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Diagnosis of internal combustion engines using an intelligent control algorithm

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Abstract — **This paper discusses the creation of an instrumentation system for a vibro-acoustic method for diagnosing engines, taking into account the algorithm for constructing a learning engine control system. The control and diagnostic signal is generated on the basis of automatic monitoring of the control actions on the engine's internal combustion engines (power and ignition systems). The proposed measuring system with multichannel vibration analyzers will allow not only in the process of driving to automatically evaluate the technical condition of the car, but also create a database of mathematical dependence of the oscillations on the variety of factors changing the engine state of a particular engine model. Fuzzy systems do not require accurate values of variables and the compilation of descriptive equations and allow us to evaluate different variants of output values. The use of the mathematical apparatus of fuzzy logic makes it possible to make informed decisions in the conditions of poorly formalized problems of rational management and control of the power supply and ignition systems of the internal combustion engine.**

Keywords — methods for diagnosing car engines, fuzzy system, adaptive ignition control systems.

I. Introduction

An internal combustion engine (ICE) is a power unit that converts the chemical energy of a fuel into heat and then mechanical as a continuous mechanical process with a discrete-action automatic control system. Engines are used in automotive vehicles, flying vehicles, quadcopters, drones. Motor control is a pressing issue presented in the work.

Studying internal combustion engines in preparing students for an enlarged group 23.00.00 Equipment and technology of ground transport vehicles is impossible without calculating the main parameters and control systems.

Currently, the development trends of the regulation systems of discrete technical units and assemblies are not complete without taking into account digital information processing technologies in traffic control systems of motor vehicles. Such systems are described by the mathematical apparatus of the theory of control of systems with a random character by varying parameters. For such systems, it is important to check the stability of control, which is possible with the help of modern digital technologies. They help implement complex information processing algorithms.

The tasks of work that have applied value include: development of the theory and methods of constructing and managing discrete dynamic systems with varying parameters, assessment of resistance to regulators, providing the required quality indicators of processes, algorithmic support of the analysis and synthesis systems.

Currently, electronic fuel metering systems have been created that allow automatic control of the amount and moment of fuel supplied to optimize the parameters of the unit at different engine operating modes (Fig. 1).

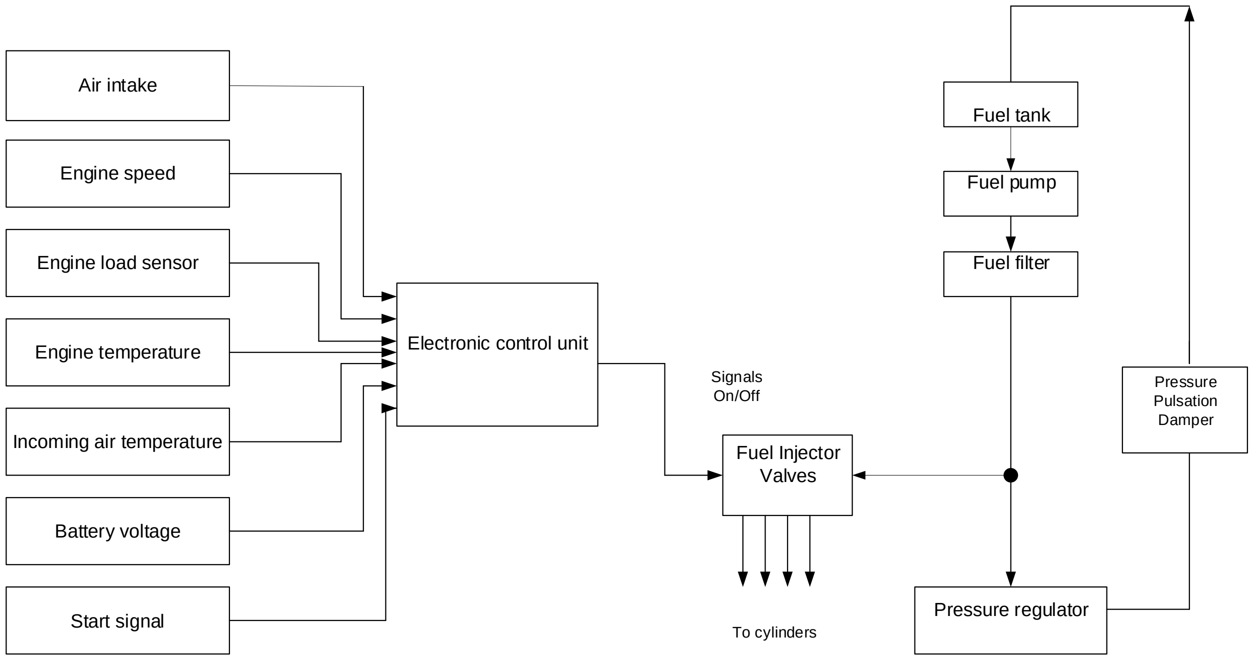

Fig. 1. Structural diagram of the management system power supply of the ICE

Under operating conditions, the internal combustion engine functions as a dynamic system with external and internal uncertainties. Internal disturbing effects are presented in the form of various kinds of disturbances, in particular under unsteady modes: start-up, warm-up, acceleration and braking, full or partial loads, including abrupt accumulation or load shedding, engine shutdown [1, 2].

External disturbing influences include: environmental parameters, changes in vehicle movement conditions, fuel characteristics, changes in the state of the holes in the injectors, etc. Disturbing effects are random and can be controlled (measured to take into account their influence in the control system) and uncontrolled.

In the process of the car in the places of pairing parts as a result of friction, shock, vibration, parts wear. To assess the state of parts of an internal combustion engine (ICE), two main diagnostic methods are used: stationary (control on special stands in the process of maintenance and repair) and built-in (during operation due to built-in measurement sensors in the design [3,4].

Widespread listening to the engine running. For example, with increasing gaps in bearings, characteristic knocks appear. In case of stationary maintenance, an auto mechanic listens with a stethoscope in certain zones and under appropriate operating modes of the unit. However, these knocks are clearly audible only at values that exceed permissible values. Moreover, the quantitative assessment of the gaps is subjective because it depends on the auditory qualities and experience of the mechanic.

The use of dynamic loads measurement based on spectral analysis of noise and vibration in an automated diagnostic system of the internal combustion engine makes it possible to establish not only the residual life, but also to determine the most worn parts of the unit without disassembling it. The use of built-in control systems will help move to the technical operation of the vehicle, depending on the actual state.

II. Research Methodology

In transmission units, it is rather difficult to estimate the technical condition of individual elements by non-sorted methods by the arising fluctuations. Diagnostic devices based on measuring the total noise level and averaging acoustic signals provide indications that can not be accurately determined which kinematic pair of a mechanism is defective, because the signal level is a fairly general characteristic that depends not only on the magnitude of the impact, but also on other characteristics of the unit (frequency, dynamic, speed).

The source of trouble can be vibration, which leads to loosening of threaded connections, weakening of fastening, the appearance of fatigue cracks. Despite its warning nature, it is advisable to check the mounting of the engine, gearbox, starter, clutch housing.

Vibration can be insignificant and therefore imperceptible during everyday non-fast driving. Finally, the vibration can have a "floating" character: now appear, then disappear (usually when changing modes of movement).

Vibration at the crankshaft rotational speed may occur after replacing the clutch basket. It will increase with increasing speed. Vibration of the propeller shaft often has a resonant nature - it increases at a certain speed [5,6].

Beats, vibrations, noises and knocks have a common basis - oscillations. The beating occurs when the parts vibrate. Often the heartbeat is accompanied by rhythmic beats when the mechanism works. Usually distinguish radial and lateral beats. Increased beats are the result of manufacturing defects, deformation of parts, disruption of their balancing, as well as increased gaps against norms.

Vibrations are high frequency and small amplitude vibrations that occur when a vehicle is moving. Increased vibrations (vibrations, trembling of the mechanism) are most often observed with improper alignment of the associated rotating parts, in violation of their balancing, deformations, significant wear of parts, as well as weakening of fit and fastenings of machine parts.

The acoustic method of diagnosis is based on the change in the frequency of sound vibrations emitted by objects in the process of work. The vibroacoustic method is based on measuring the vibration parameters of an aggregate, for example, a cylinder block, which characterizes the degree of wear of parts.

The diagnostic signal can be decomposed into components according to the amplitude, time, and frequency characteristics. With amplitude separation, the sensor should be installed in the place where the amplitude of the useful signal would be maximum and the interference signals the smallest. When temporal separation of signals, the systems assume that the moments of their appearance differ by a certain amount of time. For example, the signals that occur in the upper and lower heads of the connecting rods alternate in a certain sequence with certain time intervals between them, defined by the kinematics of the specified mechanism and the frequency of rotation of the crankshaft. The time separation of signals is called gating.

For frequency separation of signals, it is necessary to know the frequency or period of following each of them. Pulse repetition rates from collisions of various elements, as a rule, differ from each other. For example, the energy of the oscillatory process from piston transfer in the gap at the SMD-14 engine is in the range of 500 ... 4,000 Hz, and the energy from blows of piston rings on the piston grooves is 10,000 ... 14,000 Hz.

Vibration programs carry a large amount of diagnostic information. By vibrating the valve, it is possible to identify the deviations of the thermal gap in the actuator, reducing the spring stiffness.

However, the excessive complication of modern diagnostic systems leads to a significant increase in their cost. Such systems may be economically inefficient. Therefore, in practice, it is of great importance to pre-diagnose the technical condition of machines according to external signs.

Diagnostics for knocking and noise crank and Variable Valve Event and Lift (VVEL) allows to evaluate their technical condition at the moment, and in some cases - to determine the residual life.

Noises and vibrations arising from engine operation are diverse and difficult to distinguish, which complicates vibroacoustic diagnostics. However, the oscillations arising from the collision of certain mating parts differ in their parameters from oscillations of gas-dynamic origin and caused by friction [7, 8].

An increased detonation process occurs at a non-optimal ignition advance angle. The level of harmful substances in exhaust gases, engine power and fuel economy depend on the ignition phase.

The timing angle varies depending on the degree of opening of the throttle, engine speed, fuel quality, coolant temperature, air temperature in the air intake.

In this regard, the function of making decisions on specifying the phase of an ignition pulse (ignition advance angle $\varphi_з$) can be implemented by a fuzzy logic system with *n* inputs (Fig. 2), one output and four rules. The output of the fuzzy logic system is the value of the ignition timing.

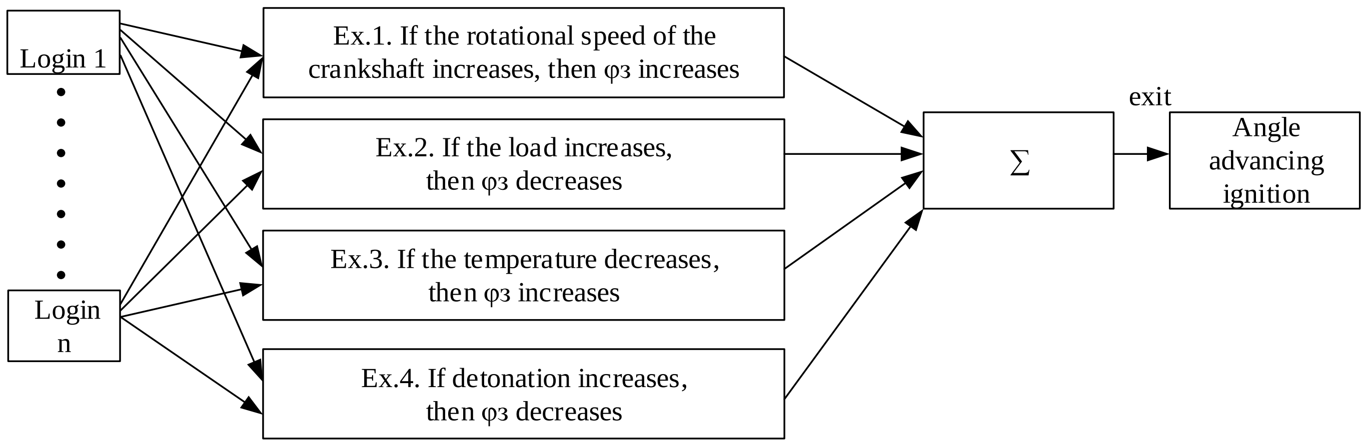

Fig. 2. Structural diagram of the algorithm for calculating the ignition timing

The four rules considered have a certain weight (from 0 to 1) depending on the degree of significance of the rule [2]. You can take the rules equivalent, and determine the weight of each rule expertly.

The system inputs are given by fuzzy sets with membership functions. Therm-sets of linguistic variables for such parameters as: X_1 - rotational speed; X_2 - load; X_3 - temperature of the internal combustion engine; X_4 - detonation, respectively defined as:

T_1 = {"small", "medium", "high"};

T_2 = {"partial", "medium", "large", "complete"};

T_3 = {"low", "medium", "high", "very high"};

T_4 = {"weak", "strong"}.

For the formation of recommendations for the ignition angle in each situation, we use the variable X_5, which characterizes a term, using the set:

T_5 = {"negatively large", "negatively small", "zero", "positively small", "positively large"}.

Zero is the standard angle set for a specific type of vehicle ICE, the increase or decrease from zero (early or late ignition) depends on the changing operating conditions.

All possible fuzzy situations can be reduced to a finite set of $3 \cdot 4 \cdot 4 \cdot 2 = 96$ typical situations.

III. Results of the Research

In the process of calculating the ignition phase, each of the parameters X_1 ... X_4 undergoes a phasification operation, on the basis of which the real values of physical variables are converted into the corresponding categories of fuzzy sets (Fig. 3) [2].

Since several rules work in parallel, we merge fuzzy sets into one fuzzy set

$$X_i^n(Y_i) = \mu_{T1}^j(X_1) \,|\, T_1^j \cup \mu_{T2}^j(X_2) \,|\, T_2^j \cup \mu_{T3}^j(X_3) \,|\, T_3^j \cup \mu_{T4}^j(X_4) \,|\, T_4^j \,, \tag{1}$$

where $\mu_{Ti}^j(X_i)$ is the degree of belonging of the parameter X_i to each i – th fuzzy set, described by the term set T_i.

In the defasification block, the fuzzy vector of the membership function is converted to the only clear value corresponding to the ignition advance angle.

The intelligent ignition system of the working mixture of an internal combustion engine allows to a large extent to ensure the efficiency and stability of the internal combustion engine, as well as to reduce the toxicity of exhaust gases. The parallel implementation of the rules of fuzzy logic systems allows us to obtain a smoother transition between the models (rules), which allows us to obtain the best technical and economic characteristics of the engine.

The engine as a system of diagnosis has non-linearity of its characteristics, non-stationarity (works in dynamic modes), uncertainty (presence of external and internal disturbances), inaccessibility of direct measurement of a number of quantities, delay, inertia of sensors and actuators. Therefore, the most relevant algorithms for diagnosing are algorithms based on a fuzzy, learning method [1].

Consider as a goal the optimal control of ICE parameters, represented as a fuzzy set G_N in X, given by the membership function $\mu G_N(u_N)$. The diagnosed ICE system A is defined by a finite number of states. At any particular time t, the system has a state x_t. Hence, you can write a finite set of various serviceable and faulty states X = $\{\sigma_1, ..., \sigma_n\}$ at t = 0,1,2 ..., with the input signal $U = \{a_1, ... ,a_m\}$. When the vehicle is moving, the load, turns, road conditions change, then the system in time can be set as a dependence of the state $x_{t+1} = f(x_t, u_t)$, $t = 0,1,2$ ..., in which f is a given function displaying XxU to X. The tracking system for the function $f(x_t, u_t)$, which is described by the previous state x_t, with the input set u_t, will allow you to determine the mismatch with the planned performance of the engine management system.

The final state x_N can be expressed in terms of the previous value of $u_1, ..., u_{N-1}$ and a valid initial x_0 by successively applying the equation $x_{t+1} = f(x_t, u_t)$.

The membership function [1] for a common system includes the intersection of sets

$$\mu_D(u_0,...u_{n-1}) = \mu_0(u_0) \wedge ... \wedge \mu_{N-1}(u_{N-1}) \wedge \mu_{G_N}(u_N) \tag{2}$$

During operation of the internal combustion engine, it carries out a continuous process of transforming input situations into output, so the solution can be represented as:

$$u_t = p_t(x_t), \text{ with } t = 0.1, ..., N\text{-}1, \tag{3}$$

where p_t is the rule of the input situation u_t depending on the previous state of the system x_t [9,10].

Thus, the task is reduced to finding the optimal strategies p_t and the corresponding sequence of input actions $u_1, ..., u_{N-1}$ optimizing μ_D. Transforming the solution by dynamic programming, we get

$$\begin{aligned} \mu_D(u_0^M,...u_{N-1}^M) &= \max_{u_0,...u_{N-2}} \max_{u_{N-1}} (\mu_0(u_0) \wedge ... \wedge \mu_{N-1}(u_{N-1}) \wedge \mu_{G_N}(f(x_{N-1}, u_{N-1}))) = \\ &= \max_{u_0,...u_{N-2}} (\mu_0(u_0) \wedge ... \wedge \mu_{N-2}(u_{N-2}) \wedge \mu_{G_N-1}(x_{N-1})) \end{aligned} \tag{4}$$

$$\mu_{G_N-1}(x_{N-1}) = \max_{u_{N-1}} (\mu_{N-1}(u_{N-1}) \wedge \mu_{G_N}(f(x_{N-1}, u_{N-1}))) \,, \tag{5}$$

where $\mu_{G_N-1}(x_{N-1})$ is the membership function of a fuzzy target at the moment $t = N$-1.

Repeating the process of inverse iterations, we obtain a system of recurrent equations

$$\mu_{G_N-\nu}(x_{N-\nu}) = \max_{u_{N-\nu}} (\mu_{N-\nu}(u_{N-\nu}) \wedge \mu_{G_{N-\nu+1}}(x_{N-\nu+1})) \,. \tag{6}$$

The solution of the problem

$$x_{N-\nu+1} = f(x_{N-\nu}, u_{N-\nu}), \nu = 1,..., N \quad (7)$$

At each time t, a fuzzy constraint G_t is imposed on the input set, for example, on emissions to the environment according to EURO5 standard, with the membership function μ_t (u_t).

Find the solution as a fuzzy set

$$D = G_0 \cap G_1 \cap ... \cap G_N \quad (8)$$

IV. DISCUSSION OF RESULTS

The refinement of the global criterion for a multicriteria task is determined through the composition $M = M_1 \circ M_2$

$$M_1 : \zeta(U^n) \to \zeta(Q^m), U^n = U_1 \times ... \times U_n, Q^m = Q_1 \times ... \times Q_m \quad (9)$$

$$M_2 : \zeta(Q^m) \to \zeta(Q), \quad (10)$$

where Q_i are sets of diagnostic states, respectively, for ICE, control parameters describing power and economic characteristics.

M_1 and M_2 are formed by sets taking into account statements like: if the values of the diagnostic states u_1, ..., u_n are evaluated by the terms t_{1i}, ..., t_{ni}, then the result satisfies the jth criterion with the estimate $t_{n+j,i}$:

$$M_1 = \{(t_{1i}, ..., t_{ni}, t_{n+j,i}) | n+1 \le j \le n+k, i = 1,..., m_1\}, \quad (11)$$

$$M_2 = \{(t_{n+1i}, ..., t_{n+ki}, t_{n+k+1,i}) | i = 1,..., m_2\} \quad (12)$$

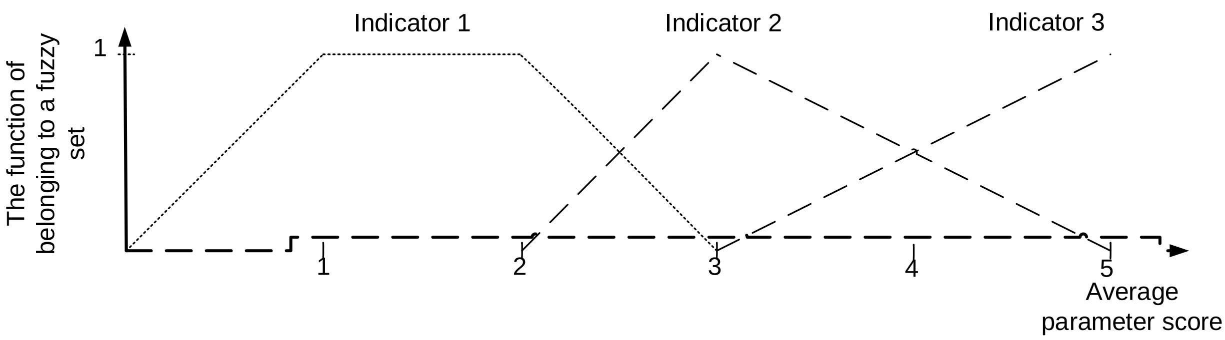

Fig. 3. The model of three classes of fuzzy sets

The use of the adaptive control algorithm allows for more flexible and, therefore, more effective diagnosis of internal combustion engines.

V. CONCLUSION

The proposed measuring system with multichannel vibration analyzers will allow not only in the process of driving to automatically evaluate the technical condition of the car, but also create a database of mathematical dependence of the oscillations on the variety of factors changing the engine state of a particular engine model. Fuzzy systems do not require accurate values of variables and the compilation of descriptive equations and allow us to evaluate different variants of output values. The use of the mathematical apparatus of fuzzy logic makes it possible to make informed decisions in the conditions of poorly formalized problems of rational management and control of the power supply and ignition systems of the internal combustion engine.

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