THE RELATIONSHIP BETWEEN THE FLUCTUATION OF THE INDICATED WORK, THE FLUCTUATION OF THE CRANKSHAFT SPEED AND THE ELECTRIC CURRENT FROM A GENERATING SET

Karol Cupiał[1], Michał Gruca[2], Janusz Grzelka[3]

Częstochowa University of Technology
Institute of Internal Combustion Engines and Control Engineering
Al. Armii Krajowej 21, 42-200 Częstochowa
[1]tel.: +48 34 3250541, e-mail: cupial@imc.pcz.czest.pl
[2]tel.: +48 34 3250543, e-mail: gruca@imc.pcz.czest.pl
[3]tel.: +48 34 3250503, e-mail: grzelka@imc.pcz.czest.pl

Abstract

The paper presents the results of introductory investigation of the relationship between the value of indicated work and variations of momentary crankshaft rotational speed and electric current from generating set. A clear correlation between engine indicated work and electric energy calculated in time interval angularly shifted regarding indicated work calculation range was stated. The indicated work of consecutive cycles also well correlates with amplitude of electric current. The correlation between crankshaft angular acceleration in determined cycle phase point and indicated work was also stated but it is less significant than it is in the previous cases. In particular Cylinder pressure courses and envelope of electric current, correlation between indicated work and transient electric current, electric energy, crankshaft mean angular acceleration, cylinder pressure, rotational speed and crankshaft angular acceleration courses, estimated values of relative indicated work on the basis of electric current value, electric power value and crankshaft angular acceleration value are demonstrated in the paper.

Keywords: *fluctuation of the indicated work, fluctuation of the electric current, generating set*

1. Introduction

The aim of the research is the analysis of correlation between fluctuation of engine indicated work and fluctuation of crankshaft rotational speed and electric current from generating set. The research also concern the usability estimation of electric current from generating set fluctuations measurement for diagnostics and control of engine specific cylinders.

The simultaneous measurement of pressure courses in individual cylinders of engine driving the generator and engine rotational speed as well as electric current from generator fluctuations is necessary in order to find the described relationship. The research are performed to find the tool dedicated to estimation of the best correlation between the current and rotational speed fluctuations and pressure courses in individual cylinders. The use of crankshaft rotational speed variations for the estimation of engine work quality is the subject of many research [1, 6, 10, 12]. Unfortunately there is lack of research concerning the use of electric current from the co-working generator for such analysis. The course of instantaneous engine flywheel rotational speed and electric current from generator will be used to estimate the non-repeatability of indicated work factor (IMEP COV) [3, 5, 7, 9] for the whole engine and for individual cylinders. Such measurement system gives significantly more information concerning pressure and indicated work courses in individual cylinders in comparison to currently applied electronic diagnostics systems, which do not gives any information about the pressure in individual cylinders and do not identify the cylinder, that causes the engine crankshaft rotational speed variations.

Keeping the IMEP COV factor below the acceptable values is significantly important in the case of spark ignited stationary gas engines powered with lean mixtures as even slight variation in fuel chemical composition and exceeding the border values of excess air factor or temporary misfiring caused e.g. by ignition system failure causes significant increase in IMEP COV value. Gaseous engine work with high IMEP COV value is very unfavourable as it causes fast changing variations of torque and as a consequence it increases the mechanical load of connecting-rod and non-steady rotational speed of the power receiver, which is significantly important in the case of engine driving the electric generator working parallel with other generators in balanced power grid because it causes big fluctuations of electric current and can initiate safety devices. On-line estimation of IMEP COV factor on the basis of current curve will be an additional and valuable diagnostic signal, which will give possibility to monitor and control the combustion engine work parameters and will improve its reliability during operation.

2. The research object

Before the beginning of the research, preliminary tests were performed on single-cylinder generating set because of the considerable complexity of both the measurement system design and the mutual influence of individual cylinders work on engine rotational speed variation as well as generated current. This investigation [4] allowed testing the designed measurement system and delivered data that made possible the pre-selection of method of analysing the correlation between the combustion engine indicated work variation and parameters of generated current. A clear relationship between engine indicated work and electric energy calculated in time interval angularly shifted regarding the beginning of engine cycle was stated in the case of single-cylinder generating set. The indicated work of consecutive cycles also well correlates with crankshaft angular acceleration in determined cycle phase point. A little worse is the correlation between amplitude of electric current and indicated work. The correlation between electric energy calculated in 90 degree angle interval and indicated work was also stated.

The second stage of the preliminary research consisted in carrying out measurements (similar as in the case of single-cylinder engine) on industrial power generating set driven by 8A20G biogas engine of 650 kW power. The following quantities were registered:

- pressure in the third cylinder,
- 3 phase voltage of the generator,
- 3 phase current of the generator,
- crankshaft instantaneous rotational speed,
- generator instantaneous rotational speed.

3. The relationship between indicated work and electric current

The preliminary tests of synchronous registered courses of pressure, crankshaft rotational speed as well as 3 phase voltage and current were meant to determine the level of correlation between indicated work of individual cycles and different parameters of generated current.

The measurements were performed for four different engine loads (generating set output power equal: 30kW, 100kW, 280kW, 400kW, 500kW, 600kW), recording above mentioned quantities for 500 cycles in every series. Fig. 1 shows the exemplary cylinder pressure course and generated electric current in 8 consecutive cycles, registered at the low (N_{el}=30kW) engine load. The instantaneous electric current was calculated as the envelope of current in all phases modules. The high level of diversification of pressure courses and its maximal values is revealed, which is confirmed by the gained IMEP COV value of 120%. Significantly lower was the variation of electric current and it gained the value of 10%. The

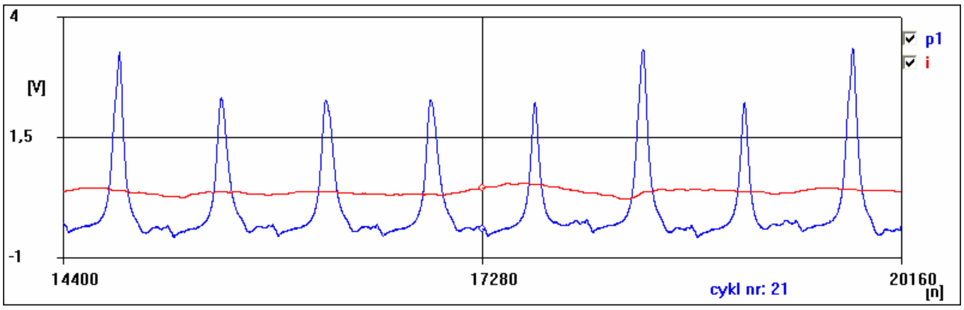

Fig. 1. Cylinder pressure courses and envelope of current registered in condition great non-repeatability of cycles (N_{el}=30kW)

diversification of current calculated at the point of highest fluctuation level gained the value of 15%. The changes in voltage amplitude and phase, which could have some connection with variation of engine work was not stated despite high variation of voltage and current phases.

Lower engine work non-repeatability (IMEP COV in the range of 1,2% to 3,3%) and electric current variations (in the range of 1,2% to 2,4%) was observed at higher engine load. The electric current variations were influenced not only by variations of engine indicated work but also reactive current and interferences in power grid resulting from reactive power. The performed analysis of level of correlation between indicated work in individual engine cycles and electric current revealed that there is a distinct relationship between them (fig. 2). The highest correlation level (r=0.989) occurs between indicated work and the momentary electric current value at the point of 283°CA after TDC.

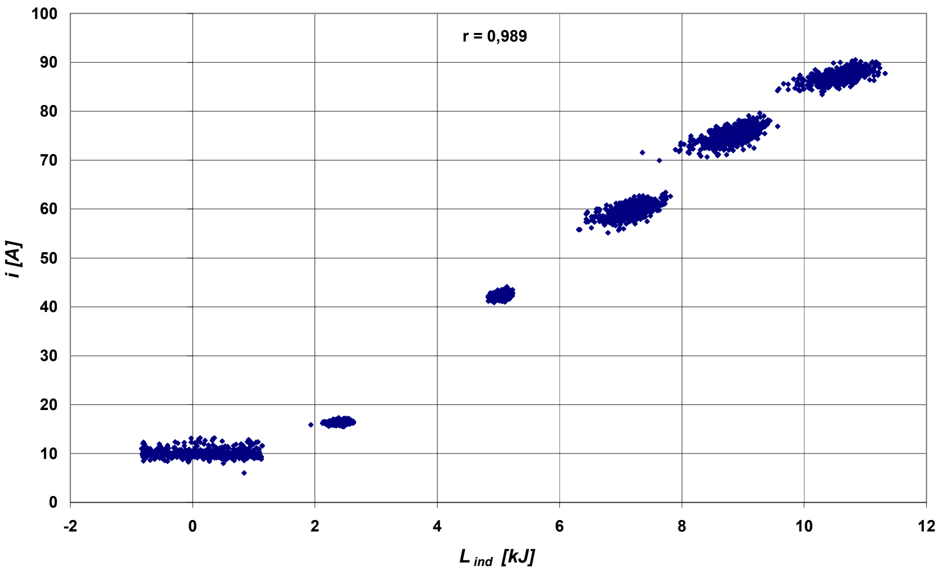

Fig. 2. Correlation between indicated work in the third cylinder and momentary electric current at 283° CA after TDC

4. Relationship between indicated work and generated electric energy

Subsequent research were performed in order to determine the level of correlation between indicated work of individual cycles and electric energy produced by the generator. Well known energetic equations connecting rms voltage, rms current and cosϕ couldn't be used during calculations of active power because of the high level of current disturbance and variation in its amplitude and phase. That is why the instantaneous power course of 3 phase current p was calculated on the basis of instantaneous voltages and phase currents: u_1, u_2, u_3, i_1, i_2, i_3,:

$$p = u_1 \cdot i_1 + u_2 \cdot i_2 + u_3 \cdot i_3 \tag{1}$$

It allowed the amount of electric energy produced by the generator to be set in the assumed range of crankshaft angle:

$$L_{e12} = \int_{t_1}^{t_2} p\,dt = \int_{\varphi_1}^{\varphi_2} p \frac{1}{\omega} d\varphi \tag{2}$$

where: $\omega = d\varphi/dt$ - crankshaft instantaneous rotational speed.

Regarding the fact that in the case of eight cylinder engine (which is meant to be the research object) the work cycles of specific cylinders are shifted by 90°CA regarding each other and their individual influence on the engine torque value as well as instantaneous rotational speed can be noticed only in 90-degree ranges of crankshaft rotation when the pressure in these cylinders gains the highest value. That is why the research concerning the relationship between indicated work and electric energy generated in the range of 90°CA angularly shifted were performed. It has been stated that the best correlation between the absolute value of indicated work L_i calculated in the range of 360° to 450°CA and electric energy calculated in 90° window occurs if the electric energy is calculated in the range shifted by 242°. Fig. 3 illustrates the dependency of power and energy in the case in which the dependency gained the value of r=0.995 measured by the correlation factor.

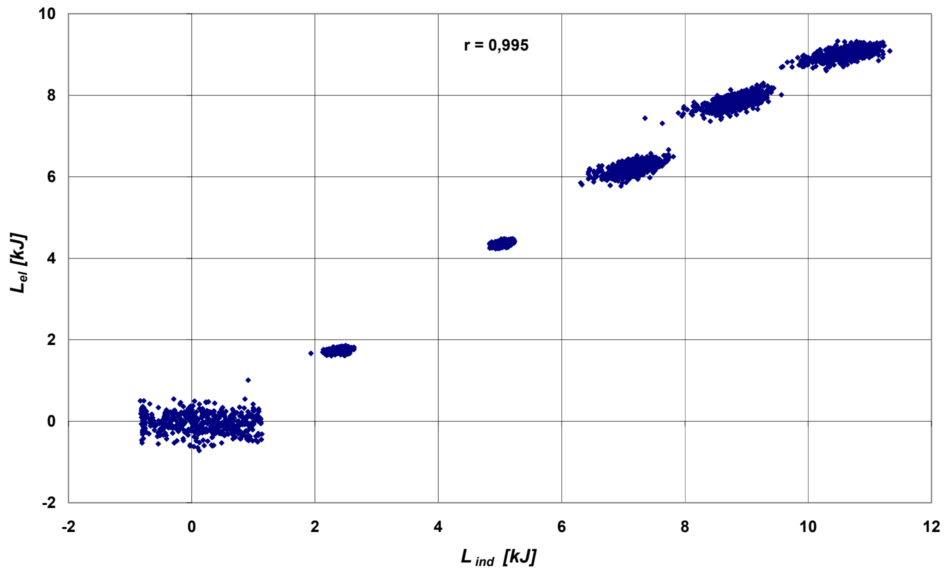

Fig.3. Correlation between indicated work calculated in interval at 360° to 450°CA and electric energy generated in interval at 602° to 692°CA

The value of indicated work for individual cycle is best described by the electric energy generated in the range, which is delayed 400° to 500°CA regarding engine cycle in case of examined single-cylinder engine when comparing on one graph the ranges corresponding to the highest values of correlation between indicated work and electric energy [4]. However in the case of eight cylinder engine this delay is two times smaller. It is most likely caused by significant diversification of natural frequencies of the engine-generator set and resulting phase angles (in the case of single-cylinder engine f_0 = 4,17 Hz and in the case of eight cylinder engine f_0 = 8,24 Hz ± 0,42 Hz).

5. Relationship between indicated work and crankshaft angular acceleration

The next quantity, which correlation with individual cycles indicated work was examined was the combustion engine crankshaft angular acceleration. Numerical direct differentiation of registered instantaneous speed causes significant oscillations of the calculated acceleration course. That is why the Digital Smoothing Polynomial *(DISPO*) was applied before rotational speed differentiation [13]. Fig. 4 illustrates the exemplary cylinder pressure, crankshaft rotational speed and angular acceleration. It can be noticed that the courses of speed and acceleration gain only seven distinct local maximums in one engine cycle in spite of the fact that it is the eight cylinder engine. Most likely it results from the influence of crankshaft torsional vibrations. The vibrations do not allow to detect the crankshaft angular accelerations caused by the cylinder, which is the furthest from the measurement point. The survey of engine crankshaft instantaneous angular acceleration that best correlates with cycle indicated work revealed that it is the mean value of acceleration in the range of 15°CA obtained by the crankshaft near 462°CA of each cycle. The maximal correlation level gained the value of r=0,871 (fig. 5).

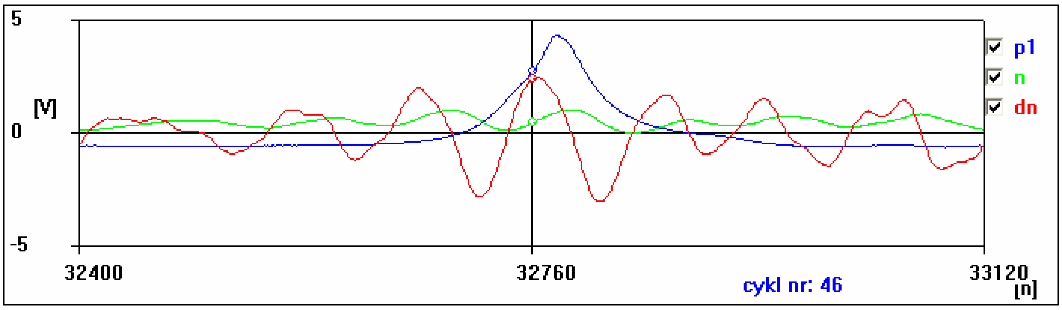

Fig.4. Cylinder pressure, rotational speed and crankshaft angular acceleration courses

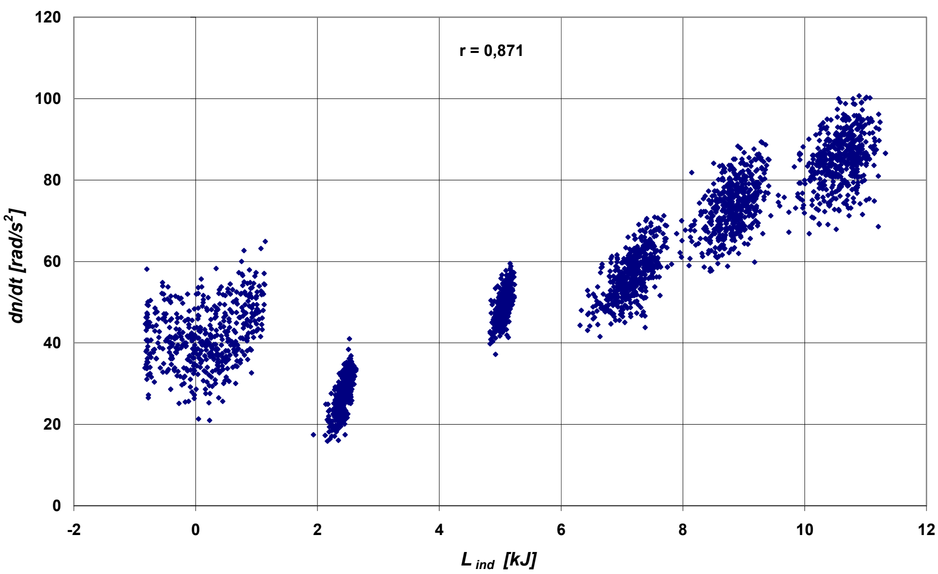

Fig. 5. Correlation between indicated work and crankshaft mean angular acceleration in interval at 455° to 470°CA

6. Applying the determined dependences to define the other cylinders work

The dependences between indicated work of the first cylinder and electric current, power and crankshaft acceleration depicted in figures 2, 3, and 5 should (according to the assumptions of this paper) give possibility to estimate the indicated work of the other cylinders. Assuming the linear dependency between the indicated work and above mentioned quantities the mean (for 500 cycles at each of six loads) values of indicated work of the other cylinders was determined on the basis of the values obtained in cycle phases shifted by 90°CA for the consecutive cylinders. Figures 6, 7 and 8 depict the estimated values of relative (related to mean indicated work of all cylinders) indicated work obtained on the basis of electric current, produced energy and crankshaft angular acceleration values.

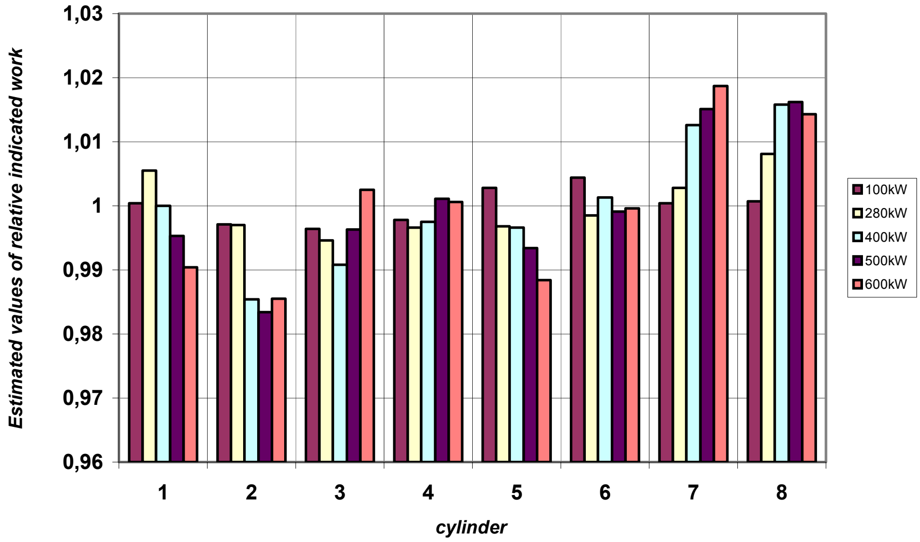

Fig.6. Estimated values of relative indicated work obtained on the basis of electric current value

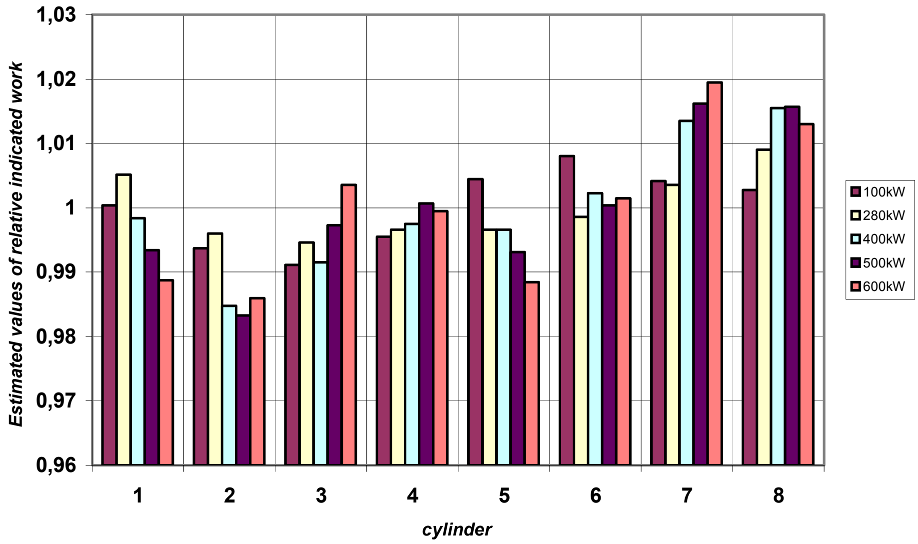

Fig.7. Estimated values of relative indicated work obtained on the basis of electric power value

Only the three highest loads (at which the linearity of dependency between the crankshaft angular acceleration and indicated work was maintained L_i>6kJ) were considered regarding the nonlinearity of the dependency for other loads (fig. 5).

The high similarity between fig. 6 and 7 is noticeable. It allows to presume that the determination of dependency between the indicated work and the electric current and power may be the basis for determining the work variations of individual cylinders of the combustion engine. However this statement must be verified during other research concerning pressure measurements in other cylinders of the engine.

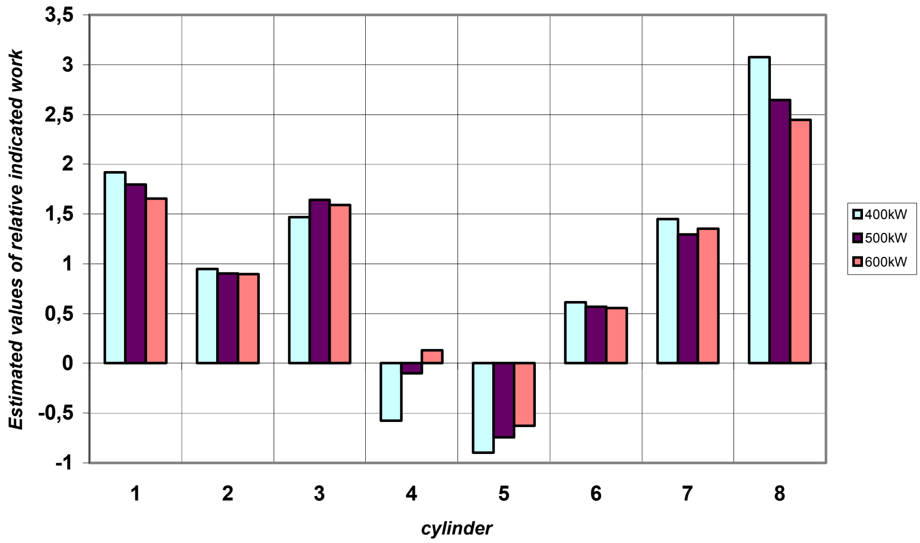

Fig.8. Estimated values of relative indicated work obtained on the basis of crankshaft angular acceleration value

Unfortunately the assuming of linear dependency between the crankshaft angular acceleration in the specified phases and indicated work of individual cylinders leads to incorrect estimation of the indicated work what can be observed in fig. 8 in the form of strongly diversified and even negative values of work of some cylinders.

6. Conclusions

The preliminary research revealed that very distinct correlations between variations of combustion engine indicated work and variations of generated electric current parameters exist in the case of generating set driven by eight cylinder engine. However the curves of crankshaft angular acceleration do not show any evident correlation with indicated work. The Combustion engine individual cylinders work variation may be determined on the basis of obtained relations between indicated work and electric current as well as generated electric power.

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