ANALYTICAL METHODOLOGY FOR TESTING COMMON RAIL FUEL INJECTORS IN PROBLEMATIC CASES

Tomasz STOECK

West Pomeranian University of Technology in Szczecin, Faculty of Mechanical Engineering and Mechatronics, The Department of Automotive Engineering, Piastów Av. 19, 70-310 Szczecin, Poland, e-mail: tstoeck@wp.pl

Abstract

The paper presents a new methodology for testing common rail fuel injectors, which extends the standard diagnostic procedure to include the analysis of the resultant fields of dosed fuel. The calculations were made on the basis of Gaussian formulas, also known as the shoelace formula. Their implementation in the digital environment was convenient from the practical side, as it eliminated the need to modify the test bench software. Thanks to the easy modification, the presented algorithms can be used in testing fuel injectors of other types or generations, for which clear assessment and verification of the technical condition is sometimes difficult. It is not required for this to increase the number of measuring points of the active experiment, which is one of the greatest advantages of the proposed solution.

Keywords: common rail fuel injector, extension of test procedures, Gauss's formulas, fuel dosage

ANALITYCZNA METODYKA BADAŃ WTRYSKIWACZY COMMON RAIL W PRZYPADKACH PROBLEMATYCZNYCH

Streszczenie

W artykule przedstawiono nową metodykę testowania wtryskiwaczy common rail, która rozszerza standardową procedurę diagnostyczną o analizę wynikowych pól dawkowanego paliwa. Obliczenia prowadzono w oparciu o wzory Gaussa, określane również mianem formuły sznurowadła. Ich implementacja w środowisku cyfrowym była wygodna od strony praktycznej, gdyż wyeliminowała konieczność modyfikacji oprogramowania stołu probierczego. Dzięki łatwej modyfikacji prezentowane algorytmy można wykorzystać w badaniach wtryskiwaczy innych typów czy generacji, dla których jednoznaczna ocena i weryfikacja stanu technicznego bywa utrudniona. Nie jest przy tym wymagane zwiększanie liczby punktów pomiarowych eksperymentu czynnego, co stanowi jedną z największych zalet proponowanego rozwiązania.

Słowa kluczowe: wtryskiwacz common rail, rozszerzenie procedur testowych, wzory Gaussa, dawkowanie paliwa

1. INTRODUCTION

Common rail fuel injectors are the most susceptible to damage elements of the fuel systems in modern compression-ignition engines [5]. For this reason, intensive research works on the development of various diagnostic methods have been carried out for several years. This applies to both non-invasive techniques, allowing to locate a malfunctioning fuel injector without the need to remove it from the engine, and invasive techniques, thanks to which it is possible to identify the causes of failure and eliminate them in tests on test benches. In the latter group of techniques, standard manufacturer's tests are usually used, which are commonly regarded as the most precise and reliable [7]. They are carried out in automatic cycles, and mainly concern the method of fuel delivery at several critical operating points [6]. However, there are problematic cases in which such measurements may turn out to be insufficient, because the fuel injector doses fuel incorrectly in other areas of the engine operation, despite the

positive test result. As a result, the regeneration process requires extended diagnostics. It is particularly troublesome with the so-called injection characteristics, generated with the full spectrum of operating parameters, as the time consumption of the experimental phase increases several times [12]. In this respect, an interesting alternative are interpolation methods or methods based on linear regression, which effectively reduce the number of additional measurements [3, 17]. However, they are less practical than the manufacturer's procedures, as they are performed with manual settings and, moreover, require some laboratory and workshop experience.

The above considerations justify the search for further solutions, which, based solely on the initial data, will enable the verification and assessment of a malfunctioning fuel injector. To achieve this goal, the analytical methodology based on Gaussian formulas was selected. It was assumed that the base points from the standard diagnostic test would be located and connected in a Cartesian coordinate

system. In this way, the resultant fuel dosing areas of the tested fuel injector were calculated and compared with the reference fuel injector. The mathematical operations were carried out in the environment of Microsoft Excel spreadsheet, which enabled quick analysis of the experimental data. This approach was convenient from the practical point of view, as it allows taking into account the results from any test bench without having to interfere with its software.

2. RESEARCH METODS

The tests were carried out on the example of a Bosch CRI 2.1 fuel injector, which was removed from a 2.4 D5 compression-ignition engine of a Volvo C30 (533) vehicle with an operational mileage of 156,000 km.
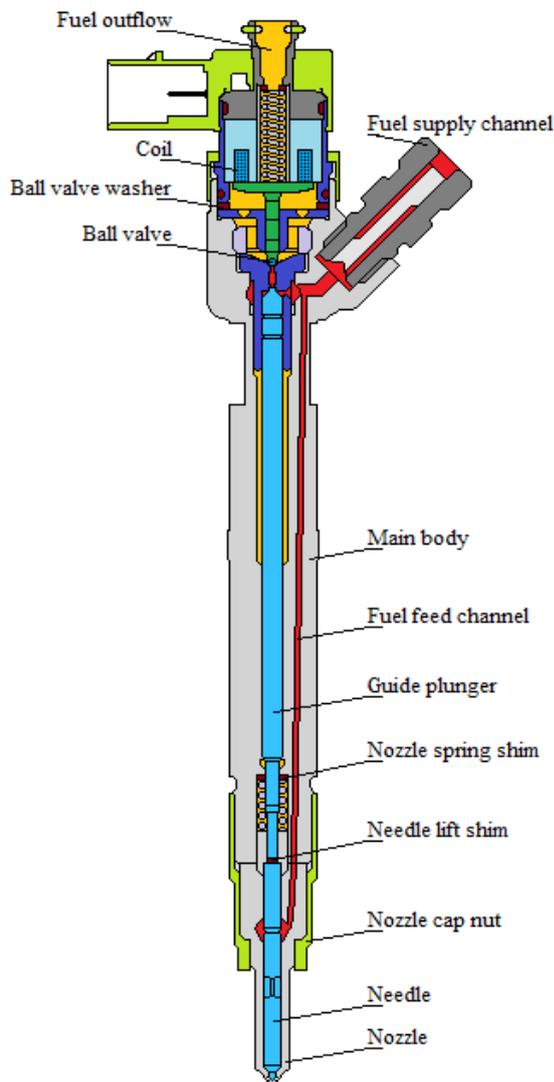

Fig. 1. Construction of the Bosch CRI 2.1 fuel injector

Electromagnetic fuel injectors of this type operate at maximum fuel delivery pressures of 160 MPa [8]. Their characteristic feature is the lack of a spring under the valve disc (Fig. 1). The simplified structure allows the regeneration to be carried out

almost to the full extent. The manufacturer made available the diagnostic technology as well as a complete set of original spare parts [11].

2.1. Test benches

At individual stages of the research, the following measuring equipment and instrumentation were used, which included, among others:
– EPS 200 test bench (Fig. 2),
– the so-called Bosch 3-phase gear, e.g. CRR 120, CRR 220, CRR 320, CRR 420 (Fig. 3), LAB / SM135,
– SZM-168 laboratory microscope with a camera for digital image recording on a PC,
– ultrasonic baths (Carbon Tech Ultrasonic Bath S15/C2, Elma Elmasonic S10H),
– presses, vices and fuel injector disassembly and assembly tool kits,
– tools and torque wrenches.

Fig. 2. Bosch EPS 200 test bench

Fig. 3. CRR 420 digital dial gauge

Before starting the tests, the fuel injector was mounted on a test bench and rinsed thermo-chemically. This decision was made in order to remove possible impurities and Internal Diesel Injector Deposits (IDIDs), the presence of which adversely affects the method of fuel delivery [4, 9, 15].

The diagnostic process was carried out in accordance with the manufacturer's requirements. Therefore, the research included a dedicated Bosch 3-phase repair kit, which ensures the highest measurement accuracy and precision when correcting fuel dosage, being a standard equipment of the injection system regeneration laboratory.

2.2. Gauss formulas

In the proposed methodology, the area of the polygon, which is presented in the Cartesian coordinate system, is calculated on the basis of the coordinates of contour turn points [1]. Assuming that the vertices x_1, y_1), (x_2, y_2), …, (x_n, y_n) are marked clockwise, the area of figure A can be determined using Gaussian formulas in the general form [10, 14]:

$$A = \frac{1}{2}\left|\sum_{i=1}^{n} x_i(y_{i+1}-y_{i-1})\right| \qquad (1)$$

and

$$A = \frac{1}{2}\left|\sum_{i=1}^{n} y_i(x_{i-1}-x_{i+1})\right| \qquad (2)$$

where:
A – polygon surface area,
n – number of vertices,
x_i, y_i – coordinated of the i-th vertex.

Formulas (1) and (2) are also known as the so-called shoelace formulas because the vertex coordinates of the polygon are multiplied crosswise [2]. They should be used together in order to control the calculations made. On the other hand, it is most convenient to put the formulas created in the spreadsheet in the form of table 1, which organises and simplifies the analytical process.

Table 1. Table for the calculation of surface areas

Point number	x_i	y_i	$x_{i+1}-x_{i-1}$	$y_{i+1}-y_{i-1}$
1	x_1	y_1	x_2-x_4	y_2-y_4
2	x_2	y_2	x_3-x_1	y_3-y_1
3	x_3	y_3	x_4-x_2	y_4-y_2
4	x_4	y_4	x_1-x_3	y_1-y_3
1	x_1	y_1	$\sum_{i=1}^{n}(x_{i+1}-x_{i-1})$	$\sum_{i=1}^{n}(y_{i+1}-y_{i-1})$

3. RESULTS AND DISCUSSION

3.1. Preliminary tests

Based on the data presented in Table 2, it can be concluded that the fuel injector passed the test procedure. The results obtained were within the limits specified by the manufacturer. However, after assembly, the engine was characterised by hard, uneven operation, particularly at idle and light loads.

For this reason, it was decided to implement the proposed methodology.

Table 2. Results of the preliminary tests

Leak Test, LKT [MPa] 170 MPa (200s)	Injection dosage	Return dosage
	0	[40.0±40.0] **15.32**
Injector Volume Metering, IVM		
Dose number	Injection pressure, p_{inj} [MPa]	Nozzle opening times, t [μs]	Injection dosage, d [mm³/H]
1	80	220	[1.4±1.1] **1.23**
2	160	1000	[43.6±6.0] **39.91**
3	80	600	[15.4±4.6] **11.12**
4	25	650	[3.2±3.0] **0.22**

The results of the volume measurements were located in the Cartesian coordinate system. The connection of the base points 1-2-3-4 made it possible to create an irregular quadrilateral whose surface area was estimated using the formulas (1) and (2). For this purpose, calculation formulas were entered into a Microsoft Excel spreadsheet. After substituting the numerical valuesconstituting the vertices of the analysed figure, the resultant fuel dosage area was obtained in the preliminary test A_{PT} (Table 3).

Table 3. Calculation of the resultant metering field A_{PT}

Dose number	t_i	d_i	$t_{i+1}-t_{i-1}$	$d_{i+1}-d_{i-1}$
1	220	1.23	350	39.69
2	1000	39.91	380	9.89
3	600	11.12	-350	-39.69
4	650	0.22	-380	-9.89
1	220	1.23	Σ=0	Σ=0
A_{PT}				
11620.70=½|(350·1.23)+(380·39.91)+(-350·11.12)+ _+(-380·0.22)|				
11620.70=½|(39.69·220)+(9.89·1000)+(-39.69·600)+ +(-9.89·650)|				

The calculations for the reference fuel injector were carried out in a similar way, using the data provided by the manufacturer (Table 4). In turn, Figure 4 shows a graphic interpretation of the results of the preliminary tests.

The disturbance of the fuel injection process causes a clear shift of the quadrilateral 1-2-3-4, and the position of individual vertices may indicate the cause of the malfunction. First of all, the very low idle dose value (point 4) is noteworthy. In such a situation, initial needle wear in the fuel injector atomiser often occurs, and thus problems with overcoming the nozzle spring tension after applying the lowest pressure on the test bench (p_{inj} = 25 MPa). It is worth emphasising that with the increase in this operating parameter, the symptoms almost

completely disappeared. This is evidenced by the similar location of points 1-1`, which correspond to the so-called pilot doses.

Table 4. Calculation of the resultant metering field A_{SI}

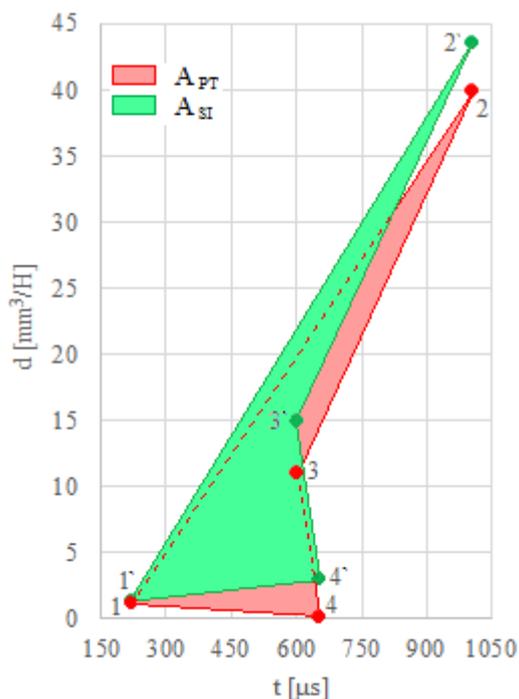| Dose number	t_i	d_i	$t_{i+1}-t_{i-1}$	$d_{i+1}-d_{i-1}$
1`	220	1.40	350	40.40
2`	1000	43.60	380	14.00
3`	600	15.40	-350	-40.40
4`	650	3.20	-380	-14.00
1`	220	1.40	$\Sigma=0$	$\Sigma=0$
A_{SI}				
10452.00=½|(350·1.40)+(380·43.60)+(-350·15.40)+ _+(-380·3.20)|				
10452.00=½|(40.40·220)+(14.00·1000)+(-40.40·600)+ +(-14.00·650)|				

Fig. 4. Graphical interpretation of the preliminary test results

On the basis of the performed calculations, it was found that the difference between the resulting fuel delivery fields for the tested fuel injector APT and the reference fuel injector A_{SI} was 10.06%. Undoubtedly, this was due to the limited operating range of the control valve. At this stage of the research, however, it is not possible to clearly answer why the values of full load dose 2 and emission dose 3 were underestimated.

3.2. Main tests

In the first step, the valve ball travel AH (German: Ankerhub) was checked. The obtained result was 0.047 μm, which was within the limit set by the manufacturer (0.046-0.056 μm [13]). Therefore, there was no need to perform a setting correction that would require changing the thickness of the valve shim at the disc (Fig. 2).

Further basic tests were preceded by the disassembly of the fuel injector into its component parts, which were bathed in ultrasonic baths. After drying them, microscopic examination was performed under high magnification. No damage was found to the valve assembly, as well as to plunger and barrel assembly, i.e. the needle with the atomiser (Figs. 5, 6 and 7).
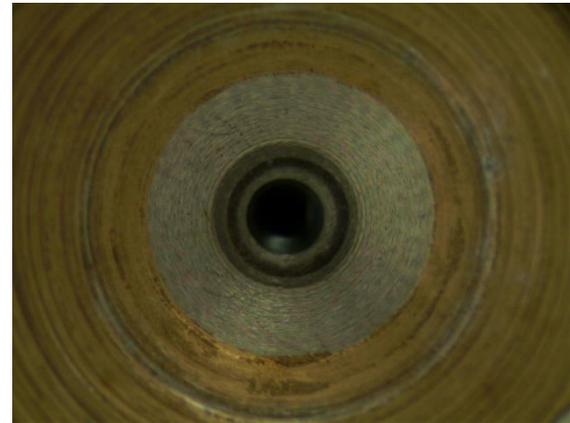

Fig. 5. View of the valve seat

Fig. 6. Needle cone

Fig. 7. Nozzle tip

Considering the low operational mileage of the engine, it was decided that no controls and actuators would be replaced with new ones. However, an adjustment was made, which consisted in increasing the idle doses and full load doses. For this purpose, the thickness of the needle washer was changed from

1.14 µm to 1.10 µm, and then the nozzle spring disc were changed from 1.46 µm to 1.26 µm.

Table 5. Results of the main tests

Leak Test, LKT [MPa] 170 MPa (200s)	Injection dosage	Return dosage
	0	[40.0±40.0] **9.32**
Injector Volume Metering, IVM		
Dose number	Injection pressure, p_{inj} [MPa]	Nozzle opening times, t [µs]	Injection dosage, d [mm³/H]
1``	80	220	[1.4±1.1] **1.41**
2``	160	1000	[43.6±6.0] **43.71**
3``	80	600	[15.4±4.6] **15.94**
4``	25	650	[3.2±3.0] **2.45**

Table 6. Calculation of the resultant metering field A_{MT}

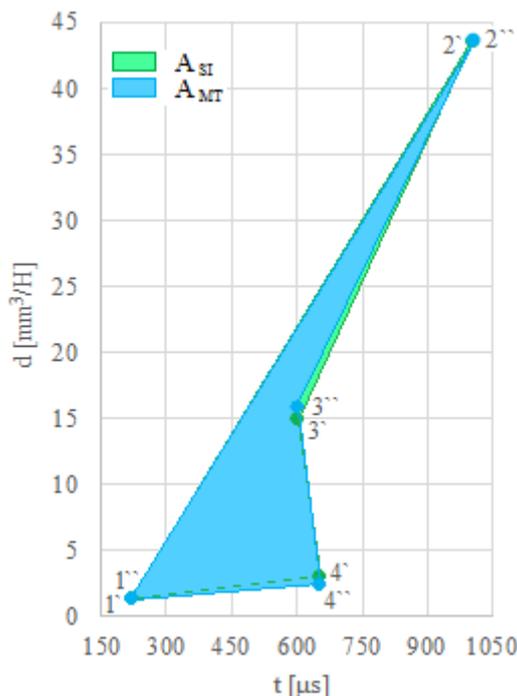| Dose number	t_i	d_i	$t_{i+1}-t_{i-1}$	$d_{i+1}-d_{i-1}$
1``	220	1.41	350	41.26
2``	1000	43.71	380	14.53
3``	600	15.94	-350	-41.26
4``	650	2.45	-380	-14.53
1``	220	1.41	Σ=0	Σ=0
A_{MT}				
10593.30=½|(350·1.41)+(380·43.71)+(-350·15.94)+ _+(-380·2.45)|				
10593.30=½|(41.26·220)+(14.53·1000)+(-41.26·600)+ +(-14.53·650)|				

Fig. 8. Graphical interpretation of the main test results

The regeneration of the tested fuel injector should be assessed positively, as the factory settings

have been restored (Tables 5 and 6). The resultant fuel dosage field A_{MT} and the standard fuel dosage field A_{SI} are comparable, as the difference between them was only 1.33%. Therefore, the quadrilaterals 1`-2`-3`-4` and 1``-2``-3``-4`` practically overlap (Fig. 8). The vertices of the two figures have a very similar position on the graph, and the shifts so characteristic for the preliminary test are almost absent. The performed correction also had a positive effect on the pilot and emission doses (half load).

4. CONCLUSION

The proposed methodology of calculations makes it possible to consider specific cases of failure of common rail injectors that work incorrectly despite meeting the required manufacturer criteria. It is worth emphasising, however, that the resultant fuel dosage fields should be treated hypothetically (arbitrarily), as they do not reflect the actual fuel delivery method at intermediate points, i.e. beyond the vertices of the generated figures. Nevertheless, they can constitute a completely new diagnostic parameter, the analysis of which allows for the verification and assessment of the technical condition of the tested design, as shown in this particular example. Moreover, in the workshop and laboratory conditions, there is no need for a graphic interpretation of the obtained results, it is enough to compare them only, hence the drawings presented in the text are only illustrative. The added value is also that there is no need for additional measurements and calculations outside the test bench, without affecting its software in any way. For the above reasons, the presented solution meets the needs of the fuel injection system maintenance service market, which have been signalled in recent years. In addition, implementation in a digital environment allows the presented algorithms to be reused in research with a similar profile [16]. This approach is convenient from the practical point of view, because it enables a very quick analysis of experimental data that may come from diagnostic tests of fuel injectors of various types or generations.

In the analysed case, there were no malfunctions related to the wear of individual fuel injector component parts. The underestimated fuel dosage resulted from the presence of internal impurities, which were removed only when cleaning the disassembled elements in ultrasonic baths. On the other hand, the control and adjustment process made it possible to restore the original (factory) settings, as their values were comparable to the reference ones.

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Tomasz STOECK, PhD graduated from the Faculty of Mechanical Engineering of the Szczecin University of Technology (currently ZUT in Szczecin). Since 2006, he has been a researcher and lecturer at the Department of Automotive Engineering. His interests are primarily related to the diagnosis and repair of diesel injection systems.