METHOD FOR DIAGNOSING INTERNAL COMBUSTION ENGINES WITH AUTOMATIC IGNITION ON THE BASIS OF TORQUE MEASUREMENT IN TRACTION CONDITIONS

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Summary

The paper presents a new method for diagnosing internal combustion engines with automatic ignition in traction conditions. Its substance involves determination of engine torque on the basis of recording of acceleration in road conditions. Extensive preliminary and primary experimental research has been conducted. Three variants of the internal combustion engine diagnostic model have been developed using a trivalent evaluation of states. Algorithms have been proposed to control a state and location of engine defects. The new method has been verified in traction conditions. A probability of a correct diagnosis of internal combustion engine is 0.85 ÷ 1.

Keywords: military vehicles, internal combustion piston engines, diagnostics.

METODA DIAGNOZOWANIA SILNIKÓW SPALINOWYCH O ZAPŁONIE SAMOCZYNNYM NA PODSTAWIE POMIARU MOMENTU OBROTOWEGO, W WARUNKACH TRAKCYJNYCH

Streszczenie

W pracy przedstawiono nową metodę diagnozowania silnika spalinowego o ZS w warunkach trakcyjnych. Istota polega na wyznaczeniu momentu obrotowego silnika na podstawie rejestracji przyspieszenia w warunkach drogowych. Wykonano obszerne wstępne i zasadnicze badania eksperymentalne. Opracowano trzy warianty modelu diagnostycznego silnika spalinowego, z wykorzystaniem trójwartościowej oceny stanów. Zaproponowano algorytmy kontroli stanu i lokalizacji uszkodzeń silnika. Zweryfikowano nową metodę w warunkach trakcyjnych. Prawdopodobieństwo poprawnej diagnozy silnika spalinowego wynosi 0,85 ÷ 1.

Słowa kluczowe: pojazdy wojskowe, tłokowe silniki spalinowe, diagnostyka.

1. INTRODUCTION

Based on analysis and assessment of diagnostic methods for internal combustion engines with automatic ignition, it should be stated that [3, 4, 6]:

1. tool-free methods for research and assessment of a state of internal combustion engines with automatic ignition, based on senses of eyesight, hearing and touch may be used as supplementary methods in mechanical vehicles diagnostic-servicing process, although they are not excluded to be used as primary methods in practical realization of processes for diagnosing and servicing internal combustion engines;
2. a considerable number of diagnostic methods being used for internal combustion engines with automatic ignition is characterized with complex diagnostic algorithms and a high labor consumption, which results in their low usefulness in diagnostics of those technical objects;
3. a large number of existing diagnostic methods for internal combustion engines with automatic ignition has no fixed boundary values of diagnostic parameters;
4. so far there are no objective diagnostic methods for quantitative determination of a wearing degree of piston-crank system and camshaft of internal combustion engines;
5. a need arises to develop methods for finding a genesis and forecasting a state in an aspect of possibilities for them to be used in practical realization of the internal combustion engines servicing process;
6. a significant number of existing methods stands for static and quasi-dynamic methods that are useless for applications in board diagnostic systems;
7. in our opinion, at present there is no sufficient set of diagnostic methods and means allowing for full and effective control of a state and location of damages in engine with automatic ignition both in stationary conditions and in particular while driving;
8. there is a need to develop an effective method to control a state and location of damages in internal combustion engine with automatic ignition for its further use in board diagnostic systems in conditions while a vehicle is in motion.

2. DIAGNOSTIC MODEL FOR VEHICLE ACCELERATION

2.1. Gist of vehicle acceleration process

In the vehicle acceleration process in a selected gear, internal combustion engine's torque from crank-shaft is transferred to a clutch, gearbox and further through distribution box, final drive – onto vehicle wheels. Driving force F_n, that is generated by the engine must be higher than total motion resistances force that consists of: inertia force F_b, rolling resistance force $F_{t,}$ and air resistance force F_p on a horizontal route.

The higher driving velocity the higher total motion resistances force and vehicle acceleration keeps declining until stability of velocity at which driving force becomes balanced by the motion resistances force, or when a maximum rotation speed of the engine has been achieved.

2.2. Equations of vehicle motion while car acceleration

General equation of vehicle's rectilinear motion on a flat route has a form of [1, 2]:

$$F_n = F_t + F_p + F_b \tag{2.1}$$

where: F_n – driving force on vehicle wheels; F_t – rolling resistances force; F_p – air resistances force; F_b – inertia resistances force;

After its transformations, expression (2.1) has a form of:

$$F_n = fmg + \gamma C_x A v^2 + \delta m a \tag{2.2}$$

where: f – rolling resistances coefficient; m – vehicle weight; g – gravitational acceleration; ρ – air density defined by a formula:

$$\rho = \rho_0 \frac{H_T}{H_0} \frac{T_0}{T_T} \tag{2.3}$$

where: ρ_0 – air density in normal conditions = 1.189 kg/m^3; H_T – air pressure at the moment of measurements taking; H_0 – reference pressure of 100 kPa; T_T – air temperature at the moment of measurements taking; T_0 – reference temperature of 293 K; C_x – air resistances coefficient; A – vehicle face surface; a – vehicle momentary acceleration; v – vehicle linear velocity; δ – vibrating masses coefficient defined by a formula:

$$\delta = 1 + \frac{(I_s + I_T) i_c^2 \eta_m + \Sigma I_k}{r_d^2 m} \tag{2.4}$$

where: I_s - moment of inertia of engine vibrating masses; I_T – coefficient to undefined states of internal combustion engine; i_c – total ratio of driving system; η_m– driving system efficiency; I_k – driving wheels moment of inertia; r_d – real, momentary dynamic radius of wheels.

2.3. Gist of New Method

The method being proposed bases on determination of engine torque on the basis of acceleration recording while vehicle is in motion in road conditions. A simultaneous measurement of fuel consumption allows for determining hourly fuel consumption in engine's rotational speed function. It is worthwhile stressing that a concept of methodology, defined below, for determining a torque of internal combustion engine has not been applied so far in diagnostic systems of mechanical vehicles in traction conditions.

2.4. Methodology for determining a set of diagnostic parameters

A problem with determining a set of diagnostic parameters of internal combustion engines in traction conditions will be solved by the following steps:

STEP I

Measurement of vehicle linear velocity and engine rotational speed

STEP II

Determination of dynamic radius of a circle r_d from dependence:

$$r_d = \frac{v * i_c}{n_s} \tag{2.5}$$

where: v – vehicle linear velocity; i_c – total ratio of driving system; n_s – engine rotational speed.

STEP III

Attempt of vehicle free rundown. A quantity being measured is a delay a_f and a_c of vehicle motion. The gist of measurement involves acceleration of the vehicle up to a possibly maximum speed, and then setting a gear-shifting lever into neutral and recording a delay $a_f = f(t)$ until the vehicle has stopped. Motion resistances are determined at velocities below 10 km/h when influence of air resistances is ommittably small. Air resistances are determined by delay a_c recorded at velocities of 75–20 km/h.

STEP IV

Determination of motion resistances coefficient from the following formula:

$$f = \frac{a_f}{g}\left(1 + \frac{\sum I_k}{m r_d^2}\right) \tag{2.6}$$

where: a_f – vehicle motion delay; g – gravitational acceleration; I_k – driving wheel moment of inertia; m – vehicle weight.

It is worth stressing that the motion resistances coefficient includes rolling resistances and frictions in: wheel bearings, meshing of gear wheels and shafts joints.

STEP V

Determination of vehicle air resistances coefficient from the following formula:

$$C_x = \left(-\frac{m}{\rho A v^2}\right)\left(fg + a_c + \frac{a_c \sum I_k}{m r_d^2}\right) \tag{2.7}$$

where: A – vehicle face surface; a_c – vehicle motion delay; ρ – air density.

A measurable quantity is vehicle motion delay a_c being recorded at velocities of 70 ÷ 20 km/h, in a rundown attempt being realized in STEP III.

STEP VI

Measurement of vehicle acceleration and fuel consumption is started upon a minimum velocity has become stable on third gear, and then through a rapid maximum stepping on acceleration pedal the vehicle gathers speed until a maximum velocity has been achieved. Vehicle dislocation, rotational speed of engine crank shaft and fuel consumption are measured.

A measured quantity is vehicle dislocation s_p. The gist behind measuring that quantity involves a rapid acceleration of the vehicle until a maximum velocity on a give gear has been achieved and recording of dislocation $s_p = f(t)$. The vehicle motion acceleration is obtained as $a_p = \frac{d^2 s_p}{dt^2}$.

STEP VII

Having the following data: dynamic radius of circle r_d, motion resistances coefficient *f*, air resistances coefficient C_x and motion acceleration a_p, it is possible to determine torque from the following dependence:

$$M_s = \left(\frac{mgfr_d + \rho C_x A v^2 r_d + \delta m r_d a_p}{i_c \eta_m} \right) \tag{2.8}$$

where: δ – vibrating masses coefficient; a_p – vehicle motion acceleration; G_e – momentary hourly fuel consumption measured in acceleration process.

2.5. Summary

Analysis of the vehicle acceleration diagnostic model authorizes to formulate the following conclusions:

1. the basis for the new method of research and assessment of a state of internal combustion engine with automatic ignition is equation of vehicle rectilinear motion on a flat route (2.1), and dependence (2.8).
2. a set of parameters of a state of internal combustion engine with automatic ignition includes:
3. engine torque M_s;
4. hourly fuel consumption G_e;
5. diagnostic parameters of vehicle state and internal combustion engine can also be as follows:
6. dynamic radius of circle - r_d;
7. motion resistances coefficient f;
8. delay a_f;
9. delay a_c;
10. acceleration a_p.
11. it should be stressed that for the above-mentioned sets of diagnostic parameters to be symptoms of a state of internal combustion engine with automatic ignition, their usefulness should be proved in a sense of meeting the hereto criteria: sensitivity, uniqueness, stability and informativeness, using experimental research.

3. EXPERIMENTAL RESEARCH

3.1. Research goal

The preliminary research goal was [5] to:

- define properties of signals being examined;
- determine an influence of factors being tested on values of physical quantities being measured;
- determine defined research terms and conditions, required by developed method to control a state and location of 4CTi90–1 BE6 engine damages.

The goal of primary research has been specified as follows:

- to select the best diagnostic parameters due to states differentiation criterion;
- determine boundary values of diagnostic parameters for selected states of 4CTi90–1 BE6 engine;
- determine states–diagnostic parameters couplings, that is, to obtain a diagnostic model of 4CTi90–1 BE6 engine, type - informative model Is.

The purpose of laboratory research is to collect data essential for comparing their values with values of results obtained in the primary experimental research, and on their basis verify the developed method for diagnosing 4CTi90–1 BE6 engine.

3.2. Research Program

Preliminary diagnostic testing program for the engine has been presented on fig. 1.

Primary diagnostic testing program for 4CTi90–1 BE6 engine has been presented on fig. 2.

Laboratory testing program for 4CTi90–1 BE6 engine has been presented on fig. 3.

3.3. Test stand and measuring apparatus

A test stand for diagnostic testing of 4CTi90–1 BE6 engine has been HONKER make vehicle.

Individual signals have been recorded using the following apparatus:

- optoelectronic sensor of linear velocity of DLS-1 vehicle made by Corrsys-Datron company:
- sensor of rotational velocity of FS2–60 engine made by Keyence company;
- 116H type of fuel flow-meter made by Pierburg company,
- fuel temperature sensor;
- data acquisition and processing station µEEP–10 made by Corrsys-Datron company

4. PRELIMINARY TESTS RESULTS ANALYSIS

4.1. Influence of whether conditions on values of physical quantities being measured

- Analysis of performed tests results has indicated essential differences in values of physical quantities being measured in diverse weather conditions. In order to reduce uncertainty of diagnosis made, an analysis has been conducted of the weather conditions impact and correction equations have been presented allowing for referring obtained results to standard ambient conditions i.e. temp. 20° C, pressure 100 kPa.

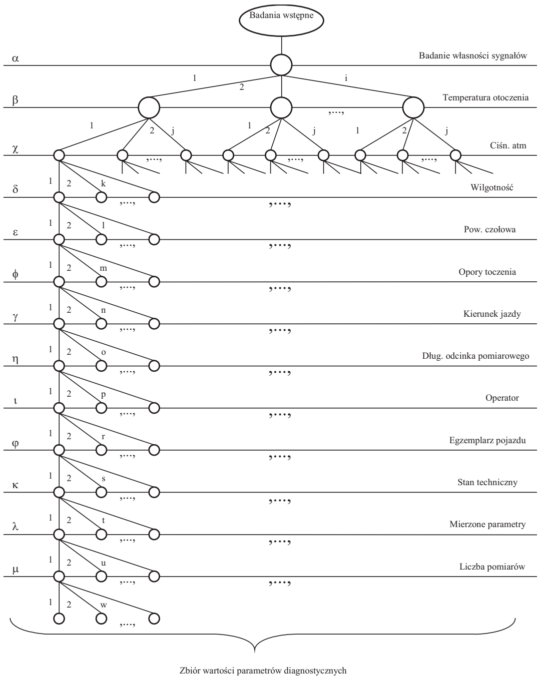

Fig. 1.Chart of preliminary diagnostic testing program for 4CTi90–1 BE6 engine

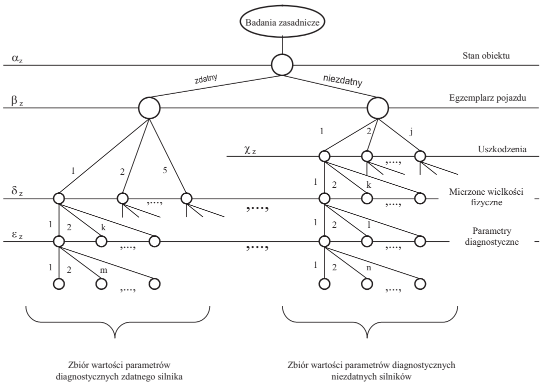

Fig. 2. Chart of primary diagnostic testing program for 4CTi90–1 BE6 engine

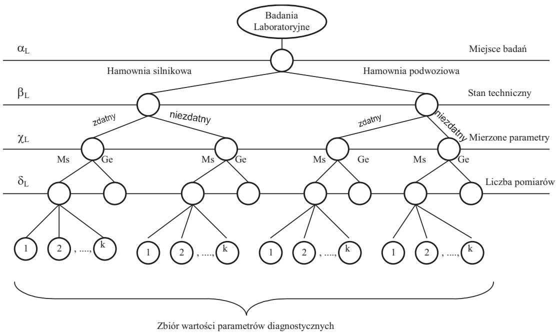

Fig. 3. Chart of diagnostic laboratory testing program for 4CTi90–1 BE6 engine

Ambient temperature

Tests performed at identical air pressure have been separated out of a set of all measurement results. Maximum values of internal combustion engine torque have been assumed for analysis. Results have been presented on fig. 4. The maximum torque value has been marked on the chart as average value and a standard deviation. This quantity characterizes a dispersion of results, that is, a statistical component of uncertainty of the measurement result (A type).

Obtained testing results are convergent with data included in technical literature. Growing ambient temperature effects in declining air density, and thus its smaller amount is sucked into the engine cylinder, which worsens a level of fulfillment and a progress of the combustion process, and therefore reduces effective pressure and engine torque.

The hereto considered process has been approximated with a straight line. Straight line inclination coefficient has been used to determine a correction equation, leading the obtained characteristics of the internal combustion engine torque to normal temperature of 20º C. The dependence takes the following form:

$$M_{sT_0} = M_s - (0{,}4060 * (T_0 - T)) \tag{4.1}$$

where: M_{sT_0} – torque corrected to temperature of 20º C; M_s – torque measured in ambient temperature *T*; T_0 – reference temperature – 20ºC;

Ambient temperature influences a temperature of fuel being delivered to engine injection pump. Injection apparatus had no temperature controlling device in the vehicle being tested. Therefore, differences in velocity characteristics of hourly fuel consumption, being measured while testing in various ambient temperatures, have been expected. Results of the performed analysis are presented on fig. 5.

A correction equation to standard ambient temperature has been determined in analogical way as that for the torque.

$$G_{eT_0} = G_e - (0{,}02142 * (T_0 - T)) \tag{4.2}$$

where: G_{eT_0} – fuel consumption corrected do temperature of 20º C; G_e – fuel consumption measured in ambient temperature *T*; T_0 – reference temperature – 20º C;

Air pressure

Corrected maximum torque values have been analyzed again due to ambient pressure value. Comparative results have been presented on fig. 6.

A correction equation of air pressure influence on torque characteristics has been determined in analogical way as that for the temperature:

$$M_{sk} = M_{sT_0} + (2{,}0042 * (p_0 - p)) \tag{4.3}$$

where: M_{sk} – torque corrected to normal conditions (temperature 20º C, air pressure 100 kPa); M_{sT_0} – torque corrected to temperature 20º C; p_0 – reference pressure (normal) reaching 100 kPa; *p* – air pressure while making measurements.

Air Humidity

Relative air humidity depends on pressure and temperature. In order to become independent from those two quantities, for the purposes of this method, a relative humidity has been measured and then converted to absolute humidity (so-called proper humidity) expressed as content of water in one kilogram of dry air. Influence of absolute humidity on torque results is presented on fig. 7.

As indicated on the above figure, absolute humidity hereto applied measurement method has no significant influence on torque value. Statistical (A type) uncertainty of results of individual measurements (performed in stable conditions) is higher than differences effecting from the impact of proper humidity.

Correction equations of the impact of weather conditions can also be determined on the basis of analysis of multiple regressions. It allows for obtaining a single equation that contains influence of all the factors being tested.

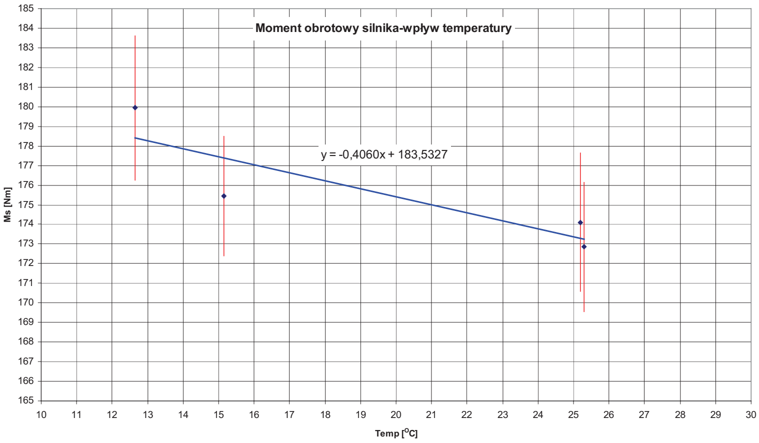

Fig. 4. Influence of ambient temperature on maximum torque values of internal combustion engine 4CTi90–1 BE6

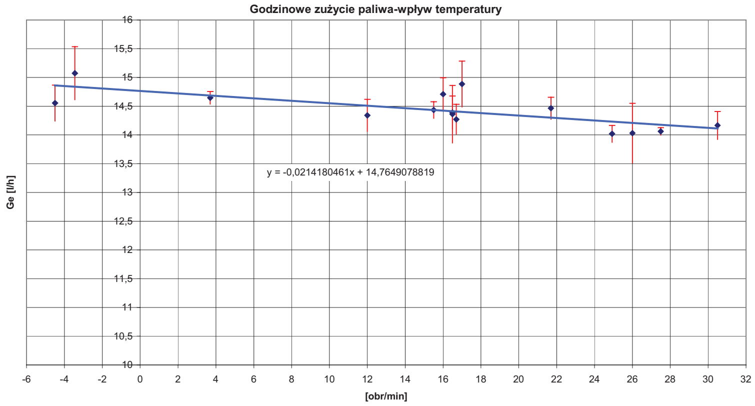

Fig. 5. Influence of ambient temperature on hourly fuel consumption of internal combustion engine 4CTi90–1 BE6

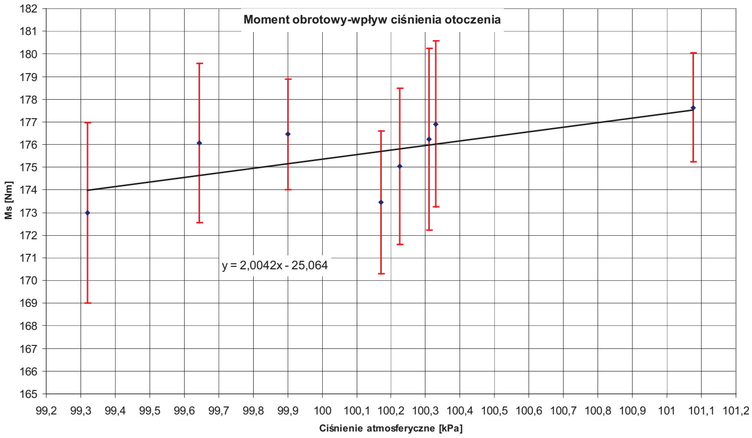

Fig. 6. Influence of air pressure on maximum values of 4CTi90–1 BE6 internal combustion engine torque

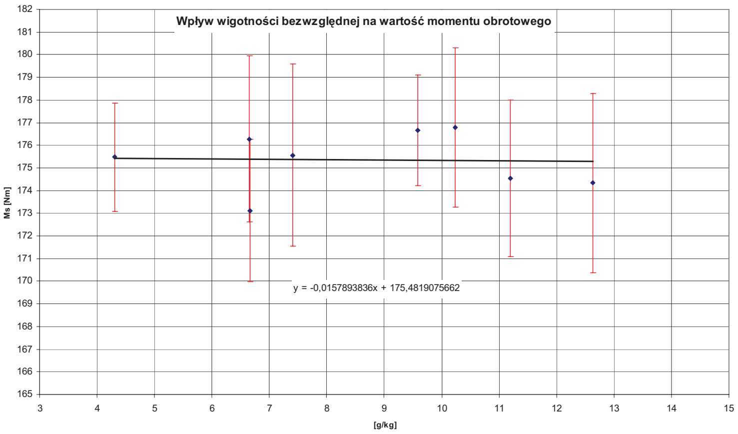

Fig. 7. Impact of air absolute humidity on obtained values of maximum torque of internal combustion engine 4CTi90–1 BE6

Summary

On the basis of performed tests and analyses of weather conditions influence on values of physical quantities being measured, it should be stated that:

1. ambient temperature has essential impact on values of parameters characterizing a process from a torque of internal combustion engine 4CTi90–1 BE6;
2. ambient pressure has a very essential influence on values of parameters related to a torque of internal combustion engine 4CTi90–1 BE6;
3. proper air humidity has a minor impact on parameters values determined for internal combustion engine 4CTi90–1 BE6 torque characteristics;
4. influence of weather conditions on parameters values related to fuel consumption by the engine is immaterial;
5. in order to obtain reliable testing results, torque and fuel consumption values being obtained should be corrected to normal conditions;
6. the most convenient method of correction to normal conditions is a use of multiple regression equations recognizing the influence of all factors being tested;
7. percentage of explained volatility for weather conditions impact on torque value is very high and exceeds 90%, and for fuel consumption 76.43%;

finally, correction equations of weather conditions influence have the following form:

- for the torque:

$$M_{sk} = M_s - (0{,}5066 * (T_0 - T)) + 2{,}1704 * \\ * (p_0 - p) + 0{,}1435 * (DP_0 - DP) \tag{4.4}$$

where: M_{sk} – torque corrected to normal conditions (temperature 20º C, air pressure 100 kPa, reference humidity defined as dew-point 10º C); M_s – torque measure in ambient temperature T, pressure p *and* humidity DP; p_0 – reference pressure (normal) reaching 100 kPa; p – air pressure while making measurements; T_0 – reference temperature: 20º C; T – ambient temperature while making measurements; DP – dew-point temperature (characterizing air humidity); DP_0 – dew-point/reference temperature: 10º C,

- for fuel consumption:

$$Ge_k = Ge + (0{,}0394 * (T_0 - T)) - 0{,}8545 * \\ * (p_0 - p) - 0{,}3013 * (DP_0 - DP) \tag{4.5}$$

where: Ge_k – fuel consumption corrected to normal conditions (temperature 20º C, air pressure 100 kPa, reference humidity defined as dew-point 10º C);Ge – fuel consumption measured in ambient temperature T, pressure p *and* humidity DP;

4.2. Influence of motion conditions on values of physical quantities being measured

Rolling resistances

Rolling resistances of the vehicle being tested have been changed by reducing air pressure in vehicle tires. Tests have been conducted in two variants: at pressure reaching 0.25 MPa and 0.42 MPa. They are extreme pressure values allowed for Goodyear tires G90 7.50 R16C that the vehicle being tested has been equipped in.

Trust ranges have been calculated for parameters following this dependence:

$$\overline{y_n} - t_\alpha \frac{s_{yn}^2}{\sqrt{n}} < y_n < \overline{y_n} + t_\alpha \frac{s_{yn}^2}{\sqrt{n}} \tag{4.6}$$

where: t_α – variable t–Student for n-1 degrees of freedom, fulfilling the relation $P(-t_\alpha < t < t_\alpha) = 1 - \alpha$; $\overline{y_n}$ – parameter average value; s_{yn}^2 – parameter variance defined by dependence:

$$s_y^2 = s_{yn}^2 = \frac{1}{n-1} \sum_{n=1}^{N} (y_n - \overline{y_n}) \tag{4.7}$$

States differentiation test has been applied for the purposes of this study, comparing average values of parameters and trust ranges for a state of usability and non-usability. Damage identifiability has been defined via trivalent assessment of a parameter. The „0" value has been assumed for no identifiability. If a value of a tested parameter keeps declining because of damage, a checking result is „-1", and if it is rising „1". Procedure of proceeding is presented on the model:

1. definition whether a change in the parameter is identifiable upon considering the trust range:

$$\left|\overline{y_0} - \overline{y_n}\right| > t_{\alpha 0}\frac{s_{y0}^2}{\sqrt{n_0}} + t_{\alpha n}\frac{s_{yn}^2}{\sqrt{n_n}} \tag{4.8}$$

where: $\overline{y_0}$ – parameter average value corresponding to a state of usability; $\overline{y_n}$ – parameter average value corresponding to a state of n-th non-usability; $t_{\alpha 0}\frac{s_{y0}^2}{\sqrt{n_0}}$ – half of trust range of parameter corresponding to a state of usability; $t_{\alpha n}\frac{s_{yn}^2}{\sqrt{n_n}}$ – half of trust range of parameter corresponding to a state of n-th non-usability.

2. if checking result is a number different from „0" definition whether a value of the tested parameter has declined or maybe grown as a result of damage.

Analysis of the presented results indicates that tire pressure, and effectively vehicle rolling resistances, have no influence on testing results. It allows to formulate a conclusion that the assumed methodology, recognizing real vehicle rolling resistances (determined in a free rundown attempt), make the measurement result independent from motion resistances impact.

Driving direction

Impact of driving direction on results of diagnostic parameters being obtained has been tested by conducting a series of measurements in both driving directions. While conducting tests, wind velocity has exceeded 2 m/s lengthwise of the measured section. Analysis has bee carried out separately for measurements performed for driving against the wind and with the wind.

The torque process analysis indicates that parameters values slightly differ. Trust levels remain at the same unchanged level. Noticeable is a shift of a maximum torque into directions of lower rotational speed, and a faster accumulation of a torque in range 1800 - 2500 rotations per minute. This results from phenomena occurring during cooperation of turbo-compressor with the engine. Higher motion resistance (adverse wind) cause higher load on the engine, higher combustion pressure, and thus combustion fumes that generate higher supercharge pressure at low rotational velocities. Therefore, wile driving against the wind torque is higher than that at low rotational velocities; however, upon considering trust ranges the differences are insubstantial.

The states differentiation test does not show any significant differences in values of parameters, determined on the basis of measurements made with the wind and against the wind. This proves a correctness of the assumed testing methodology.

Surface type of measured section

Research tests on influence of a surface type have been conducted on two measurement sections: local road section Halinow – Cisie with asphalt surface and on military airfield Sochaczew with concrete surface. Honker vehicle with EURO-3 engine version has been the testing object in both cases. Measurements have been taken with an interval of two days with slightly different weather conditions, therefore results have been corrected to normal conditions, following equations of (4.4) and (4.5).

The performed tests results indicate that there are no significant differences in the proposed values of diagnostic parameters.

Vehicle face surface

The analysis of vehicle face surface impact on measurements results has been conducted on the basis of measurements made on Honker and Scorpion vehicles. The face surface in the first tested object has reached 3.55 m^2, while in the second case 3.82 m^2. Characteristics have been compared and corrected to normal conditions.

Values of parameters related to engine torque slightly differ. Upon considering trust ranges, there are no differences between average values. This allows saying that the assumed methodology including in its calculations real resistances in vehicle motion is a correct one. The states differentiation test detects differences in parameters related to fuel consumption: consumption at rotational speed of maximum torque Ge_M, and maximum consumption Ge_{max}. The reason behind this situation is probably a production dispersion of engines. The two vehicles originated from different production batches: Honker from year 2002, while the vehicle marked with a cryptonym of Scorpion from year 2003.

4.3. Conclusions

Based on performed preliminary rests and analyses of results obtained, it should be said that:

1. results repeatability tests has indicated that the proposed parameters are characterized with repeatability for the engine usability state;
2. point and range estimations of research results indicate that average values of the proposed parameters are characteristic for the usability state and individual damages, which proves their usefulness for building a diagnostic model of internal combustion engine;
3. weather conditions have been found to have essential impact on engine torque values, but a small influence on fuel consumption average value;
4. based on many variances uniqueness test, it has been found that there are no basis for rejecting a hypothesis about equality of variances in tested parameters for usability state, but the torque variance value differs for individual damages;
5. on the basis of correlation analysis, a dependence has been found of average torque on weather conditions;

6. an analysis has been made of weather conditions impact and regression analysis and equations have been generated correcting the testing results to normal ambient conditions;
7. results of motion conditions influence allow for formulating the following conclusions:

- impact of rolling resistances on values of physical quantities being measured is immaterial;
- driving direction has no influence on values of physical quantities being measured;
- type of surface has no influence on values of physical quantities being measured;
- vehicle face surface has no influence on values of physical quantities being measured;

8. diagnostic parameters for usable internal combustion engine have been proposed and determined;
9. states differentiation test (4.4) has been proposed that contains trust ranges for states of usability and non-usability. This has resulted in a trivalent assessment of internal combustion engine states.

5. PRIMARY RESEARCH RESULTS ANALYSIS

5.1. Characteristics of usable engine

Characteristics of usable 4CTi90–1 BE6 engine have been determined based on 8 measuring sessions conducted in various weather conditions. Some 30 measurements have been taken during each of the sessions. Characteristics of usable engine have been presented on fig. 8. ÷ fig. 9. The charts also present trust ranges for proposed diagnostic parameters and characteristics curves equations. Trust range of a parameter has been determined from dependence (4.6).

Table 1 presents values of proposed diagnostic parameters of usable 4CTi90–1 BE6 engine, in EURO2 version, corrected to normal ambient conditions, and their trust ranges.

5.2. Influence of damages on values of physical quantities being measured

Weak links of the engine being tested, which have been determined on the basis of vehicles maintenance monitoring at military bases, have been assumed as a criterion for selection of damages to be diagnosed. Table 2 presents weak links of internal combustion engine 4CTi90–1 BE6

Testing results of individual damages impact on values of proposed diagnostic parameters, corrected to normal conditions, have been presented in a comparison with usable engine parameters. Trust ranges of proposed diagnostic parameters have been calculated for individual damages and the states differentiation test has been performed based on dependence (4.4).

Results have been presented on fig. 10 ÷ fig. 11.

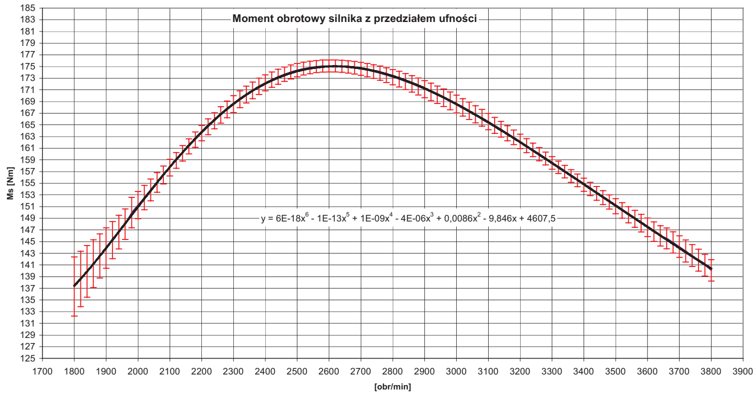

Fig. 8. Torque characteristics of usable 4CTi90–1 BE6 internal combustion engine in EURO2 version

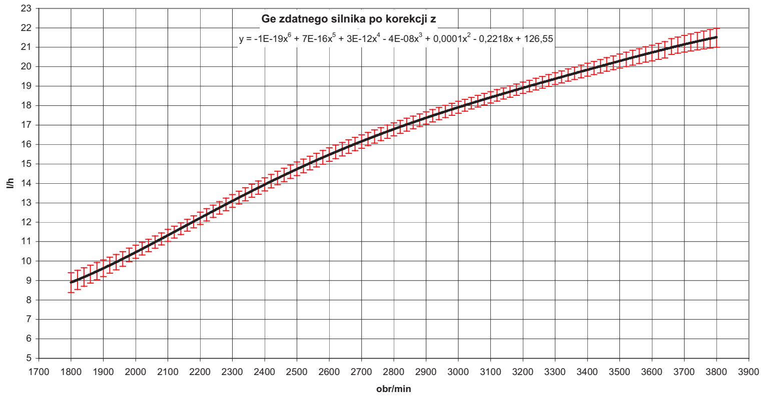

Fig. 9. Fuel consumption characteristics of usable 4CTi90–1 BE6 internal combustion engine in EURO2 version

Table 1. Proposed diagnostic parameters of usable 4CTi90–1 BE6 internal combustion engine

	Marking	Value of diagnostic parameter	Half of trust range
Average. torque [Nm]	$\overline{M_s}$	160.64	± 2.28
Max torque [Nm]	M_s	175.11	± 1.02
Torque at min. speed [Nm]	M_{s0}	137.31	± 5.07
Torque at max speed [Nm]	M_{si}	140.07	± 1.84
Rotational speed of max. torque [rotations/min]	n_M	2600	± 21
$\frac{M_{s0}}{M_{\max}}$	C_{M1}	0.7842	± 0.0415
$\frac{M_{si}}{M_{s\max}}$	C_{M2}	0.7999	± 0.0112
Average fuel consumption [l/h]	$\overline{Ge}$	16.14	± 0.74
Consumption at rotational speed of max. torque [l/h]	G_{eM}	15.48	± 0.35
Consumption at min. rotational speed [l/h]	G_{emin}	8.89	± 0.51
Consumption at max. speed [l/h]	G_{emax}	21.49	± 0.48
$\frac{Ge_M}{Ge_{\min}}$	C_{Ge1}	0.5744	± 0.0343
$\frac{Ge_{\max}}{Ge_M}$	C_{Ge2}	0.7204	± 0.0306

Table 2. Weak links of 4CTi90–1 BE6 engine

No	Element-	Damage probability	Non-usability state
1	injection pump	0.1	w_1^0
2	turbo-compressor	0.1	w_2^0
3	air filter	0.4	w_3^0
4	injectors	0.3	w_4^0
5	cylinder damage	0.05	w_5^0
6	timing gear system	0.05	w_6^0

Based on primary experimental research that has been conducted in traction conditions, it should be said that:

1. states differentiation test with trivalent assessment of state has been prepared;
2. a set of diagnostic parameters has been proposed and their values have been determined for usable 4CTi90–1 BE6 engine;
3. values of parameters have been determined corresponding to six selected damages;
4. states differentiation test has been made for introduced individual damages and a damage identifiability has been determined;

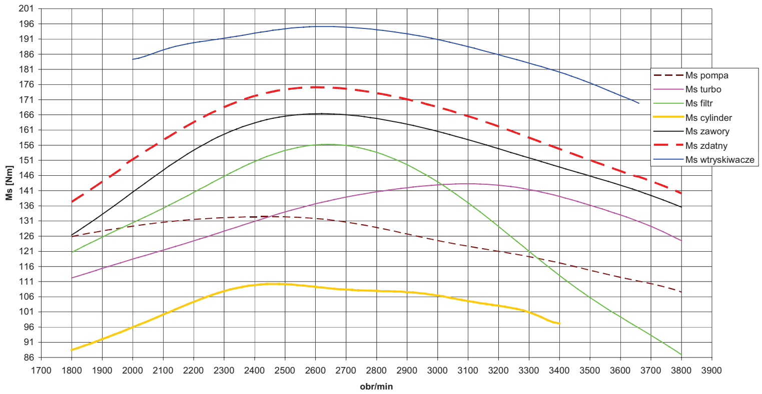

Fig. 10. A comparison of torque characteristics for usable engine and for individual damages

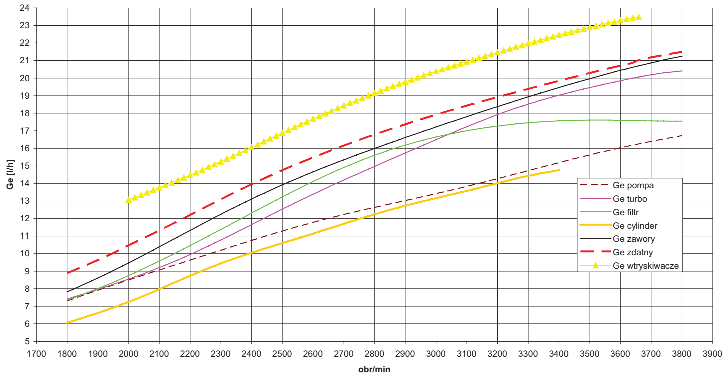

Fig. 11. A comparison of torque characteristics for usable engine and for individual damages

Table 3 presents results of the states differentiation test for individual damages. An analysis of Table 3 indicates that:

1. results of the states differentiation test for individual damages vary for specific damages, which proves that parameters have been correctly matched;
2. the most information providing parameters are: $\overline{M_s}$, M_s M_{s0}, for which a change in parameter value is differentiable in all tested damage cases;
3. the least information providing parameters are: C_{Ge2} – no differentiability for four damages, C_{M1} (see item 6.1) – no differentiability for four damages,
4. the easiest identifiable are: injection pump damage – a change in all parameters besides C_{M2} and C_{Ge2}, and injectors damage – a change in all parameters besides n_M and C_{Ge2} , however, the value of all parameters keeps growing for this type of damage;
5. the most difficult identifiable is a damage involving a leaky combustion chamber. In this case, only three parameters change: $\overline{M_s}$, M_s *and* M_{s0} (see item 6.1);
6. Table 3 is information model (diagnostic matrix) enabling a control of a state and location of selected damages of 4CTi90–1 BE6 engine.

Table 3. Information model (diagnostic matrix) of internal combustion engine 4CTi90-1 BE6

Marking	Pump corrector	Turbo	Air Filter	Injectors	Cylinder	Leaky combustion chamber	Usable
$\overline{M_s}$	**0**	**-1**	**-1**	**-1**	**1**	**-1**	**-1**
M_s	**0**	**-1**	**-1**	**-1**	**1**	**-1**	**-1**
M_{s0}	**0**	**-1**	**-1**	**-1**	**1**	**-1**	**-1**
M_{si}	**0**	**-1**	**-1**	**-1**	**1**	**-1**	**0**
n_M	**0**	**-1**	**1**	**0**	**0**	**-1**	**0**
C_{M1}	**0**	**1**	**0**	**0**	**1**	**0**	**0**
C_{M2}	**0**	**0**	**1**	**-1**	**1**	**0**	**0**
$\overline{Ge}$	**0**	**-1**	**0**	**0**	**1**	**-1**	**0**
G_{eM}	**0**	**-1**	**1**	**0**	**1**	**-1**	**0**
G_{emin}	**0**	**-1**	**-1**	**-1**	**1**	**-1**	**0**
G_{emax}	**0**	**-1**	**0**	**-1**	**1**	**-1**	**0**
C_{Ge1}	**0**	**1**	**-1**	**0**	**1**	**0**	**0**
C_{Ge2}	**0**	**0**	**1**	**1**	**0**	**0**	**0**

6. INTERNAL COMBUSTION ENGINE 4CTI90–1 BE6 DIAGNOSTIC METHOD

6.1. Diagnostic Model

Based on experimental research analysis results, three variants have been developed of diagnostic model of 4CTi90–1 BE6 engine. This paper will present the most extended variant. The variant is characterized with the highest precision – accuracy of diagnosis being made. Its disadvantage is a high cost and labor consumption when taking measurements. It requires fuel consumption measurement, which is associated with a purchase of expensive apparatus and time-consuming assembly inside the vehicle.

Those diagnostic parameters in the model are as follows:

1. average torque $\overline{M_s}$
2. maximum torque value M_{smax} at rotational speed n_M;
3. torque value M_{s0} at minimum rotational speed $n_0=n_{min}$;
4. torque value M_{si} at maximum rotational speed $n_i=n_{max}$;
5. placement of maximum torque on rotational speed axis - rotational speed of maximum torque n_M;
6. a ratio of torque at minimum rotational speed to maximum torque:
$$C_{M1}=\frac{M_{s0}}{M_{\max}} \tag{6.1}$$
7. a ratio of torque at maximum rotational speed to maximum torque:
$$C_{M2}=\frac{M_{si}}{M_{s\max}} \tag{6.2}$$
8. average fuel consumption $\overline{Ge}$;
9. fuel consumption G_{eM} at rotational speed of maximum torque n_M;
10. consumption at minimum rotational speed G_{emin};
11. consumption at maximum speed G_{emax} ;
12. ratio of fuel consumption at maximum torque to a minimum consumption:
$$C_{Ge1}=\frac{Ge_M}{Ge_{\min}} \tag{6.3}$$
13. ratio of maximum fuel consumption to consumption at maximum torque:
$$C_{Ge2}=\frac{Ge_{\max}}{Ge_M} \tag{6.4}$$

The research results obtained are compared to values of quantities of usable-model engine and then a parameter value is being determined:

- „0" – no changes (the parameter value corresponds to the state of usefulness);
- „1" – the parameter value has been suspended compared to the value corresponding to the state of usefulness;
- „-1" – the parameter value has declined compared to the state of usefulness.

If all parameters have „zero" value, then object is usable. If „1" or „-1" has been recorded in the results sheet, then a set of results of parameters checks is compared to combinations of results characteristic for individual damages. A non-usability state is determined on that basis and damage is located.

Then location of the damage is verified through a comparison of absolute values of obtained parameters with values corresponding to individual damages. Accuracy (probability) of diagnosis is calculated on the basis of a number of parameters that reflect changes with their character („0", „1" or „-1") and absolute value of parameters describing a given damage.

State control and 4CTi90–1 BE6 engine damages location algorithm, developed on the basis of model I, has the following form:
State control:
If ($\overline{M_s}$ = 0) and (M_s = 0) and (M_{s0}= 0) and (M_{si} = 0) and (n_M = 0) and (C_{M1}= 0) and (C_{M2}= 0) and ($\overline{Ge}$ =0) and (G_{eM} = 0) and (G_{emin} = 0) and (G_{emax} = 0) and (C_{Ge1}= 0) and (C_{Ge2}= 0) **then the state is w^1**;
Location of damage:
If ($\overline{M_s}$ = –1) and (M_s = –1) and (M_{s0}= –1) and (M_{si} = –1) and (n_M = –1) and (C_{M1}= 1) and (C_{M2}= 0) and ($\overline{Ge}$ = -1) and (G_{eM} = –1) and (G_{emin} = –1) and (G_{emax} = –1) and (C_{Ge1}= 1) and (C_{Ge2}= 0) **then the state is w_1^0**;

Supplementary test aiming at higher certainty of diagnosis
If ($\overline{M_s}$ =126,59± 1,48 Nm) and (M_s =134,44± 1,59 Nm) and (M_{s0}= 127,85± 2,03 Nm) and (M_{si}=109,56± 3,32 Nm) and (n_M =2440± 109 rotations/min) and (C_{M1}=0,9510± 0,0159) and (C_{M2}=0,8150± 0,0211) and ($\overline{Ge}$ =12,39± 0,54 l/h) and (G_{eM} =10,94± 0,57 l/h) and (G_{emin}=7,28±0,50l/h) and (G_{emax} = 16,70± 0,09 l/h) and (C_{Ge1}= 0,6653± 0,0440) and (C_{Ge2}=0,6552± 0,0504) **then the state is w_1^0**;

If ($\overline{M_s}$ = –1) and (M_s = –1) and (M_{s0}= –1) and (M_{si} = –1) and (n_M = 1) and (C_{M1}= 0) and (C_{M2}= 1) and ($\overline{Ge}$ =0) and (G_{eM} = 1) and (G_{emin} = –1) and (G_{emax} = 0) and (C_{Ge1}= –1) and (C_{Ge2}= 1) **then the state is w_2^0**;

Supplementary test aiming at higher certainty of diagnosis
If ($\overline{M_s}$ =133,54± 1,81 Nm) and (M_s =144,08± 2,33 Nm) and (M_{s0}= 113,04± 1,88 Nm) and (M_{si}=125,33± 1,80 Nm) and (n_M =3100± 83 rotations/min) and (C_{M1}=0,7846± 0,0115) and (C_{M2}=0,8699± 0,0130) and ($\overline{Ge}$ =15,11± 0,83 l/h) and (G_{eM} =17,77± 0,24 l/h) and (G_{emin} = 7,95± 0,19 l/h) and (G_{emax} = 20,94± ± 0,16 l/h) and (C_{Ge1}= 0,4473± 0,0186) and (C_{Ge2}=0,8485± 0,0328) **then the state is w_2^0**;

If ($\overline{M_s}$ =–1) and (M_s = –1) and (M_{s0}= –1) and (M_{si} = –1) and (n_M = 0) and (C_{M1}= 0) and (C_{M2}= –1) and ($\overline{Ge}$ =0) and (G_{eM} = 0) and (G_{emin} = –1) and (G_{emax} = –1) and (C_{Ge1}= 0) and (C_{Ge2}= 1) **then the state is w_3^0**;

Supplementary test aiming at higher certainty of diagnosis
If ($\overline{M_s}$ =132,78± 4,02 Nm) and (M_s =157,10± 4,47 Nm) and (M_{s0}= 121,46± 2,07 Nm) and (M_{si}=87,72± 7,35 Nm) and (n_M =2640± 67 rotations/min) and (C_{M1}=0,7731± 0,0681) and (C_{M2}=0,5584± 0,0363) and ($\overline{Ge}$ =14,80± 0,68 l/h) and (G_{eM} =14,98± 0,20 l/h) and (G_{emin} = 7,88± ± 0,07 l/h) and (G_{emax} = 18,08± 0,45 l/h) and (C_{Ge1}= 0,5263± 0,0154) and (C_{Ge2}=0,8281± 0,0363) **then the state is w_3^0**;

If ($\overline{M_s}$ = 1) and (M_s = 1) and (M_{s0}= 1) and (M_{si} = 1) and (n_M = 0) and (C_{M1}= 1) and (C_{M2}= 1) and ($\overline{Ge}$ =1) and (G_{eM} = 1) and (G_{emin} = 1) and (G_{emax} = 1) and (C_{Ge1}= 1) and (C_{Ge2}= 0) **then the state is w_4^0**;

Supplementary test aiming at higher certainty of diagnosis
If ($\overline{M_s}$ =187,76± 1,51 Nm) and (M_s =195,14± 1,53 Nm) and (M_{s0}= 184,33± 1,59 Nm) and (M_{si}=169,85± 1,98 Nm) and (n_M =2620± 39 rotations/min) and (C_{M1}=0,9446± 0,0054) and (C_{M2}=0,8704± 0,0205) and ($\overline{Ge}$ =18,89± 0,70 l/h) and (G_{eM} =17,83± 0,08 l/h) and (G_{emin} =13,07± 0,09 l/h) and (G_{emax} = 23,49± 0,08 l/h) and (C_{Ge1}=0,7328± 0,0121) and (C_{Ge2}=0,7591± 0,0123) **then the state is w_4^0**;

If ($\overline{M_s}$ =–1) and (M_s = –1) and (M_{s0}= –1) and (M_{si} = –1) and (n_M = –1) and (C_{M1}= 0) and (C_{M2}= 0) and ($\overline{Ge}$ =–1) and (G_{eM} = –1) and (G_{emin} = –1) and (G_{emax} = –1) and (C_{Ge1}= 0) and (C_{Ge2}= 0) **then the state is w_5^0**;

Supplementary test aiming at higher certainty of diagnosis
If ($\overline{M_s}$ =104,54± 1,32 Nm) and (M_s =111,07± 2,77 Nm) and (M_{s0}= 89,27± 2,33 Nm) and (M_{si}=98.02± 2,39 Nm) and (n_M =2460± 115 rotations/min) and (C_{M1}=0,8037± 0,0248) and (C_{M2}=0,8825± 0,0494) and ($\overline{Ge}$ =11,41± 0,58 l/h) and (G_{eM} =10,92± 0,08 l/h) and (G_{emin} =6,60± 0,12 l/h) and (G_{emax} = 15,29± 0,16 l/h) and (C_{Ge1}=0,6048± 0,0340) and (C_{Ge2}=0,7141± 0,0497) **then the state is w_5^0**;

If ($\overline{M_s}$ =–1) and (M_s = –1) and (M_{s0}= –1) and (M_{si} = 0) and (n_M = 0) and (C_{M1}= 0) and (C_{M2}= 0) and ($\overline{Ge}$ = 0) and (G_{eM} = 0) and (G_{emin} = 0) and (G_{emax} = 0) and (C_{Ge1}= 0) and (C_{Ge2}= 0) **then the state is w_6^0**;

Supplementary test aiming at higher certainty of diagnosis

If ($\overline{M_s}$ =153,50± 2,21 Nm) and (M_s =167,19± 1,24 Nm) and (M_{s0}= 127,22± 1,49 Nm) and (M_{si}=136,42± 2,93 Nm) and (n_M =2620± 32 rotations/min) and (C_{M1}=0,7609± 0,0086) and (C_{M2}=0,8159± 0,0165) and ($\overline{Ge}$ =15,99± 0,79 l/h) and (G_{eM} =15,34± 0,12 l/h) and (G_{emin} =8,36± 0,12 l/h) and (G_{emax} = 21,78± 0,11 l/h) and (C_{Ge1}=0,5451± 0,0090) and (C_{Ge2}=0,7040± 0,0135) **then the state is w_6^0**;

Probability of a accurate diagnosis is calculated on the basis of the following expression:

$$p_d = \frac{n_1}{n} * 100\% \geq p_{dgr} \qquad (6.5)$$

where: n_1 – a number of diagnostic parameters whose value is convergent with a value set for a given damage; n – total number of diagnostic parameters; p_{dgr} – boundary probability of diagnosis accuracy $p_{dgr} = 0{,}85$.

6.2. Method Verification

The method for diagnosing internal combustion engines with automatic ignition, based on torque measurement in traction conditions, has been verified using:

- tests of smokiness of usable engine fumes and at selected damages;
- traction tests of a vehicle with usable engine and with selected damages.

Accuracy of a diagnosis made in torque measurement method in traction conditions is an assessment criterion. Verification tests results allow for making a conclusion that diagnosis accuracy probability is above 85%.

7. SUMMARY AND FINAL CONCLUSIONS

Summing up this paper on **„Method for diagnosing internal combustion engines with automatic ignition based on torque measurement in traction conditions,”** the following should be stated:

1. analysis and assessment of existing diagnostic methods have been conducted and on the basis of which it has been found that there is a need to develop a new diagnostic method allowing for making a diagnosis of internal combustion engine in real road conditions and that may become applicable to both board and external diagnostic systems;
2. theoretical assumptions have been presented of a new diagnostic method the gist of which is vehicle acceleration process in traction conditions. A set of state parameters includes: engine torque Ms and hourly fuel consumption Ge;
3. algorithm for determining diagnostic parameters has been developed;
4. algorithm for research method structure and assessment of states of internal combustion engines with automatic ignition has been developed:
5. preliminary experimental research have been conducted under which the following have been realized:
6. primary experimental research in traction conditions have been conducted;
7. primary experimental research in conditions of engine and chassis test benches have been conducted:
8. a total uncertainty of torque measurement and fuel consumption have been estimated under the method for diagnosing internal combustion engine in traction conditions;
9. based on performed tests and analyses of their results, a three-variant 4CTi90–1 BE6 engine diagnostic model has been developed;
10. diagnostic models have become the basis for development of algorithms to make a diagnosis – assessment of a state and location of 4CTi90–1 BE6 engine damages;
11. research conducting conditions have been presented that guarantee maintenance of assumed probability to make accurate diagnosis;
12. the method has been verified on the basis of: a comparison of results to combustion fumes smokiness research results, and through tests of a vehicle with introduced damages in traction conditions. On the basis of verification tests it has been found that the diagnosis accuracy probability obtained in the course of verification is not lower than 85%.

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