Determination of the stages of the injection process for Common Rail injectors using vibration pulses

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Abstract. The study and modeling of the combustion process of diesel engines require knowledge of the injection characteristics. The information on the exact start, duration and end of the injection is required. For Common Rail injectors with electromagnetic control, the beginning and duration of the electronic control pulse are precisely known. The actual start and duration of the injection are not the same as those of the impulse and they are related to the movement of the nozzle needle. The experimental determination of the movement of the nozzle needle requires specially prepared experimental installations and expensive measuring instruments. In addition, the experimental injector must be prepared with design modifications allowing the incorporation of sensors. The article presents a method for determining the start and duration of injection of Common Rail injectors using the registration and analysis of vibration pulses generated in the injector body. The method is based on the fact that the nozzle needle causes vibrations in the injector body when lifting and seating.

1. Introduction

In modern Common Rail systems, fuel control is realized by changing the start and duration of the electronic pulse that triggers the electromagnetic injector. This, combined with the different injection pressures, allows precise fuel metering. The start of the actual injection is considered to be the moment of raising the nozzle needle, and the end is considered the moment of its closing [1]. The start and end of the control pulse do not coincide with the start and end of the injection. This is a result of the principle of operation of the electromagnetic injectors and the processes accompanying the injection [2]. Determining the delay with which the injection starts and ends relative to the control pulse is important both for the design stages in the development of fuel systems for new engines and in determining the impact of wear of the injector elements during their operation. The changed delay of injection as a result of operation compared to the beginning of the control pulse changes the advance of injection and significantly affects the working process of the engine. This is the reason for the large number of scientific studies in this field.

Different methods can be used to determine the needle lift, with custom build sensors - Hall effect or optical sensors [3]. Common to these methods is the need to make changes to the construction of the test injector and the need for specialized equipment. This makes it impossible to study a large number of different injectors, including ones with long-term operation.

To study the lift of the needle for gasoline [4] and gas [3] engines, a method based on the recording of vibration pulses of injector body was used. When the valve needle with solenoid armature move
and especially at reaching its end positions, distinct vibration pulses are generated, which can be registered.

The purpose of the presented work is to show to what extent the recorded vibration pulses in the injector housing can be used to determine the beginning and end of lifting of the nozzle needle.

2. Experimental Studies

The experiments were performed on a standard injector test bench Common Rail CRI-NTR816E. The elements of the system delivering, measuring and regulating the pressure belong to the company “Bosch”. The measurement is performed by the "Cobolt" system, with a measurement accuracy of 0.1 mm$^3$. The tests were performed with two BOSCH injectors with numbers 0445110259 and 0445110044. In addition to the stand, additional accelerometers and pressure transducer were used, figure 1.

![Figure 1. Scheme of the experimental setup.](image)

To measure the pressure in front of the injector (1), a body (2) with a minimum volume is used, on which is mounted a standard car fuel pressure sensor (3). An accelerometer (5), type RFT KD35, is firmly mounted in the front part of the nozzle housing to read the vibration pulses by means of a plate (4). In addition to accelerometer (5), a movable one (6) of the same type is used to read the vibration pulses at the top part of the nozzle housing. The contact between the accelerometer and the injector is made by means of a rod, which is held by hand. Fuel (7) is supplied from the stand via high pressure tubes, and the excess fuel (8) is sent to the flow meter of the stand. A control pulse (9) is generated by the stand, which is recorded simultaneously with the signal (10) from the pressure sensor, with the signal (11) from the vibration sensor (5) and the signal (12) from the vibration sensor (6). Figure 1 shows recorded signals using a digital oscilloscope. At each attempt, the amount of injected fuel is measured.

The experiment was performed with two different injectors, figure 2. They differ significantly in length. The mass of the nozzle needle and the armature of the electromagnet of the two injectors are approximately equal, but the length and mass of the control piston (valve rod) of injector 1 are
approximately twice as large as those of the injector two. This implies greater inertia and longer injection delays in this injector.

![Tested Bosch injectors](image1)

**Figure 2.** Tested Bosch injectors

![Current, armature and nozzle needle lift](image2)

**Figure 3.** Current, armature and nozzle needle lift

During the preliminary analysis of the vibration signals, a clear repeatability of the signal change was found. This allows five points to be determined during the operation of the injector, figure 3: (1) - the impact of the armature of the electromagnet at the stop at maximum lift; (2) - the beginning of the lifting of the nozzle needle, the housing of the injector shakes and moves back from the movement of the needle; (3) - the impact of the control piston at the stop, the end of the lifting of the needle; (4) - the impact of the anchor of the electromagnet when closing; (5) - the impact of the needle during its squatting, end of the injection.

For each of the injectors, experiments were performed at three different pressure levels in the fuel accumulator - 25MPa, 80MPa and 135MPa. For each pressure two different durations of the control signal are used - 1800µs and 900µs.

For each point of the experiment, multitude of consecutive groups of vibration pulses are recorded, which correspond to the injection of the given injector. Figure 4 shows the records for one injection of the two injectors with a pressure of 25MPa, durations of the control signal - 1800µs and 900µs.
Figure 4. Recorded signals of the injectors at injection pressure 25MPa.

Above each recording is marked the injector number, the injection pressure in MPa and the duration of the control signal in $\mu$s, for example (1-25-1800). In addition to the moments explained in figure 3 and numbered from 1 to 5, figure 4 shows: the beginning of the drop in fuel pressure in front of the injector - (6); restoring the pressure to its initial level.

Figure 5 shows the records recorded at injection pressure of 80 MPa, and Figure 6 shows the records at injection pressure of 135 MPa.

It is noteworthy that after the initial deviation of the vibration signal registered with the mobile accelerometer (6), figure 1, oscillations with large amplitude and low frequency appear. They are a consequence of the used method (holding by hand) and are caused by the short-term loss of contact between the sensor and the nozzle housing. These vibrations depend on the clamping force and are largely random in nature, so they are only used to establish the initial moment of the movement of the injector associated with the beginning of lifting of the nozzle needle.

Characteristic signal variations are used to determine the moments (1) to (5) in the figures, taking into account the injection delay times for Bosch injectors shown as examples in [1].
Figure 5. Recorded signals of the injectors at injection pressure 80MPa.

Figure 6. Recorded signals of the injectors at injection pressure 135MPa.
From the set of records for one point of the experiment, three random records were selected and the times from (1) to (7) were determined. They represent the time from the beginning of the control signal to the corresponding point. The obtained values of these times for the two injectors are averaged and are shown in table 1.

Table 1. Delay times relative to the start of the control signal.

| Times (μs) | 0-1 | 0-2 | 0-3 | 0-4 | 0-5 | 0-6 | 0-7 |
|------------|-----|-----|-----|-----|-----|-----|-----|
| 25MPa      | 900μs | 184 | 292 | 832 | 1084 | 1704 | 976 | 1988 |
| 80MPa      | 900μs | 184 | 296 | 828 | 2048 | 2908 | 940 | 3004 |
| 135Mpa     | 1800μs | 170 | 264 | 776 | 2040 | 2778 | 688 | 3048 |
| 25MPa      | 900μs | 168 | 248 | 760 | 1020 | 1864 | 688 | 2244 |
| 80MPa      | 900μs | 184 | 248 | 768 | 2036 | 2760 | 700 | 2828 |
| 135Mpa     | 1800μs | 164 | 248 | 768 | 2036 | 2760 | 700 | 2828 |

Based on the times in table 1, determined from experiments, are calculated: the delay $\Delta t_1$ of injection relative to the beginning of the control signal; the delay of the injection end $\Delta t_2$ relative to the end of the control pulse; injection duration $t_{inj}$, figure 3. The results of the calculation are shown in table 2.

Table 2. Delay times and injection duration.

| Delay and injection times (μs) | $\Delta t_1$ | $\Delta t_2$ | $t_{inj}$ | $t_p$ |
|-------------------------------|-------------|-------------|-----------|------|
| Injector 1 0445110259         |             |             |           |      |
| 25MPa                        | 900μs       | 292         | 804       | 1412 |
| 1800μs                       | 296         | 1108        | 2612      | 2548 |
| 80MPa                        | 900μs       | 266         | 1004      | 1638 |
| 1800μs                       | 264         | 978         | 2514      | 2360 |
| 135Mpa                       | 900μs       | 248         | 964       | 1616 |
| 1800μs                       | 248         | 960         | 2512      | 2388 |
| Injector 2 0445110044         |             |             |           |      |
| 25MPa                        | 900μs       | 272         | 768       | 1396 |
| 1800μs                       | 272         | 1112        | 2640      | 2520 |
| 80MPa                        | 900μs       | 232         | 941       | 1609 |
| 1800μs                       | 233         | 836         | 2403      | 2152 |
| 135Mpa                       | 900μs       | 236         | 892       | 1556 |
| 1800μs                       | 228         | 880         | 2452      | 2280 |

The last column in table 2 shows the duration $t_p$ of the fuel pressure drop in front of the injector as a result of the fuel injection. It is obtained as the difference between the times at points (7) and (6), figure 4, figure 5 and figure 6. This time $t_p$ can be used to assess the correctness of determining the injection duration.
3. Analysis of the Experimental Results

In order to assess the adequacy of the shown method, the influence of the injection pressure and the control pulse duration on the delay times $\Delta t_1$, $\Delta t_2$ and the injection duration $t_{inj}$ was evaluated. The presence of a logical relationship between the specified parameters would confirm the correctness of the method. Figure 7 shows the effect of the injection pressure on the delay at different control pulse durations for the two injectors.

![Graph](image-url)

**Figure 7.** Delay of start and end of injection depending on pressure.

The delay of the start of injection $\Delta t_1$ relative to the beginning of the control pulse is in the range of 232-296 μs.

The delay of the start of injection is not affected by the control pulse duration and decreases with increasing injection pressure by 13-16%. This is due to the increased reaction speed of the system with increasing pressure in it.

The injector with shorter length and lower mass of the control piston has less delay 20-30 μs, which is 8-12%. This is due to the lower inertia of the system.

The delay of the end of the fuel supply $\Delta t_2$ relative to the end of the control pulse is significant 800-1100 μs. Here, the effect of pressure and injection duration are mixed and further studies are needed for an accurate assessment. However, in all cases the injector with less mass of the control piston has shorter delays.

The dependences shown in figure 7 are determined by the values of the different times using the presented method. Certain influences and dependencies have repeatability and logical explanation.

Figure 8 shows how the injection duration is affected by the change in injection pressure for both injectors.

It can be seen that with different control signal durations, the injection pressure affects the injection duration differently. This is a result of the joint influence of various factors: wave phenomena in the dense medium of the fuel and the deformations of the elements of the fuel system under the influence of high pressure; combination of the action of inertial, spring and pressure forces on the movable elements in the injector. In any case, the injector with lower mass of its moving parts has a shorter injection time, which is mainly due to the shorter delay at the end of the injection.
The interval in which there is a pressure drop is delayed in relation to the movement of the needle and the injection interval. This is completely natural, given the delayed reaction of the pressure wave in the hydraulic system. Therefore, the time values $t_p$ of the pressure drop in front of the injector cannot be used directly to determine the injection duration $t_{inj}$. Nevertheless, the close values of the two times can be noted. The nature of the change of the two times is very close, figure 8, in both injectors.

4. Conclusion

The proposed method for determination of injection phases gives adequate results and can be used for research purposes. It is characterized by simplicity and ease in building the experimental setup. No design changes are required to the tested injectors.

The duration of the injection is much longer than the duration of the control pulse, the difference between them is in the range of 500-800µs and is influenced by the duration of the pulse and the injection pressure.

The determined influences of the injection pressure and the mass of the movable elements in the injector on the injection delay and duration have a logical character and confirm the non-random nature of the times determined by the presented method.

5. References

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Acknowledgments

This work was completed thanks to the generous cooperation of Diesel Service Varna, which provided its equipment, benches and injectors for research.