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DIAGNOSTIC ASPECTS OF A CRANKSHAFT TORSIONAL OSCILLATIONS MONITORING BY IAS MEASUREMENT

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Abstract

Continuous monitoring of diesel engine performance under its operating is critical for prediction of malfunction development and subsequently functional failure detection. Analysis of Instantaneous Angular Speed (IAS) of the crankshaft is considered as one of non-intrusive and effective method of detection of combustion quality deterioration. The article contains presentation of attempt of monitoring of piston engine's crankshaft torsional vibrations by measurement of Instantaneous Angular Speed at free, and power output ends of the engine's crankshaft. The angular speed measurements was done using two optical sensors for reading the IAS, mounted at shaft line's opposite ends, one at free end of the crankshaft and second at end of generator's shaft. In the article is presented description of the measurement system and explanation of its mode of work. Experiments were based at two kinds of malfunction possible to be simulated at test bed. First one was simulation of a leak of fuel injection pump, the second one relayed on mounting of sets of injection valves with different nozzles characteristics (spraying nozzle angle), giving different parameters of fuel injection. Presented results of experiment derives from test cycle carried out using laboratory stand of Gdynia Maritime University equipped with 3- cylinder self − ignition engine, powering electric generator.

Keywords: *diagnostics, diesel engine, torsional vibrations, torque and angular speed.*

1. Introduction

Compression-ignition engines (CI) are ne of most critical machinery installed in power plants and electric plants of ships. Unpredicted failures or malfunctions of diesel engines can cause severe consequences. This is critical to mitigate unpredicted failures of engines to ensure safety of continuous operation and proper quality of engine's performance [1]. In internal combustion piston engines, reciprocating movement of pistons is converted to rotary movement of the crankshaft. The angular speed is strongly affected by tangential force coming from gas pressure and vertical imbalance inertial forces induced by reciprocating masses of piston and connecting rod. The character of acting forces let assume that IAS can be utilized for detecting engine faults related to combustion process [2, 4]. Because of sequential ignition in cylinders and differences of combustion quality (i.e. burning process's speed and duration, heat emission, pressure expansion) occurring between cylinders, angular speed of a crankshaft is not uniform. Variations of instantaneous angular speed value are reflecting level of unsteady character of subsequent pistons contribution [7]. Causes of engine failures can come from combustion related subsystems, such as the fuel injection system elements (injection valves, high pressure fuel pumps), inlet and outlet valves, tightness of combustion chamber, as well as non-combustion related systems including turbocharges, electronic control units, governors etc. All faults occurring in combustion related subsystems affect directly the combustion process and quality of engine performance parameters such torque and power [2, 5]. The most common and typical fault symptoms are misfire, low power output, excessive exhaust smoke, abnormal noise and vibrations [3]. In order to prevent or minimize probability of unpredicted failure occurrence, the operating state of an engine needs to be under monitoring procedure continually, what gives possibility of early stage diagnosis and deal with promptly enough to avoid more serious consequences in form of functional failure.

Working condition and performance of compression-ignition engines in general depends on combustion process. IAS signal directly reflects effect of various exciting torques associated with combustion dynamics [4]. Because of that, it can be used to diagnose combustion related faults. Optical IAS measurement of diesel engine has advantages of simple and convenient installation of encoders, long service life and reliable work, thus it is very promising to develop that technology for detecting failures of cylinder work condition [2].

2. Description of IAS measurement system and characteristics of the test rig

General idea of torsional vibrations observation relays on simultaneous measurement of the distance done at opposite ends of the shaft. Twist of the crankshaft is result of difference of the angular distance done by the two random points placed on shafts opposite ends circumference (see Fig. 1). In order to determine the differential value of the distance, simultaneous measurement of angular speed of both ends of the shaft is necessary. Value of angular shift at perpendicular plains is to be calculated by formula (1).

$$\varphi = (\omega_A - \omega_B) \cdot \tau, \qquad (1)$$

where:
ω_A, ω_B – angular speed of points A and B,
τ – time of single sample period.

Accuracy and reliability of measurement depends on relation between torsions frequency and sampling frequency. In the worst case, torsional changes can take place in the time between subsequent samples and torsion will not be detected.

In order to mark the position of the disc in correspondence to the crankshaft position, the trigger in a form of one additional window (slot) narrow and asymmetric is to be placed in the zone of one tooth. That slot has to be placed at position "cutting" laser ray when piston in first cylinder is in TDC (Top Dead Centre). It lets allocate every part of IAS record to crankshaft angle and specific cylinder, what is absolutely necessary for further diagnostic analyses.

The angular speed calculation depends of number of windows around the disc, and it can be presented in form of formula (2).

$$\omega = \frac{\frac{2\pi}{w}}{i \cdot f} \left[\frac{rad}{s}\right], \qquad (2)$$

where:
ω – angular speed,
w – number of pairs "window-tooth",
i – number of impulses register for pair window-tooth,
f – frequency of laser emitter.

Mounting of the discs and measurements heads are presented in Fig. 1 encoder, and makes reference for time counting. The angular speed of the second one B, in "slave" position, was calculated using time interval determined by master disc. It was assumed that basic measurement sample is a pair of slot- tooth, and number of impulses registered for such pair is the base of time calculation.

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In presented system, the disc A mounted at free end of the crankshaft plays the role of "master"

It was assumed, that basis for angular displacement calculation shall be the time of displacement of "master" disc A, and formula of the angular shift distance is:

$$\phi = (\omega_a - \omega_b)\tau_A. \tag{3}$$

Of course that mode of thinking is correct only for first pair, repetition of the way for second pair slot- window, subsequent calculation must take under consideration already done angular distance and is described by formula:

$$\phi_n = \sum_{i=1}^{n}(\omega_{Ai} \cdot \tau_{Ai}) - \sum_{i=1}^{n}(\omega_{Bi} \cdot \tau_{Ai}). \tag{4}$$

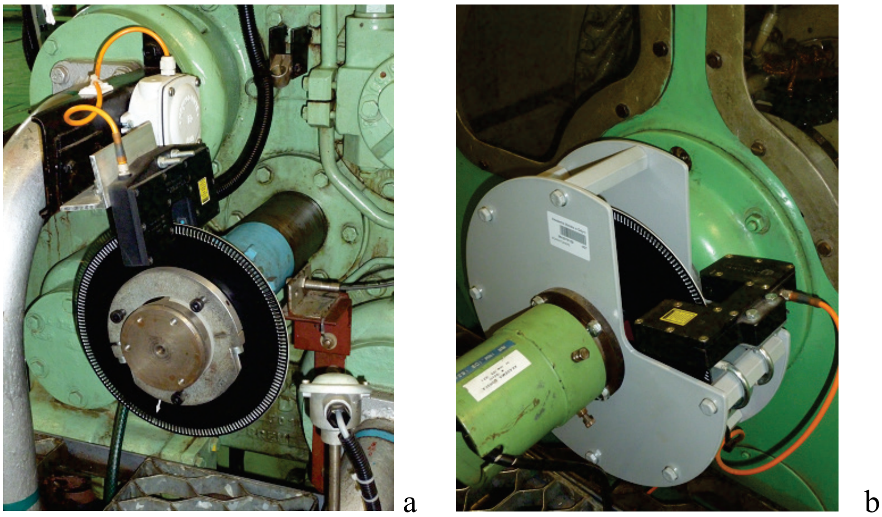

Fig. 1. Master disc A mounted at engine's free end (a) and sleeve disc B mounted at generator shafts end (b)

Above formula, provide us with data set containing number of i values of angular shifts between shaft ends in domain of crank angle, what is the measure of torsional twist. In order to verify implemented formula of distance calculating, one has to compare total distance of disc run after 90 slots and multiplication. Both ends of the shaft must do the same angular distance minus value of instantaneous torsion. Above was verified and proved during experiment, and gave correct results.

3. Description of experiment assumptions and measurements plan

First part of experiment was focused on detection of fuel delivery malfunction. Typical problems in exploitation are leakage of high-pressure piping or wear of high-pressure pump pistons. As result of above problems, not sufficient dose of fuel is delivered to a fuel valve. Such situation causes deterioration of combustion process, changes of gas force maximum value and mean effective pressure. Deviations of gas force run must affect instantaneous value of torque and obviously must have impact at torsional vibrations of a shafting. In order to detect potential changes, series of measurements under normal conditions and with simulated failure of fuel pump were conducted. Malfunction of fuel system was simulated in way of creating controlled leakage from fuel pump responsible for delivery to cylinder number two. Second approach to examination of detection possibility was based on application of two different fuel valves, with different construction of nozzles. One set of valves with 9 holes in nozzle and 150° angle of spraying holes, the second one had 8 holes in nozzle and 158° angle of spraying hole. It was assumed that different parameters of fuel delivery have to affect parameters of combustion and to cause different runs of force value during working stroke. If would be possible to detect and evaluate deviation caused by such changes, is obviously possible to detect malfunction of injection valves related to clogging of nozzle's holes or improper fuel injection pressure.

Records of torsional vibrations are presented as function of instantaneous value of torsion angle φ in domain of a crank position. In Fig. 2 is presented example of torsion record encompassing four subsequent revolutions what is two working cycles of four-stroke engine. Raw signal is quite sharp, but even before smoothing, three peaks of torsion reflecting contribution of every one from three cylinders can be spotted (see Fig. 2).

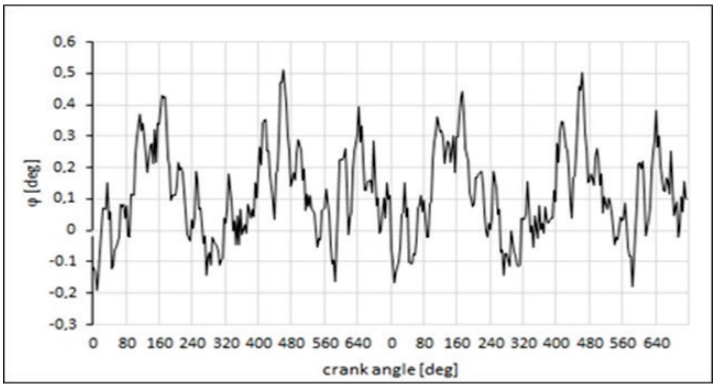

Fig. 2. Raw signal waveform of torsional deflection encompassing two cycles (4 revolutions of a crankshaft)

Raw signal after smoothing by Savitzky – Golay filter gives much clearer picture. In Fig. 3, torsional vibration after filtration is presented. Angular position of each peak and value of the magnitude can be easy observed. Such picture let us make preliminary evaluation of gas force quality in every cylinder (Fig. 3).

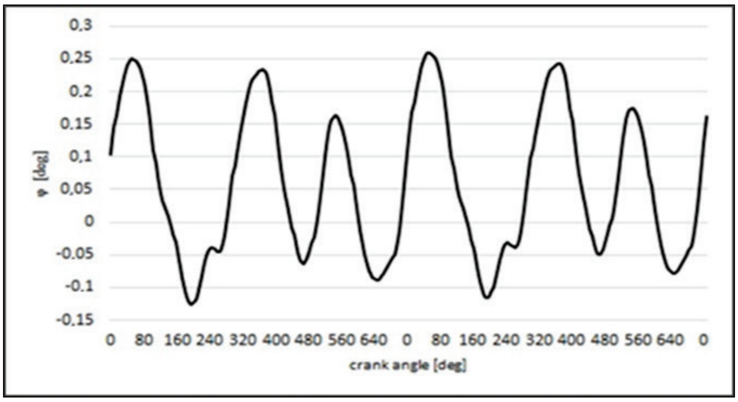

Fig. 3. Waveform of torsional deflection after smoothing by Savitzky – Golay filter

3. Influence of revolutionary speed at torsional vibrations spectrum

Much more information is included in FFT spectrum of torsional deflection's run. The engine used for experiments is generator's mover, thus its basic rotational speed is 750 rev/min for 50 Hz current frequency. In test, bed is possible to set up different revolutionary speed from range of 650 to 750 RPM and rotational frequency from 10.82 Hz – 650 rev/m to 12.5 Hz – 750 Hz. Assuming different torsional behaviour at different revolutionary speed, subsequent experiment was carried out. Keeping constant load of generator, rotation of the engine was set up at three different levels, 650, 700 and 750 rev/ min. In all cases, run of torsional deflection was different, what was detected after spectral analysis of basic orders. In Fig. 3 are presented spectra of magnitude of harmonics in range of 50 Hz of raw signal for 650 RPM and 700 RPM Can be observed different values of magnitude, especially in frequency brackets up to 25 Hz. That observation is in accordance with diesel generator's technical documentation, where is stated that higher magnitude of harmonics occur when engine is running 700 RPM due to approach to resonance frequency.

In order to get cleaner picture of harmonics, values of magnitude of orders number 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4 were separated. In Fig. 4 are presented torsional magnitudes of harmonic orders recorded during engine run with revolutionary speed of 650, 700 and 750 RPM Picture shows, that order number 1,5, related to contribution of three cylinders during the cycle has highest magnitude for 700 RPM and lowest for 750 rev/min (dedicated for normal exploitation). Those results are according to expectation, and confirm reliability of the measurement method.

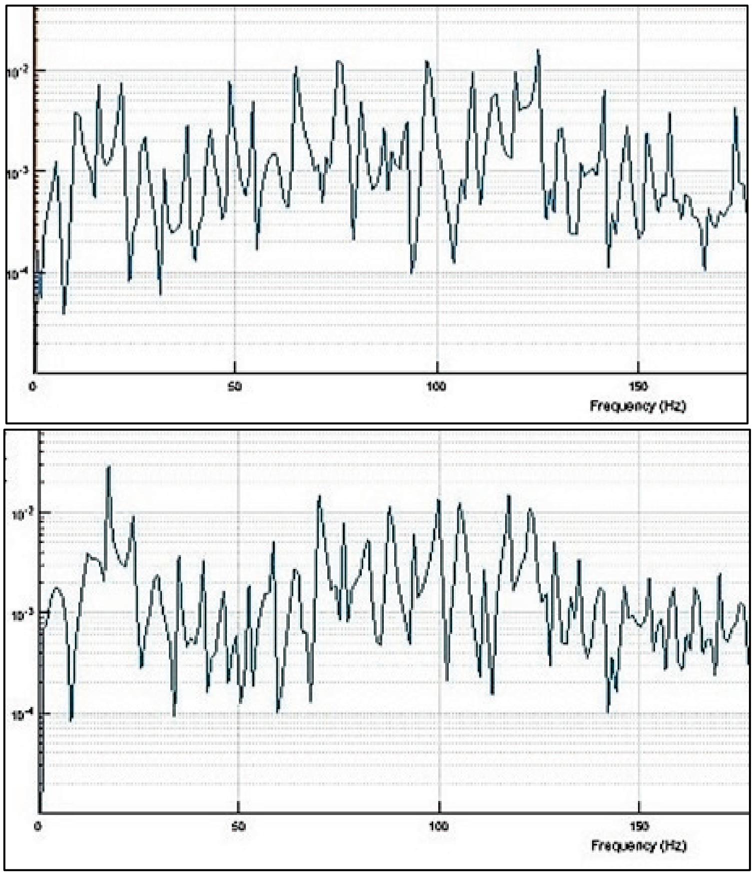

Fig. 4. Harmonic Spectrum of torsional deflection's raw signal, a − 650 RPM; b – 700 RPM

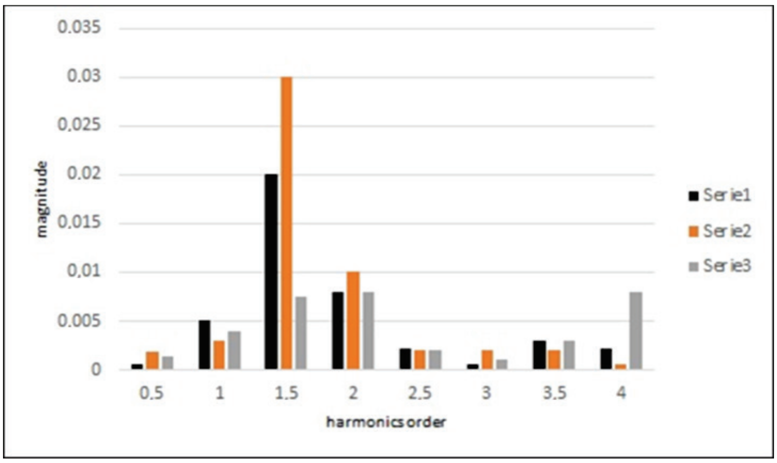

Fig. 5. Harmonic spectrum of torsion of 650 rev/min [serie 1], 700 RPM [serie 2] and 750 RPM [serie 3]

4. Influence of fuel injection pump leakage at torsional vibrations

Very interesting results coming out from comparison of harmonics spectra obtained after FFT of torsional vibrations registered with simulation of fuel leak from injection system and run of engine in proper condition. In that case, magnitudes of order number 1.5 are equal, but magnitudes of order number 0.5 were different. Magnitude of run with malfunction has much higher value in comparison with healthy engine run. That effect can come out from typical reaction of speed regulator which role is to keep constant speed. When one cylinder contribution drops, system provides higher fuel dose for other cylinders, what results with higher gas force and increase of torque. FFT spectrum does not give answer what is number of affected cylinder, but detection is possible after analysis of IAS waveform. It means that malfunction of one cylinder was detected (Fig. 6).

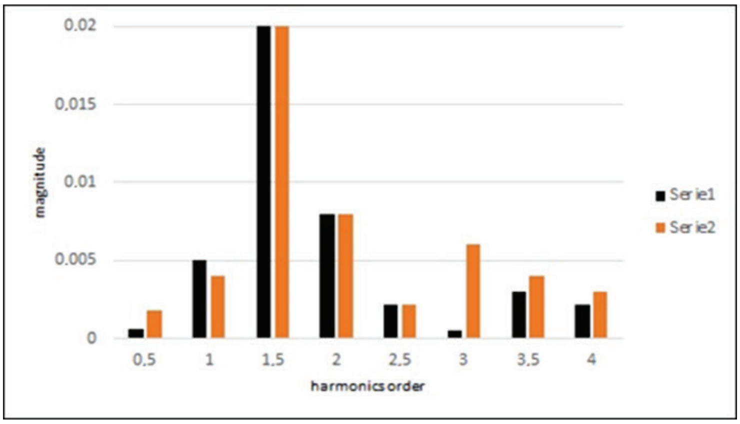

Fig. 6. Harmonic spectrum of torsion; healthy engine [serie 1] and malfunction of injection [serie 2]

5. Impact of injector nozzle construction at torsional vibration

The experiment based on confrontation of torsional vibrations being measured at different load levels repeated for two types of injectors. Measurement started from level of 65% of nominal load, and subsequently 70% and 75% was set up. First part of experiment was carried out after installation of injectors with 9 spraying holes and holes angle 150°. After warming up, engine was set up at planned load levels and 5 subsequent records were done for each load. The procedure was repeated after installation of second type of injectors, with 8 spraying holes and angle of 158°. Obtained results were interesting and quite promising as subject for further investigation. At low level of load, different runs of torsion waveforms in domain of crank angle were observed. For better comparison, results of measurements, after filtration, were presented as function of deviations from mean value of cycle. It enabled avoiding errors due to phenomenon of waving of torsion waveform with low frequency due to speed governor action. Different maximum value and slight shift between peak position occurred for all three cylinders (see Fig. 7). Comparison of waveforms in way of differential value in crank angle domain shows differences at level close to maximum torsion. That behaviour of function is observed always when shift of peaks phase occurs. Above observations let assume, that different angle of spray holes and its number changes condition of combustion strong enough to be transferred to the shaft.

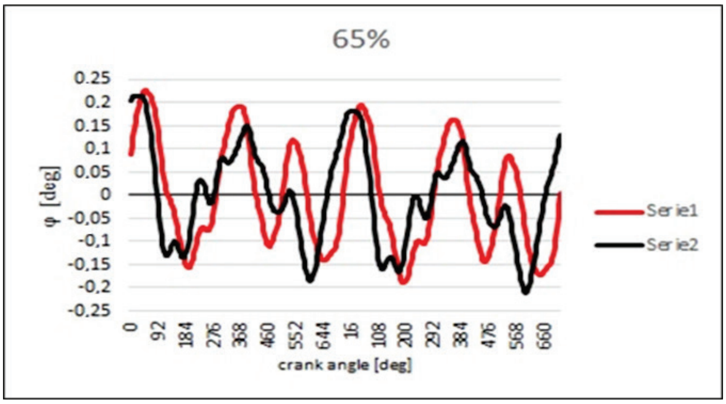

Fig. 7. Comparison of oscillation, load 65%, injector with 9 holes (serie 1), injector with 8 holes (serie 2)

Increase of load up to 75%, resulted with significant transformation of waveforms relations. Level of correlation is very high, phase shift between peaks disappeared, and only differences between maximum values can be spotted. It means that at higher load impact of nozzle construction descends. Subsequent rise of load up to 75% of nominal almost eliminated differences between waveforms.

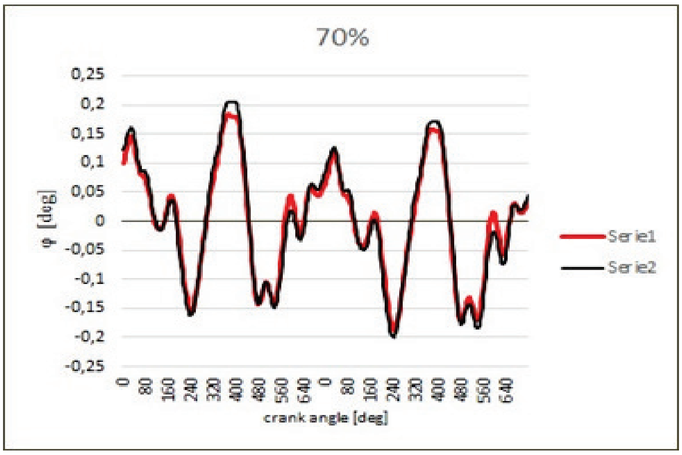

Fig. 8. Comparison of oscillation, load 70%, injector with 9 holes (serie 1), with 8 holes (serie 2)

Increase of fuel dose injected in cycle and dynamics of combustion caused elimination of differences between gas force creation process, so eventually differences are too weak to be reflected by crankshaft torsion (Fig. 8).

In Fig. 9 are presented waveforms of differential value of torsion recorded with two types of injectors at loads implemented for experiment. It is obvious that rise of load is eliminating differences between dynamics of torsional reaction of the shaft, due to combustion parameters.

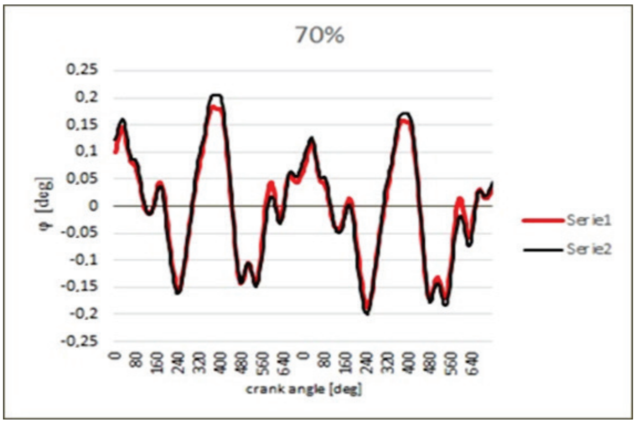

Fig. 9. Waveform of differential comparison of torsional magnitudes caused by number of injector holes; load 75% − serie 1, 70% serie 2, 65% − serie 3

6. Summary

Proposed method of torsional deviations measurement is very convenient due to easy way of mounting of measurement system elements, simple and not expensive construction, high durability and reliability. Data processing is not complicated and can be proceed with MS Excel program. High frequency of laser emitter gives high level of accuracy and ensures broad range of implementation, according to evaluation calculations; system is effective up to 4000 RPM what cover all ranges of diesel engines. Presented results seem to be very promising. Possibility of detection of fuel system malfunction will be very important tool for diagnostic prediction. Results obtained during experiment with different injectors nozzles, gives interesting information about accuracy of the method. Possibility to detect the difference between torsional vibrations caused by installation of two types of nozzles, let assume that other deviations or disturbances related to combustion process can be detected.

Proposed method seems to be good tool for verification of various kind of theoretical models simulating malfunction of diesel engines.

Further steps of method's development shall be directed to proof obtained results by repetition of experiment under various outer condition. It is absolutely necessary to define impact of atmospheric pressure, humidity and temperature at torsional deflection waveforms. Discovering straight relations between registered torsion variations and engine malfunctions, one is creating reliable basis for formulation of diagnostics conclusions.

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