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INFLUENCE OF THE INDICATOR DIAGRAMS SMOOTHING ON THE INDICATED PARAMETERS OF MARINE DIESEL ENGINES

Rafał Pawletko

Gdynia Maritime University, Faculty of Marine Engineering
Morska Street 83, 81-225 Gdynia, Poland
tel.: + 48 58 6901319
e-mail: pawletko@am.gdynia.pl

Abstract

The topic of this article is to analyze the influence of indicator diagrams smoothing methods on diagnostic parameters determined on their basis such as the maximum combustion pressure, mean indication pressure and heat release characteristics. Indicator diagrams of marine engines are subject to serious distortions arising primarily from the measuring method for in-cylinder pressure. Measurements are performed on the indicator valve which connect with the combustion chamber through the indicator channel. Depending on the engine design the channel length can reach a considerable length and introduces significant distortion in both the phase and amplitude of the pressure signal. Further analysis of the indicator diagram eg. in order to determine the heat release characteristics requires the use of methods of smoothing and filtering of interference. The results confirm no effect of indicator diagram smoothing for the value of the mean indicated pressure, which is one for the most important indicated parameters. A significant influence of smoothing on the maximum value of the heat release rate was observed. The differences in this case exceed 50%. At the same time confirmed that the heat release rate curve determined on the basis of a diagram without smoothing, carry a high level of interference, which precludes their practical use. Smoothing allows getting heat release rate curves that carry vital information about the working process of the engine.

Keywords: *indicator diagrams, smoothing the interference, engine indicated parameters*

1. Introduction

Indicator diagrams are a major source of information of the working process of the piston engines. Among other things, they allow determination of the heat release characteristics and the number of parameters describing the combustion process. Reliability of the indicator graphs is of particular importance with regard to restrictive environmental regulations and the need to reduce toxic exhaust emissions. It is also envisaged to use the heat release characteristics to combustion control of diesel engines in online control systems.

Indicator diagrams carry a range of diagnostic information useful to assess the technical condition of the engine, especially injection equipment and the combustion chamber.

In order to obtain reliable heat release characteristics, it is necessary to have the pressure curve as possible “smooth” free from interference. The fulfilment of this condition in practice it is extremely difficult.

In the field of in-cylinder pressure measurements can distinguish, a number of important factors that make the resulting pressure are significantly distorted:

- pressure sensor is not located directly in the combustion chamber but on the indicator valve,
- an indicator valve connects with the combustion chamber via an indicator channel, which, depending on the engine design can achieve a considerable length and volume,
- pressure measurement via an indicator channel causes distortion in phase and amplitude of the signal, and introduces an oscillating noise, which is result from vibrations of the gases in the indicator channel,
- measurements under variable temperatures and high pressures put high demands on precision and reliability with respect to the sensor,

– used measuring system is susceptible to electrical noise generated by the engine systems and engine room devices that emit electromagnetic fields.

The difficulties associated with the in-cylinder pressure measurement forcing the need of post processing of the indicator diagrams. It is expected that the method of filtering and noise smoothing substantially affect the value of indicated parameters.

The topic of this article is to determine the impact of smoothing methods to indicate parameters determined because of indicator diagrams, such as the maximum combustion pressure, mean indicated pressure and heat release characteristics.

2. Indicator diagrams smoothing

Disturbances affecting the shape of the indicator diagram can be divided into two major groups. The first group of interference is caused by means of measurement of pressure in marine engines and mainly to the influence of the indicator channel. The second group consists of electrical noise, which is related to the operation of the engine systems and auxiliary equipment recorded by measuring lines of the system. Disruption of such nature is of particular importance in the engine room environment [5].

Pressure sensors are not placed directly in the cylinder but on the indicator valve. Depending on the engine construction the indicator channel length, which connects an indicator valve with the combustion chamber can be up to one meter. Channel so considerable length and relatively small diameter causes pressure absolute errors and phase errors resulting from the need to overcome by the pressure wave the distance between the combustion chamber and measurement sensor. According to [3], the indicator channel geometry and engine speed significantly affect the shape of the indicator diagram. Maximum pressure value error increases with the length of the indicator channel and with increasing engine speed, while decreases with increasing diameter of the indicator channel. There was no effect of the engine load to the pressure error [3].

A study carried out in [2] showed a significant relationship between the diameter of the indicator channel and the diameter of the pressure sensor. It has been shown that in the case where those two diameters are close to each other it is possible to eliminate the resonant frequency and obtain diagram free of an oscillating interferences.

Influence of indicator channel to the pressure signal was also found in work [2]. A proposal to modify the channel construction and special placement of the probe adapter to eliminate resonant vibration was presented.

The problem of distortion introduced by the channel indicated is extremely important as evidenced by the results of research in this area. Despite the theoretical possibility of such modifications to the channel measurement errors were minimized, especially in terms of the resonant frequency, these solutions will not find application that is more practical. An alternative to the structural modification is an attempt to smooth-filtering interference in the processing of indicator diagrams (post processing) [2].

Example of medium speed marine engine indicator diagram is shown in Fig. 1.

The basic, now commonly used method of smoothing indicator diagrams is averaging, diagrams measured in stationary conditions. Averaging can range from a few up to several dozen curves. This method allows eliminating interference primarily of a random occurring in single pressure curve.

The most popular method of measurement data smoothing is the moving average. This method consists in the fact that each value in the data set is replaced with the average value of the range of a predetermined width.

Generalization of the moving average filtering method is Savitzki-Golay filter [8]. The filter coefficients are determined by polynomial approximation to the original curve desired degree by the least squares method. Similarly, to the moving average approximation is implemented in the moving interval of predetermined width. For this reason, Savitzki-Golay filter is called a moving

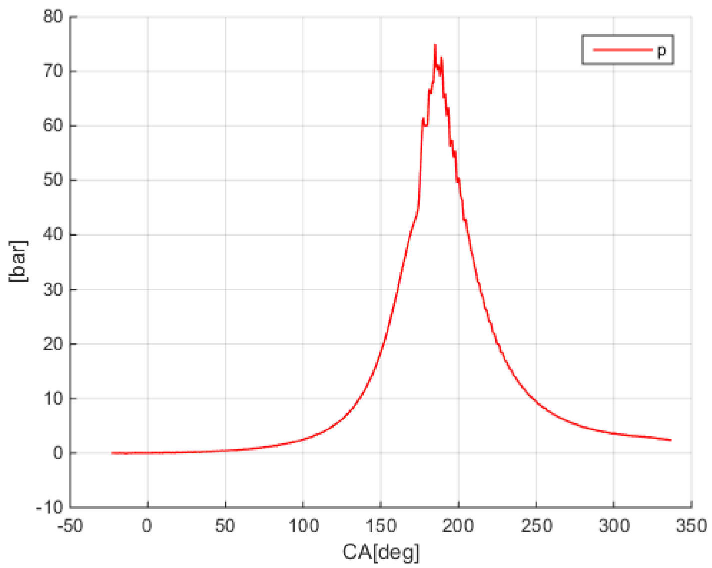

Fig. 1. Indicator diagram of marine diesel engine Sulzer 3Al 25/30

polynomial approximation. The use of a sufficiently high degree polynomial allows for highly effective anti-aliasing without worrying about losing important information contained in the original signal. Savitzkiego-Golay filter is very effective with regard to maintain of high-frequency components of the signal. Compared with a moving average may instead be less effective in the removal of random noise.

While moving approximation can be considered a development of the idea obvious moving average, the use of multiple moving approximation for processing the measurement data to be considered for achieving great importance. The moving approximation is based on calculate the value of the approximated at one point approximation interval, movable along the measurement axis or created as the arrival of measurement data analysis systems on-line. Data set on which the approximation is made in the next step (transition), the results from the previous step approximation. At every step of approximation are obtained new sets of coefficients of the approximating expressions.

In order to filter out disturbances of the indicator diagram is also possible directly to apply digital filters. Given the nature of interference are primarily low-pass filters with finite impulse response due to the linear characteristic of the phase [1].

Based on own research, a significant advantage Sawitzki-Golay filter with respect to the moving average method was found. Comparison of waveforms obtained from the two methods is shown in Fig. 2 and 3.

3. Research results

The experimental study was carried out on a four-stroke medium speed engine Sulzer 3AL 25/30. This engine is characterized by a relatively long indicator channel connecting the combustion chamber with the indicator valve. This channel introduces significant oscillatory disruption, which greatly restricts the diagnostic use of diagram.

Engine indication was made with electronic indicator Unitest 201 equipped with combustion sensors Kistler type 6353A24.

In order to determine the effect of smoothing on the indicated parameters, the values determined from the original untreated diagram and smoothed with Savitzky-Golay filter were compared.

The calculations were performed for an engine load of 50 kW which is about 10% nominal load, 100 kW, 150 kW, 200 kW and 250 kW which is about 70% nominal load.

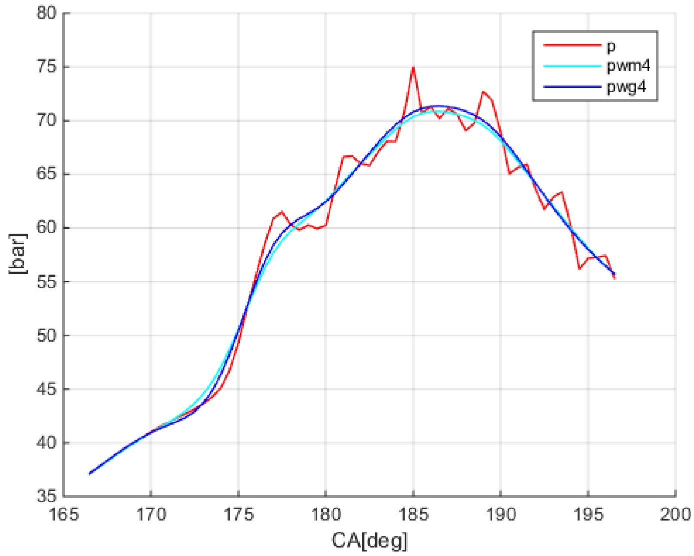

Fig. 2. Indicator diagram smooth by moving average, of the interval width k = 5 points pwm4 and Savitzkiego-Golay filter pwg4 width interval k = 12 points

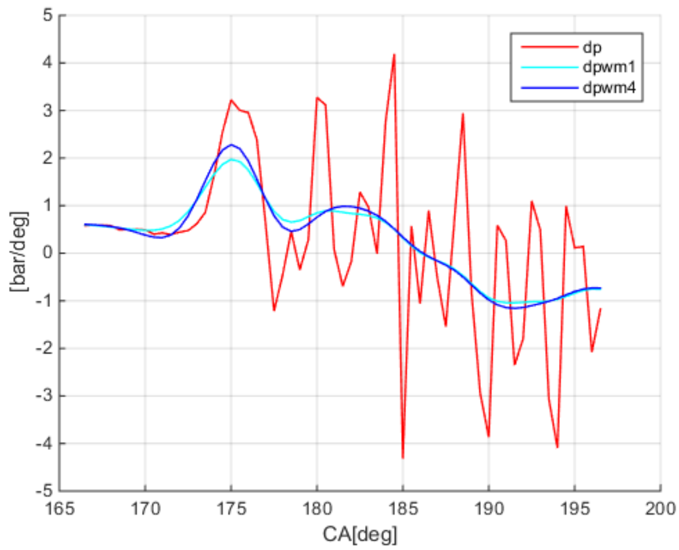

Fig. 3. The first order derivatives of indicator diagram designated on dpwg4 and dpwm4

An analysis of the following parameters defined because of indicator diagrams was done:

- maximum combustion pressure P_{max},
- mean indication pressure MIP,
- expansion pressure P_{exp} (36 CA after TDC),
- maximum heat release rate q_{max},
- released heat Q_{max}.

3.1. The influence of indicator diagram smoothing on the maximum combustion pressure

The influence of smoothing on the maximum combustion pressure was shown in Tab. 1.

The absolute difference of the maximum combustion pressure for the smoothed and original indicator diagram is between 1.12 to 1.59 bars. For the whole load range, it is relatively about 2%. This difference is primarily due to smoothing impulse noise caused by vibrations of the column of gases in the indicator channel, which around the maximum combustion pressure have a large amplitude.

Tab. 1. Comparison of the results of the maximum combustion pressure for the original curve P_{max} and smoothed curve P_{max_w}

Load [kW]	P_{max} [bar]	P_{max_w} [bar]	dif [bar]	dif_% [%]
50	51.02	49.68	1.34	2.6
100	59.99	58.68	1.30	2.2
150	69.51	68.40	1.12	1.6
200	78.72	77.22	1.51	1.9
250	87.63	86.04	1.59	1.8

However, taking into account that the error value is systematic in the whole range of loads can be considered admissible. This confirms the very high Pearson correlation coefficient between p_{max} and p_{max_w}, which is 1.

3.2. The influence of indicator diagram smoothing on the mean indicated pressure

The influence of smoothing on the mean indicated pressure was shown in Tab. 2.

There was no influence of the indicator diagram smoothing on the value of mean indicated pressure. For all investigated load identical results were obtained for the smoothed diagram and an original one.

Tab. 2. Comparison of the results of the mean indicated pressure for the original curve MIP and smoothed curve MIP_w

Load [kW]	MIP [bar]	MIP_w [bar]	dif [bar]	dif_% [%]
50	4.60	4.60	0	0
100	6.29	6.29	0	0
150	8.27	8.27	0	0
200	10.08	10.08	0	0
250	12.01	12.01	0	0

3.3. The influence of indicator diagram smoothing on the expansion pressure

The influence of smoothing on the expansion pressure was shown in Tab. 3.

The effect of the indicator diagram smoothing on the value of the expansion pressure is negligible and does not exceed 0.5 bar. At this point the diagram 35 CA after TDC, the influence of interference is small, so even a strong smoothing no longer causes large errors in pressure.

Tab. 3. Comparison of the results of the expansion pressure for the original curve P_{exp} and smoothed curve P_{exp_2}

Load [kW]	P_{epx} [bar]	P_{epx_w} [bar]	dif [bar]	dif_% [%]
50	20.40	20.60	0.20	1.0
100	25.80	25.30	0.50	1.9
150	31.40	31.40	0	0
200	36.50	37.10	–0.60	–1.6
250	43.50	43.20	0.30	0.7

3.4. The influence of indicator diagram smoothing on the maximum heat release rate q_{max}

The influence of smoothing on the heat release rate was shown in Tab. 4.

The maximum heat release rate is a parameter, which strongly depends on smoothing of the indicator diagram. Effect of anti-aliasing in this case results from the fact of elimination of high-frequency components from the curve, so the result is a smoother curve of the first order derivative and the second order derivative.

Tab. 4. Comparison of the results of the maximum heat release rate for the original curve q_{max} and smoothed curve q_{max_w}

Load [kW]	q_{max} [kJ/CA]	q_{max_w} [kJ/CA]	dif [kJ/CA]	dif_% [%]
50	1.13	0.46	0.67	59.4
100	1.21	0.51	0.70	58.2
150	1.49	0.56	0.93	62.6
200	1.35	0.61	0.73	54.5
250	1.25	0.66	0.60	47.7

The relative difference of maximum heat release rate exceeds 50%. Such a big error in theory should eliminate this indicated parameter. If we take into account the all course of the heat release rate, it seems that it may be useful for the analysis of the working process of the engine.

Figure 4 shows the curve of heat release rate based on the original diagram while Fig. 5 shows the curve of heat release rate determined because of the smoothed indicator diagram.

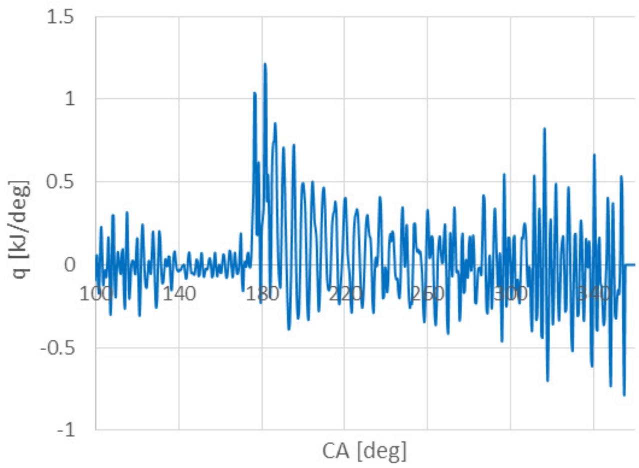

Fig. 4. Heat released rate determined because of the original indicator diagram

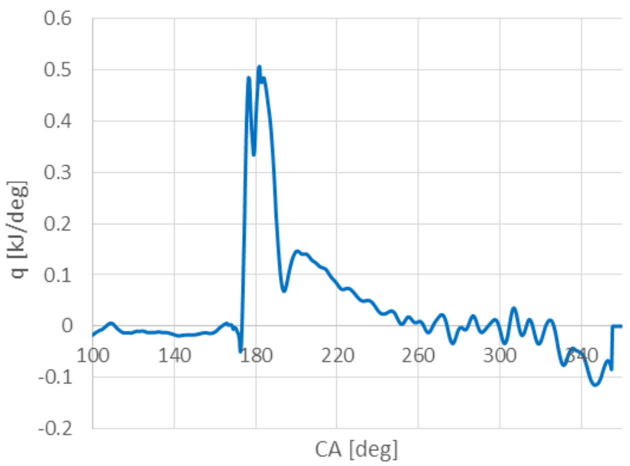

Fig. 5. Heat released rate determined because of the smoothed indicator diagram

High frequency noise visible in Fig. 4 eliminates the usefulness of heat release rate determined on the basis on original diagram. At the curve shown in Fig. 5, despite the limitations the maximum heat release rate, it is possible to identify specific points of combustion, which are important diagnostic, particularly in relation to the assessment of the injection system.

In Fig. 6 shows a comparison of the maximum heat release rate determined for the smoothed and original indicator diagram for all test engine load.

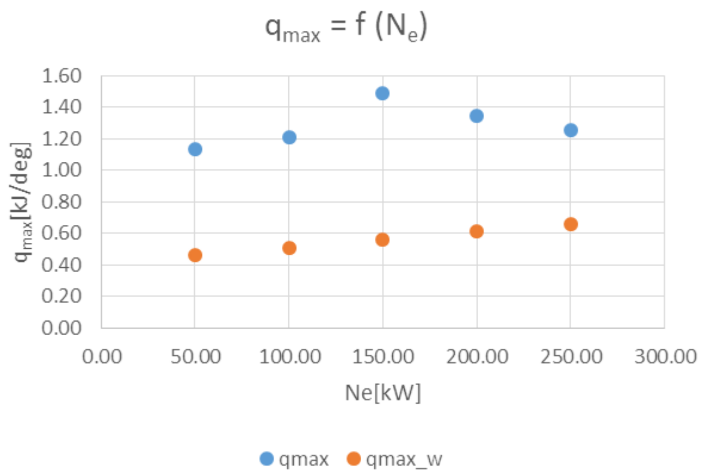

Fig. 6. Maximum heat released rate determined for the smoothed q_{max_w} and original indicator diagram q_{max}

In the case of q_{max_w} curve, a linear relationship between the maximum heat release rate and the engine load is present. In the case of q_{max} to the value of the load 150 kW heat release rate increases, but decreases above load 150 kW. It must be assumed that the differences in the results depending mainly from a significant level of interference that determine the maximum values in relation to q_{max}.

3.5. The influence of indicator diagram smoothing on the released heat Q

The influence of smoothing on the released heat was shown in Tab. 5.

The absolute difference of the released heat for the original and smoothed diagram is of about 0.3 kJ. Relative error for the entire load range is from 1.3% to 3.7%.

However, taking into account that the error value is systematic in the whole range of loads can be considered admissible. This confirms the very high Pearson correlation coefficient between Q and Q_w, which is 1.

Tab. 5. Comparison of the results of the released heat for the original curves Q and smoothed curve Q_w

Load [kW]	Q [kJ]	Q_w [kJ]	dif [kJ]	dif_% [%]
50	8.13	7.84	0.30	3.7
100	11.11	10.76	0.35	3.1
150	14.50	14.27	0.23	1.6
200	18.31	18.02	0.29	1.6
250	22.06	21.77	0.29	1.3

4. Conclusions

The aim of this study was to determine the effect of indicator diagrams smoothing for parameters determined on their basis.

The obtained results show that, the majority of the studied indicated parameters, the impact of smoothing is small and does not exceed 3%. The error introduced by smoothing is also systematic in the all tested engine load.

The results confirm no effect of indicator diagram smoothing for the value of the mean indicated pressure, which is one for the most important indicated parameters.

A significant influence of smoothing on the maximum value of the heat release rate was observed. The differences in this case exceed 50%. At the same time confirmed that the heat release rate curve determined because of a diagram without smoothing, carry a high level of interference, which precludes their practical use. Smoothing allows getting heat release rate curves that carry vital information about the working process of the engine.

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