Irregularity of static working states of ship combustion piston engine

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ABSTRACT

Variability of static working conditions of combustion engine in the range of higher frequencies has character of noise resulting from phenomena not taken directly into account in test program as well as from features of measuring systems. Knowledge of features of the noise contained in observed static signals is important for determining the representative values taken as static and slow-changeable in conditions of unavoidable disturbances. The tests in question were carried out in the static working conditions of a 6AL 20/24 Sulzer diesel engine, determined by the torque Me = 4.33 kNm and the rotational speed n = 660 min^{-1}*. The following quantities characterizing emission of pollutants contained in exhaust gas in the conditions described by the engine working point : torque, rotational speed and concentrations of carbon oxide, hydrocarbons and nitrogen oxides, were selected for analyses. The tests were performed in the domains of time, process values and frequency. It was stated that the observed runs of the noise generated by phenomena not directly accounted for in combustion engine static test program and by measuring systems, had mainly the character of uncorrelated broad-band normal noise. The results justify a.o. correctness of averaging the measurement results obtained in static conditions as well as synchronous averaging in steady conditions.*

Key words : combustion piston engine, static conditions, statistics, broad-band noise, uncorrelated noise.

INTRODUCTION

A way of considering the investigated quantities depends on researcher's intention [3÷5]. The relation is especially important in the case of quantities observed in time domain: the same processes may be considered dynamic or static depending on the frequency ranges taken into account [3]. Combustion engine is characterized by cyclic work, therefore it is always possible to transform time variable (independent one) in such a way as to make analyzing some engine processes as steady ones possible. Simultaneously the unavoidable fluctuations of the quantities not directly accounted for in test program cause that signals observed in unlimited frequency range are always of dynamic and – additionally – unsteady character. Static working conditions of engine are equivalent to the postulate of time independence of processes in an assumed frequency range usually corresponding with engine working conditions [3]. Time variability of the conditions in the range of higher frequencies has a character of noise resulting from the phenomena not directly accounted for in test program as well as from features of measuring systems [3÷5]. Knowledge of features of the high-frequency noise contained in observed static signals is important for procedures of determining the representative values taken as static and slow-changeable in conditions of unavoidable disturbances characteristic for cognitive processes [4,5]. This paper is devoted to the above mentioned processes.

EXAMPLE INVESTIGATIONS OF RECORDED PROCESSES OCCURRING IN THE COMBUSTION ENGINE

The investigations were carried out on Sulzer 6AL 20/24 ship diesel engine of 37.7 dm^3 piston displacement and 420 kW rated output at 750 min^{-1} rotational speed, installed at the laboratory test stand.

The tests were carried out in static working conditions, i.e. those which are independent on time in the frequency range corresponding with engine's real working conditions [3]. Processes of the frequencies higher than those corresponding with engine's real working conditions are considered fast changeable, and those of the lower frequencies – slow-changeable. It is possible to differentiate the interpretation of fast changeable, slow changeable processes and those corresponding with engine's real working conditions from the point of view of separation of their frequencies. The slow-changeable processes play a role of initial conditions respective to the processes corresponding with engine's real working conditions, and the last ones may be considered statical respective to the fast changeable processes [3].

Measurement accuracy of particular quantities was compliant with ISO 8178–2 standard, and for the used value ranges it was equal to :

- ★ ± 0.5% for torque and rotational speed
- ★ ± 1% for concentration of carbon oxide, hydrocarbons and nitrogen oxides.

The example processes occurring in the engine working point [Me = 4.33 kNm; n = 660 min^{-1}] were selected from among the tests carried out in static conditions (Fig.1).

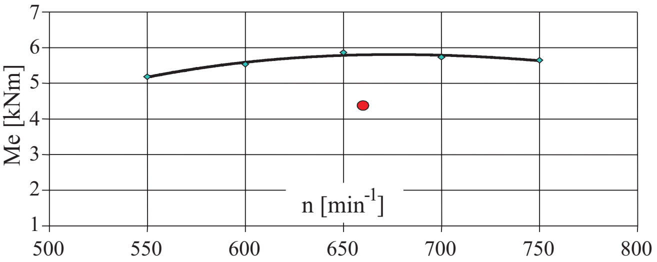

Fig. 1. The selected test working point on the engine speed characteristics .

During the tests were recorded the quantities which characterize operation of the engine including its power, ecological and economical features as well as a.o. temperatures and flow rates of cooling medium and air in intake system. The following quantities which characterize emission of pollutants contained in exhaust gas in the conditions described by the engine's working point, were selected to be analyzed in this paper :

- ➢ torque : Me(t)
- ➢ rotational speed : n(t)
- ➢ carbon oxide concentration : C-CO(t)
- ➢ concentration of hydrocarbons : C-HC(t)
- ➢ concentration of nitrogen oxides : C-NOx(t).

Signals of the following parameters were digitally recorded :

- ⇨ sampling time : $\Delta t = 1$ s
- ⇨ number of samples in a set : $N = 64$.

The analyses were performed in the domains of time, process quantity and frequency [1÷3, 10, 11, 15].

The respective recorded runs are presented in Fig.2÷6.

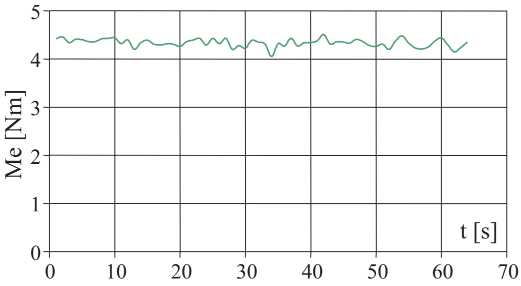

Fig. 2. *Run of engine's torque .*

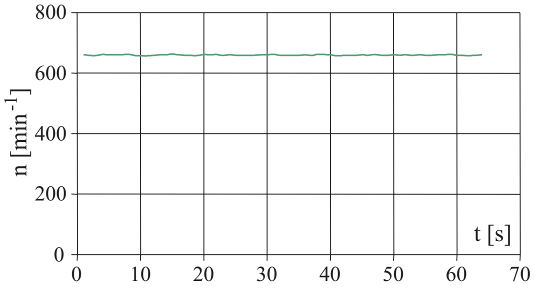

Fig. 3. *Run of engine's rotational speed .*

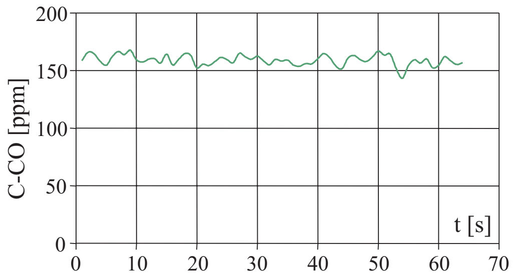

Fig. 4. *Run of carbon dioxide concentration .*

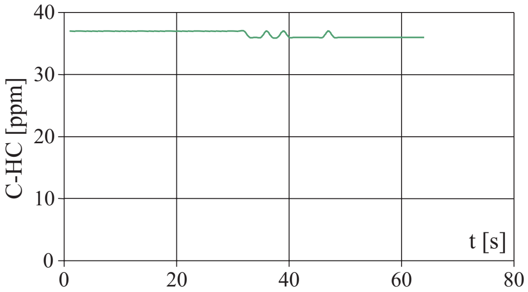

Fig. 5. *Run of concentration of hydrocarbons .*

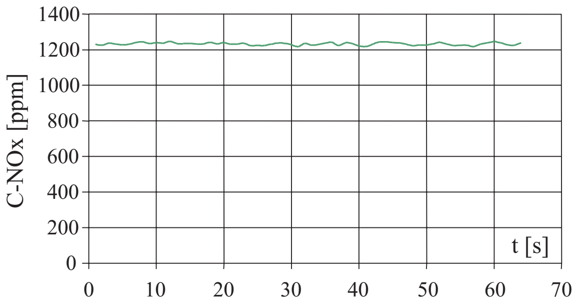

Fig. 6. *Run of concentration of nitrogen oxides .*

In Fig.7 the coefficients of variation (ratio of standard deviation and mean value [7]) of the recorded runs are presented. The smallest variation characterizes the run of engine's rotational speed (0.002) that results first of all from inertial features of mechanical systems of the engine, as well as the concentration of nitrogen oxides (0.006). Variations of the remaining quantities are similar to each other (0.014 ÷ 0.028).

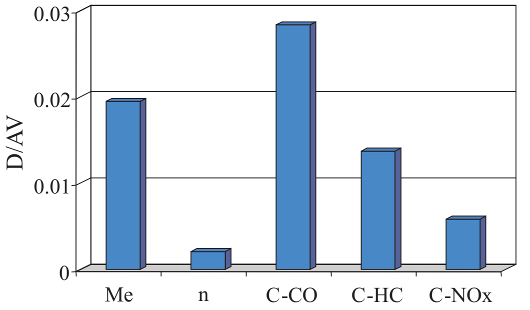

Fig. 7. *Coefficients of variation of the sets of values of : engine's torque and rotational speed, as well as concentrations of carbon oxide, hydrocarbons and nitrogen oxides .*

For carrying out the successive analyses the recorded signals were converted, i.e. their linear trends were removed and standardization (mean value converted to 0 and standard deviation to 1) of the recorded runs free from linear trends, performed [1, 7, 10, 11].

For further analyses stationarity tests of the standardized processes were made. The process stationarity x(t) [1, 7, 10, 11, 15] was assessed on the basis of runs of the mean value AV(x) and standard deviation D(x) determined beginning from the initial sampling point of the tested runs (Fig.8).

$$AV(x)=\frac{1}{x}\int_{0}^{x} x(t)\,dt \tag{1}$$

$$D(x)=\left\{\frac{1}{x}\int_{0}^{x}[x(t)-AV(x)]^{2}dt\right\}^{0.5} \tag{2}$$

The average values of the processes and their standard deviations become stable after time greater than 50 s. This stabilization is distinct though it takes place as late as in the second part of the observations. The fact of the relatively late stabilization first of all results from short observation times of the tested processes.

For particular processes some differences occur respective to their stationarity, e.g. for the standardized concentration of hydrocarbons the characteristic run of average values of the process and its standard deviation is determined by a low resolution of signal sampling.

For the standardized runs probability densities were determined. In Fig.9 the probability densities of the sets of standardized values of : engine torque, rotational speed, and concentrations of carbon oxide, hydrocarbons and nitrogen oxides, are presented in a collective form.

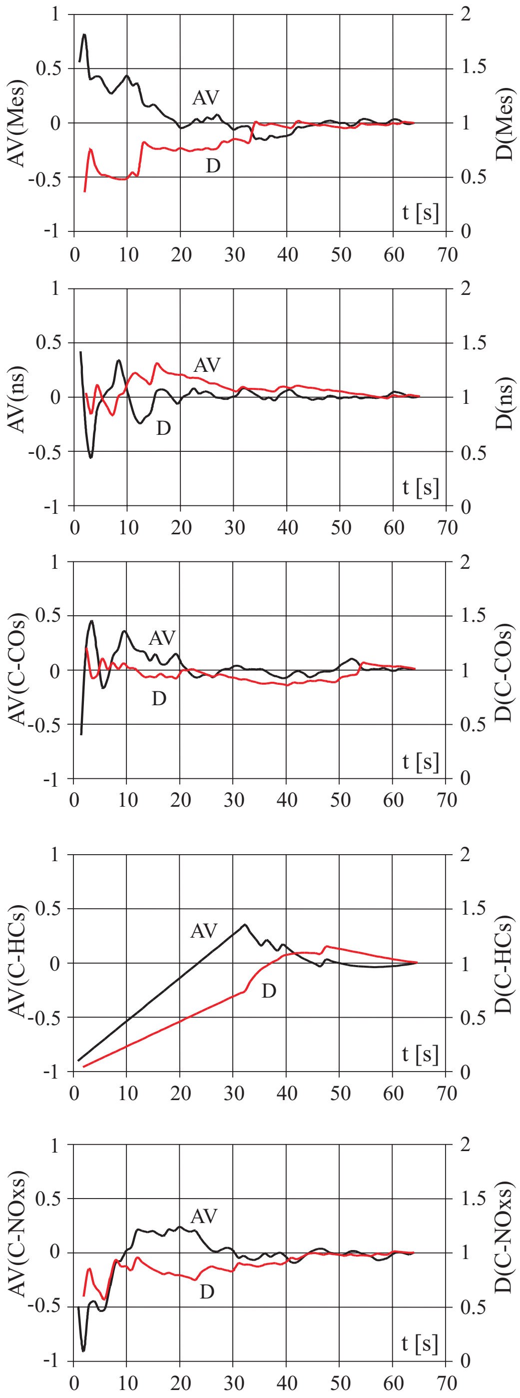

Fig. 8. Results of stationarity test of the runs of standardized values of : engine torque, rotational speed, and concentrations of carbon oxide, hydrocarbons and nitrogen oxides .

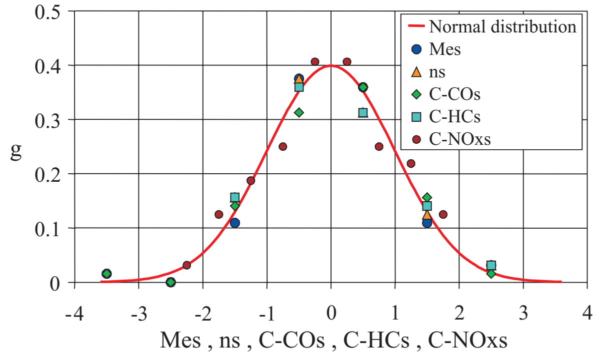

Fig. 9. The probability density of the sets of standardized values of : engine torque, rotational speed, and concentrations of carbon oxide, hydrocarbons and nitrogen oxides .

Tests of normality of estimated distributions were performed. To assess conformity of a sample with normal distribution the following hypotheses were applied :

- Shapiro–Wilk hypothesis [2,13]
- Kolmogorov–Smirnov hypothesis [2, 8, 14]
- Lilliefors hypothesis [2,9]
- Pearson chi–square hypothesis [2,12] .

Results of the normality tests are presented in Fig.10÷13.

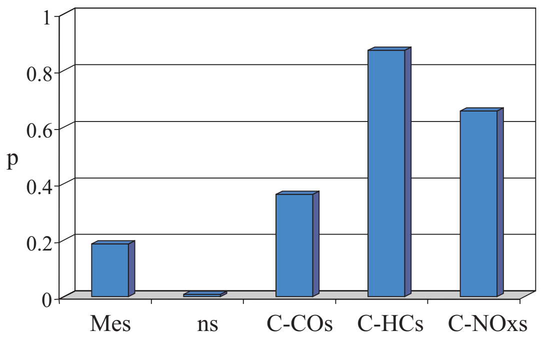

Fig. 10. Probability of non-rejection of the Shapiro–Wilk hypothesis on conformity of a given sample with normal distribution .

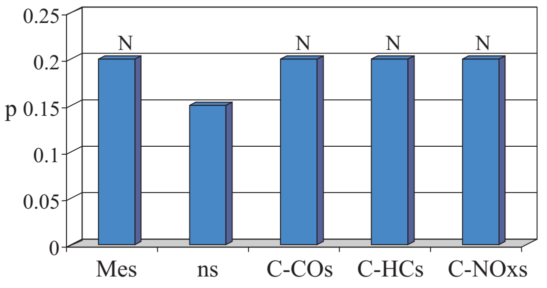

Fig. 11. Probability of non-rejection of the Kolmogorov–Smirnov hypothesis on conformity of a given sample with normal distribution .

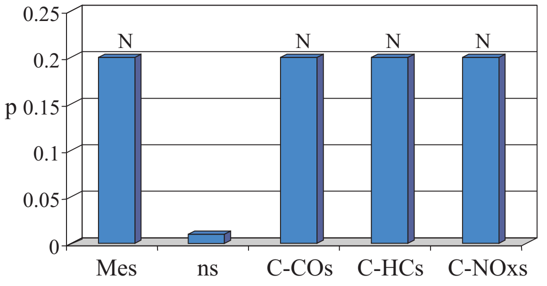

Fig. 12. Probability of non-rejection of the Lilliefors hypothesis on conformity of a given sample with normal distribution .

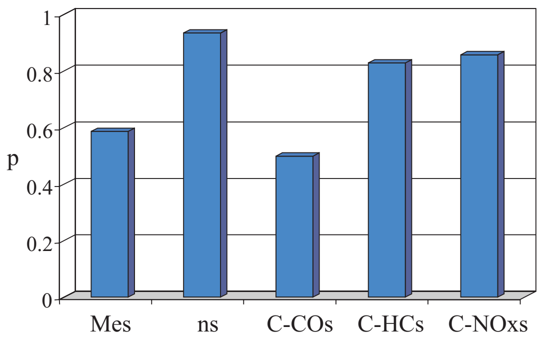

Fig. 13. Probability of non-rejection of the Pearson's chi–square hypothesis on matching a given sample with normal distribution .

For the normality tests in question Statistica 6.1 software of StatSoft Inc. were used. The software makes it possible a.o. to determine probability of non-rejection of the Shapiro–Wilk hypothesis on conformity of a given sample with normal distribution, whereas in the case of Kolmogorov–Smirnov and Lilliefors hypotheses only the threshold values which qualify them to the non-essential categories respective to calculated statistic value, are determined. In the Statistica 6.1 software the probability of non-rejection equal to 0.2 was assumed to be the statistic non-essentiality criterion. In the diagrams the statistic non-essentiality is marked „N". In the case of Pearson's chi–square hypothesis, the probability of non-rejection of the hypothesis on matching a given sample with normal distribution is determined.

The results of Kolmogorov–Smirnov and Lilliefors tests are consistent: there is no basis for rejection of the hypothesis on normality of the estimated probability densities in the case of the sets of standardized values of : engine torque and concentrations of carbon oxide, hydrocarbons and nitrogen oxides. The Kolmogorov–Smirnov and Lilliefors tests have the same statistic and they differ to each other only by a way of treating the mean value and variance, namely in the case of Lilliefors test – as an estimate of the values and not as a' priori given data assumed in the case of the Kolmogorov–Smirnov test [2,6]. The results are also confirmed by the Shapiro–Wilk test : the value of rejection probability of the hypothesis on normality of probability density function is very small (0.008) only in the case of the standardized rotational speed. The results of the Pearson's chi–square test do not confirm the results of the hypotheses on normality of the determined probability densities, however the former test deals only with the hypothesis on matching the normal distribution and not conformity with it.

The results obtained from the Shapiro–Wilk test are taken the most credible as this test is of the greatest power as compared with another ones considered here [2, 6, 13].

Also, correlation tests of the sets in question were performed [1, 2, 6, 7÷15]. In Fig.14 are presented the correlation relationships of the sets of standardized values of : engine torque, rotational speed, and concentrations of carbon oxide, hydrocarbons and nitrogen oxides.

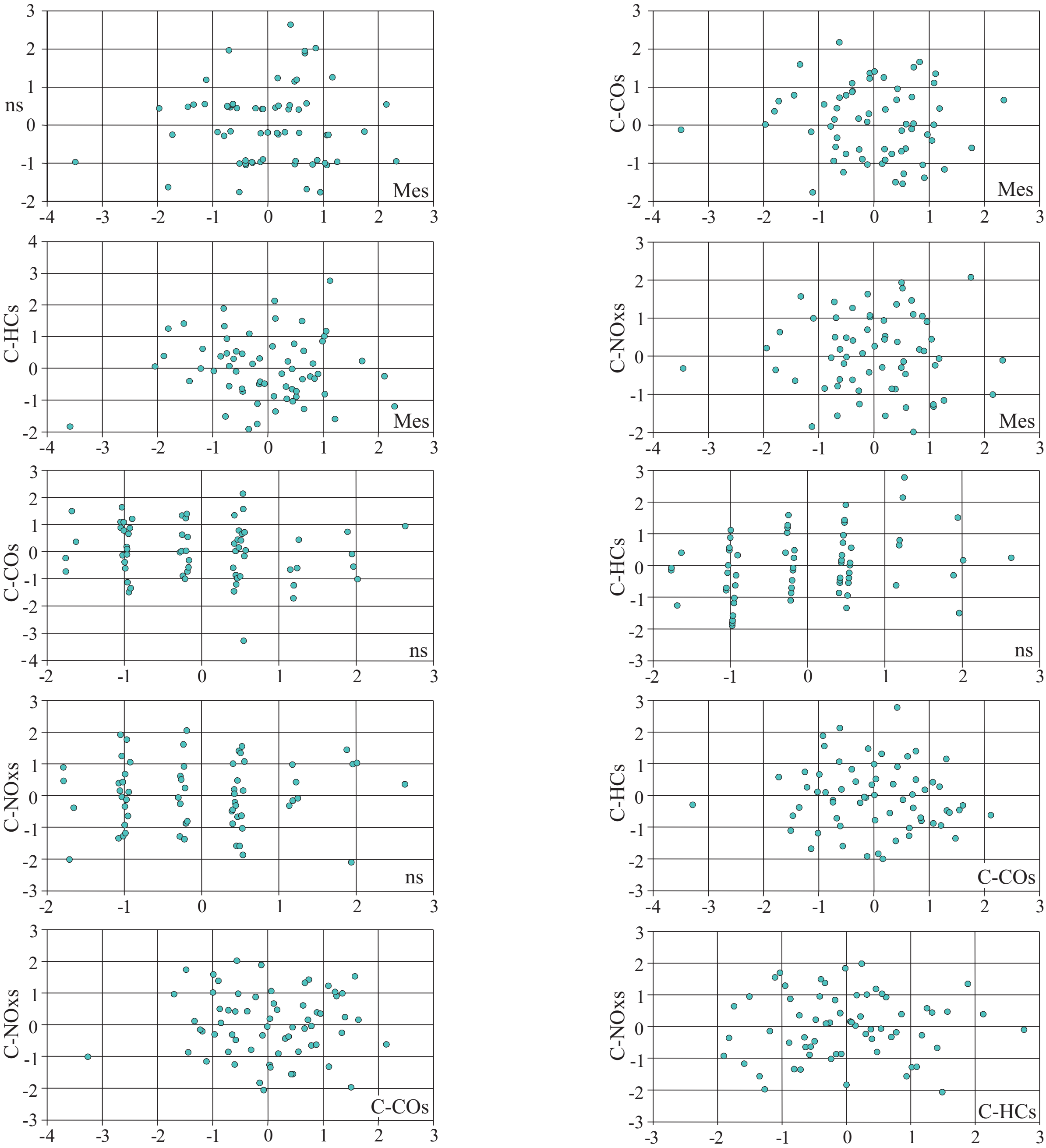

Fig. 14. The correlation relationships of the sets of standardized values of : engine torque, rotational speed, and concentrations of carbon oxide, hydrocarbons and nitrogen oxides.

In Fig.15 and 16 the results of correlation tests of the sets of the standardized runs are presented. For the investigations the following tests were applied :

- Spearman's range correlation
- Kendall's γ and τ correlations
- Pearson's linear correlation.

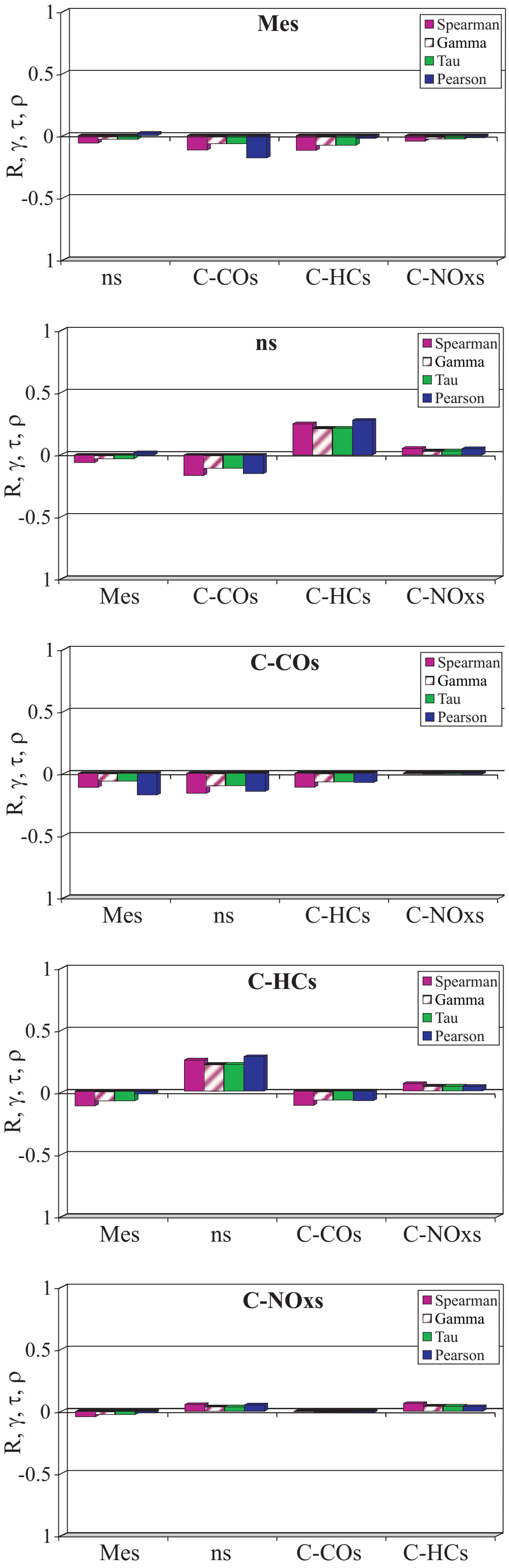

Fig. 15. *Coefficients of Spearman's R correlation, Kendall's τ and γ correlation and Pearson's ρ correlation for the sets of standardized values of : engine torque, rotational speed, and concentrations of carbon oxide, hydrocarbons and nitrogen oxides .*

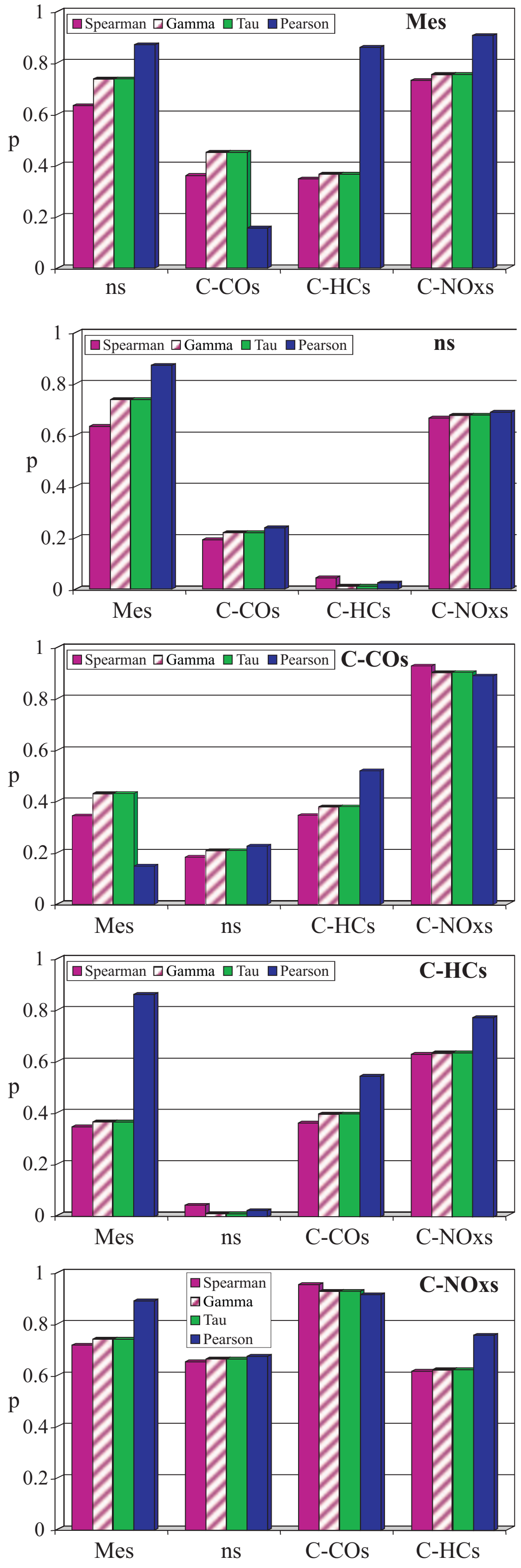

Fig. 16. *The probability (p) of non-rejection of the hypothesis on lack of correlation between the sets of standardized values of : engine torque, rotational speed, and concentrations of carbon oxide, hydrocarbons and nitrogen oxides .*

In all correlation tests the same signs regularly appear in each of the tested sets. Dispersions of values of correlation coefficients for the same sets are rather small.

For the set of standardized values of torque and carbon oxide concentration, values of the coefficients of correlation with the remaining sets of values are negative. For other sets such regularity was not observed.

Values of the probability of non-rejection of the hypothesis on lack of correlation, $p < 0.05$, occur in the case of the sets of standardized values of rotational speed and concentration of hydrocarbons, that can not find any content-related justification. In the remaining cases there are no statistical grounds to formulate a hypothesis on correlation of the tested sets.

FINAL REMARKS

The tested runs of the noise generated by phenomena directly not accounted for in the engine's static test program as well as by measuring systems, have mainly character of a non-correlated, normal broad-band noise. Generality of the conclusion is weakened by the limitations resulting from a preliminary character of the tests in question. Among them the following are the most important :

- the relatively low sampling frequency limiting the upper frequency of observed signals
- the small number of samples (64) limiting the frequency resolution of signals, hence also the estimation accuracy of power spectral density; the small number of samples also influences the estimation accuracy of probability density
- not accounting for, in the analyses, results of tests in another engine working points, which could make it possible to generalize the formulated conclusions.

The last of the limitations is of an entirely technical character. These authors have at their disposal also results of the engine's tests in other working points and their analysis have confirmed the above formulated conclusions. Only due to editorial limitations these results are not presented here.

The performed investigations of statistical features of the combustion engine working in static conditions have character of a preliminary research, in spite of that their results are not only of theoretical importance but also practical one as they justify a.o. correctness of averaging the measurement results obtained in static conditions and synchronous averaging the results obtained in steady conditions.

NOMENCLATURE

AV – average value
C-CO – carbon oxide concentration
C-COs – standardized carbon oxide concentration with removed linear trend
C-HC – concentration of hydrocarbons
C-HCs – standardized hydrocarbons concentration with removed linear trend
C-NOx – concentration of nitrogen oxides
C-NOxs – standardized nitrogen oxides concentration with removed linear trend
D – standard deviation
g – probability density
Me – torque
Mes – standardized torque with removed linear trend
n – rotational speed
ns – standardized rotational speed with removed linear trend
N – number of samples of a set
p – probability of non-rejection of a hypothesis
R – Spearman's range correlation coefficient
t – time
T – observation time of samples of a set
Δt – sampling time
φ – argument of Fourier's simple transformation of a time run
φ_0 = 1Hz
γ – Kendall's gamma correlation coefficient
ρ – Pearson's linear correlation coefficient
τ – Kendall's tau correlation coefficient

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