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Real-Time Diagnostic Approaches for Marine Diesel Engines in the Context of IMO Decarbonization Goals

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Abstract. Methods for monitoring the operating parameters of marine diesel engines in real time are considered. The methods and hardware are developed to improve the operational efficiency of marine engines, as well as in the context of modern IMO requirements for decarbonization of the marine fleet. In parallel with the gas pressure diagrams in the cylinders, the vibroacoustic diagrams of the cylinder head units and fuel equipment are measured and analyzed. This method makes it possible to evaluate the actual and geometric phases of fuel supply and gas distribution. Also, the vibroacoustic method makes it possible to assess the technical condition of the fuel equipment and valve drive mechanism. The data obtained are used to refine the mathematical model of the working process in the engine cylinders, determining the indicator parameters and power, as well as emissions of harmful substances that must be controlled in accordance with the current IMO requirements. The considered hardware and software methods are implemented in a real-time system for diagnostics of marine engines during operation. The system is developed on the basis of a modern dual-core controller with high performance and low power consumption, including a high-speed ADC with sufficient capability to monitor the operating process with a resolution of up to 0.1 degrees of crankshaft rotation for all types of main and auxiliary marine engines. The system also uses wireless data transmission technology. A modern smartphone or tablet based on Android/iOS serves as a computing and graphic component of the system. The developed real-time diagnostic system allows using all the advantages of parallel analysis of pressure in the working cylinders and vibroacoustics. The system determines in real time the main parameters of the working process, fuel injection phases and valve timing. A specially developed algorithm is used to determine TDC, taking into account that the compression ratio in the cylinder can vary due to valve control or for operational reasons. The system being developed takes advantage of the use of a digital twin - an online mathematical model of the working process of an engine cylinder. These solutions will improve the quality of diagnostics and ultimately improve the operating efficiency of marine engines by reducing operating costs, reducing vibration and emissions of harmful gases, and extending reliable trouble-free operation.

Keywords: marine diesels; real-time diagnostics; vibroacoustics; performance analysis.

1. Introduction

As of early 2024, the global fleet includes approximately 109,000 vessels with a gross tonnage of over 100 GT, comprising both cargo and non-cargo ships (UNCTAD, 2024). According to Statista (2024), maritime transport handles about 90% of global trade. Projections suggest that, in the absence of further measures, greenhouse gas (GHG) emissions from shipping could increase by up to 130% of 2008 levels by 2050 (Reuters, 2025). In 2023, international shipping emitted approximately 706 million tonnes of CO_2, accounting for nearly 3% of total global emissions (Lloyd's Register, 2025).

In response, the International Maritime Organization (IMO, 2023) adopted a revised GHG reduction strategy, targeting the following milestones:

- A 40% reduction in carbon intensity of international shipping by 2030, compared to 2008 levels;
- Achievement of net-zero GHG emissions from ships by 2050;
- A 5–10% adoption rate of zero or near-zero GHG emission fuels and technologies by 2030.

Low-speed two-stroke engines continue to dominate the marine propulsion sector, especially on supertankers, ultra-large cargo ships, and container vessels, due to their high efficiency and output. In 2023, approximately 1,914 new shipbuilding contracts were signed, the highest annual number since 2015 (Fortune Business Insights, 2024; Riviera Maritime Media, 2023).

In alignment with IMO regulations and national environmental agency requirements, active efforts are underway to reduce emissions of harmful substances during the operation of marine diesel engines. The most critical pollutants include sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM). Amendments to Annex VI of the MARPOL Convention have established a global sulfur cap of 0.5% m/m in marine fuels since January 1, 2020 (UNCTADstat, 2023). In Emission Control Areas (ECAs) such as the Baltic Sea, the North Sea, and North America, the sulfur content limit is 0.1% m/m (Lloyd's Register, 2025). Additionally, from May 1, 2025, the Mediterranean Sea will be designated as a SO_x ECA, requiring fuel with a sulfur content not exceeding 0.1% m/m (European Commission, 2023).

The transition to ultra-low sulfur diesel (ULSD) poses several technical challenges, particularly for engines originally designed to operate on high-viscosity, high-lubricity fuels. The desulfurization process reduces the lubricating properties of the fuel, potentially leading to increased wear on fuel system components, especially under conditions of low viscosity. For reliable operation of fuel injection systems, fuels with a viscosity of at least 2 cSt at 40 °C are recommended (ABS, 2010; CIMAC, 2007).

To mitigate the reduced lubricity of ULSD, specialized additives are used, and updated fuel standards such as ISO 8217 now include lubricity specifications. Nevertheless, the adaptation of existing marine engines to ULSD requires further technical solutions and real-time monitoring of fuel combustion quality in engine cylinders (Peninsula, 2022).

Today, advanced technologies are available to improve fuel efficiency and reduce NO_x and CO_2 emissions from ships. Among them, in-cylinder combustion monitoring and control is a key method for assessing the operational and environmental performance of marine diesel engines (Melnyk, Koskina et al., 2023). Properly optimized combustion not only reduces NO_x, CO_2, and carbon particulate emissions but also minimizes wear and damage to engine cylinders and auxiliary systems (Neumann et al., 2022; Minchev et al., 2021).

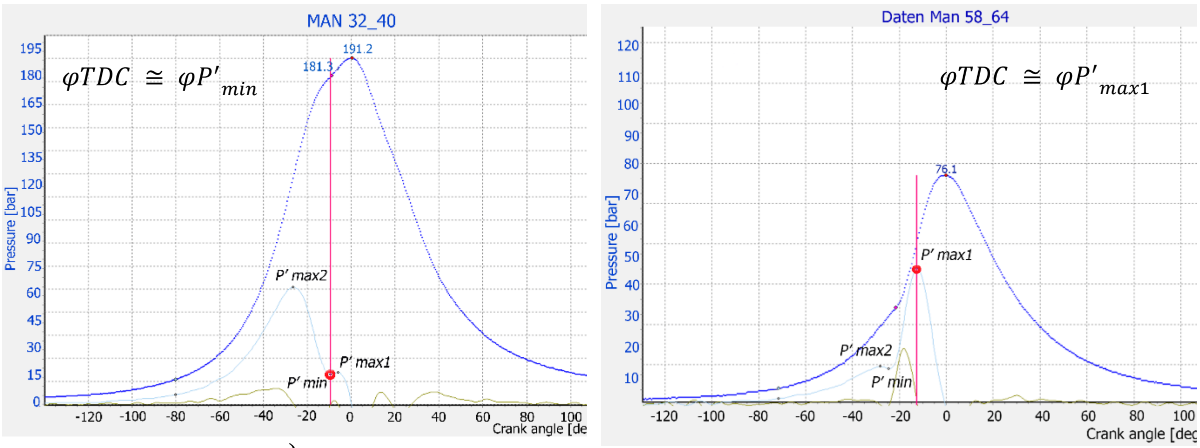
The development of new diagnostic methods for assessing the technical condition of main and auxiliary marine engines enhances operational efficiency, reduces fuel consumption, and supports compliance with IMO decarbonization targets. The data analysis approaches presented in this paper underpin the functionality of a novel real-time parametric diagnostic system for marine engines (Varbanets et al., 2022).

2. Method of determining the initial approximation of tdc by analysing dp/dt diagrams

Data synchronization, i.e. the translation of pressure data in the cylinder from a function of time to a function of the crankshaft angle (Heywood, J. B., 2018) is often necessary when no information is available about the actual degree of compression in the cylinder. This is typical for modern engines with variable valve timing.

The compression ratio in the cylinder $\varepsilon = V_a/V_c$, where ε is the compression ratio in the cylinder, Va is the working volume of the cylinder, and Vc is the compression chamber volume.

$$P(t, ms) \rightarrow P(deg, °CA) \tag{1}$$



a) b)

Fig. 1. Initial approximation of TDC for (a) MAN 32/40 and (b) MAN 58/64 engines (Varbanets et al., 2024)

The problem of analytically determining TDC has been addressed by many authors (Tunestal,2009, Pipitone, 2009, Staś, 2000, Tazerout, 1999, Varbanets, 2020). We note that for certain types of diesel engines, this problem is relatively straightforward. These are low-speed and medium-speed diesel engines with autoignition after TDC. In this case, the curve of the rate of change in pressure during compression dP⁄dφ crosses zero at the position of TDC (excluding minor thermodynamic shift

(Heywood, J. B., 2018). In other cases, the curve dP⁄dφ closely approaches zero, and the extrapolated curve intersects zero at the position of TDC, with a very small extrapolation error (Varbanets, 2020).

An initial value for TDC is necessary to implement the method described above for determining the position of TDC and the boost pressure Pa. However, rapid determination of the initial value of TDC, which is calculated from the temporal diagrams P(t, ms), is required for the operation of marine diesel engine diagnostic systems in real time. We introduce an empirical formula for determining TDC, based on an analysis of dP/dt diagrams obtained by numerical methods and processed by a digital filter (Neumann, Varbanets, 2022), as shown in Fig. 1.

The initial phase of TDC is conventionally accepted as the point Pmax, and the displacement to the initial approximation is calculated; the position of TDC is then refined by the method described above. An analysis of data obtained from marine engines using IMES sensors (Neumann et al., 2022) and from working process models obtained in the Blitz-PRO environment (Minchev D, 2025) showed that the relationship between the magnitudes and corresponding phases of the extrema of the pressure change rate diagrams in the working cylinder enabled the initial approximation of TDC to be determined. An analysis of marine engine indication data of different types (Heywood, J. B., 2018) showed that in most cases, depending on the nature of the working process and the type of indicator diagram, the TDC position lies between the phases $[\varphi P'_{min},\ P'_{max1}]$ of the minimum of the first derivative and the maximum of the first derivative of the combustion stroke.

The phase relationships between the maxima of the first derivatives during combustion $\varphi P'_{max1}$ and compression $\varphi P'_{max2}$, and the position of TDC, are experimentally obtained as shown in Figs. 4 and 5. It is found for various types of marine engines that in the case of ‘soft’ combustion, where the rate of pressure change during combustion is lower than during compression, the position of TDC is closer to the phase of the minimum of the first derivative $\varphi P'_{min}$, which occurs between compression and combustion, as illustrated in Fig. 1(a) (red point).

For engines with ‘intense’ combustion, where the maximum of the first derivative during combustion is greater than during compression, the position of TDC is closer to the phase of the maximum derivative during combustion, $\varphi P'_{max1}$, as depicted in Fig. 1(b) (red point). Two extreme cases are identified depending on the ratio of the magnitudes of P'_{max1}/P'_{max2} (these ratios are empirical, and need to be specified for a given type of engine).

$$\frac{P'_{max1}}{P'_{max2}} < 0.5 \rightarrow \varphi\, TDC \cong \varphi_{P'min1}, \quad (2)$$

$$\frac{P'_{max1}}{P'_{max2}} > 3.0 \rightarrow \varphi\, TDC \cong \varphi_{P'max1} \quad (3)$$

For modern engines, the ratio of the rates of pressure change during combustion and compression, P'_{max1} / P'_{max2}, may be less than 1.0; in other words, the rate of pressure increase during combustion is less than during compression, which characterizes 'soft' combustion (Varbanets et al., 2020) without significant dynamic loads on the crank-connecting rod mechanism and bearings, as shown in Fig. 1(a). In this case, $\varphi TDC \cong \varphi P'_{min}$. In general, the relationship between the position of TDC and the extrema of the first derivative can be represented by the following empirical formula:

$$\Delta\varphi_{TDC} = \varphi_{P'min} + \frac{\varphi_{P'max1} - \varphi_{P'min1}}{\theta_1 - \theta_2} \cdot \left(\frac{P'_{max1}}{P'_{max2}} - \theta_2\right), \quad (4)$$

where $\theta_1 = [3\text{–}5], \theta_2 = [0.3\text{–}0.9]$ are empirical coefficients; $\varphi_{P'min}$ is the minimum phase of the rate of pressure change between the maximum phases of compression and combustion; $\varphi_{P'max1}$ is the phase of the minimum rate of pressure change during fuel combustion; and P'_{max1} and P'_{max2} are the maximum rates of change in compression and combustion pressure. The calculated results for the initial approximation of TDC for several engines in which different methods are used to organise the work processes are shown in Figs. 1 and 2.

A further advantage of this algorithm is its low sensitivity to noise in the first derivative of pressure experimental data. Although one disadvantage of this approach is the need for tuning of the coefficients θ1, θ2, we note that once tuned, these coefficients can be subsequently used for the main operating modes of the engine, therefore allowing for real-time analysis of the pressure diagram in the cylinder.

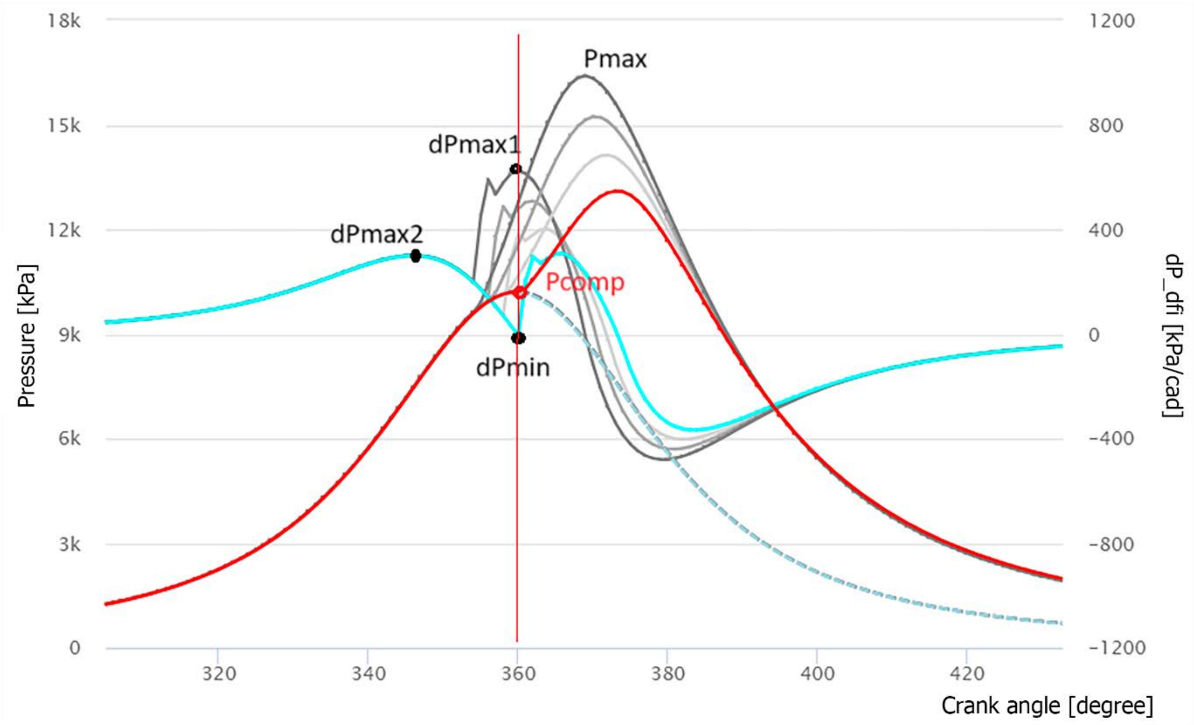


Fig. 2. Working process of the Wartsila 16V32 engine
with different fuel injection advance angles (Varbanets et al., 2024)

3. Method of determining cycle-to-cycle irregularity

One of the tasks of a real-time diagnostic system for marine diesel engines is to assess the unevenness in the operating cycles in real time. When analysing a series of indicator diagrams of one cylinder, changes in the peak pressure values (Pmax) are primarily seen, and with a more detailed analysis, changes in compression end pressures (Pcomp) and mean effective pressures (IMEP) can be observed. In fact, changes occur from one cycle to the next throughout the indicator diagram curve P(φ, °CA) or P(t, ms). Unevenness in the operating cycles is mainly caused by the operation of the systems that are responsible for the quality of fuel combustion in the cylinder, i.e., the high-pressure fuel system and the valve timing control system.

Unevenness in the working cycles is a highly undesirable feature of marine diesel engines, since it leads to the following negative consequences:

- Increased overall levels of vibration of the engine;
- Uneven distribution of mechanical loads on the cylinders;
- Overloading of individual cylinders.

As a general consequence of these factors, there is a decrease in the effective efficiency and limitations on the power of the engine (Heywood, J. B., 2018).

The uneven distribution of loads across cylinders leads to increased concentrations of toxic emissions in exhaust gases, which is currently strictly regulated by IMO requirements (IMO, 2023).

To reduce engine vibration and minimise the emission of harmful substances, it is necessary to control the irregularity in the operating cycles during engine operation. In the following, we identify some criteria of irregularity that can be obtained and analysed during engine operation in real time. Unlike other engine parameters (IMEP, IPOWER, etc.), an analysis of irregularity criteria can be performed via a 'quick scan' of the engine in real time, as the temporal diagrams P(t, ms) can be used for this purpose. It can be said that evaluation of the irregularity in engine operating cycles is the main task of a real-time diagnostic system for marine diesel engines.

One of the main reasons for cycle-to-cycle variations is irregularity in fuel delivery, which can be caused by cycle-to-cycle variations in the injected fuel dose, injection timing angle Δφ, and injection duration Δφinj. In this case, changes occur in the main parameters of the working process, including IMEP and IPOWER for each cycle, thus reducing the operational efficiency of the engine. As it is approximately proportional to the percentage change in cycle fuel delivery, the indicated power of the cylinder changes, thus increasing the level of vibration and decreasing the effective efficiency of the engine.

By recording and analysing the pressure in the cylinder over several consecutive working cycles, a real-time system can compare the differences in the parameters during the compression and combustion stages, and hence assess these differences numerically. Numerical analysis of vibrograms during fuel injection and valve closing stages can also be performed in real-time mode. A comparative analysis of the vibrograms during the compression stages enables an evaluation of the unevenness in the operation of the valve mechanism, whereas a comparative analysis during the combustion stages enables an assessment of the irregularities in the operation of the high-pressure fuel equipment.

Assessment of the unevenness in the working cycles as a diagnostic parameter should be carried out under a constant engine load. Since the load varies constantly due to external conditions during the operation of marine diesel engines, it is necessary to select stable periods of operation when assessing unevenness and to take into account the engine runtime.

Let us consider a certain number of indicator diagrams m of working processes (j = 1,…,m), recorded under a constant load of a main S60MC-C engine. The maximum pressure at each j-th cycle $P_{max\,j}$ and the maximum average pressure over m cycles $\overline{P_{max}}$ can be written as:

$$P_{max\,i} = \max\left(P_{ij}\right);\ \overline{P_{max}} = \frac{1}{m}\sum_{j=1}^{m} P_{max\,ij} \quad (5)$$

where i=1,..N is the number of points in one cycle when recording an indicator diagram; m is the number of recorded cycles; and j is the cycle index.

In most modern marine diesel diagnostic systems, step recording is used for pressure diagrams, with values of ΔP = 0.1°CA for four-stroke engines and ΔP = 0.05°CA for low-speed two-stroke engines. Such a small step allows for an analysis of the working process and its irregularity with the maximum degree of detail, and for an evaluation of the detonation coefficient during fuel combustion using spectral analysis methods (Varbanets et al, 2020).

To assess the unevenness in the working cycles, we use the popular coefficient of variation (COV) criterion (Varbanets, 2024), which can be applied to the entire pressure curve, thus obtaining a graph of COV_{Pi} values as an estimate of the unevenness in the engine operation. We can express the coefficient of variation of working cycles as a percentage that is equal to the ratio of the standard deviation to the current mean value of the selected quantity (in this case, pressure), as follows:

$$COV_{Pi} = \frac{\sigma_{pj}}{\overline{P_j}} * 100\ \%, \quad (6)$$

where $\overline{P_i} = \frac{1}{m}\sum_{j=1}^{m} P_{ij}$, and the standard deviation σ_{pj} is calculated as:

$$\sigma_{pj} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_i - \overline{P_i})^2}. \tag{7}$$

We propose to calculate and analyse the maximum value $COV_{P.max}$ [33]. In our opinion, in addition to $COV_{P.max}$, it is also possible to analyse the current (diagram COV_{Pi}) and average $\overline{COV_P}$. From a chart of the current values of COV_{Pj}, the part of the diagram representing the greatest deviation of the operating cycles can be observed, and depending on the results, a conclusion can be drawn about the irregularity of fuel injection or the irregularity of the gas distribution valves (Fig. 7).

$$COV_{P.max} = max(COV_{Pi})\ \%;\ \overline{COV_P} = \frac{1}{N}\sum_{j=1}^{N} COV_{Pi}\ \%; \tag{8}$$

It is possible to formulate a complex criterion for the irregularity of the operating cycles based on the pressure, referred to here as CII. This generally characterises the cyclic irregularity of the engine, and is defined as follows:

$$CII = \sqrt{\overline{COV_P}\ *\ COV_{P.max}}\ ,\ \%. \tag{9}$$

CII is expressed as a percentage. As shown by a numerical analysis of computational and experimental data, Fig. 3, it is a convenient means of analysis, and allows for an overall characterisation of cycle-to-cycle variability.

4. Results and discussions

This analysis revealed significant cyclic irregularity in the old NVD24 laboratory engine and, as expected, low cyclic irregularity in the new WeiChai engine (Deutz 226). When analysing the operating cycles of the WeiChai, the values of $COV_{P.max}$, $\overline{COV_P}$ and CII_p were found to be significantly lower than the values of the same metrics for the other engines. A joint analysis of these three metrics showed that the generalised criterion CII_p is a good overall qualitative assessment of cycle-to-cycle variability, and can be applied in real time to evaluate the irregularity in the engine operation under load.

An assessment of the fuel injection irregularity in the engine cylinder can be carried out by analysing the phase fronts of the vibration signal of the injector, as shown in Fig. 3. The principle used to obtain and analyse vibration diagrams for the injectors and gas distribution valves has been published in several sources (Neumann et al., 2022, Minchev et al., 2021, Varbanets et al., 2024). Since the pressure and vibration signals are measured simultaneously, after aligning the working cycles, it is possible to estimate the dispersion of the phase spread of the front fronts of the injection vibration diagram. φ_{adv} and $\Delta\varphi_{inj}$,Fig. 3.

Table 3. Comparison of COV and CII values for five types of engines (Varbanets et al., 2024)

	6S60MC-C	Wärtsilä 16V32	WUXI	NVD	WeiChai
$\overline{COV_P}$ %	0.943	0.980	0.852	1.906	0.451
CII, %	1.822	3.977	3.759	4.778	1.168
$COV_{P.max}$ %	3.524	16.142	16.594	11.976	3.025

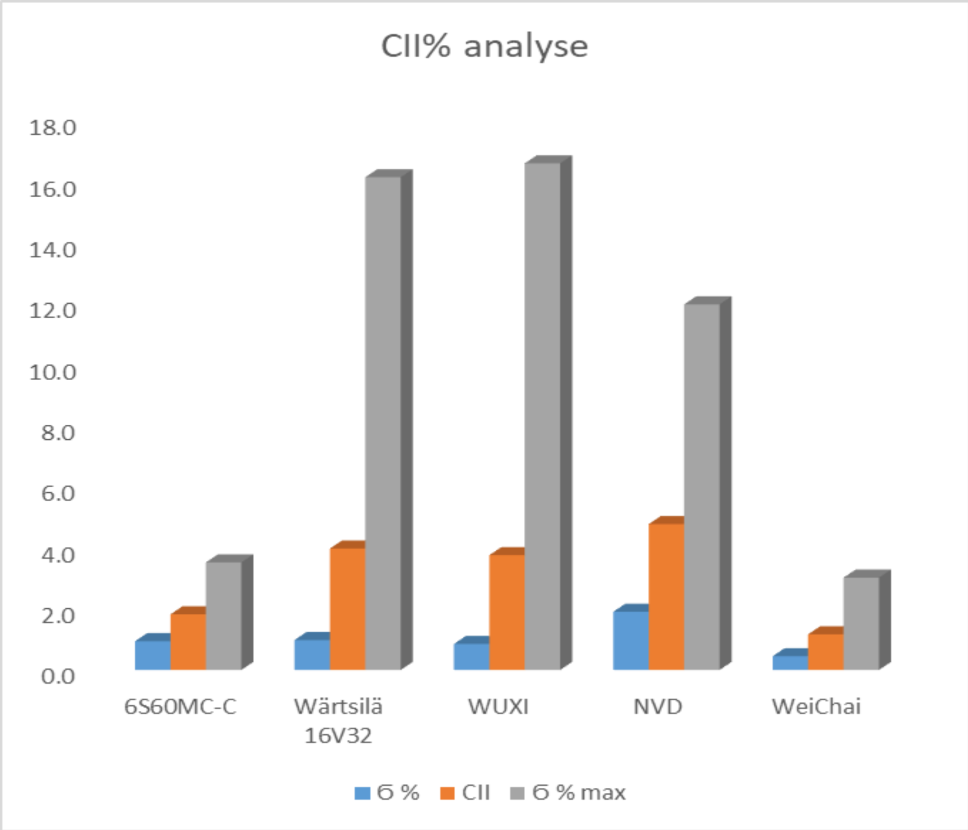


Fig. 3. Comparison of the CII % metric for five types of engines (Varbanets et al., 2024)

Visual monitoring of the cycle-to-cycle variability metrics offers convenience, and can be carried out in real time through an analysis of the temporal diagrams prior to solving the data synchronization task.

5. Conclusions

Real-time diagnostics of marine engines offers significant advantages, as it allows us to analyse the current condition of the cylinder-piston group, the high-pressure fuel equipment, and the valve train mechanism directly, during operation. A real-time diagnostic system enables better adjustment of the corresponding mechanisms and facilitates monitoring of the results of this adjustment during operation.

Enabling the real-time operation of portable diagnostic systems represents a significant development in terms of expanding their capabilities. This advance required a number of problems to be solved, including the development of an efficient algorithm for piston TDC estimation, based exclusively on the cylinder pressure diagram, and the development of special methods for assessing the cycle irregularity. Two sensors are proposed here as a standard configuration of the portable system: a gas pressure sensor, to enable the creation of the pressure diagram for the engine cylinder, and a vibration sensor, which provides data on the fuel injection and gas distribution timing. Real-time assessment of cycle-to-cycle irregularity is suggested, based on the calculation of the following coefficients and indexes: the maximum and average values of coefficients of variation for in-cylinder gas pressure $COV_{P.max}$, $\overline{COV_P}$, the standard deviation for fuel injection and gas distribution timing σ_{φ}, and the cycle irregularity index CII. These factors are calculated from sensor data before real-time cycle synchronisation.

The proposed *original* method for determining the TDC of the piston is based on an analysis of the compression curve segment in the cylinder. Compared to other methods, it possesses greater accuracy, as it does not rely on derivatives of the pressure curve, which may contain a high level of noise when drawn from experimental data. The proposed method for determining TDC can be applied without information on the actual compression ratio in the cylinder, a typical scenario for modern engines with variable valve timing.

An algorithm is proposed for preliminary synchronisation in which the initial position of TDC is determined with sufficient accuracy for most practical cases; this algorithm is used as the first approximation for the method developed here.

To enable a comprehensive assessment of engine irregularity in real time, we propose a factor called CII, which is expressed as a percentage. Coefficients for assessing the irregularity in the timing of the fuel injection and the gas distribution valves are also proposed, using dispersion analysis of the vibrogram fronts. These coefficients are expressed in degrees of rotation of the crankshaft.

Practical implications. The data processing methods presented in this article form the basis for the operation of a new system for real-time parametric diagnostics of marine engines. The system is developed on the basis of a modern dual-core controller with high performance and low power consumption, including a high-speed ADC with sufficient capability to monitor the operating process with a resolution of up to 0.1 degrees of crankshaft rotation for all types of main and auxiliary marine engines. The system also uses wireless data transmission technology. A modern smartphone or tablet based on Android/iOS serves as a computing and graphic component of the system. The developed real-time diagnostic system allows using all the advantages of parallel analysis of pressure in the working cylinders and vibroacoustics. The system determines in real time the main parameters of the working process, fuel injection phases and valve timing.

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Author contributions:

- Conceptualization: V.R., V.M.
- Methodology: V.R., P.S.
- Investigation: P.S., M.T., B.V.
- Writing original draft: V.R.
- Writing review and editing: M.T., B.V., V.M.
- Supervision: R.A., V.M.

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