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EVALUATION OF OPERATION IN PISTON–CON–ROD SYSTEM OF SHIP PROPULSION ENGINE ON THE BASIS OF HARMONIC TORQUE

Jan Rosłanowski, Adam Charchalis

Gdynia Maritime University
Morska Street 83-87, 81-225 Gdynia, Poland
e-mail: rosa@am.gdynia.pl, achar@am.gdynia.pl

Abstract

The following paper has been confined to evaluation of correctness of piston–con–rod system of main engine, on the basis of momentary value changes, measured on the propulsion shaft, caused by decreasing of fuel dose delivered to cylinder until its cut-off. It has been assumed that the engine does not meet requirements if the cost of using it is higher than the outlay or if the engine does not ensure the safety of the ship. At specified external conditions, the load of combustion engine is determined unmistakably by means of two parameters: rotational speed of the engine and the torque. The torque is measured on few ships only and for this reason the position of the injection pump indicator is used as the engine coordinate. This way of qualification of the engine point of work is not precise. The loss of efficiency in one piston – con – rod unit can cause a decrease of the torque developed by the engine. As a result of this, one can establish a new point of engine cooperation with the propeller on the propeller curve at unchanged terms of outside load. It causes a decrease of engine rotational speed which is, however, brought back to the previous one by the governor. Reaction of the engine governor consists in an increase of a fuel dose of injection pumps which, in turn, causes overload of its remaining units. Operation diagnostics of piston – con – rod system of ship propulsion engine, while analysed on the basis of torque momentary values, enables us to control the quality of its operation. It also prevents the engine from getting overloaded in the ship propulsion system, and at the same time increases the safety of its exploitation.

Keywords: *diagnostic procedure based on the torque measurements on ship propulsion shaft, frequency of ignitions in engine cylinders, inertia forces of elements mass of piston – con – rod system*

1. Introduction

Momentary values of the turning moment are a leading parameter, because of effectiveness state identification of propulsion engine operation. Diagnostic procedure based on the torque measurements on a ship propulsion shaft analyses dependences of their values on a technical condition of the engine, and on this basis makes a diagnosis [1, 6].

The knowledge of the torque during engine performance allows to prevent engine overload or its respective cylinders.

The torque meters of low time constants, measure momentary values of the turning torque. Momentary values of the torque make random realizations during state work of the engine of sinusoidal character. These realizations have a constant amplitude equal to medium value of the torque and a constant frequency defined by frequency of ignitions inside engine cylinders (Fig. 1). Frequency of ignitions in engine cylinders does not depend on the size of amplitudes or signal phases but it is connected with a rotational speed of an engine. As shown in papers [2, 6, 7] it does not depend on external conditions of sailing either. Sailing conditions cause an increase of amplitude at unchanged frequency. Defined rotational speed of torsional vibration amplitude, depends on the value of contact forces which generate these vibrations and due to this fact, they include information about the course of gas forces in particular cylinders.

The influence of respective cylinders on the torque values is not identical and depends on cylinder position in relation to vibration centre of observed form [3, 8]. Unequal combustion pressures cause the appearance of the first from vibrations.

It can be visible in a distinctive way in case, when one cylinder is out of combustion. The course of momentary values of torque is influenced by such quantities as: speed of escalation pressure in engine cylinder, its load, rotation speed and the moment of friction taking place in piston – con – rod system.

Momentary values of the turning moment are caused, on the one hand, by pressure of gases, and on the one other hand, by inertia forces of elements mass of piston – con – rod system. Medium moment coming from one cylinder is only a small fraction of maximal turning moment that rises during working stroke.

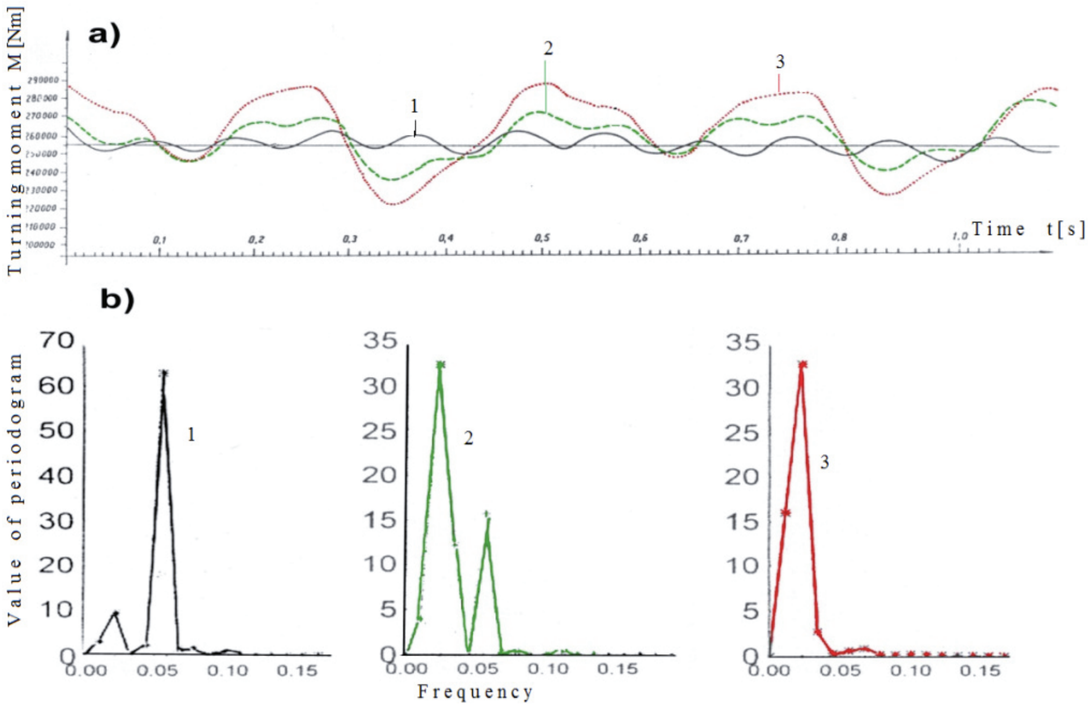

Fig. 1. Changes of momentary values of the torque during different amounts of injected fuel into two-stroke cylinder of the ship in its steady motion. Explanations: a) measured every 0.02 s values of the torque of Sulzer 5 RD 68 engine on the propulsion shaft of the ship, b) Fourier transform presenting frequency structure of momentary values of the engine torque: 1 – during undisturbed time of engine running, 2 – during fuel drop by way of deaeration of the injector, 3 – complete absence of fuel injection into engine cylinder

Courses of contact force when operating five cylinder engine in presence of different computer simulations of combustion disturbances in its respective cylinders, is shown in Fig. 2. Computer simulation were carried out by means of calculation sheet of Microsoft Excel programme. Simulations show that even small changes in operation of one cylinder, influence negatively the operation of the whole engine.

Greater number of engine cylinders allows only to diminish the result of faulty operation of one of them, because the remaining ones take over the operation. It is dangerous for the engine as it causes an additional load of the hull, foundation, crank bearings and the main ones.

Analysing changes of the whole engine operation during its normal performance can be difficult. It is caused by the fact that in the engine of five cylinders, faulty operation of one cylinder is made up for by other respective cylinders. This, however, affects negatively technical condition of the whole engine. In case of multi-cylinder engines, the influence of inefficiency of one cylinder on the components of the torque is concealed by the components of the remaining systems of the engine. The concealment level rises together with an increase of the cycles realized by the engine during one rotation of the crankshaft. In spite of concealment influence and many factors disturbing measurements of momentary values of the torque, they can be used in order to achieve diagnostic aims [1, 5, 6].

The harmonics of torque momentary values allows to recognize the piston–con–rod system of a multi-cylinder engine that works incorrectly with phase orientation, by means of, the marker indicating the position of the crankshaft. Using momentary value course of the turning, torque has the following advantage. Information about the work of all engine cylinders is concentrated in the course of one quantity which can be measured by means of one measurement system. In order to determine the torque of the engine it is necessary to measure the torsion angle of the ship propulsion shaft. This measurement can be realized by means of tensometric or optical sensors.

The information about a technical condition of the ship propulsion engine included in momentary values of the torque, is coded and cannot be read directly from measurements.

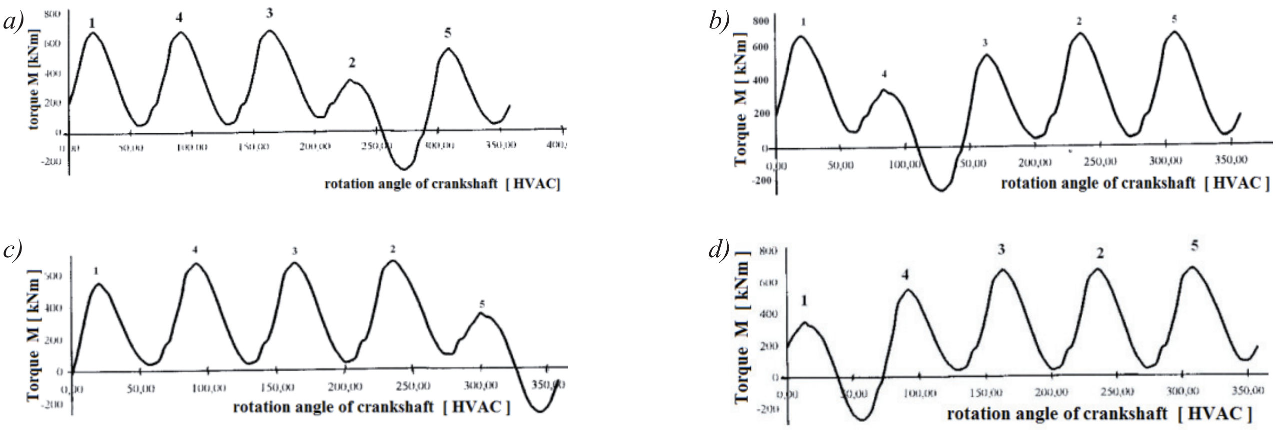

Fig. 2. Computer simulations of torque momentary values during operation disturbances of one cylinder in two-stroke, five cylinder engine. Explanations: a) lack of fuel combustion in cylinder 2, b) lack of fuel combustion in cylinder 4, c) lack of fuel combustion in cylinder 5, d) lack of fuel combustion in cylinder 1

For this reason the proposal of harmonic analysis of engine torque values measured in short moments of time, as a diagnostic method of its technical condition, is an adequate diagnostic tool. Such tool allows, on the basis of momentary changes of the torque, to draw a conclusion about the operation correctness of the engine's piston-con-rod systems and its respective cylinders.

2. The harmonic of the torque on the ship propulsion shaft during steady running of the engine

The operation of two-stroke piston combustion engines which are mainly used to feed power to the cargo ships, brings about the appearance of the harmonics of only total order during the torque. The reason of the above are periodical changes of the torque in accordance with duration of working stroke, that means, every two rotations of the shaft. The torque caused by gas pressure is positive, which is the reason why the second harmonic of the torque originating from gas pressure, is always directed contrary to the second harmonic of the torque inertial force [3, 4, 8].

Maximal values of the first three harmonic of the torque are more than twice higher than its medium value. On the other hand, the participation of higher harmonics of the torque decreases with their grade (for the 18^{th} harmonic it is of minor importance) [4, 8].

Every harmonic of the engine torque will cause forced vibrations of the propulsion shaft of the same frequency. Therefore the moment on the propulsion shaft has the same harmonics number as the engine torque. Most of those harmonics have frequency distant from the frequency of the shaft itself, which is the reason why adequate amplitudes of frequency are so little that they can be disregarded. With the exception of such situations where the frequency of one of torque harmonic is exactly the same as their own frequency.

Ship propulsion system is influenced by many forces and moments coming from the engine, propeller, bearings and the unbalance of shaft and propeller. Propulsion system is influenced by torsional vibrations because it constitutes the system of considerable inertia. It has a few frequencies of its own, dependent on a number of vibrating masses, so called, forms of own vibrations.

The first vibration form of the lowest own frequency has one centre of vibrations, that is one place remaining at rest. The second form of vibrations has a frequency higher than the first one and two centres of vibrations etc. [3-5].

Figure 3 shows the position of vibration centres of the first forms for the ship propulsion system with a long shafting (a) and the position of the centres of torsional vibrations for the ship's engine without shafting (b), also distribution of relative values of the torque. In the centres of torsional vibrations, the amplitude is of the lowest character and the contact stresses reach maximal values. The position of propulsion shaft in the vibration centre, undergoes torsion, being affected by the forces of the engine. Vibrations of the first form cause big stresses of intermediate and propeller shafts and minimal stresses of the crankshaft (Fig. 3). Vibrations of the second form cause stresses of the crankshaft and minimal ones of intermediate shaft with angle displacement of the propeller, almost equal to zero [1].

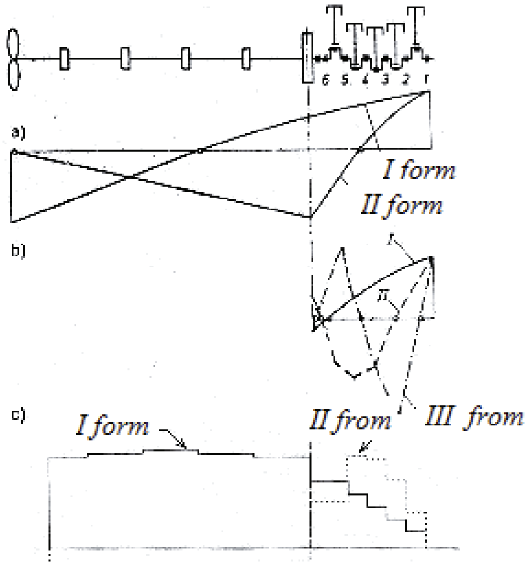

Fig. 3. Position of torsional vibrations centres: a – for ship propulsion system with a long shafting, b – for the propulsion engine , c – distribution of relative values of the torque [1]

The performance of the engine has a decisive influence on the frequency of vibrations. Forced actions of the engine come from the power of gas pressure in cylinders, dependent on heat generation in the combustion process. Heat generation in the engine is of random character determined, on the one hand, by the course of fuel injection and on the other hand, by a series of factors connected with forming of combustive mixture and kinetics of chemical reactions of combustion. It influences changes of pressure and temperature in cylinders and quantity of internal work transferred to the piston, also the level of thermal and mechanical load of the engine.

The best parameter describing technical condition of the engine is the quantity of useful work produced during heat generation in cylinder, which can be measured by momentary values of the torque [2, 6, 7].

In case when one of the cylinders performs work of a different value than the remaining ones, it means a change of combustion pressure course and the change of the torque friction.

Forced actions affecting the propeller come into being as a result of pressure pulsation on the blades of the propeller and non-uniform water flow during blades passing through hydraulic cross-section area of the propeller. These forced actions are of random hydrodynamic character of periodical course equal to multiple number of propeller blades. The propeller is affected by the following moments: propulsive and a damping one of inflowing water.

Resisting moment of the propeller is defined by hydrodynamic characteristics. While a damping moment is caused by changeable speed of inflowing water on the propeller, induced by the change of characteristics of the hull flow round and wavy motion of the sea. Forced actions originating from the unbalance of the shaft and propeller change at the frequency equal to rotational speed of the shaft. Those forced actions, with the exception of emergency cases like breaking loose of the propeller blade or twisting of the shaft, are really not big and can be disregarded. In propulsion systems of the ships with piston engines, only two elements induce considerable torsional vibrations that is the engine and the screw propeller. Vibration frequency of these elements is situated in remote ranges, in case when the number of cylinders and propeller blades is not similar or divisible. It means that the forced actions coming from elements of ship propulsion system different than the engine propeller, countershafts, flying wheel have a minor influence on the changes of momentary values of the engine's torque.

Forces of gas pressure and inertia change periodically and the change period of inertia force is equal to one rotation of the shaft. They have an essential influence on vibrations of the first six main harmonics because they are the effect of reciprocating motion of the piston and the part of connecting rod (so called mass of stroke). Contact forces extorting torsional vibrations of crankshafts cause momentary acceleration or retardation of the shaft in its rotational motion and recur periodically the curve of contact forces indeed recurs periodically but within the range of one period and depending on the type of an engine, is of much varied course. The course of the contact force is of periodical character but not harmonic. The influence of contact forces on torsional vibrations of propulsion shaft, one can analyse by means of fast Fourier transform

(FFT) of momentary values of the rotation moment [6, 7]. In pistons engines for one changeability period of contact force, falls one period of the first harmonic, two periods of the second one, three periods of the third etc. Adequately to this, the frequency of the first harmonic is two times lower than the second, three times lower than the third etc. Frequency of the first harmonic equals to angle speed of the crankshaft in two stroke engine.

In two stroke engine, heat generation proceeds during one crankshaft rotation, so harmonic order is equal to numbers of contact forces, taking place in the cranks of engine crankshaft.

The rotational moment from inertia forces which can also be involved in torsional vibration, can be divided into four harmonics [1, 3, 4]. Inertia forces do not affect incomplete harmonic orders (0.5, 1.5,…) because their period encloses one rotation of the shaft.

Because for a defined rotational speed, amplitudes of torsional vibrations depend on the values of contact forces, which generate these vibrations, so they include information about the course of gas forces in respective cylinders. The influence of particular cylinders is not identical and depends on cylinder position towards the vibrations centre of the form under observation [1, 3–5, 8].

To achieve diagnostic aims, it is enough to examine the spectrum presenting the frequency structure of standardized momentary values of the torque. Developing periodical function of torque into Fourier series, one can achieve its harmonic distribution, the frequency of which, is a multiple of basis frequency [6].

3. Harmonics determination of the torque of ship engine propulsion shaft as symptoms of piston – crank system correctness of operation

To analyse harmonics of torque momentary values, one can take advantage of the spectrum achieved by means of fast Fourier transform, so called, FFT method. Elementary distributing frequency of such spectrum depends on the number of samples, by the help of which, one can present temporal course of torque momentary values [6].

Values of the torque on the ship propulsion shaft were measured in order to determine spectrum of propulsion engine torque. The propulsion engine, under examination, was a two-stroke, five cylinder engine of ignition sequence 1-4-3-2-5 of the Sulzer firm 5 RD 68. After the measurements had been carried out, it was possible to state that the analysis of frequency band of the torque signal up to 50 Hz and distributing ability up to 0.5 Hz, allows us to isolate and determine precisely harmonic components connected with heat generation process in cylinders during steady work of an engine.

Figure 4a shows courses of momentary changes of torque values during normal work of the engine, measured on the propulsion shaft, by means of tensometric torque meter. During one rotation of the propulsion shaft it is clearly visible that there are five forced actions coming from respective cylinders. Having known the sequence of ignitions in respective cylinders and in what cylinder we measure pressure, it is possible to identify these forced actions caused by a cylinder. Measured momentary values of the torque reveal lower harmonics in the spectrum, with the exception of the dominant of the fifth order (Fig. 4b). Measured on the shaft, irregularity of the curve course of the torque during one rotation is caused by non-repetition of injection that means, by a random process which causes different pressures of combustion in the engine.

On the basis of the analysis of torque momentary values on the ship propulsion shaft, it was found that little changes of combustion pressure in respective cylinders are clearly visible in the course of the torque curve.

To state the influence of disturbances in heat generation process in engine cylinder on the spectrum of torque momentary values, fuel from injector was dropped by gradual opening of the air value.

The above mentioned experiment, allows us to state that by dropping 14.3% of fuel dose delivered to one cylinder, the harmonic of second order started to dominate in the spectrum of the torque, with a considerable of the fifth harmonic [6, 7] (Fig. 5).

With an increase of fuel dropped from the injector, the fifth harmonic started to disappear in the torque spectrum. Because of disturbances in heat generation process, the combustion in cylinder becomes non-cyclic. In this situation, mass forces start to dominate in cylinder, and together with gas forces cause an unbalanced torque.

Governor operation of rotational speed of the engine causes the following situation. When in case of faulty operation of one or more cylinders, the remaining cylinders have to deliver more energy to obtain required rotational speed and the moment assigned to these rotations, demanded by the propeller, there follows a change, among others, of fuel dose necessary for one rotation in particular cylinders, pressure of combustion and the course of injection. One can observe in these correctly functioning cylinders, a considerable increase of combustion pressure in relation to nominal value.

a) b)

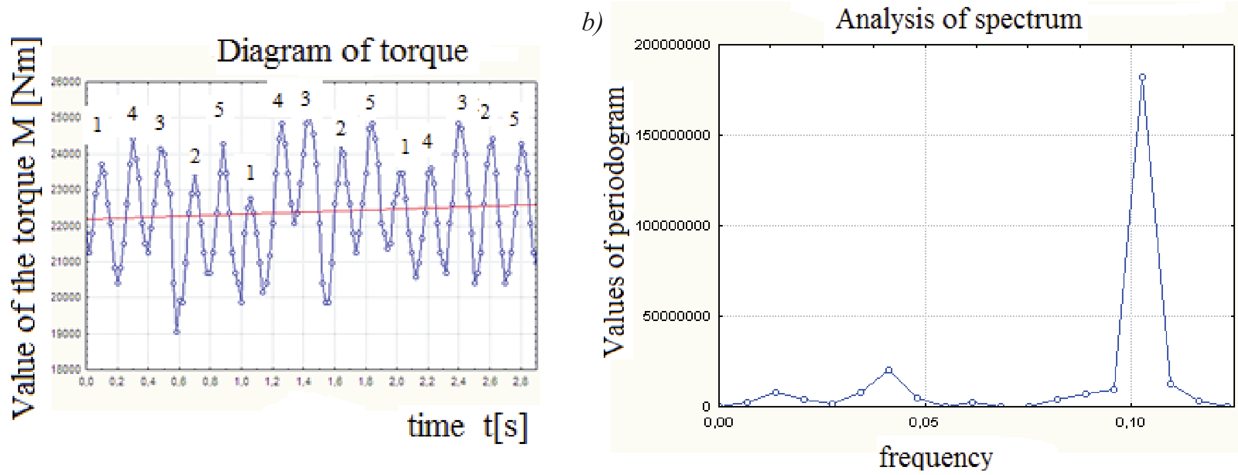

Fig. 4. Measured values of the turning moment on the propulsion shaft of five cylinder in two-stroke engine in moments of time every 0.02 s during ship's voyage: a) during three rotations of crank; b) the spectrum of the engine torque for three rotations of the crankshaft. Explanations: numbers in Fig. 4a designate the sequence of ignitions in engine cylinders

Random process of heat generation in engine cylinders causes different pressure of combustion, which can be visible in engine torque spectrum of lower harmonics (Fig. 5). They are of wide-band character of random noise with a little coefficient of asymmetry close to normal [6, 7].

a) b)

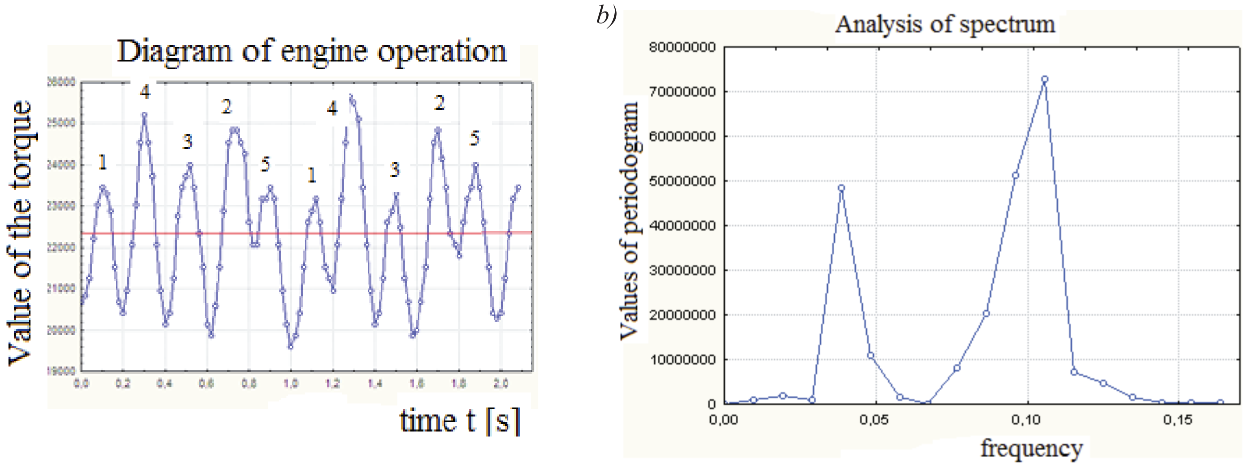

Fig. 5. Measured values of the torque on the propulsion shaft of five cylinder, two-stroke engine in temporal moments, every 0.02 s during ship's voyage with a decrease of fuel dose delivered to the first cylinder: a) during two rotations of crankshaft, b) torque spectrum of the engine for two rotations of the crankshaft. Explanations: numbers in fig. 5a designate the sequence of ignitions in engine cylinders

An extreme case of getting the cylinder out of operation by a complete drop of fuel from the injector, causes in engine torque spectrum, domination of only second harmonic with a distinct influence of the first one and a complete disappearance of the harmonic of the fifth order (Fig. 5b).

Domination of harmonic component in spectrum of the engine torque, next an increase of the first amplitude and the second harmonic function of the amount of dropped fuel from the injector, are connected with an increased participation of unbalanced gas forces.

With a considerable disturbance in heat generation process in cylinder, mass forces start to dominate. These mass forces together with gas forces cause an unbalanced operation of the engine.

4. Conclusions

Frequency analysis of torque momentary values measured in very short time reveals uncorrectness of piston-crank system operation.

It allows us unmistakably to expose basic diagnostic symptoms in the spectrum structure of torque momentary values on the shaft with operational, rotation speed of the propulsion engine, three spectral components: the first, the second and a harmonic one of the order equal to the engine ignitions amount.

Immediate possibility to discover operation uncorrectness of piston-crank system and evaluation of its size, on the basis of frequency structure of momentary torque values, allows us to prevent the results of faulty heat generation in engine cylinders.

Operation diagnostic of piston-crank system, on the basis of frequency analysis of momentary torque values, enables us to carry out a fast quality control of their operation.

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