INFORMATION TECHNOLOGY OF MONITORING OF PHASE DELAY FLUCTUATIONS BASED ON INDIRECT MEASUREMENT DATA PROCESSING

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Abstract – The paper proposes the use of correlation analysis to process experimental data from indirect measurements to monitor phase delay fluctuations in fuel-air mixture supply to internal combustion engine cylinders. The oscillatory movements of model masses are described by a system of second-order linear differential equations, normalized using similarity theory methods. The deterministic system is solved via the Laplace transform under zero initial conditions.
Frequency characteristics of cylinder torque transfer functions are analyzed in Matlab, while a measurement signal simulation scheme is developed in Mathcad. Additive noise is modeled as structured "white noise" with a frequency spectrum limited to ten harmonic components. Neural network techniques adjust the length of information links in the simulation, allowing for variation in amplification coefficients of cylinder torque amplitudes.
The application for cross-correlation function calculation is implemented in Mathcad. Analysis of mutual correlation function graphs shows that its maxima correspond to the standard torque phases of the second, third, and first cylinders, respectively. It is established that a 60% uncertainty in crankshaft rotation unevenness measurement still enables unambiguous identification of these maxima.
Additionally, the influence of additive "white noise" on cross-correlation function graphs is investigated under varying gain coefficients of the measurement signal modeling scheme. Results show that even with a 15% measurement uncertainty of a deterministic crankshaft rotation unevenness signal, the mutual correlation function remains effective for monitoring phase delay fluctuations in cylinder torques relative to standard engine settings.

Keywords Information Technology, Software and Hardware, Mathematical Model, Transfer Function, Fluctuations of Phase Delays, Mutual Correlation Function, Uncertainty.

1. Introduction

The economic performance of internal combustion engines (ICE) is determined by the regular setting of the angles of fuel supply to the cylinders [1]. A well-known indirect method of monitoring fluctuations of phase delays relative to the standard setting of fuel supply angles uses a frequency-modulated signal (FM signal) of the crankshaft rotation speed as a source of input information [2, 3]. The algorithmic support of the method is based on the following actions: approximation using limited Fourier series of cylinder torques; assembly of a mechanical model of the torque circuit of the power unit; the use of numerical methods to solve the system of differential equations of mass movements of the crankshaft of an ICE; comparison of the obtained results and correction of the angles of fuel supply to the required cylinders in order to obtain the regular setting.

The implementation of software and hardware means of setting the standard setting of the fuel-air

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mixture supply angles to the cylinders of the ICE will reduce fuel consumption by approximately 5% and increase the service life of the power unit [2].

The use of piezo-controlled injectors as the acting mechanisms of fuel supply to the cylinders of the ICE ensured the development of software and hardware means of setting the standard angle adjustment with feedback based on the state of the crankshaft rotation unevenness signal. When building hardware and soft-ware tools, a fundamental issue is the choice of a method for monitoring fluctuations in phase delays relative to the regular setting of fuel supply to the cylinders of an ICE. A well-known indirect method of monitoring fluctuations of phase delays uses the signal of irregular rotation of the crankshaft as measurement in-formation [2]. The authors propose the idea of its modernization thanks to the application of correlation analysis methods for processing the measurement in-formation signal. Thus, the development of the methodology of a new method of monitoring fluctuations of phase delays and the construction on its basis of soft-ware and hardware means of setting standard angles of supply of the fuel-air mixture to the cylinders of the ICE, which will collectively ensure less uncertainty in the processing of indirect measurement data and improved performance, deter-mines the relevance of this scientific and applied problem.

The modern state of the machine-building industry has made it possible to introduce injectors with electro-hydraulic or piezoelectric control as mechanisms that perform the processes of supplying the fuel-air mixture to the cylinders of power units. This circumstance, in turn, created the conditions for the rapid development of hardware and software tools for individually specifying the phases of fuel supply processes to cylinders with feedback based on the state of the crankshaft speed fluctuation signal. When solving this applied problem, the main component of the computer system, which significantly affects the metrological and dynamic characteristics of the control of the processes of supplying the fuel-air mixture to the cylinders, is the measuring converter (MC) of the parameters of the FM-signals of the speed of rotation of the crankshaft. Thus, the development of new methods of measuring the parameters of FM-signals and, on their basis, the construction of hardware and software tools with improved metrological characteristics and increased processing speed of indirect measurement data determines the relevance of this scientific and applied task.

1.1 Analysis of Literary Data and Statement of the Problem

The issue of monitoring fluctuations of phase delays relative to the standard set-ting of the angles of supply of the fuel-air mixture to the cylinders of the ICE under conditions of incomplete information is given attention in the technical literature. In work [3], the capabilities of the Matlab software environment were used to process the signal of uneven rotation of the crankshaft of the ICE. A high-frequency filter with a finite impulse response was applied, and the effect of random interference on the FM signal of measurement information was reduced. In [4], the influence of the working process of the ICE on the deviation of the indicator pressure of the cylinder was established thanks to the analysis of the power connections of the crank-connecting mechanism. Mathematical modelling of the D50 engine operating conditions was performed. Algorithmization of the mathematical model was carried out and application software was developed. In the works [4, 5], machine learning methods were used to generalize the results of studies of the crankshaft rotation irregularity signal. Based on them, the expressions of the corresponding objective functions were obtained. In works [6, 7], the parameters of the unevenness of the crankshaft rotation signal were used and, based on them, a technique for assessing the technical condition of the ICE was developed. The work [8] established information links between the crankshaft rotation irregularity signal, the value of the indicator torque, and quantitative changes in the cylinder capacities of four-stroke ICEs in the form of experimental data.

In [9], a complex mathematical model of the signal of unevenness of rotation of a vibration apparatus on elastic supports with an eccentric unbalanced rotor is proposed. When calculating the signal, the plane-parallel movement of the working chamber of the asynchronous electric motor is also taken into account. Reduction of rotor shaft vibrations due to rational selection of the eccentricity value was established. The start-up mode of the electric motor was also investigated and a geometric interpretation of the shaft rotation irregularity signal was obtained. In work [10], a mathematical model of the signal of unevenness of rotation of the robot control device is proposed for studies of the start-up mode, stable modes and spatial movements of arbitrary points. The methods of sensitivity theory were used to develop a methodology for the synthesis of a robot control device with feedback based on the state of the rotation unevenness signal.

In [11], to reduce the amplitude of oscillations of the torque circuit of the ICE, a method of synthesis of the parameters of the nonlinear flexible coupling is pro-posed. A rather economical form of the method of harmonic linearization of the integral equations of motion of the masses of the torque circuit with the help of pulse-frequency characteristics is used. In [12], a method of researching stable dynamic processes of torsional oscillations of nonlinear mathematical models of power units is proposed. The Newton-Kantorovich method was used and algorithmic support for the solution of nonlinear integro-differential equations was developed. In [13], algorithmic support for the solution of integral equations is proposed under the condition of stable dynamic processes of torsional oscillations of nonlinear mathematical models of the ICE. The algorithm provides con-vengeance from an arbitrary initial approximation to some solution of the system of nonlinear integral equations. In [14], a mathematical model of the camshaft drive of the fuel pump of the ICE is proposed. Integral equations of mass movements of the torque circuit, which were obtained with the help of pulse-frequency characteristics, were used, and the results of the research of the drive parameters were given.

In [15], the Laplace transformation was used to solve the differential equations of motion of the crankshaft masses of an ICE. A redefined system of incompatible algebraic equations is obtained. The column vector of its right part is the frequency representation of the crankshaft rotation irregularity signal. The left part is formed by the product of the vector-column of the weight coefficients of the cylinders and the matrix, the coefficients of which are set based on the results of the analysis of the "cylinder-first mass of the crankshaft" transmission functions. The well-known method of radial basis functions when solving similar problems operates with completely filled matrices, which significantly limits the performance of the procedure for monitoring fluctuations of phase delays relative to the standard setting of fuel supply to the cylinders of the ICE.

The idea is proposed to use the methods of correlation processing of crankshaft rotation unevenness signals to monitor fluctuations of phase delays relative to the standard setting of fuel supply to the cylinders of the ICE. Specialized multi-channel correlators for calculating autocorrelation and cross-correlation functions of the radar scattering signal are considered in [16]. The works [17, 18] set the requirements for the characteristics of the radar signal and considered the methods of increasing the stability of information messages under the conditions of random interference. In [19], a significant improvement in the signal/interference ratio of information messages was achieved due to the use of a correlator for accumulation of pulses of a useful information signal in the receiver. As a result, it was possible to ensure the possibility of information transmission, if the amplitude of the useful signal is significantly lower than the interference level in a wide frequency range.

In [20], the authors proposed a structure of modernized hardware for the implementation of the mode of additional processing of the orthogonal components of the radar incoherent scattering signal. The separate reception of circularly polarized components of the signal with multiplication was investigated by computer simulation and the situation of the effect of random interference on it was taken into account. In [21], it is proposed to increase the frequency of analogous-digital signal conversion and achieve a larger number of ordinates of the autocorrelation function at a given length of the correlation interval. In addition, the un-certainty of estimating the autocorrelation function of the signal and, accordingly, the uncertainty of obtaining the parameters of the ionosphere have been reduced. In [22], in order to eliminate the shortcomings of the analogy I/Q demodulator, a method for estimating the quadrature components of the autocorrelation function of an incoherent scattering signal using one channel of a radio receiver and an analogous-digital converter is proposed. It was established that the developed method of correlation processing of the signal reduces the uncertainty of the calculation of the autocorrelation function.

In [23], in order to reduce the frequency of sampling during further processing, a modification of the computer representation of radar signals is proposed. An improvement in sensitivity to small values of the Doppler shift was obtained un-der the condition of a long duration of the radio pulse. The paper [24] presents the results of the spectral analysis of the Faraday Double Pulse experiments regarding the comparison of electron densities. The first was determined using the method of spectral analysis, the second was obtained using standard correlation analysis. A satisfactory coincidence of results was obtained. The work [25] gives an example of restoring the height profile of the power of an incoherent scattered radar signal using special calculations. The reference function of the analytical polynomial is introduced, which additionally connects the power values of scattered signal readings by neighbouring parts of the ionosphere, when establishing the high-altitude electron density. Substantial compensation of the smoothing effect caused by the use of a long probing radio pulse was obtained.

In [26], an extended series in terms of compactly supported B-spline functions is used, which allows appropriate processing of the heterogeneous distribution of experimental data, including their gaps. Based on them, a global presentation of the vertical total electron content was developed. The corresponding series coefficients and additional parameters constitute a set of unknown parameters. The modern radio air is littered with signals of various nature [27], which arise in the frequency range of the incoherent scattering radar. As a result, reception of a useful signal occurs with a small (less than one) signal/interference ratio.

In [28], a useful model for measuring the correlation characteristics of signals scattered by the ionospheric plasma is proposed. Calculations became possible due to the input of several auxiliary correlation channels in a multi-channel de-vice that works in real time. Work [29] gives examples of improving modes of pulsed radiation of high-frequency radio waves and processing of the received signals. A computing device with analogous-digital conversion units at the input is proposed, which is used to calculate the autocorrelation function of the radar scattering signal.

The disadvantage of the known methods of processing FM signals of the speed of rotation of the crankshaft with subsequent control of the fuel supply to the cylinders of the ICE is the unsatisfactory dispersion of the measurement of instantaneous periods and the insufficient performance of hardware and software tools for monitoring fluctuations of phase delays relative to the standard setting, as well as the lack of algorithmic and application software for processing the measurement information signal.

1.2 The Purpose and Objectives of the Research

The purpose of the work is to improve the performance of hardware and software tools and reduce the uncertainty of monitoring fluctuations of phase delays relative to the standard setting of fuel supply to cylinders based on the processing of the FM signal of the crankshaft rotation speed. To achieve the set goal, the following tasks were set and solved in the work:

- to develop the conceptual principles of monitoring fluctuations of phase delays in relation to the regular setting of the fuel-air mixture supply to the cylinders of the ICE based on the processing of indirect measurement data;
- carry out computer simulation of input signals of the model using experimental data of cylinder pressure;
- build a mathematical model of the control object and identify its parameters;
- to investigate the frequency characteristics of mechanical torque trans-mission channels;
- to develop an information technology for calculating the perfectly deterministic signal of unevenness of rotation of the first mass of the crankshaft;
- make a diagram of computer modelling of the signal of measurement in-formation in the form of irregular rotation of the crankshaft;
- to build a mathematical model of additive interference, which affects the signal of measurement information of hardware and software monitoring of phase delay fluctuations;
- develop a methodology for processing the measurement information signal using correlation analysis methods;
- to create algorithmic and application software for monitoring fluctuations of phase delays relative to the regular setting of fuel supplies based on the processing of the FM signal of the rotation speed.

2. Materials and Research Methods

Among the above-considered methods of building software and hardware tools for processing the FM signal of measurement information, the most promising from the authors' point of view is the use of correlation analysis. A mutual correlation function is proposed as an estimate of fluctuations of phase delays relative to the regular setting of fuel supply to the cylinders. The information technology for calculating the mutual correlation function uses the FM signal of the speed of rotation of the crankshaft and the torque created on the shaft of the ICE by the first cylinder. Let's move on to the development of methodological principles for the construction of software and hardware tools for monitoring fluctuations of phase delays relative to the regular setting of fuel supplies based on measurements of the signal of uneven rotation of the crankshaft of the ICE using the mutual correlation function.

2.1 Approximation of the Input Signals of the Computer Simulation Circuit

The prototype of the 3TD-1 engine is a six-cylinder ICE of the 6TD-1 type. Reducing the number of its cylinders (to three) significantly changed the spectral properties of the original mathematical models of the kinematic scheme. The complete kinematic diagram of the ICE 3TD-1 is a mechanical system that has 21 masses and 7 non-linear connections in the form of a pair of gear wheels. The intake and exhaust shafts are connected to each other by means of four toothed joints. When analysing the kinematic diagram of the power unit, the authors found that the first mass of the lower crankshaft has no loads in the form of components connected to it. In accordance with the first mass, the authors connected the primary converter of the PDF-3 type and with its help received the measurement information signal. The crankshaft of the ICE. summarizes torques of cylinders 1, 2 and 3. The final torque ensures the rotation of the crankshaft at the required average speed. A limited Fourier series using the capabilities of the Mathcad software environment [31] will carry out approximation of torques. At the same time, the indicator diagram of the first cylinder with an iteration step of three degrees was used as input information. The discrete frequency spectrum of the torque of the first cylinder was obtained in [32] and presented in the table 1.

Table 1. Amplitudes of sine and cosine harmonic components (Nm)

A_n,	954.7	854.9	555.3	366.2	241.0	162.8
B_n,	322.0	-24.1	-68.0	-82.0	-106.2	-86.4

Based on the data in the table 1 torque of the first cylinder of the power unit has the following mathematical model

$$M_1(t)=\sum_{n=1}^{6}\left(A_n \sin n\Omega t + B_n \cos n\Omega t\right). \quad (1)$$

Mathematical models of torques of the second and third cylinders are similar to the first, taking into account phase delays of multiples of 120°, the value of which determines the order of operation of cylinders 1-2-3. Accordingly, the presentation of the torque of an arbitrary cylinder takes the following form

$$M_i(t)=M_1(t)e^{-j\Omega\tau_i}, \quad (2)$$

where τ_i – phase delay of the *i-th* cylinder relative to the first.

The differential torque ensures the rotation of the crankshaft of the ICE with a given angular velocity is determined using the following expression

$$M_5(t)=M_1(t)-M_4(t), \quad (3)$$

where $M_4(t)$ – torque, which is obtained because of processing the compression diagram in the Mathcad software environment.

Under the conditions of this presentation of the mathematical model of the torque, the authors organize the software control of the fuel supply to the cylinders of the power unit as follows $D_i - 1 \rightarrow 0$. Therefore, it is advisable to present the proposed differential torque of an individual cylinder in the form of expression (3), the amplitude of which is determined by the weight coefficients of the cylinders $D_i = 0\ldots1$. Accordingly, setting the values of these coefficients is the main task of monitoring the amount of fuel that is supplied to a separate cylinder of the power unit for one revolution of the crankshaft. Based on these considerations, the mathematical model of the torque of an arbitrary cylinder takes the following form

$$M_i(t)=\left[D_i M_5(t)+M_4(t)\right]e^{-j\Omega\tau_i}. \quad (4)$$

The authors through appropriate calculations using the Mathcad software environment established the feasibility of such a presentation. In fig. 1 shows the graphs of the computer simulation of the torque of the first cylinder and its components. After receiving a presentation of the input influences, we will proceed to the construction of a mathematical model of the torque circuit of the control object.

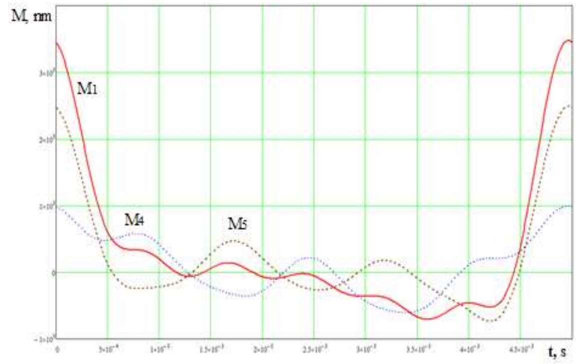


Figure 1: Results of computer simulation of the torque of the first cylinder

2.2 Development of a Mathematical Model of the Control Object

The structure of the lower crankshaft of the ICE 3TD-1 is formed by three cylinder masses and a gear wheel, which connects it with the upper one. Therefore, it is quite appropriate to present the lower crankshaft in the form of a deterministic mechanical system, which has four degrees of freedom. With this representation, the gear joints, which have nonlinear transformation characteristics, were not included in the mathematical model. Accordingly, the dynamics of rotation of cylindrical masses of a mechanical system with four degrees of freedom is described by the authors as a system of linear differential equations, the parameters of which are normalized based on the application of theorems and methods of similarity theory [30]

$$J\varphi_i^{//}(t)+\beta\varphi_i^{/}(t)-\frac{1}{e}\left[\varphi_{i+1}(t)-\varphi_i(t)\right]+\frac{1}{e}\left[\varphi_i(t)-\varphi_{i-1}(t)\right]=M_i(t), \quad (5)$$

where $i=1,2,\ldots,4$; $\varphi_i(t)$ – the angle of rotation of the *i-th* mass as a function of time; $M_i(t)$ – torque of the *i-th* cylinder as a function of time; $\beta=4.2$ *Nms* – the amount of friction; $e=3.84\cdot10^{-7}$ $(Nm)^{-1}$ – flexibility of connections between torque masses; $J=0.715$ Nm^2 – moments of inertia of cylinder masses; $J_1=0.225$ Nm^2 – the moment of inertia of the gear wheel of the connection, which in a dimensionless form is $J_2=0.315$. The rotational speed of the crankshaft of the ICE varies in the frequency range 80÷280 s^{-1}.

The conditions of similarity of the system of differential equations of motion of the masses of the lower crankshaft and the normalized system (5) are as fol-lows [31]

$$\frac{J_b\varphi_b}{M_b t_b^2}=1,\quad \frac{\beta_b\varphi_b}{M_b t_b}=1,\quad \frac{\varphi_b}{e_b M_b}=1. \quad (6)$$

The values are selected by the authors J_b, β_b, e_b as the basic parameters of the system of linear differential equations (5) and the basic angle of rotation of the shaft $\varphi_b = 1\,rad$. With the help of conditions (6), the basic torque coefficients and time functions are established $M_b = 19.6 \cdot 10^6\ Nm,\ t_b = 0.333 \cdot 10^{-6}\text{s}$. The Laplace transform under zero initial conditions gives the system of dimensionless differential equations (5) in the following form [32]

$$\left(p^2 + p + 2\right)\varphi_i(p) - \varphi_{i+1}(p) - \varphi_{i-1}(p) = M_i(p). \tag{7}$$

After simple mathematical transformations, the dimensionless system of algebraic equations (7) takes the following form:

$$\begin{cases} \varphi_1 - \dfrac{1}{p^2+p+1}\varphi_2 = \dfrac{1}{p^2+p+1}M_1 \\ \varphi_2 - \dfrac{1}{p^2+p+2}\varphi_3 - \dfrac{1}{p^2+p+2}\varphi_1 = \dfrac{1}{p^2+p+2}M_2 \\ \varphi_3 - \dfrac{1}{p^2+p+2}\varphi_4 - \dfrac{1}{p^2+p+2}\varphi_2 = \dfrac{1}{p^2+p+2}M_3 \\ \varphi_4 - \dfrac{1}{p^2+p+1}\varphi_3 = 0. \end{cases} \tag{8}$$

Further mathematical transformations of system (8) are as follows: in the fourth equation, we define φ_4 and substitute in the third. As a result, the system of equations (8) takes the following form

$$\begin{cases} \varphi_1 - \dfrac{1}{p^2+p+1}\varphi_2 = \dfrac{1}{p^2+p+1}M_1 \\ \varphi_2 - \dfrac{1}{p^2+p+2}\varphi_3 - \dfrac{1}{p^2+p+2}\varphi_1 = \dfrac{1}{p^2+p+2}M_2 \\ \dfrac{p^4+2p^3+4p^2+3p+1}{p^4+2p^3+4p^2+3p+2}\varphi_3 - \dfrac{1}{p^2+p+2}\varphi_2 = \dfrac{1}{p^2+p+2}M_3. \end{cases} \tag{9}$$

Based on the system of algebraic equations (8) using the method of determinants, the authors established the expressions of the transmission functions of the torques of the cylinders of the power unit. For the corresponding mathematical transformations, the capabilities of the Mathcad software environment were used. In fig. 2 shows the boxes of the main and all determinants of the system of equations (8).

Based on the received expressions of the determinants, the corresponding transfer functions of cylinder torques after simple transformations took the following form:

$$\begin{aligned} W_1(p) &= \frac{p^{12}+6p^{11}+25p^{10}+70p^9+154p^8+262p^7+360p^6+391p^5+338p^4+223p^3+109p^2+45p+6}{p\left(p^{13}+7p^{12}+31p^{11}+95p^{10}+224p^9+416p^8+563p^7+755p^6+739p^5+577p^4+250p^3+131p^2+48p+8\right)}, \\ W_2(p) &= \frac{p^{12}+6p^{11}+25p^{10}+70p^9+153p^8+258p^7+350p^6+375p^5+320p^4+209p^3+102p^2+33p+6}{p\left(p^{13}+7p^{12}+31p^{11}+95p^{10}+224p^9+416p^8+563p^7+755p^6+739p^5+577p^4+250p^3+131p^2+48p+8\right)}, \\ W_3(p) &= \frac{p^8+4p^7+13p^6+25p^5+39p^4+41p^3+34p^2+17p+6}{p\left(p^9+5p^8+18p^7+42p^6+75p^5+99p^4+98p^3+70p^2+32p+8\right)}. \end{aligned} \tag{10}$$

$$\left|\begin{pmatrix} 1 & \dfrac{-1}{p^2+p+1} & 0 \\ \dfrac{-1}{p^2+p+2} & 1 & \dfrac{-1}{p^2+p+2} \\ 0 & \dfrac{-1}{p^2+p+2} & \dfrac{p^4+2p^3+4p^2+3p+1}{p^4+2p^3+4p^2+3p+2} \end{pmatrix}\right| \to \frac{p^6+3\cdot p^5+7\cdot p^4+9\cdot p^3+6\cdot p^2+2\cdot p}{p^6+3\cdot p^5+7\cdot p^4+9\cdot p^3+9\cdot p^2+5\cdot p+2}$$

$$\left|\begin{pmatrix} \dfrac{1}{p^2+p+1} & \dfrac{-1}{p^2+p+1} & 0 \\ \dfrac{1}{p^2+p+2} & 1 & \dfrac{-1}{p^2+p+2} \\ \dfrac{1}{p^2+p+2} & \dfrac{-1}{p^2+p+2} & \dfrac{p^4+2p^3+4p^2+3p+1}{p^4+2p^3+4p^2+3p+2} \end{pmatrix}\right| \to \frac{p^6+3\cdot p^5+9\cdot p^4+13\cdot p^3+16\cdot p^2+10\cdot p+3}{p^8+4\cdot p^7+12\cdot p^6+22\cdot p^5+32\cdot p^4+32\cdot p^3+25\cdot p^2+12\cdot p+4}$$

$$\left|\begin{pmatrix} 1 & \dfrac{1}{p^2+p+1} & 0 \\ \dfrac{-1}{p^2+p+2} & \dfrac{1}{p^2+p+2} & \dfrac{-1}{p^2+p+2} \\ 0 & \dfrac{1}{p^2+p+2} & \dfrac{p^4+2p^3+4p^2+3p+1}{p^4+2p^3+4p^2+3p+2} \end{pmatrix}\right| \to \frac{p^6+3\cdot p^5+9\cdot p^4+13\cdot p^3+15\cdot p^2+9\cdot p+3}{p^8+4\cdot p^7+12\cdot p^6+22\cdot p^5+32\cdot p^4+32\cdot p^3+25\cdot p^2+12\cdot p+4}$$

$$\left|\begin{pmatrix} 1 & \dfrac{-1}{p^2+p+1} & \dfrac{1}{p^2+p+1} \\ \dfrac{-1}{p^2+p+2} & 1 & \dfrac{1}{p^2+p+2} \\ 0 & \dfrac{-1}{p^2+p+2} & \dfrac{1}{p^2+p+2} \end{pmatrix}\right| \to \frac{p^2+p+3}{p^4+2\cdot p^3+5\cdot p^2+4\cdot p+4}$$

Figure 2: Boxes of determinants of the system of equations (8)

In expressions of transfer functions, an operator is present in the denominator p, which implies the presence of an integration circuit in the circuit architecture of the computer simulation of the rotational unevenness signal. The output signal of the scheme is a perfectly deterministic signal of unevenness of rotation of the first mass of the crankshaft of the ICE.

Expressions of the transfer functions (6) are obtained because of transformations of the system of differential equations (5) under the condition that the fluctuations of the twist angles of the first mass are a signal of measurement information. The information connection between the signals of the rotation angles and the unevenness of the rotation of the first mass of the crankshaft establishes the following equation:

$$\omega(t) = \frac{d\varphi(t)}{dt}, \tag{11}$$

where $\omega(t)$ – instantaneous speed of rotation of the crankshaft, $\varphi(t)$ – the spin angle of the first mass as a function of time.

The agreement of the output signal of the computer simulation scheme with the system of differential equations (5) is achieved by removing the operator p from the expressions of the transfer functions. Accordingly, the expressions of the transmission functions of the mechanical torque transmission channels take on the following form:

$$W_1(p)=\frac{p^{12}+6p^{11}+25p^{10}+70p^9+154p^8+262p^7+360p^6+391p^5+338p^4+223p^3+109p^2+45p+6}{p^{13}+7p^{12}+31p^{11}+95p^{10}+224p^9+416p^8+563p^7+755p^6+739p^5+577p^4+250p^3+131p^2+48p+8},$$
$$W_2(p)=\frac{p^{12}+6p^{11}+25p^{10}+70p^9+153p^8+258p^7+350p^6+375p^5+320p^4+209p^3+102p^2+33p+6}{p^{13}+7p^{12}+31p^{11}+95p^{10}+224p^9+416p^8+563p^7+755p^6+739p^5+577p^4+250p^3+131p^2+48p+8}, \quad (12)$$
$$W_3(p)=\frac{p^8+4p^7+13p^6+25p^5+39p^4+41p^3+34p^2+17p+6}{p^9+5p^8+18p^7+42p^6+75p^5+99p^4+98p^3+70p^2+32p+8}.$$

For further studies of mechanical torque transmission channels, we will use the opportunities provided by the Matlab software environment. Let us proceed to the analysis of their frequency characteristics.

2.3 Analysis of Frequency Characteristics of Torque Transmission Channels

The command line for specifying transfer function expressions in the Matlab programming environment has the following form: W1=tf([1 6 25 70 154 262 360 391 338 223 109 45 6],[1 7 31 95 224 416 563 755 739 577 250 131 48 8]). The authors using the following command lines set special points of the transfer function: zero(W1) and pole(W1). The search for the zeros and poles of the expressions of the transfer functions of the mechanical channels "cylinder-first mass of the crankshaft" provides an opportunity to obtain their representation in the form of a serial connection of elementary chains. At the same time, it is possible to simplify the expressions of the transfer functions. The roots of the numerator and denominator, which coincide in the magnitude of the conversion factor, cancel each other out. In addition, the roots are unstable and of the second order of smallness are removed from the expressions of the transfer functions [17]. Because of the analysis of the received zeros and poles of the transfer functions, the values of the roots (table 2) that meet these conditions were determined. The results of calculations and further analysis of the special points of the transmission functions of the "cylinder-first mass of the crankshaft" mechanical channels are given in the table 2.

Based on the data in the table 2 expressions of the transfer functions took the following form:

$$W_4(p)=\frac{(p+a_1)^2+b_1^2}{\left[(p+a_2)^2+b_2^2\right](p+a_3)},$$
$$W_5(p)=\frac{(p+a_4)^2+b_4^2}{\left[(p+a_5)^2+b_5^2\right](p+a_6)}, \quad (13)$$
$$W_6(p)=\frac{(p+a_7)^2+b_7^2}{\left[(p+a_8)^2+b_8^2\right](p+a_9)}.$$

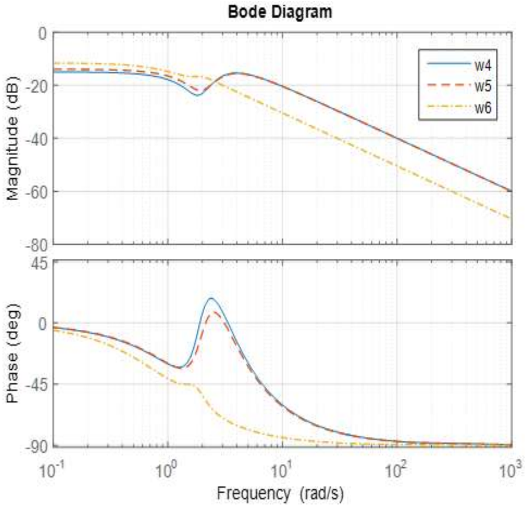
After simple mathematical transformations, the authors obtained the following transmission functions of the mechanical channels "cylinders-first mass of the crankshaft"

$$W_4(p)=\frac{p^2+2a_1p+a_1^2+b_1^2}{p^3+(2a_2+a_3)p^2+\left(a_2^2+b_2^2+2a_2a_3\right)p+\left(a_2^2+b_2^2\right)a_3},$$
$$W_5(p)=\frac{p^2+2a_4p+a_4^2+b_4^2}{p^3+(2a_5+a_6)p^2+\left(a_5^2+b_5^2+2a_5a_6\right)p+\left(a_5^2+b_5^2\right)a_6}, \quad (14)$$
$$W_6(p)=\frac{p^2+2a_7p+a_7^2+b_7^2}{p^3+(2a_8+a_9)p^2+\left(a_8^2+b_8^2+2a_8a_9\right)p+\left(a_8^2+b_8^2\right)a_9}.$$

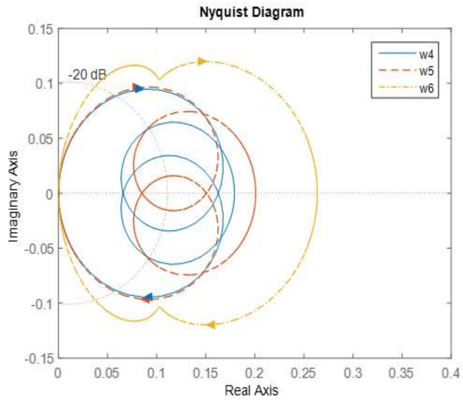
After substituting the values of the coefficients a and b, the expressions of the transfer functions took the following form:

$$W_4(p)=\frac{p^2+0.8364p+3.4611}{p^3+5.9641p^2+16.307p+19.3089},$$
$$W_5(p)=\frac{p^2+p+3.8794}{p^3+5.9641p^2+16.307p+19.3089}, \quad (15)$$
$$W_6(p)=\frac{0.3p^2+0.3p+0.9}{p^3+2p^2+4.4141p+3.4141}.$$

The command line for specifying expressions of transfer functions in the Matlab program environment has the following form: W4=tf([1 0.8364 3.4611],[1 5.9641 16.307 19.3089]). The logarithmic amplitude-frequency characteristics (LAFC) of the mechanical channels for transmitting cylinder torques are obtained using the command bode(W4,W5,W6). The calculation results are presented in fig. 3a. The Nyquist hodograph is built using the command nyquist(W4,W5,W6). The calculation results are shown in fig. 3b.



a)



b)

Figure 3: The results of the calculation of the LACH and the Nyquist hodograph

Because of the analysis of the LAFC mechanical channels for the transmission of torques, it was established that there are significant oscillations in the frequency band 0.5 - 7. In the LAPC transmission of the torque of the third cylinder, there is practically no swaying. In addition, LPFC of mechanical channels are non-linear. Accordingly, the process of transmitting cylinder torques through communication channels is characterized by significant distortions of the input signal. This leads to the fact that the torque graphs at the output of the mechanical channels look different from the input ones. Let us move on to the development of information technology for calculating the perfectly deterministic signal of unevenness of rotation of the first mass of the crankshaft.

2.4 Information Technology for Calculating the Signal of Measurement Information

The transition from the Laplace transform to the frequency representation of the transfer functions of mechanical channels is made by such a replacement. The information technology for calculating the signal of uneven rotation of the first mass of the crankshaft consists of the following calculation actions:

- obtained the expression of the frequency representation of the torque of the first cylinder $M_1(p) = M_1(i\omega)$;
- the expressions for the torques of the second and third cylinders are obtained by multiplication $M_1(i\omega)$ to the corresponding delay function $e^{-i2\pi/3}$ or $e^{-i4\pi/3}$;
- for simulating various signals of uneven rotation of the first mass of the crankshaft by setting the values of the gain coefficients of the blocks μ_1, μ_2, μ_3, which provides the possibility of changing the cylinder torque graphs [33, 34]. Such calculations allowed the authors to investigate the influence of deviations from the average value of the cylinder torque graphs on the perfectly deterministic signal of measurement information;
- by summing the output signals of the blocks μ_1, μ_2, μ_3 we will get the frequency representation of the perfectly deterministic signal of the unevenness of rotation of the first mass of the crankshaft $\Delta\Omega(i\omega)$.

Let us proceed directly to the development of a computer simulation scheme of a perfectly deterministic signal of unevenness of rotation of the first mass of the crankshaft.

2.5 Development of a Computer Simulation Scheme

When developing a scheme for computer simulation of the signal of uneven rotation of the first mass of the crankshaft of the ICE, the Mathcad software environment was used and the effect of adaptive interference on its output signal was taken into account. The summation performs the summation procedure of the perfectly deterministic signal of the unevenness of rotation of the first mass of the crankshaft of the ICE and additive disturbances. Because of expressions (1), (4) and (11), a scheme of computer simulation of the signal of unevenness of rotation of the first mass was created, the architecture of which is shown in fig. 4.

The results of computer simulation of the perfectly deterministic signal of the first mass rotation irregularity under the condition of different gain coefficients of the blocks μ_1, μ_2, μ_3 graphs of cylinder torques during two revolutions of the crankshaft are shown in fig. 5.

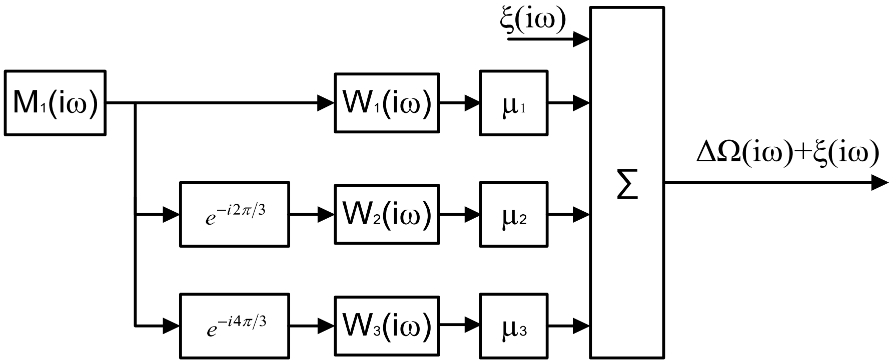
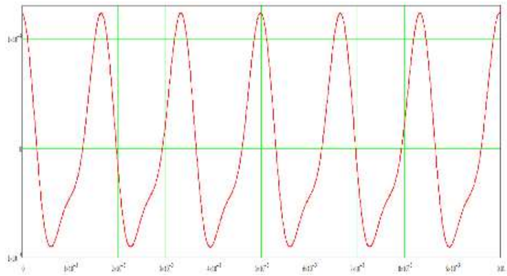
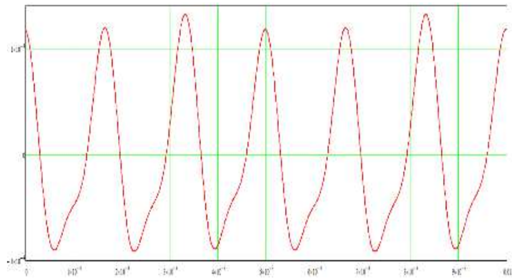


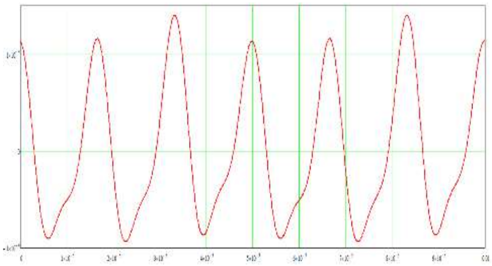
Figure 4: Architecture of the circuit of the computer simulation of the unevenness signal



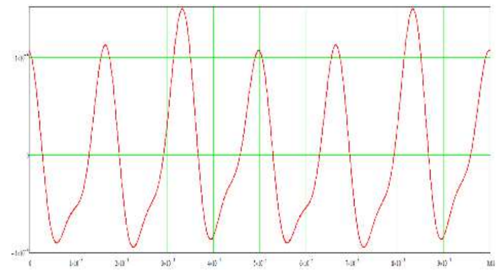
a) provided $\mu_1 = 1,\ \mu_2 = 1,\ \mu_3 = 1$



b) provided $\mu_1 = 0.95,\ \mu_2 = 1,\ \mu_3 = 1.05$



c) provided $\mu_1 = 0.9,\ \mu_2 = 1,\ \mu_3 = 1.1$



d) provided $\mu_1 = 0.85,\ \mu_2 = 1,\ \mu_3 = 1.15$

Figure 5: Results of computer simulation of perfectly deterministic signals of crankshaft rotation irregularity

2.6 Modeling of Additive Interference

By their very nature, the software and hardware means of controlling the fuel supply to the cylinders of the power unit are devices of cyclic action that are affected by disturbances of various physical nature. We assume that all disturbances affect the output signal of the computer simulation scheme and have an additive nature of influence. In the event that there are several random interferences, the task of summing up their effects on the measurement information signal arises. Among known methods, the method of summing random components based on the use of the information approach of measurement theory has become the most widespread [35]. We will also assume that the interference of the perfectly deterministic signal of the irregularity of the rotation of the first mass of the crankshaft is a regular "white noise", the frequency spectrum of which is limited to ten harmonic components.

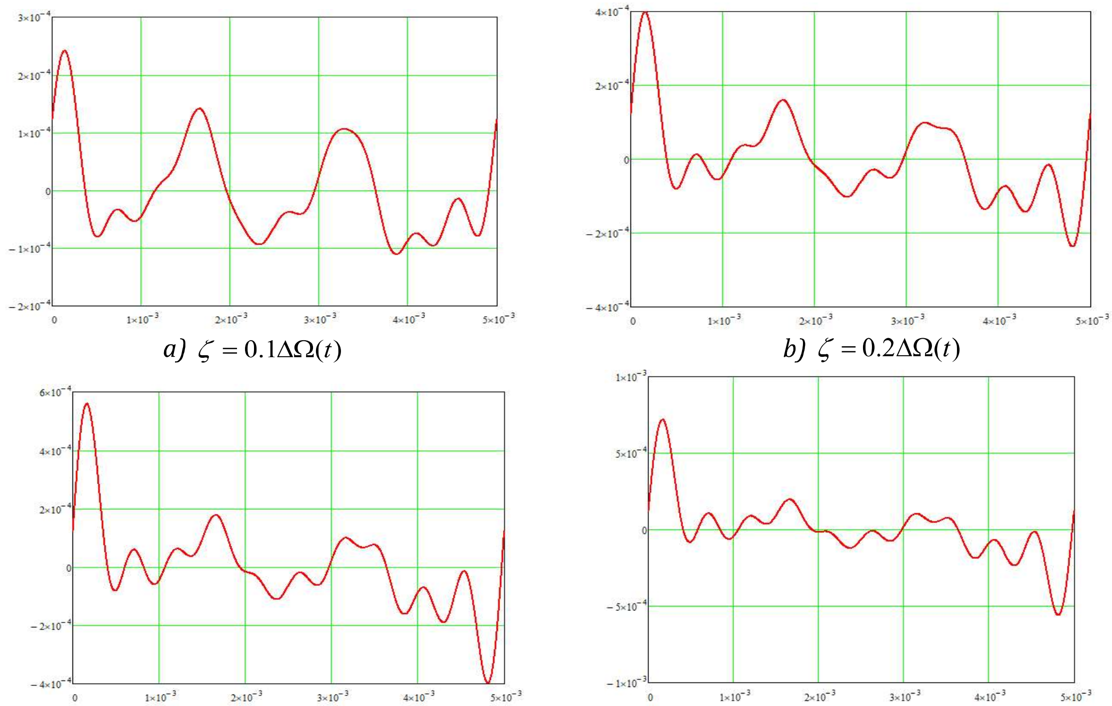
$$\xi(t) = \zeta \sum_{i=1}^{10} \sin i\Omega t, \tag{16}$$

where the coefficient ζ – sets the percentage of the sum of the maximum and minimum values of the unevenness of rotation signal of the first mass of the crankshaft.

The Mathcad software environment was used to summarize the perfectly deterministic signal of measurement information and disturbances in the form of regular "white noise" with a limited frequency representation. The application software of the summation procedure implements the following expression:

$$\Theta(t) = \Delta\Omega(t) + \xi(t). \tag{17}$$

Results of computer simulation of a perfectly deterministic signal of rotation irregularity, the appearance of which was changed by an additive disturbance of different magnitudes ζ, during the execution of one revolution by the crankshaft of the power unit is shown in fig. 6.



a) $\zeta = 0.1\Delta\Omega(t)$ *b)* $\zeta = 0.2\Delta\Omega(t)$

c) $\zeta = 0.3\Delta\Omega(t)$ *d)* $\zeta = 0.4\Delta\Omega(t)$

Figure 6: Results of computer simulation of the perfectly deterministic signal of the first mass rotation irregularity in the presence of additive interference

The analysis of the obtained graphs allowed us to draw the following conclusions: additive interference of different amplitudes leads to the reception of an amplitude-modulated signal of irregular rotation of the crankshaft; the depth of modulation of this signal depends on the amplitude of additive interference. The proposed additive interference signal varies between maximum and minimum values, the latter being negative.

The authors used the method of setting the percentage of the sum of the maximum and minimum values of the crankshaft rotation unevenness signal. Accordingly, when establishing the uncertainty of the measurement information signal distortions, the percentage of the setting used must be increased by two times, that is, for $\zeta = 0.1\Delta\Omega(t)$ the uncertainty is $\delta = 0.2$ %. After choosing the type of additive disturbance of the perfectly deterministic signal of unevenness of rotation of the first mass of the crankshaft, we will proceed to the development of information technology for monitoring fluctuations of the phase lags of cylinder torques relative to the regular setting of the power unit.

2.7 Information Technology of Signal Processing of Measurement Information

The authors used the correlation method for the first time when monitoring the fluctuations of the phase lags of the cylinder torques relative to the ICE regular setting based on the signal processing of the irregularity of the rotation of the first mass of the crankshaft. The cross-correlation function between the discrete presentation of the rotation irregularity signals and the torque of the first cylinder is calculated using a standard algorithm. The structural diagram of the calculation of the mutual correlation function is shown in fig. 7. It is marked: $\{\Delta\Omega\}$ – an array of discrete values of the crankshaft rotation unevenness signal, $\{M_1\}$ – an array of discrete torque values of the first cylinder.

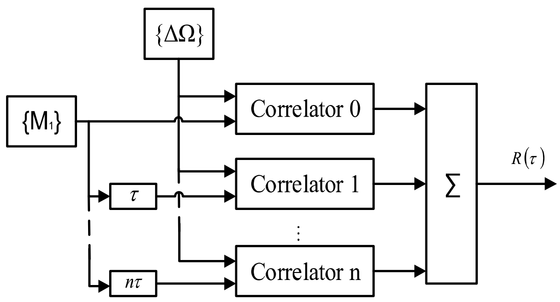


Figure 7: Structural diagram of the calculation of the mutual correlation function

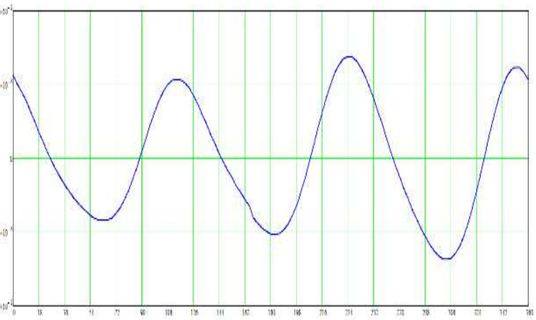
Correlator k calculates the cross-correlation function $R(\tau)$ in accordance with such an expression

$$R(k) = \frac{1}{n-k}\sum_{i=1}^{n-k}\Delta\Omega(t_i)M_1(t_{i+k}), \qquad (18)$$

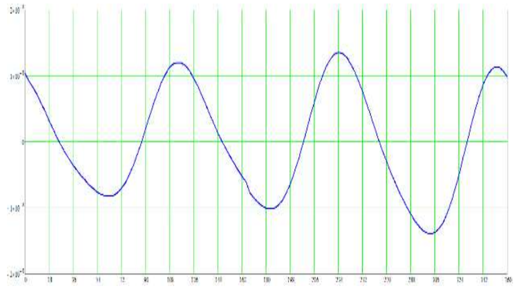
where n – the number of iterations of the measurement information signal presentation.

In the Mathcad environment, based on expression (13), the software for calculating the mutual correlation function was developed.

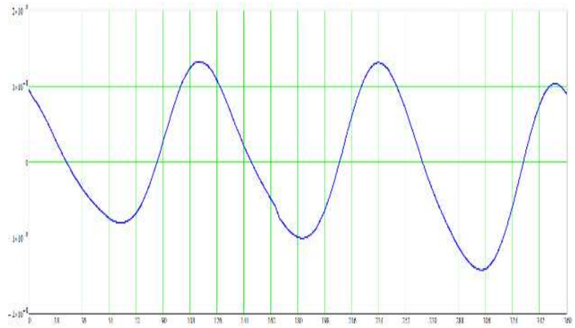
The results of the summation of the torques of the cylinders with different values of their amplification coefficients when receiving a perfectly deterministic signal of unevenness of rotation of the first mass of the crankshaft are shown in fig. 8.



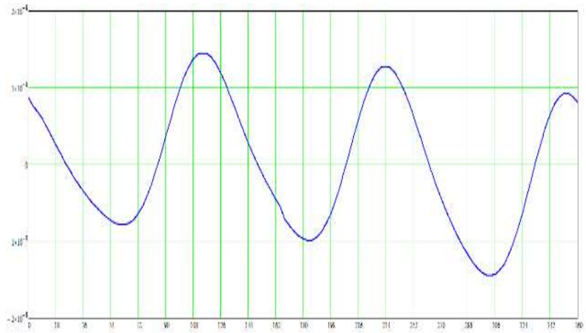
a) provided $\mu_1 = 1, \mu_2 = 1, \mu_3 = 1$



b) provided $\mu_1 = 0.95, \mu_2 = 1, \mu_3 = 1.05$



c) provided $\mu_1 = 0.9, \mu_2 = 1, \mu_3 = 1.1$



d) provided $\mu_1 = 0.85, \mu_2 = 1, \mu_3 = 1.15$

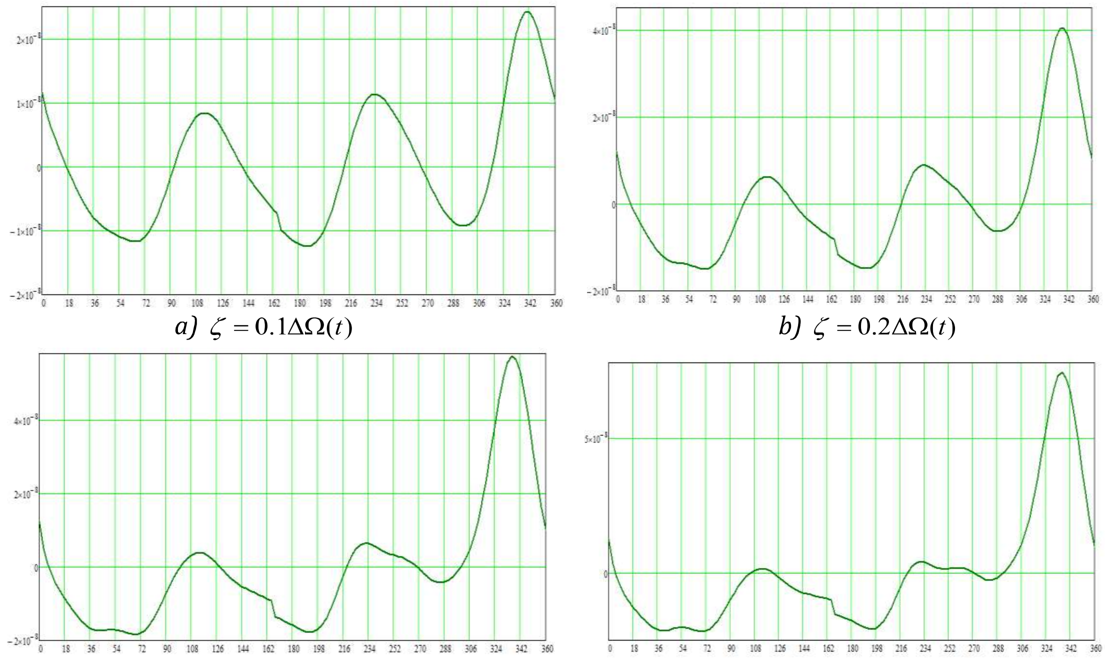
Figure 8: Results of the calculation of the mutual correlation function for different torque amplification coefficients of the computer simulation scheme

Graphs of mutual correlation functions were obtained within the limits of rotation of the crankshaft of the power unit. Analyzing their appearance, taking into account the known sequence of operation of the cylinders, made it possible to draw the following conclusions. The first maximum corresponds to the phase of the torque of the second cylinder, the second maximum corresponds to the phase of the torque of the third cylinder, and the third maximum corresponds to the phase of the torque of the first cylinder. In addition, the ratio of the maxima of the graphs of the mutual correlation functions corresponds to the values of the gain coefficients of the blocks μ_1, μ_2, μ_3 torques of the circuit of the computer simulation of the signal of the unevenness of the rotation of the first mass of the crankshaft.

2.8 Discussion of Research Results

The results of computer modeling of the mutual correlation function between the measurement information signal and the torque of the first cylinder under the condition of additive interference in the form of regular "white noise" with a limited frequency representation are shown in fig. 9. These graphs are obtained under the condition of the following values $\mu_1 = 1, \mu_2 = 1, \mu_3 = 1$ coefficients of cylinder torque amplification. The view of the graphs (Fig. 9*a*, 9*b* and 9*c*) makes it possible to unambiguously identify the maxima of the mutual correlation function under the condition of acting on a perfectly deterministic signal of unevenness of rotation of the first mass of the crankshaft with an additive disturbance of 30%. The appearance of the graphics of fig. 9*d* allows to uniquely identifying the first and second maxima of the mutual correlation function. The third peak in this graph is slightly out of phase with respect to the torque of the first cylinder. Based on the calculated data, we conclude: under the following conditions $\mu_1 = 1, \mu_2 = 1, \mu_3 = 1$ of cylinder torque amplification coefficients, the uncertainty of 60% measurement uncertainty of the first crankshaft mass rotation unevenness signal allows the use of a mutual correlation function to monitor fluctuations in the phase lags of cylinder torques relative to the standard ICE setting.

The results of computer modeling of the mutual correlation function between the signal of measurement information and the torque of the first cylinder under the condition of the effect of additive disturbances and the values of the gain coefficients of the scheme $\mu_1 = 0.9, \mu_2 = 1, \mu_3 = 1.1$ shown in fig. 9. The view of the graphs (Fig. 9*a*, 9*b* and 9*c*) makes it possible to unambiguously identify the maxima of the mutual correlation function under the conditions of action on the perfectly deterministic signal of the rotation irregularity of the first additive disturbance with a value of 7.5%. The appearance of the graphics of fig. 9*d* allows us to unambiguously identify the first, second and third maxima of the mutual correlation function. In addition, an additional maximum appeared on the 9*d* chart. On the basis of the obtained data, we conclude: given the values of the gain coefficients of the computer simulation scheme $\mu_1 = 0.9, \mu_2 = 1, \mu_3 = 1.1$ uncertainty of 15% measurement uncertainty of the signal of unevenness of rotation of the first mass of the crankshaft allows the use of the mutual correlation function to monitor the fluctuations of the phase lags of the torques of the cylinders relative to the regular setting of the power unit.



a) $\zeta = 0.1\Delta\Omega(t)$ *b)* $\zeta = 0.2\Delta\Omega(t)$ *c)* $\zeta = 0.3\Delta\Omega(t)$ *d)* $\zeta = 0.4\Delta\Omega(t)$

Figure 9: Results of the calculation of the mutual correlation function in the presence of additive interference

3. Conclusions

For the first time, the methods of correlation processing of indirect measurement data were applied in order to monitor the fluctuations of phase delays relative to the regular setting of the supply of fuel-air mixture to the cylinders of internal combustion engines. Injectors with piezoelectric control were used and the conceptual principles of building hardware and software control of fuel supply to the cylinders of the power unit with feedback based on the state of the measurement information signal were developed. A frequency-modulated signal of unevenness of rotation of the first mass of the crankshaft was used to monitor the fluctuations of the phase delays of the feeds relative to the regular setting of the internal combustion engine. Software setting of the required angles of fuel supply to the cylinders by hardware will reduce the costs of prevention, maintenance and repair of the power unit.

A mechanical system with four degrees of freedom is proposed as a mathematical model of the torque circuit of the internal combustion engine. The oscillatory movements of the model masses are described by a deterministic system of linear differential equations under the conditions of taking into account friction. The parameters of the system of equations are reduced to a dimensionless form based on the application of theorems and methods of similarity theory. Conditions of similarity have been established, with the help of which the results of this work can be used in the analysis of torque circuits of engines of a similar structure. As a mathematical apparatus for solving the normalized system of differential equations of oscillating mass movements of the mathematical model, the Laplace transformation was used under zero initial conditions.

Using the method of determinants, the information links between the torques of the cylinders and the signal of fluctuations in the speed of rotation of the first mass of the crankshaft were established. With the help of the Mathcad software environment, the expressions of the transmission functions of the mechanical paths "cylinders-first mass of the crankshaft" were obtained. In the Matlab soft-ware environment, the value of the special points of the transmission functions of the torques of the cylinders was determined, and because of their analysis, a simplified mathematical representation was obtained. A limited Fourier series was used to approximate cylinder torques. Using the capabilities of the Mathcad software environment, a presentation of six harmonic components was obtained.

The additive interference of the measurement information signal is represent-ed by "white noise" with a regular structure, the discrete frequency spectrum of which is limited to ten harmonic components. A scheme of computer modeling of perfectly deterministic signals of unevenness of rotation of the first mass of the crankshaft in the Mathcad software environment has been compiled. The method of adjusting the length of information links of neural network technologies was used to set the values of the amplification coefficients of the cylinder torque amplitudes. Due to this, it became possible to perform a study of the effects of various deviations of the cylinder torque graphs from the average value on the measurement information signal.

The calculation of the mutual correlation function between the signals of measurement information and the torque of the first cylinder is the basis of the construction of the algorithmic support for monitoring fluctuations of phase de-lays relative to the standard setting of fuel supply to the cylinders of the power unit. The Mathcad environment was used to implement the application software for calculating the cross-correlation function.

Computer modeling of the perfectly deterministic signal of unevenness of rotation of the first mass of the crankshaft under the conditions of adjustment of the gain coefficients of the cylinder torque graphs was carried out. Corresponding graphs of the mutual correlation function were obtained, as a result of the analysis of which it was established: the first maximum corresponds to the phase delay of the torque of the second cylinder, the second maximum corresponds to the phase delay of the torque of the third cylinder, the third maximum corresponds to the phase of the torque of the first cylinder. It was also established that the adjustment of the gain coefficients of the computer modeling scheme of the perfectly deterministic crankshaft rotation unevenness signal corresponds to the ratio of the magnitude of the maxima of the mutual correlation function.

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