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The assessment of the fuel atomization based on vibroacoustic processes

Abstract: Diesel engine ecological parameters greatly depend on the course of the combustion process. An appropriate course of this process is conditional upon a proper mixture formation in the combustion chamber i.e. charge swirl and fuel atomization. The swirl of the charge results from the adopted design of the intake manifold, geometrical parameters of the combustion chamber and engine speed. The fuel atomization depends on the injection parameter and the conditions of the injector itself, particularly its nozzle. To date, the issue of a clear evaluation of the injector ability of obtaining appropriate atomization parameters remains unresolved. The paper presents the concept and the results of its validation based on the preliminary tests of fuel atomization in open space with the use of vibroacoustic processes.

Key words: *diesel engine, injection, fuel atomization, vibroacoustic methods*

1. Introduction

The components of a diesel engine fuel system are among its most sensitive subassemblies. It is particularly the precision pairs that are prone to damage – the pressure element in the pump and the nozzle. The nozzle is particularly important because of the function it plays in the system. Its operativeness and functionality decides about the course of the process of combustion of the fuel fed to the cylinder. The deterioration of the nozzle conditions deteriorates the quality of combustion, which in turn results in a reduction of the operating and ecological parameters of the engine. It reduces the overall efficiency of the engine and results in a growth of the exhaust emissions [5, 6]. The operational and ecological problems of combustion engines may have a variety of reasons. That is why a precise engine diagnostics is of the utmost importance. The advancement of electronics added to the 'electronization' of engines − fuel systems in particular. Injectors whose control is done by the electric signals have been introduced. Yet, the injector opening mechanism remained unchanged and still relies on the hydraulic energy. The needle of the injector nozzle lifts as a result of forces exerted on both of its ends. These forces are a product of the pressure and area on which these forces are exerted. The value of the pressure exerted on the nozzle depends on the accuracy of its fitting into the body of the nozzle as well as the conditions of the spray holes. The deterioration of the injector nozzle influences the fuel spray atomization [5, 6]. To date, the issue of injector nozzle diagnostics has not been resolved [1–4, 7]. However, there are methods of the evaluation of its operation consisting in optical observations of the fuel spray. These methods are subjective and dependent on the person carrying out the observation.

The authors of this paper have attempted to resolve the issue through developing of a method of injector nozzle diagnostics based on the fuel spray atomization with the use of vibroacoustic processes accompanying the injection process. The essence of the presented problem is the use of the values of the vibroacoustic parameters (originating in the injection process) for the description and diagnostics of the fuel spray atomization. The effects accompanying the fuel injection process thus its atomization into open space were the sound and the vibration impulse. The authors decided to identify selected parameters, measure their values and determine their dependence on the operating parameters of the injectors.

2. Research methodology

2.1. Test stand

The tests were conducted on a stand (Fig. 1), whose schematic diagram has been shown in figure 2. The test stand was composed of several basic components. The first one is the reaction-actuation component. It is composed of the electromagnetic injector 0 445 110 131 (tab. 1) by BOSCH located in the reaction sleeve.

The injector was fed with fuel from the Common Rail fuel system that was the main system in the Common Rail Pump and Injector Test Stand (STPiW-1). The injector control impulse was generated by an injector tester CR – a module of a STPiW-1 test stand. On the injector body and on the sleeve vibration converters were placed (Triaxial Delta Tron Accelerometer type 4504 A by Brüel

& Kjær, Fig. 3). For the measurement of the acoustic quantities during the test the authors used a microphone ½” type 4189 by Brüel & Kjær (Fig. 4). This microphone recorded the acoustic pressure.

Fig. 1. View of the test stand

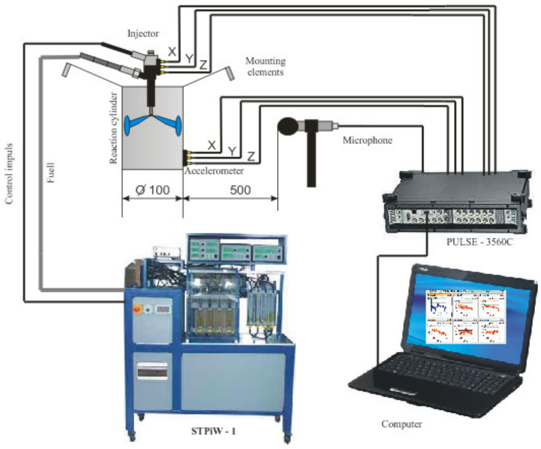

Fig. 2. Schematic diagram of the test stand

Table 1

Basic injector specifications

Injector name	*Common Rail* electromagnetic injector by Bosch
Injector identification	BOSCH 0445 110 131
Number of holes	6
Hole diameter D	0,19 [mm]
Hydraulic throughput	1100 [cm^3/min] at p = 100 [bar]
Angle between the fuel sprays	60°
Minimum fuel pressure opening the injector	20 MPa

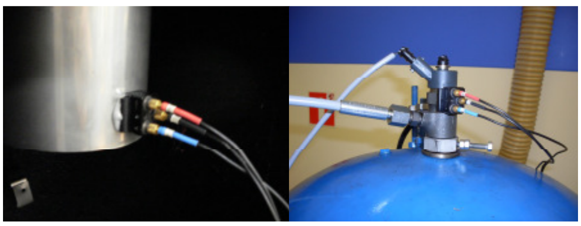

Fig. 3. Vibration accelerometer placed on the measurement sleeve and on the injector

Fig. 4. Microphone ½” Typ 4189 by Brüel & Kjær

In the tests the authors also used PULSE - a system of multi-channel data acquisition and analysis. It is a 5-channel measuring cassette - type 3560-C (Fig. 5).

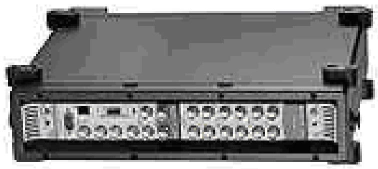

Fig. 5. Measuring system for dynamic signals acquisition by B&K PULSE - 3560C

2.2. Scope of the tests

The aim of the tests was to evaluate the vibration and acoustic signals that accompany the fuel injection into open space in the point of view of using them in the evaluation of the fuel atomization in open space. The performed tests determine the usability of the vibroacoustic signals in the evaluation of the proper fuel atomization and the conditions of the injector nozzle. The tests were performed on a single injector in which the nozzles were regularly replaced based on the classified value of the play in the needle-nozzle precision pair (tab. 2).

Table 2

Classification of the tested nozzles

Nozzle identification	Needle-nozzle play [μm]
K – conventional nozzle.	–
A	5
B	10
C	15

The tests were performed in pre-set operating points characterized by the values of the fuel pressure in the fuel accumulator p_{wtr}= 35; 60; 90 MPa and the duration of the injection t_{wtr}= 0,4; 0,7; 1,2 ms. Hence, for each nozzle there were 9 measuring points and for each point there were 3 repeated measurements with a continuous recording of 10 injections.

3. Test results and analysis

While performing the tests the changes of the courses of the acoustic signal L_p were recorded as well as the signals of the vibration accelerations in the direction X (a_x), Y (a_y) and Z (a_z) during the fuel injection into the measurement chamber as a response of the sleeve to the fuel injection. The authors also measured the signals of the vibration acceleration in the direction X (a_x), Y (a_y) and Z (a_z) on the injector body as a response of the injector to the fuel injection into open space. The signals were recorded for a selected series of nozzles marked K, A, B, C. Below example courses of the signals have been presented: acoustic (fig. 6, 10, 14), vibration acceleration from the measurement sleeve (Fig. 7, 8, 9, 11, 12, 13, 15, 16, 17), vibration acceleration from the body of the injector (Fig. 18, 19, 20).

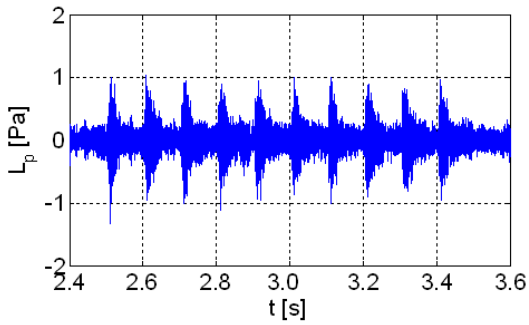

Fig. 6. The time course of the changes of acoustic signal (L_p) during the fuel injection into the measurement chamber as a response of the sleeve to the fuel injection process for:
p_{wtr} = 35 MPa, t_{wtr} = 0,7 ms
(conventional injector K)

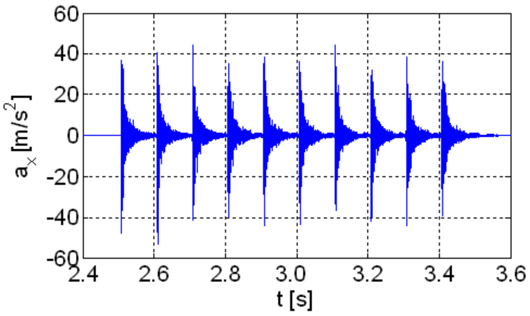

Fig. 7. The time course of the changes of the signal of vibration acceleration in direction X (a_x) during fuel injection into the measurement chamber as a response of the sleeve to the injection process for:
p_{wtr} = 35 MPa, t_{wtr} = 0,7 ms
(conventional injector K)

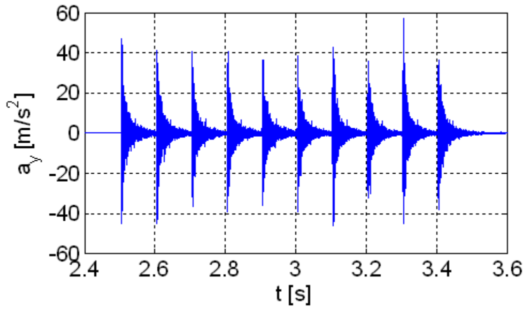

Fig. 8. The time course of the changes of the signal of vibration acceleration in direction Y (a_y) during fuel injection into the measurement chamber as a response of the sleeve to the injection process for:
p_{wtr} = 35 MPa, t_{wtr} = 0,7 ms
(conventional injector K)

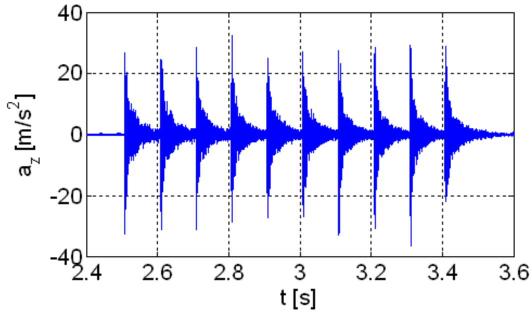

Fig. 9. The time course of the changes of the signal of vibration acceleration in direction Z (a_z) during fuel injection into the measurement chamber as a response of the sleeve to the injection process for:
p_{wtr} = 35 MPa, t_{wtr} = 0,7 ms
(conventional injector K)

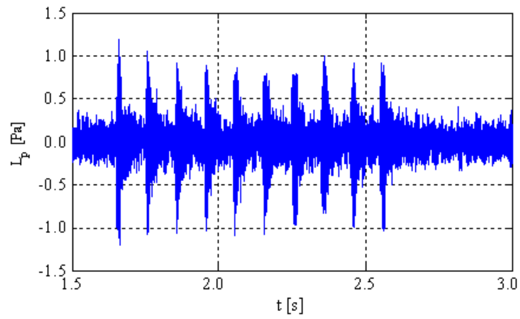

Fig. 10. The time course of the changes of acoustic signal (L_p) during the fuel injection into the measurement chamber as a response of the sleeve to the fuel injection process for:
p_{wtr} = 35 MPa, t_{wtr} = 0,7 ms
(injector A)

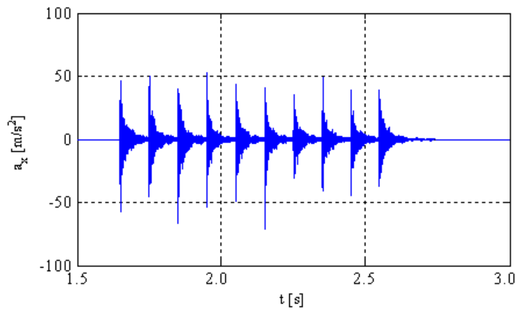

Fig. 11. The time course of the changes of the signal of vibration acceleration in direction X (a_x) during fuel injection into the measurement chamber as a response of the sleeve to the injection process for: p_{wtr} = 35 MPa, t_{wtr} = 0,7 ms (injector A)

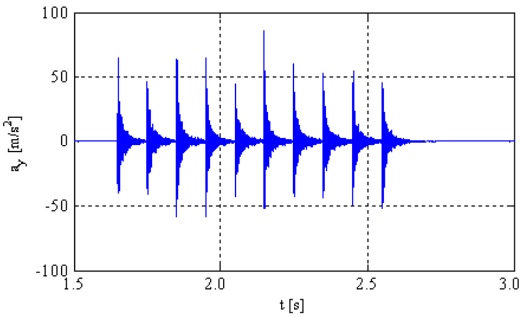

Fig. 12. The time course of the changes of the signal of vibration acceleration in direction Y (a_y) during fuel injection into the measurement chamber as a response of the sleeve to the injection process for: p_{wtr} = 35 MPa, t_{wtr} = 0,7 ms (injector A)

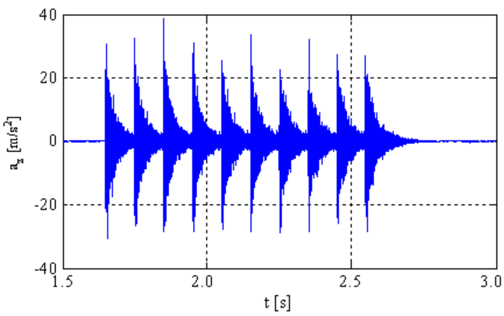

Fig. 13. The time course of the changes of the signal of vibration acceleration in direction Z (a_z) during fuel injection into the measurement chamber as a response of the sleeve to the injection process for: p_{wtr} = 35 MPa, t_{wtr} = 0,7 ms (injector A)

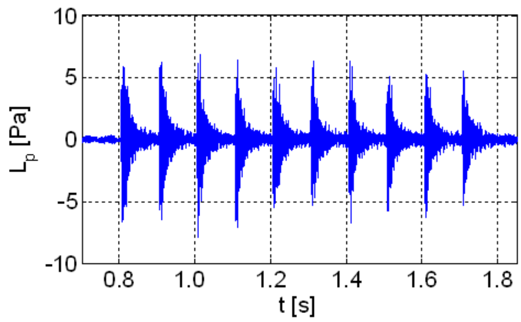

Fig. 14. The time course of the changes of acoustic signal (L_p) during the fuel injection into the measurement chamber as a response of the sleeve to the fuel injection process for: p_{wtr} = 35 MPa, t_{wtr} = 0,7 ms (injector A)

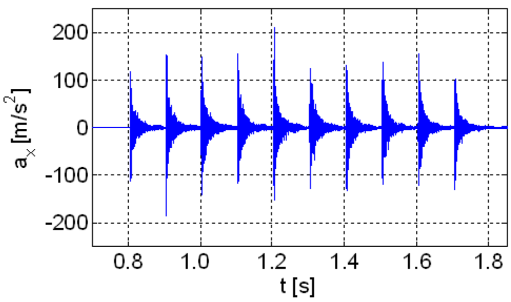

Fig. 15. The time course of the changes of the signal of vibration acceleration in direction X (a_x) during fuel injection into the measurement chamber as a response of the sleeve to the injection process for: p_{wtr} = 90 MPa, t_{wtr} = 0,7 ms (injector A)

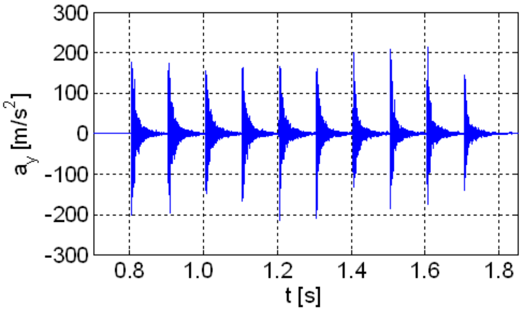

Fig. 16. The time course of the changes of the signal of vibration acceleration in direction Y (a_y) during fuel injection into the measurement chamber as a response of the sleeve to the injection process for: p_{wtr} = 90 MPa, t_{wtr} = 0,7 ms (injector A)

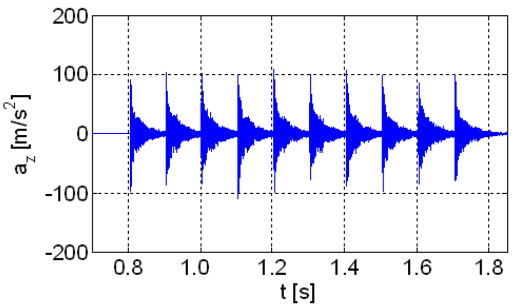

Fig. 17. The time course of the changes of the signal of vibration acceleration in direction Z (a_z) during fuel injection into the measurement chamber as a response of the sleeve to the injection process for: p_{wtr} = 90 MPa, t_{wtr} = 0,7 ms (injector A)

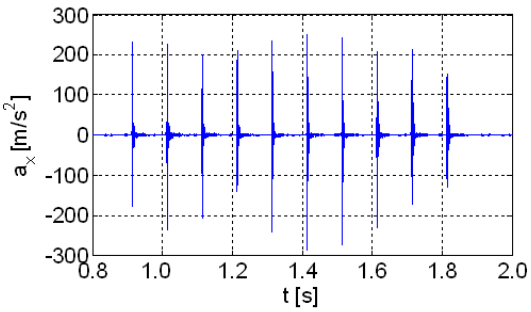

Fig. 18. The time course of the changes of the signal of vibration acceleration in direction X (a_x) during fuel injection into the measurement chamber as a response of the sleeve to the injection process into open space for: p_{wtr} = 90 MPa, t_{wtr} = 0,7 ms (injector A)

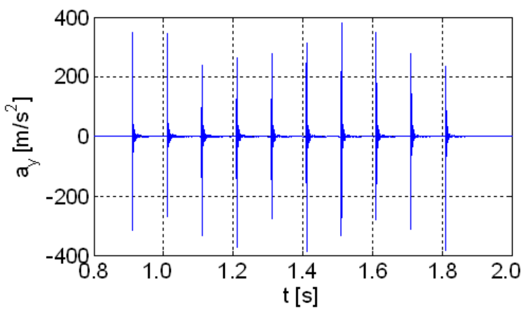

Fig. 19. The time course of the changes of the signal of vibration acceleration in direction Y (a_y) during fuel injection into the measurement chamber as a response of the sleeve to the injection process into open space for: p_{wtr} = 90 MPa, t_{wtr} = 0,7 ms (injector A)

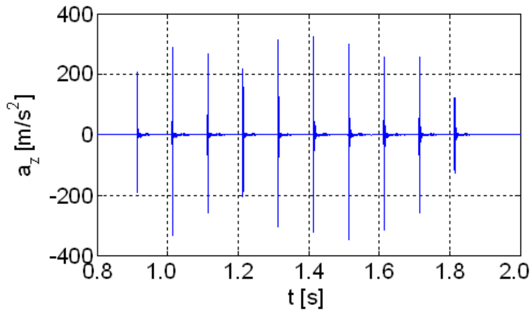

Fig. 20. The time course of the changes of the signal of vibration acceleration in direction Z (a_z) during fuel injection into the measurement chamber as a response of the sleeve to the injection process into open space for: p_{wtr} = 90 MPa, t_{wtr} = 0,7 ms (injector A)

The first stage of the analysis of the vibroacoustic signals obtained during the injector testing pertains to the evaluation of the time courses of the signals. Already at this stage of the analysis we can conclude that there is a possibility of using these residual processes in the analysis of the selected atomization processes including the diagnostic evaluation of the correctness of their course. The qualitative evaluation of these courses provides a possibility of determining of the diagnostic relations in the case of a change in the geometrical and functional characteristics of the elements of the fuel system whose incorrect operation adds to the changes of the injection parameters. The above evaluation enabled validation of the usefulness of the method for the diagnostics of the discussed processes and elements of the fuel system. It lay grounds for further evaluations and validated their usefulness of the vibrations acceleration and acoustic signals in this evaluation. It enabled determining of the sensitivity of the signals to the changes in the parameters of fuel injection (injection pressure and duration of the injection) and the geometrical changes of the injector elements that force the system improper operation. The recorded time courses confirmed the differences in the amount of information that can be obtained from the above parameters of vibration and acoustic pressure. We need to note that the signals of changes in the acceleration are clear and much more suitable for further analysis with the use of statistical tools.

The second stage of the analysis of the vibroacoustic signals obtained in the tests of the injection into the measurement chamber pertains to the evaluation of the point measures - both dimensional and non-dimensional.

Based on the selected point measures for the pressure in the cylinder and for the accelerations and velocities of vibrations in the direction of X, Y and Z the authors performed a selection of the direction of the measurement signal recording, analyzed parameters and the point measure most sensitive to the occurrence of the phenomenon. The dimensioned point measures were: mean, effective, peak and peak-to-peak values. Additionally, non-dimensional point measures were calculated such as: shape coefficient, peak coefficient, impulsivity coefficient, clearance coefficient and a kurtosis and the 4th power root of the kurtosis. The listed point measures were calculated based on the following definitions [7]:

a) Mean value

$$u_{śr} = u_{śr}(\theta) = \frac{1}{T}\int_0^T |u(t,\theta)|\, dt \qquad (1)$$

b) Effective value

$$u_{sk} = u_{sk}(\theta) = \left[\frac{1}{T}\int_0^T u^2(t,\theta)\, dt\right]^{1/2} \qquad (2)$$

c) Peak value

$$u_{sz} = u_{sz}(\theta) = E\left\{\underset{0<t<T}{\mathrm{Max}} |u(t,\theta)|\right\} \qquad (3)$$

d) Peak-to-peak value

$$u_{rozst} = u_{rozst}(\theta) = |u_{max} - u_{min}| \qquad (4)$$

e) Shape coefficient

$$K = \frac{u_{sk}}{u_{śr}} = \frac{\left[\frac{1}{T}\int_0^T u^2(t,\theta)\, dt\right]^{1/2}}{\frac{1}{T}\int_0^T |u(t,\theta)|\, dt} \ [-] \qquad (5)$$

f) Peak coefficient

$$C = \frac{u_{sz}}{u_{sk}} = \frac{E\left\{\underset{0<t<T}{\mathrm{Max}} |u(t,\theta)|\right\}}{\left[\frac{1}{T}\int_0^T u^2(t,\theta)\, dt\right]^{1/2}} \ [-] \qquad (6)$$

g) Impulsivity coefficient

$$I = \frac{u_{sz}}{u_{śr}} = \frac{E\left\{\underset{0<t<T}{\mathrm{Max}} |u(t,\theta)|\right\}}{\frac{1}{T}\int_0^T |u(t,\theta)|\, dt} \ [-] \qquad (7)$$

h) Clearance coefficient

$$L = \frac{u_{sz}}{u_p} = \frac{E\left\{\underset{0<t<T}{\mathrm{Max}} |u(t,\theta)|\right\}}{\left[\frac{1}{T}\int_0^T |u(t,\theta)|^{1/2}\, dt\right]^2} \ [-] \qquad (8)$$

i) Kurtosis (concentration coefficient)

$$\beta = \frac{\frac{1}{T}\int_0^T |u(t,\theta) - u_{śr}(\theta)|^4\, dt}{\left[\frac{1}{T}\int_0^T |u(t,\theta) - u_{śr}(\theta)|^2\, dt\right]^2} \ [-] \qquad (9)$$

j) 4th power root from the kurtosis

$$\sqrt[4]{\beta} = \frac{\left[\frac{1}{T}\int_0^T |u(t,\theta) - u_{śr}(\theta)|^4\, dt\right]^{1/4}}{\left[\frac{1}{T}\int_0^T |u(t,\theta) - u_{śr}(\theta)|^2\, dt\right]^{1/2}} \ [-] \qquad (10)$$

where:

- θ – time of object existence,
- t – duration of the dynamic processes,
- T – duration of the signal,
- $u(t, \theta)$ – instantaneous value of the signal,
- $E\{\}$ – operator of the average value after possible maximum values of the signal,
- u_{max} – maximum value of the signal amplitude,
- u_{min} – minimum value of the signal amplitude,
- u_p – root value of the signal.

The quantitative evaluation of the changes in the accompanying processes related to the fuel injection and its impact on the injector and sleeve structure that the fuel spray reaches is possible to realize with the use of the analysis of the values of the accompanying processes. In this case the measurement signals were subjected to a time selection by dividing the whole signal time into portions corresponding to the individual processes. So obtained signals were then evaluated in terms of the point measures both dimensional and non-dimensional. Among the dimension estimates there were values: mean, effective, peak and peak-to-peak. The authors also determined the coefficients of: shape, peak, impulsivity, clearance, kurtosis and its root. These measures were then averaged within a single measure, direction and set of signals in the course of time depending on the measurement conditions.

The evaluation of the point measures of the vibroacoustic processes allowed a formulation of the following conclusions:

The most sensitive measure in the case of the vibroacoustic process is the coefficient of peak. For both the analyses of the signals from the injector and the sleeve the highest values of the above index were obtained, irrespective of the value of the injection pressure and the level of the injector improper operation. The growth in the level of improper injector operation goes along the decrease of the value of the peak coefficient. Yet, its value is dependent on the pressure and duration of the injection.

Besides the peak coefficient also the coefficients of clearance, impulsivity and kurtosis are characterized by a sensitivity to the process, yet, their values are much lower than for the coefficient of peak. The dimensioned measures obtained low values. Only the values of the peak and inter peak amplitude of the acoustic signal have a higher sensitivity.

The growth in the injection pressure and the injection duration influences the value of the peak coefficient for the acoustic pressure. The relation between the indexes is not always preserved for different levels of the level of improper injector operation. This confirms the variability of the measurement parameters in terms of the amplitude for a given case as there is no single direction of changes of the measure of the physical parameter along the energy change that follows the process. In each case though, the extension of the injection duration resulted in a growth of the peak coefficient.

The evaluation of the acoustic signal for the fuel spray impact on the sleeve and that from the injector indicates a low sensitivity of this signal on the change of the sound source. The relations between the values of the amplitudes do not always fulfil the criterion of unequivocally and easiness of analysis of the diagnostic parameter, which clearly makes it more difficult to separate the useful component from the signals from other sound sources.

A relative change of the values of the most sensitive point measures for the acoustic pressure while the injection duration was changed was: from -22% to 28% (Fig. 21) for the signals recorded on the sleeve and from -23% to 56% (Fig. 22) for the signals recorded on the injector.

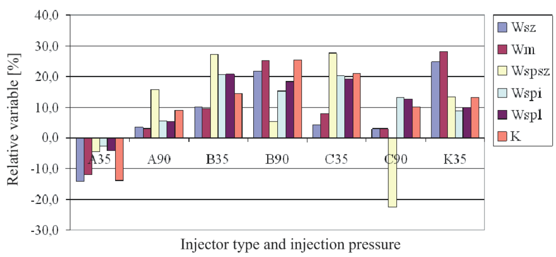

Fig. 21. The values of the point measures for the acoustic pressure while the fuel was injected into the measurement chamber as a response of the sleeve to the process of injection for:
p_{wtr} = 35 i 90 MPa, t_{wtr} = 0,7 i 1,2 ms
(injector A, B, C, K)

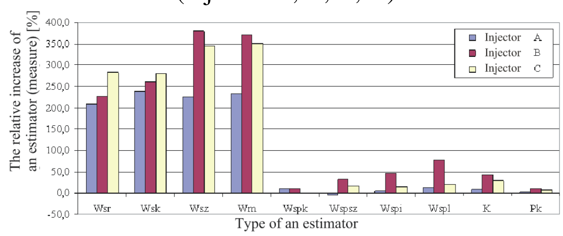

Fig. 22. The values of the point measures for the signal of vibration acceleration in direction Y (a_y) while the fuel was injected into the measurement chamber as a response of the sleeve to the process of injection for:
p_{wtr} = 35 i 90 MPa, t_{wtr} = 0,7 i 1,2 ms
(injector A, B, C)

4. Conclusions

The performed investigations in terms of the identification of the values of the measurable effects accompanying the injection process into open space with the use of the Common Rail injectors allowed determining of parameters based on which it is possible to evaluate the fuel atomization. From the performed measurements of the vibroacoustic signals and based on the statistical analyses we can indicate that the most valuable in the assessment of the fuel atomization is the signal of the vibrations acceleration in the direction Y (a_y). This is a vibration signal of the measurement sleeve, generated by a fuel spray impinging on the sleeve during the injection.

The measured acoustic signal (acoustic pressure generated during the injection) turned out to be a signal highly distorted by the operating subassemblies of the test stand. The vibration signal from the body of the injector covers many dependable variables having impact on the proper operation of the injector and is not directly related to the atomization of the diesel oil. It only constitutes a source of information on the technical conditions of the whole injector.

Nomenclature/*Skróty i oznaczenia*

p_{wtr} pressure in the rail

t_{wtr} fuel injection time

θ time of object existence
t duration of the dynamic processes
T duration of the signal
u (t, θ) instantaneous value of the signal
E{} operator of the average value after possible maximum values of the signal,
u_{max} maximum value of the signal amplitude,
u_{min} minimum value of the signal amplitude,
u_p root value of the signal.

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