RESEARCH OF THE INFLUENCE OF MARINE DIESEL ENGINE SULZER AL 25/30 LOAD ON THE TDC POSITION ON THE INDICATION GRAPH

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Abstract

The article presents the research results of load influence on errors of the piston Top Dead Centre (TDC) position determined on indication graph with combustion. For TDC determination the method proposed by Polanowski is applied. This method is based on least-squares approximation with model of thermodynamic compression using a polynomial exponent. So, designated TDC are kinematics. This method make possible determination the TDC on the indicator diagram with combustion, as well as the total compression ratio and the dynamic error of pressure (offset). Research were done on the laboratory engine Sulzer 3A L25/30 for load range of 50-250 kW and rotational speed 750 rpm, which corresponds to 15-90% nominal load. Cylinder pressures were recorded with a resolution of 0.5 OWK by means of multichannel recorder UNITEST 205. For pressure measurements were applied strain gauge pressure sensors Spais Company. For the analysis of indicator diagrams used its own specially developed algorithm and program for the automatic determination of TDC, based on the model of the compression process with the exponent of the polynomial. Simultaneously three parameters were determined: the position of TDC, the total compression ratio and offset the pressure. Additionally set the position of the zeros of the second order derivatives, which are sometimes considered as reference points to TDC of pistons. For smoothing of indicator diagrams their own algorithms and programs of moving approximation by polynomials of 3rd degree was used. The results of research have shown the essential load influence on the errors of TDC positions on indicator diagrams.

Keywords: *kinematic TDC determination, coordinate of zero value of second derivative, load influence on TDC position*

1. Introduction

The TDC location in an indicator chart is one of the major problems of indicator chart processing. It's main impacts are on the accuracy of setting the mean indicated pressure and the characteristics of heat release.

The indicator charts are delayed and deformed as a result of influence of gas channels located between a cylinder and a sensor. Additional errors are introduced by torsional vibrations of the shaft. The total delays of TDC in the case of medium speed engines, type A, at rotational speeds of 750-1000 rpm may reach to 3.5° OWK, according to the type of the indicator valve used. In the case of slow speed engines, the delays of TDC are smaller and do not exceed 0.5-1 OWK, but these are still the values causing significant errors of setting the mean indicated pressure and characteristics of heat release .

There are known the concepts of dynamic TDC, as well as thermodynamic TDC, and the methods of their determination [5, 6]. The TDC dynamic location is burdened with the error of delay of the pressure signal in gas channels. The thermodynamic TDC is determined on the basis of the curves of pure compression. Its essence is not obvious, owing to the fact that TDC is by definition a kinematic notion. A separate publication will be devoted to explain this issue.

Sometimes, in operational measurements, one adopts as TDC the point of occurrence of maximum compression pressure or zero place of the derivative of the first grade. To set the above parameters, as well as thermodynamic TDC, it is necessary to dispose of the charts of pure compression, which requires a shutdown of the fuel supply to the cylinders, for the measurement time. In the case of marine engines, this kind of measurement threatens to breach the tightness of the fuel systems, cause unstable engine operation, as well as being associated with changes to the thermodynamic condition of a cylinder after a shutdown of the fuel supply. A shutdown of the fuel supply to the cylinders on higher engine loads in the operation conditions is simply not feasible, and these loads are most diagnostically reliable.

The used method of TDC determination [3, 4] allows TDC location not only in the chart of pure compression, but also in an indicator chart with combustion. The foundations of the method come from the assumption that the compression interval, the variable exponent of the curve of compression, can be presented with a power multinomial. The TDC being determined is a kinematic TDC. The paper has also examined the method consisting in referencing the positions of TDC to zero places being second grade derivatives of compression curves [1]. Though this method does not give the possibility of direct location of TDC, it could be beneficial in the diagnostic practice of marine engines, in the case of sufficiently stable positions of those points in respect of the positions of TDC.

2. Determination of kinematic TDC location based on the model of compression process with a multinomial exponent

Multi-parameter model of compression process [3, 4] is based on two main assumptions:

- at each point, the compression process is polytropic,
- in the compression interval, the exponent of the curve of compression can be described with a polynomial degree a.

Taking into account the above assumptions, the model of compression can be written as follows:

$$pV^{m_x}=const=c, \tag{1}$$

where:

p - pressure,
V - gas volume,
m_x - exponent of compression process.

Dividing equation (1) by piston displacement, one obtains the form of a compression equation in which the volume is present in a non-dimensional form:

$$pv^{m_x}=const=c, \tag{2}$$

where:

υ - on-dimensional volume.

Compression curve exponent m_x can be written as a multinomial function of a non-dimensional way of a piston s_x:

$$m_x=m_0+m_1s_x+\cdots+m_as_x^a, \tag{3}$$

where:

$m_0, m_1, \ldots, m_a$ - the coefficients determined as a result of approximation of the curve of pressure,
a - degree of polynomial (in work was accepted $a = 3$ [3]).

Non-dimensional way of a piston made from DMP, for a central crank mechanism, is expressed by the following formula:

$$s_x=\frac{1}{2}\left(1-\lambda^{-1}+\sqrt{\lambda^{-2}-(\sin\alpha)^2}-\cos\alpha\right). \tag{4}$$

Non-dimensional gas volume υ has been defined as follows:

$$v=v_{xs}+v_{cx}, \tag{5}$$

where:

$$v_{xs}=1-s_x,\ v_{cx}=v_\varepsilon+v_z+v_{px},\ v_\varepsilon=(\varepsilon-1)^{-1}, \tag{6}$$

where:

v_ε - non-dimensional geometric volume of a combustion chamber,

v_z - non-dimensional change of the cylinder volume due to contamination, wear and assembly errors,

v_{px} - apparent non-dimensional change of the cylinder volume due to gas blow-by (piston wey function).

Summary influence of the cylinder volume changes on the process of compression is characterized by the parameter ε_c named as a total degree of compression, which is determined from the model and can be used as a diagnostic parameter.

$$\varepsilon_c = (1 + v_c)v_c^{-1}, \tag{7}$$

where:

v_c - non-dimensional volume of a combustion chamber, $v_c = v_{cx}(s_x = 1)$

The curve and values of blow-by are assumed, since the method of distinguishing the effect of their changes on the curve of compression from the influence of the exponent m_x changes has not been determined.

As a consequence of the delay of the curve of pressure, the angular axis of an indicator graph a_w is shifted by the error a_G of piston TDC location. Actual angular axis a is determined from a formula:

$$\alpha = \alpha_w + \alpha_G. \tag{8}$$

The sensors applied to indicate the cylinders do not usually carry the constant component or they are burdened with a large margin of error and are removed, which is equal to cutting the absolute compression pressure value by the error of pressure curve cut-of p_u (offset). The actual pressure value is calculated from the formula:

$$p = p_w + p_u, \tag{9}$$

where:

p_w - measured pressures.

Values p_w may be determined from a model or assumed on the basis of the charging pressure value.

The model parameters searched for are: α_G, v_c i p_u. In order to set them, the indicator charts are approximated with the above model using the method of smallest squares on the selected interval of pure compression a_A (Fig. 1). The criterion of smallest squares is used in a two-level manner.

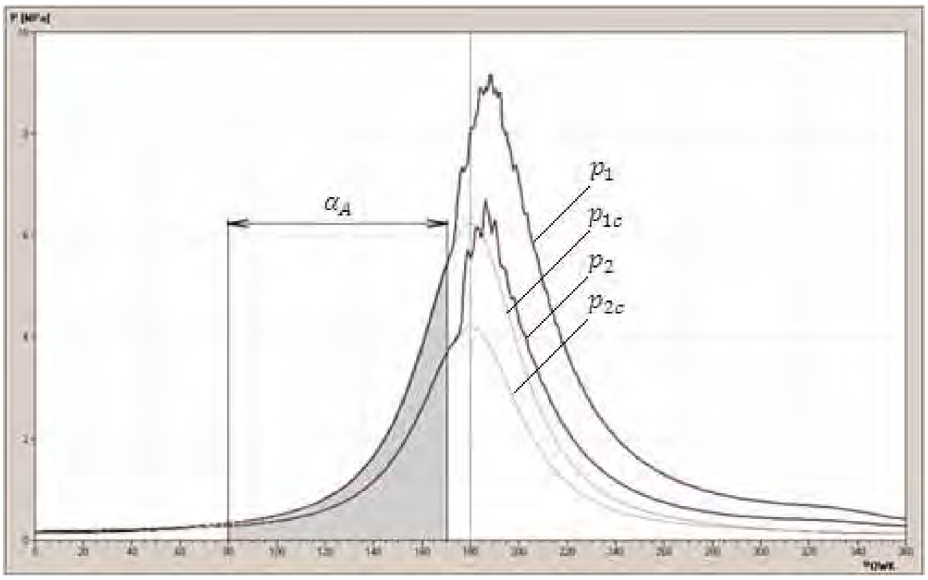

Fig. 1. The examples of indicator charts of the examined engine 3AR25/30 for two loads, for which one has determined the location of kinematic TDC and the curves of pure compression on the basis of the approximation of pressure curves with model (2)-(9) in approximation interval α_A

At the first level of approximation, within a linear procedure, the m_x exponent coefficients are fixed automatically. Determination of the parameters being sought is a non-linear issue. To set out the TDC location and the values of the remaining parameters, programs have been created in Excel and Delphi languages. The program in Delphi gives the parameter values in an automatic mode. The programs can also generate the curves of pure compression (Fig. 1).

3. Determination of the coordinate of zero value of the second derivative

Occurrence of distinctive neutral places (before TDC) of derivatives of the second grade before and after TDC have a kinematic nature and result from application on the thermodynamic process in a cylinder of kinematic dependency in cases of the measurements made in the function of angle of rotation of a crankshaft. These points are the points of bending the curve of pressure. The point of bending occurring on the right side of TDC is of no importance, in the case of combustion. If the indicator chart is to be assigned the function of the cylinder volume or the piston rod, these points will not occur. There are proposed uses of zero places of derivatives of the second grade, occurring before TDC as links to TDC location.

Determination of the location of zero places of the derivatives of the second grade is a difficult task to perform with adequate accuracy. In the case of medium rotating engines, the proximity of the point of bending and beginning of autoignition may prevent determination of the location of this item on the indicator chart with combustion. Even the normally occurring measurement interferences of the curve of compression have a strong impact on the error value of setting the location of this item. This also has a significant impact on the method of determining the location of zero place. For this purpose, once used, e.g. approximation of the curve of compression on the selected interval with the polynomial of 6 degree [1]. Another method for smoothing pressure curves is to use multiple moving approximation (Fig. 2).

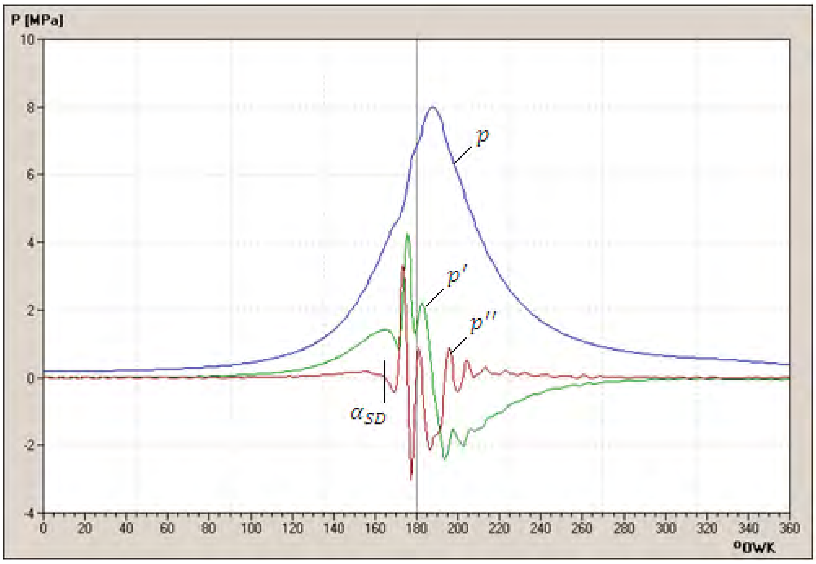

Fig. 2. Example of setting the derivatives of the first grade p' and second grade p '' from indicator graph p of the examined engine 3AR25/3 with the method moving approximation with a multinomial of 3 degree: α_{SD} - zero place of the derivative of the second grade for which $p''(\alpha_{SD}) = 0$

The most credible results can be expected if, for this purpose, one will use the multinomial model (item 2). In this case, the derivative of the second grade can also be conveniently determined using a moving approximation with regard to the curve of pure compression, designated from approximation. To avoid the phase errors, one applies possibly narrow intervals of approximation. In the case of a multinomial of 3 degrees, one applies parameter $K = 2$, which corresponds to approximation interval width amounting to five measuring points.

4. Post tests of the impact of load on the location TDC and zero places of derivatives of the second grade on indicator charts

The primary purpose of the tests was to identify the impact of the level of load on the results of determination of kinematic TDC, as well as repeatability of the obtained results for particular cylinders of a multi-cylinder engine. A further goal of the tests was to identify the impact of load, as well as the selection of a cylinder on the location of zero places of the derivative of the second grade.

The tests were conducted in a laboratory test bed post of four-stroke marine engine, type Sulzer 3Al 25/30, with nominal power $N_{en} = 408\ kW$ at nominal rotational speed n = 750 rpm (Fig. 3).

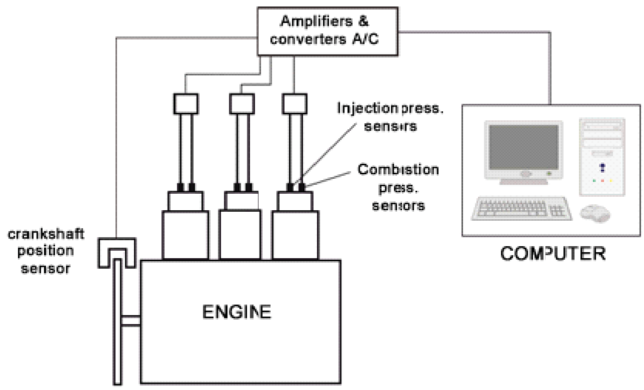

Fig. 3. Laboratory experimental stand

The curves of indicator charts have been recorded with an electronic indicator Unitest 205 with angular resolution of 0.5º OWK for pressure measurement, one has used tensometric pressure sensors from Spice. The curves were averaged for 16 work cycles.

The engine indication was conducted at the load range $N_e = 50\text{-}300kW$ every 50 kW, which, with regard to nominal load, corresponds approximately to the scope of 12.5-75% N_{en}. In order to increase the credibility of the test results, the research experiment was conducted twice.

After each load change, the tester waited for the period necessary to determine a thermodynamic balance of the engine, following the stabilization of flue gas temperatures and cooling factors.

5. Test results

5.1. Load influence on the location of kinematic TDC

In both experiences, the tester has observed significant growth in value α_T for the loads above 50% N_{en} (Fig. 4).

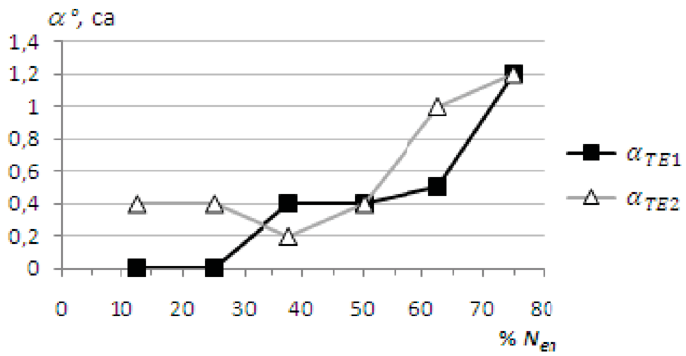

Fig. 4. Load influencet on the location of kin ematic TDC: a_{TE1} - TDC locations set out in experiment 1; a_{TE2} - TDC locations set out in experiment 2

This growth can be estimated as linear. Growth in value a_T with regard to 50-100% N_{en} can be evaluated at about 1° OWK. One cannot exclude committing, during the tests, systematic errors resulting from the breach of the independent principles of the experiments. The correlation coefficient between sets a_{G1} i a_{G2} amount $R(\alpha_{TE1};\ \alpha_{TE2})=0.77$.

5.2. Load influence on the zero location of the second derivative

The paper, to set out zero places, uses triple approximation with a multinomial of 3 degree and the method based on the model of compression process with a multinomial exponent.
Smoothing with the method of moving approximation was conducted for the values of smoothing parameter $K_1 = 6$ and $K_2 = 12$, which correspond to approximation interval width 13 and 25 measuring points. For $K_2 = 12$ the tester obtained high compliance of zero place positions in both experiments (Fig. 5).

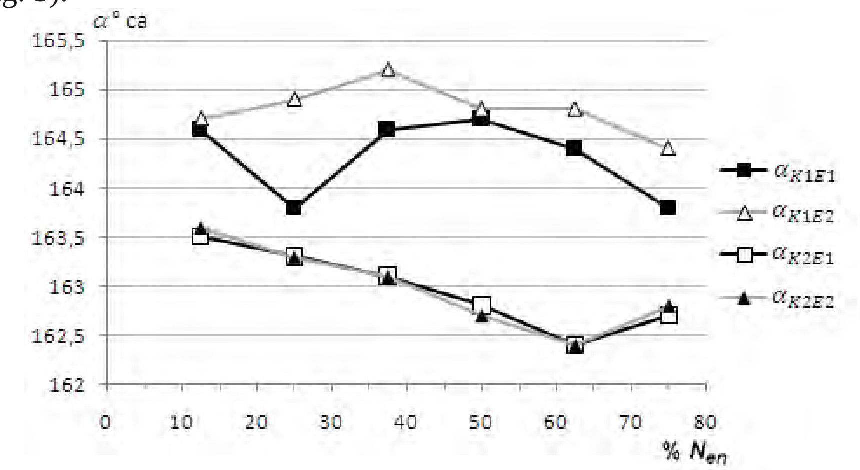

Fig. 5. Load influence on the zero location of the second derivative determined with moving approximation method: α_{K1E1} - experiment 1, K = 6; α_{K2E2} - experiment 1, K = 12; α_{K1E2} - experiment 2, K = 6; α_{K2E2} - experiment 1, K = 12

The correlation coefficient $R(\alpha_{K2E1};\ \alpha_{K2E2})=0.99$ while the $R(\alpha_{K1E1};\ \alpha_{K1E2})=0.45$, which is a consequence of improper selection of smoothing parameters. The difference (shift) between points obtained for the smoothing of $K_1=6$ and $K_2=12$ is a visible on Fig. 5. This shift up to 2° OWK, is caused of the used method and accepted values for smooth parameter K.

The results indicate the same impact load on the location of the zeros places of derivatives of second grade as the kinematic location of the TDC. As can be seen from the comparison of waveforms α_{K2E1} and α_{K2E2} points (Fig. 5) the variability in the investigated load range has led to different positions of the zeros reach 1° OWK.

Similar results of load impact on the location of the zeros of the derivative of the second grade were obtained for the method of determining the positions of the zeros of the curve of pure compression determined from the model (Fig. 6).

The correlation coefficient for the sets of points in Fig. 6 was $R(\alpha_{SDE1};\ \alpha_{SDE2})=0.34$, while for the smoothing method of moving approximation with $K = 12$ (Fig. 5) was for both experiments, $R(\alpha_{K2E1};\ \alpha_{K2E2})=0.99$. We can, however, observe the full convergence of the results of determination of TDC from the model and reference points for the zeros of derivatives of second grade since the first experiment $R(\alpha_{SDE1};\ \alpha_{TE1})=0.95$, for the second experiment, $R(\alpha_{SDE2};\ \alpha_{TE2})=0.91$.

6.Conclusions

The conducted research proved the existence of significant influence of load of combustion engine on the location of kinematic TDC on the curve of an indicator graph, and on the location of zero points of second derivatives of the pressure curves.

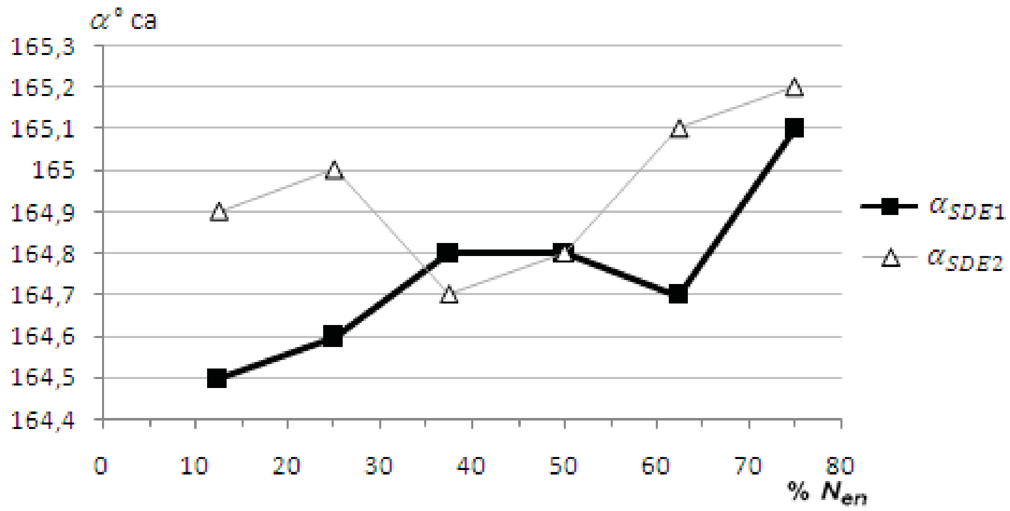

Fig. 6. Load influence on the zero locations of the second deriv ative, determined from the curve of compression, determined from the model (point 2): α_{SDE1} - the location of zero point of thesecond derivative determined for experiment 1; α_{SD1E2} - the location of zero point of thesecond derivative determined for experiment 2

Change in load of the examined engine with regard to 12.5-75% N_{en} caused change of location of kinematic TDC reaching 1.2° OWK. So, significant differences of TDC location cause considerable errors in the curve of setting the mean indicated ressure, as well as the characteristics of heat generation amounting to 10%.

The changes of the location of zero point of second derivatives in relation to the changes of load in the examined range are similar and amounted to approximately 1° OWK.

Simultaneously, the tester has observed significant influence of the method of determination of zero location of the second derivative on the obtained results. The most accurate and secure method is indicator graph approximation in a compression interval with a polynomial model, and then the use of moving approximation to set out the second derivative. Smoothing the indicator graph in order to determine the second derivative may result in the occurrence of significant errors of location of its zero places: for too small values for K due to the influence of disturbances, for too large values for the phase error.

In the case of low speed engines, both the locations of kinematic TDC and zero places of the second derivatives are determined with much greater accuracy, due to the presence of autoignition near or after TDC. However, one should expect that the impact of load on the locations of those points will be the same.

Significant influence on the rate of error may be the kind of sensor. It is planned to test also for other types of sensors and to conduct more experiments on more cylinders.

References

[1] Gałecki, W., Tomczak, L., *Metoda określania położenia wału korbowego silnika okr ętowego na podstawie analizy krzywej spr ężania*. Journal of KONES Internal Combustion Engines, Bielsko Biała 1997.

[2] Łutowicz, M., *Ocena szczelności komory spalania okrętowego tłokowego silnika spalinowego w czasie eksploatacji*. Diagnostyka 2(48), 2008.

[3] Polanowski, S., *Determination of location of Top Dead Centre and compression ratio value on the basis of ship engine indicator diagram*. Polish Maritime Research, No. 2(56), Vol. 15, 2008.

[4] Polanowski S.: *Studium metod analizy wykresów indykatorowych w aspekcie diagnostyki silników okrętowych*. Zeszysty Naukowe Nr 169 A, Akademia Marynarki Wojennej, Gdynia 2007.

[5] Staś, M. J., *Thermodynamic Determination od T.D.C. In Piston Combustion Engines*. SAE Paper, No. 960610.

[6] Tazerout, M., Le Corre, O., Rousseau, S., *TDC Determination in IC Engines Based on the Thermodynamic*. SAE Paper, No. 1999-01-1489.