RESULTS OF THE RESEARCH ON THE ADAPTIVE CONTROL OF THE INJECTION TIMING IN THE DIESEL ENGINE

Jacek Poleszak

College of Enterprise and Administration in Lublin
Ul. Bursaki 12, 20-150 Lublin, Poland
tel.: +48 81 7408410, fax: +48 81 7408413
e-mail: jpoleszak@wp.pl

Abstract

The basic aim in controlling the diesel engine is to obtain a maximal effective torque for a given fuel dose with keeping at minimum toxic exhaust compounds. This postulate can be realized by matching the appropriate fuel injection timing. In this paper the research results of the control system are presented, which allow for the constant matching of the injection advance in the CI engine to the varying characteristics of the controlled object, that is the engine. Quality factor of the working process which is defined as an effective engine torque, is estimated on the base of the instantaneous crankshaft torsion measurement. This concept, unlike the currently used systems, suggest the use of efficient torque (Me) measurement to generate control quantities, which control the work process of an engine. Realization of such measurements leads to the treatment of the control system as an extreme control unit (maximizing quantitative parameters) as well as an adaptive control system (possibility of unit's reaction on high changes of the parameters influencing the work process of an engine). Combining the idea of the crankshaft torsion measurement with the idea of extreme control, a system can be designed, which makes use of torsion measurement for the adaptive control of the injection timing. The object of the research was a Diesel engine ISUZU Y17DT with electronically controlled injection pump and engine diagnostic system. Realization of the research aim required design and construction of the measurement system of the crankshaft torsion.

Keywords: *transport, combustion engines, adaptive control, injection timing, crankshaft torsion*

1. Introduction

Development of compression combustion engines is possible thanks to the advances in the combustion control technology. The highest influence on the course of combustion is exerted by the fuel injection process. Optimizing of the combustion can be done by the exact dosage of fuel during the working process. Precise dosage refers to both the fuel mass and the time course of the injection. As the highest influence on the general efficiency of the Diesel engine, apart from the fuel dose itself, is exerted by the angle of the injection advance, the author of this paper decided to concentrate on the issues related to the adaptive (self-learning) control of the injection advance in the Diesel engine.

So as to compensate changes of object's characteristics, injection timing control system should be expanded by the function of adaptive regulation. In the proposed control system numerical elements were introduced, which gather the data *a posteriori*. If, in a given period of time, optimal value of the injection advance angle (i.e. value resulting in the maximum value of the torque at given engine operating conditions) differs from the value memorized in the factory ECU, the difference is recorded and automatically added to the factory-set value. In the real conditions of operation it can be related to the fuel properties or engine ageing.

Object's characteristics i.e. internal combustion engine and injection timing control methodology are available in the literature, however development of the on-board torque transducer and its characteristics is still a problem being solved [1, 4].

There is a relatively inexpensive and simple in application method of the engine torque measurement, which uses measurement of the torsion of the engine crankshaft [7, 11]. The idea of torsion measurement of the crankshaft was patented by Scotson [8]. The system is based on the two sensors which measure the position of the teeth of the toothed wheels mounted on the opposite sides of the crankshaft. The measurement method described in the patent was already used by many researchers for the diagnostics of the engine working process [2, 6, 7].

Combining the idea of the crankshaft torsion measurement with the idea of extreme control, a system can be designed, which makes use of torsion measurement for the adaptive control of the injection timing [3, 5]. However, still unsolved scientific problem is a question, whether the accuracy of the torque estimation, which uses the measurement of the crankshaft torsion angle is sufficient for the needs of the adaptive control of the injection timing in a Diesel engine.

2. Aim and scope of work

The leading idea of the work resulted from the author's conviction, that the injection timing as a factor determining engine operation, can be adaptively adjusted on the basis of the crankshaft torsion signal, which is a measure of the effective rotational torque. Such method of controlling the angle of injection advance would allow for constant adjustment of its value for the optimum value from the point of maximum general efficiency of the working process.

The aim of the research was to develop the adaptive injection advance control system in a Diesel engine, and to evaluate the usability of the crankshaft torsion measurement in a extreme control system by the modification of the injection advance. The objective function in this optimization task is a value of the effective rotational torque. The aim of optimization is finding the maximum of the objective function, i.e. max $M_e(\alpha_w)$.

As a source of information about instantaneous rotational torque of the engine a signal from the crankshaft torsion transducer was used. By the measurement of torsion angle of the crankshaft the author understands the time difference measured between signals from the corresponding teeth of the toothed gears, expressed in the angular measure. As a reference signal a torque signal was used, which was measured by the transducer of the engine electric dynamometer.

3. Test stand and crankshaft torsion measurement system

The object of the research was a Diesel engine ISUZU Y17DT with electronically controlled injection pump and engine diagnostic system. Experimental research was done using engine test stand equipped with the eddy-current dynamometer Elektromex EMX-201/100 in the laboratory of the Dept. of Internal Combustion Engines and Transportation in the Lublin University of Technology.

Realization of the research aim required design and construction of the measurement system of the crankshaft torsion. Methodology of measurements used the dependence of the engine torque from the phase overlap of the impulses generated by the sensors recording consecutive teeth transitions of the toothed gears mounted on the flywheel rim and on the other end of the crankshaft. Measurement of the crankshaft torsion angle was done using ENI 4 sensors and developed electronic measurement module DTS-700 with the computer software for the visualization and recording of the measurement data.

Control of engine actuators, monitoring and recording of engine operating parameters was done using dedicated software designed in the Dept. of IC Engines and Transportation - KISSI (Computer Interface of the ISUZU Engine). This software communicates with the original engine controller using diagnostic transmission OBD II [10].

One of the problems related to the measurement of the crankshaft torsion angle was estimation of the initial torsion, resulting from the mutual relative revolution of the consecutive teeth of the toothed gears. A special methodology was developed, which takes into account the offset of toothed gear mounted on the crankshaft. This method is based on the comparison of the recorded crankshaft torsion signal with the signal obtained in a strictly defined operating conditions (in this case it was the course of torsion signal during idle engine operation). The scheme of the crankshaft torsion angle measurement system is shown on Fig. 1.

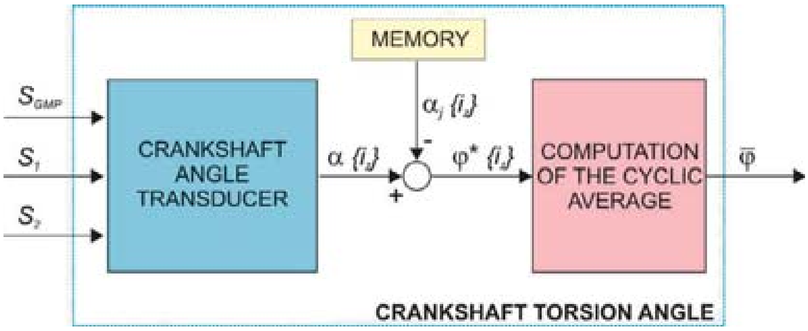

Fig. 1. Scheme of signal processing in the crankshaft torsion angle transducer

Denotations on the Fig. 1:
S_{GMP} - analog signal of the crankshaft position,
S_1 *i* S_2 - analog measurement signals from the sensors mountend on the toothed gears,
i_z - index of the tooth number,
α - shift angle between the teeth of both toothed gears,
α_j - shift angle between the teeth of both toothed gears at idle operation,
φ^* - relative instantaneous torsion angle of the crankshaft,
$\overline{\varphi}$ - average in a cycle torsion angle of the crankshaft.

4. Results of the test stand experiments

Identification research was done on the engine test stand, which included estimation of the characteristics of the crankshaft torsion angle transducer. Experiments were performed in 34 points of engine operation defined by the rotational speed and engine load. Selection of points was done so as to cover as much as possible range of rotational speeds and loads.

During the research, input value of α was modified in the range of 10 to 45 ° of crankshaft angle (c.a.) before TDC. Measured output values were effective rotational torque M_e and the φ angle of crankshaft torsion. Monitoring of measurable interferences included rotational speed and amount of injected fuel defined as a percentage value of the maximum dose.

Elaborated method of analysis of the measurement data was based on the fact, that recorded course of the crankshaft torsion was later on averaged (Fig. 2-3), then from the obtained average value values for the idle run were subtracted (Fig. 4). The resulting quantity was a relative angular course of the crankshaft torsion, and its average value was also an average value of the torsion angle. Fig. 5 shows an example of the course of relative crankshaft torsion angle.

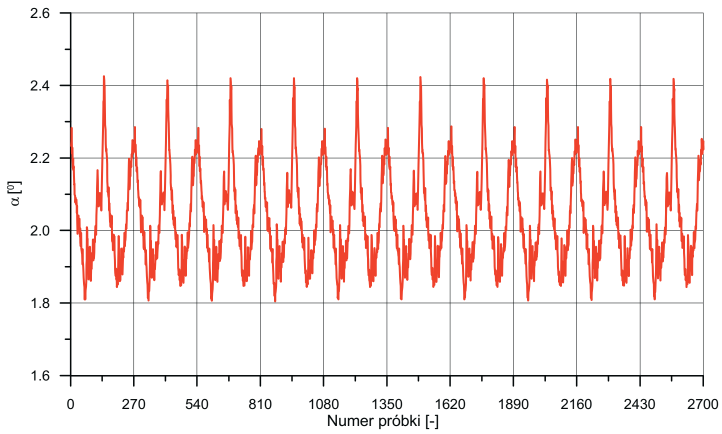

Fig. 2. Course of crankshaft torsion angle for 10 consecutive engine cycles

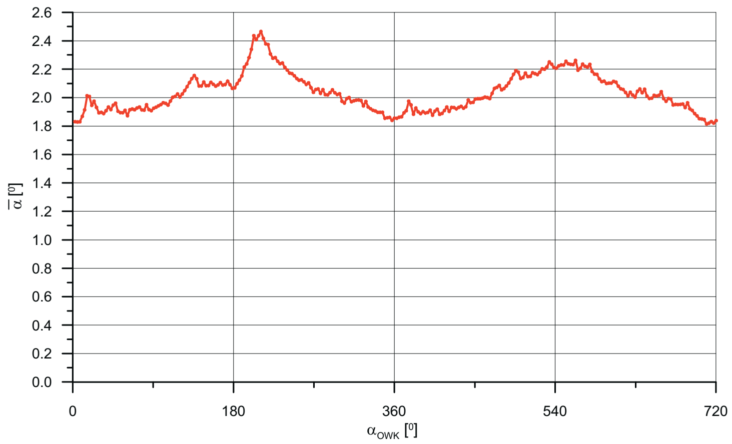

Fig. 3. Averaged course of the crankshaft torsion angle

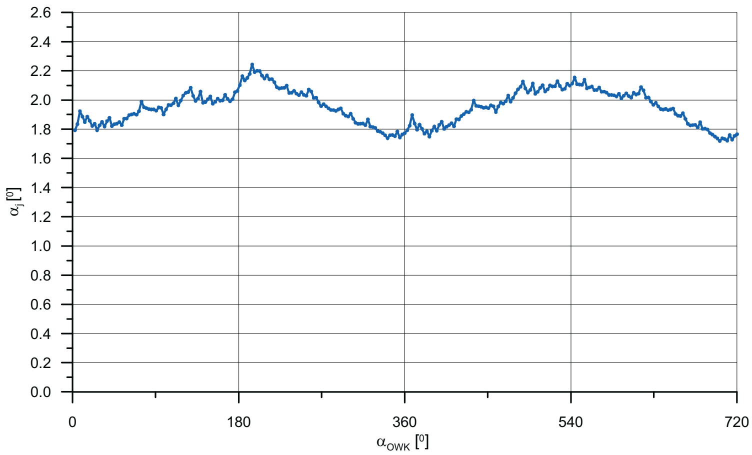

Fig. 4. Averaged course of the crankshaft torsion angle at engine idle operation

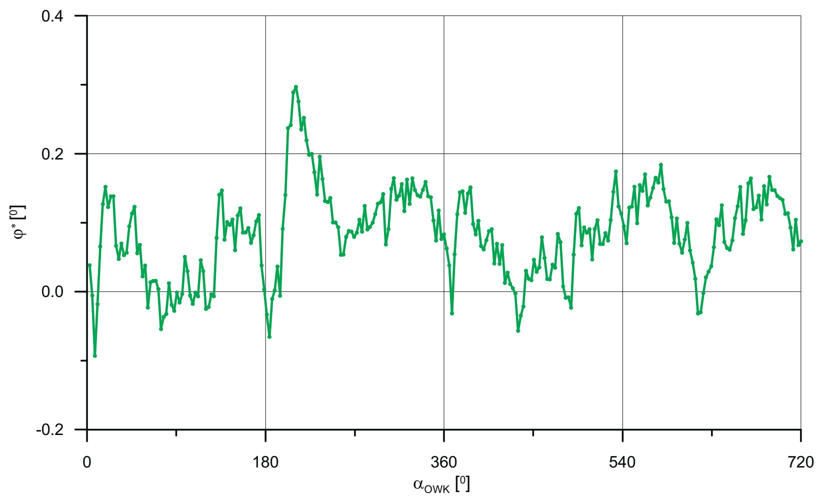

Fig. 5. Averaged course of the relative angle of the crankshaft torsion

Then multi-cycle average values of the rotational torque were compared with mean values of the torsion angle for the same engine operating conditions (load and rotational speed). Significant correlation between rotational torque and torsion angle of the crankshaft was observed. So as to prove the existing correlation statistically, a numerical analysis was made, giving as a result characteristics of the crankshaft torsion transducer (Fig. 6). Verification of the obtained characteristics was done using statistical analysis, what allowed for positive verification of the thesis.

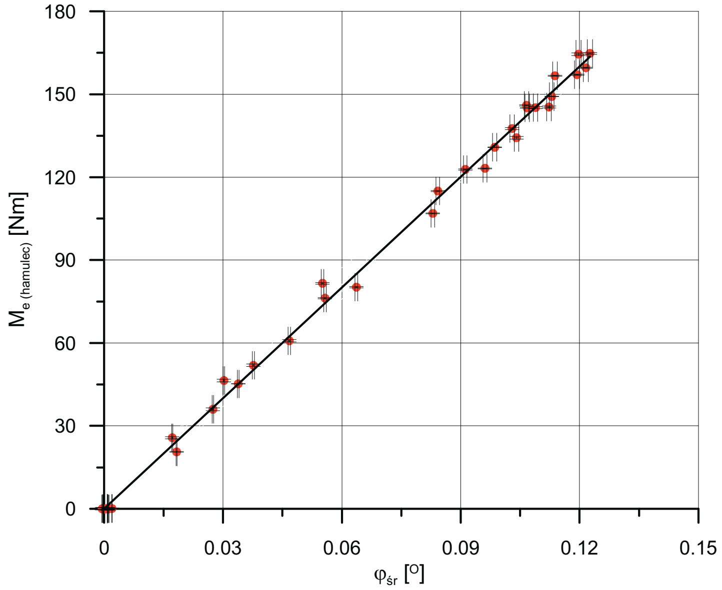

Fig. 6. Characteristics of the effective torque transducer

5. System of adaptive control of the injection timing

The general idea of measurement and control system of injection timing on the basis of the crankshaft torsion angle is shown on Fig. 7. The control algorithm for the search of the optimum injection advance uses simple gradient method. Experiments were done for the two variants of engine operating conditions: *P01 (n = 2500 rpm, load = 40%)* and *P02 (n = 3000 rpm, load = 60%)*.

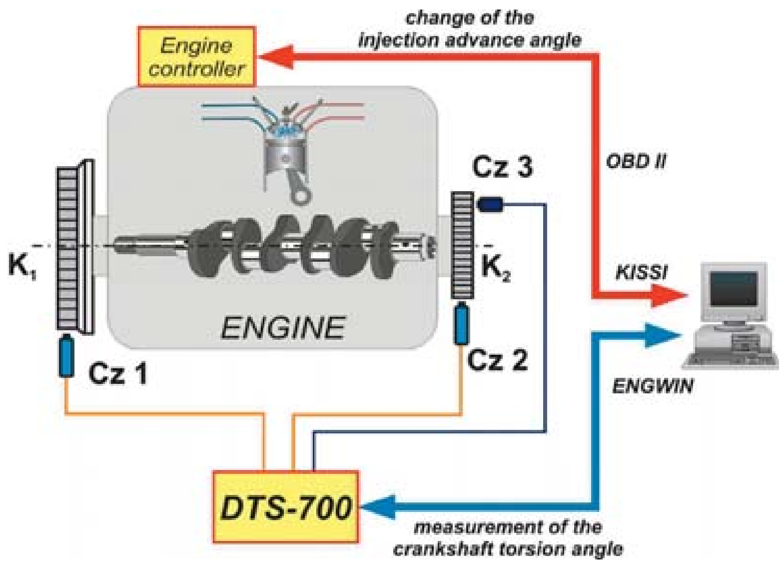

Fig. 7. Diagram of adaptive control system controlling injection timing using the torsion angle of the crankshaft

Comparison of effective torque characteristics measured using dynamometric sensor and using crankshaft torsion transducer is shown on Fig. 8.

For the complete evaluation of the data, a correlation analysis was made between measurements of the effective engine torque and estimation results obtained on the basis of the average angle of crankshaft torsion. For the operating point *P02 (n = 3000 rpm, load = 60%)*, correlation coefficient equaled to 0.9968 and mean relative error was 0.21%. Examples of results are shown on Fig. 9.

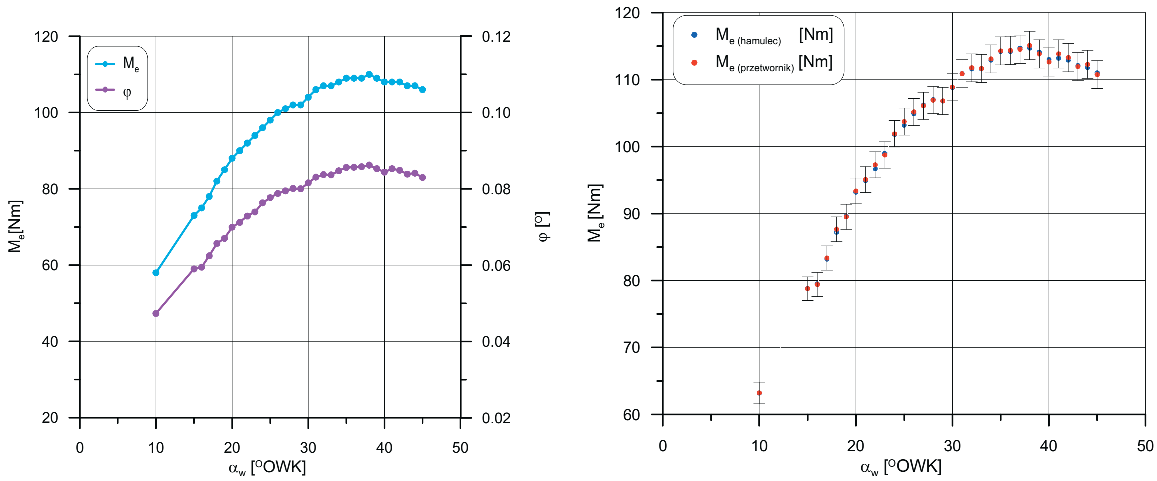

Fig. 8. Control characteristic of the effective torque and crankshaft torsion as a function of the injection timing for n = 3000 rpm and load = 60%. Torque values were measured using dynamometric sensor and later estimated from the transducer in a function of injection timing

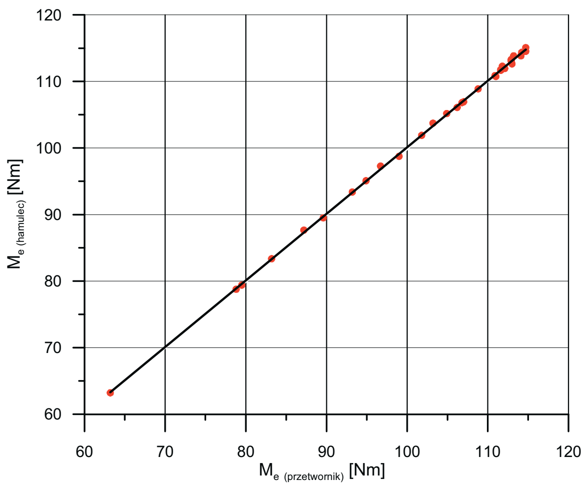

Fig. 9. Correlation of the effective torque measured with the dynamometric sensor and extimated using crankshaft angle transducer, for n = 3000 rpm

During further investigations a practical verification of the algorithm was made. The algorithm searched for the optimum injection advance on the basis of the crankshaft angle of torsion (Fig. 10). Three experiments were done at each of chosen points. Experiments differed with the set value of the e step (1, 2, 5).

6. Sumary

Comparison of experimental results obtained for the two engine operating conditions allows for some conclusions:

- for the operating point P01 (n = 2500 rpm, load = 40%) the value of the effective torque increased from 52 Nm to 56 Nm. It means, that the difference between the value from the model recorded in the controller's memory and accepted analytical model is about 7.7%. The value of the injection timing adaptively calculated by the controller was increased from 25°c.a. BTDC to 36°c.a. BTDC (Fig. 11),
- for the operating point P02 (n = 3000 rpm, load = 60%) the value of the effective torque increased from 103 Nm to 110 Nm. It means, that the difference between the value from the model recorded in the controller's memory and accepted analytical model is about 6.8%. The value of the injection timing adaptively calculated by the controller was increased from 28°c.a. BTDC to 38°c.a. BTDC (Fig. 11).

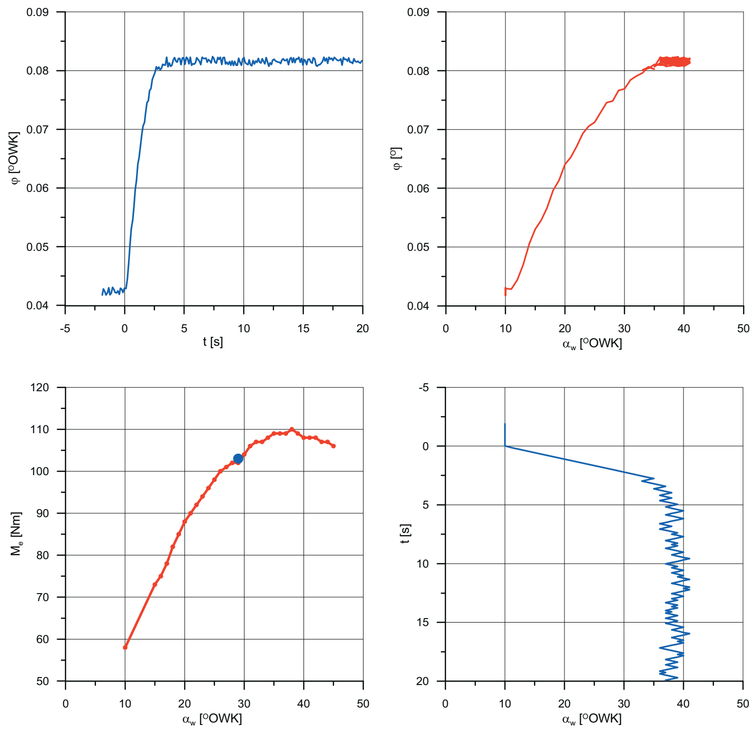

Fig. 10.Course of injection advance adaptation for the point P02 and step e = 1 (blue point on the chart denotes factory set value of the injection advance)

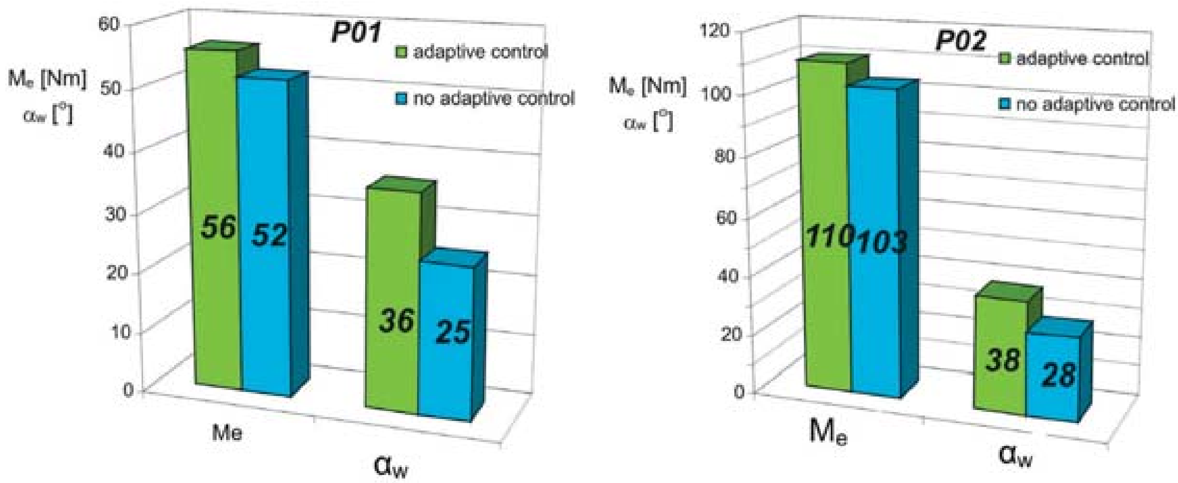

Fig. 11.Comparison of obtained values of Me and αw for the a priori model recorded in the controller's memory and a posterior adaptive model for the points P01 and P02

Experimental research allows to draw some basic observational conclusions:

Relative uncertainty for the average values of the effective torque under 10 Nm exceeds boundary value of 5%. In this range the uncertainty results from the relatively high value of standard deviation in relation to the average value. In the remaining area average uncertainty of measurements from all measurement points was δMe = 2.42%. Maximum value of the average uncertainty for the torque range above 10 Nm equals δMe = 3.01%. Therefore, the torsion transducer can be used for the control under conditions of mean to high engine loads:

- for low loads it is necessary to compensate the high uncertainty of indirect measurement of the effective torque,
- there is linear dependence between the torque calculated using the course of crankshaft torsion angle, and effective engine torque measured using dynamometric sensor.

Verification of the optimization algorithm of the effective torque with the use of crankshaft torsion angle sensor and gradient algorithm proved, that:

- in the both examined points of engine operation, differing with rotational speed and load, maximum values of the effective torque were obtained and maintained,
- there is a possibility for constant adaptive identification of engine model in the form of the dependence between the injection advance angle and engine rotational speed and load,
- it was observed, that measurement uncertainty of the designed transducer of the effective rotational torque in the boundaries of accepted confidence intervals does not exceeds q = 0.05, i.e. typical values for engineering purposes.

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