom} = \arg\max_f S\left(f\right), \tag{3}$$

where $S(f)$ – the amplitude spectrum of the signal.

When an anomaly occurs in the form of a disruption of the projectile's leading belt, this method will allow the current wear W_b to be determined by the value of the dominant frequency f_{dom} and the necessary adjustments to be made before the next series of shots.

However, in addition to the above-mentioned predicted and random disturbances, there is another type of anomaly in which the initial velocity of the projectile υ_0 can drop abruptly without a sharp increase in wear W_b. This anomaly can be caused by the low quality of the charge used in the current shot. At the same time, if the charge of the next shot is of normal quality, then all indicators, including the initial velocity υ_0, will be within the nominal values, and this shot will be effective with a high probability. In this case, the method considered in [14] will not allow to distinguish the cause of the anomalous decrease in velocity υ_0 and will consider it as a sharp increase in wear W_b. If such an anomaly occurs at the beginning or inside the firing series, this will in no way affect the effectiveness of the next series, since the wear value will be determined correctly on the last shot. At the same time, if an anomaly of this type appears on the last shot, further corrective calculations will be incorrect, and the entire next series will most likely be ineffective. To overcome the shortcomings of both of the above approaches (model and experimental), an improved method is proposed in this work, which will allow to establish the cause of the decrease in velocity υ_0 and correctly determine the current wear W_b of the barrel. Thus, if any of the considered anomalous disturbances occur in the last shot of the series, the adjustments will be made correctly, which will allow to maximize the efficiency of the next firing series. For this, in addition to determining the dominant frequency f_{dom}, it is necessary to introduce two additional information channels. As the first additional channel, which will allow to distinguish the types of random disturbances, it is advisable to choose the depth of frequency modulation of the ballistic wave M_{bw}, which is calculated based on the expression

$$M_{bw} = \frac{f_{max}\left(t\right) - f_{min}\left(t\right)}{f_{mean}}, \tag{4}$$

where f_{max}, f_{min}, f_{mean} – the values of the maximum, minimum and average frequencies of the ballistic wave per shot.

With low charge quality (the second type of anomaly), the projectile exits the barrel with a reduced speed, but the process of its movement in the barrel remains more or less stable. This corresponds to insignificant fluctuations in the frequency of the ballistic wave, and the modulation depth in this case is very small or equal to zero ($M_{bw} \approx 0$). In turn, when the leading belt of the projectile breaks (the first type of anomaly), in addition to a decrease in the initial speed, the obturation is disturbed, pressure fluctuations increase, which, accordingly, creates larger fluctuations in the frequency of the ballistic wave. Thus, when an anomaly of the first type appears, the modulation depth is significantly greater than zero ($M_{bw} \neq 0$).

As a second additional channel, which will allow taking into account a priori information about the current value of barrel wear, the total gun shot N_{sh} should be selected.

Therefore, in the proposed method, the current value of wear W_b for each shot will be determined based on the dependence

$$W_b = F\left(N_{sh}, f_{dom}, M_{bw}\right). \tag{5}$$

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After finding this value for the last shot of the current series, adaptive adjustment of the artillery mount settings for the next firing series will be performed.

Since certain inaccuracies may occur when evaluating the input variables N_{sh}, f_{dom} and M_{bw}, it is advisable to formalize the dependence (5) in the proposed method based on fuzzy logic [25]. In this case, the most appropriate is to build a fuzzy model of the Mamdani type, which will allow creating an intuitively understandable rule base and fairly easy interpretation of the obtained results [26].

The first 2 variables (N_{sh} and f_{dom}) should be fuzzified using 5 linguistic terms (LT) for each with Gaussian functions of the first kind. For example, for the variable N_{sh} this function has the form

$$\mu\left(N_{sh}\right)=e^{-\frac{\left(N_{sh}-b\right)^2}{2a^2}}. \tag{6}$$

For fuzzification of the third variable M_{bw}, it is logical to choose two LTs with trapezoidal MFs, since when determining anomalies it can take only 2 states (zero or non-zero modulation depth). For these functions, the expression is used

$$\mu(M_{bw})=\begin{cases}0, \text{ at } M_{bw}\le a;\\ \dfrac{M_{bw}-a}{b-a}, \text{ at } a<M_{bw}\le b;\\ 1, \text{ at } b<M_{bw}\le c;\\ \dfrac{d-M_{bw}}{d-c}, \text{ at } c<M_{bw}<d;\\ 0, \text{ at } M_{bw}\ge d.\end{cases} \tag{7}$$

For granulation of the working range of the output variable W_b, it is most appropriate to choose 7 terms with triangular MFs described by the dependence

$$\mu(W_b)=\begin{cases}0, \text{ at } W_b\le a;\\ \dfrac{W_b-a}{b-a}, \text{ at } a<W_b\le b;\\ \dfrac{c-W_b}{c-b}, \text{ at } b<W_b<c;\\ 0, \text{ at } W_b\ge c.\end{cases} \tag{8}$$

In turn, in expressions (6)–(8) the parameters a, b, c, d are adjustable coefficients of functions.

When creating the rule base (RB) of this fuzzy logic model, each rule will be given in the form of the expression

$$\begin{aligned}&\text{IF "}N_{sh}=LT_{1ini}\text{" AND "}f_{dom}=LT_{2inj}\text{"AND "}M_{bw}=LT_{3inl}\text{"}\\ &\text{THEN "}W_b=LT_{outk}\text{"},\end{aligned} \tag{9}$$

where LT_{1ini}, LT_{2inj}, LT_{3inl} – the i-th, j-th and l-th linguistic terms of the corresponding input variables; LT_{outk} is the k-th LT of the output variable of the model. Moreover, $i \in \{1, ..., 5\}$, $j \in \{1, ..., 5\}$, $l \in \{1, 2\}$, $k \in \{1, ..., 7\}$.

The size of this RB s (total number of rules) is determined by the product of the values of the number of linguistic terms of each input variable and in this case is equal to 50 ($s = 5 \cdot 5 \cdot 2 = 50$). At the same time, when determining and establishing consequences for each of the RBs, it is advisable to adhere to the following logic. If there is a discrepancy between the values of the total firing N_{sh} and the dominant frequency f_{dom}, and the modulation depth M_{bw} is zero, then when determining the wear W_b, it is necessary to focus more on the value of the firing N_{sh}. In the opposite case (the modulation depth M_{bw} is non-zero) – on the value of the dominant frequency f_{dom}.

As computational procedures for aggregation, activation and accumulation, it is advisable to establish standard operators for a fuzzy mechanism of the Mamdani type [27]. The most suitable method for implementing the defuzzification procedure in this case is the center of gravity method.

To study the effectiveness of the proposed method and compare it with the other two considered approaches, it is necessary to develop a stochastic simulation model of the process of cyclic firing of an artillery mount in short series under conditions of uncertain disturbances. This model should consist of two main components. The first component, using a probabilistic-analytical approach, will allow quantitatively assessing the effectiveness of a firing series based on calculating the mathematical expectation of the number of successful shots (hits). At the same time, when calculating the mathematical expectation, three different states should be distinguished, for which this value will be calculated differently. If, before the current firing series, the determination of wear W_b and the corresponding corrective settings were made correctly, the artillery mount is in the S_C state – series after correct adjustments. In the opposite case (due to the appearance of an anomaly in the last shot of the previous series), the mount is in the S_I state – firing series after incorrect adjustments. The mount can enter the third state S_{2I} if 2 series in a row were ineffective due to incorrect previous adjustments or other reasons. After this event occurs, in order to prevent further ineffective firing, unnecessary ammunition consumption, increased risks and equipment wear, the mount ceases fire and is removed from the combat mission. Next, it is withdrawn from the firing zone to further clarify the reasons for ineffective operation.

Thus, for the S_C state, the mathematical expectation E_C will be calculated as follows. When an anomaly of the first type (shell belt rupture) appears on any of the shots in the series, to simplify the calculations, it is possible to take the pessimistic scenario as a basis. Namely, it is possible to assume that this occurred on the first shot in the series, so all shots in this series will have the same (low) probability of hits p_{a1}. The probability of such an event (shell belt rupture at least once in the series) will be denoted as p_{sa1}. Accordingly, the probability that this will not happen in the current series is $1 - p_{sa1}$. If the series of shots does not have an anomaly of the first type, then when each of its shots is fired, one of two events is possible: a shot without an anomaly, a shot with an anomaly of the second type (low-quality charge). The probabilities of the occurrence of these options are p_{swa} and p_{sa2}. In turn, $p_{swa} + p_{sa2} = 1$. Also, the probabilities of hitting in these options, respectively, are p_{wa} and p_{a2}. Thus, the mathematical expectation E_C for the firing series in this case will be determined by the expression

$$E_C=n\left(p_{swa}p_{wa}+p_{sa2}p_{a2}\right)\left(1-p_{sa1}\right)+np_{sa1}p_{a1}, \tag{10}$$

where n – the number of shots in the firing series.

In turn, for the S_I state, the mathematical expectation E_I will be calculated based on the expression

$$E_I=np_{ic}, \tag{11}$$

where p_{ic} – the probability of hitting each shot in the firing series after incorrect adjustments.

For the third state, since the shooting stops, the mathematical expectation will always be equal to 0.

The second component of the simulation model will allow simulating the process of possible transitions between the S_C, S_I and S_{2I} states from cycle to cycle. It is advisable to build the above component on the basis of the Markov chain [28]. In turn, this Markov chain has the structure presented in Fig. 2, where the notation is adopted: p_{CI} – the probability of transition from the S_C state to the S_I state; p_{IC} – the probability of returning from the S_I state to the S_C state; p_{CC} – the probability that the mount will remain in the S_C state in the current cycle; p_{I2I} – the probability of transition from state S_I to state S_{2I}.

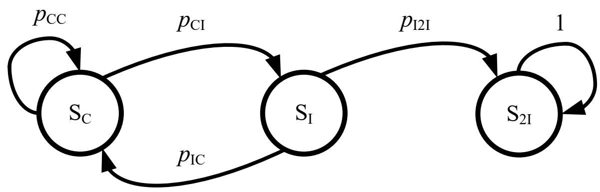


Fig. 2. Structure of a Markov chain for modeling transitions between states during cyclic firing of an artillery mount

Transitions from S_C to S_{2I}, from S_{2I} to S_C or S_I are impossible, therefore the corresponding probability values are equal to 0. The probability that the mount will remain in the S_I state is 0, since in this case the transition to the S_{2I} state occurs immediately. The probability that the mount will remain in the S_{2I} state is 1, since in this case the firing stops, and the Markov process is completed. Thus, the S_{2I} state is absorbing.

Based on this Markov chain (Fig. 2), it is possible to form the corresponding transition probability matrix **P**

$$\mathbf{P}=\begin{pmatrix} p_{CC} & p_{CI} & 0 \\ p_{IC} & 0 & p_{I2I} \\ 0 & 0 & 1 \end{pmatrix}. \tag{12}$$

In order to calculate the values of all probabilities of the matrix **P** on the k-th firing cycle of the mount, it is necessary to raise this matrix to the power of k.

To combine the two considered components into a single stochastic simulation model, it is necessary to apply the probability distribution vector $\boldsymbol{\theta}$. In turn, the value of this vector on each k-th cycle can be calculated using the expression

$$\boldsymbol{\theta}_k=\begin{pmatrix}\theta_{Ck} & \theta_{Ik} & \theta_{2Ik}\end{pmatrix}=\begin{pmatrix}\theta_{C0} & \theta_{I0} & \theta_{2I0}\end{pmatrix}\begin{pmatrix} p_{CC} & p_{CI} & 0 \\ p_{IC} & 0 & p_{I2I} \\ 0 & 0 & 1 \end{pmatrix}^k. \tag{13}$$

To calculate the total value of the mathematical expectation of the number of hits E_k on the k-th firing cycle, it is advisable to apply the following matrix equation

$$E_k=\boldsymbol{\theta}_k\mathbf{E}=\boldsymbol{\theta}_0\mathbf{P}^k\mathbf{E}, \tag{14}$$

where $\boldsymbol{\theta}_0$ – the row vector of the initial probability distribution (before the first firing cycle); **E** – the column vector of the mathematical expectations E_C, E_I and 0 in the states S_C, S_I and S_{2I}, respectively. In turn

$$\mathbf{E}=\begin{pmatrix} E_C \\ E_I \\ 0 \end{pmatrix}. \tag{15}$$

Thus, the total value of the mathematical expectation E_Σ of the number of hits after executing m planned firing series can be calculated based on the expression

$$E_\Sigma=\sum_{k=1}^{m}E_k=\sum_{k=1}^{m}\boldsymbol{\theta}_0\mathbf{P}^k\mathbf{E}. \tag{16}$$

Also, based on this equation, it is possible to determine the required minimum number of firing series m_{min} to achieve the desired value of the mathematical expectation of the number of hits $E_{\Sigma D}$ required to destroy the target. Further, based on this value, it is possible to calculate the total firing efficiency η and the total time the mount stays at the firing positions t_Σ. In turn:

$$\eta=\frac{E_\Sigma}{m_{min}n}; \tag{17}$$

$$t_\Sigma=m_{min}t_s, \tag{18}$$

where t_s – the execution time of one firing series (together with emplacement, laying and displacement).

In addition, based on the expression (13), for each k-th firing series, it is possible to determine the probability θ_{2Ik} of the system entering the S_{2I} state and completing the firing.

The following section presents a step-by-step method for determining barrel wear and adaptive adjustment of artillery mount settings under conditions of uncertain disturbances. Also, synthesized models are presented: fuzzy-logical – for calculating the current value of gun barrel wear; simulation – for simulating short-burst firing processes under conditions of uncertain disturbances. To study the effectiveness of the developed method and fuzzy model, computational experiments are conducted with a detailed discussion of the results obtained.

3. Results and Discussion

3.1. Formation of a step-by-step structure of the method for determining barrel wear and adaptive adjustment of artillery mount settings under conditions of uncertain disturbances

To build a method for determining barrel wear and adaptive adjustment of artillery mount settings under conditions of uncertain disturbances, the implementation of the following step-by-step procedure is proposed.

Step 1. Initialization. In this step, the preliminary parameters necessary for determining gun barrel wear and performing further corrective settings are set. In particular, the values of the current N_{sh0} and the maximum possible N_{shmax} of the shot, which leads to complete wear of the gun barrel, are set. In addition, the minimum f_{dommin} and maximum f_{dommax} values of the dominant frequency of the ballistic wave and the maximum value of the modulation depth M_{bwmax} are set. Also, at this step it is necessary to set the number of shots in one firing series n and all the necessary parameters for carrying out corrective ballistic calculations (coordinates and data of topographic reference of the available firing positions and targets, meteorological data, etc.). In turn, the minimum and maximum values f_{dommin}, f_{dommax}, N_{shmax} and M_{bwmax} are set for each specific artillery system to normalize the corresponding input variables before they are fed to the input of the fuzzy model.

Step 2. Measurement of the acoustic signal of the ballistic wave of the last shot from the current series. At this step, the measurement of the ballistic wave signal of the n-th shot from the m-th firing series is performed using acoustic sensors installed near the artillery mount.

Step 3. Determination of the parameters of the ballistic wave of the shot from the acoustic signal. At this step, based on the measured ballistic wave signal for the last shot from the current series, the parameters f_{dom}, f_{max}, f_{min}, f_{mean} and M_{bw} are determined. At the same time, the depth of frequency modulation of the ballistic wave M_{bw} is determined based on expression (4).

Step 4. Normalization of input variables of the fuzzy model. At this step, based on the values of the current shot N_{sh}, the frequency f_{dom} and the modulation M_{bw} obtained in the previous steps, their normalized values N^*_{sh}, f^*_{dom} and M^*_{bw} are calculated in relative units. This allows the fuzzy model to be used in the proposed method as a universal tool for determining the wear value for artillery systems of various types. In particular, the normalized data values of the three input variables of the fuzzy model are calculated based on the dependencies:

$$N^*_{sh}=\frac{N_{sh0}+kn}{N_{shmax}}; \tag{19}$$

$$f_{dom}^{*}=\frac{f_{dom}-f_{dommin}}{f_{dommax}-f_{dommin}};\qquad(20)$$

$$M_{bw}^{*}=\frac{M_{bw}}{M_{bwmax}},\qquad(21)$$

where k – the number of the current firing series, which consists of n shots, $k\in\{1, ..., m\}$.

Step 5. Determining the current value of wear W_b using a fuzzy model. In this step, based on the normalized values of the variables N_{sh}, f_{dom} and M_{bw} obtained in the previous step, the corresponding current value of gun barrel wear W_b is calculated using a fuzzy logic model.

Step 6. Adjusting the artillery mount settings. In this step, the artillery mount settings are adjusted taking into account the value of gun barrel wear W_b obtained in the previous step. These adjustments are made based on the ballistic model used and are used for laying at the next firing position.

The above method is used for each firing series to determine the current value of gun barrel wear and make corrective settings for the next series. When unspecified disturbances appear in the form of the above-considered anomalies of the first and second types in the current firing series, this method will allow to correctly determine the current wear W_b. This will allow to effectively conduct the next firing series and, accordingly, to increase the overall efficiency of firing and reduce the total time the mount is in firing positions. To implement the proposed method, a system for diagnosing barrel wear and adaptive adjustment of artillery mount settings can be used, the structure of which is shown in Fig. 3.

In the considered structure (Fig. 3), the ASS (acoustic sensor system) measures the ballistic wave signal bw_s during the last shot of the artillery mount in each firing series. The corresponding output signals ASS are fed to the ASPU (acoustic signal processing unit), which determines the parameters f_{dom} and M_{bw}. The DNU (data normalization unit) normalizes the variables N_{sh}, f_{dom} and M_{bw} and transfers them to the input of the fuzzy model. In turn, the fuzzy model, based on the received data, calculates the current value of the barrel wear W_b and transfers it to the fire monitoring and control unit. The specified unit, based on the value W_b, the previously specified mount data $\mathbf{U}_S$, as well as the data received in real time about the state of the mount $\mathbf{Y}_{AM}$ and the environment $\mathbf{X}_A$, makes adaptive adjustments. The corresponding vector of all adjusted laying parameters $\mathbf{U}_L$ before each new firing series is transmitted to the mount before its arrival at the new firing position. In addition, the fire monitoring and control unit constantly records the value of the total gun fire N_{sh} and transmits it to the DNU unit.

Below is the development of a fuzzy model that is used to calculate the current value of gun barrel wear.

3.2. Development of a fuzzy model for calculating the current value of gun barrel wear

Since the variables N_{sh}, f_{dom}, M_{bw} are fed to the input of the fuzzy model in a normalized form, and the wear W_b is primarily a relative value, the operating ranges [0, 1] were selected for all variables. For the selected linguistic terms of the model, certain fixed values of the parameters of their membership functions were set within these ranges (Table 1).

After setting the parameters of the terms, a fuzzy logic model rule base was synthesized, which reproduces the basic logic of determining the wear of the gun barrel depending on the shot, dominant frequency and depth of frequency modulation. Each rule of this RB is given in the form of equation (9). For convenience, the synthesized rule base is presented in matrix form in Table 2. In turn, the cells of the leftmost column, the top row and the rightmost column contain the LTs of the corresponding input variables, the combinations of which form the antecedents of the rules. The internal cells of Table 2 contain the LTs of the output variable, which act as the corresponding consequents.

Three-dimensional graphs of the dependence of wear on the selected input variables, which are constructed on the basis of a fuzzy model with a synthesized RB, are shown in Fig. 4, *a*, *b*.

In turn, Fig. 4, *a* shows a graph of the dependence of barrel wear on the firing rate and dominant frequency at a fixed modulation depth of 0.05. Fig. 4, *b* shows a graph of the dependence of wear on the firing rate and dominant frequency at a fixed modulation depth of 0.5.

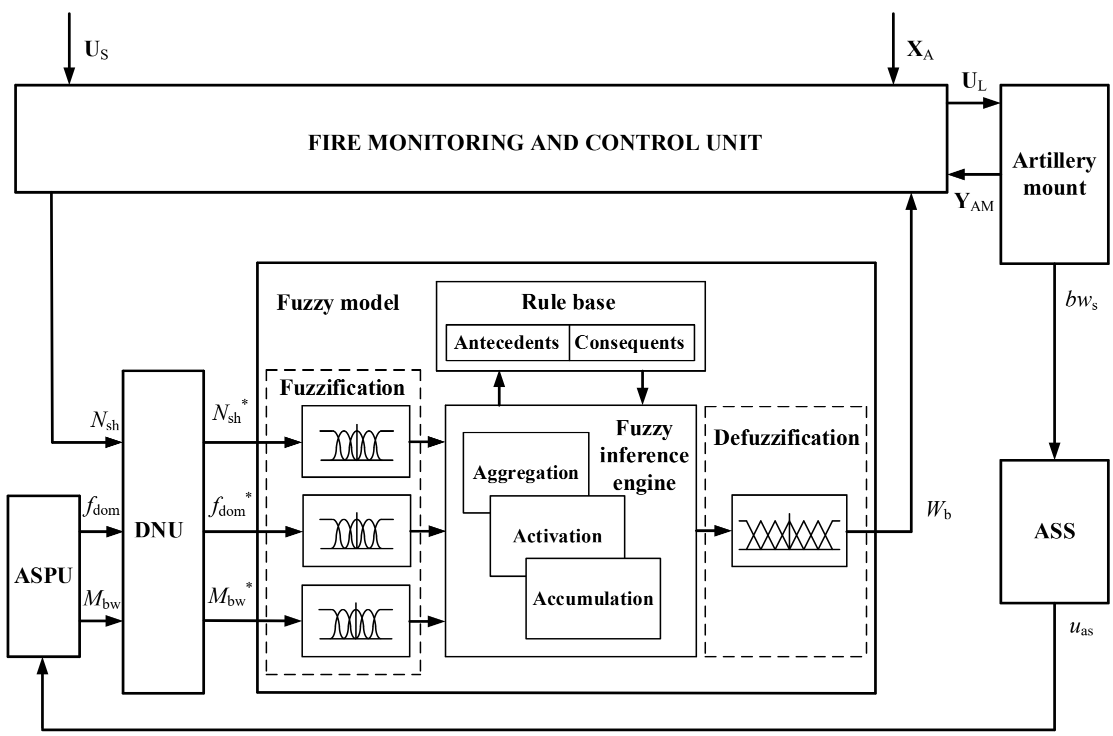


Fig. 3. Structure of the barrel wear diagnostics system and adaptive adjustment of artillery mount settings

Table 1

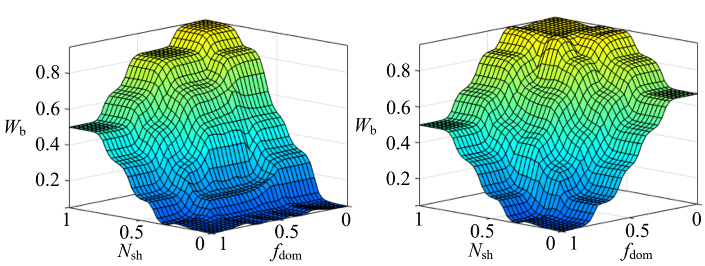
Parameters of the fuzzy-logical model's LTs

No.	LT	MF	Parameter values
Input variable N_{sh} (total number of shots fired)			
1	VS – very small	Gaussian	$a = 0.15$; $b = 0$
2	S – small	Gaussian	$a = 0.0528$; $b = 0.35$
3	A – average	Gaussian	$a = 0.0528$; $b = 0.5$
4	B – big	Gaussian	$a = 0.0528$; $b = 0.65$
5	VB – very big	Gaussian	$a = 0.15$; $b = 1$
Input variable f_{dom} (dominant frequency)			
1	VS – very small	Gaussian	$a = 0.15$; $b = 0$
2	S – small	Gaussian	$a = 0.0528$; $b = 0.35$
3	A – average	Gaussian	$a = 0.0528$; $b = 0.5$
4	B – big	Gaussian	$a = 0.0528$; $b = 0.65$
5	VB – very big	Gaussian	$a = 0.15$; $b = 1$
Input variable M_{bw} (modulation depth)			
1	Z – zero	trapezoidal	$a = 0$; $b = 0$; $c = 0.1$; $d = 0.3$
2	NZ – non-zero	trapezoidal	$a = 0.1$; $b = 0.3$; $c = 1$; $d = 1$
Output variable W_b (gun barrel wear)			
1	NB – new barrel	triangular	$a = 0$; $b = 0$; $c = 0.167$
2	VSW – very small wear	triangular	$a = 0$; $b = 0.167$; $c = 0.333$
3	SW – small wear	triangular	$a = 0.167$; $b = 0.333$; $c = 0.5$
4	AW – average wear	triangular	$a = 0.333$; $b = 0.5$; $c = 0.667$
5	BW – big wear	triangular	$a = 0.5$; $b = 0.667$; $c = 0.833$
6	VBW – very big wear	triangular	$a = 0.667$; $b = 0.833$; $c = 1$
7	CWO – completely worn out	triangular	$a = 0.833$; $b = 1$; $c = 1$

Table 2

Matrix of the rule base of the fuzzy logic model

LT for N_{sh}	LT for f_{dom}					LT for M_{bw}
	VS	S	A	B	VB	
VS	NB	NB	NB	NB	NB	Z
S	SW	VSW	VSW	VSW	NB	
A	AW	AW	AW	SW	VSW	
B	VBW	BW	BW	AW	SW	
VB	CWO	VBW	VBW	BW	AW	
VS	BW	AW	SW	VSW	NB	NZ
S	VBW	BW	AW	SW	NB	
A	CWO	VBW	BW	AW	VSW	
B	CWO	CWO	BW	AW	SW	
VB	CWO	CWO	VBW	BW	AW	



a *b*

Fig. 4. Three-dimensional graphs of the dependence of wear on the selected input variables: *a* – $W_b = F(N_{sh}, f_{dom})$ at $M_{bw} = 0.05$; *b* – $W_b = F(N_{sh}, f_{dom})$ at $M_{bw} = 0.75$

3.3. Development of a stochastic simulation model of artillery firing under conditions of uncertain disturbances

To conduct computational experiments based on equations (10)–(18), a stochastic simulation model of artillery firing under conditions of uncertain disturbances was developed. In this model, for each of the three studied methods, the transition probability matrices **P** were determined differently. Thus, for the first method, which determines wear solely depending on the shot, the probability p_{CI} of transition from the S_C state to the S_I state is determined by the probability p_{sa1} of the appearance of the first type of anomaly (projectile belt rupture). Since when this anomaly occurs, barrel wear will increase abruptly, which will not be reflected in the model characteristics. Therefore, further adjustments will be incorrect, and all subsequent firing series will have low efficiency. Therefore, the probability p_{IC} of returning to the S_C state from the S_I state will be 0, and the probability p_{I2I} of transitioning to the absorbing S_{2I} state will be 1. Accordingly, the probability that the mount will remain in the S_C state will be $p_{CC} = 1 - p_{sa1}$. Thus, the matrix **P** for this method will have the form

$$\mathbf{P}_1 = \begin{pmatrix} 1-p_{sa1} & p_{sa1} & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 1 \end{pmatrix}. \quad (22)$$

For the 2nd and 3rd methods, in addition to the two main anomalies mentioned above, the appearance of an additional anomaly was also considered – a failure (incorrect functioning) of the measuring equipment for fixing the parameters of the ballistic wave during the shot. For the 2nd method, presented in [14], the probability p_{CI} is determined by the probability p_f of the appearance of the second type of anomaly (low-quality charge) or a sensor failure on the last shot of the series. The appearance of any of these two anomalies will cause incorrect adjustments and low efficiency of only the next series. Accordingly, the probability p_{IC} of returning to the S_C state from the S_I state will be equal to $1 - p_f$, and the probability p_{I2I} of transitioning to the absorbing state S_{2I} will also be equal to p_f. The probability that the mount will remain in the S_C state will be $1 - p_f$. Therefore, the matrix **P** for this method will have the form

$$\mathbf{P}_2 = \begin{pmatrix} 1-p_f & p_f & 0 \\ 1-p_f & 0 & p_f \\ 0 & 0 & 1 \end{pmatrix}. \quad (23)$$

In turn, the probability p_f is calculated by the formula

$$p_f = 1 - \left(1 - p_{sa2}/n\right)\left(1 - p_{fs}/n\right), \quad (24)$$

where p_{fs} – the probability of failure of the measuring equipment on any shot of the series.

Since the proposed method allows to distinguish between anomalies of the first and second types, when using it, the transition to the S_I state is possible only due to the failure of the sensors on the last shot of the previous series. Therefore, the matrix **P** for this (third) method can be constructed in a similar way to the matrix (23) for the second method, only instead of the probability p_f the probability p_{fs}/n will be used. In turn

$$\mathbf{P}_3 = \begin{pmatrix} 1-p_{fs}/n & p_{fs}/n & 0 \\ 1-p_{fs}/n & 0 & p_{fs}/n \\ 0 & 0 & 1 \end{pmatrix}. \quad (25)$$

Therefore, the synthesized simulation model for conducting computational experiments consists of equations (10), (11), (15)–(18), (22)–(25).

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3.4. Conducting computational experiments

To confirm the effectiveness of the proposed method in this work, a number of computational experiments were conducted in comparison with the model approach that uses only the shot values, and the method presented in [14]. In particular, two groups of experiments were conducted with different values of the probabilities of certain events. For the first group of experiments, the probabilities are given in Table 3, for the second – in Table 4.

Table 3

Probability values of the stochastic simulation model (1 group)

Probability	p_{swa}	p_{sa1}	p_{sa2}	p_{fs}	p_{wa}	p_{a1}	p_{a2}	p_{ic}
Value	0.9	0.1	0.1	0.1	0.9	0.1	0.1	0.1

Table 4

Probability values of the stochastic simulation model (2 group)

Probability	p_{swa}	p_{sa1}	p_{sa2}	p_{fs}	p_{wa}	p_{a1}	p_{a2}	p_{ic}
Value	0.8	0.2	0.2	0.2	0.9	0.1	0.1	0.1

In addition, for each group of experiments, calculations were performed with two different values of the required number of hits to destroy the target. Namely, for the first group of experiments: $E_{\Sigma D11} = 10$, $E_{\Sigma D12} = 20$; for the second group of experiments: $E_{\Sigma D21} = 7$; $E_{\Sigma D22} = 14$. Also, for all experiments, each firing series included four shots ($n = 4$), and its execution time (together with emplacement, laying and displacement) was equal to $t_s = 3$ min. These values are averaged for a sufficiently large number of modern artillery systems, taking into account the limitations on the rate of fire and the safe time of staying at firing positions after the first shot. In turn, the vector of the initial probability distribution was

$$\boldsymbol{\theta}_0 = \begin{pmatrix} 1 & 0 & 0 \end{pmatrix}. \tag{26}$$

The results of the computational experiments are summarized in Table 5 and Table 6, respectively. In the course of the experiments, the minimum required number of firing series $m_{\min}$ was calculated for each case using the developed model to achieve the desired number of hits $E_{\Sigma D}$ required to destroy the target. Also, the value of the overall firing efficiency η and the total time the mount was at the firing positions t_{Σ} were calculated for the corresponding numbers of $m_{\min}$ series. In addition, the corresponding achieved values of the probability θ_{2I} of transition to the absorbing state S_{2I} and completion of firing were additionally determined.

The obtained experimental results showed that the proposed method for determining wear allows achieving higher efficiency of artillery firing under conditions of uncertain disturbances in comparison with the other two considered methods.

Table 5

Results of computational experiments (1 group)

Parameter	Model approach	The method presented in [14]	Proposed method
$E_{\Sigma D} = 10$			
$m_{\min}$	5	4	4
η	0.5	0.625	0.625
t_{Σ}	15	12	12
θ_{2I}	0.344	0.0094	0.0025
$E_{\Sigma D} = 20$			
$m_{\min}$	13	8	7
η	0.385	0.625	0.714
t_{Σ}	39	24	21
θ_{2I}	0.718	0.016	0.0037

Table 6

Results of computational experiments (2 group)

Parameter	Model approach	The method presented in [14]	Proposed method
$E_{\Sigma D} = 7$			
$m_{\min}$	6	4	3
η	0.292	0.438	0.583
t_{Σ}	18	12	9
θ_{2I}	0.6723	0.0267	0.0049
$E_{\Sigma D} = 14$			
$m_{\min}$	–	7	6
η	–	0.5	0.583
t_{Σ}	–	21	18
θ_{2I}	–	0.052	0.012

Thus, when compared with the method presented in [14], the developed method based on the fuzzy model required one less cycle to complete the firing task in three out of four simulated cases. This ensured a reduction in ammunition consumption by 4 shells and a reduction in the total time of the artillery mount spent at the firing positions by 3 minutes. Only in the first case was the value of the firing efficiency η the same for these two methods, which is explained by the rather small set values of the probability of occurrence of all disturbances and the small number of required hits. While in the third case (with significant values of the probability of occurrence of disturbances) the proposed method had efficiency 14.5% higher. Also, for all experiments conducted, the value of the probability θ_{2I} of premature termination of firing for the developed method was on average 4 times less than for the method from work [14].

When compared with the method that uses only the model dependence of wear on firing, the proposed method has significantly better all indicators for all studied cases. Thus, at low values of the probability of occurrence of anomalies and $E_{\Sigma D} = 10$ (1st case), the increase in firing efficiency and the reduction in the time spent at firing positions were, respectively, 12.5% and 3 min. At $E_{\Sigma D} = 20$ (2nd case), the proposed method based on the fuzzy model had already 33% higher efficiency and 18 min less time t_{Σ}. In turn, at significant probabilities of occurrence of anomalies and $E_{\Sigma D} = 7$ (3rd case), due to the use of the developed method, it was possible to halve the number of firing series and the time spent at positions. As for the 4th case, when using the model approach, it was not possible to complete the firing task at all. Since even after the 32$^{\text{nd}}$ cycle, the desired value of hits $E_{\Sigma D} = 14$ was not achieved, and the probability value θ_{2I} was 0.999, which practically guaranteed the premature termination of firing and the withdrawal of the mount.

Thus, the conducted studies confirmed the high efficiency of the proposed method and the feasibility of its application for determining wear and performing adaptive adjustments when conducting artillery firing in short series from different positions. A feature of this method is the presence of robust properties when changing the probabilities of the appearance of various types of uncertain disturbances and increasing the specified number of required hits $E_{\Sigma D}$ to destroy the target.

In addition, the proposed method does not require significant computational costs and is fully suitable for implementation in real time when using the "shoot-and-scoot" artillery fire tactics. The main computational operations of the method include determining the parameters of the ballistic wave from the measured acoustic signal and their further processing using relatively simple fuzzy logic model procedures. These operations require significantly less computational resources compared to the operations of complex ballistic models used to calculate the main laying parameters. Also, all calculations for determining wear and subsequent adjustments are carried out during the movement of the mount between positions, which ensures that there is sufficient time without reducing the rate of fire.

3.5. Limitations and directions of research development

A limitation of the developed method of wear control and adaptive adjustment of artillery mount settings under conditions of uncertain disturbances is a possible decrease in efficiency with a strong influence of noise interference on the measuring equipment. This can significantly distort acoustic signals and increase the probability of sensor failures. To eliminate this effect in further studies, it is advisable to consider possible ways to increase noise immunity when measuring signals. Also, it is advisable to use highly effective methods for identifying object parameters by experimental characteristics under conditions of noise [29]. Another promising direction of further research is to improve the developed fuzzy model for determining the current wear value by using the latest parametric [30] and structural [31] optimization algorithms.

4. Conclusions

1. A step-by-step structure of the method for determining the current wear of the gun barrel has been formed, which allows for adaptive adjustment of the settings of the artillery mount when firing in short series from different positions under conditions of uncertain disturbances. The proposed structure for correct determination of wear when implementing the method involves the use of three information channels, including the dominant frequency and depth of frequency modulation of the ballistic wave, as well as the general gun firing rate. This allows for distinguishing the types of operating disturbances and establishing the cause of the decrease in the initial velocity of the projectile from the gun. As a result, when any different types of disturbing influences occur on the last shot of the series, the settings are adjusted correctly, which allows for maximum increase in the efficiency of the next firing series. The proposed method can be applied in diagnostic and control systems of a wide class of artillery mounts, taking into account their technical characteristics.
2. To formalize the dependence of the current wear of the gun barrel on the dominant frequency of the ballistic wave, the depth of its modulation and the total firing of the gun, a fuzzy-logical model of the Mamdani type was used in the presented method. The synthesized fuzzy model has an intuitive rule base consisting of 50 rules. This allows for fairly accurate determination of the value of the gun barrel wear in the presence of such random disturbances as a projectile belt failure and low charge quality.
3. To study the effectiveness of the proposed method based on a fuzzy model for determining wear, a stochastic simulation model of the process of cyclic firing of an artillery mount in short series under conditions of uncertain disturbances was developed. This model, based on a probabilistic-analytical approach and a Markov chain, allows for simulation and quantitative evaluation of random processes of firing in short series under conditions of uncertain disturbances.
4. Based on the synthesized simulation model, a number of computational experiments were conducted, confirming the high efficiency of the developed method in comparison with two other existing methods. A comparative analysis of the obtained results showed that the proposed method based on a fuzzy model with significant values of the probability of occurrence of random disturbances significantly outperforms both considered methods in all main indicators. In particular, the firing efficiency is 14.5% higher and the total time spent at firing positions is 3 min less than that of the method that uses only the measurement of the dominant frequency of the ballistic wave. In turn, compared to the method based on the model dependence of wear on the shot, the firing efficiency is 29.2% higher, and the time spent at positions is 9 min less. Thus, the use of the developed method under the influence of uncertain disturbances provides an increase in firing efficiency and a reduction in the time spent by the artillery mount at firing positions, which confirms the achievement of the goal of this work.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies in creating the submitted paper.

Authors' contributions

Maksym Maksymov: Conceptualization, Validation, Writing – review and editing, Supervision; ***Oleksiy Kozlov***: Conceptualization, Methodology, Formal analysis, Writing – review and editing; ***Oleksiy Maksymov***: Methodology, Software, Formal analysis, Writing – original draft; ***Ruslan Riaboshapka***: Methodology, Software, Writing – original draft.

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