Statistical investigations of fast changeable processes occurring in ship piston combustion engine

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ABSTRACT

Combustion piston engine is one of the devices in which fast changeable processes occur in operational conditions. In this paper are presented basic problems associated with research on fast changeable processes occurring in diesel engines , exemplified by the processes of indicated pressure and fuel pressure injected to engine's cylinder. Dynamical characteristics of the investigated processes were analyzed and problems of synchronous averaging of pseudo-periodical signals were considered in order to limit high frequency noise content in useful signal. Some limitations of elimination effectiveness of high frequency noise from tested signals have been revealed.

Keywords : piston combustion engine, fast changeable processes, stochastic processes, high frequency noise

INTRODUCTION

Investigations of fast changeable processes, related to the dynamical features characteristics typical for operational conditions of devices, cause many methodological problems. This is especially important because of a high level of ignorance on disturbances of the processes associated with measurement systems as well as occurrence – in real objects – of factors not directly accounted for in testing program. The piston combustion engine is a typical object in description of which such problems appear [3 ÷ 6].

The processes occurring in the combustion engine can be classified from the point of view of their dynamical features, and a role they play in the engine's operation, namely [3] :

- processes associated with particular working cycles of the engine as well as the fast changeable ones in comparison with those characteristic for the typical use of the engine
- processes associated with the typical use of the engine
- processes associated with service (tribological) wear of the engine as well as slowly changeable ones in comparison with the processes characteristic for the typical use of the engine.

The first group of the processes contain all the processes connected with engine's cycle. Processes not fully connected with the cyclic work of the engine, however generated by it, e.g. vibration of its elements, can be also considered as belonging to that group. Frequencies of the processes, conventionally considered as characteristic[1)] for them, should be at least one-order higher than those of engine working cycles as they occur in intervals corresponding to fragments of single cycles [3].

The processes characteristic for the typical use of the engine are associated with operational forcing factors affecting the engine. The main service forcing factors are the following : control of the engine by its operator, and its loading from the side of power consumer.

The power consumer reacts by rate of its task realization, and the engine – by changing its rotational speed. On the basis of analyses of the processes it can be stated that the characteristic frequencies of the processes associated with the typical use of the engine are contained within the interval (0.01 ÷ 10) Hz, with a large safety margin [3].

The slowly changeable processes in comparison with those connected with the typical use of the engine are of entirely different dynamical character. To this category can be counted the thermal processes which characterize engine's thermal state described by the set of temperatures of engine parts and systems. Such processes have time constants in the order of several or a dozen or so minutes, a few dozen of seconds at least. The processes even more slowly changeable than the thermal ones are those describing atmospheric conditions , all the more tribological processes associated with engine's wearing [3].

In the combustion engine it is characteristic – due to its working principle – that the fast changeable processes, especially those connected with working cycles, are pseudo-periodical. The pseudo-periodicity, but not periodicity, of the processes results : firstly from the fact that periodic function is determined for unlimited set of independent variable values,

1) The conventional notion of „characteristic frequencies" is assumed equivalent to the range of frequency values for which amplitudes of frequency representation of a process have significant values arbitrarily assumed by a researcher (and sometimes customary assumed by specialists to be valid) [3].

and secondly from that the investigated processes are real. Due to the pseudo-periodicity of the processes associated with particular engine working cycles, high-frequency disturbances of signals can be modelled as the signal amplitude disturbances and also as independent variable ones. In this case the independent variable is usually :

time - t ; crank angle - α.

Let x(t) be a pseudo-periodical signal such that :

$$\left|x(t) - x(t + j \cdot T)\right| < \varepsilon \qquad (1)$$

where :

particular phase j = 1, 2, ..., N

$\varepsilon > 0$

T - a quantity estimated as a tested signal pseudo-period.

Therefore the inaccuracy ε depends on :

- high-frequency noise amplitudes
- characteristics of the set of successive pseudo-periods, $\{T_i\}$, where : i = 1, 2, ..., N – 1.

The synchronous averaging of the signal x(t) consists in determining the function [1, 12, 13] :

$$\overline{x}(t) = \frac{1}{N}\sum_{j=0}^{N} x(t + j \cdot T) \qquad (2)$$

On the assumption that values of elements of the set $\{T_i\}$ are constant, the synchronous averaging of the signal makes it possible – in compliance with the laws of large numbers (inequality of Chebyshev, laws of Markov and Chintsin [2, 9, 17]) – to significantly limit high-frequency noise content in useful signal, for a certain class of processes describing high-frequency noise, e.g. normal ones :

$$\lim_{N\to\infty}\left[\overline{x}(t) - x(t)\right] = 0 \qquad (3)$$

The most important limitations of effectiveness of the synchronous averaging of signals are the following problems : determination of a tested signal pseudo-period as well as of features of the set of particular pseudo-periods.

In the case of signal digital processing the accuracy of the pseudo-period estimation depends on [1, 3, 4, 12, 13] :

- resolution of quantization of the signal, that determines accuracy of assessing independent variable values
- sampling frequency which determines Nyquist frequency of an observed signal
- signal observation time deciding on frequency resolution of an observed signal.

Influence of sampling frequency on accuracy of pseudo--period estimation is solely theoretical because it is only required the sampling frequency to be at least two times greater than that corresponding to expected value of pseudo-period. In order to obtain a small inaccuracy value of pseudo-period estimator it is necessary to use a large value of quantization resolution as well as long observation times [1, 3, 4, 12, 13].

To satisfy the conditions is sometimes really difficult, e.g. when the conditions not directly accounted for in testing program influence qualification of processes as stationary ones – – in this case an increase of observation time can make it impossible to qualify a process as stationary one.

The other effectiveness limitation of the synchronous averaging of signals depends on how large deviations of particular pseudo-periods from a value estimated as representative for a tested signal, are. In the case of too large deviations the synchronous averaging of signal can lead to a significant limitation of amount of information about useful signal, hence – in fact – to generation of additional noise instead of limitation of noise content in a tested signal (it is obvious that any processing of signal inevitably contributes to noise generation [1, 3, 4, 12, 13]).

Effective improvement of quality of the synchronous averaging of pseudo-periodical signals occurring in piston combustion engine can be obtained by signal sampling in the domain of crankshaft rotation angle, but not in the domain of time [1, 3, 4, 12, 13]. This way influence of rotational speed fluctuations on effectiveness of the synchronous averaging of signals may be avoided.

INVESTIGATIONS OF THE PROCESSES OF INDICATED PRESSURE AND INJECTION PRESSURE

The presented basic problems associated with research on fast changeable processes occurring in diesel engines are here exemplified by the processes of indicated pressure and fuel injection pressure in cylinder. The investigations have been carried out at the laboratory stand equipped with 6AL 20/24 Sulzer ship diesel engine of 37.7 dm^3 piston displacement, 420 kW rated output and 750 min^{-1} rotational speed.

The tests were carried out in statical working conditions, i.e. those independent on time [3] in the frequency range corresponding to real engine working conditions. In Fig.1 the testing point of the engine in question is presented.

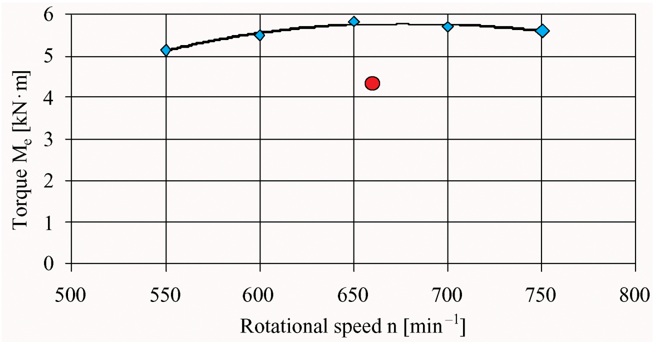


Fig. 1. *Testing point of the tested engine operating in compliance with rotational speed characteristics*

For testing the signals quantized by means of a 12–bit transducer and recorded at the sampling interval Δt = 50 µs , the sample sets of 32 000 elements each were used.

The analyses were performed in the domains of [1, 3, 12, 13, 17] :

- time
- process values
- frequency.

The recorded signals are presented in Fig.2 and 3.

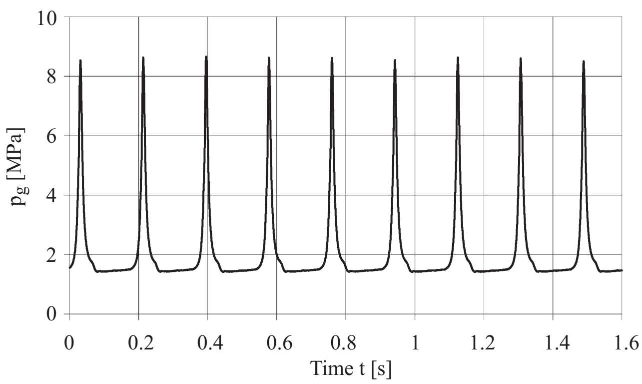


Fig. 2. *Indicated pressure* $\mathbf{p_g}$ *in function of time*

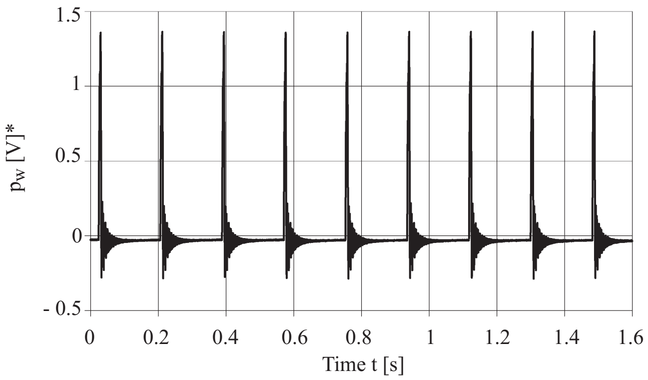


Fig. 3. Fuel injection pressure $\mathbf{p_w}$ *in function of time*

In Fig. 4 the correlation relationship of the indicated pressure and injection pressure is presented. The correlation coefficients are of relatively large values : beginning from 0.2441 of Kendall's τ and 0.2471 of Kendall's γ [2,9], 0.2855 of Spearman's range coefficient [2,9] up to 0.6079 of Pearson's linear coefficient [2, 9, 14], for this reason there is no ground to reject hypotheses on lack of correlation between analyzed signals (Fig.5).

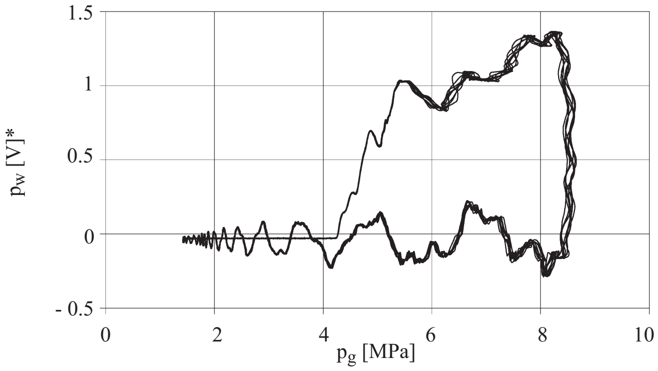


Fig. 4. Correlation relationship of injection pressure $\mathbf{p_w}$ *and indicated pressure* $\mathbf{p_g}$

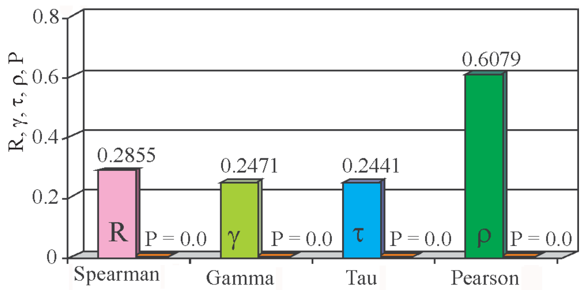


Fig. 5. The correlation coefficients of Spearman : **R** *, Kendall :* $\boldsymbol{\gamma}$ *and* $\boldsymbol{\tau}$*, and Pearson :* $\boldsymbol{\rho}$ *- for sets of indicated pressure and injection pressure, as well as the probability of non-rejection of hypotheses on lack of correlation of the sets ,* **P**

The tested signals were subjected to stationarity analysis [1, 12, 13, 17]. To this end the mean values and standard deviations were determined in particular phases corresponding to pseudo-periods (Fig.6 and 7). On the basis of the performed analysis the assumption on stationarity of the tested signals was adopted.

The signals of indicated and injection pressures were subjected to time and frequency analyses. For the investigations an algorithm based on Fourier's fast transformation as well as Hamming's five-sample-wide window was applied [1, 12, 13]. The signal power spectral density of indicated pressure and injection pressure, with eliminated linear trends, are presented in Fig.8.

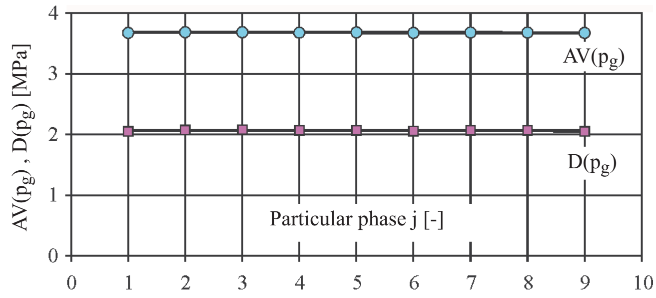


Fig. 6. Mean value **AV** *and standard deviation* **D** *of indicated pressure* $\mathbf{p_g}$ *in course particular phases*

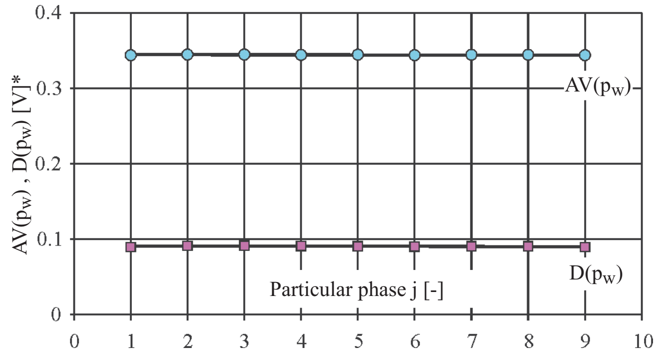


Fig. 7. Mean value **AV** *and standard deviation* **D** *of injection pressure* $\mathbf{p_w}$ *in course particular phases*

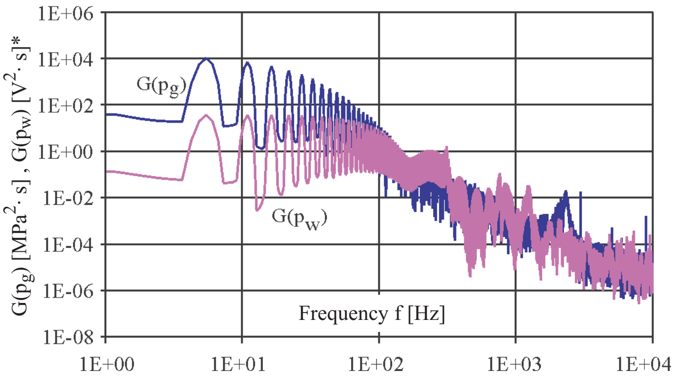


Fig. 8. Signal power spectral density **G** *of indicated pressure* $\mathbf{p_g}$ *and injection pressure* $\mathbf{p_w}$

The first maximum of power spectral density of both signals appears at the frequency f = 5.4931640625 Hz, which corresponds to the pseudo-period T = 1/f = 0.182044 s. The pseudo-period of that value corresponds to the rotational speed :

$$n = f \cdot 2 \cdot 60 \; [\text{min}^{-1}] \qquad (4)$$

where : frequency f [Hz]

On substititions : $n = 659.2 \text{ min}^{-1}$ the mean rotational speed recorded during the test series at the frequency of 1 Hz, was equal to 659.3 min^{-1} [6]. On the basis of the results, inaccuracy of pseudo-period estimation of the tested signals can be assessed : it is smaller than 0.023%.

Also, the auto-correlation function of indicated and injection pressures was determined (Fig. 9).

Also, the results of the correlation analysis of signals confirmed the determined pseudo-period value : the maximum of correlation function occurred at the time-lag $\Delta t = 0.182044$ s. The mutual testing of the signals of indicated and injection pressures was also performed (Fig.10 and 11).

*) The injection pressure Pw was measured in voltage units and due to technical reasons it was not converted into pressure units

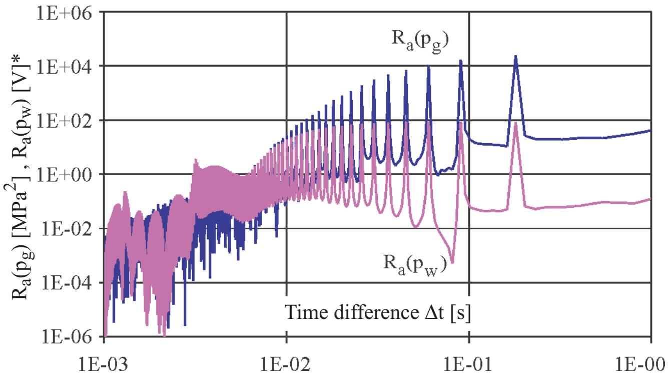


Fig. 9. Auto-correlation function $\mathbf{R_a}$ *of indicated pressure* $\mathbf{p_g}$ *and injection pressure* $\mathbf{p_w}$

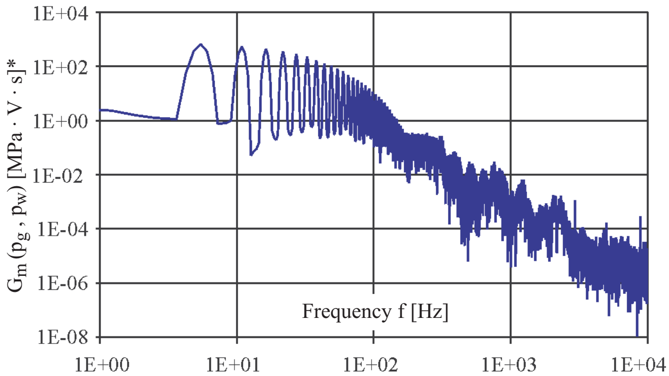


Fig. 10. The module of mutual spectral density of power $\mathbf{G_m}$ *of indicated* $\mathbf{p_g}$ *and injection* $\mathbf{p_w}$ *pressures*

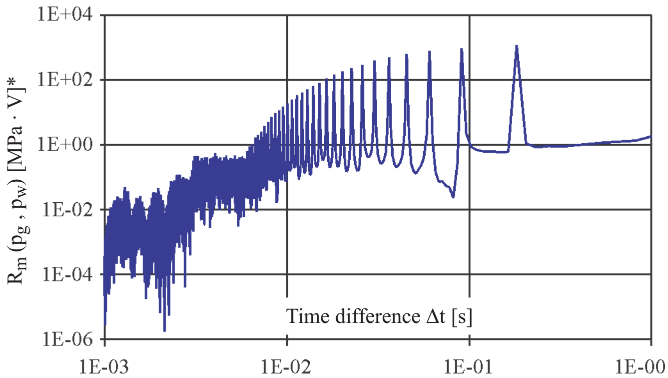


Fig. 11. Mutual correlation function $\mathbf{R_m}$ *of indicated* $\mathbf{p_g}$ *and injection* $\mathbf{p_w}$ *pressures*

This mutual testing of the signals confirmed the estimated pseudo-period value representative for the tested signals.

By making use of the determined pseudo-period value of the tested signals their synchronous averaging was performed. Before the synchronous averaging the courses were subjected to the lowpass filtering of 1 kHz limit frequency to decrease high-frequency noise content in the tested signals. For realization of the operation a filter with applied Fourier's fast transformation algorithm, was used [1, 4, 5, 12, 13].

In Fig.12 a fragment of the initial course and the averaged one of indicated pressure, and in Fig.13 – of injection pressure, was presented.

In both the cases the mean deviations of initial courses are rather small. The courses of the deviations in particular phases are presented in Fig.14 and 15, and the sets of all deviations – – in Fig.16 and 17.

Despite the relatively small deviations of signal values from the averaged one, the interference phenomenon is here characteristic, especially distinct for injection pressure the course of which shows content of high-frequency components of a gre-

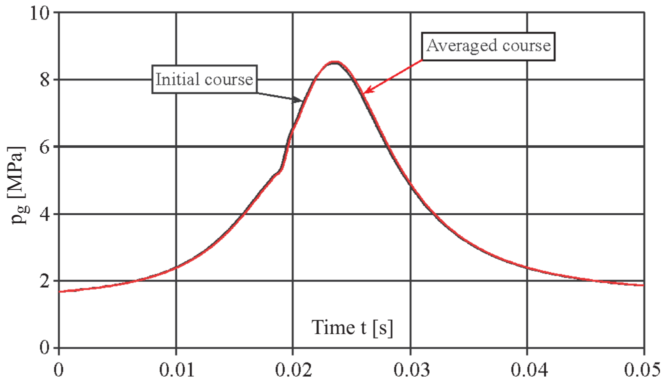


Fig. 12. A fragment of the initial course and the averaged one of indicated pressure $\mathbf{p_g}$

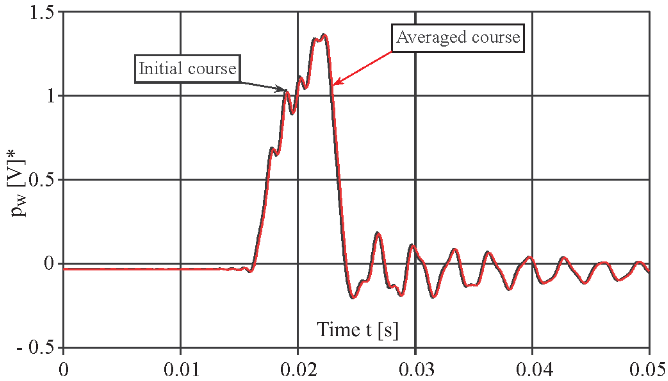


Fig.13. A fragment of the initial course and the averaged one of injection pressure $\mathbf{p_w}$

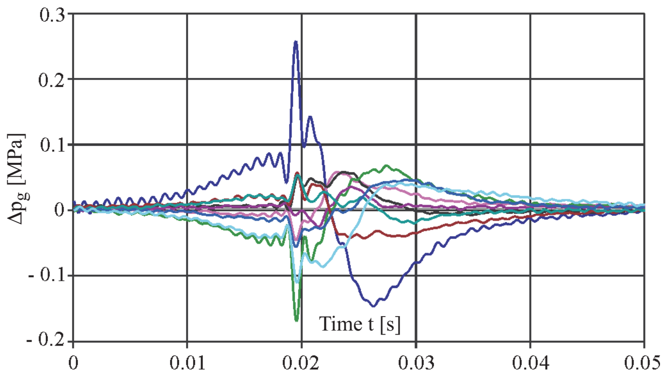


Fig. 14. Fragments of the courses of deviations from the averaged value of indicated pressure $\mathbf{\Delta p_g}$ *in particular phases*

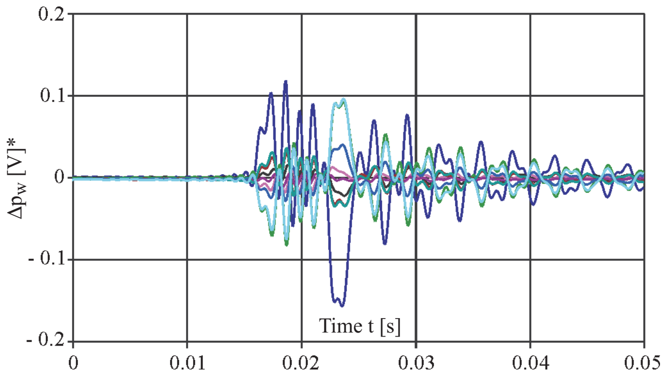


Fig. 15. Fragments of the courses of deviations from the averaged value of injection pressure $\mathbf{\Delta p_w}$ *in particular phases*

ater amplitude than in the case of indicated pressure. The interferences occuring in the sets of deviations are due to : on one hand – real non-periodicity of the tested courses, on the other hand – very small difference of estimated pseudo-period and successive real pseudo-periods.

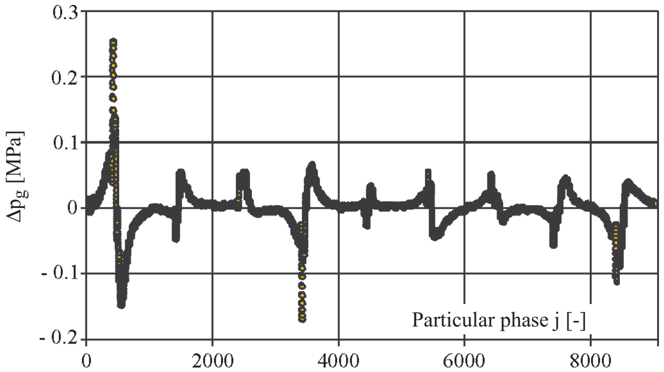


Fig. 16. *Set of deviations from the averaged value of indicated pressure* $\mathbf{\Delta p_g}$ *in particular phases*

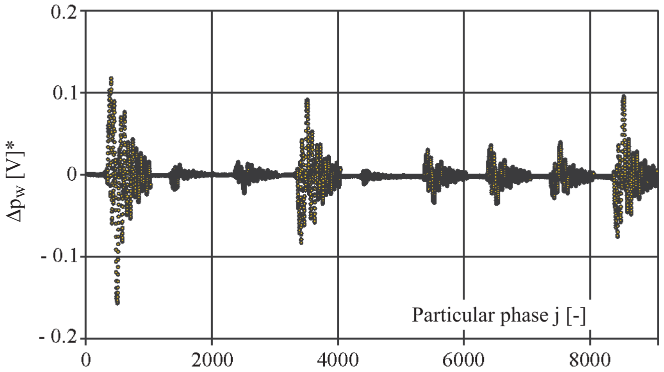


Fig. 17. *Set of deviations from the averaged value of injection pressure* $\mathbf{\Delta p_w}$ *in particular phases*

In Fig.18 and 19 are presented the results of analysis of standard deviation of the tested signals and deviations from their averaged value. Small values of standard deviations and deviations of these deviations, relative to the standard deviations of the initial signals, were observed : smaller – of about 1.5% - for indicated pressure, and greater – of about 5% - for injection pressure – in this case a greater content of high-frequency noise not eliminated from the initial signal, can be clearly observed (Fig. 20).

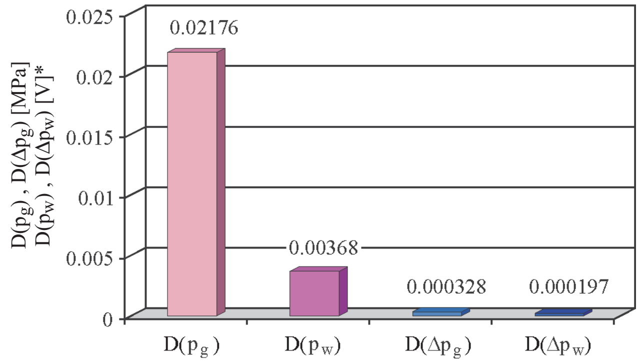


Fig. 18. *Standard deviation* **D** *of the sets : of indicated pressure* $\mathbf{p_g}$ *and of injection pressure* $\mathbf{p_w}$ *, as well as of deviations from averaged values of these pressures* $\mathbf{\Delta p_g}$ *,* $\mathbf{\Delta p_w}$

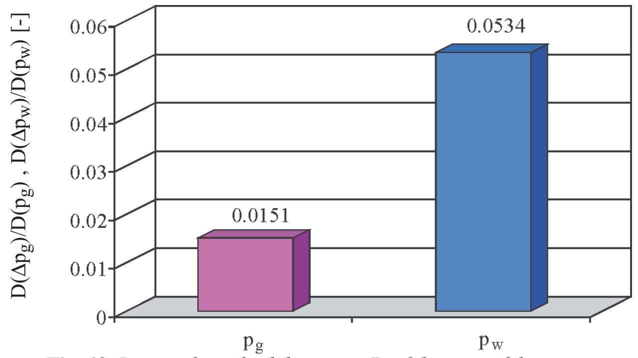


Fig. 19. *Ratios of standard deviations* **D** *of the sets: of deviations from averaged values of indicated and injection pressures, (*$\mathbf{\Delta p_g}$ *,* $\mathbf{\Delta p_w}$*) as well as of indicated pressure* $\mathbf{p_g}$ *and injection pressure* $\mathbf{p_w}$

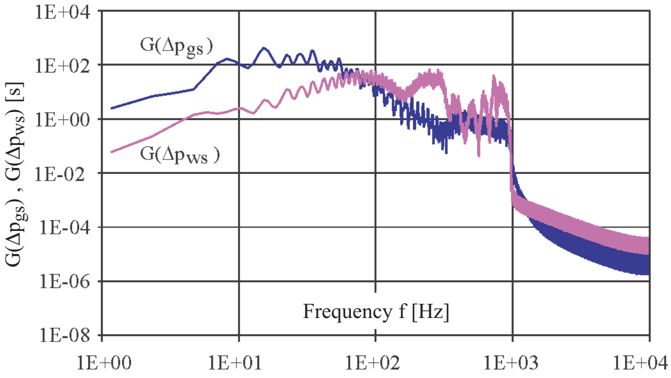


Fig. 20. *Power spectral density* **G** *of standardized deviations from averaged values of indicated and injection pressures (*$\mathbf{\Delta p_{gs}}$ *,* $\mathbf{\Delta p_{ws}}$*)*

Also, correlation relationship of deviations of the standardized indicated pressure (of the mean value equal to zero and standard deviation equal to 1 [1, 2, 9, 12, 13]) and deviations of the standardized injection pressure, was determined. The correlation coefficients of Spearman, Kendall and Pearson of the analyzed sets , as well as the probability of non-rejection of hypotheses on lack of correlation of the sets are presented in Fig.21 [2, 9, 14].

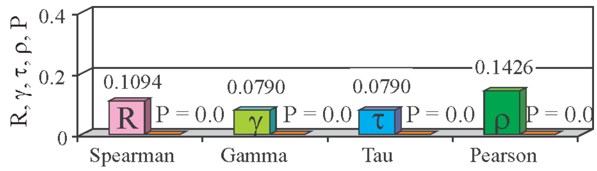


Fig. 21. *Correlation coefficients of : Spearman,* **R***, Kendall,* $\boldsymbol{\gamma}$ *and* $\boldsymbol{\tau}$*, as well as of Pearson,* $\boldsymbol{\rho}$*, of the sets of standardized deviations from averaged values of indicated pressure* $\mathbf{\Delta p_{gs}}$ *and injection pressure* $\mathbf{\Delta p_{ws}}$ *, and the probability of non-rejection of hypotheses on lack of correlation of the sets,* **P**

On the basis of the performed analysis it was stated that there is no ground to reject hypothesis on lack of correlation between the sets of standardized deviations from averaged values of indicated pressure and injection one.

The sets of deviations of the pressures in question as well as standardized deviations were analyzed in the value domain. In Fig.22 the histograms of standardized sets of deviations of indicated pressure and injection one from their averaged values, are presented, and in Fig.23 – the probability density of the tested sets.

Also, conformity of the tested sets to normal distribution was assessed. To this end the following hypotheses were applied: of Kolmogorov and Smirnov [2, 9, 10, 16], of Lilliefors [2, 9, 11], and of Shapiro and Wilk [2, 9, 15]. In Fig.24 for instance the Kolmogorov–Smirnov statistics of the sets of the standardized deviations of indicated pressure and injection pressure from their averaged values, are presented; the probability of non-rejection of the above mentioned hypotheses equals zero.

As a result of the tests of the analyzed sets it was stated that there has been no ground to accept the used hypotheses on conformity to normal distribution of the sets of standardized deviations of indicated and injection pressures from their averaged values. Probably, a big interference content in the analyzed sets to a large extent decided on the observed, different from normal, character of the analyzed deviations. In the case of strictly synchronous averaging the tested signals, the normally distributed deviations from averaged value should be rather expected.

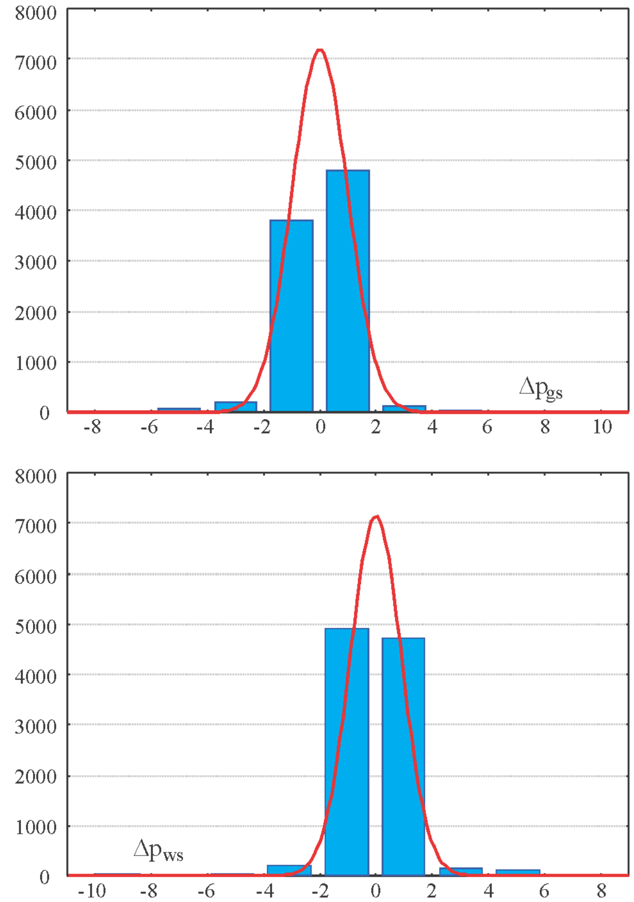


***Fig. 22.** The histograms of sets of the standardized deviations of indicated pressure ,* $\mathbf{\Delta p_{gs}}$ *, and of injection pressure,* $\mathbf{\Delta p_{ws}}$ *, from their averaged values (continuous lines stand for respective normal distributions)*

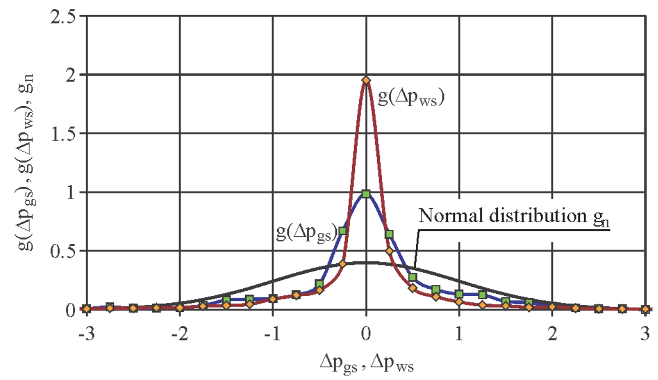
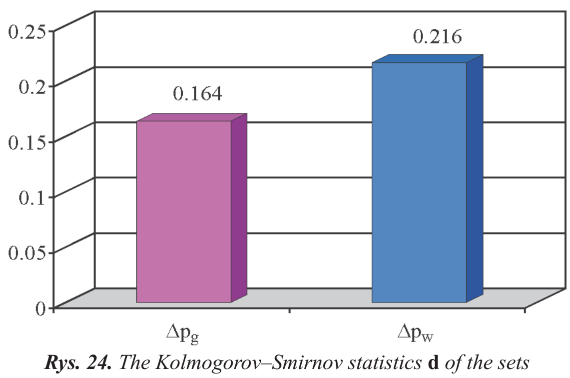


***Fig. 23.** The probability density* **g** *of sets of the standardized deviations of indicated pressure,* $\mathbf{\Delta p_{gs}}$ *, and of injection pressure,* $\mathbf{\Delta p_{ws}}$ *, from their averaged values*



***Rys. 24.** The Kolmogorov–Smirnov statistics* **d** *of the sets of the standardized deviations of indicated pressure* $\mathbf{\Delta p_g}$ *and injection pressure* $\mathbf{\Delta p_w}$ *from their averaged values*

SUMMARY

- Investigations of fast changeable processes make great difficulties which can result in over-interpretation of test results, namely in formulating judgements on investigated phenomena, on the basis of the investigation of features of measurement systems, as well as on the knowledge gained during analyzing the phenomena not directly accounted for in the test program. Therefore a formal critical analysis of measurement results, based on real knowledge on investigated phenomena as well as formal tools for processing the measurement results, is necessary.

- The example analyses presented in this paper have confirmed that it is reasonable to comprehensively test recorded signals as well as noise features. Such tests can a.o. to justify the thesis on a physical nature of noise eliminated from the initial signal. As a result of the analysis it can be also stated that the transformations performed on a recorded signal may be a factor deciding on the nature of noise. Such case was also revealed in this work: some features of the tested noise originated from the process of selecting it out of the initial signal, namely the interferences due to synchronous averaging.

- The comprehensive testing of recorded signals is necessary to avoid subject-matter errors difficult to be predicted in further analyses. Examples of such errors resulting from transformations of the signals containing noise of an unknown nature are numerous in the field of combustion engines; for instance, the determination of heat rate generated in engine cylinder, performed on the basis of indicated pressure signal. In this case noise due to numerical differentiation of indicated pressure is usually subjected to such procedures [4, 5].

NOMENCLATURE

AV	– mean value
d	– Kolmogorov–Smirnov statistics
D	– standard deviation
f	– frequency
g	– probability density
G	– spectral density of power
G_m	– mutual spectral density of power
H	– occurence frequency of a process value on histogram
M_e	– effective torque
n	– rotational speed
p_g	– indicated pressure
p_w	– injection pressure
P	– probability of non-rejection of a hypothesis
R	– Spearman's range correlation coefficient
R_a	– auto-correlation function
R_m	– mutual correlation function
t	– time
T	– signal pseudo-period
x	– process
$\bar{x}$	– synchonously averaged process
Δt	– time-lag
Δp_g	– indicated pressure deviation
Δp_{gs}	– standardized deviation of indicated pressure from its averaged value
Δp_w	– injection pressure deviation
Δp_{ws}	– standardized deviation of injection pressure from its averaged value
γ	– Kendall's gamma correlation coefficient
ρ	– Pearson's linear correlation coefficient
τ	– Kendall's tau correlation coefficient

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Conference

COMPOWER'04

On 2-3 December 2004 Gdańsk University of Technology and Alstom Power Ltd organized the 3rd International Scientific Symposium on :

Technical, Economic and Environmental Aspects of Combined Cycle Power Plants

It was first of all aimed at drawing attention of engineers and economists onto application of turbines to propulsion and heating systems, especially those based on so called gas-steam cycles. They are characterized by technical, economical and ecological advantages such as :

- the improvement of the power plant performance
- the increase of the energy conversion efficiency
- the decrease of the coal consumption
- the decrease of the environmental pollution.

29 papers, split into 5 topical chapters, were prepared for presentation during the Symposium :

- *Modelling and simulation of turboset characteristics* (6 papers)
- *Neural network application to turboset simulation* (6 papers)
- *Turbine plant diagnostics* (4 papers)
- *Analysis and improvement of turbine plant characteristics* (8 papers)
- *Turbine plant operation, reliability and control* (5 papers).

The papers were mainly prepared by Polish scientific workers from : Institute of Fluid-Flow Machinery of Polish Academy of Sciences, Gdańsk University of Technology, Silesian University of Technology, Warsaw University of Technology, Technical University of Zielona Góra, Gdynia Maritime University, Naval University of Gdynia. 3 papers were elaborated by foreign authors : from Mexico, Russia and Sweden. Employees of Alstom Power Ltd much contributed to the Symposium, and presence of representatives of two Polish firms : Polteknik and Diagnostyka Maszyn could be also clearly observed.

An interesting part of the Symposium was Round Table Discussion on :

"*Turbine Industry and Energetics Dilemmas* (*efficiency, reliability, diagnostics, control*)"

A very attractive accent of the scientific meeting was the trip to Władysławowo, a Baltic port, where the Symposium's participants had the occasion to visit a gas heat-generating plant. The modern object built in 2003 takes natural gas, through the longest-in-Europe underwater pipeline, from a gas production rig 82 km distant offshore.