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Analysis of Uncertainty in Pressure Measurement with a Piezoelectric Transducer for a Combustion Engine

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Abstract: This paper analyses the uncertainty of pressure measurements in-cylinder and in injection pipe conducted during the studies of a compression ignition engine. Type A and type B evaluations were used to determine the uncertainties of the results. The results are presented for the engine running on diesel or fatty acid methyl ester (FAME) and operating under full load conditions.

Keywords: Measurement Uncertainty; Diesel Engines; Piezoelectric Transducer.

1 Introduction

Engineering systems are often subject to uncertainties (noise) that are associated with the lack of precise knowledge of system parameters and operating conditions [1]. In this paper the experimental study was conducted on a three-cylinder diesel Perkins AD3.152 UR. The test system was designed to measure the pressure in the combustion chamber, the pressure in the injection pipe, the injector needle lift, and the crank angle. The in-chamber pressure was measured using a piezoelectric sensor AVL QC34D mounted directly in the cylinder and cooled with a liquid [2]. Piezoelectric pressure sensors use the effect of electrical charges appearing on the transducer surfaces in the direction parallel or perpendicular to the strain wave propagation (longitudinal or transverse piezoelectric effect) what is shown in Fig. 1 [3].

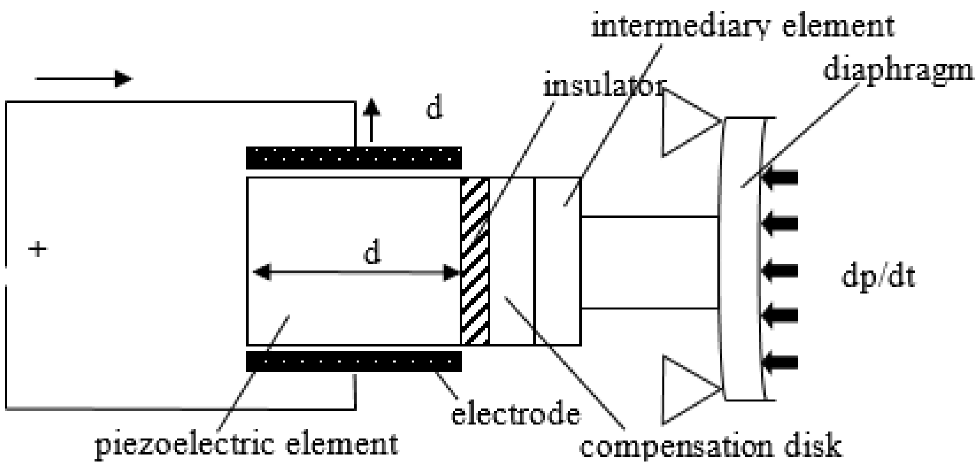


Fig. 1: The principle of work of a piezoelectric pressure sensor [2].

Piezoelectric properties of materials (e.g. SiO2, LiNbO3, or LiTAO3) are strongly dependent on the temperature – they decline along with the rising temperature. A rapid decrease in piezoelectric properties of silicon (SiO2) is observed at a temperature of 523 K while at 846 K the piezoelectric properties disappear. Gallium orthophosphate (α GaPO4) is stable up to the temperature of 1206 K and its sensitivity remains constant up to the temperature of 773 K. By the reason of the above, particular attention should be paid to maintaining low

Tab. 1: Specification of the piezoelectric transducers used in the study.

Parameter	Transducer AVL QC34D	Transducer CL31 ZEPWN Marki
Measurement range	$0 \div 25$ [MPa]	$0 \div 100$ [MPa]
Sensitivity	190 [pC/MPa]	126 [pC/MPa]
Non-linearity	≤ 0.2 [%]	$\leq$ 0.5 [%]
Overload capacity	20 [%]	10 [%]
Resonant frequency	69 [kHz]	50 [kHz]
Eigen capacity	10 [pF]	8 [pF]
Working temperature	$293 \div 353$ [K]	$253 \div 323$ [K]

(below the Curie point) and stable working temperature of the piezoelectric transducer. A variety of piezoelectric transducer designs are used to indicate a diesel engine, typically cooled with water. Cooling with a liquid prevents the transducer from overheating, reduces thermal drift (voltage variation caused by the change in temperature), prevents the reduction in insulation resistance, and enables installation of the transducer directly in the combustion chamber. It is important that the cooling system of the engine provide a constant flow rate, constant temperature, and the pulse-free flow of the coolant. Technical difficulties that occurred during the tests rendered accurate control of these parameters impossible. Very high temperatures of the combustion process impose high thermal loads on pressure sensors. When the cooling system operates properly, the temperatures in the front zone reach 373 K and the temperatures of the measuring element are about 20 K higher than the temperature of the liquid. The temperatures of the connection and the coolant are similar. Large variations in pressure and temperature values cause that the sensor sensitivity changes [4] up to 1 %. The pressure in the injection pipe just near injector was measured using a piezoelectric sensor CL31 ZEPWN Marki, thus preventing the necessity to cool it with water. Tab. 1 summarizes the parameters of the piezoelectric transducers used for pressure measurements.

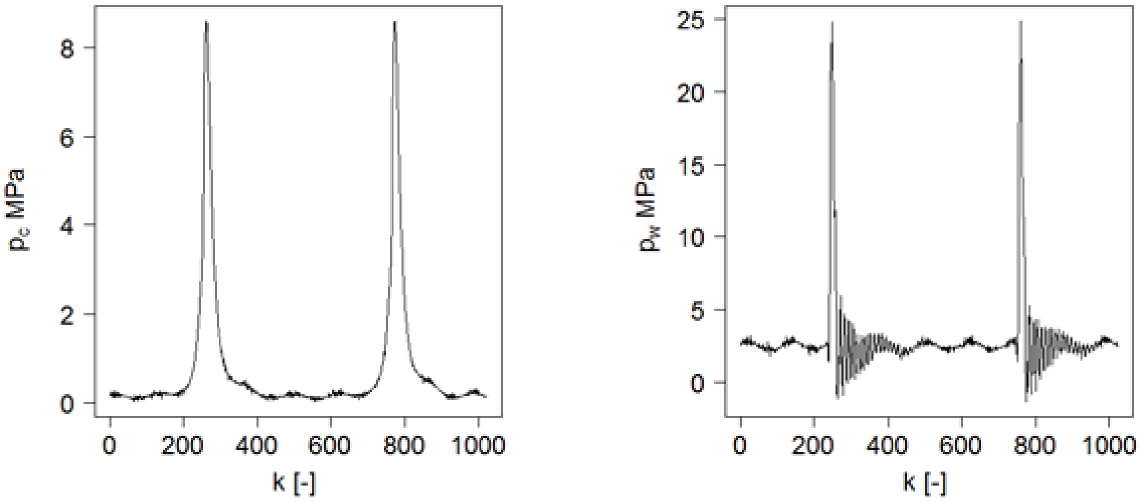
Analysis of the data from Tab. 1 for the unrepeatability of the measurement results indicates that both transducers vary primarily in sensitivity, non-linearity and resonant frequency. In pressure measurements, the CL111 ZEPWN Marki charge amplifier was also used. Analog voltage signals from the amplifiers were converted into digital values by a 12-bit analog-to-digital converter KPCI-3110 manufactured by Keithley Instruments Inc. All parameters were measured as a function of the crank angle with a resolution of 1.4^o. This was possible owing to the PFI60 shaft rotation-to-impulse converter produced by INTROL included in the measurement system, and the unit for sensing and synchronizing the crankshaft position, manufactured by ZEPWN Marki. Fifty full working cycles were recorded in each experiment. In this paper, the results used were obtained for the diesel or bio-fuel FAME driven engine [5] running at full load and engine speed in the range from 1000 to 2000 rpm.

2 Statistical Analysis of Selected Results from Experimental Studies

Fig. 2 shows examples of the pressure measurement results recorded for the first two working cycles of a diesel-fuelled engine. Fig. 2 shows that in both cases, for the in-chamber pressure and the injection pressure, the values recorded in subsequent working cycles vary. In the first step of the analysis, the data were checked to see whether the signals contain components with frequencies unrelated to the cyclic work of the combustion engine. The analysis indicated the presence of such a component with a low amplitude and frequency of about 50 Hz, which was regarded as electromagnetic disturbance and further considerations were continued on a filtered signal.

In the next step, the authors of this paper checked whether the signal maximum values were stationary. An example of a plot for the maximum pressure recorded in the combustion chamber of the diesel-fuelled engine running at a rotational speed of 1800 rpm is shown in Fig. 3a.

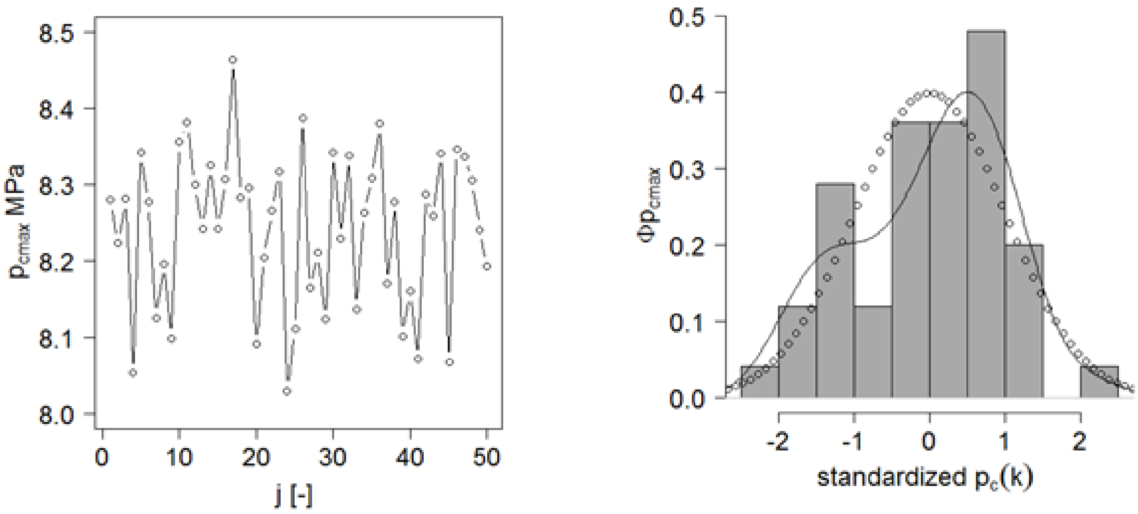
If there is only one random process, it is assumed to be stationary when its basic statistical properties determined for short time intervals remain unchanged for the subsequent intervals [4]. The results of the



(a) the combustion chamber

(b) injection pressure

Fig. 2: Pressure recorded for the first two working cycles of a diesel-fuelled engine working at a speed of 1400 rpm.



(a) maximum values of pressure recorded in the combustion chamber

(b) the probability density distribution for standardized pressure values, diesel-fuelled engine working at 1800 rev/min

Fig. 3: a) Maximum values of pressure recorded in the combustion chamber, b) the probability density distribution for standardized pressure values, diesel-fuelled engine working at 1800 rev/min.

Tab. 2: Type A uncertainty determined for the measurement of in-chamber pressure maximum values for the engine powered with diesel and bio-fuel FAME.

	1000	1200	1400	1600	1800	2000
			diesel			
u_A [MPa]	0.015	0.014	0.012	0.015	0.014	0.012
			bio-fuel FAME			
u_A [MPa]	0.012	-	0.015	0.013	0.012	0.013

Tab. 3: Type A uncertainty of the maximum values of pressure at the injector nozzle for the engine powered with diesel and bio-fuel FAME.

	1000	1200	1400	1600	1800	2000
			diesel			
u_A [MPa]	0.051	-	0.078	0.067	0.100	-
			bio-fuel FAME			
u_A [MPa]	0.047	0.034	0.056	0.032	0.025	0.032

analysis indicated that the signals recorded could be regarded as stationary. The authors also checked whether there was enough evidence to reject the null hypothesis (H0) about the distribution of maximum values of the recorded pressure being consistent with the normal distribution - at the significance level of 5 %. Fig. 3b presents a histogram with the probability density distribution for the standardized maximum values of pressure in the combustion chamber, recorded for the diesel-fuelled engine running at a speed of 1800 rpm. From this figure it is evident that the probability distribution of the measurement data has features that make it is similar to the left-skewed distribution and different from the density of the theoretical distribution. The results of the Shapiro-Wilk statistical test did not provide grounds to reject the null hypothesis at the assumed level of significance. In the case of the maximum values of the in-chamber pressure signal only for the bio-fuel driven engine running at 1200 rpm, the Shapiro-Wilk tests provides enough evidence to reject the H0 at the assumed level of significance. Also for the pressure signal recorded at the injector nozzle, there was enough evidence to reject the H0 for speeds 1200 and 2000 rpm of the diesel-oil fuelled engine.

3 In-Chamber and Injection Pressure Measurement Uncertainty

Uncertainty, i.e., the parameter relating to measurement results, describing the dispersion of the results that can be attributed to the measured quantity, was evaluated using type A and B evaluations [6]. Standard uncertainty determined in type A evaluation in direct measurements is the estimator of standard deviation for the mean, expressed by

$$u_A = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n(n-1)}}, \tag{1}$$

where $\bar{x}$ is the estimator of the mean value of measured quantities x_i. Tab. 2 summarizes standard uncertainties determined using type A evaluation for maximum values of pressure p_c. In the cases for which there was enough evidence to reject the H0, type A evaluation was not used to determine standard uncertainty.

Type A uncertainty of the in-chamber pressure measurement has lower values in the case of the bio-fuel-powered engine. Tab. 3 shows analogous summary of type A uncertainties determined for pressure measurement at the injector nozzle.

For injection pressure, standard uncertainty of maximum pressure reaches higher values than those obtained for the in-chamber pressure. These values are lower for the engine fuelled with FAME.

Type B uncertainty equal to the standard deviation of the assumed probability distribution is typically determined when the measurement results are affected by systematic error resulting from the accuracy of the measuring gauges used. A variety of factors have an influence on both the measurement system and the object being measured, and thus on the measurement results uncertainty. It was assumed that the following factors affected the uncertainty of the obtained results: errors from the piezoelectric transducers, error from the charge amplifier, and error from the A/C KPCI-3110 transducer. The following errors were taken into account while determining standard uncertainty of the pressure measurement:

- error of the QC34D AVL sensor, which is equal to the root of the sum of squares of linearity and temperature drift errors

$$\delta_c = \sqrt{\delta_{cl}^2 + \delta_{ct}^2}, \tag{2}$$

where

$$\delta_{cl} = 0.2\ \%$$

is the relative error in the sensor linearity, and

$$\delta_{ct} = 0.12\ \%$$

is the drift resulting from temperature changes. The relative error of the piezoelectric pressure sensor measurement was δ_c = 0.23 %.

- error of the CL111 charge amplifier, comprised of the relative linearity error and the error associated with the amplifier noise

$$\delta_w = \sqrt{\delta_{wl}^2 + \delta_{ws}^2}, \tag{3}$$

where

$$\delta_{wl} = 0.1\ \%$$

is the relative amplifier linearity error, and

$$\delta_{ws} = 0.2\ \%$$

is the relative error resulting from the noise. With the above data taken into account, the calculated relative error from the charge amplifier was δ_w = 0.22 %.

- error of the A/C KPCI-3110 transducer resulting from its resolution and measurement range

$$\delta_{ac} = \frac{\theta}{range} \times 100\ \%, \tag{4}$$

where

$$\theta$$

is the quantizing interval of the transducer [V], which can be determined as

$$\theta = \frac{range}{2^r} range \tag{5}$$

– the range of work of the A/C KPCI-3110 transducer: $range = \pm 10\ V$, where

$$r$$

is the resolution of the transducer, r = 12 bit. The relative error from the A/C converter used in the measurements was δ_{ac} = 0.024 %.

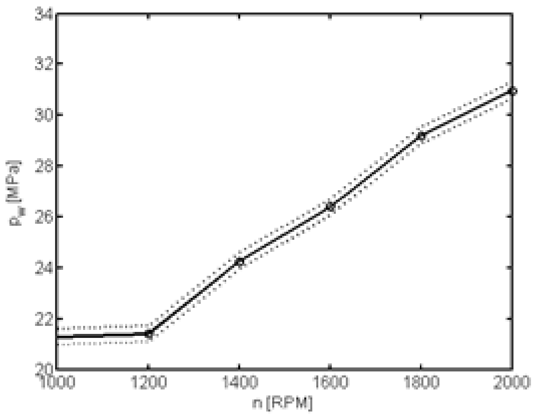
The relative measurement error for pressure p_c, associated with the measurement system used can be determined from

$$\delta = \sqrt{\delta_c^2 + \delta_w^2 + \delta_{ac}^2} \tag{6}$$

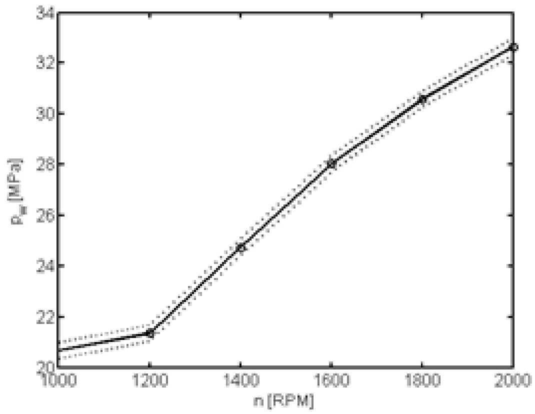
This error was: δ = 0.32 %. The absolute value of this error, related to the measurement range of the QC34D sensor, 25 MPa, is: Δp_c = 0.080 MPa. Type B uncertainty was determined assuming the uniform distribution of probability that the range $\pm\Delta p_c$ includes the true value.

$$u_B = \frac{\Delta p_c}{\sqrt{3}} \tag{7}$$

Type B uncertainty of the pressure measurement was: u_b = 0.046 MPa.



(a) diesel



(b) FAME and running at full load and speeds in the range from n = 1000 – 2000 rpm

Fig. 4: Average injection pressure values with marked type B uncertainty interval for the engine fuelled by.

The procedure used to find type B uncertainty of the measurement results for the pressure at the injector nozzle was analogous to that used for the measurement of in-chamber pressure. The errors from the piezo-electric sensor, charge amplifier and A/C KPCI-3110 transducer were taken into account in the value of the determined uncertainty, which was u_B = 0.32 MPa. Fig. 4 shows the changes in maximum pressure average values recorded at the injector nozzle for the engine running at full load, along with the marked interval of uncertainty calculated using type B evaluation.

The uncertainties of pressure measurements calculated using type B evaluation reach higher values than those determined using type A evaluation.

4 Conclusion

In all cases of engine work analyzed, much higher values of uncertainties for in-chamber pressure and the pressure at the injector nozzle were acquired when type B evaluation was used. Based on the analysis results, it is possible to conclude that sensor quality has the greatest influence on the uncertainty calculated using type B evaluation. Joint standard measurement uncertainty was u_B = 0.05 MPa for the in-chamber pressure and u_B = 0.32 MPa for the injector nozzle pressure. Slightly lower values of standard uncertainty of maximum pressure measurement calculated using type A evaluation were acquired for the engine running on bio-fuel.

Acknowledgement

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References

[1] V. Dekys, et al., Understanding of the dynamical properties of machines based on the interpretation of spectral measurements and FRP, Applied Mechanics and materials 486 (2014), 1660-9336.

[2] D. Kurczyński, The effect of biofuels and their blends with diesel on operations parameters in self-ignition engine. Kielce University of Technology, Kielce 2007, PhD thesis (in Polish).

[3] A. V. Bueno et al., Internal Combustion Engine Indicating Measurements, in Z. Haq (Ed.), Applied Measurement Systems, InTech 2012, 23-44.

[4] R. K. Maurya et al., Investigations on the effect of measurement errors on estimated combustion and performance parameters in HCCI combustion engine, Measurement 46 (2013) 80-88.

[5] P. X. Pham et al., The influence of fatty acid methyl ester profiles on inter-cycle variability in a heavy duty compression ignition engine, Fuel 116 (2014) 140–150.

[6] S. Adamczak et al., Stress and strain measurements in static tensile tests, Metrology and Measurement Systems, 19/3 (2012) 531-540.