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Diagnostic method for a piezoelectric injector using the Newton-Cotes formula

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The article presents a method for regenerating common rail injectors, which involves extending the standard diagnostic procedure with a phase of analytical calculations. The closed-type Newton-Cotes formula (referred to as the trapezoidal rule) was employed to estimate the resulting fuel spray patterns and compare them with the manufacturer's reference. In the discussed example, it was demonstrated that the proposed solution is particularly useful in challenging situations where a definitive assessment of the injector's technical condition remains difficult. Several other advantages were also highlighted, making this method suitable for application in laboratory and workshop conditions.

Key words: *common rail system, piezoelectric fuel injector, Newton-Cotes formula, regeneration process*

1. Introduction

In recent years, there has been an increased demand for the regeneration of common rail fuel injectors, as this process allows for the restoration of factory performance parameters. Consequently, there is a need for precise and reliable monitoring of their technical condition, which is ensured by diagnostic tests on dedicated test benches. In the vast majority of cases, standard procedures are sufficient, primarily based on determining the fuel dosing at selected base points [8, 13, 21]. Unfortunately, problematic situations arise where improper injector operation is observed on the engine, despite meeting rigorous manufacturer criteria during testing. A solution can be extended diagnostics, involving the creation of a fuel delivery characteristic across the full range of working pressures and injection times (nozzle opening) [6, 9, 17]. It is essential to emphasize that this is a significantly more time-consuming process and is only available on advanced test benches, such as STPiW3 [12]. There is also the possibility of employing strictly scientific methods, the use of which is not always feasible in typical workshop conditions [3, 14, 18].

The above reasons led to the proposal of a technique based on the closed Newton-Cotes formula. It is widely known for numerical integration and is used to determine the surface area bounded by a function's graph [4, 25]. However, the mathematical algorithm itself can be easily implemented in the environment of any spreadsheet, allowing for quick calculations, verification of their accuracy, and ultimately the assessment of the technical condition of the injector based on the results of the standard test procedure. Such an approach is practical, as it does not increase the number of measurements in the experimental phase. As a result, costs and labor remain unchanged. As an example, a piezoelectric injector was chosen for which repair technology has been made available, along with a complete set of spare parts (excluding the crystal stack).

2. Methods

2.1. Test beds

The research was conducted on a test bench equipped with a Bosch EPS 205-type table (Fig. 1).

Fig. 1. View of the Bosch EPS 205 test bench

This is a versatile diagnostic device with a single measurement tower, allowing for automatic testing, coding, and internal cleaning of injectors. The results are compared with the manufacturer's database, which is accessible from the control screen and subsequently saved and printed as a final report. The functionality of the tester has been significantly enhanced compared to previous versions (EPS 200/200A), as the manufacturer has installed sets (attachments, adapters, connectors) and software adapted for testing piezoelectric injectors. Due to its compact size and affordable price, the device is very popular in the service market.

During the regeneration process, additional equipment and specialized tools are also used, with the most important ones being:
– Yizhan 13MP HDMI VGA industrial camera
– Bene YesWeCan 3L ultrasonic cleaner

– Facom E.316A200S torque wrench
– clamps, holders, and workshop tools
– PC-class computer.

2.2. Test object

The research was conducted on a piezoelectric injector from Bosch, which was removed from the N47 D20 engine of a BMW X3 vehicle with a mileage of 268,000 kilometers.

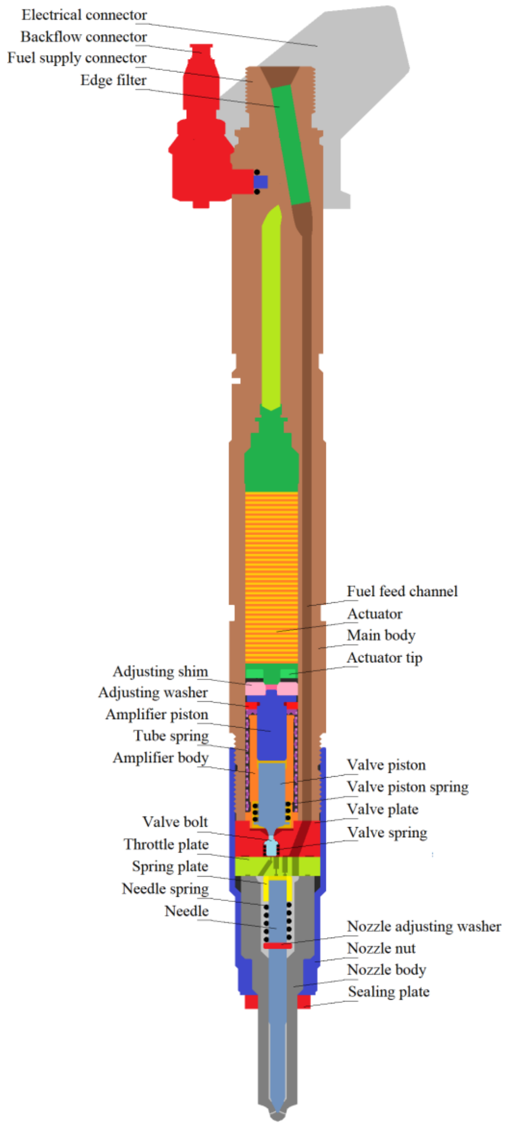

Fig. 2. Structure of the Bosch CRI3-18 injector: a proprietary development based on [16, 19]

Injectors of this type are classified as third-generation systems, operating at maximum pressures up to 180 MPa [15]. Figure 2 illustrates the internal structure, detailing the components of the hydraulic amplifier group, control valve, and nozzle. A characteristic feature is the absence of a lateral fuel supply channel in the nozzle, resulting in the central delivery of fuel in the spaces around the needle. Consequently, this component has a triangular cross-section in the guiding part, which is essentially unique among other manufacturers. The sealing of the tip is achieved solely through the valve assembly [11].

2.3. Research plan

Table 1 presents the research plan, which in the experimental and operational part closely aligned with the manufacturer's procedure [23]. The exception was the additional phase of analytical calculations conducted in a spreadsheet on a workstation with a computer. Typically, it is also used for visualization and recording of images generated from a microscopic industrial camera [24].

Table 1. Research plan with division into stages and workstations

Workplace	Stage I	Stage II
Bosch EPS 205 test bench	Electrical test	Main flow tests
	Leak test	
	Internal cleaning	Injector coding
	Preliminary flow tests	
Tool station (Fig. 3)	Disassembly into parts	Final acceptance
	Ultrasonic washing	
	Part drying	
	Microscopic examination	
	Parts exchange	
	Assembly	
Computer station	Calculation phase	

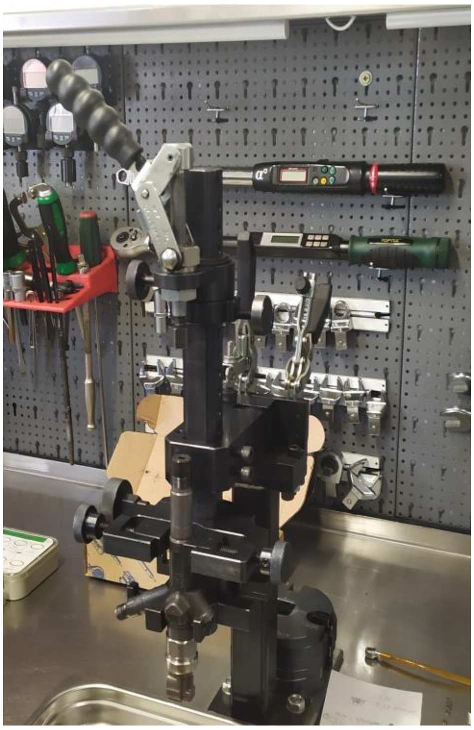

Fig. 3. General view of the tool station

It should be noted that the scope of service-diagnostic activities may change depending on the type of identified malfunctions or the initial condition of the injector. For example, in the case of severe coking of the nozzle (sprayer), the manufacturer recommends performing preliminary cleaning with an ultrasonic cleaner. This process requires placing the injector vertically in the device's basket, eliminating the possibility of damaging its electrical components. Its purpose is to ensure the openness of the outlet holes before conducting a flow test on the test bench.

2.4. Newton-Cotes formula

In the Cartesian coordinate system, points corresponding to the fuel doses of the reference injector were located.

By connecting them, a non-rectangular quadrilateral with vertices 1-2-3-4 was obtained (Fig. 4). Subsequently, trapezoids were extracted, and their surface areas were calculated using the closed Newton-Cotes formula [2]:

$$A_T = (t_{i+1} - t_i)\frac{d_i + d_{i+1}}{2} \tag{1}$$

To simplify the calculations, formula (1) was replicated in spreadsheet cells. The total area of the shape was determined using the relationship [7]:

$$A_{1-2-3-4} = A_{T1} + A_{T2} + A_{T3} - A_{T4} \tag{2}$$

This way, a reference base (a benchmark) for the results was established, which was estimated based on the preliminary and main tests of the regenerated injector.

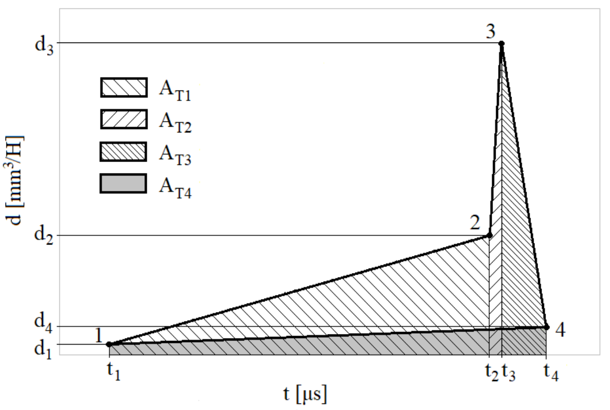

Fig. 4. Graphical interpretation of the trapezoidal method for the discussed example

The Newton-Cotes formula has not been applied in the diagnosis of common rail fuel injectors so far, hence the presented calculations are not reflected in the literature on the subject. However, the presented example indicates that it can be effectively applied in scientific and engineering practice. To automate the computational process, a spreadsheet was used, enabling rapid results at each stage of the conducted operations.

3. Analysis results and discussion

3.1. Preliminary tests

According to the standard procedure, the injector was mounted on the test bench, where it underwent internal cleaning, a leakage test, and testing of basic electrical parameters. In the latter case, crystal stack failure was ruled out, as values consistent with the manufacturer's specifications were obtained, i.e., capacitance C = 2.3 µF (1.5–3.3 µF) and resistance R = 186 kΩ (150–210 kΩ). There was also no evidence of insulation damage between the actuator and the main body ($R_I = \infty$). Similar conclusions were drawn after preliminary flow tests (IVM), as all fuel doses fell within the specified ranges (Table 2). Unfortunately, during the final acceptance on the vehicle's dashboard, the warning light would illuminate, and the engine would enter what is known as 'limp mode'. As a result, the injector was disassembled once again, and the proposed calculation method was implemented.

Table 2. Results of preliminary IVM flow tests

Test name	Point	p_{inj} [MPa]	t_i [µs]	d_i [mm^3/H]
Pre-injection	1`	80	190	[1.5 ±1.2] 1.3
Emission point	2`	80	490	[18.9 ±3.6] 15.4
Maximum load	3`	180	500	[49.3 ±5.0] 44.4
Idle	4`	30	535	[4.3 ±2.2] 4.1

3.2. Calculation stage

From the data presented in Tables 3 and 4, it can be observed that the injection process disturbance caused a displacement of the quadrilateral 1`-2`-3`-4`. Although the fuel doses met the requirements of the test procedure, their values were significantly underestimated compared to the reference. This was especially true for points 2` and 3`, which corresponded to engine operating conditions at half and full load. As a result, the surface area for the tested injector was 18.5% smaller (Fig. 5). The cause should be attributed to the improper functioning of the valve group, which should be replaced after disassembly. A similar decision was made regarding the precision pair (nozzle, needle). In this regard, the decisive factor was the relatively high mileage of the vehicle rather than the nature of any dysfunction.

Table 3. Results of surface area calculations for the reference figure

Point	t_i	d_i	A_{T1}	A_{T2}	A_{T3}	A_{T4}
1	190	1.5	3060			
2	490	18.9		341		
3	500	49.3			938	
4	535	4.3				1000.5
1	190	1.5				
$A_{1-2-3-4}$						
3338.5						

Table 4. Results of surface area calculations for the figure 1`-2`-3`-4`

Point	t_i	d_i	$A_{T1`}$	$A_{T2`}$	$A_{T3`}$	$A_{T4`}$
1`	190	1.3	2505			
2`	490	15.4		299		
3`	500	44.4			848.8	
4`	535	4.1				931.5
1`	190	1.3				
$A_{1`-2`-3`-4`}$						
2721.3						

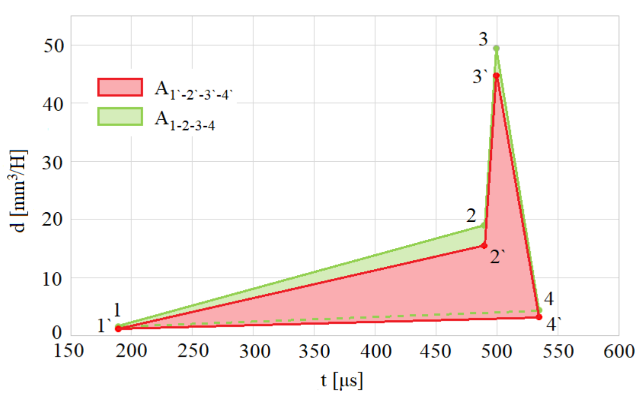

Fig. 5. Graphical interpretation of the results of preliminary tests

3.3. Microscopic examination and injector assembly

The microscopic examination was preceded by disassembling the injector into its components and cleaning them with an ultrasonic cleaner.

During the inspection under high magnification, corrosion was observed on most components that had direct contact with fuel, such as the needle, valve plate, throttle, and the hydraulic amplifier body (Fig. 6). This process had an adverse effect on the dynamics of individual assemblies, and the resulting contaminants further polluted the interior of the injector, leading to accelerated wear of interacting surfaces. It should be noted that corrosion intensification is a commonly encountered phenomenon in injectors operating at such high working pressures. This occurs despite the structural and material modifications employed by manufacturers [1, 5, 10].

Fig. 6. Observation of corrosion on the hydraulic amplifier body

Consequently, it was decided that restoring full functionality would only be possible by replacing all executive and control groups, except the piezoelectric actuator.

During the injector assembly process, it is essential to purge the hydraulic amplifier by assembling its components in diesel oil and then compressing them using a specially dedicated press. This step is of fundamental importance for ensuring accurate fuel delivery during primary investigations, as it eliminates the possibility of result distortion, namely, zero doses. Subsequently, the nozzle assembly (nozzle, needle, spring, washer) is assembled and securely fastened to the main body using a nut. Throughout this operational procedure, strict adherence to the manufacturer's guidelines is crucial, utilizing a torque wrench for this purpose (Fig. 7).

Fig. 7. Tightening the nut with a torque wrench

3.4. Main tests

In Table 5, the results of the main flow tests are presented, while Table 6 compiles the results of calculations conducted after the regeneration process.

Table 5. Results of main IVM flow tests

Test name	Point	p_{inj} [MPa]	t_i [μs]	d_i [mm^3/H]
Pre-injection	1`	80	190	[1.5 ±1.2] 1.5
Emission point	2`	80	490	[18.9 ±3.6] 18.5
Maximum load	3`	180	500	[49.3 ±5.0] 48.6
Idle	4`	30	535	[4.3 ±2.2] 4.4

Table 6. Results of surface area calculations for figures 1``-2``-3``-4``

<table>
<tr><th>Point</th><th>t_i</th><th>d_i</th><th>$A_{T1``}$</th><th>$A_{T2``}$</th><th>$A_{T3``}$</th><th>$A_{T4``}$</th></tr>
<tr><td>1``</td><td>190</td><td>1.5</td><td rowspan="2">3000</td><td></td><td></td><td></td></tr>
<tr><td>2``</td><td>490</td><td>18.5</td><td rowspan="2">335.5</td><td></td><td></td></tr>
<tr><td>3``</td><td>500</td><td>48.6</td><td></td><td rowspan="2">925.9</td><td></td></tr>
<tr><td>4``</td><td>535</td><td>4.4</td><td></td><td></td><td rowspan="2">1017.8</td></tr>
<tr><td>1``</td><td>190</td><td>1.5</td><td></td><td></td><td></td></tr>
<tr><td colspan="7">$A_{1``-2``-3``-4``}$</td></tr>
<tr><td colspan="7">3245.3</td></tr>
</table>

It can be observed that the replacement of key components yielded favorable results. There was an increase in the values of all fuel doses compared to the preliminary tests. As a result, the surface area of the quadrilateral 1``-2``-3``-4`` almost completely overlapped with the reference, with a difference of only 2.8% (Fig. 8). This suggests that the factory settings of the tested injector have been restored. Of course, new codes were assigned before installation in the engine. This process was carried out automatically on the same test bench where fuel dosing measurements were taken.

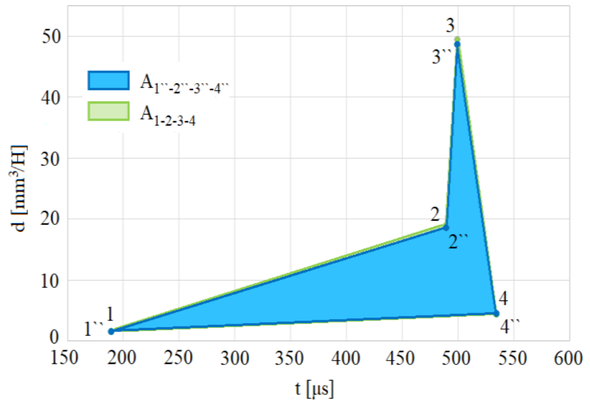

Fig. 8. Graphical interpretation of the results of the main tests

3.5. Validation of calculations

In authorial publications [20, 22], Gauss formulas were employed for the computation of surface areas of polynomials localized in Cartesian coordinate systems. In the context of the considered case, these formulas can be expressed in the following form:

$$A_T = \frac{1}{2}\left|\sum_{i=1}^{n} t_i(d_{i+1} - d_{i-1})\right| \tag{3}$$

and

$$A_T = \frac{1}{2}\left|\sum_{i=1}^{n} d_i(t_{i+1} - t_{i-1})\right| \tag{4}$$

The results presented in Table 7 unequivocally indicate that the formulas (3) and (4) can be successfully applied to verify the accuracy of calculations conducted using the Newton-Cotes method. Their implementation in a spreadsheet environment proceeds in a similar manner and does not pose significant difficulties. Simultaneously, the formulas introduced into the appropriate cells of the program can be reused in their unchanged form, providing the user with a ready computational tool for future research.

Table 7. Example of alternative calculations for figure 1``-2``-3``-4``

Point	t_i	d_i	$t_{i+1} - t_{i-1}$	$d_{i+1} - d_{i-1}$
1	190	1.5	–45	14.1
2	490	18.5	310	47.1
3	500	48.6	45	–14.1
4	535	4.4	–310	–47.1
1	190	1.5	Σ = 0	Σ = 0
$A_{1``-2``-3``-4``}$				
3245.3 = ½|(–45·1.5) + (310·18.5) + (45·48.6) + (–310·4.4)|				
3245.3 = ½|(14.1·190) + (47.1·490) + (–14.1·500) + (–47.1·535)|				

4. Conclusions

The proposed method enables the application of extended diagnostics for common rail injectors that operate incorrectly despite meeting the criteria specified by the manufacturer. Among its most significant advantages are:

1. The use of the standard procedure's baseline points does not require additional measurements in the experimental phase. This eliminates the need to create a complete fuel dosing characteristic, which is only available on selected test benches.
2. There is no need to modify the software used by the tester.
3. Transferring the analytical process to a spreadsheet environment does not increase the regeneration costs. The formulas can be successfully applied in the examination of injectors of various types or generations (including electromagnetic solutions).
4. The position of the vertices of the analyzed figures indicates possible causes of malfunction. However, in laboratory workshop conditions, there is no need for a graphical interpretation of the results. Therefore, the drawings presented in this article are purely illustrative.
5. The accuracy of the conducted calculations can be easily verified using alternative mathematical methods, such as Gauss's formulas. Since these studies were conducted on injectors from different manufacturers and on distinct test benches, the presented conclusions and observations have a more general nature. Simultaneously, the choice of computational technique has no impact on the final results and depends on individual preferences.

It should be emphasized that the resulting dosage areas presented in the form of polygons in the Cartesian coordinate system should be treated purely hypothetically. This is because they do not accurately reflect the actual fuel injection method at intermediate points, i.e., beyond the vertices of the generated figures. Nevertheless, the proposed method allows for the assessment of the technical condition of common rail injectors in problematic situations, as demonstrated in a specific example. In this way, it constitutes an effective solution that has been addressing the needs reported by service companies for years.

Acknowledgments

The research was conducted at the service company AUTO NEXT SERWIS, located in Szczecin, which provided a complete set of measurement equipment and specialized tools necessary for the injector regeneration process.

Nomenclature

A_T surface area of the component trapezoid
A surface area of the quadrilateral (indices):
 1-2-3-4 – reference
 1`-2`-3`-4` – in preliminary tests
 1``-2``-3``-4`` – in main tests
d_i injection dosage
C piezo actuator capacitance
CRI common rail injectors
IVM injector volume metering
p_{inj} injection pressure
R piezo actuator resistance
R_I piezo actuator insulation resistance
t_i nozzle opening time

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