Bivariate Process Capability Analysis of Fuel Injection Nozzles Production

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Abstract: - The evaluation of the production process accuracy using process capability analysis are becoming more frequent. Many industrial processes have more than one quality characteristic and the need of the multivariate evaluation of process performance becomes more and more important. This article deals with the process capability analysis of injection nozzles production.

Key-Words: process capability analysis, high-speed camera, injection nozzle, quality of production

1 Introduction

In spite of all progress, that could be observable in the area of alternative powertrains up to now, the piston internal-combustion engine is expected to be globally dominant as vehicles powertrain in medium-term horizon. Although decrease of quantity of pollutant emissions per exhaust gas unit has been reached over the last decades, this theme is still very up-to-date due to continually escalating traffic volume. The formation of pollutant, mainly hydrocarbons, carbon monoxide, soot and nitrogen oxides, is a very complex process which can be suggested by air movement and just by the fuel spray atomization.

The effective ecological and also economical way to reduce emissions at source is the improvement of fuel injection systems capable of meeting the required demands. [1] Therefore the fuel injection nozzles production should be controlled on the basis of statistical analysis.

Statistical process capability provides a common standard of product quality for suppliers and customers. Process capability analysis of production of fuel injection nozzles was previously carried out by functional tests (which are not accurate). Now there could be used optical methods (with high-speed cameras), which allows to identify the key parameters to evaluation.

2 Problem Formulation

2.1 Injection Nozzles Production

The injection nozzle includes holes (usually 5-6), which serves to disperse the fuel in the chamber. The diameter of these holes varies between 50-200 µm, therefore, the holes are produced by EDM (Electro Discharge Machining process), which is the thermal erosion process in which metal is removed by a series of recurring electrical discharges between a cutting tool acting as an electrode and a nozzle. Small hole EDM is similar to a conventional drilling operation but very low machining forces make the drilling of small hole possible and the angle of entry have no detrimental impact on performance.

Direct measurement of the parameters of the nozzle holes is very difficult (can by be partly realized by transmission electron microscopy). In the production of the injection nozzles is very important to ensure the elimination of non-conforming nozzles (no uniform amount of fuel through an every single hole, the wrong angle between the holes).

New developed injectors have to meet the demands on spray formation and penetration to the combustion chamber, uniform fuel/air mixing, fuel evaporation and fluid flow.

2.1.1 Fuel Injection Nozzles Testing

The test chamber which meets the requirements for evaluating the quality of injection (i.e. the analysis of velocity of particles in the fuel flow and the symmetry of injection) enabled us to realize the optical measurement with a high-speed camera. The test chamber was designed for inspection and visualization of fuel injection.

For the fuel injection nozzles testing there was used the high speed camera, the capturing rate was 7 000 frame/s (result are in figure 1).

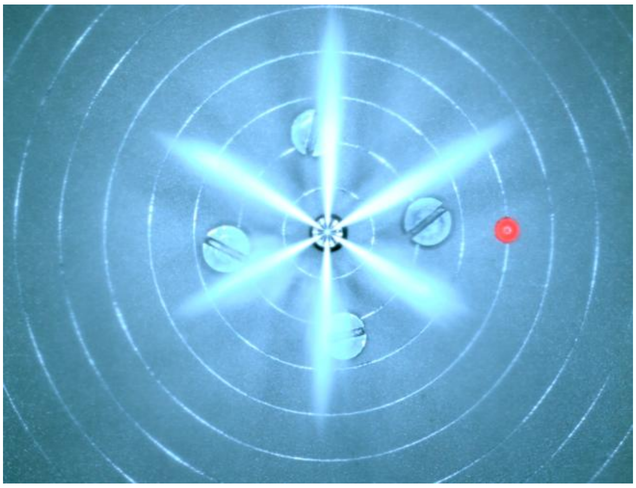


Fig. 1: Captured data from high speed camera

Tracking algorithm gives results with subpixel accuracy – full-field image analysis method based on grey value of set of digital images that allows determination of the contour displacements. [2]

3 Process Capability Analysis

3.1 Traditional Process Capability Analysis

Process capability refers to the inherent ability of a process to produce the same quality parts for a period of time under a given conditions when operating in a state of statistical control.
The key indicators of the quality of the injectors are the symmetry of injection (uniform distribution of holes in the nozzle) and uniformity of aerosol density in individual injections. This means that if we want to analyze the capability of the manufacturing process, it is necessary to use bivariate process capability analysis. Process capability analysis for more than one quality variables is a complicated problem.
In the field of statistical quality control, it is generally assumed that the distributions of quality characteristics have normal distribution. When these variables are non-normal characteristics, the situation becomes even more complex. [3]
Capability Index is based on certain assumptions which are as follow:

• Data are collected from an in-control process.
• Collected process data are independent.
• Collected process data are normally distributed.
• Capability ratio Cp and process capability ratio for off center process Cpk can be calculated from equations (1) and (2).

$$C_p = \frac{USL - LSL}{6\,\sigma} \tag{1}$$

$$C_{pk} = \min\left(\frac{\mu - LSL}{3\sigma}, \frac{USL - \mu}{3\sigma}\right) \tag{2}$$

where USL is upper specification limit, LSL is the lower specification limit, μ is the process mean, and σ is the process standard deviation.

For bivariate process capability analysis using of the conventional capability analysis is not appropriate. [4]

3.2 Bivariate Process Capability Analysis

Among all the real world multivariate capability indices applications, the case of just two quality characteristics is the most common. [5] Despite this, very few methods dedicated to the two quality characteristics case have been developed. [6]
Consider an injection nozzles production process with a 2-dimensional characteristic $X = (X_1, X_2)$ - symmetry of injection (uniform distribution of holes in the nozzle) and uniformity of aerosol density in individual injections.
In case of bivariate process capability analysis an item produced by a process is said to be nonconforming, if its characteristic is not within the tolerance zone. The process is considered to be capable, if the expected proportion of nonconforming products is small enough (mostly 0.27 %). [7]
Generally multivariate process capability indices can be obtained from a number of different methods. Among them five methods:

• the ratio of a specification limit to process variation or modified process variation,
• the probability of nonconforming products over rectangular tolerance zone,
• implementing loss functions and vector representation,
• theoretical proportion of non-conforming products over convex polygons
• global approach viewing multivariate quality control. [8]

When the process mean vector equals the target vector, and the index has the value 1, then 99.73% of the process values lie within the modified tolerance region.

4 Testing of injection nozzles

4.1 Symmetry of Injection

A picture taken 2.2 ms after the injection beginning was used for analysis, when the injection is fully developed.

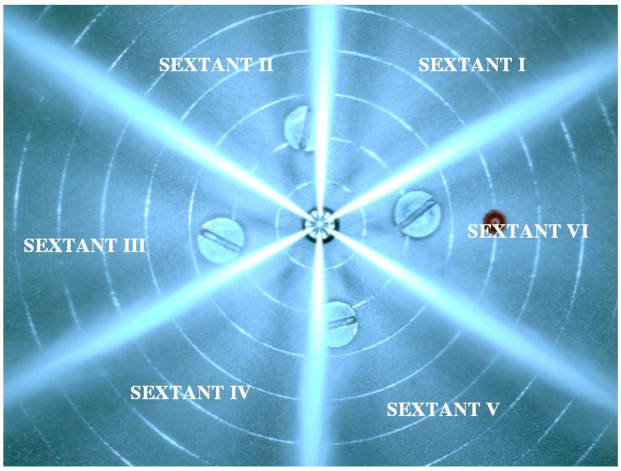


Fig. 2: Analysis of symmetry outlining the injection angles and sextants

Parameter, which is characteristic for the evaluation of symmetry of injection is the standard deviation of all angles of sextants.

$$s_{N1} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2} \qquad \textbf{(3)}$$

where s_{N1} is standard deviation of symmetry of injection, x_i is the observed value of the sextant angle and x is the mean value of these observations, while the denominator N stands for the number of jets (for previous type of nozzle the number N is 6).

4.2 Uniformity of Aerosol Density

The lower speed and lower aerosol density is due to the difference of effective diameter of the nozzle, possibly limiting the flow cross-section. Parameter, which is characteristic for the evaluation of uniformity of aerosol density is the standard deviation of all velocities of jets.

$$s_{N2} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - \bar{y})^2} \qquad \textbf{(4)}$$

where s_{N2} is standard deviation of uniformity of aerosol density, y_i is the observed value of the velocity of jet and y is the mean value of these observations, while the denominator N stands for the number of jets (for previous type of nozzle the number N is 6).

4.3 Example of Measured Data

Test of statistical sample of nozzles was carried in the described testing chamber. Example of measured data (for 3 different intervals from the injection start and for 5 different nozzles) is presented in figure 3.

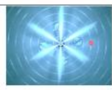
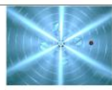
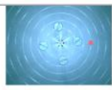
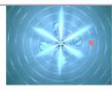
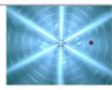
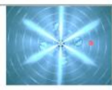
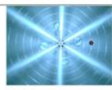
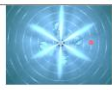
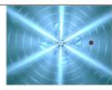
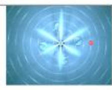
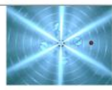
Nozzle	Time 1	Time 2	Time 3
1			
2			
3			
4			
5			

Fig. 3: Example of measured data

5 Capability Analysis of Fuel Injection Nozzles Production

Two quality characteristics for fuel injection nozzles production (Symmetry of injection - s_{N1} and Uniformity of aerosol density – s_{N2}) were calculated from measured data from testing chamber. One hundred samples were taken and analyzed for every parameter.

For capability analysis were used the Taam index [8]. The index MCpm is used in this capability analysis – it is defined as the ratio of elliptical tolerance region converted from the engineering specifications of elliptical process tolerance region.

$$MC_{pm} = \frac{\pi s_{N1C} s_{N2C}}{V_{R2}} \qquad \textbf{(5)}$$

where MCpm is Taam index, s_{N1C} is standard deviation of symmetry of injection converted from the engineering specifications, s_{N2C} is standard deviation of uniformity of aerosol density converted from the engineering specifications and V_{R2} is volume of a scaled 99.73% process region (scaled by the process mean square errors) – shown in figure 4.

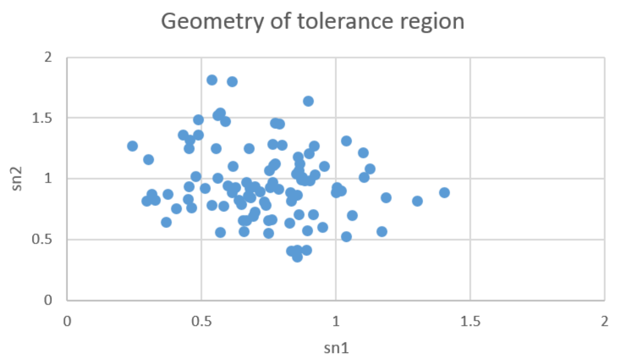


Fig. 4: Geometry of tolerance region

Tab. 1 shows the descriptive statistics of data sets. Data sets have the normal distribution. Anderson-Darling test was applied on the calculated data sets (p-Val was 0,854). Since the values for both the variables are not less than 0.05, there is not sufficient evidence to reject the hypothesis that the variables come from a normal distribution at the 5.0 % significance level.

Tab. 1: Descriptive statistics of data set

Characteristic	s_{N1}	s_{N2}
$\overline{X}$	0.7341	0.9635
min.	0.2410	0.3614
max.	1.4034	1.8146

Fitted multivariate normal distribution for two variables is displayed in Fig. 5.

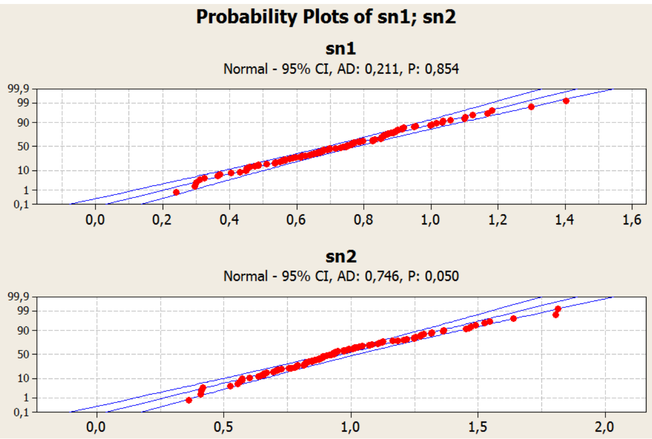


Fig. 5: Probability plot of s_{N1} and s_{N2}

Capability histograms of s_{N1} and s_{N2} are in fig. 6.

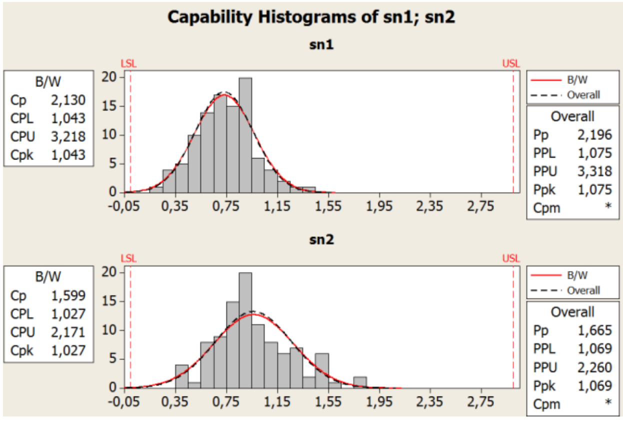


Fig. 6: Capability histograms of s_{N1} and s_{N2}

6 Description of Developed Software

In 2013, Evalin 1.0 software was developed (opening screen in figure 7). Evalin evaluates data obtained from proprietary software of Olympus high speed camera. The user can directly use the results of nozzle test to perform the capability analysis.

Basic features are:

• Calibration of the scanned area.
• Evaluation and visualization of symmetry of injection.
• Calculation of velocity of injection from the nozzle.
• Evaluation of the uniformity of aerosol density in individual injections.

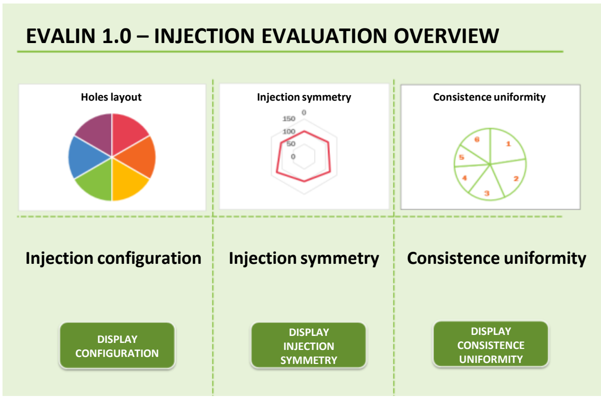


Fig. 7: Evalin software opening screen

7 Conclusion

In the production of the injection nozzles is very important to ensure the capability of production process. In this paper, we have presented a method for estimating process capability for two quality variables.

For the measuring of injection nozzles the test chamber was designed. High speed camera in the test chamber can record a set of images of injection.

Evalin 1.0 software was developed, this software can numerically analyze data from injection nozzle tests and allows to evaluate the parameters of the nozzle and becomes a support tool to perform the capability analysis.

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