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Monitoring Phase Increments in Fuel Supply Adjustment Based on Correlation Analysis of Indirect Measurement Data

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Abstract: It is proposed to use correlation analysis methods to process indirect measurement data when monitoring the incremental cylindrical phase delays referenced to the first cylinder. A method is proposed for restoring the optimal parameters of stratified charge delivery to the combustion chambers of piston-type internal combustion engines. TThe conceptual framework for the development of software and hardware systems incorporating feedback control based on the state of the measurement signal, represented by crankshaft rotational irregularities, has been established. A deterministic mathematical model representing the torque transmission architecture of the powertrain is formulated as a mechanical system with three degrees of freedom, taking into account energy dissipation due to friction. The motions of the masses of the mathematical model are described by a deterministic system of linear differential equations. The parameters of these equations are normalised using the theorems and methods of similarity theory. The Laplace transform under zero initial conditions is applied to solve the resulting system of differential equations. Using the method of determinants and the Mathcad software environment, the information links between the cylinder torques and the signal of uneven rotation of the first crankshaft mass were established. In the Matlab software environment, special points were identified and a simplified representation of the torque transfer functions was obtained as a result of their analysis. A limited Fourier series using Mathcad software approximated the cylinder torques. A computational scheme was developed for simulating deterministic signals characterizing the rotational irregularity of the first crankshaft mass. The additive disturbance superimposed on the measurement signal is modeled as structured white noise with a frequency spectrum constrained to ten harmonic components.

Within the computer modeling framework, the output signal generation utilizes an approach based on the regulation of information pathway lengths in neural network structures to define the gain coefficients corresponding to the aggregated torque amplitudes of individual cylinders. For the first time, an auxiliary algorithm was developed to monitor incremental phase delays of the cylinders relative to the reference (first) cylinder by calculating the mutual correlation function between the rotational irregularity signal of the first crankshaft mass and the torque output of the first cylinder. The software application for calculating the reciprocal correlation function is implemented in the program Mathcad. As a result of the analysis of the mutual correlation function graph, three distinct maxima were identified. The initial peak of the computed mutual correlation function corresponds to the phase associated with the nominal torque generation of the second combustion chamber. The second peak reflects the standard torque phase of the third chamber, while the third peak indicates the reference phase for the first combustion unit. Furthermore, the proportional values of these maxima align with the gain factors assigned to each cylinder's torque in the computational summation scheme. The cross-correlation between the processed measurement signal and the torque signal of the first cylinder was evaluated under conditions of additive stochastic interference. Analysis of the correlation curve demonstrates that a measurement uncertainty of approximately 14% in the rotational non-uniformity of the primary crankshaft mass does not preclude the effective application of correlation analysis techniques for phase shift tracking in the fuel delivery timing across engine cylinders.

Index Terms: Software, Mathematical Model, Hardware, Transfer Function, Information Technology, Phase Increment, Mutual Correlation Function, Non-uniformity of Rotation, Uncertainty.

1. Introduction

This study introduces a methodology for tracking the phase displacement distribution of combustion chambers relative to a reference unit, with the aim of re-establishing the optimal timing of fuel delivery in internal combustion engines (ICEs). The proposed approach relies on the analysis of indirect diagnostic signals—specifically, fluctuations in crankshaft angular velocity—through the application of correlation analysis techniques. By quantifying the relative phase offsets between the torque outputs of individual chambers and the rotational irregularity of the crankshaft, it becomes possible to construct mutual correlation functions that serve as diagnostic indicators. The integration of piezoelectrically actuated injectors as precision-controlled fuel delivery components enables the development of an adaptive software-hardware system with feedback capabilities based on the dynamics of crankshaft motion. Such a control architecture is expected to enhance fuel efficiency by up to 5%, extend engine operational lifespan, and reduce the overall costs associated with preventive maintenance and mechanical servicing [1, 2].

1.1. Analysis of Literature Review and Problem Statement

An established indirect approach for managing the incremental phase shifts of individual cylinders relative to the reference first cylinder, aimed at restoring the correct fuel supply regulation, utilizes the crankshaft rotational irregularity signal as the primary input data [1, 3]. The computational framework of this method includes several key steps. First, cylinder torque profiles are represented using truncated Fourier series. Next, a mathematical model of the powertrain torque transmission is developed. Then, the system of differential equations describing the dynamic behavior of the crankshaft masses in the internal combustion engine is solved numerically. Finally, a comparative analysis of the simulation results is conducted to adjust the fuel injection timing toward the optimal operational setting.

The issue of tracking phase deviations with respect to the baseline configuration of fuel-air mixture delivery to internal combustion engine (ICE) cylinders under conditions of limited or incomplete data has been investigated in the engineering literature. For example, in [3], it was demonstrated that applying a finite impulse response (FIR) upper-frequency filter significantly reduces the impact of random disturbances on the frequency-modulated (FM) measurement signal. The Matlab environment was employed to process the signal reflecting irregularities in the crankshaft rotation. Reference [4] presents an analysis of power interactions within the crank–connecting-rod assembly, highlighting the impact of cylinder combustion processes on variations in indicated pressure. Mathematical modeling of the operational modes of the D50 engine was performed, accompanied by the development of specialized application software. Additionally, studies [4, 5] applied machine learning methods to formulate objective functions that integrate and synthesize experimental data outcomes. In [6, 7], a methodology was proposed for evaluating engine technical condition based on parameters of the crankshaft's angular velocity irregularity signal. Finally, in [8], quantitative changes in cylinder capacities of four-stroke ICEs were analyzed as functions of the crankshaft rotation irregularity signal and the indicated torque.

In [9], a complex mathematical model of the dynamic processes of unevenness of rotation of a vibrating apparatus on elastic supports with an eccentric unbalanced rotor is proposed. In the calculations, it is assumed that the working chamber of an asynchronous electric motor carries out plane-parallel motion. It was also established that thanks to the rational selection of the eccentricity, it was possible to reduce the vibrations of the rotor shaft. A geometric interpretation of shaft rotation irregularities during the startup phase of an electric motor has been established. In [10], a mathematical model describing the uneven rotation signal of an industrial robot's control mechanism was developed. This model facilitates the analysis of various operational states of the robot, including startup, steady-state functioning, and spatial movements of its individual components. Employing concepts from sensitivity theory, a methodology was proposed for synthesizing a control system that incorporates an inverse state feedback based on the irregularity signal of the robot's control device rotation.

Reference [11] presents a method for synthesizing the parameters of a nonlinear flexible coupling aimed at reducing the amplitude of oscillations in the torque transmission system of an internal combustion engine (ICE). This approach relies on an economic variant of the harmonic linearization technique applied to the integral equations governing the mass dynamics, which are formulated using impulse-frequency characteristics. In [12], a method is proposed for analyzing stable dynamic processes in nonlinear models of power units. The study includes the development of algorithmic tools for solving nonlinear integro-differential equations based on the Newton-Kantorovich method. In reference [13], an algorithm is presented for solving integral equations that characterize steady-state dynamic behavior in nonlinear mathematical models of power units. This method guarantees convergence to a solution of the nonlinear integral equation system regardless of the initial approximation. In [14], research findings on the parameters of the camshaft drive mechanism of the ICE fuel pump are presented. Integral equations of mass dynamics, expressed through impulse-frequency characteristics, were employed as the mathematical model.

The authors in [15] propose an algorithmic approach for monitoring the volumetric capacity of cylinders in an internal combustion engine (ICE), which is based on solving an overdetermined system characterized by inconsistent algebraic relationships. The right-hand side column vector of this system represents the frequency-domain signal of rotational speed fluctuations. The left-hand side is constructed as the product of the column vector of cylinder weighting coefficients and a matrix whose elements are derived from the transfer functions describing the relationship between each cylinder and the first mass of the crankshaft. The standard approach employing radial basis functions to address such problems involves the use of fully dense matrices, which significantly constrains the computational performance of the monitoring process.

Fundamentally, correlation analysis techniques applied to signals of crankshaft rotational irregularities can be utilized for tracking phase deviations relative to the standard timing of fuel injection in internal combustion engine cylinders. Reference [16] provides multiple instances demonstrating the use of specialized multi-channel and programmable correlators designed to calculate both autocorrelation and cross-correlation functions of radar backscatter signals. Studies [17, 18] define requirements for the characteristics of radar signals operating under conditions of electromagnetic interference and discuss approaches for enhancing the resilience of information transmission against random disturbances. In [19], a method employing a correlator to accumulate useful signal pulses at the receiver is presented, which significantly enhances the signal-to-interference ratio of the transmitted data. This approach enables effective information transmission over a broad frequency spectrum, even when the signal amplitude is considerably weaker than the interference level.

Reference [20] introduces a design for enhanced hardware capable of performing supplementary processing of the orthogonal components of incoherent scattering signals. The work includes a simulation example demonstrating the individual reception and multiplication of circularly polarized signal components in the presence of interference. Reference [21] introduces a correlation processing method that increases the number of ordinates of the autocorrelation function within the correlation interval by raising the sampling frequency of the analog-to-digital conversion. This method decreases the uncertainty in estimating the autocorrelation function of the signal, which enhances the precision of ionospheric parameter measurements across different altitudes. In [22], a novel technique is introduced for extracting the quadrature components of the autocorrelation function of incoherent scattering signals by utilizing a single radio receiver channel combined with an analog-to-digital converter, effectively overcoming the drawbacks inherent to the analog I/Q demodulator. The suggested correlation processing method effectively reduces the uncertainty in the estimation of the autocorrelation function.

Reference [23] presents the results of modifying the digital representation of radar signals to reduce the required sampling frequency during subsequent processing. An increase in sensitivity to small Doppler shifts was achieved by employing long-duration radio pulses. In [24], the outcomes of spectral analysis of Faraday double-pulse experiments are discussed, including a comparison between electron density estimates obtained via spectral analysis and those derived from conventional correlation analysis. The comparison showed satisfactory agreement between the two methods. In reference [25], a computational technique is presented for reconstructing the vertical distribution profile of the power of an incoherently scattered signal. To determine the electron density at different altitudes, an analytical polynomial reference function was introduced, establishing an additional connection between the scattered signal power in adjacent ionospheric regions. The approach additionally corrects for the smoothing distortions caused by employing extendedduration probing radio pulses.

The global model of vertical total electron content presented in [26] is constructed using a series expansion based on compactly supported B-spline functions. This approach facilitates the effective processing of non-uniformly distributed experimental data, including cases with missing observations. The corresponding expansion coefficients, along with additional parameters such as differential code biases of satellites and GNSS signal receivers, are treated as a set of unknowns to be estimated. Currently, the radio airwaves are very clogged with signals of various nature [27], which arise in the frequency range of the incoherent scattering radar, which leads to their superimposition on the useful signal. As a result, in most cases, signal reception 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, which are returned as reflections to the pulse radar receiver when it probes the ionosphere in the method of incoherent scattering of radio waves, is proposed. The computations are enabled by incorporating auxiliary correlation channels within a multi-channel system operating in real-time. Paper [29] discusses data correlation methods that are commonly used at the preparation stage. In this case, the output features are filtered according to their relationship with class labels. Paper [30] discusses a method that includes procedures for converting data into a specific format to reduce the correlation of input data.

A significant drawback of current techniques for processing frequency-modulated signals that reflect crankshaft rotational speed, used subsequently for regulating fuel delivery to internal combustion engine cylinders, is the unsatisfactory variability in measuring instantaneous periods. Furthermore, the computational efficiency of software and hardware systems tasked with tracking phase deviations relative to the standard fuel injection timing remains limited. In addition, there is a deficiency of dedicated algorithmic and application software designed to effectively handle the processing of such measurement signals.

1.2. Research Aim and Specific Objectives

Section 2.1 introduces the conceptual basis for detecting relative phase shifts among the ICE cylinders with respect to the first cylinder, aiming to re-establish the standard timing of fuel–air mixture injection. Section 2.2 is dedicated to the formulation of a mathematical representation of the system under control, including the identification of its defining parameters. Section 2.3 details the computer simulation of the model input signals, utilizing processed experimental data on the pressure in the first cylinder. Section 2.4 describes the construction of a computer-based simulation scheme for the measurement information signal, represented as fluctuations in the crankshaft's rotational speed. Section 2.5 is devoted to constructing mathematical representations of additive disturbances affecting both software and hardware components designed to monitor cylinder phase shift increments. Section 2.6 presents a signal processing methodology grounded in correlation analysis. As part of this section, dedicated algorithmic and application-level tools were developed to track incremental phase deviations of individual cylinders relative to the first, thereby facilitating accurate regulation of fuel injection timing. The core of this approach lies in computing the mutual correlation function between the signal of crankshaft rotational irregularities and the torque response of the reference (first) cylinder. Section 2.7 evaluates the resulting correlation function plots under the influence of structured "white noise" affecting the measurement signal. The advantages and limitations of the proposed phase delay monitoring method are also discussed. Section 3 presents the main conclusions drawn from the conducted research.

1.3. Research Novelty

The scientific contribution of this research lies in formulating the conceptual principles of a closed-loop regulation system for managing the delivery of the air–fuel mixture to the cylinders of an internal combustion engine (ICE). The proposed control strategy is based on the analysis of indirect diagnostic signals, namely the variations in crankshaft rotational velocity. A key innovative aspect of the study is the introduction— for the first time—of an approach that employs the mutual correlation function between the crankshaft speed fluctuation signal and the torque signal of the first cylinder to detect and monitor phase shift increments across all cylinders. This enables the recalibration of the fuel delivery phases to achieve a nominal operating configuration.

2. Research Methodology and Analytical Tools

Among the discussed approaches to the design of software and hardware systems for processing measurement information signals, the authors identify correlation analysis as the most promising. The mutual correlation function is introduced as a robust analytical tool for quantifying the incremental phase shifts of engine cylinders with respect to the reference (first) cylinder. In order to design an information technology framework for its computation, the analysis utilizes input signals characterizing crankshaft rotational non-uniformity and the torque generated by a selected cylinder of the internal combustion engine (ICE). The next step involves formulating the methodological principles for designing software and hardware systems aimed at monitoring phase increments relative to the standard fuel supply setting. It is proposed that this monitoring be performed through indirect measurements based on the mutual correlation function.

2.1. The Concept of Software and Hardware Construction

The paper introduces a method for monitoring incremental phase delays of cylinders with respect to the first one by calculating the mutual correlation function between crankshaft rotational irregularity signals and the torque signal of the reference (first) cylinder. As actuating elements for restoring the nominal fuel injection timing, piezoelectrically controlled injectors were implemented, enabling precise fuel delivery in response to control commands. The synchronization of the software and hardware components responsible for monitoring phase deviations is achieved via the crankshaft rotational phase, using the top dead center (TDC) signal of the first cylinder as a reference. The structural layout of the proposed hardware–software system is presented in Fig. 1. They include the following components: speed sensor (SS), top dead center sensor of the first cylinder (TDC), measuring transducer (MT), computing device (CD) in the form of a microcomputer and three actuators (A1 - A3).

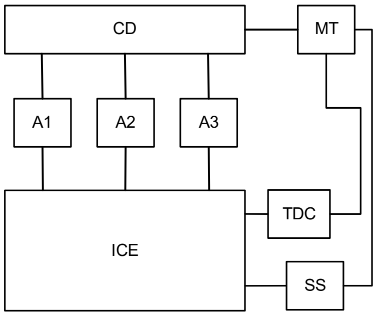


Fig.1. Architecture of hardware and software for fuel supply control

The hardware–software architecture for fuel injection control is designed following the principle of feedback regulation, which relies on the current state of the measurement information signal. The computational algorithm for monitoring incremental phase shifts relative to the nominal fuel injection timing of the power unit's cylinders comprises the following steps:

- capturing instantaneous periods of the frequency-modulated (FM) signal representing crankshaft rotational speed over multiple engine cycles;
- averaging the obtained data to construct a representative sample of instantaneous periods within a single crankshaft revolution;
- generating a discrete-value array representing the signal of crankshaft rotational irregularity;
- identifying deviations in cylinder phase increments with respect to the reference (nominal) fuel injection setting;
- formation of control signals A1 - A3.

The algorithmic framework for detecting deviations in cylinder phase timing relative to the standard fuel injection configuration in internal combustion engines is structured around the following computational procedures:

- construction of a mechanical model of the torque circuit of an ICE;
- approximation of cylinder torques;
- identification of functional relationships between individual cylinder torque profiles and the measurement signal representing crankshaft rotational irregularities;
- assessment of phase shift deviations relative to the nominal fuel injection configuration, carried out through analysis of the mutual correlation function computed between the crankshaft speed fluctuation signal and the torque response of the first cylinder.

The initial step in addressing the tasks involves the construction of a deterministic mathematical model of the system under control.

2.2. Determination of the Parameters of the Mathematical Model Representing the Controlled System

The ICE 3TD-1 is developed on the basis of the six-cylinder engine 6TD-1. The reduction of the number of cylinders to three led to a significant alteration in the spectral characteristics of the initial kinematic models of the 6TD-1 engine. The full kinematic scheme of the internal combustion engine (ICE) represents a mechanical system comprising 21 masses and 7 nonlinear connections realized as gear pairs. During the analysis of the power unit’s construction, it was determined that it is fundamentally feasible to obtain a measurement information signal via a primary converter of the PDF-3 type, which is attached to the first mass of the lower crankshaft. Given that the ICE consists of three cylinders, it is appropriate to model its torque transmission system as a deterministic mechanical system with three degrees of freedom. In this simplified model, nonlinear elements such as gear joints with nonlinear transformation characteristics are excluded. Therefore, the rotational behavior of the cylindrical masses within this three-degree-of-freedom mechanical system is characterized by the following set of linear differential equations

$$J\phi_i^{//}(t)+\beta\phi_i^{/}(t)-\frac{1}{e}\left[\phi_{i+1}(t)-\phi_i(t)\right]+\frac{1}{e}\left[\phi_i(t)-\phi_{i-1}(t)\right]=M_i(t) \tag{1}$$

where $i=1,\ 2,\ 3$; $\varphi_i(t)$ denotes the angular displacement of the i-th mass as a function of time; $M_i(t)$ represents the torque generated by the i-th cylinder over time; $\beta=4.2$ Nms corresponds to the frictional torque; $e=3.84\cdot10^{-7}$ (Nm)$^{-1}$ characterizes the compliance (flexibility) of the connections between rotating massess; $J=0.715$ Nm^2 signifies the moments of inertia of the cylinder masses. The crankshaft rotational velocity of the internal combustion engine fluctuates within the frequency range of 80÷280 s^{-1}.

The research results of this work have a generalized form, therefore theorems and methods of similarity theory [30] were used to reduce the system of linear differential equations (1) to a dimensionless form. The following parameters were chosen as basic parameters by the authors $J_b,\ \beta_b,\ e_b,\ M_b,\ \varphi_b,\ t_b$ system of equations (1) and the following notations are introduced

$$J^*=J/J_b,\quad \beta^*=\beta/\beta_b,\quad e^*=e/e_b,\quad M^*=M/M_b,\quad \varphi^*=\varphi/\varphi_b,\quad t^*=t/t_b\,. \tag{2}$$

After multiplying each parameter of the system of differential equations (1) by the ratio of basic values and taking into account the accepted notations, we reduce it to a dimensionless form

$$\frac{J^*J_b\varphi_b}{M_bt_b^2}\varphi_i^{//}+\frac{\beta^*\beta_b\varphi_b}{M_bt_b}\varphi_i^{/}-\frac{\varphi_b}{e^*e_bM_b}(\varphi_{i+1}-\varphi_i)+\frac{\varphi_b}{e^*e_bM_b}(\varphi_i-\varphi_{i-1})=M_i^*\,. \tag{3}$$

The simplification of the expressions of the differential equations of the dimensionless system (3) is achieved due to the following conditions [31]

$$\frac{J_b\varphi_b}{M_bt_b^2}=1,\quad \frac{\beta_b\varphi_b}{M_bt_b}=1,\quad \frac{\varphi_b}{e_bM_b}=1\,. \tag{4}$$

The parameters specified by the authors in equation (1) serve as the fundamental constants for the system of linear differential equations (3), together with the reference shaft rotation angle. By applying the conditions outlined in (4), the primary torque coefficients and their associated time-dependent functions are derived $t_b=0.333\cdot10^{-6}$ s , $M_b=19.6\cdot10^6$ Nm. Applying the Laplace transform with zero initial conditions allows the system of dimensionless differential equations (2) to be expressed in the following form [33]

$$\left(p^2+p+2\right)\varphi_i(p)-\varphi_{i+1}(p)-\varphi_{i-1}(p)=M_i(p)\,. \tag{5}$$

The results of this work are generalised. Accordingly, they can be used to analyse internal combustion engines with a similar kinematic scheme. The transition to the analysis of a different type of engine is carried out using conditions (4), taking into account the ratios of friction values, the malleability of the links between torque masses, and the moments of inertia of the cylinder masses. The amplitude of the torque of the first cylinder of any engine is adjusted depending on the ratio of cylinder powers. The number of equations in system (5) depends on the complexity of the mechanical model. For example, if the engine has four cylinders, system (5) also has four equations.

After simple mathematical transformations, the dimensionless system of algebraic equations (5) takes the following form

$$\begin{cases}\varphi_1-\dfrac{1}{p^2+p+1}\varphi_2=\dfrac{1}{p^2+p+1}M_1\\ \varphi_2-\dfrac{1}{p^2+p+2}\varphi_3-\dfrac{1}{p^2+p+2}\varphi_1=\dfrac{1}{p^2+p+2}M_2\\ \varphi_3-\dfrac{1}{p^2+p+1}\varphi_2=\dfrac{1}{p^2+p+1}M_3\end{cases} \tag{6}$$

Utilizing the system of algebraic equations (6), the authors applied the determinant method to obtain expressions for the transfer functions corresponding to the torques produced by the cylinders of the power unit. The mathematical manipulations required for these derivations were executed using the computational tools available in the Mathcad environment. Figure 2 depicts the blocks representing both the principal determinant and all other determinants within the system of equations.

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

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

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

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

Fig.2. Determinant boxes

Using the derived determinant expressions, the respective transfer functions for the cylinder torques were subsequently formulated in the following manner

$$W_1(p) = W_2(p) = W_3(p) = \frac{\Delta_1}{\Delta} = \frac{p^2+p+3}{p\left(p^3+2p^2+4p+3\right)}. \tag{7}$$

Within expression (7) for the transfer function, the presence of an integration chain is identified, which may potentially cause misinterpretations in subsequent analyses. The computer simulation framework generates an output signal representing the irregular rotation of the first mass of the crankshaft in the internal combustion engine. The transfer function expressions for the cylinder torques are derived through transformations of the differential equation system (1), assuming that the measured signal corresponds to fluctuations in the rotational angles of the first crankshaft mass. The resulting informational relationship between the non-uniformity signals and the angular fluctuation signals is characterized by the following equation

$$\omega(t) = \frac{d\varphi(t)}{dt}, \tag{8}$$

where $\omega(t)$ – instantaneous angular velocity of the crankshaft, $\varphi(t)$ – angular displacement of the first mass as a function of time.

Therefore, to obtain the output signal of the computer simulation scheme in the form of unevenness of rotation, the operator *p* we remove from the expression (7) of the transfer function. When researching the frequency characteristics of the obtained transfer function, the authors used the capabilities of the Matlab software environment. The command line for setting the transfer function expression looks like this W1=*tf*([1 1 3],[1 2 4 3]). Special points of the transfer function are set in using the following command lines: *zero*(W1) and *pole*(W1). The results of the calculations are given in the table. 1.

Table 1. Zeros and poles of the transfer function

***zero*(W1)**	***pole*(W1)**
-0.5000 + 1.6583i	-0.5000 + 1.6583i
0.5000 + 1.6583i	0.5000 + 1.6583i
	-1.0000 + 0.0000i

As a result of the analysis of the obtained values of zeros and poles, the coincidence of their values was established, accordingly, the transfer function is given by the following expression

$$W_1(t) = \frac{1}{p+1}. \tag{9}$$

Upon analysis of expression (9), the authors determined that the torque transmission system of the power unit can be represented as a mechanical system with a single degree of freedom. The next step involves developing mathematical models for the input signals acting on this mechanical system.

2.3. Approximation of Input Signals within the Computational Model of the Fluctuation Signal Circuit

The torques generated by cylinders 1, 2, and 3 were employed as input signals for the computational model simulating the fluctuation of the internal combustion engine's crankshaft rotational speed. These torques were represented using a truncated Fourier series approximation implemented within the Mathcad software environment [31]. The indicator diagram of the first cylinder, sampled at six-degree intervals, served as the source data. The discrete frequency spectrum of the first cylinder's torque is summarized in Table 2

Table 2. Amplitudes of harmonic components in sine and cosine functions

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

Based on the data of this table, the torque of the first cylinder of the power unit is mathematically represented by the following expression

$$M_1(t) = \sum_{n=1}^{6} \left(A_n \sin n\Omega t + B_n \cos n\Omega t \right) \cdot \tag{10}$$

Mathematical representations of the torque profiles for the second and third cylinders are constructed analogously to that of the first cylinder, incorporating phase shifts in increments of 120°, which correspond to the operational sequence of cylinders 1-2-3. Accordingly, the torque of any given cylinder can be formulated as follows

$$M_i(t) = M_1(t) e^{-j\Omega\tau_i} , \tag{11}$$

where τ_i – phase shift of the cylinder with respect to the first cylinder.

Following the derivation of the required mathematical models for cylinder torques and transmission functions, the next step involves constructing a computer simulation framework to generate an ideally deterministic signal representing the crankshaft rotational irregularities of the power unit.

2.4. Formulation of a Computer Simulation Methodology

The authors used the capabilities of the Mathcad software environment when constructing a computer simulation scheme of an ideally deterministic unevenness signal. It is also taken into account that the system of algebraic equations (6) is linear, therefore, in order to simplify the structure of the circuit of the computer simulation of the signal of uneven rotation of the crankshaft of the ICE, the block $W_1(i\omega)$ is set at the output of the first adder of torque signals. When developing the computer simulation scheme, the effect of adaptive interference is also taken into account $\xi(i\omega)$ to its output signal. The second summator will perform the summation procedure of crankshaft rotation irregularity signals and interference. On the basis of expressions (9), (10) and (11), a computer simulation scheme of the perfectly deterministic crankshaft rotation irregularity signal is drawn up and shown in Fig. 3.

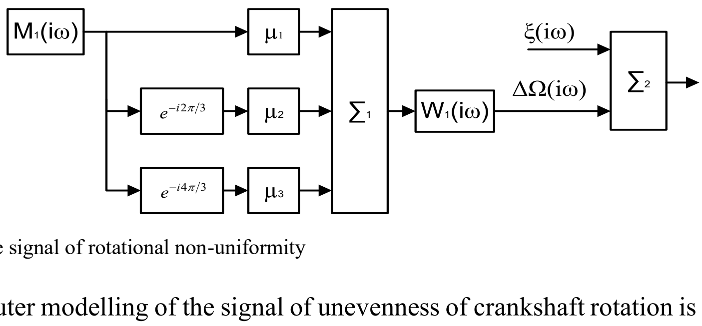
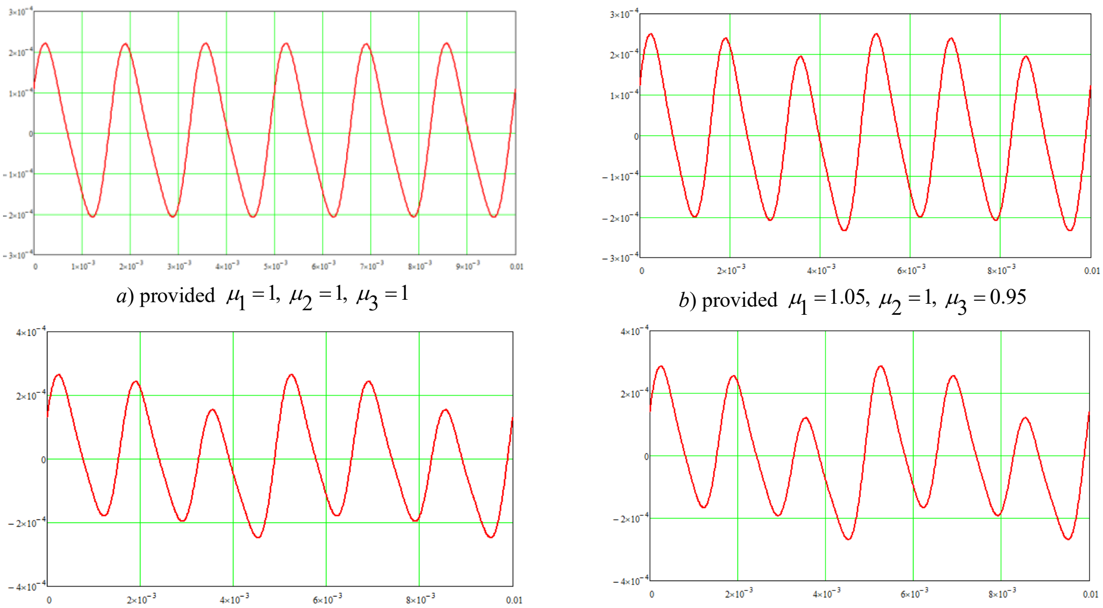


Fig.3. Modeling approach for the signal of rotational non-uniformity

The scheme of computer modelling of the signal of unevenness of crankshaft rotation is implemented in the Mathcad software environment. The discrete frequency spectrum of the perfectly deterministic irregularity signal is computed in its complex form. This discrete frequency spectrum serves as the primary input data for subsequent analyses.

This scheme can also be employed to simulate various signals of irregular rotation of the first mass of the crankshaft by adjusting the gain coefficients, which enables modification of the amplitudes of the cylinder torques [33, 34]. Such simulations allow for the investigation of the effects of deviations from the mean torque values on the ideally deterministic unevenness signal. The results of computer modeling of the perfectly deterministic rotation unevenness signal of the first mass over two crankshaft revolutions are presented in Figure 4.



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

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

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

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

Fig.4. Computer simulation results of various roughness signals

As a result of the analysis of the obtained graphs of perfectly deterministic signals of unevenness of rotation of the first mass of the crankshaft of the ICE, it was established that the third harmonic is the largest in amplitude in their frequency spectrum. The developed computer simulation scheme also has the option of adjusting its own parameters by comparing the output unevenness signal with experimental data of the speed of rotation of the first mass of the crankshaft. To identify the parameters of the computer simulation scheme, the authors used the learning model method [33, 34]. By tuning the gain coefficients, a match between the simulated signals of the first crankshaft mass rotation irregularity and the experimental data is achieved. Following the parameter adjustment of the computational model for perfectly deterministic rotation irregularity signals of the first crankshaft mass, the next step involves developing a mathematical model representing additive interference within the hardware and software systems controlling fuel supply.

2.5. Modeling of Additive Interference

The hardware components responsible for controlling fuel delivery to the power unit's cylinders operate cyclically and function under the influence of interferences originating from various physical sources. At the same time, software and hardware tools operate with pulse signal sequences. We will assume that all disturbances are additive in nature and affect the output signal of the computer simulation circuit. In the presence of multiple stochastic interferences, it becomes necessary to aggregate their cumulative impact on the measurement information signal. Among the recognized methodologies, the summation of random components grounded in the information-theoretic principles of measurement theory is the most commonly applied approach [35]. This method operates with root mean square deviations and kurtosis of the random interference components. If more than two random components are involved, the summation and calculation of the combined root mean square deviation and kurtosis are performed sequentially: first, between the first and second components; then the resulting sum is combined with the third component; this process continues with subsequent components iteratively. Consequently, the estimated values of the overall root mean square deviation and kurtosis for any number of random components are obtained. This procedure additionally facilitates the estimation of statistical parameters of the resultant random disturbance, which enables the selection of a suitable probability distribution function. In the context of this study, the interference imposed on the perfectly deterministic signal of the first crankshaft mass's rotational irregularity is modeled as structured "white noise" with a frequency spectrum constrained to ten harmonic components.

$$\xi(t) = \zeta\left[\sum_{i=0}^{4}\sin(2i+1)\Omega t + \sum_{k=1}^{5}\cos 2k\Omega t\right], \tag{12}$$

where the coefficient ζ specifies the percentage ratio between the sum of the maximum and minimum amplitudes of the rotational irregularity signal of the crankshaft's first mass.

The Mathcad environment was utilized to combine the perfectly deterministic measurement signal with an additive interference modeled as structured "white noise" constrained within a limited frequency range. The developed application software for this summation procedure is based on the following mathematical expression

$$\Theta(t) = \Delta\Omega(t) + \xi(t)\cdot \tag{13}$$

Figure 5 illustrates the outcomes of computer simulations of the perfectly deterministic rotational irregularity signal of the first crankshaft mass, altered by additive disturbances with varying amplitudes ζ, over six complete revolutions of the power unit's crankshaft.

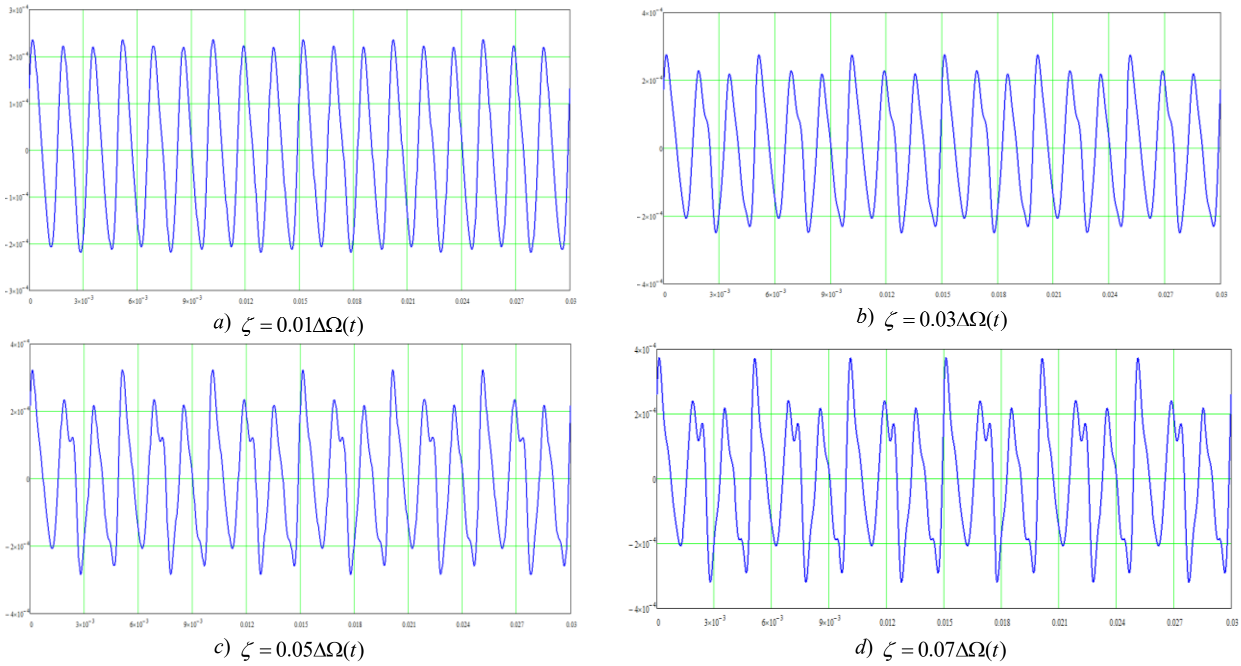


Fig.5. Results of computer simulation of the perfectly deterministic rotational irregularity signal of the first mass under the influence of additive disturbances

3. Information Technology of Signal Processing of Measurement Information

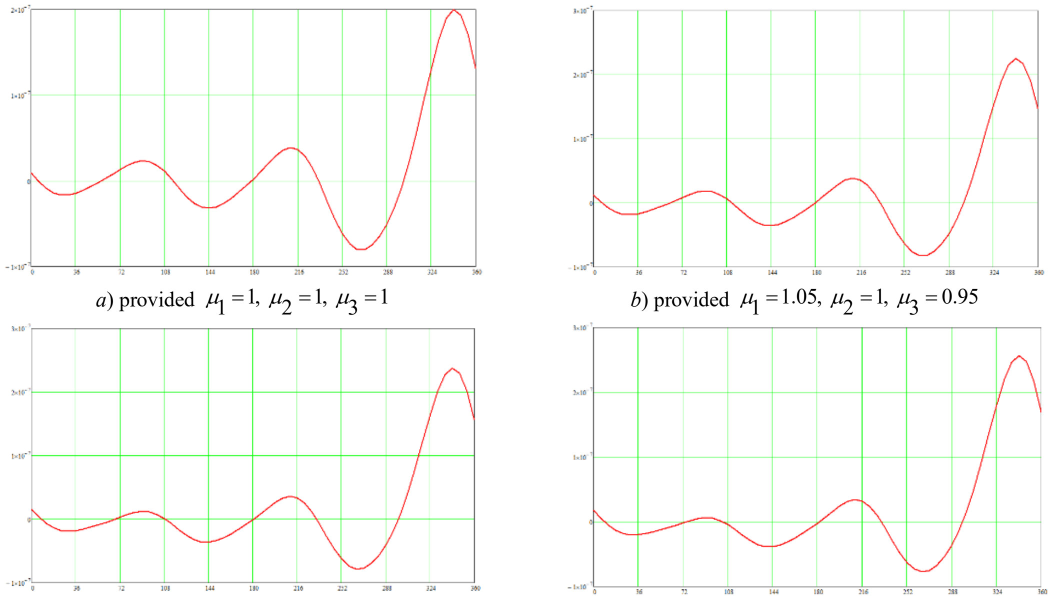
To determine the phase increments of the torques of the second and third cylinders relative to the first cylinder's standard setting, the authors employed, for the first time, a correlation analysis method. This method processes discrete measurement signals and torque data of an arbitrary cylinder. The authors computed the mutual correlation function between the signal of the first crankshaft mass rotational irregularity and the torque of the first cylinder using the following formulation

$$\begin{aligned} R(0) &= \frac{1}{N}\sum_{i=1}^{N} \Delta\Omega_1(t_i) M_1(t_i); \\ R(1) &= \frac{1}{N-1}\sum_{i=1}^{N-1} \Delta\Omega_1(t_i) M_1(t_{i+1}); \\ &\vdots \\ R(N-1) &= \Delta\Omega_1(t_1) M_1(t_{N-1}), \end{aligned} \tag{14}$$

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

The second algorithm computes the mutual correlation function between the signal of rotational irregularities of the first crankshaft mass and the torque of the first cylinder, subsequently generating the corresponding graphical representation. For its implementation, the authors used the Mathcad version 15 software environment and a personal computer WIN-02V1DG5KL68 with an Intel(R) Core(TM) i5-6300U CPU @ 2.40GHz 2.50GHz and 16 GB of RAM. The input information for this program is the discrete frequency spectra of the irregularity signals, white noise with a regular structure, and torque of the first cylinder. The procedure for summing the irregularity and white noise signals implements expression (13).

To calculate the mutual correlation function, the authors used the Mathcad software environment. The application software implements expressions (14). Fig. 6 presents the results of the mutual correlation function calculations performed under varying magnitudes of the amplification coefficients of the cylinder torque moments, as these torques are combined within the signal of the first crankshaft mass rotation irregularity.



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

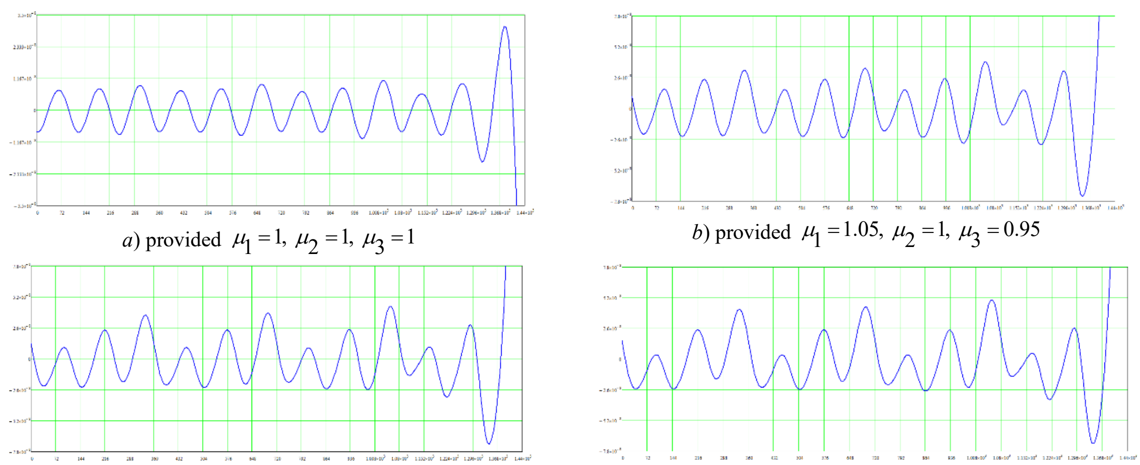
c) provided $\mu_1 = 1.1,\ \mu_2 = 1,\ \mu_3 = 0.9$ *d*) provided $\mu_1 = 1.15,\ \mu_2 = 1,\ \mu_3 = 0.85$

Fig.6. Outcomes of the mutual correlation function computations across varying amplification coefficients within the computational simulation framework

Mutual correlation function graphs were generated for a complete revolution of the power unit's crankshaft. Analysis of these graphs, taking into account the established firing sequence of the cylinders, led to the following conclusions: the first peak corresponds to the phase of the nominal torque setting for the second cylinder, the second peak corresponds to that of the third cylinder, and the third peak corresponds to the phase of the nominal torque setting of the first cylinder. Furthermore, the relative amplitudes of these peaks in the mutual correlation function graphs correspond to the gain coefficient μ_1, μ_2, μ_3 parameters applied in the computational model of the rotational irregularity signal of the crankshaft's first mass

4. Discussion of the Research Results

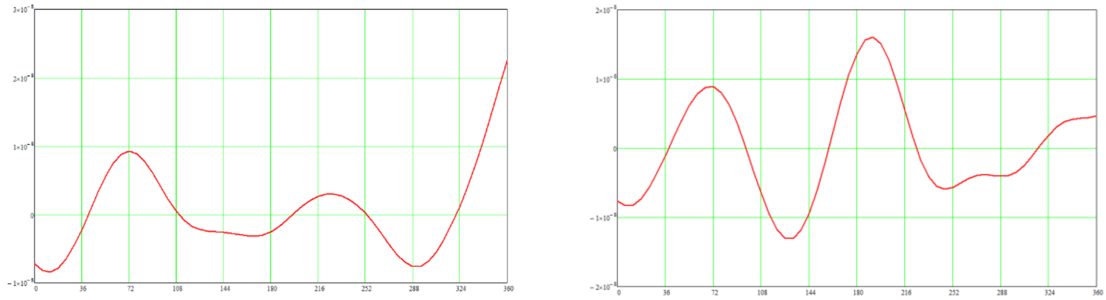
The developed application software enables the computation of the mutual correlation function over multiple revolutions of the internal combustion engine's crankshaft. Figure 7 illustrates the results of calculating the mutual correlation function across four crankshaft revolutions, considering varying amplitudes of the cylinder torque amplification coefficients as they are aggregated within the signal representing the uneven rotation of the first crankshaft mass. Analysis of these mutual correlation function graphs yielded conclusions consistent with those drawn from the analysis of the previous figure. It was also established that the graphs of the first three periods of the mutual correlation function coincided in appearance, and the graph of the fourth significantly differs in amplitude. This discrepancy can be attributed to the limited number of sampling points in the measurement information signals and the torque data of the first cylinder, which were utilized in constructing the mutual correlation function graph.



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

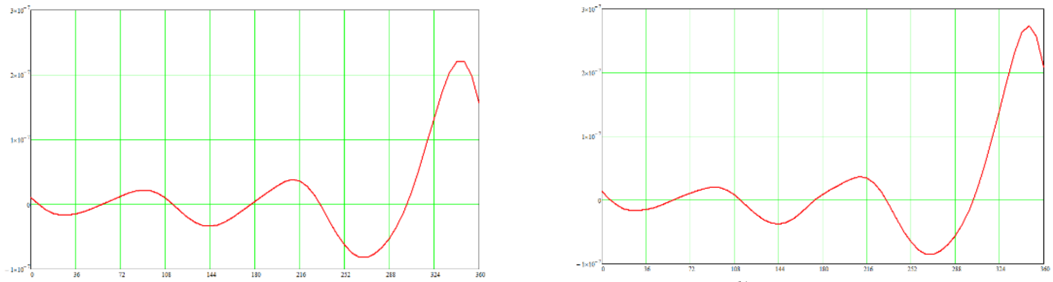
c) provided $\mu_1 = 1.1,\ \mu_2 = 1,\ \mu_3 = 0.9$ *d*) provided $\mu_1 = 1.15,\ \mu_2 = 1,\ \mu_3 = 0.85$

Fig.7. Results of the calculation of the mutual correlation function during four revolutions of the shaft

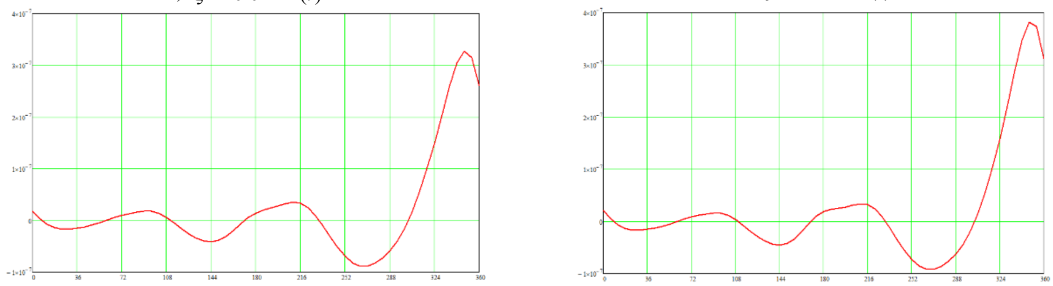


a) moment of the second cylinder   *b*) moment of the third cylinder

Fig.8. Results of the mutual correlation function computation over a single revolution of the power unit's crankshaft



a) $\zeta = 0.01\Delta\Omega(t)$ *b*) $\zeta = 0.03\Delta\Omega(t)$



c) $\zeta = 0.05\Delta\Omega(t)$ *d*) $\zeta = 0.07\Delta\Omega(t)$

Fig.9. Results of the mutual correlation function analysis under conditions of additive interference

The authors additionally explored the application of torques from the second and third cylinders for computing the mutual correlation function. The outcomes of the computer simulation are presented in Figure 8. When analyzing graphs of mutual correlation functions, it was established that there is no third maximum. The graphs also show some inconsistency in the phases of the second and third maxima. Therefore, employing the torques of the second or third cylinders for the calculation of the mutual correlation function is deemed impractical.

Figure 9 illustrates the outcomes of computational modeling of the mutual correlatiosn function between the measurement information signal and the torque of the first cylinder in the presence of additive noise disturbances.

The distinct appearance of the mutual correlation function graphs enables clear identification of their maxima. Consequently, a 14% uncertainty in measuring the rotation unevenness of the crankshaft's first mass permits the use of correlation analysis methods for monitoring phase increments relative to the standard fuel-air mixture supply settings of the ICE cylinders. Moreover, the relative magnitudes of the peaks in the mutual correlation functions align with the values μ_1, μ_2, μ_3 of the gain coefficients utilized in the computational model of the rotational irregularities of the crankshaft's first mass.

The application software proposed in this paper has some drawbacks and limitations:

- the presence of two programmes requires manual transfer of data from the first to the second;
- using the Mathcad software environment also involves manual entry of expressions (13). Since their number is determined by $N = 361$, typing such a large number of mathematical expressions takes a rather long period of time. It is advisable to organize the program for calculating the mutual correlation function by multiplying the elements of the array $\Delta\Omega_1(t_i)$ by the corresponding elements $M_1(t_i)$;
- the calculation of the graph of the mutual correlation function takes 2-3 minutes;
- to establish the maximums of the graphs of the mutual correlation function between the signals of uneven rotation of the first crankshaft mass and the torque of the first cylinder, the differentiation procedure allows. Therefore, the second program requires appropriate revision;

- the use of gain coefficients μ_1, μ_2, μ_3 allows to build a neural network with one layer. Accordingly, the proposed scheme of computer modelling of the signal of uneven rotation of the first mass has limitations when using;
- the development of a computational model for the irregularity signal based on a two-layer neural network is theoretically feasible. Its implementation requires the utilization of expressions for the mechanical transfer functions. By determining the zeros and poles of these functions, it becomes possible to represent the transfer functions as a summation of elementary circuit components. Incorporation of gain coefficients facilitates the organization of the neural network's second layer.

5. Conclusions

For the first time, the authors implemented correlation processing techniques on measurement information signals to monitor phase increments relative to the nominal fuel supply timing of internal combustion engine (ICE) cylinders. Piezoelectric-controlled fuel injectors were selected as actuators, and conceptual feedback control principles based on the state of the measurement signal were developed. The software and hardware architecture for monitoring phase increments relative to the nominal fuel supply timing was designed using indirect measurement data processing. The input signal utilized was a frequency-modulated representation of the rotational speed of the crankshaft's first mass. Implementing software-controlled adjustment of the fuel supply phase settings via hardware is expected to achieve fuel consumption savings of approximately 5%, while significantly reducing expenses related to maintenance, prevention, and repair of the power unit.

A mathematical model of the torque transmission system in an internal combustion engine is proposed in the form of a mechanical system possessing three degrees of freedom and incorporating frictional effects. The dynamics of masses in this deterministic model are described by a system of linear differential equations with fixed parameters. By applying theorems and methods from similarity theory, the system parameters were normalized into a dimensionless form. The derived similarity conditions enable the extension of the obtained results to engines with analogous structural configurations. The normalized system of differential equations governing the mass dynamics was solved using the Laplace transform, assuming zero initial conditions.

By applying the determinant method, the functional dependencies between the cylinder torques and the signal of rotational speed fluctuations of the crankshaft's first mass were determined. The Mathcad software environment facilitated the derivation of transfer function expressions for the mechanical pathways linking the cylinders to the first crankshaft mass. Further analysis in the Matlab environment allowed identification of characteristic points of the torque transfer functions, which led to a simplified system representation. Initially, the power unit's torque scheme was modeled as a mechanical system possessing a single degree of freedom. Cylinder torques were approximated using truncated Fourier series within the Mathcad environment.

Additive interference affecting the measurement information signal was simulated as structured "white noise" with a frequency spectrum confined to ten harmonic components. A computational framework for modeling perfectly deterministic signals representing the rotational irregularity of the crankshaft's first mass was implemented using the Mathcad software environment. The approach employed a method for regulating the length of information links within neural network architectures, which facilitated the determination of amplification coefficients for the amplitudes of cylinder torques. This methodology allowed for a systematic analysis of the influence of deviations from the mean cylinder torque profiles on the deterministic signal characterizing the rotational unevenness of the crankshaft's first mass.

For the first time, an algorithmic approach to monitoring phase increments relative to the nominal fuel supply timing of power unit cylinders is based on calculating the mutual correlation function between the signals of rotational irregularity of the crankshaft's first mass and the torque of the first cylinder. The corresponding application software for cross-correlation function computation has been developed and implemented using the Mathcad software environment.

A computer simulation of the perfectly deterministic signal characterizing the rotational irregularity of the crankshaft's first mass was performed, yielding the corresponding mutual correlation function graphs. Analysis of these graphs indicated that the first maximum corresponds to the phase of the nominal torque setting for the second cylinder, the second maximum corresponds to the phase of the nominal torque setting for the third cylinder, and the third maximum corresponds to the phase of the nominal torque setting for the first cylinder. Additionally, it was established that the ratio of the amplitudes of the mutual correlation function maxima matches the ratio of the gain coefficients applied in the computational model of the perfectly deterministic crankshaft rotation irregularity signal.

A study of graphs of mutual correlation functions during several revolutions of the crankshaft of the power unit was also conducted. It was established that the graphs of the first three periods of the mutual correlation function coincided in appearance, and the graph of the fourth significantly differs in amplitude. This difference is explained by the insufficient number of sampling points of the measurement information signals and the torque of the first cylinder, which took part in the formation of the graph of the mutual correlation function.

The calculation of the mutual correlation function between the signals of measurement information and the torque of the first cylinder under the condition of additive disturbances was performed. When analyzing the graphs, it was established that the uncertainty of the first mass rotation unevenness signal measurement of 14% allows the use of the correlation analysis method to monitor phase increments relative to the regular setting of fuel supply to the cylinders of the power unit.

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