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SIMULATION MODEL OF THE INFORMATION TECHNOLOGY FOR THE TECHNICAL DIAGNOSIS OF THE IMPULSE HEAT MACHINE

Є.В. Добринін, В.О. Давидов. **Імітаційна модель інформаційної технології для технічного діагностування каналів імпульсних теплових машин**. Розроблено та досліджено імітаційна модель для інформаційної технології технічного діагностування каналів імпульсних теплових машин. Модель складається з математичних моделей: дульної енергії; параметрів балістичної хвилі; тиску порохових газів, що стікають з дульного зрізу ствола за снарядом і дульної хвилі і визначення швидкості її загасання. Інформаційна модель дозволяє отримати параметри балістичної хвилі, яка супроводжує постріл. Спрощена математична модель дозволяє визначити значення кута нахилу косого стрибка до напрямку потоку, що набігає в залежності від числа Маха, яка представлена плоским обтіканням клину. Модель тиску порохових газів, які стікають з дульного зрізу ствола за снарядом заснована на застосуванні закону збереження енергії для стислих порохових газів, та дозволяє уникнути розв'язання складної модифікованої задачі Лагранжа. У процесі поширення дульної хвилі на початковому етапі можлива ситуація, при якій ця хвиля потрапить в точку реєстрації раніше балістичної хвилі. При відповідному підборі кута цього явища можна уникнути. Прийнята математична модель визначає закон поширення дульної хвилі і дозволяє оцінити швидкість її загасання. Модель дульної енергії полягала в рішенні оберненої задачі піростатики шляхом визначення складу газу продуктів згоряння пострілу. В основу покладено підхід побудови моделі процесу горіння сумішей пального і окислювача. Особливістю є необхідність знання складу всіх компонентів суміші компонентів довільного складу. Обмеженням була необхідність знаходження їх в газоподібному стані. Особливістю даного випадку є розробка моделі горіння однокомпонентної твердої речовини (нітроцелюлози пороху) при можливості зміни складу її активної частини внаслідок геронтологічної деградації.

Ключові слова: дулова енергія, зворотна задача піростатики, діагностика імпульсних теплових машин, балістична хвиля, дулова хвиля, інформаційна технологія, імітаційна модель акустичних сигналів

Ye. Dobrynin, V. Davydov. **Simulation Model of the Information Technology for the Technical Diagnosis of the Impulse Heat Machine**. A simulation model of the information technology for the technical diagnosis of the impulse heat machine has been developed and studied. The model incorporates such mathematical models as barrel energy; ballistic wave parameters; pressure of powder gases blasting from the barrel face behind the shell and the shot blast and determination of its attenuation rate. The information model enables to obtain parameters of the ballistic wave that accompanies an shot. A simplified mathematical model allows of determining the oblique shock inclination angle to the stream speed depending on Mach number which is represented by the two-dimensional flow wedge. The model of powder gas pressure blasting from the barrel face behind the shell is based on the energy conservation law for the compresses powder gases and makes it possible to avoid solution of the complicated modified Lagrange problem. While the shot blast propagates, at the initial stage it is possible that this blast reaches the record point earlier than the ballistic wave. Such phenomenon can be avoided by selecting a proper angle. The adopted mathematical model determines the shot blast propagation law and allows of evaluating the shot blast speed attenuation. The barrel energy model was based on the solution of the inverse problem of pyrostatics by determining a composition of the combustion gas of the shot. The applied approach provided for use of the model that describes combustion of the fuel and oxidizer mixture. The peculiarity is a necessity to know composition of all components of the arbitrary mixture. The limitation is a necessity that all components are gaseous. The considered case needs to develop a combustion model of a single-component solid substance (nitrocellulose powder) that provides for a possibility to vary the composition of its active part because of its degradation with time.

Keywords: barrel energy, inverse problem of pyrostatics, diagnostics of the impulse heat machine, ballistic wave shot blast, information technology, simulation model of acoustic signals

1. Introduction

Currently there is a growing development of the information technologies connected with processing information associated with the impulse heat machine systems. The most large-scale information technologies include the Artillery Systems Cooperation Activities (ASCA) that provides a targeting standard for data transmission interface [1].

This trend attracts interest to the neighbouring information technologies that can be of use as the auxiliary tools for diagnosing the ordnance, in this context the impulse heat machine. Such direction

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includes simulation modelling. Simulation modelling of any information technology becomes a priority because of the considerable volumes of the initial data and its variations that should be accounted for at the verification ands validation stages.

More often than not the simulation models of a facility are designed on the basis of the existing mathematical models that describe individual processes. Selection of the resources for performing a simulation test is made on the basis of information concerning the computational complexity and performance of the computational system. Hence, in such cases the researchers intend to simplify mathematical dependencies and regularities. As a rule, the distribution in the model space is reduced to the models distributed in a plane. Such problems include the simulation model of the information technology applied for the technical diagnosis of the bore with the aid of acoustic signals of shots.

2. Survey of the current research

Acoustic waves can be recorded by a system of the distributed microphone sensors used for determining coordinates of the firing gun [2]. A trend in development of the information technologies dealing with recording of the ballistic wave and shot blast at sufficiently small distances from the impulse heat machine position was revealed. Analysis of the temporal and spectral characteristics of the acoustic signal that have been recorded in such way makes it possible to obtain the “acoustic signature” of the “impulse heat machine – shell” system [3]. According to [4], the analysis of the impulse heat machine system acoustic portraits can be used for assessing the gun type, shell calibre and other parameters that characterize a gun. In its turn, it paves the way to develop a new technology for diagnosing the barrel wear [5].

However, all methods to analyse the signals produced by ballistic and shot waves so as to evaluate the barrel wear level necessitate their separate recording by the recording instrument. There exist comprehensive monographs devoted to the formation of acoustic fields at a shot [6] as well as rather detailed research of the topic [7].

Nevertheless, there is no simulation model that describes the formation of the ballistic wave and shot blast and the dynamics of their behaviour during the first seconds after the shot. A number of works have demonstrated a possibility of such accomplishment [8, 9]. Therefore, a study of various mathematical models of acoustic wave formation at an shot and of a possibility of the separate recoding and their automated processing using an information technology present a sufficiently relevant objective.

3. Objective and tasks

The objective of this paper is to develop a simulation model of the information technology for the technical diagnosis of the impulse heat machine which comprises the mathematical models of the charge pyrostatics, gas flow from the barrel face at a shot and formation of the ballistic wave and shot blast, which enables to obtain parameters of the ballistic wave and the shot blast.

In order to achieve this objective it is required to develop the mathematical models of:

– the barrel energy – by solving the inverse problem of pyrostatics via determination of the composition of the combustion gas of the shot;

– the ballistic wave parameters;

– pressure of the powder gases flowing from the barrel face behind the shell; and

– the shot blast and determination of its attenuation speed.

4. Simulation model of the information technology for diagnosing the impulse heat machine

4.1. Mathematical model of the barrel energy achieved by solving the inverse problem of pyrostatics

The model can be based upon the approach described in [10] and accomplished in [11]. The paper [10] describes the approach to design of the model of the fuel and oxidizer mixture combustion process. The peculiarity is a necessity to know composition of all components of the mixture and to preset the coefficient of the oxidizer excess. The paper [9] describes the method to compute the process of combustion of the arbitrary mixture of the components. The limitation is a necessity that all components are gaseous. The considered case needs to develop a combustion model of a single-component solid substance (nitrocellulose powder) that provides for a possibility to vary the composition of its active part because of its degradation with time.

The research of the Livermore National Laboratory (USA) made the basis for [12] which describes degradation of the plastic blasting explosives and contains the model of the initial stage of nitrocellulose degradation:

$$\begin{gathered} C_6H_{7.7}N_{2.3}O_{9.6} \rightarrow C_{5.95}H_{7.99}N_{1.9}O_{8.76} + \text{DFA nitrated derivative} + \\ +0.001N_2 + 0.024N_2O + 0.012CO + 0.012H_2O, \end{gathered} \tag{1}$$

where, DFA means difenylamine.

The gross formula for computing the constant for a long period will include four chemical elements: C, H, N, O. The number of atoms of the corresponding elements proceeds from their mass fractions:

$$b_k = \sum_i q_i \cdot b_{ki} \ , \tag{2}$$

where, b_k – mass fraction of the k-th element;

q_i – mass fraction of the i-th substance in the mixture;

b_{ki} – mass fraction of the k-th element in the i-th substance.

The gross formula as reduced will be:

$$C_1H_{1.4}N_{0.37}O_{1.57} \ . \tag{3}$$

Hereafter, the model for powder combustion computation will be according to [9]. In this case the gaseous powder combustion products may be:

$$[\text{CO}], [\text{CO}_2], [\text{H}_2], [\text{O}_2], [\text{H}_2\text{O}], [\text{OH}], [\text{N}_2], [\text{NO}], [\text{C}], [\text{H}], [\text{O}], [\text{N}] \, . \tag{4}$$

The task is to find the quantitative composition of the combustion products at preset pressure of their mixture and the enthalpy of the initial substance (powder). The computation is based on determination of the combustion product mixture temperature.

The first 8 equations can be written through the partial pressures of the combustion products following the mass action law.

$$\frac{P_{\text{C}} \cdot P_{\text{O}}}{P_{\text{CO}}} = K_{\text{CO}}(T) \, ; \tag{5}$$

$$\frac{P_{\text{C}} \cdot P_{\text{O}}^2}{P_{\text{CO}_2}} = K_{\text{CO}_2}(T) \, ; \tag{6}$$

$$\frac{P_{\text{H}}^2 \cdot P_{\text{O}}}{P_{\text{H}_2\text{O}}} = K_{\text{H}_2\text{O}}(T) \, ; \tag{7}$$

$$\frac{P_{\text{H}} \cdot P_{\text{O}}}{P_{\text{OH}}} = K_{\text{OH}}(T) \, ; \tag{8}$$

$$\frac{P_{\text{H}}^2}{P_{\text{H}_2}} = K_{\text{H}_2}(T) \, ; \tag{9}$$

$$\frac{P_{\text{O}}^2}{P_{\text{O}_2}} = K_{\text{O}_2}(T) \, ; \tag{10}$$

$$\frac{P_{\text{N}}^2}{P_{\text{N}_2}} = K_{\text{N}_2}(T) \, ; \tag{11}$$

$$\frac{P_{\mathrm{N}} \cdot P_{\mathrm{O}}}{P_{\mathrm{NO}}} = K_{\mathrm{NO}}(T) . \tag{12}$$

The chemical equilibrium constants are tabulated depending on the temperature in the appropriate handbooks, and can be selected for the appropriate temperature or can be computed with the aid of the approximation polynomials. Also, they can be computed on the basis of enthalpies of the formation and entropy of the substances that enter into the considered reactions which, in their turn, can also be tabulated or computed on the basis of the approximation polynomials [7].

The following equations have been compiled on the basis of the energy conservation law for each chemical element included in the gross formula (3) of the powder.

$$\mathrm{C}_{b_\mathrm{C}}\mathrm{H}_{b_\mathrm{H}}\mathrm{N}_{b_\mathrm{N}}\mathrm{O}_{b_\mathrm{O}} . \tag{13}$$

Thus, the resulting expressions are:

for [C] $$b_{\mathrm{C}} \cdot M_T = P_{\mathrm{CO}} + P_{\mathrm{CO_2}} + P_{\mathrm{C}} , \tag{14}$$

for [H] $$b_{\mathrm{H}} \cdot M_T = 2 \cdot P_{\mathrm{H_2O}} + P_{\mathrm{OH}} + 2 \cdot P_{\mathrm{H_2}} + P_{\mathrm{H}} , \tag{15}$$

for [N] $$b_{\mathrm{N}} \cdot M_T = 2 \cdot P_{\mathrm{N_2}} + P_{\mathrm{NO}} + P_{\mathrm{N}} , \tag{16}$$

for [O] $$b_{\mathrm{O}} \cdot M_T = P_{\mathrm{CO}} + 2 \cdot P_{\mathrm{CO_2}} + P_{\mathrm{H_2O}} + P_{\mathrm{OH}} + 2 \cdot P_{\mathrm{O_2}} + P_{\mathrm{NO}} + P_{\mathrm{O}} . \tag{17}$$

In the case under study the comparison of (3) and (13) gives the following result:

$$b_{\mathrm{C}} = 1;\ b_{\mathrm{H}} = 1.44;\ b_{\mathrm{N}} = 0.37;\ b_{\mathrm{O}} = 1.57 . \tag{18}$$

The considered model has 13 unknown quantities (12 partial pressures of substances (4) and 12 equations (5–12) and (14–17). To close the system, the Dalton equation is used – the mixture pressure equals the sum of partial pressures of its components:

$$P_\Sigma = P_{\mathrm{CO}} + P_{\mathrm{CO_2}} + P_{\mathrm{H_2O}} + P_{\mathrm{OH}} + P_{\mathrm{H_2}} + P_{\mathrm{O_2}} + P_{\mathrm{N_2}} + P_{\mathrm{NO}} + P_{\mathrm{C}} + P_{\mathrm{H}} + P_{\mathrm{O}} + P_{\mathrm{N}} . \tag{19}$$

The obtained equation system is non-linear.

The solving process according to the model (5) – (19) is accomplished within the frame of the following algorithm:

Step 1. To select a pair of values out of the considered range of possible changes of the charge enthalpy (barrel energy) $(I_{\mathrm{ch}})_i$ and the charge combustion products pressure $(P_\Sigma)_j$ at a blank shot. All following computations are made for these parameters. Computations for all possible combinations of $(I_{\mathrm{ch}})_i$ and $(P_\Sigma)_j$ make it possible to fill in the desired computation “library”;

Step 2. To assume a certain arbitrary value of the charge combustion products temperature T^0;

Step 3. To compute, using the iterative process, the combustion products composition that corresponds to the assumed temperature with the aid of the model (5) – (19);

Step 4. To determine the enthalpy of each element in the mixture and the enthalpy of the entire mixture for the combustion products composition at the selected temperature;

Step 5. To compare the computed value of the combustion products enthalpy with the selected (see item 1) powder charge enthalpy. If the values differ, the temperature of the combustion products (powder gases) is adjusted upwards or downwards. Move towards item 3. The temperature adjustment and the computations are made until the enthalpies coincide with the required accuracy;

Step 6. To move towards Step 1.

4.2. Model of the ballistic wave parameters

From the equation contained in [13] we find geometric parameters of the ballistic wave:

$$\sin\beta\left[\sin\beta - \frac{\gamma+1}{2}\frac{\sin\theta}{\cos(\beta-\theta)}\right] = \frac{1}{M_1^2} , \tag{20}$$

where, angle θ equals a half angle of the wedge width and the shell “tip”,

$M_1 = u_1 / a_1$ – Mach number (M_1>1),

a_1 – sound speed in the air not compressed by the wave,

u_1 – speed of the air stream meeting the shell (or shell speed in air),

γ – air polytrope index ($\gamma = 1.4$) [8].

Pressure p_2 and density ρ_2 behind the oblique shock front are determined out of the relations using the formulas applied for computing the oblique shock of compression [8, 14].

$$\frac{p_2}{p_1} = \frac{2\gamma}{\gamma+1} M_1^2 \sin^2\beta - \frac{\gamma-1}{\gamma+1}, \tag{21}$$

$$\frac{\rho_2}{\rho_1} = \frac{\gamma+1}{2} M_1^2 \sin^2\beta (1 + \frac{\gamma-1}{2} M_1^2 \sin^2\beta)^{-1}. \tag{22}$$

where, β means the oblique shock inclination angle relative to the direction of the airstream.

Under normal conditions the shell speed u_1 =1,000 m/s and the angle value $\theta = 15°$, the angle for β should be $\widehat{\beta} = 33°$.

The mathematical model as expressed by equations (20) – (22) enables to determine the ballistic wave parameters [8].

The ballistic wave parameter model (20) – (22) may not be applied in the cases when $\theta > \theta_{\max}$, where, $\theta_{\max}$ is a certain angle which value depends on M_1. Computation of such shock wave parameters presents a much more complex problem which can be computed numerically only [14].

4.3. Pressures of the powder gases exhausting from the barrel face behind the shell

The shot blast is being formed even at the moment when the shell leaves the barrel and the compressed powder gas, which was held until that moment by the rear surface of the shell, bursts out in the atmosphere. In order to study the process of the shot blast propagation, it is necessary to know the barrel pressure p_d, i.e., the powder gas pressure at the barrel face at the moment when the shell completely leaves the barrel [8]. In its turn, determination of the barrel pressure p_d is determined by the interior ballistics models. Of special interest is the value of p_d that reflects the powder gas pressure p in the barrel face at the moment when the shell leaves the barrel, and the value which corresponds to this density pressure p_d.

$$p_d = \frac{p_* L}{L+l} - \frac{(\gamma-1)F_{fr} l}{S(L+l)} - \frac{(\gamma-1)(m-\rho_* SL)u_d^2}{2S(L+l)}, \tag{23}$$

where, S means the cross-section area of the barrel bore;

L means the bore length filled with compressed powder gases at pressure p_* and temperature T_*;

l means the bore length;

m means the shell mass;

u_d means the shell speed when it leaves the barrel.

Values of F_{fr} and u_d can be considered known out of the solutions of the interior ballistics tasks.

$$\rho_d = \rho_* \left(\frac{p_d}{p_*} \right)^{\frac{1}{\gamma}}. \tag{24}$$

Density ρ_d is determined based on the isoenthropic of the flow [8].

Modelling in accordance with (23) indicates that pressure p_d depends on the powder charge that determines values of p_* and ρ_*. Modelling also depends on the shell characteristics (primarily on its mass and the steering band) and the barrel (calibre and rifling that determine the shell friction force F_{fr}). Hence, the obtained equation (23) in combination with expression (24) makes it possible to find the initial pressure and density of the powder gases in the shot blast [8].

4.4. Shot blast model and determination of its attenuation speed

The law determining the shot blast is of the form [16]:

$$r = \left(\frac{E_d}{\alpha\rho_2}\right)^{\frac{1}{5}} t^{\frac{2}{5}}, \tag{25}$$

and its speed D is expressed as:

$$D = \frac{2}{5}\left(\frac{E_d}{\alpha\rho_2}\right)^{\frac{1}{5}} t^{\frac{3}{5}}, \tag{26}$$

where, r – a distance from the shot blast front from the barrel face; the constant α is computed according to [16] provided the flow behind the shot blast is adiabatic:

$$\alpha = 0.31245(\gamma-1) - (1.409 + 0.117351 g(\gamma-1)\text{, } 1.2 \le \gamma \le 2\,. \tag{27}$$

Pressure p at the shot blast is changing following the law:

$$p = \frac{2\rho_2 D^2}{\gamma+1}, \tag{28}$$

because $D \sim t^{-\frac{6}{5}}$.

Formulas (25) – (28) are true in the relative proximity to the shot blast origination only [8].

When the shot blast propagates, at the initial stage it is possible that this blast “catches up” with the ballistic wave (that is arrives at the observation point simultaneously with the ballistic wave) because $D > u_1 \sin\beta$. It I clear from the physical viewpoint: the shot blast propagates in the gas that has been already compressed by the ballistic wave, just as important is that pressure p_d, that initiates the shot blast is very high.

Let us model the shot blast propagation in the absence of the shot blast and the ballistic wave as follows:

– before the time moment t_{st}, when pressure p at the shot blast front has been formally reached so that $p > p_d$ (the criteria accomplishing this inequality can be different), the shot blast computation is accomplished according to formulas (25) – (28);

– beginning from the time moment t_{st} (if the wave front radius equals r_{st}) the shot blast is considered to be weak and attenuations according to the known law [14]:

$$\frac{p-p_1}{\rho_1 a_1^2} = \sqrt{\frac{4}{\gamma+1}\frac{Q}{r_{st}\rho_1}}\,\frac{r_{st}}{r}\,\frac{1}{\sqrt{\ln\frac{r}{r_{st}}}}, \tag{29}$$

where,

$$Q = \int_0^{+\infty} \rho u(r_{st}, t)\,dt = \text{const} > 0, \tag{30}$$

ρ, u – speed and density distributions in the shot blast;

– beginning from the time moment t_{ac}, when $p \approx p_1 (p > p_1)$, the shot blast can be considered to be linear acoustic (however, this acoustic wave has a rather high amplitude).

We note that the gas parameters before the shot blast front in equation (29) have index “1”. This gas corresponds to the atmospheric air under the conditions that are close to normal. Index “2” corresponds to the air compressed by the ballistic wave because by the time moment t_{st} the action of the ballistic wave far in front is already not felt.

The model represented by expressions (25) – (30) determines the law that describes the shot blast propagation and allows of evaluating its attenuation speed [8].

5. Formation of the information technology signals

Expressions (1 – 30) represent a simulation model of the information technology for technical diagnosing of the impulse heat machine. This model forms **N** records of the signals, that simulate acoustic signals recorded when firing from the barrels without wear, and **K** records of the signals that simulate acoustic signals, recorded when firing from the barrels with wear, by microphones located at a distance of S meters from the barrel face, at the ground level along the line which is perpendicular to the fire trajectory projection [5].

A time-domain section that separates the ballistic wave signal and shot blast signal at each shot was cut out from each record.

Each record was processed according to the algorithm that transforms the ballistic wave signals and shot blast signals with the aid of Fourier transformation to the frequency domain and computes the energy spectrum of the ballistic wave and shot blast signals.

For each simulated signal in the time-domain and spectral areas a set of parameters is computed that characterize disturbance of the atmosphere at a shot: ballistic wave amplitude, ballistic wave signal duration, shot blast amplitude, duration of the first half-cycle of the shot blast, spectrum width at 0.707 level of the ballistic wave signal, central frequency (frequency of the maximum) of the shot blast signal spectrum, excess of the ballistic wave signal spectrum, and obliquity of the ballistic wave signal spectrum [5].

Seven averaged indices that characterize a shot made from the barrel without wear and seven averaged indices that characterize a shot made from the barrel with wear and from the barrel without wear were computed for N signals that simulate a shot from the barrel without wear and K signals that simulate a shot from the barrel with wear.

The listed averaged sets of parameters for two kinds of barrels (without wear and with wear) present the initial data to be used in the information technology for technical diagnosing the impulse heat machine [5].

The results of the simulation modelling are shown in the Table below.

Results of the simulation modelling of the technical diagnosing the impulse heat machine

Description of the parameter / unit of measurement	Parameter value	
1. Barrel quality	without wear	with wear
2. Distance from the gun to the measuring microphone, m	300	
3. Tabulated firing range with the gun sight, m	9.000	
4. Ballistic wave amplitude, Pa	380	240
5. Duration of the ballistic wave signal, ms	4.8	4.1
6. Shot blast amplitude, Pa	140	90
7. Duration of the first shot blast half-cycle, ms	22	14
8. Spectrum width at 0.707 level of the ballistic wave signal, Hz	180	250
9. Centre frequency (maximum frequency) of the shot blast signal spectrum, Hz	12	16

Conclusions

1. A simulation model of the information technology for technical diagnosing of the impulse heat machine is proposed that comprises mathematical models of the charge pyrostatics, blast of the gases flowing from the barrel face at a shot and formation of the ballistic wave and shot blast, and presents, as distinct from the existing models, formation of the barrel energy by solving the inverse problem in order to determine a composition of the combustion products of the shot and the parameters of the oblique shock wave through the two-dimensional flow wedge, which enables to obtain the parameters of the ballistic wave and the shock (barrel) wave.

2. The simulation model of the modelled signal in the time-domain and spectrum range allows of computing a set of parameters that characterize disturbance of the atmosphere at a shot. These are the

ballistic wave amplitude, ballistic wave signal duration, shot blast amplitude, duration of the first half-cycle of the shot blast, spectrum width at 0.707 level of the ballistic wave signal, central frequency (frequency of the maximum) of the shot blast signal spectrum, excess of the ballistic wave signal spectrum and obliquity of the ballistic wave signal spectrum.

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