ESTIMATION OF COMBUSTION PROCESS IN CYLINDERS OF DIESEL ENGINE BASED ON ITS WORKING ACHIEVEMENTS

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Abstract

Elements of Modern ships' main combustion driven engines are subject to immense heat and mechanical loads. It is therefore advisable to supervise the regularity of heat generation in engine's cylinders. In order to diagnose the process of heat generation in engine's cylinders, this article propagates the use of momentmetre. Described method allows estimating faulty combustion on the basis of autocorrelation of moment temporary values on the shaft after three successive rotations.

The paper brings to attention how the work of diesel engine may be used for estimation of combustion process correctness in this engine cylinder. The work of diesel engine is connected with transfer of effective energy to ship propeller during its operation. Due to accidental nature of combustion inside engine cylinders it stochastic internally stationary process. To say more it is stochastic internally stationary process with ergodic feature. It makes possible to describe expected engine work by means of stochastic second order characteristics. They are autocorrelation functions and spectrum density of self power functions depending on time and frequency. Both above mentioned functions are uniquely connected with combustion in engine cylinders and it is possible to estimate the correctness of engine operation. It is also possible to estimate if the work of engine in given sail conditions is equal to requirements of imposed tasks. If this requirement is not met in the case of one propeller ship it can lead to the loss of ship stability and as a result can cause the ship sink.

Keywords: *stochastic process of engine operation, energy transformation, periodogram of engine operation, diagnosis of heat generating process in engine cylinder.*

1. Introduction

Assurance of safe ship operation requires from the propulsion engine very high performance, dependent however on sailing conditions. Therefore during ship operation propulsion engine requires most active participation of people and continuous control. Propulsion engines on account of their intricate and complicated construction, high level of thermal load and many other factors are exposed to a variety of failures estimated at 38% in relation to 46 ships during five year period [6].

For this reason it seems right to control connect ness of the engine operation which consists in conversion of chemical energy, contained in fuel, into a mechanical one by means of thermal process taking place in its cylinders. Heat generating process in the cylinder of combustion engine takes place when the cylinder is filled with load of fresh air followed by injection of fuel and then burning fuel. Thermal exchange between working medium and cylinder walls during movement of the piston (volume changes) was connected.

In connection with the above, engine operation understood as energy release at a definite time can be assessed. This assessment consists in comparison of engine operation with dimensional physical quantity of measurement unit called by J. Girtler in his works [1-3] Joule-second.

Besides conversion of energy, should be independent of all kinds of sailing conditions. This means the propulsion engine operation must be so good as not to fail fast because of thermal or mechanical overload. In case of single engine propulsion unit the break-down of an engine can cause the loss of directional or transverse stability by the ship what in most cases ends up in a catastrophe [3].

2. Ship propulsion engine performance as the energetic reaction with the environment in the form of work and heat

Operation of ship propulsion engine can be considered in time in which it carries into effect expansion of combustion gases in cylinders during stroke of work [1-3]. About the same time one can witness transformation of chemical energy contained in fuel into mechanical energy through generated heat in engine cylinders. Mechanical energy generates the torque of the crankshaft at a defined rotational speed of an engine and transmits it to the screw propeller. As the torque of the crankshaft and its rotational speed are time functions so the engine performance interpreted as energy conversion in the form of useful work can be expressed by the formula:

$$D = 2\pi \int_0^t n(\tau) \cdot M_0(\tau) \cdot d\tau \,, \tag{1}$$

where:
D - performance of propulsion engine in [Js],
$n(\tau)$ - function of rotational speed of an engine from time τ in [1/s],
$M_0(\tau)$ - torque function of the crankshaft from time τ in [Nm],
t - time of propulsion engine operation in [s].

At the same time, according to the second law of thermodynamics, one can observe partial transfer of thermal energy obtained from combustion gases into engine cooling factors.

Each transformation of thermal energy into a mechanical one ending up in a torque can be treated as realization of stochastic process dependent on time which is not random variable but the parameter of this process.

Engine operation in a probabilistic formulation during steady motion of the ship can be looked at in two ways:

1) as the set of variable momentary values of the torque also as jointly random values in a probabilistic space with each of them being given time parameter index, which allows to treat torque values as vectors of Hilbert space,
2) as the set of deterministic time functions being statistic characteristics of the second order where each of them is the set of scalar values.

The difference between the two consists in the fact that in the second method random variable momentary values of the torque do not include all regularities of probabilistic character [6, 7].

Generating heat in engine cylinder is of probabilistic character and for this reason the process of burning fuel is of undetermined character because it is affected by different disturbances of accidental character. For this reason engine operation can be characterized by sinusoidal functions distorted by accidental disturbances. Frequency of these functions is settled by frequent occurrence of ignitions in engine cylinders. It does not depend on the size of amplitudes and the phases of the functions but it is connected with the revolution speed of the engine [7].

Engine operation during steady work can be determined by measuring, among other parameters, during short moments, the torque by means of strain gauge of small time constant. Propulsion engine operation Sulzer 5RD68 has been presented in Fig. 1 determined on the measurement basis during steady ship motion. For a definite revolution speed of the engine, amplitudes of torque changes on the shaft and its performance depend on the value of tangent forces generating these changes. They include thereby information about the course of gas forces in respective cylinders. The influence of respective cylinders is not of identical character and depends on cylinder position with regard to vibration knot of the observed from [8, 9]. Sailing conditions as has been indicated in the paper [7] cause an increase of random sinusoidal amplitude function of engine operation at the unchanged frequency. Tangent and inertial forces extorting changes of momentary values of the torque, cause momentary acceleration or deceleration of the crankshaft in its rotational movement and are repeated periodically. Diagrams of forces are repeated periodically, but in the limits of one period, depending on the type of an engine, they are of different run which means they are not harmonic ones.

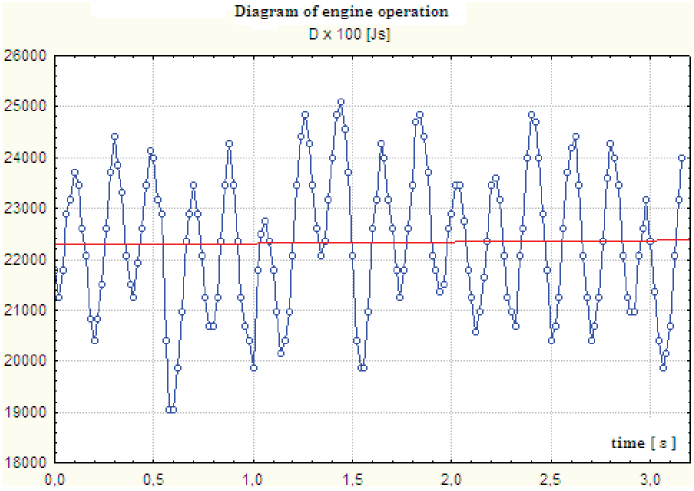

Fig. 1. Performance of propulsion engine Sulzer 5RD68 determined an the basis of torque measurement during steady motion of the ship

In ship propulsion units only the engine and the screw propeller induce significant changes of the torque. Frequency of induced by them changes are located in distant ranges [7]. That means that the influence of ship propulsion elements other than the engine and the propeller is of minor significance on momentary value changes of engine operation. It allows estimating technical condition of the engine and thus is of great importance for the ship safety [1, 2, 6].

3. Structure of ship propulsion engine as the symptom of its technical condition

In the following paper [7] it has been indicated that time realizations of engine torque during steady work create stationary stochastic process partly ergodic containing definite periodic constants. It allows determining on the basis of torque realization statistic characteristics of engine operation in the domain of frequency or time. In domain of time such characteristic describes to what extent values of engine operation at the present moment exert in fluency on moments values in the future and is called autocorrelation. Thus it characterizes time variability of stochastic values of engine operation. Estimator of autocorrelation function value binding standardized values of engine operation D**(t)** in **t** and **t+Δt** can be obtained by the product calculation of these two ordinates and by averaging the product value in the observation time interval of **T**. With **T** tendency to infinity, calculated average value of the product tends towards the exact value of normalized function of autocorrelation:

$$r_{DD}(\Delta t) = \lim_{T \to \infty} \frac{1}{T} \int_0^T D(t) \cdot D(t + \Delta t) \cdot dt \, , \tag{2}$$

where:

D(t) - standardized value of engine operation at the moment,

D(t+ Δt) - standardized value of engine operation delayed about Δt from the **t** moment.

Autocorrelograms of engine operation possess characteristics to retain periodicity of frequency changes of the torque for all time delays but without information about the phase. It means that this function contains also harmonic components originating from cylinder ignitions. Autocorrelation functions can be calculated on the basis of its estimation by means of direct computer calculations of product average of set values in relation to engine operation, taking advantage of the formula:

$$\hat{r}_{DD}(R \cdot \Delta t) = \begin{cases} \dfrac{1}{N} \sum\limits_{i=1}^{N-R} D(i \cdot \Delta t) \cdot D(i \cdot \Delta t + R \cdot \Delta t) & for\ R < N \\ 0 & for\ R > N \, , \end{cases} \tag{3}$$

where:

$\hat{r}_{DD}(R \cdot \Delta t)$ - estimator of normalized autocorrelation function of engine operation,

$D(i\Delta t)$ - standardized value of engine operation at a given moment (iΔt), i = 1,2,..,N,

N - measured number of engine operation values in random sequence,

Δt - time of digitization (step of sampling),

R - delay of normalized autocorrelation function of engine operation R = 0,1,2,..,m.

Estimator characteristics of normalized autocorrelation function of engine operation (3) are specified by the precision of its determination, dependent on measurement time of engine operation value. Variance and covariance of the above estimator tend to decrease at the increase of recording time of measured engine operation values i.e. $T = N \cdot \Delta t$. Therefore estimator autocorrelograms of normalized autocorrelation function of engine operation is calculated to maximal shift equal to 30% of record time of measured values. In Fig. 2 following the paper [6] we can see operation autocorrelograms of five cylinders two stroke propulsion engine calculated by means of formula (3) at different work disturbances of one cylinder during steady movement of the ship.

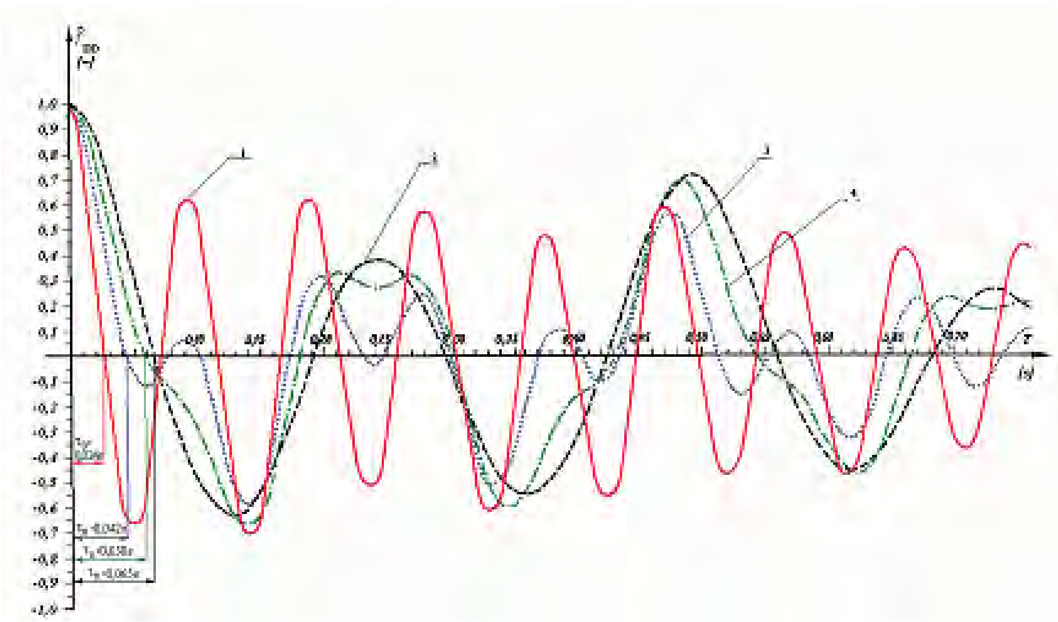

Fig. 2. Autocorrelograms of five cylinder two stroke propulsion engine operation with different work disturbances of one cylinder during steady motion of the ship [6]. Denotations: 1 – steady work of an engine without disturbances, 2 – engine work with fuel supply into one of cylinders disturbed however by deaerating fuel loss up to 14.3% of its amount, 3 – engine work with fuel supply into one cylinder disturbed by fuel loss during deaerating up to 68.4% of its amount, 4 – engine work with no fuel supply into one cylinder

In Fig. 2 one can see that the 14.3% fuel loss of the amount delivered into the cylinder, starts to be visible in the autocorrelogram of engine operation as the influence of periodical components of low frequency. In comparison with autocorrelogram of operation determined at normal injector work, autocorrelogram with fuel loss from the injector shows partial decline of influence of higher frequency periodical components. Such frequency used to appear in time of fixed undisturbed engine work. With total lack of heat generation in the cylinder in which only compression of air takes place (cylinder out of work by suspension of fuel pump) only periodical components of low frequency dominate in the autocorrelogram of engine operation (Fig.2). In Fig.2 times of correlation compound also of autocorrelation functions have been marked they increase from 0.024 [s] to 0.065 [s] proportionally with an increase of fuel loss from the injector. Thus correlation increase can be observed between momentary values of the torque. It has been caused by the character of heat generation process in the cylinder, which together with the loss of fuel becomes more incidental.

However in the frequency domain characteristics of spectral density of its own power in engine operation presents the influence of spectrum components taking place in a given range of value sequence, on the mean square of their changes. Own power spectral density of engine operation during steady motion of the ship can be determined by means of quick Fourier transformation. The method consists in developing periodical function of engine operation into the Fourier series containing simple periodical components whose frequency are multiples of basic frequency. It reduces calculation time of discrete forms of Fourier transform defined by formula:

$$Z_D(f) = \Delta t \cdot \sum_{i=0}^{N-1} Z(i) \cdot e^{-j \cdot 2\pi \cdot f \cdot i \cdot \Delta t}, \tag{4}$$

where:

$Z_D(f)$ - combined values of engine operation components with frequency f,

Δt - digitizing time,

$Z(i)$ - combined values sequence of engine operation,

i=0,….,N-1 - integers,

$f_k = k \cdot \Delta f = \frac{k}{T} = \frac{k}{N \cdot \Delta t}$ - frequency values for which Fourier transform is calculated,

T - basic period of engine operation being equal to one torque of crankshaft,

N - measured number of engine operation values,

$k = 0, 1, \ldots, \frac{N}{2}$ - integers.

Set of all harmonic components amplitudes so called spectrum does not have continuous character but exists only for discrete frequencies. Elementary frequency separation of such spectrum depends on measured number of torque values an basis of which, run of engine operation values has been defined. To calculate fast Fourier transform one can take advantage of program included in Statistic or Microsoft Excel. Above mentioned characteristics allow to decode information about technical condition of the ship. Propulsion engine operation of the ship during steady motion has been determined on the basis at the parameters of its work.

Measurements of parameters were determined at time intervals every 0.02 [s] which allowed to analyze frequency bands of measured torque up to 25 [Hz] and separation ability up to 0.05 [Hz]. Such time of torque digitization allows isolating and defining precisely harmonic components connected with the heat generation process taking place in the cylinders during steady work of an engine. Calculated values of ship propulsion engine operation Sulzer 5RD68 with sequence of ignitions: 1-4-3-2-5 on the basis of torque measurements has been presented in Fig.2. Fig. 2 shows precisely five inputs originating from respective cylinders during one torque. Being aware of ignition sequence in respective cylinders and knowing in which cylinder the compression is measured, it is easy to identify in which cylinder the input took place. Calculated values of engine operation show irregular run during one revolution of the crankshaft. It is caused by non-repetition of injection i.e. random process causing diverse compression of burning in engine cylinders. It is clearly visible while observing lower harmonics in the periodogram of engine operation (Fig. 3b). Apart from this the following periodogram includes also dominating harmonic of the fifth grade in accordance with the frequency of ignitions taking place in the cylinders of the engine.

To find how disturbances of heat generating process in the cylinder affect the band, the fuel was dropped from the injector by gradual opening of air valve. Such disturbances were carried out normal exploitation during ship at sea [7].

14.3% fuel drop of the whole amount supplied into the cylinder is the reason why the harmonic of second order starts to dominate in the band periodogram of engine operation accompanied by a significant influence of the first harmonic (Fig. 4b) The combustion in the cylinder supplied with a reduced dose of fuel was of non-cyclic character because of disturbances in the heat generating process. Extreme case i.e. cylinder out of operation through complete drop of fuel from an injector

a) b)

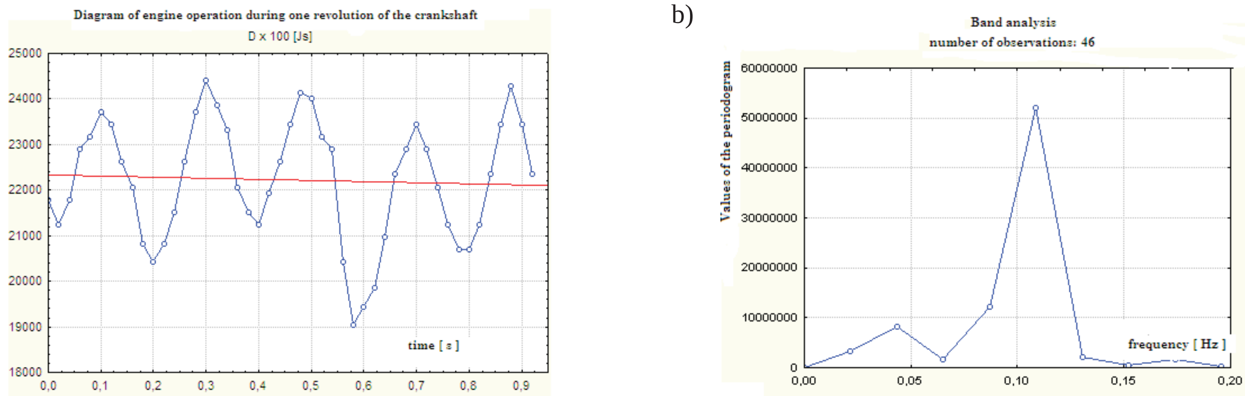

Fig. 3. Calculated value of two stroke five cylinder 5RD68 engine operation, during steady motion of the ship on the basis of torque measurement with digitization time every 0.02 [s]: a) realization of engine operation, b) periodogram engine operation

a) b)

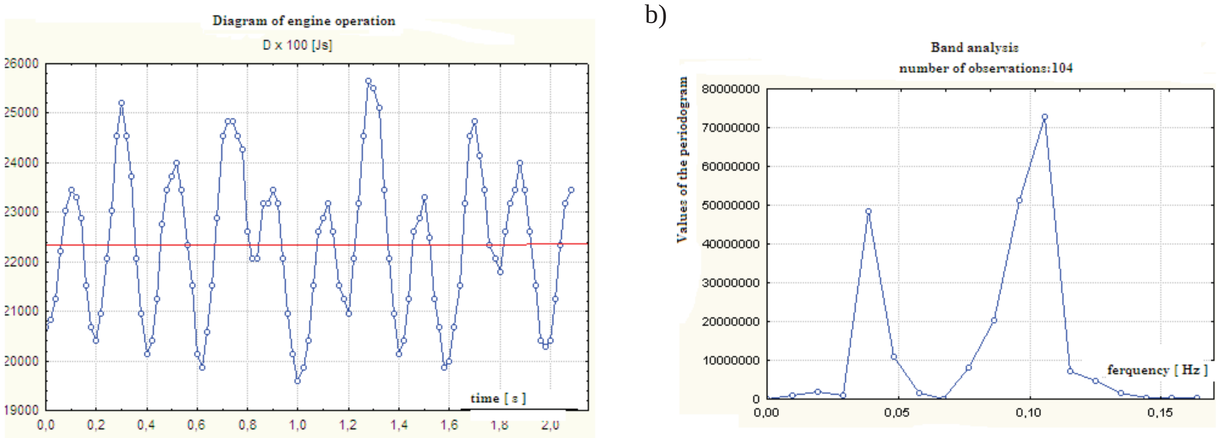

Fig. 4. Calculated values of ship propulsion engine of motion determined on the basis of the torque during 14.3% reduction of fuel supplied into the third cylinder: a) realization of two strokes, five cylinder engine operation observed every 0.02 [s], b) periodogram of engine operation

a) b)

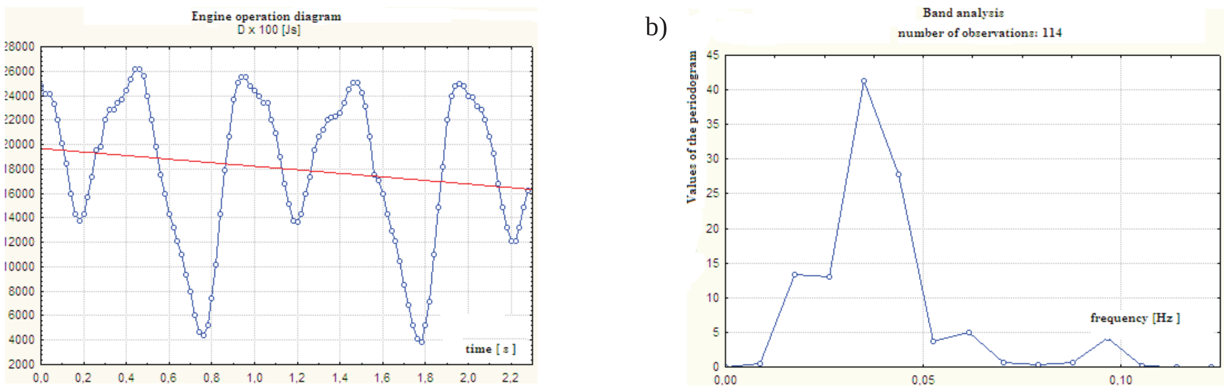

Fig. 5. Calculated values of ship propulsion engine of steady motion determined on the basis of the torque during complete stoppage of fuel supply into one cylinder; a) realization of five cylinder, two stroke engine operation observed every 0.02 [s]; b) engine operation periodogram

has been presented in Fig. 5. Engine operation periodogram in this case shows the band containing domination of second harmonic with a distinct influence of the first one and complete disappearance of the fifth order harmonic (Fig.5b). Domination of harmonic component of second order in the periodogram band of engine operation and an increase of the amplitude of first and second harmonic function of lost fuel amount from the injector are connected with an increased participation of non-balanced earth piston forces.

Operation of propulsion engine speed governor corrects the work of the remaining cylinders if one or more of them do not work properly. Work of the remaining cylinders in such situation must be more effective to deliver greater torque and to keep the fixed revolution speed and the torque assigned to those revolutions needed by the screw- propeller. It causes excessive increase of thermal and mechanical overload in cylinders resulting in cylinder overloading and other consequences connected with this situation [5].

4. Conclusions

Information about technical condition of an engine on the basis of its operation cannot be read directly from time observation therefore the proposal of harmonic analysis of engine operation periodograms as the diagnosis method of its technical condition can be the most adequate diagnostic instrument [4].

Harmonic analysis of engine operation periodograms shows the operation faults of any cylinder. In the structure of band periodograms during engine operation at normal speed, the above mentioned harmonic analysis allows to distinguish unmistakably basic diagnostic symptoms i.e. three spectral components: first, second and harmonic of the order equal to ignitions number of the engine.

Engine operation of incomplete efficiency caused by incorrectly working cylinder results in overloading of remaining cylinders which can cause its break-down.

Engine failures caused by defective heat generation in cylinders are detected due to speed governor action and are noticeable only when they cause visible results.

Therefore the immediate detection of a failure is undoubted great advantage of band periodogram analysis In engine operation.

It allows stopping overloading of the propulsion engine, and in the same way, to prevent a break-down and loss of steering ability by the ship.

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