INFLUENCE OF TDC DETERMINATION METHODS ON MEAN INDICATED PRESSURE ERRORS IN MARINE DIESEL ENGINES

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Abstract

The paper presents the results of comparative analysis of influence of different methods of TDC determination for the calculation errors of mean indicated pressure (MIP). Lemag method based on zero point of first order derivative, used in PREMET pressure analyzers, was compared to the method based on a polynomial model of the compression process. Comparisons were made on the operating measurement data obtained on the low speed marine engine RTA96C which forms the main propulsion of the vessel and the medium speed engine MAN L28/32A. Measurements were made with onboard combustion PREMET analyzer. It was found that the method based on zero point of first order derivative can give the deviations of position of TDC in excess of 2°CA which is caused by disturbances associated with the measurement of pressure and interference associated with the generation of the angular axis. These errors are related to the accuracy of the methods of determining of the first derivative and the availability of a sufficient range of pure compression after TDC. The best results of determining the TDC position was obtained from the original method based on a polynomial model of the compression process. It should be emphasized that the proposed method enables individual adjustment of TDC for each cylinder and can be used even when the combustion begins before TDC. The conducted research proved the existence of significant influence of indicator graph TDC location on the mean indicated pressure calculation errors.

Keywords: *TDC determination, coordinate of zero value of second derivative, TDC position influence on MIP errors*

1. Introduction

The TDC (Top Dead Center) location on an indicator graph is one of the major problems of indicator graphs processing. To obtain sufficient accuracy and repeatability of the mean indication pressure (MIP) and heat release curves results, TDC determination error should not exceed ±0.1°(±0.3°) CA.

The indicator graphs 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°CA, according to the type of the indicator valve used. In the case of low speed engines, the delays of TDC are smaller and do not exceed 0.5-1°CA, but these are still the values causing significant errors of setting the mean indicated pressure and characteristics of heat release.

2. TDC determination methods for indicator graphs analysis

For comparison, two methods for TDC determination was used for indicator graphs analisis: the LEMAG method (PREMET indicator producer) [4] and an original method based on a polynomial model of the compression process [3].

A method based on a polynomial model of the compression process is an example of practical application of uses compression model for TDC determination [1-3]. Multi-parameter model of compression process 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 .

The proposed method of TDC determination allows TDC location not only in the graphs of pure compression, but also in an indicator graph 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. 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.

In operating diagnosis of marine engines TDC is usually attributed to the zero coordinate of the first order derivative of pressure. To set the above parameters, as well as thermodynamic TDC, it is necessary to dispose of the graphs 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.

Figure 1 illustrates a method of determining TDC patented by LEMAG (Lehmann & Michels) [11], known in shipbuilding PREMET manufacturer of electronic indicators. The operator raises the cursor to the vertical marker (straight) on the visually estimated mid-point between the peak and valley of the derivative (Fig. 1). Then rotate the marker to the position of approximation. Following the approximation is designated zero point derivation, which is associated with a dynamic TDC. Indicator graph is pushed to the designated angle.

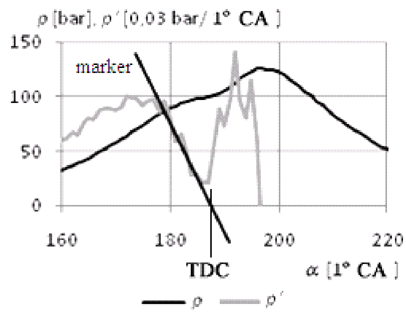

Fig. 1. Principle of forecasting of zero first order derivative on the indicator graphs proposed by Lehmann & Michel company

4. Operational tests

The primary purpose of the tests was to identify the impact of TDC determination errors on the results of mean indication pressure (MIP) results. A further goal of the tests was to compare different methods of TDC determination and try to estimate their errors.

The tests were conducted on two ships diesel engines during sea journey. First engine Wartsilla 9 RTA 96C, two-stroke low speed marine engine with nominal power N_{en} = 24 000 kW at nominal rotational speed n = 82 rpm. Secound engine 8 MAN L28/32A, four-stroke medium speed marine engine with nominal power $\mathbf{N_{en}}$ = 1960 kW at nominal rotational speed n = 720 rpm.

The curves of indicator graphs have been recorded with an onboard electronic indicator Premet with angular resolution of 1 ^{o}CA for pressure measurement. Electronic indicator has used tensometric pressure sensors.

5. Test results

5.1. TDC and MIP determination using the Lemag method

In order to designate the TDC position Lemag automatic method was used. This method is an available in PREMET software indicator measurement system. Despite the use by the manufacturer angular crankshaft positioning, angular error of indicator diagrams came to few degrees of crankshaft angle. Additional difficulties, hindering the analysis of the indicator diagrams, were that the actual TDC determination errors were random in nature. Collection form of indicator graphs for the all cylinders before and after automatic TDC correction are shown in Fig. 2.

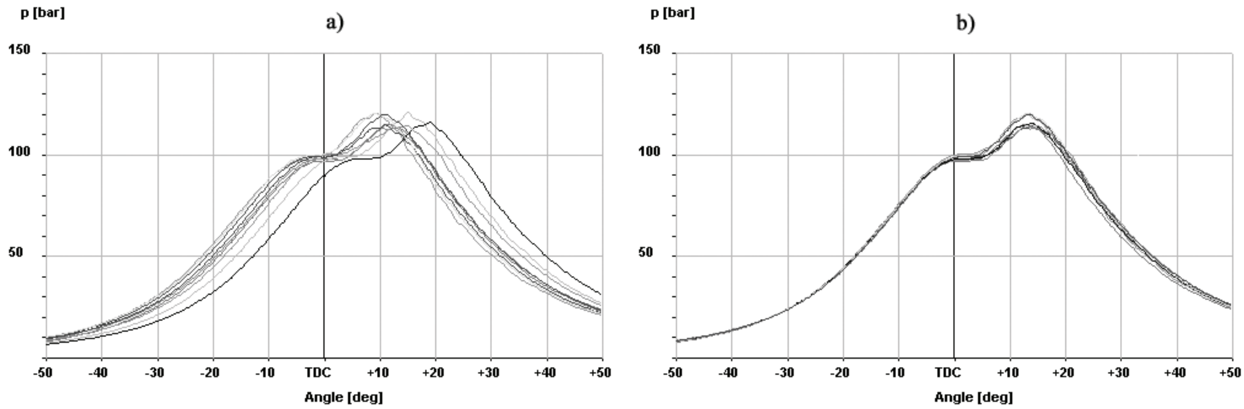

Fig. 2. Comparison of indicator graphs for all cylinder of low speed engine 9RTA96C: a - before TDC correction (directly from measurement), b - after automatic TDC correction (Lemag method)

For compare the impact of TDC location on the mean indicated pressure (MIP) calculations were made twice for indicator graphs without TDC correction and with the correction performed by the Lemag method. Summary of calculation results with MIP percentage deviations from the average of nine cylinders for the two data sets are presented in Tab. 1

Tab. 1. Mean indicated pressure calculation results for nine cylinders before TDC correstion (MIP) and after TDC correction (MIP cor), dif MIP - percentage deviations from the average

	Cyl 1	**Cyl 2**	**Cyl 3**	**Cyl 4**	**Cyl 5**	**Cyl 6**	**Cyl 7**	**Cyl 8**	**Cyl 9**	**Average**
MIP [bar]	10.9	10.6	14.9	8	8.9	17.9	12.8	8.4	10.4	11.4
dif MIP [%]	-5%	-8%	23%	-43%	-28%	36%	11%	-36%	-10%	-
MIP cor [bar]	12	12.7	12.7	12.6	12.7	12.5	13.1	12.8	13.2	12.7
dif MIP cor [%]	-6%	0%	0%	-1%	0%	-2%	3%	1%	4%	-

The obtained results are different significantly. Deviations from the average for non-corrected TDC results reach 36%, while with the correction does not exceed 6%. MIP deviation for each cylinder may not be, of course, confirmation of the correctness of the method, since it may result in with a variety of technical condition of individual cylinders and a bad engine regulation. However, given the clear phase shift of indicators graphs shown in Fig. 2, adjustment of the TDC does not appear to be disputed.

An interesting comparison is reference the TDC deviations for the two series of data made for the same engine in a short period of time. Statement of deviations are illustrated in a Fig. 3.

Taking into account the values of TDC deviations for two data series, can be concluded that they are random and unique. This indicates the necessity of TDC correction individually for each data set, and it is not possible to establish fixed values of the correction for each cylinder. It should be stressed, very high values in excess of the designated TDC correction which exceed 5 oCA. This situation virtually excludes the possibility of any diagnostic use of indicator graphs without TDC correction.

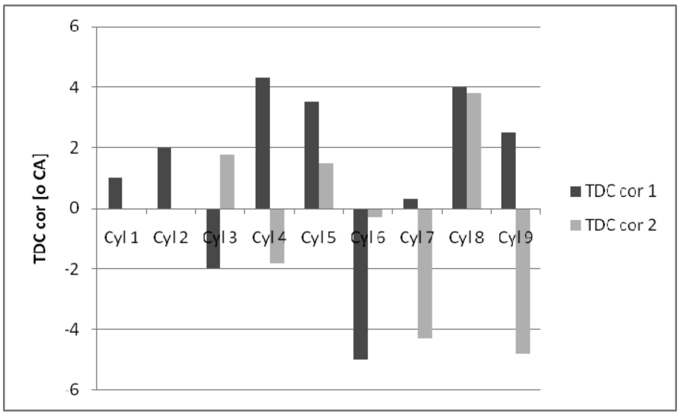

Fig. 3. The TDC deviations values for the two data series RTA96C (TDC cor 1, TDC cor 2)

A similar impact analysis of TDC position for MIP values was performed for the medium speed engine MAN L28/32A. Determined MIP values and their deviations from average values after TDC correction according to Lemag automatic method for the three data sets are presented in Tab. 2 and Fig. 5.

Tab. 2. MIP values and deviations from average values after TDC correction for MAN L28/32A engine (three date sets), dif MIP - percentage deviations from the average

	Cyl 1	**Cyl 2**	**Cyl 3**	**Cyl 4**	**Cyl 5**	**Cyl 6**	**Cyl 7**	**Cyl 8**	**Average**
MIP s1 [bar]	18.8	19.6	17.2	16.4	19.1	16.6	15.4	15	17.3
dif MIP s1 [%]	8%	12%	0%	-5%	10%	-4%	-12%	-15%	-
MIP s2 [bar]	17.6	19.2	18.1	19.4	20.6	19.4	17.4	17.9	18.7
dif MIP s2 [%]	-6%	3%	-3%	4%	9%	4%	-7%	-4%	-
MIP s3 [bar]	19	18.8	19.3	18.4	19.7	19	18.3	18.4	18.7
dif MIP s3 [%]	1%	0%	2%	-3%	4%	1%	-3%	-3%	-

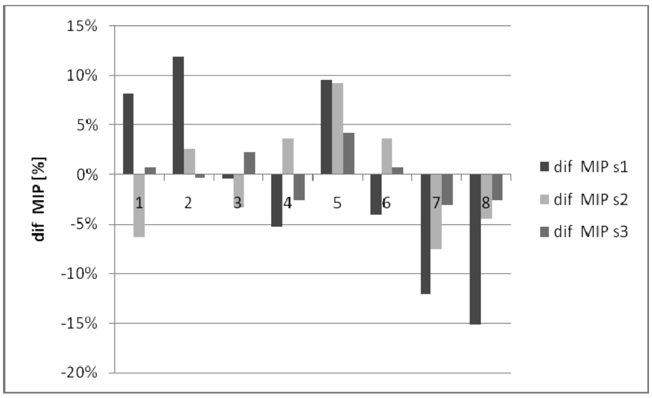

Fig. 5. MIP deviations from average (8 cylinders) values after TDC correction for the three data sets of MAN L28/32A engine

In the case of the MAN L28/32A engine, even after TDC correcion, there are clear differences in mean indicated pressure between the cylinders reaching up to 12%. Such differences can obviously provide a poor technical state engine or wrong regulation, in that case, however, the proportion of variation between the cylinders in each measurement series should have similar values. In this case a pattern is visible only to cylinders 5, 7 and 8 (Fig. 5) in other cases, the differences between cylinders are random. The reason for this may be the sensor measurement errors or TDC correction errors of Lemag automatic method.

The TDC deviations for the three series of data for the MAN L28/32A engine are illustrated in a Fig. 6.

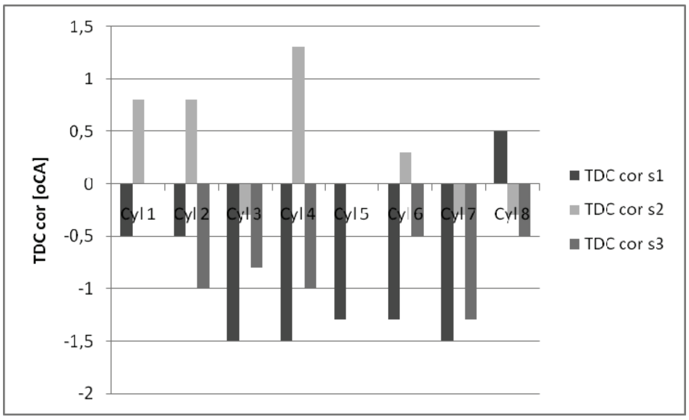

Fig. 6. TDC correcions values for 8 cylinders for the three data sets of MAN L28/32A engine

As with the RTA engine obtained TDC corrections are purely random and unique. TDC adjustment value, however, are much smaller and do not exceed 1.5 ^{o}CA. In this case, before indicator graphs analysis, it is necessary revision of TDC, as well as in the case of RTA engine.

5.2. Comparison of TDC correction designated by the Lemag method with the method base on polynomial model of compression

The next stage of research was to compare the value of TDC correction identified by the Lemag method with the values correction designated under the multinomial model compression. Statement of obtained values for the two series of measurements for the low speed engine RTA 96C are shown in Tab. 3.

Tab 3. Comparsion of methods of TDC correcions values for 9 cylinders for the two data sets of RTA 96C engine: cor s1, cor s2 – corrections of Lemag method, cor s1 Mod, cor s2 Mod - corrections of method based on compression model dif TDC - deviations between methods

	Cyl 1	**Cyl 2**	**Cyl 3**	**Cyl 4**	**Cyl 5**	**Cyl 6**	**Cyl 7**	**Cyl 8**	**Cyl 9**
TDC cor s1 [^{o}CA]	1	2	-2	4.3	3.5	-5	0.3	4	2.5
TDC cor s1 Mod [^{o}CA]	-0.2	-0.2	-3.9	2.6	1.2	-6.7	-1.9	1.8	0.2
Dif TDC cor s1 [^{o}CA]	**1.2**	**2.2**	**1.9**	**1.7**	**2.3**	**1.7**	**2.2**	**2.2**	**2.3**
TDC cor s2 [^{o}CA]	0	0	1.8	-1.8	1.5	-0.3	-4.3	3.8	-4.8
TDC cor s2 Mod [^{o}CA]	-0.7	-1.4	0.6	-3.1	0.1	-1.3	-6.3	2.2	-6.6
Dif TDC cor s2 [^{o}CA]	**0.7**	**1.4**	**1.2**	**1.3**	**1.4**	**1**	**2**	**1.6**	**1.8**

There are clear differences between the two methods. Differences in the first series of measurements are an average of 2°CA, in the case of the second series of 1.3°CA. Comparison of results for the medium speed MAN L28/32A engine is shown in Tab. 4.

Tab 4. Comparsion of methods of TDC correcions values for 8 cylinders for the three data sets of MAN L28/32A: cor s1, cor s2, cor s2 – corrections of Lemag method, cor s1 Mod, cor s2 Mod, cor s3 Mod, corrections of method based on compression model dif TDC - deviations between methods

	Cyl 1	**Cyl 2**	**Cyl 3**	**Cyl 4**	**Cyl 5**	**Cyl 6**	**Cyl 7**	**Cyl 8**
TDC cor s1 [^{o}CA]	-0.5	-0.5	-1.5	-1.5	-1.3	-1.3	-1.5	0.5
TDC cor s1 Mod [^{o}CA]	-0.6	-1.3	-1.5	-1.2	-1.3	-1	-1.1	0.2
Dif TDC cor s1 [^{o}CA]	**0.1**	**0.8**	**0**	**-0.3**	**0**	**-0.3**	**-0.4**	**0.3**
TDC cor s2 [^{o}CA]	0.8	0.8	-0.3	1.3	0	0.3	-0.3	-0.3
TDC cor s2 Mod [^{o}CA]	-0.5	-0.1	-1.3	-0.5	-1.3	-1.2	-1.1	0.3
Dif TDC cor s2 [^{o}CA]	**1.3**	**0.9**	**1**	**1.8**	**1.3**	**1.5**	**0.8**	**-0.6**
TDC cor s3 [^{o}CA]	0	-1	-0.8	-1	0	-0.5	-1.3	-0.5
TDC cor s3 Mod [^{o}CA]	-0.6	-0.7	-1.5	-1.6	-0.1	-0.8	-1.5	-0.6
Div TDC cor s3 [^{o}CA]	**0.6**	**-0.3**	**0.7**	**0.6**	**0.1**	**0.3**	**0.2**	**0.1**

The results of calculations for the TDC possition of the MAN L28/32A engine confirmed significant differences between the two test methods of determining the TDC correction. The differences are not quite as large as the RTA engine, however, significant enough to affect significantly the value of determined mean indicated pressure.

Since is not possible to determine the actual TDC position on the indicator graph it was only an attempt to estimate the errors of both used methods. In view of the fact that in the tested engines, beginning of the combustion starts a few degrees after TDC, zero point of first order derivative of pressure curve was choosen as a reference point to error estimation. Differences between the appointed position of TDC location and zero possition of first order derivative is shown in Fig. 6.

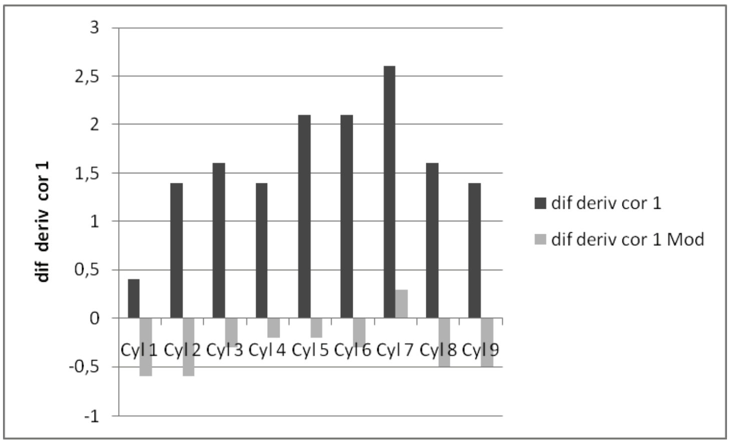

Fig. 7. Differences between the appointed position of TDC location and zero possition of first order derivative of pressure: dif poch cor 1 - differences between Lemag method, dif poch cor 2 Mod - differences between method based on compression model

The results shown in the Fig. 7 clearly shows the correctness of the TDC determination method which base on the polynomial model of compression. Differences between the appointed position of TDC location and zero possition of first order derivative of pressure does not exceed 0.6°CA. In the case of LEMAG method the differences are between 0.5 to 2.6°CA.

Certain differences between the TDC position obtained in the case of a method based on polynomial model are caused to difficulties related to determination of the position of zero point of first order derivative. The curve of the derivative is burdened with significant interference that may cause inaccuracies in the designation of zero crossings. The solution to this problem would be to smooth the course of pressure, however, it will introduce phase errors. It should be stressed that given difficulties of determining the zero position of first order derivative of pressure does not affect the proposed method of TDC determination because it is based on compression process model and does not use a direct derivative of zero. The curve of derivative of pressure near TDC is shown in Fig. 8.

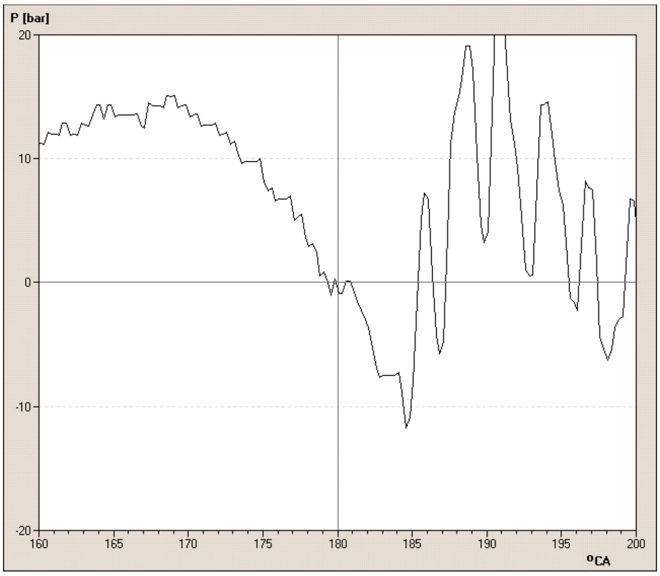

Fig. 8. The curve of first order derivative of pressure near TDC

5.3. Influence of TDC determination error on calculated MIP values

The results of calculations of mean indicated pressure for a selected cylinder of RTA 96C engine and MAN L28/32A engine for different TDC corrections are shown in the Tab. 5 and 6. Calculations were performed within the range ±1°CA from nominal TDC position with a resolution of 0.2°CA.

Tab. 5. Influence of TDC determination error for MIP calculation results - RTA 96C engine (-0,2 correct possition of TDC)

TDC cor [CA]	-1.2	-1	-0.8	-0.6	-0.4	**-0.2**	0	0.2	0.4	0.6	0.8
MIP [bar]	9.2	10.1	10.4	10.6	10.8	**11**	11.2	11.4	11.6	11.9	12.1
dif MIP [%]	16%	8%	5%	4%	2%	**0%**	2%	4%	5%	8%	10%

Tab. 6. Influence of TDC determination error for MIP calculation results - MAN L28/32A engine (-0,6 correct possition of TDC)

TDC cor [CA]	-1.6	-1.4	-1.2	-1	-0.8	**-0.6**	-0.4	-0.2	0	0.2	0.4
MIP [bar]	17.4	17.7	18	18.3	18.6	**18.9**	19.1	19.4	19.7	20	20.3
dif MIP [%]	8%	6%	5%	3%	2%	**0%**	1%	3%	4%	6%	7%

The results confirm the significant effect of TDC determination error for the value of the mean indicated pressure. In the case of the RTA 96C engine, TDC position changes about the value 2°CA causes an error in MIP determining equal to 3 bar and therefore the relative error of 26%. Similar results were obtained for the MAN L28/32A engine, the relative errors were smaller resulting in higher values of MIP, but the absolute values as well as for the RTA engine amounted to approximately 3 bar.

6.Conclusions

The conducted research proved the existence of significant influence of indicator graphs TDC location on the mean indicated pressure calculation errors.

In the case of low speed engines RTA 96C, TDC position changes about the value of 1°CA causes an error in MIP calculation equal to 2 bar and therefore the relative error of 16%. Similar results were obtained for the medium speed engine MAN L28/32A. So, significant differences of TDC location cause considerable errors in characteristics of heat generation amounting to 10%.

Correction of TDC position is particularly important in relation to low speed engines, which are the main propulsion of the ship. Despite the use of special methods of the angular axis determination with an accuracy of 1°CA, research shows that the error of TDC determination could amount up to 7°CA. Such large errors virtually exclude the use of indicator graphs to any inference about the technical condition of the engine. Much smaller TDC errors were obtained for medium speed engines for which the errors do not exceed 2 TDC °CA.

The problem of TDC determination errors began to notice the producers of electronic indicators. An example could be LEMAG company, which proposed an automatic method for correcting the position of TDC. This method allows to adjust the TDC position of each engine cylinder based on the cylinder which the TDC error is found to be lowest. This approach is certainly convenient, but carries significant risks associated with the transfer of error in determining the position of the base cylinder for all others. Research has shown that these errors can be as high as 2°CA.

The best results of determining the TDC position was obtained from the original method based on a polynomial model of the compression process. The verification of the method was based on an analysis of a designated distance from the TDC position to zero possition of first order derivative. These were possible because the combustion in analyzed engines began with a few degrees after TDC. The distance of determined TDC in no case was greater than 0.5 oCA from the zero possition of first order derivative, but these errors are rather due to large interference of curve of the derivative and are not caused by the same method. It should be emphasized that the proposed method enables individual adjustment of TDC for each cylinder and can be used even when the combustion begins before TDC.

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 different engines.

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