ENGINE TRANSIENT TEST TECHNIQUE

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INTRODUCTION

The knowledge about combustion engine operation under transient conditions makes it possible to control the combustion process more precisely. A thorough investigation on diesel operation under transient conditions has been carried out. It concerned engine diagnostic tests [7], engine start-up problems [6] and the use of renewable fuels [4, 5]. It is generally known that the engine operation under transient conditions takes the most of its life span.

A typical testing of combustion engines and assessment of their parameters consists in making many records of successive work cycles (100 or more) in the same conditions [2, 8, 9]. Then average values of parameters describing engine operation at every test point are calculated. Those values such as mean indicated pressure, torque, specific fuel consumption, efficiency and others are used for further comparisons and assessments.

The combustion engine testing under transient conditions requires a special technique. It is impossible to obtain any number of identical successive cycles in a transient process because of the necessary change of a basic parameter, for example engine speed. Thus the test should be carried out in series that concern the whole tested process or its main part. It means that all the work cycles of a transient process should be recorded in one test series Next an adequate number of series should be performed to obtain enough amounts of data. Obviously test series should be executed in the same conditions. The obtained data could be calculated and averaged between series but with respect to their position within registered series. Usually the engine speed should warrant the calculations.

TRANSIENT TEST SET-UP CONFIGURATION

Transient tests are mostly performed on a quick response test bench [9] or brakeless test set-up. A typical test bench could be easy modified to brakeless test set-up by detaching the brake and installing the quick actuator of injection pump control lever. It should also be equipped with a quick response data acquisition system. Then it is also possible to use all the additional equipment of the test house for external conditions measurement and control.

Engine internal losses could be used as brake means for the transient test purposes. Therefore transient test may be performed on engines built in the vehicles. This makes it possible to perform exploitation tests and check an engine's operation in the field and on-road conditions. A wider diagnostic tests range is also possible.

The brakeless test set-up with the data acquisition system has been developed in order to perform transient test. The block diagram of the test set-up is shown in Fig.1. The developed test set-up comprises crankshaft angular acceleration measurement system made at The Automotive Vehicles Department of The Lublin University of Technology [3] and an engine indicator parameter measurement system made at The Department of the Technical Exploitation of Vehicles of The Radom University of Technology [5].

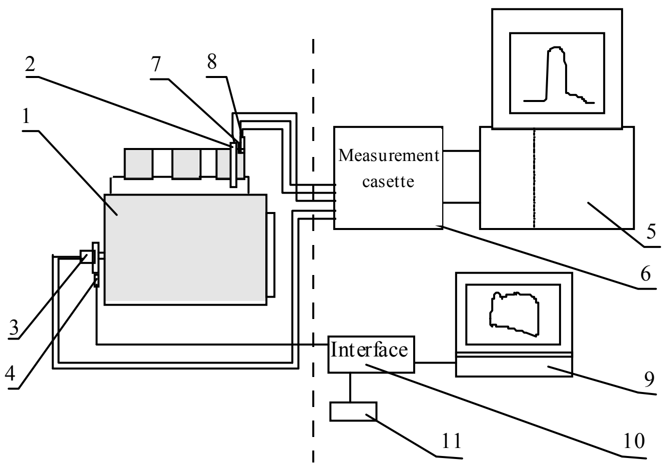

Fig.1. Block diagram of the test set-up sample configuration: 1 – tested engine, 2 – AVL cylinder pressure sensor, 3 – INTROLL crankshaft angle position transducer, 4 – angular velocity sensor, 5 – computer PC 486/33 with AMBEX A/C transducer, 6 – ZEM measurement cassette, 7 – AVL injection pressure sensor, 8 – ZEM needle lift sensor, 9 - notebook 486/33MHz, 10 - measurement interface, 11 - supply

The angular acceleration measurement system is the component of the test's set-up which is characteristic for transient tests. The measurement system enables measuring and recording instantaneous rotational speed and determining instantaneous angular acceleration of an engine crankshaft. Computer controlled acceleration meter may obtain signal from photoelectric or magnetic sensor (from engine crankshaft), inductive (from ignition), piezoelectric (from injection system), and also from crankshaft angle decoder (TTL signal). Functional scheme of speed (acceleration) measurement channel is shown in Fig. 2.

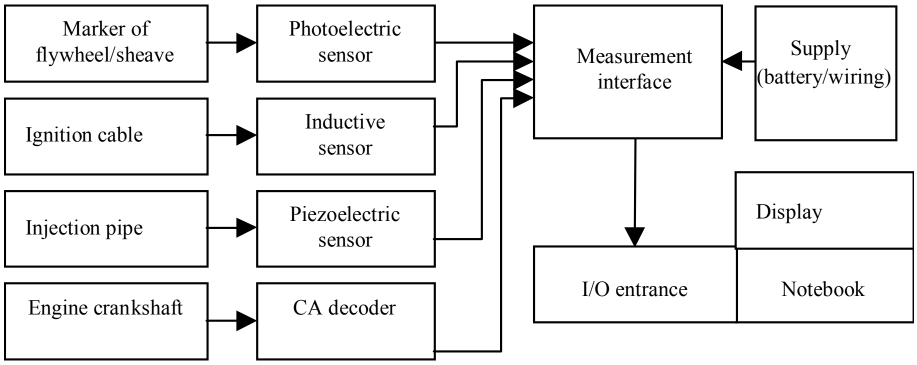

Fig. 2. Block diagram of data acquisition system for transient test

In transient tests the most important set-up properties are response time, sampling step and unit memory capacity. The main problems of such tests are the identity of measurement start, work cycle's identification and process control. Hardware sampling is necessary in transient tests. Smaller sampling step offers higher accuracy but also causes information transfer problems and needs more unit memory. The necessity of work cycle and measurement start identification may be solved by hardware or program means, which however complicate measurement technique or work out of data, respectively.

TRANSIENT TEST TECHNIQUE

The presented technique of transient test is based upon unloaded engine response for step change of fuel dose. This type of transient work is distinctive for automotive engines [1, 8]. The full possible change of fuel dosage (caused by quick changes of pump lever position from its minimum to maximum value) has been used at the present research stage.

Transient conditions of engine work may be roughly classified in terms of four characteristic time scales [8]:
I – 0-0.2 seconds, II – 0.5-2 seconds, III – 1.0-10 seconds, IV – 1-10 minutes.

Acceleration process of automotive engines continues within 1.2-1.9 seconds; thus the presented conditions may be classified to scale II. In practice this time scale is characteristic of gear shifts and the obtained research results could be used for the assessment of this period of vehicle operation.

Functional dependencies among engine parameters in transient conditions are shown in the formula

$$M_e = f(\omega, p_e, h, \dots, t) \tag{1}$$

where:

M_e, p_e – torque and mean effective pressure of the engine,
h – injection pump control element position,
ω – crankshaft angular velocity,
t – time.

The components of the formula (1) have instantaneous running values dependent on time t. The static equilibrium condition is not preserved when the engine does not work in a steady state. That can be noted as:

$$J_z \cdot \frac{d\omega}{dt} = M_e - M_{op} \qquad \frac{d\omega}{dt} \neq 0 \tag{2}$$

where:

M_e – running output torque,
M_{op} – running resistance torque, including receiver inertia,
J_z – equivalent mass moment of inertia of mobile engine elements in relation to crankshaft axis.

If the energy receiver is detached (M_{op} = 0), the equation (2) will be as:

$$M_e = J_z \cdot \frac{d\omega}{dt} = J_z \cdot \varepsilon \tag{3}$$

and it will present the engine torque change caused by a quick increase of the fuel dose supplying engine cylinders. In fact the majority of it will be used for overcoming the internal losses of the engine.

But in case of engine supply switched off (M_e = 0), the equation (2) will be the following

$$M_{op} = -J_z \cdot \frac{d\omega}{dt} = J_z \cdot (-\varepsilon) \tag{4}$$

Then it will present the engine internal resistance change during retardation process started at a high initial rotational speed.

Engine transient operation could be described by speed dynamic characteristics [1, 7] representing changes of such parameters as crankshaft angular acceleration, torque and power as functions of engine rotational speed (or angular speed). Dependencies obtained under transient conditions at regulation sets analogous to the ones during test bench measurements are comparable to adequate engine operational characteristics obtained on the engine test bench [1].

Free running engine acceleration and next retardation may be connected in one measurement cycle. Then the energy obtained by the engine in the end of running up process is used for self-propelling during the retardation without the combustion. That enables quick determination of the speed characteristics of output and internal resistance torque. The exemplary courses of rotational speed and angular acceleration of engine crankshaft during the tests are shown in Fig. 3 and Fig. 4. There are five periods of the measurement cycle [5, 7]:

I. Engine operation at low rotational speed, close to idling speed n_{bj} (when h = 0). Rotational speed changes are the result of engine idle run inequality.

II. Engine operation during acceleration. This period begins at the moment when injection pump control lever is shifted into max position – h = 1 – (it should take less than 0.1 s) and lasts until the engine gains its maximum speed. Diesel engine acceleration time t is about 1.5 s.

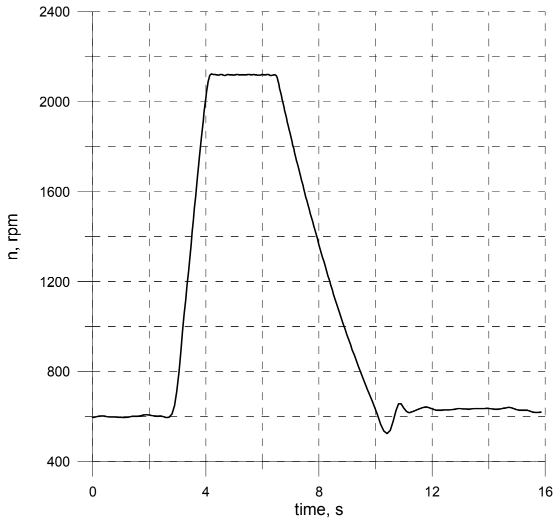

Fig. 3. Course of engine speed $n = f(t)$ of S-4002 diesel during acceleration-retardation cycle

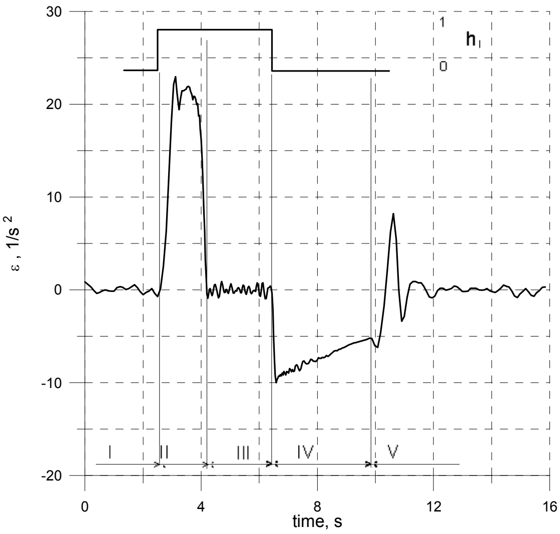

Fig. 4. Course of crankshaft angular acceleration $\varepsilon = f(t)$ of S-4002 diesel during acceleration-retardation cycle

III. Engine operation at its maximum speed (h = 1). Engine speed fluctuations with amplitudes higher than in case of idle run can be observed in this period.

IV. Engine operation connected with overcoming its own internal losses (mechanical resistance and charge exchange) by engine movable masses. The process starts at the moment when injection pump control lever is shifted into stop position (h = 0) and lasts until rotational speed decreases to n_{bj}. Diesel engine retardation time t' is about 4 s.

V. Engine operation after re-switching on fuel dosing to maintain engine operation. This phase turns into the I-st phase of succeeding measurement cycle.

TEST RESULTS DESCRIPTION TECHNIQUE

The transient process is usually of stochastic type. Existing divergences of the process, shown enlarged in Fig. 5, cause the necessity of the statistic method use when transient process parameters are worked out [3, 5, 7]. Only the averaged course of crankshaft angular acceleration $\varepsilon = f(n)$ would be representative for an engine's operation description. Thus the main principle of transient tests consists in performing the measurements in series, for each tested factor successively. Each series comprises 15-20 acceleration-retardation cycles, executed in the same test start conditions: rotational speed (close to idle speed) and constant temperature of the motor oil and the coolant (according to the manufacturer's specifications).

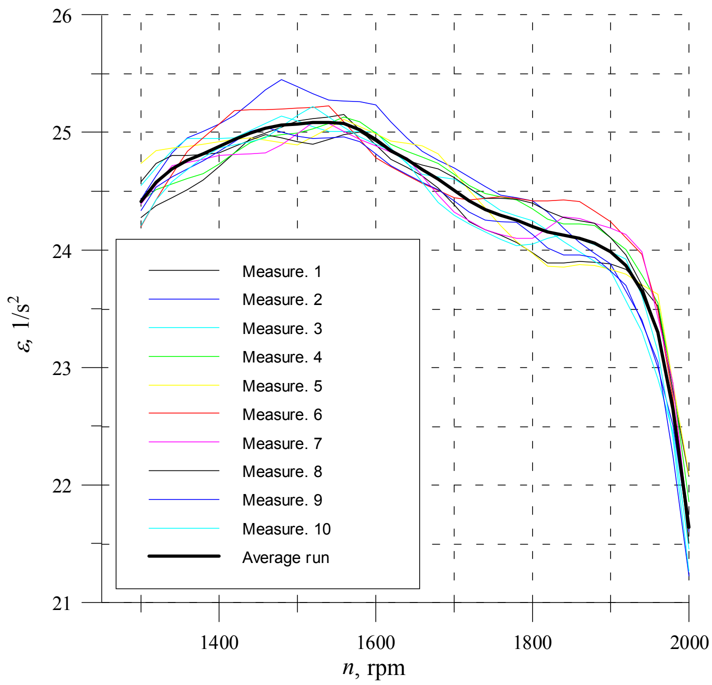

Fig. 5. Divergences of diesel running up process. Average run has been determined by arithmetic mean method

An average course obtained from the closest 10 tests is recognised as representative one for the tested object. The standard deviation of transient test results for some engines is presented in Fig. 6. The values obtained for different engines and all tested factors (for example fuels) are within the range of 0.1 to 0.5. It is possible to state that the repeatability and accuracy of engine dynamic parameters are sufficient.

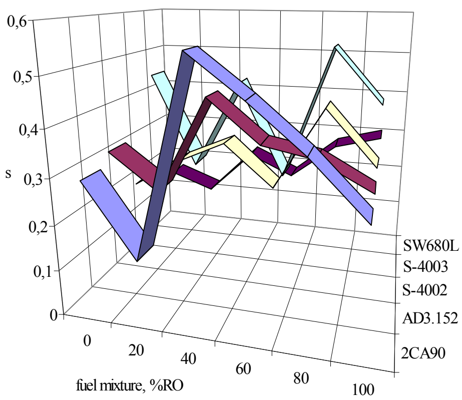

Fig. 6. Standard deviation of angular acceleration at engine speed equal to n_M (maximum torque speed)

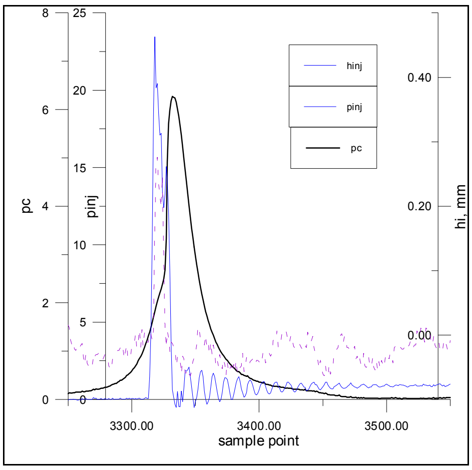

Fig. 7. Sample engine indicator parameters (p_c, p_{inj}, h_{inj}) registered during transient test

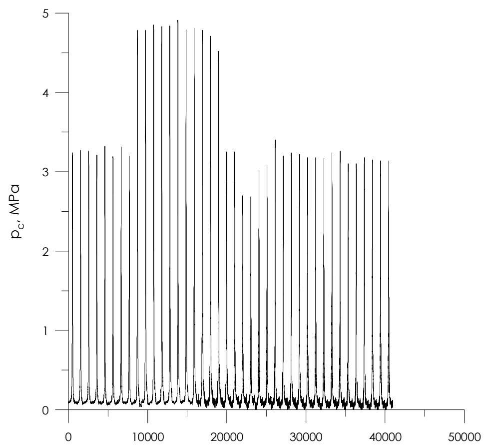

Fig. 8. Course of cylinder pressure changes of AD3.152 diesel during free acceleration, k – consecutive number of measurement point

An exemplary course of cylinder pressure, injection pressure and needle lift during free acceleration is shown in Fig. 7. Measurement system enables to register forty successive work cycles during transient test, as it is shown in Fig. 8. It is possible to consider work cycle parameters as a whole but with respect to conditions mentioned earlier. In the case of pressure courses, the one which is the closest to the averaged course should be taken into further consideration. As it has been stated in paper [5], the mean indicated pressure changes are referred to angular acceleration changes.

ENGINE WORK PARAMETER COMPARISON TECHNIQUE

The test results are mostly obtained as the courses of angular acceleration $\varepsilon = f(n)$ which could be used for engine torque description and power as well [1, 7]. However the courses of crankshaft angular acceleration could be used in comparative analysis. The comparison may be performed in several ways. The first way consists in the comparing absolute values of measured parameter (for example angular acceleration or mean indicated pressure) that have been obtained for different factors at the same engine speed values. The sample characteristics $\varepsilon = f(n)$ used for comparisons of this kind are shown in Fig. 4.

The second way is the comparing relative (percentage) changes of measured parameter values. More general information can be obtained from comparisons of this kind. Additionally when parameter value changes are monotonic it is possible to simplify the procedure which consists in comparing the obtained values only at chosen speed values. Two characteristic engine speed values are usually taken for comparison: maximum torque speed n_M and rated power speed n_N. The exemplary comparison of fuel effect (by relative values) at maximum torque speed n_M is shown in Fig. 9.

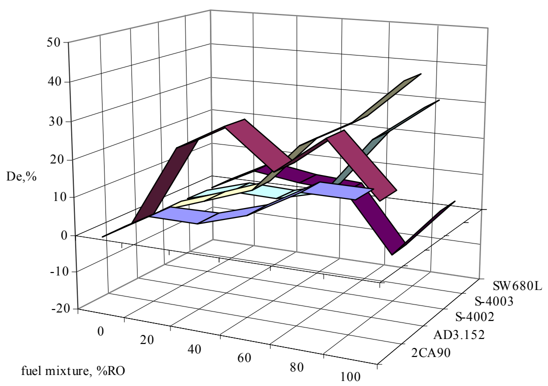

Fig. 9. Comparison of angular acceleration percentage changes of tested engines at engine speed equal to n_M (maximum torque speed)

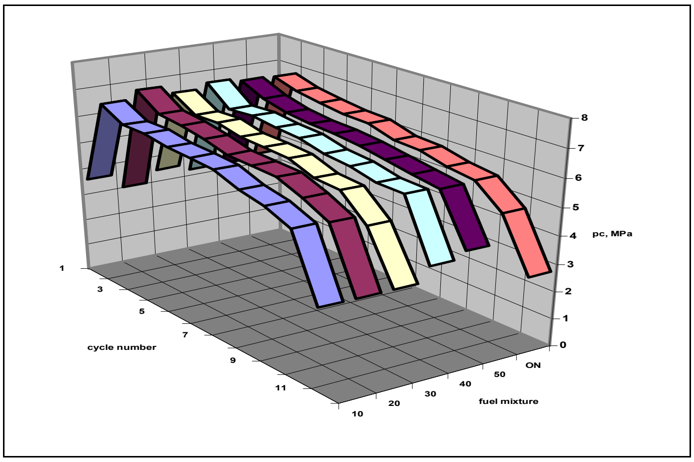

Fig. 10. Mean indicated pressure values of AD3.152 diesel during free acceleration versus fuel composition and cycle number

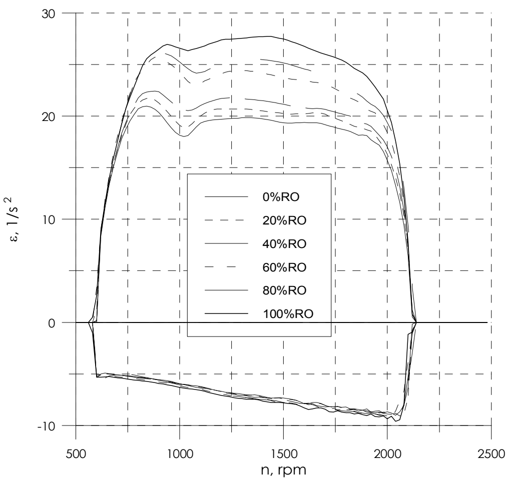

Fig. 11. Dynamic characteristics $\varepsilon = f(n)$ of S-4002 DI diesel fuelled with rape biofuel

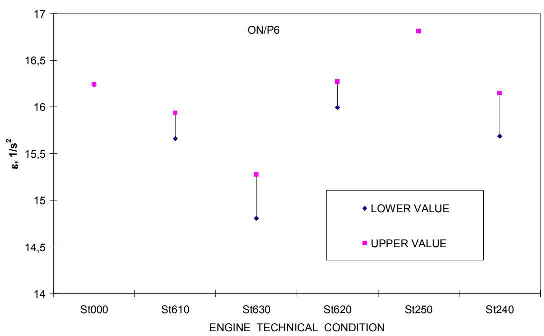

Fig. 12. Sample confidence intervals of engine diagnostic parameter obtained under transient conditions

In the case of indicator parameters analysis (they are referred to single work cycle) the comparison based on the following work cycle number may be used. Precise determination of engine acceleration start is important in this case. The exemplary fuel impact comparison based on mean indicated pressure is shown in Fig. 10.

DIAGNOSTIC TESTS TECHNIQUE

The research methods based on the changes of the engine speed parameters seem to be the most usable ones for diagnostic applications. The appearance of methods such as engine speed measurement easiness, exertion possibility without expensive stands for engine loading, possibility of work effectiveness parameters determination, called for the development of their research. The measurement technique and device for engine diagnosis uses engine dynamic parameters. Parameter set comprises averaged values of angular acceleration describing characteristic points of the chart and their quotients. Border values and confidence intervals are determined for all technical states of the object (shown in Fig. 12). Individual states are recognised by sets of distributing functions. Parameters with short confidence intervals are most usable for diagnosis purpose. Distinguishable diagnostic parameter set of engine good condition is used for state checking. Other sets are used for inefficiency identification as the second phase of diagnostic test.

CONCLUSIONS

The developed transient test technique enables the determination of engine operation parameters in transient conditions and their analysis and comparisons. Performed measurements and obtained results prove that the developed test set-up enables the recording of an engine's indicator and operation parameters in transient conditions. A sufficient accuracy and repeatability of measurements has been achieved. The presented measurement technique may be used for the research of combustion engines under transient conditions.

Dynamic characteristic courses obtained for the tested engines are analogous to adequate dynamic characteristic courses of other DI diesels published earlier. Dynamic courses are of characteristic shape despite their engine features and fuel type.

Angular acceleration of engine crankshaft is a suitable factor for any comparison analysis of engine operation under transient conditions. Engine parameters measured during transient tests could be handled by typical statistic methods but after selection that ensures an adequacy of averaged values.

It is stated that angular acceleration changes are in accordance with mean indicated pressure changes. The presented transient test technique might be used for widening the range of engine tests. It might concern fuel injection and burning under engine transient operation and different diagnostic aspects as well.

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SUMMARY

Engine test technique under transient conditions has been presented in the paper. The values obtained in transient conditions, such as crankshaft angular acceleration, torque, maximum cylinder pressure, mean indicated pressure, efficiency and others could describe an engine's transient operation. Those values are used for further comparisons and assessments. An adequate research set-up and data acquisition system has been described. The use of this technique for an assessment of an engine's operation has been presented. Sample research results of DI diesels tested under transient conditions are presented. The obtained results could be useful in the modelling of DI diesel transient work and for diagnostic aims as well.