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STUDY OF UNCERTAINTIES OF CYLINDER POWER MONITORING BASED ON COMPUTER SIMULATION

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Abstract - It is shown that the known methods and hardware and software tools for monitoring the cylinder capacities of internal combustion engines require manual labour. With a sufficiently large number of power unit cylinders and the absence of output electrical signals from the primary pressure transducers, the speed of operation of this method of monitoring cylinder capacities is significantly limited. Emphasis is placed on its use as a signal of measurement information for uneven rotation of the crankshaft of the internal combustion engine. Algorithmic support for monitoring the distribution of cylinder powers implements the principle of deviation control and is reduced to the solution of a redefined system of linear differential equations of the second order, the number of which determines the number of cylinders. The Laplace transform under zero initial conditions was used to solve the deterministic system of linear algebraic equations. The information links between the measurement information signal and the torques of individual cylinders in the form of transfer functions have been established. Sources of random malfunctions of hardware and software were analysed. It was established that the first component of hardware uncertainty has a multiplicative nature, and the second and third components have an additive nature. Also, the difference between them is that the first and second uncertainties act at the input of the computer system, and the third at its output. The hardware operates with sequences of pulse signals, which in mathematical representation are considered as a sum of individual pulses. A linear random process, presented as a stochastic integral, is used to describe the thermal disturbances of hardware. The Monte Carlo method was used as a mathematical tool for the computer simulation of random disturbances. Calculating the insensitivity bands around the nominal characteristics of the component conversion is performed based on summing up the uncertainties of the input signals and disturbances. When developing it, it was assumed that all components of the input signals' uncertainties are random variables specified by their one-dimensional and multidimensional distribution laws. The Lamer scheme, the standard algorithm for determining the speed of building numbers for a given period of the maximum length of a series, and the algorithm for modelling random numbers were also used. The requirements for the measurement uncertainty of the irregularity signal of the crankshaft rotation of the internal combustion engine have been established.

Keywords: Hardware and software; Information technology; Algorithmic support; Laplace transformation; Linear random process; Computer simulation; The Monte Carlo method; Lamer scheme.

1. Introduction

Determining the individual characteristics of consecutive working cycles of internal combustion engines (ICE) is possible by measuring cylinder pressure and constructing indicator diagrams [1]. Further comparison of the obtained diagrams allows monitoring of cylinder capacities. This monitoring method involves the modification of ICE to install primary pressure transducers (PPT). Also, each

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individual ICE has individual characteristics of consecutive work cycles, so there is always insufficient objectivity of measurements. The described method involves manual labour, which, with a large number of cylinders and in the absence of output electrical signals in the PPT, significantly limits its speed.

1.1 Analysis of Literary Data and Statement of the Problem

As a result of the analysis of power connection schemes of the crank-connecting mechanism of the engine in [2], a relationship between the average indicator pressure and the instantaneous speed of rotation of the crankshaft was established. In the works [3, 4], machine learning methods were used to generate initial data. At the same time, the parameters of mathematical models for monitoring the state of the internal combustion engine, which were reflected in the program algorithm, were used. Many attempts have been made to use the unevenness of the angular speed of the crankshaft as a measurement information signal for monitoring the technical condition of the engine [5, 6].

Recently, information and measurement systems have been used to register the combustion chamber pressure, which are built based on the E14-140 analog-to-digital converter of the L-Card company (system board L-783) with the primary converter 8QP505CS of the AVL company. Using the "Power Graph" application software, a method of computer processing of a series of indicator diagrams was developed for the indicated systems. As a result of the conducted experiments, indicator diagrams of all ICE cylinders were obtained, the further comparison of which allows establishing their identity. If it is necessary to change the settings of the fuel-air mixture supply phases to the cylinders, it is performed at the engine tuning stage. These information and measurement systems significantly increase the productivity of the calculation process of establishing the identity of cylinder capacities, however, they do not exclude the difficulties associated with setting the PPT. Also, this method is characterized by the uncertainties of averaging several indicator charts.

The system of differential equations of the second order establishes the information connection between the unevenness of the crankshaft rotation and the torques of the cylinders. The number of equations of the system depends on the number of masses of the mathematical model of the kinematic scheme of the ICE. As a result of its solution, we will get the distribution of cylinder torque amplitudes.

The authors accept the deviation of the calculated amplitudes from the average value as an estimate of the identity of the cylinder capacities.

Also, solving the problem of monitoring cylinder capacities of power units can be performed using one of the well-known numerical integration methods. At the same time, it is considered that the solution of the system of differential equations has the required degree of smoothness for applying one or another numerical method. Among the most used are the Euler, Runge-Kutta, Adams, Adams-Bashforth, and Adams-Moulton methods. The system of differential equations can also be solved in the following way [19]:

- reduce it to algebraic using the Laplace transform under zero initial conditions;
- solving systems of overdetermined incompatible algebraic equations using numerical methods.

In work [7], thanks to the use of the dynamic analysis method, the parameters of the movements of vibrating devices on elastic supports with an eccentric rotor, imbalances and an asynchronous motor were determined. In works [8, 9], the equations of motion of the mechanical model of an asynchronous motor at constant operating modes were obtained. In work [10] it was established that using linearized differential equations to describe the transient processes of electric motors leads to overestimating the calculated torque. In work [11], a mathematical model of the dynamic processes of an asynchronous motor on elastic supports using an eccentric unbalanced rotor was developed. In the calculations, plane-parallel movement of the working chamber of the electric motor was used. It has been proven that the rational selection of the eccentricity of the rotor reduces vibrations. In [12], a mathematical model of the unevenness of rotation of the robot control device is proposed, which allows to study the start-up process, stable modes and spatial movements of any points of the robot.

The Bayesian algorithm was also used to diagnose ICE indiscriminately. At the same time, transitional functions based on the frequency of rotation of the crankshaft, as well as fuel and air supply, were used as diagnostic signs. The final choice of information technologies and the construction of an algorithmic support for the processing of indirect measurement data under the conditions of random disturbances depends on the specifics of the control of the supply of the fuel-air mixture of ICE. Random disturbances distort the measurement information signal and affect the operation of individual components of the computer system (CS) to monitor ICE's cylinder capacities. Therefore, the development of software and hardware tools that are resistant to interference and increase the productivity of the cylinder power monitoring procedure is an urgent scientific and applied task.

1.2 The Purpose and Objectives of the Research

The purpose of the work is to reduce uncertainties and improve the performance of information technology for monitoring the cylinder capacity of ICE based on the processing of the crankshaft rotation irregularity signal using methods of computer simulation of random faults. To achieve the set goal, the following tasks were set and solved in the work:

1. The information technology of signal processing of measurement information is proposed.
2. An analysis of the sources of random software and hardware malfunctions was carried out.
3. Mathematical models of random disturbances were built, and parameters were identified.
4. A technique for summarizing random component uncertainties of hardware and software tools has been developed.
5. Algorithmic support for monitoring the distribution of cylinder powers has been developed based on processing the signal of uneven rotation of the first mass of the crankshaft.
6. A method of computer modeling of random interference signals is proposed.
7. Uncertainties of algorithmic support for monitoring the distribution of cylinder capacities are studied.

2. Materials and Research Methods

The authors used the signal of irregular rotation of the crankshaft and, based on it, developed algorithmic support for monitoring the distribution of cylinder capacities of ICE. With the use of computer modeling methods, the uncertainties of the application software were investigated. The solution of the set tasks began with the development of information technology for processing the signal of uneven rotation of the crankshaft.

2.1 Information Technology of Unevenness Signal Processing

The basis of the construction of the measuring transducer (MT) of the periods of the frequency-modulated signal (FM signal) of the angular speed of rotation of the crankshaft is the method of discretization by the time of the intervals of the passage near the sensitive element of the transducer of two consecutive marks of the primary transducer. For measurements of the instantaneous periods of the FM signal in the architecture of the CS for controlling the supply of the fuel-air mixture, the use of a pulse signal generator is provided, and the frequency of the output signal is stabilized using a quartz resonator. Information technology for processing the FM signal of measurement information involves the following actions:

- measuring time intervals (T_i);
- averaging the received information and forming a sample within one revolution of the crankshaft;
- calculation of the average value of time intervals (T_{cp});
- obtaining an array of discrete values of the crankshaft rotation unevenness signal.

2.2 Analysis of Hardware and Software Failures

Sources of accidental malfunctions of hardware, which significantly affect the uncertainty of monitoring the cylinder capacities of the power unit, are:

- the technological uncertainty of manufacturing crankshafts is manifested in the change of phase lags between the torques of individual cylinders and the first. It has a multiplicative effect on the measurement information signal;
- temporary instability of fuel combustion processes in cylinders;
- accidental hardware failures.

2.3 Mathematical Modeling of Random Disturbances

Hardware devices are cyclical devices that operate under random interference conditions. They operate with sequences of pulse signals, which are considered a sum of individual pulses in mathematical representation. Therefore, it is quite appropriate to present hardware interference in the form of a sum of random variables [13]

$$\xi(t) = \sum_{k=1}^{\chi(t)} \alpha_k \varphi(t - t_k) \ , \tag{1}$$

where α_k – are constant coefficients; $\chi(t)$ – the number of simple events that have the repetition frequency of the measurement information signal; $\varphi(t)$ – is a non-random function of the discrete presentation of the measurement information signal.

As a result of the analysis of experimental data, it was established that simple events obey Poisson's law. Then you can write [14]

$$P\{\chi(t) = n\} = e^{-\lambda t} \frac{(\lambda t)^n}{n!} \text{, at } n = 0, 1, 2, \ldots, \tag{2}$$

where $\lambda > 0$ – parameter of Poisson's law.

Random hardware failures are non-stationary in nature. Therefore, the mathematical model described by expression (1) is suitable only for certain presentation cases. For the general case, the model needs to be modified.

The modification of the display of random hardware malfunctions was modified under the following conditions. At random moments of time (t_k), random events occur; moreover, k = 0, 1, 2,... That is, elementary pulse signals of this type are formed $\alpha_k \varphi(t_{k_i}, t)$. Based on this assumption, we present the random interference in the form of work [15]

$$\xi(t) = \sum_{k=1}^{\chi(t)} \alpha_k \varphi(t_k, t) = \sum_{i=1}^{m} \sum_{k=1}^{\chi(t)} \alpha_{ki} \varphi(t_{ki}, t) \tag{3}$$

Using a generalized Poisson process in which the breakpoints coincide with time points t_{ki}, and the values of the jumps of the function are equal, respectively α_{ki}, we have [16]

$$\bar{\pi}_i(t) = \sum_{ki=1}^{\chi_i(t)} \alpha_{ki} V(t - t_{ki}) \tag{4}$$

where $V(t)$ – Heaviside unit function.

Expression (3) in integral form is replaced as follows

$$\xi(t) = \sum_{i=1}^{m} \int_{-\infty}^{\infty} \varphi(\tau, t) d\bar{\pi}_i(\tau) = \int_{-\infty}^{\infty} \varphi(\tau, t) d\left[\sum_{i=1}^{m} \bar{\pi}_i(\tau)\right] \tag{5}$$

It is proved in the work that for each m = 1, 2, ... the sum of generalized Poisson processes is a random process with independent increments. Therefore, expression (5) leads to a class of random processes, which we will call impulse random processes and define as follows.

Real Hilbert process $\{\xi(t), t \in T\}$ is a linear random process if it can be represented by a stochastic integral of this form:

$$\xi(t) = \int_{-\infty}^{\infty} \varphi(\tau, t) d\eta(\tau), \tag{6}$$

where $\varphi(\tau, t) \in L_2(-\infty, \infty)$ – a non-random real function at each fixed time step $t \in (-\infty, \infty)$, and $\{\eta(\tau), \eta(0) = 0,\ \tau \in (-\infty, \infty)\}$ – stochastic continuous homogeneous random process with independent increments.

A random process $\eta(\tau)$ and function $\varphi(\tau, t)$ respectively, is the generative process and the core of the random process (6). If the kernel $\varphi(\tau, t)$ satisfies the condition $\varphi(\tau, t) \equiv \varphi(\tau - t)$, then the linear random process (6) is stationary in the narrow sense.

Expression (6) taking into account the definition of white noise can also be formally written in the form:

$$\xi(t) = \int_{-\infty}^{\infty} \varphi(\tau, t) \eta'(\tau) d\tau. \tag{7}$$

This equation describes the response of a non-stationary linear system with a known impulse transient function $\varphi(\tau, t)$ to the influence of white noise $\eta'(\tau)$. In the case of using an invariant linear system, that is, when $\varphi(\tau, t) \equiv \varphi(\tau - t)$, expression (7) will take the form

$$\xi(t) = \int_{-\infty}^{\infty} \varphi(t - \tau) \eta'(\tau) d\tau \tag{8}$$

This expression describes the response of a stationary linear system with an impulse transient function $\varphi(\tau)$. Thus, the linear random process (6) has a clear physical interpretation. It can be interpreted as the response of a non-stationary (7) or stationary (8) linear system to a random influence in the form of white noise $\eta'(\tau)$.

As the basic initial model, we will choose a random process described by expression (6). This homogeneous process with independent increments has the following characteristic function in Levy form [17]

$$\ln f_n(t, U) = |t| \cdot \left[iU\mu - \frac{\sigma^2 U^2}{2} + \int_{-\infty}^{\infty} \left(e^{iUX} - 1 - \frac{iUX}{1 + x^2} \right) d\Pi(x) \right] \tag{9}$$

where $\{\mu, \sigma^2, \Pi(x)\}$ – parameters of the characteristic function.

Based on expression (9), the one-dimensional characteristic function of a linear random process (6) in Levy form will be written as follows:

$$\begin{aligned} \ln f_\xi(t, U) &= iU\mu \int_{-\infty}^{\infty} \varphi(\tau, t) d\tau - \frac{\sigma^2 U^2}{2} \int_{-\infty}^{\infty} \varphi(\tau, t) d\tau + \\ &+ \int_{-\infty}^{\infty} \int \left[e^{iUX\varphi(\tau, t)} - 1 - \frac{iUX\varphi(\tau, t)}{1 + X^2} \right] d\pi(x) d\tau. \end{aligned} \tag{10}$$

If $\sigma^2 = 0$, then the linear random process (6) does not contain a Gaussian component and is an impulse linear random process. The given process is a stochastic functional of a random process with independent increments $\eta(\tau)$. The characteristic function of this process is infinitely divided. This allows us to state that the linear random process's characteristic function (5) is also infinitely divided. It is also possible to present the characteristic function (10) in the form of Kolmogorov and Levy-Khinchin.

The thermal noise of the hardware is also described by a linear stochastic process, which allows representation in the form of a stochastic integral

$$\xi(t) = \int_{-\infty}^{\infty} \varphi(\tau, t) d\eta(\tau) \text{ at } t \in (-\infty, \infty), \quad (11)$$

where $\varphi(\tau, t)$ at $t \in (-\infty, \infty)$ – integrated numerical non-random function, $\eta(\tau)$ at $\tau \in (-\infty, \infty)$ – a random process with independent increments.

Note that the random process $\xi(t)$, which is defined according to expression (6), is also linear in a certain sense. Formally, it can be presented as the limit of process (7) as follows

$$\xi(t) = \sigma \int_{-\infty}^{\infty} \lim_{f_0 \to \infty} \frac{\sin[2\pi f_0 (t - \tau)]}{\pi (t - \tau)} dw(\tau) \quad (12)$$

The random process (12) can be considered a closing element of the class of linear processes using a boundary transition in their kernels. The limit in expression (12) does not exist in the usual sense and is meant in a generalized sense. Its kernel satisfies the conditions imposed on the process's kernel (12), since it is a delta function (there is no square integral).

Based on expression (12), we determine the dispersion of thermal noise of hardware [18]

$$\sigma_o^2 = Mv_o^2(t) = \frac{2\pi^2 k_1^2 T_a^2 R}{3h_n} \approx 1{,}8928 \cdot 10^{-12} T_a^2 R \quad (13)$$

Taking into account expressions (13) and (12), we obtain the correlation function of a random process in the form

$$R(S) = \frac{h_n R}{2\pi^2 S^2} - \frac{2\pi^2 k_1^2 T_a^2 R}{h_n} \operatorname{cosech}^2\left(\frac{2\pi^2 k_1 T_a S}{h_n}\right) \quad (14)$$

Let's move on to the development of the method of summarizing random components of hardware and software.

2.4 The Method of Summation of Random Components

In order to calculate the insensitivity bands around the nominal characteristics of the transformation of the components of the CS, it is necessary to perform the procedure of summing up the uncertainties of the input signals and disturbances. In this summation, we will assume that all components of the uncertainties of the input signals are random variables, which are given by their one-dimensional and multidimensional distribution laws. When developing the summarization method, it is also taken into account that:

- the numerical characteristics of the distribution laws of random components are not constant as a function of the input signals;
- individual random components of uncertainty can be correlated with each other;
- when random variables are summed up, the laws of their distributions are significantly deformed.

Mathematical models of random disturbances of the CS allow using any expression. However, if mathematical noise models describe different classes of distributions, then it is also necessary to decide to which class the distribution of the resulting uncertainty belongs. We will use the informational approach to establish the class of the resulting distribution. At the same time, the kurtosis value of the distribution of the sum of two independent random variables can be calculated analytically. The fourth moment of the composition of two random variables with independent distributions is described by the expression [19]

$$\mu_{4\Sigma} = \mu_{4,1} + 4\mu_{3,1}\mu_{1,2} + 6\mu_{2,1}\mu_{2,2} + 4\mu_{1,1}\mu_{3,2} + \mu_{4,2}$$

For symmetric (unscrewed) distributions, we have $\mu_{3,1} = 0$ and $\mu_{3,2} = 0$, under this condition

$$\mu_{4\Sigma} = \mu_{4,1} + 6\sigma_1^2\sigma_2^2 + \mu_{4,2} \quad (15)$$

The excess of the total distribution is in the form

$$E_\Sigma = \frac{\mu_{4\Sigma}}{\sigma_\Sigma^4} - 3 = \frac{\mu_{4,1} + 6\sigma_1^2\sigma_2^2 + \mu_{4,2}}{\left(\sigma_1^2 + \sigma_2^2\right)^2} - 3 \quad (16)$$

Denoting the weight of the variance of the first distribution in the total variance as follows

$$d_1 = \frac{\sigma_1^2}{\sigma_1^2 + \sigma_2^2} \quad (17)$$

we will finally get

$$E_\Sigma = \left[E_1 d_1^2 + 6d_1(1 - d_1) + E_2 (1 - d_1)^2\right] - 3 \quad (18)$$

To calculate the resulting uncertainty of the hardware, one needs to know the estimates σ_1, E_1 and σ_2, E_2. Next are defined σ_Σ, then the weight of the variance of one component, then there is the kurtosis of the total distribution. If more than two random components are summed, then summation and definition E_Σ is carried out sequentially: the first from the second, then obtained because of summation from the third, again obtained because of summation from the fourth, etc.

Thus, calculated values are determined σ_Σ and E_Σ when summing any number of random components. Let's proceed to the development of algorithmic support.

2.5 Algorithmic Monitoring of Cylinder Capacities

Algorithmic support for monitoring the distribution of cylinder capacities of ICE implements the principle of deviation control $D_i - 1 \to 0$ and is based on setting the value of the weight coefficients of individual cylinders (D_i). For this, a system of algebraic equations of the following form is solved [19]

$$BD = \varphi_1 - \varphi_{1,0} \tag{19}$$

where B – matrix size $m \times n$, the coefficients of which are determined based on transfer functions and torques, depending on the selected calculation method; φ_1 – column vector of the measurement signal; D – column vector of cylinder weights; $\varphi_{1,0}$ – the column vector of the unevenness of the crankshaft rotation signal, which is obtained as a result of computer simulation by multiplying the torque of the cylinder in the absence of fuel supply by the corresponding transfer function with subsequent summation. In case of frequency presentation of the measurement information signal, the matrix coefficients are determined as follows:

$$B_{n,m} = \sum_{n=1}^{6}\sum_{m=1}^{5} W_{1m}(in\Omega) M_{m,p}(in\Omega).$$

The number of equations in system (19) is determined by the convergence of the obtained solutions upon reaching the given uncertainty of the software for calculating the weighting factor D_i taking into account the effect of random interference on the measurement information signal. The number of discretization intervals of the unevenness of rotation of the first mass of the crankshaft during one revolution is chosen based on Kotelnikov's theorem. We will also assume that the laws of the distribution of random disturbances are known since they can be established in advance as a result of theoretical studies or by statistical processing of a series of tests with multiple observations. Thus, we will obtain a specific implementation of a random disturbance and set its distribution parameters as mean value, mean square deviation, skewness, and kurtosis. Such calculations were called computer simulation of random disturbances, as a mathematical apparatus for the development of which researchers use the Monte Carlo method.

2.6 Methods of Processing Experimental Data

As a result of processing the experimental data of the signal of the unevenness of rotation of the first mass of the crankshaft of the power unit, we have a random point with coordinates $Q(\xi^1, \xi^2, \ldots, \xi^n)$, the distribution law of which $F_Q(x)$ established based on the use of the information approach of measurement theory - is known. It is necessary to establish the probabilistic characteristics of a scalar quantity $\eta = f(Q), Q \to F_Q(x)$, provided that the form of the random function is known. When given $M[\eta], P(\eta \in \Delta)$ (Δ given interval) and a random function $f(x_1, x_2, \ldots, x_n)$ complex (the algorithm is given), then calculate the distribution function analytically $F_\eta(y)$ fails. Therefore, we will use the Monte Carlo method to construct a scatter histogram of the experimental data of the signal of the unevenness of the rotation of the first mass of the crankshaft of the power unit:

- we find independent implementations Q_i ;
- we install $\eta_i = f(Q_i)$ using expressions

$$\hat{\eta} = M[\eta] \cong \frac{1}{N}\sum_{i=1}^{N}\eta_i, \hat{P}(\eta \in \Delta) \cong \frac{1}{N}\sum_{i=1}^{N} x_\Delta(\eta_i) \tag{20}$$

- choose the intervals Δ ;
- a histogram $h_N(y)$ scatter of experimental data of the signal of unevenness of rotation of the first mass of the crankshaft of the power unit was built.

Segment $[a,b] \Rightarrow \eta_1, \eta_2, \ldots, \eta_n$ covers all sample values of the random function. We divide it into several equal intervals r

$$\bigcup_{j=1}^{r} R_j = R \equiv [a,b], [a,b] = \sum_{j=1}^{r}[y_{j-1}; y_j) \text{ at } y_0 = a, y_r = b \tag{21}$$

in addition, set the number of sample values of the signal of unevenness of rotation of the first mass of the crankshaft of the power unit that fell into each interval $\nu_1, \nu_2, \ldots, \nu_r$.

The histogram $h_N(y) = (\nu_i / N)/(y_j - y_{j-1})$ of the scatter of the experimental data is built under the condition at $y \in (y_{j-1}, y_j)$. It is a stepped line. Based on the scatter histogram of the experimental data of the signal of the unevenness of rotation of the first mass of the crankshaft of the power unit, we select the distribution law $F_Q(x)$ under the following condition:

$$\int_{x_{\min}}^{x_{\max}} F_Q(x)dx - \frac{1}{N}\sum_{i=1}^{N} p(x_i)\Delta_i \to \min \tag{22}$$

To calculate the values of random variables, it is enough to be able to generate one random variable that has the required distribution law. The following sequence is usually chosen as such a random variable

$$a \in Rav(0,1), f_a(x) = 1, F_a(x) = x, M[x] = 0.5, D[x] = 1/12 .$$

The problem arises: how to get the value $a \in Rav(0,1)$. A microcomputer always provides a real number with limited uncertainty, so we will generate integers x_n in the interval from 0 to some m. Then a fraction $a_n = x_n / m$, where m – word size always falls within the interval (0, 1). All known primary converters of the instantaneous speed of rotation of crankshafts when forming the signals of measurement information implement some cases of the Lamer scheme

$$x_{n+1} = (ax_n + c) \bmod m, n \geq 0 , \tag{23}$$

where $a \geq 0$ – multiplier, $x_0 \geq 0$ – initial value, $c \geq 0$ – increment, $m > x_0, m > a, m > c$ – module.

Choosing a value is particularly important when constructing this sequence a (specifies the period of the maximum length of a series of numbers) and value m (sets the number construction speed). When simulating random processes, to ensure the required statistical uncertainty of the result, it is necessary to establish the amount of experimental data of the signal of unevenness of rotation of the first mass of the crankshaft of the power unit. The main criterion for implementing this procedure is the appearance of the performance indicator. The method of its installation is as follows.

Let the event A describes the fact of task performance, which is described using the uniform distribution law $P(A) = m/N$. Due to the presence of the limit theorem, we have the following:

$$P\left(\left|\frac{m}{N} - p\right| < t_\alpha \sigma\right) = \alpha , \; t_\alpha = \Phi^{-1}\left(\frac{\alpha}{2}\right),$$

$$\Phi(t_\alpha) = \frac{1}{\sqrt{2\pi}} \int_0^{t_\alpha} e^{-\frac{z\alpha}{2}} dz = \frac{\alpha}{2} , \quad \varepsilon = t_\alpha \sigma ,$$

$$\sigma^2 = \frac{p(1-p)}{N} .$$

From here we get the expression for establishing the required number of realizations of the random value of the signal of the unevenness of rotation of the first mass of the crankshaft of the power unit with the given uncertainty of the evaluation ε and confidence probability α

$$N = t_\alpha^2 \frac{p(1-p)}{\varepsilon^2} . \tag{24}$$

For the case when $\delta = \varepsilon / p$, which we will consider relative uncertainty. Then we have the following expression

$$N = \frac{t_\alpha^2 (1-p)}{\sigma^2 p} \approx \frac{t_\alpha^2}{p \sigma^2} . \tag{25}$$

The results of calculations of the possible number of realizations of the random value of the signal of the unevenness of rotation of the first mass of the crankshaft of the power unit with the given uncertainty of the assessment ε and confidence probability α given in the table 1.

Table 1. Calculation results

P	(1-P)	ε		
		0.05	0.02	0.01
0.1	0.9	141	904	3607
0.2	0.8	249	1498	6189
0.3	0.7	352	2108	8405
0.4	0.6	378	2297	9409
0.5	0.5	385	2412	9789

We believe that the efficiency indicator E is a certain function of the parameters and structure of the system, as well as the algorithm of the functioning of the hardware. Its mathematical expectation is established as a result of processing experimental data in this way:

$$\hat{E} = \frac{1}{N} \sum_{i=1}^{N} E_i \tag{26}$$

where E_i – the value of the efficiency indicator of the i-th experiment. After simple mathematical transformations, we have:

$$P\left(| E - m_e | \leq t_\alpha \sigma_E / \sqrt{N}\right) = \alpha , \quad N = \frac{t_\alpha^2 \sigma_E^2}{\varepsilon^2} \tag{27}$$

Thus, the best way to determine the number of trials is to use a sequential algorithm for multiplying the number of samples. The requirements for the uncertainty of the MT will be formed when processing the results of the solution of the system of algebraic equations (19). Calculations take into account:

- additive effect of random interference on the measurement information signal;
- a random additive change in the phase delays of individual cylinders relative to the first.

2.7 Information Technology for Software Uncertainty Calculation

The results of solving the system of algebraic equations (19) represent a number of measurements with multiple observations. Uncertainty of calculation of weighting coefficients D_i finds its quantitative manifestation in the fluctuations of their values. To establish the uncertainty value, the calculated data was statistically processed using the informational approach of measurement theory. In fig. 1 shows a histogram of the scatter of calculated data. The main statistical parameters of this distribution are as follows

$$\overline{X} = 0, \ \sigma = 0.036, \ A = 0, \ E = -0.504. \tag{28}$$

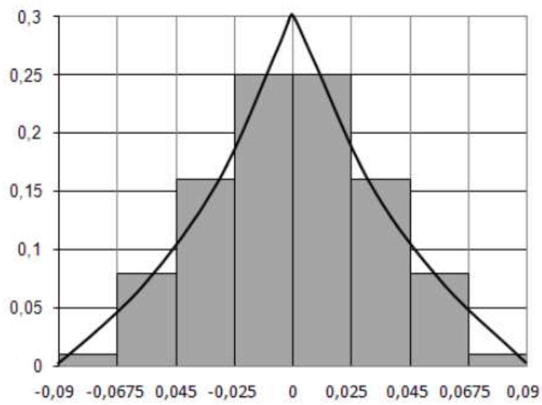

Figure 1: Scattering histogram of calculation data

The histogram of the scatter after performing the computational smoothing procedure is represented by an exponential law, which in its appearance is close enough to a triangular one. The equation of the smoothed curve, after applying the *Stat graft* program, has the following form [20]

$$f_1(x) = \frac{1}{2\sigma} e^{-\frac{|x|}{\sigma}} \text{ at } x \in (-0.09, 0.09). \tag{29}$$

For this distribution law, the entropy uncertainty interval was

$$\Delta_1 = \sigma e^{\frac{\mu_1}{\sigma}} = 0.036. \tag{30}$$

Information technology for processing the results of calculations consists of the following actions:

- we determine the average of the real and imaginary parts of the complexes of weight coefficients of cylinders D_i;
- based on the informational approach of measurement theory, we calculate the absolute and relative value of uncertainties in the calculation of coefficients;
- we build uncertainty graphs of software for calculating weighting factors using the *Mathcad* software environment.

2.8 Discussion of Research Results

In fig. 2 shows the uncertainty graphs of the software for calculating the weight coefficients of cylinders D_i, which are obtained using the *Mathcad* software environment. At the same time, the authors used the Lamer scheme for computer simulation of additive random interference, which distorts the measurement information signal. A system of algebraic equations (19) of the following form is solved [19]

$$BD = \varphi_1 + \delta_4(t), \tag{31}$$

where $\delta_4(t)$ – additive random interference that acts on the measurement information signal.

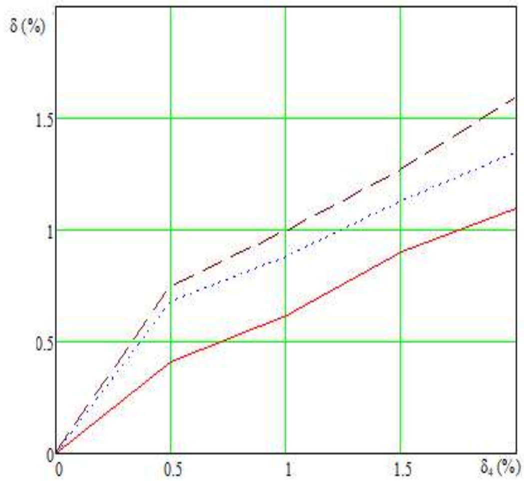

Figure 2: Calculation uncertainty graphs: continuous D_1, point D_2, dashed D_3

Uncertainty graphs of the software for calculating the weighting coefficients of cylinders D_i (fig. 3) obtained at different levels of multiplicative random disturbance (δ_5), which changes the phase delay of individual cylinders relative to the first. This uncertainty modifies the left-hand side of the system of equations (19) by introducing a random lag or lead. In computer simulation of multiplicative random interference, the authors used a standard algorithm, the block diagram of which is shown in fig. 4. Application software was developed on the basis of this scheme. In this case, the following system of algebraic equations is solved [19]

$$BDe^{j\delta_5(t)} = \varphi_1. \tag{32}$$

In fig. 5 shows the uncertainty graphs of the software for calculating the weighting factors D_i, to establish which was used:

- additive random disturbance ($\delta_4 = 1.0\%$), which is generated according to the Lamer scheme and affects the measurement information signal;
- multiplicative random disturbance (δ_5), which changes the phase delays of the cylinders relative to the first.

$$BDe^{j\delta_5(t)} = \varphi_1 + \delta_4(t)\,. \tag{33}$$

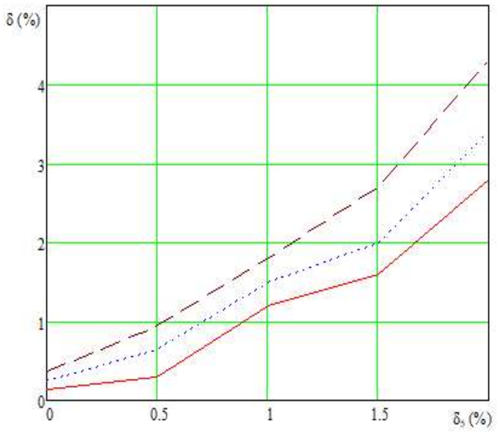

Figure 3: Calculation uncertainty graphs: continuous D_1*, point* D_2*, dashed* D_3

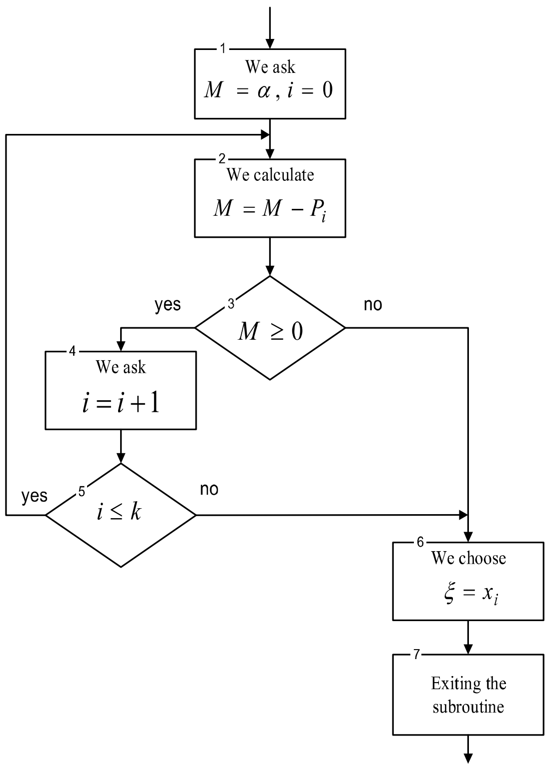

Figure 4: Standard algorithm for determining m given a given value α

A standard algorithm was also used for the computer simulation of the interference, the diagram shown in Fig. 6. Based on this scheme, the authors developed application software. In this case, the following system of algebraic equations is solved [19]

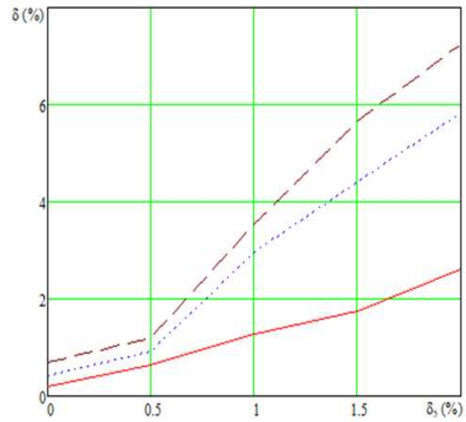

Figure 5: Calculation uncertainty graphs: continuous D_1*, point* D_2*, dashed* D_3

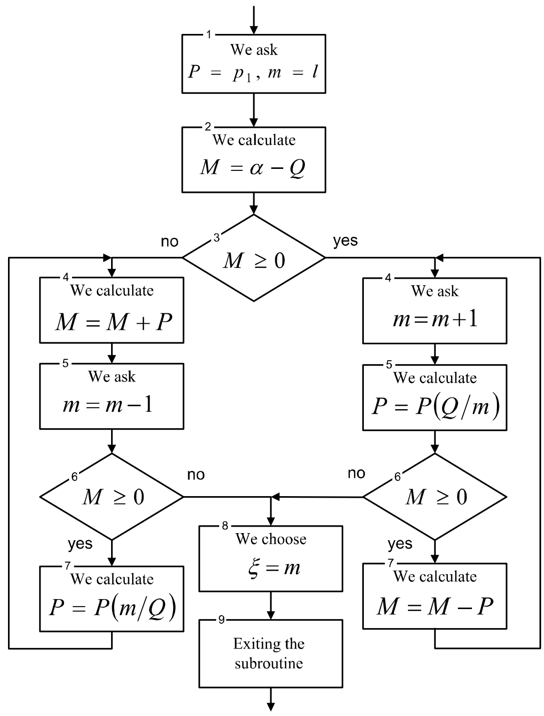

Figure 6: Scheme of the random number modeling algorithm

3. Conclusions

Algorithmic support for monitoring cylinder capacities is built on the principle of deviation control and frequency reporting of the measurement information signal in the form of irregular engine crankshaft rotation. The sources of random disturbances affecting the output signals of the hardware and software controls for the supply of the fuel-air mixture have been established. Their difference lies in the additive and multiplicative effect on the measurement information signal and the influence on the hardware.

As a mathematical model of thermal disturbances of hardware, a linear random process, presented as a stochastic integral, is first proposed. An information technology for summarizing the uncertainties of input signals and random disturbances has been developed. At the same time, we conclude that all components of the uncertainties of the input signals are given by their one-dimensional and multidimensional distribution laws.

The informational approach of measurement theory and the Monte Carlo method are used as a mathematical apparatus for researching the uncertainty of the software for setting weighting coefficients of cylinders. In the computer simulation of additive and multiplicative random disturbances, the Lamer scheme and the standard algorithm for determining the speed of building numbers at a given value of the period of the maximum length of the series were used.

The influence of random disturbances on the results of solving the system of algebraic equations was investigated using the computer modeling method to determine the values of the weighting coefficients of the cylinders. Algorithmic and application software for computer simulation of several types of random disturbances has been developed. In the Mathcad software environment, graphs of the software uncertainties for calculating the weighting coefficients of cylinders are constructed. As a result of analyzing the graphs, the requirements for the metrological characteristics of the hardware for measuring the signal of the instantaneous speed of rotation of the crankshaft were established.

Assuming the presence of an additive random disturbance with a confidence interval of 0.5%, which affects the measurement information signal, the software's maximum uncertainty for setting the cylinders' weighting coefficients is 0.75%. In the presence of a multiplicative random disturbance, which changes the phase delays of the cylinders relative to the first one within a confidence interval of 0.5%, the largest uncertainty of the software for calculating the weighting coefficients of the cylinders is also 1%. Under the conditions of the presence of an additive random interference of the measurement information signal with a confidence interval of 1.0% and a multiplicative interference that changes the phase delays of the cylinders relative to the first within 0.5%, the final maximum uncertainty of the software for calculating the weighting coefficients of the cylinders is approximately 1.3%. The given values of uncertainties of the software for calculating the weight coefficients of the cylinders should be considered when designing software and hardware for controlling the supply of the fuel-air mixture.

References

[1] Bilyk S., Bozhko E. Analysis of methods and methods of diagnosing internal combustion engines by non-assembly control methods. Bulletin of the National Technical University "KhPI". Series: New solutions in modern technology. Kharkiv: NTU "KhPI", 2021, no. 4(10), pp. 3-8, doi:10.20998/2413-4295.2021.04.01.

[2] Zadvornov Ya., Riazantsev V. Osoblyvosti vibroakustychnoho diahnostuvannia tekhnichnoho stanu spriazhen detalei dyzelnykh dvyhuniv. Mekhanizatsiia ta elektryfikatsiia silskoho hospodarstva. 2016. 4. c. 175-185. http://nbuv.gov.ua/UJRN/mesg_2016_4_21

[3] Ved M., Feature Selection and Feature Extraction in Machine Learning: An Overview. 2018. 19. 7. https:// medium.com/@mehulved1503/featureselection-and-featureextraction-in-machine-learningan-overview-57891c595e96

[4] Vasyliev Ye. A., Prokopenko A. S. Metodyka diahnostuvannia porshnevykh dvyhuniv vnutrishnoho zghoriannia za rezultatamy yikh nepriamoho vidobrazhennia. Zbirnyk naukovykh prats studentiv elektromekhanichnoho fakultetu. – Poltava: PoltNTU, 2015. Vyp. 6. S. 184-192. http://reposit.pntu.edu.ua/handle/PoltNTU/1129

[5] Nakonechnyi A., Hetman O. Metody ta zasoby diahnostuvannia roboty dvyhuna avtomobilia za otsinkoiu yoho vibroakustychnykh kharakterystyk. Visnyk Natsionalnoho universytetu "Lvivska politekhnika". Seriia: Avtomatyka, vymiriuvannia ta keruvannia. 2018. 907. 38-43. https://ena.lpnu.ua/collections/58e96f5b-ea33-4c2c-8e88-4fd882d01b2b

[6] Shkrehal O., Lymarenko V., Rylskyi D. Zastosuvannia suchasnykh diahnostychnykh metodiv ta zasobiv pidvyshchennia tekhnichnoho rivnia mashyn. Visnyk Kharkivskoho natsionalnoho tekhnichnoho universytetu silskoho hospodarstva imeni Petra Vasylenka. 2014. 145. 174-178. http://nbuv.gov.ua/UJRN/Vkhdtusg_2014_145_29

[7] Sylyvonyuk A. V., Yaroshevich A. V. About some features of dynamic acceleration of vibration machines with self-synchronisation inertion vibroexciters, Proceedings of XLI International Summer School–Conference APM 2013, 662-670.

[8] Niselovskaya E. V., Panovko G. Ya., Shokhin A. E. Oscillations of the mechanical system, excited by unbalanced rotor of induction motor. Journal of Machinery Manufacture and Reliability, 42 (2013), n.6, 457-462.

[9] Shokhin A. E., Nikiforov A. E. On the Rational Dynamic Modes of Vibrating Machines with an Unbalanced Vibration Exciter of Limited Power. Journal of Machinery Manufacture and Reliability, 46 (2017), n.5, 426-433.

[10] Karmakar S., Chattopadhyay S., Mitra M., Sengupta S. Induction Motor Fault Diagnosis. Approach through Current Signature Analysis, XXV (2016), 161.

[11] Shatokhin V., Sobol V., Wójcik W., Duskazaev G., Jarykbassov D. Dynamical processes simulation of unbalanced vibration devices with eccentric rotor and induction electric drive. Przegląd Elektrotechnicz. Vol 2019. No 4. P. 79-85. http://doi.org/10.15199/48.2019.04.14

[12] Shatokhin V., Sobol V., Wójcik W., Mussabekova A., Baitussupov D. Dynamical processes simulation of vibrational mounting devices and synthesis of their parameters. Przegląd Elektrotechnicz. Vol 2019. No 4. P. 86-92. http://doi.org/10.15199/48.2019.04.15

[13] Scherbak L., Nazarevych O., Gotovych V., Tymkiv P., Shymchuk G. "Multicomponent Model of the Heart Rate Variability Change-point," 2019 IEEE XVth International Conference on the Perspective Technologies and Methods in MEMS Design (MEMSTECH), Polyana, Ukraine, 2019. 110-113.

[14] Fryz M. Ye., Shcherbak L. M. Statystychnyi analiz periodychnoi avtorehresii z vypadkovymy koefitsiientamy v zadachakh operatyvnoho prohnozuvannia elektrospozhyvannia pidpryiemstv. Tekhnichna elektrodynamika. 2019. №2. S. 38-47.

[15] Fryz M., Scherbak L., Karpinski M., Mlynko B. Characteristic Function of Conditional Linear Random Process, Proceedings of the 1st International Workshop on Information Technologies: Theoretical and Applied Problems, CEUR Workshop Proceedings, 2021. 129-135.

[16] Mykhailovych T., Fryz M., Lytvynenko I. Water Consumption Periodic Autoregressive Time Series Iterative Forecasting, Proceedings of the 1st International Workshop on Information Technologies: Theoretical and Applied Problems, CEUR Workshop Proceedings. 2021. 182-191.

[17] Yenikieiev O., Zakharenkov D., Korotenko Ye., Razzhyvin O., Yakovenko I., Yevsyukova F., Naboka O. A Computer System for Reliable Operation of a Diesel Generator on the Basis of Indirect Measurement Data Processing. International Conference on Reliable Systems Engineering (ICoRSE) 2022. Pp 30-44. DOI: 10.1007/978-3-031-15944-2_4.

[18] Yenikieiev O., Zakharenkov D., Gasanov M., Yevsyukova F., Naboka O., Ruzmetov A. Improving the Productivity of Information Technology for Processing Indirect Measurement Data. International Conference on Reliable Systems Engineering (ICoRSE) 2022. Pp 80-94. DOI: 10.1007/978-3-031-15944-2_8.

[19] Yenikieiev O, Shcherbak L. Information technology for protecting diesel-electric station reliable operation. Tekhnichna Elektrodynamika. 2019. (4), 85-91.

[20] Yenikieiev O., Zakharenkov D., Gasanov M., Yevsyukova F., Naboka O., Borysenko A., Pavlova N. Comparison of Metrological Characteristics of Measuring Transducer of Parameters Frequency-Modulated Signals. International Conference on Reliable Systems Engineering (ICoRSE). 2023. Lecture Notes in Networks and Systems, vol 762. Springer, Cham. pp 586-603. doi: 10.1007/978-3-031-40628-7_47.