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EVALUATION OF CURRENT DEVELOPMENTS AND TRENDS IN THE DIAGNOSIS OF MARINE DIESEL ENGINES BASED ON THE INDICATOR DIAGRAMS ANALYSIS

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Abstract

The paper analyses the current offer of combustion pressure sensors for use on marine engines under operating conditions, methods of data acquisition, methods of determining TDC position and methods of obtaining diagnostic information from the indicator diagrams. Terms of continuous work on marine engines themselves only: new ABB cylinder pressure sensor, the piezoelectric sensors from KISTLER and AVL companies, but with limitations, the main ones being stability at high temperature.

Another important issue for the accuracy of mean indicated pressure and heat released characteristics determination is referred to TDC position on the indicator diagrams. TDC is appropriate thermodynamic point, it is hardly determinable in the presence of interference and lack of sufficient information – but is used, for example in ABB solution. One of the sources of diagnostic information is to analyse trends in some parameters, which, unfortunately, is very difficult in environments with varying engine loads.

Further progress in the diagnostic use of indicator diagrams should be associated with the use of the heat released characteristics and the net internal efficiency, which as shown by the results of preliminary tests can be used to assess the accuracy of the injection and combustion of fuel, including gas fuel. Supplementing these methods may be the use of vibration and noise to detect certain malfunctions.

Keywords: *combustion pressure sensor, indicator diagram analysis*

1. Introduction

Indicator diagrams are the primary source of diagnostic knowledge about the work process and condition of the fuel systems and charge exchange systems of marine engines. From the beginning of the application piston engines in the propulsion system periodic indications are performed in marine engines using mechanical indicators, what is troublesome, but the measurements are reliable and can be decisive in relation to the indications of electronic devices.

The actual tendency to crew number reduction, increase of vessels displacement and power of drive systems has generated the need for surveillance of online diagnostic of marine engines. The emergence of electronic pressure analysers, MIP calculators and measurement that is even more complex and diagnostic systems based on the measurement computing has met one of the conditions for the possibility of building such systems. This is not however a sufficient condition. Sufficient condition for the possibility of building on-line diagnostics systems is to have sufficiently durable and accurate pressure sensors in terms of measurements on indicator valves where the highest temperatures prevail. In particular, it is difficult to provide reliable measurements for engines operating on heavy fuel.

The second important measuring issue is the angular axis creation and the TDC location on the indicator diagrams, which problem constructors and users of pressure analysers faced from the beginning of their creation.

The third important issue is the acquisition of diagnostic information from the indicator diagram, in which the field is observed stagnation. The three problems were re-evaluated after three years of previous analogous assessment [1].

2. The cylinder pressure sensors design assessment in terms of their application to continuous indication of marine diesel engines

The basic requirements for the cylinder pressure sensors for use on marine engines under operating conditions are:

- thermal resistance of the sensor in the continuous operation of the indicator valves,
- fatigue strength for cyclically varying loads,
- resistance to pollution,
- the compliance characteristics of sensors in the set,
- the accuracy and repeatability of measurements,
- temporal stability of the measurement characteristics.

The order of the above requirements is correlated with the weight of the features in terms of applications the sensors on the indicator valves of marine engines in continuous operation.

Thermal resistance is characterized by the allowable temperature of the membrane, the housing element and output cables. Mainly because of the above reason, Optrand [2] company sensors are removed from classification as useful for gas engines indication. These sensors are applied before the indicator valves of gas engines, which drive GMVH moto compressors, underwent rapid damage and contamination. It should be noted that the gas temperature measurements before indicator valve of GMVH engine indicator does not show a value greater than 250°C. Company declarations are not clear in relation to the acceptable temperature and places, which they relate. The company declares Sensor Housing Temperature Range -40°C to 350°C and Cable Operating Temperature -40°C to 200°C [2]. It is not inconceivable that given small size of the sensors in such conditions may occur over temperature of the sensor casing.

Keep in mind that methane-fuelled engine exhaust emissions are not as clean as is commonly believed because lubricating oil it is also burned. Flash hider used as inserts (rod) with sintered metal balls prevents damage to the sensor. Silencers are relatively quickly polluted and they require replacement.

In summary, the disadvantage of the sensors in above applications on the engines is their small size. The membranes are too small. Optrand sensors are not taken into account as meeting the requirements for their use for continuous measurements on or before the indicator valves.

Table 1 summarizes the sensors of different companies declaring the possibility of continuous indication on the engine on the indicator valves or before them.

From the last review of the sensors structure made in 2011, three years passed. During this period, new sensors were designed by Kistler and AVL company (Tab. 1). These sensors have a structure adapted for mounting before indicator valves (Fig. 1 and 2).

Fig. 1. The Kistler Cylinder pressure transmitter type 7621CQ [5]

Fig. 2. The cylinder pressure sensor GT-27 uses in the KONGSBERG NK 600 MIP® calculator [7]

*Tab. 1. Main determined parameters of cylinder pressure sensors can be used on marine engines**

Manufacturer Sensor type	Long life – warranty Maximum working temperature	Place of measurement
Kistler		
6613CA [3] ---------------- 350°C	>20 000 h can be achieved in a diesel and gas engine running. Optimum sensor life is achieved at an average temperature of 200... 300 °C in the sensor body.	Can be installed underneath the indicator valve with adapter.
6013C...[4] ---------------- 350°C	The life expectancy of the sensor has been designed for a service life of >16'000 h in a gas engine running.	Can be installed underneath the indicator valve with Kistler adapter.
7621CQ...[5] -------------------- 350°C	"A very good lifetime and stability are ensured." "Especially suitable for heavy fuel operation."	The transmitter installed with hollow bolt
AVL		
GO41DA [6] ----------------- Front of sensor: 350°C. Cable: 200°C.	$\geq 10^9$ load cycles	Not declared
KONGSBERG		
GT-26; GT-27 (AVL) [7] --------------------	Warranty of cylinder pressure sensor is 3 years or 16000 running hours	The GT-27 is installed before indicator valve for continuous measurements
ABB		
PFPL… [8] ----------------------- Max. ambient temp. of transducer cable: 150°C for PFPL 201, 200°C for PFPL 202.	The transducer is designer for continues combustion measurement: 24 h per day, 365 days without recalibration	Before indicator valve
Imes		
HTT-04CA [9] Max. temp. at measuring cell 300°C	The life expectancy of the sensor has been designed so that the life of 16.000 h or more can be achieved in a gas engine. Optimum sensor life is achieved at an average temperature at the measuring element of 200-250°C.	Not declared

** These data are taken from the currently available information posted on the Internet. In order to obtain definite confirmation contact with their manufacturer or supplier is necessary.*

Draws attention to the high endurance declaration (20000 h) of the Kistler company to the sensor 6613CA and the declaration 3 years warranty regarding the sensor GT-27 of the Konsberg company.

Imes company in place of the previously presented sensor HTT-04 [1] is now offering a new type of sensor HTT-04CA [9]. Declaration of the thermal resistance of the sensor remains unchanged (Tab. 1), but made the following remark: "Optimum sensor live is achieved at an average temperature at the measuring element of 200-250°C", which weakens the declaration of admissibility temperature of 300°C. No declaration of the engine rotational frequency, and as we know the durability of the sensors depends on the number of stress cycles.

It should also be noted that the Imes company determine the place and manner of application of the sensor to the engine in a following way: "The sensor should be installed close to the combustion chamber; the length of the bore pressure between the sensor and combustion chamber mainly depends on engine speed" [9]. The possible applications on the indication valves the company does not comment, in the light of their own experience of research seems to be obvious. While a miniature sensor face temperature measured at indicator valve medium speed engine reached 250°C, the face of an identical sensor positioned in the engine head at a distance of 5 mm from the surface of the combustion chamber has reached a temperature of 150°C. This temperatures difference is due to cooling.

It should be emphasized that the Imes company acquired Marine Qualification of: Bureau Veritas, Det Norske Veritas, Germanischer Lloyd, A. Bureau of Shipping and Lloyd's Register, but the possibility of the use of these sensors for continuous measurement on the indicator valves should not be taken into account.

Imes company sensors are tensometric type. So far, a number of analogous tesnometric structures were done. However, it is not a solution that meets the requirements of the work on the indicator valves. The precursor in this area was the company Autronica, but two of its other structures cylinder pressure sensor proved to be too unreliable for continuous operation on the indicator valves.

3. Indication accuracy

The issue of indication accuracy is characterized by two aspects of measurement: accuracy of pressure amplitude and accuracy of angular position of the sample. The accuracy of measurement is significant disruption brought by the gas channels and the oscillations and torsional vibrations of the crankshaft where the shaft position sensors are installed. Sometimes there is yet another type of interference, such as contributed by electromagnetic pulses generated by the engine room equipment, for example, the ignition coil of spark ignition engines. This kind of interference hampers indication of engines, which drives GMVH natural gas moto compressor. Tab. 2 lists the basic sensor accuracy of the data listed in Tab. 1.

Tab. 2. Lists the basic sensor accuracy of the data listed in Tab. 1

Sensor type	Linearity	Thermal shock	Frequency range [Hz]
KISTLER [3, 4, 5]			
6614CA	≤±1% FSO	≤±0.5 bar at 1500 min^{-1}, p_{mi} = 9 bar	0.032-20 000 (-3 dB)
6013C...	≤±1% FSO	≤±0.5 bar at 1500 min^{-1}, p_{mi} = 9 bar	Natural frequency 85 kHz
7621CQ...	≤±1.5% FSO	-	0.032-20 000 (-3 dB)
AVL [6]			
GO41DA	≤±0.5% FSO	$\Delta p \leq \pm 0.5$ bar, $\Delta p_{mi} \leq \pm 1.5\%$ at 1500 min^{-1}, p_{mi} = 9 bar	Natural frequency 90 kHz
KONGSBERG [7]			
GT-27	"For technical data of the sensors see Kongsberg datasheet "Cylinder pressure sensors" doc. 364260"		
ABB [8]			
PFPL	"The measuring accuracy is 0.5% over the full measuring range and the accuracy is not influenced by any clogging or heat flash from the combustion gases"		
Imes [9]			
HTT-04CA	Accuracy ≤±1% Full scale	< ±0.5 bar at 1500 min^{-1}, p_{mi} = 9 bar	2

Declared sensors measuring parameters of Kistler and AVL companies are very similar. The sensors have a wide bandwidth of pressure signal. This may have implications for the accuracy of determining the rate of pressure rise. In the case of low-speed engines rate of pressure rise are the smallest. For HTT-04CA sensor bandwidth is 2 kHz, which is a relatively small value. Therefore, the spectrum should be analysed for the frequency of pressure for specific engine in terms of Nyquist frequency.

From the diagnostic viewpoint, the accuracy characteristics of the sensor are not as important as their repeatability for the different units of the same type of sensors. It is about the interchangeability of sensors and comparability of the results for each cylinder. Previous experience with the Kistler company sensors showed that these sensors comply with these demands.

Significantly greater measurement inaccuracies can bring gas ducts connecting the interior of the cylinder with the measuring sensor. The gas channels cause signal delays, amplitude errors and oscillation pressure curves. Pressure oscillations hinder identification of TDC position on the indicator diagram, the first order derivative determination and subsequent determination of the heat released characteristics. It turns out, however, that for each channel interference engine type, these are systematic and closely overlap. For the diagnosis disturbances of this nature is not an obstacle.

Another source of indication error is angular axis. Generating the angular axis can be achieved in two ways, either on the basis of the wheel turning gears teeth, tags mounted on the flywheel (Fig. 3) or by using special markers discs mounted on the output shaft (Fig. 4).

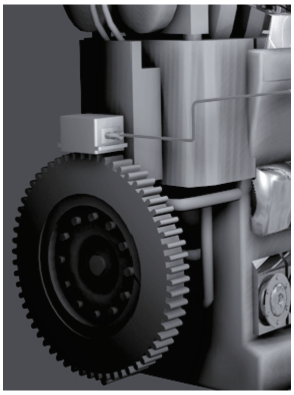

Fig. 3. The concept of the formation of the angular axis in the Climate ABB System [8]

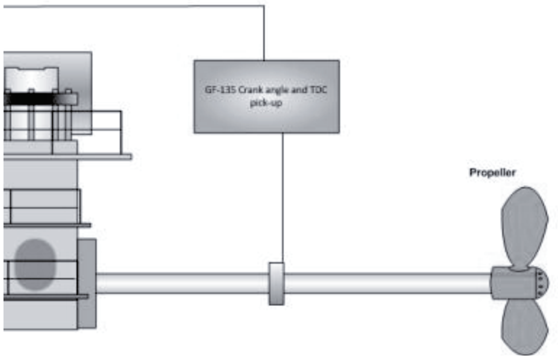

Fig. 4. The concept of the formation of the angular axis in the NK-600 Kongsberg System [7]

The idea of generating pulses to construct the angular axis shown in Fig. 4 has been used extensively. Also mounted markers, e.g., on the side surface of the flywheels or by drilling holes such as holes 360 on the circumference of the flywheel having a relatively large diameter.

In the Cylmate ABB system [8], the sectoral sensors are mounted on the ring gear wheels turning gears (Fig. 3), and the sampling angle is predicted based on the previous four angular pulses using a second-degree polynomial. It should check that the linear prediction is not sufficient or better.

The use discs with a large number of marks (teeth or holes), which is possible in the system shown in Fig. 4, enables a very accurate sampling, for example with a resolution of 0.5°CA.

The use of discs with a large number of teeth in addition to providing high accuracy angular sampling pulses allows torsional vibration analysis, which can be a source of additional diagnostic information.

If we provide sampling of the angular resolution of 0.5°CA, which is now widely used, it is for an average speed of 40 rpm sampling rate will be about 482 Hz, and at the speed of 100 rpm would be about 1206 Hz, and so these frequency determined by the Nyquist frequency, and not, for example the upper frequency bandwidth sensor HTT-04CA amounting to 2 kHz. Decisive as to the sufficiency of the bandwidth would be pressure signal spectral analysis for a particular case.

To ensure proper accuracy of determining the mean indicated pressure and the heat-released characteristics is necessary to determine TDC position on the indicator diagram. For this purpose, special marker is mounted on the flywheel or on the output engine shaft. It is also necessary to know how far from the marker positions are TDC position for individual cylinders.

From a theoretical point of view, the right solution is to determine the thermodynamic TDC. Doubts are raised from method patented by ABB [10], ignoring the validity of such patent to the available knowledge at the time of the existence of inflection points of pressure and its subsequent derivatives. First to even small disturbances of pressure there are problems with the accuracy of determining a zero of the second derivative of the pressure. Fundamental objection, however, is that we do not know what is the actual distance of GMP from the inflection point. It should be noted that the inflection point is only on the course that we set as a function of the angle of rotation of the crankshaft. This point is not available on the pressure curve measured in the field of gas volume.

4. The diagnostic use of indicator diagrams

Taking into account the information obtained from the indicator diagrams analysis in modern systems (Cylmate system - ABB, NK 600 MIP calculator – Kongsberg, EPOS – AVL) it should be noted that the basic parameters available in these systems, no different from those offered by one of the first indicators Autronica NK-5. The exception is the new parameter dp/dα, which has no very important in large low speed diesel engines. The most important diagnostic parameters determined on the basis on indicator diagram analysis are:

- maximum combustion pressure,
- the angle referred to TDC where maximum combustion pressure occurs,
- pressure at TDC,
- pressure 36° after TDC,
- MIP (Mean Indicated Pressure),
- maximum dp/dα.

The values of listed parameters are compared in bar charts or deviations from the average, as well as in tabular form. The history of course parameters is also presented. there is a fundamental difference between history and trends of diagnostic parameters. This diagnostic parameter should be independent from the engine load and should be referenced to the pattern. Please note that marine engines are subjected to varying loads. As a pattern average value for all cylinders may be used and tested deviations from this average, which is commonly used in the diagnosis.

Diagnosis based on the above parameters can detect only a few failures. The amount of diagnostic information can be significantly increased by application advanced processing of the indicator diagram in the form of the net heat release rate characteristic, net generated heat and the net thermal efficiency [12].

Figure 5 shows an example of failure identification of the injection system, which is clearly visible on the heat release characteristics, while in the primary pressure curve is not perceptible.

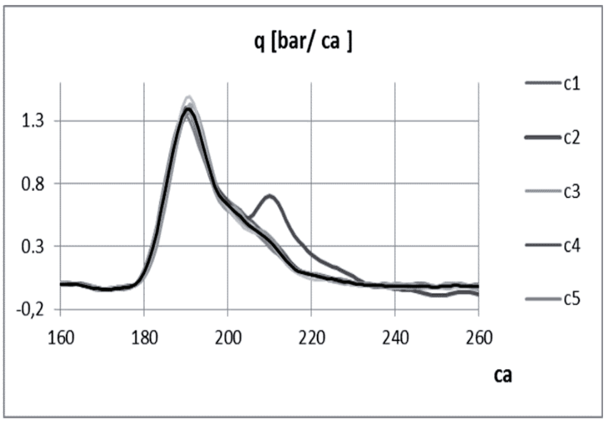

Fig. 5. The curve of heat release rate for different cylinders of marine engine MAN 9K90MC

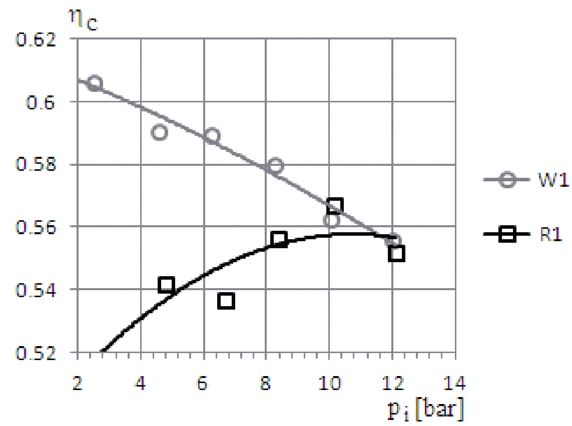

Fig. 6. Traces of net thermal efficiency as a function of mean indicated pressure for the nominal state (W1) and simulated fault (clogged injector) (R1)

Particularly useful may be introduced by the authors of the paper net thermal efficiency indicator [13]. It is expected that its use will allow early detection of failure of the injection system resulting in deterioration of the combustion process. This would be a universal indicator also for gas engines. Fig. 6 shows an example of curve of net thermal efficiency for clogged injector.
It should be emphasized that the Kongsberg company probably recognized the need to use a heat release characteristics as indicated by the designation of an exemplary application in cooperation with AVL [11]. The heat release characteristics of the system K-Chief 600 (Fig. 6).

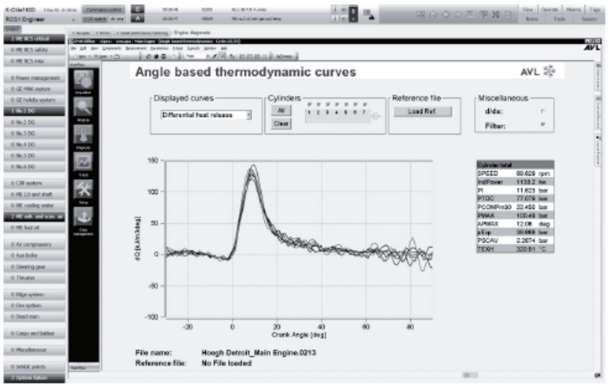

Fig. 6. Example of designation of heat release rate in an integrated system K-Chief 600 and AVL EPOS [11]

Article not considered their construction, the so-called portable indicators [14].

5. Conclusion

In the three years since 2011, when the authors of this article reviewed the state of marine engine diagnostic issues [1] there has been significant progress in the level of reliability parameters of pressure sensors. Essential in this regard are statements of Kistler, AVL and ABB companies about the sustainability of the sensors. So far, declared durability combustion pressure sensors to their high prices restrict development and use of diagnostic systems based on the use of the information contained in the indicator diagrams.

Diagnostic use of the information contained in the indicator diagram practically has not changed since the time the offer and use Autronica NK-5 system if you do not take account of later entered parameter dp/dα.

The results of diagnostic tests and indication results analysis of engines on different ships, carried out by different pressures analysers indicate the need to use for diagnostic parameters of net heat release characteristics and net thermodynamic efficiency.

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