A METHOD OF CONTROL OF INJECTION RATE SHAPE BY ACTING UPON ELECTROMAGNETIC CONTROL VALVE OF COMMON RAIL INJECTOR

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ABSTRACT

For effective decrease of nitrogen oxide content in exhaust gases and noise level of diesel engines, a multistage fuel injection combined with control of the front edge shape of the main injection is used. In the Moscow Automobile and Road Construction State Technical University (MADI), a method of control of injection rate shape using an electric impulse was proposed which is applied to the electromagnet of the control valve of the injector of the Common Rail fuel system. The impulse consists of a primary, main and following them additional stages. Duration of the primary impulse defines the amplitude of the initial stage of the injection diagram, and the interval between the primary and main impulses – the amplitude between the initial and the main stages of the injection rate. The interval between the main and additional electric impulses is adjusted so that the post-injection stage of the injection rate should start after the end of the main stage but without any interval between them.

Keywords: diesel Common Rail fuel system, Common Rail injector, injection rate shaping, electric control impulse, testing of diesel fuel system

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1. INTRODUCTION

Today, for all engines, ecological standards are set that differ significantly both by the quantity of limited toxic components and by their maximum permissible levels depending on the engine destination. In addition, ecological standards permanently become more stringent.

This stipulates the need for perfection of fuel systems of diesel engines, in particular the most popular of them – Common Rail (CR) systems.

The main fields of the development of Common Rail systems – raising injection pressure [1-3] and assuring multiple injection with desired shape of the front edge of the injection rate of the main injection [4, 5]. This is the dependence of mass speed of fuel supply $dQ/d\tau$ from the nozzle of the Common Rail injector (CRI) on time $\tau$.

The front edge control is needed for a smoother increase of pressure in the diesel engine cylinder which assures the decrease of noise and mechanical stress of the engine parts, decrease of NOx emissions (Figure 1).

![Figure 1](image-url) Injection rate of the Common Rail fuel supply system: 1, 2 – pre-injections for decrease of NOx emissions and lowering noise level; 3, 4 – main injection; 5 – post-injection for intensification of oxidation of incomplete combustion products of fuel in the cylinder at the final stages of the working cycle, as well as in the oxidation catalyst; 6, 7, 8 – a series of post-injections for regeneration of the particle filter and raising the catalyst temperature; a – square-type injection rate shape; b – ramp-type injection rate shape; c – boot-type injection rate shape

The following basic methods of deliberate impact on the injection rate shape $dQ/d\tau = f(\tau)$ are highlighted:

- Using wave processes in the fuel accumulator and CRI,
- Control of several valves of the CRI,
- Control of one valve of the CRI.

A wave adjustment of the CR system elements [6] requires balancing of the volumes of cavities of the CRI and fuel accumulator, the lengths of the fuel lines with the engine operation mode. The present method of controlling the front edge is implemented for stationary energy plants operating in a narrow range of modes and not requiring expensive technical solutions.

Control of the injection pressure by several valves mounted in the CRI [4], is effected by increasing or decreasing its value during the fuel injection process in relation to pressure in the fuel accumulator.

Increase of pressure in the control chamber of the CRI which is higher than the pressure in the accumulator is achieved by fuel pressure amplifier (multiplicator) and matching the operation of its control valve with the valve controlling displacement of the needle valve.

Despite the advantage of the CR fuel system controlled by several valves in the CRI in providing the desired shape of the front edge of the injection rate (any shape of the front edge...
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of the main injection of the injection rate demonstrated in Figure 1: a, b, c is possible) they have a number of serious drawbacks:

- Complicated design and as a consequence – high requirements for manufacturing equipment for attaining the required reliability,
- High price compared with traditional CR systems,
- No full compatibility with the existing CR systems (the presence of a great number of additional parts compared with a traditional CRI injector results either in increasing the size of the injector body, either in the use of additional external devices which should be taken into account when locating the CR system elements on the engine) – adaptation of engine parts is required.

It is planned to solve these problems by sophistication of the algorithm of the control system of the CRI having one electromagnet valve \([7, 8]\). The advantage of this method is preservation of the traditional design of the CRI.

Control of the shape of the curve \(dQ/d\tau = f(\tau)\) using an electric impulse offered by MADI is aimed at the elimination of one of the drawbacks of the indicated method – limited opportunities of acting upon the front edge of the injection rate shape imposed by specific features of the design of the CRI.

2. DESCRIPTION OF THE PROPOSED METHOD OF THE INJECTION RATE SHAPING

The method proposed is illustrated by the results (Figures 2…4), obtained with the aid of the modeling complex developed in MADI for computer modeling of working processes of the CR systems.

![Diagram](image)

**Figure 2** The force of an electric magnet formed by two primary and one basic control impulses
Electric impulses supplied from the electronic control module to the electromagnet valve of the CRI consist of two and more primary impulses and one main impulse (Figure 2).

Duration of the first primary control impulse determines the amplitude of the front edge of the first stage of the boot-type injection rate shape (Figure 3).

The intervals between the control impulses in case of a multiple injection are selected so that to assure a boot-type of injection rate shape with the desired value of oscillations of the first stage of the boot-type fuel injection rate shape (Figure 4).

The amplitude of the first stage of $dQ/d\tau = f(\tau)$ amounts to 20 … 80 % of the amplitude of its second stage (Figure 4). Oscillations of the amplitude of the first stage of $dQ/d\tau = f(\tau)$ do not exceed 10 … 15 % of the amplitude of the second stage (Figure 4).
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When supplying an electric impulse from the electronic control module, the force $F$ of the electromagnet overcomes the force of the spring pressing the control valve to its seat and it opens. The fuel from the control chamber enters the drain line and the pressure in it drops. A pressure drop between the injector nozzle volume close to the needle valve and pressure in the control chamber originates. The needle valve lifts and fuel injection via the nozzle holes takes place. As the result of the injection, a curve $dQ/d\tau = f(\tau)$ is formed which is presented in Figure 4.

The reviewed method of injection rate shaping is applicable in cases when the control impulse consists of:

- Primary and main impulses (Figures 5 and 6),
- Main and additional impulses, following the main impulse (Figure 7),
- Primary, main and post impulses (Figure 8).

![Figure 5 Results of computer modeling of the influence of the time of the main electric impulse start on the control valve rise $h_v$, needle valve lift $h_{nv}$ of the Common Rail injector and on the injector rate shaping](image)

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Figure 6 Results of computer modeling of the influence of variation of the duration of the primary electric impulse on the control valve lift $h_c$, needle valve lift $h_n$, of the Common Rail injector and on the injector rate shaping.
Figure 7 Results of computer modeling of the influence of the variation of duration of the additional electric impulse on the control valve lift $h_v$, needle valve lift $h_{nv}$ of the Common Rail injector and on the injector rate shaping.
Duration of the primary impulse defines the amplitude of the primary stage of the injection rate (Figure 6). The amplitude between the primary and the main stages of the curve $\frac{dQ}{d\tau} = f(\tau)$ depends on the interval between the primary and the main impulses.

The interval between the main and additional impulses is matched so that the additional part of the injection rate starts immediately after the end of the main stage (Figure 7).

If the control electric impulse consists of the primary and main impulses, duration of the primary impulse (Figure 6) determines the amplitude of the primary stage of the diagram $\frac{dQ}{d\tau} = f(\tau)$, and the interval between the primary and main impulses (Figure 5) – the amplitude between the primary and main stages of the injection rate curve.

The interval between the control electric impulses and amplitude of the main impulse are selected so that the main stage of the injection rate starts immediately after termination of the primary stage (Figures 5 and 6).

If the control electric impulse consists of the primary and additional parts, the interval between these control impulses is selected so that the additional stage of the curve $\frac{dQ}{d\tau} = f(\tau)$ starts immediately after the end of the main stage (Figure 7).

If the control electric impulse consists of the primary, main and following it additional impulses, the duration of the primary impulse determines the amplitude of the primary stage of the diagram $\frac{dQ}{d\tau} = f(\tau)$, and the interval between the primary and the main impulses – the amplitude between the primary and the main stages of the injection rate.

The interval between the main and the additional electric impulses is selected so that the additional stage of the injection rate starts immediately after the end of the main stage (Figure 8).
3. EXPERIMENTAL SETUP

Estimation of the injection rate shape was carried out at the testing complex for investigations of working processes of diesel engines and their fuel systems with electronic control.

Diagrams $\frac{dQ}{d\tau} = f(\tau)$ were registered at different operation modes of the CRI 4 (Figure 9) using the stand forming a part of the testing complex for investigations of the working processes of diesel engines and their fuel systems with electronic control of direct action and accumulator type.

![Research stand for registration of injection rate diagrams of Common Rail injectors](image1)

**Figure 9** Research stand for registration of injection rate diagrams of Common Rail injectors: 1 – AC electric motor; 2 – high pressure fuel pump; 3 – digital oscillograph; 4 – Common Rail injector; 5 – engine speed governor; 6 – bed plate

The stand consists of a bed plate 6 on which the high pressure fuel pump 2 driven by the electric motor 1 (11 kW power, maximal speed 1445 rpm) with the speed governor 5 is mounted.

For registration of $\frac{dQ}{d\tau} = f(\tau)$, a special registration camera 1 (Figure 10) with internal cavity volume of about 1000 mm$^3$ is used. The camera is filled with the diesel fuel and the injector nozzle of the CRI 2 is mounted on it. The drain hole of the camera has a jet which creates an injection backpressure in it.

![Common Rail injector mounted on a test bench for registration of injection rate diagrams](image2)

**Figure 10** Common Rail injector mounted on a test bench for registration of injection rate diagrams: 1 – chamber for registration of the injection rate diagram; 2 – Common Rail injector; 3 – fuel accumulator
Cross section of the jet was selected so that the pressure in the chamber was 5 ... 6 MPa (pressure corresponding to the backpressure of fuel injection when the fuel is injected into the combustion chamber of a diesel engine).

From the opposite side of the channel with the jet, a channel was drilled for mounting a strain sensor DMP 330L registering pressure variation in the chamber. Its precision is 0.5% of the measured pressure range 0…25 MPa.

For pressure stabilization in the CRI investigated, an external fuel accumulator 3 is connected to it.

Fuel pressure variation \( p_{ch} \) in chamber 1 (Figure 10) is registered by the AKIP 4126/2 type digital oscillograph 3 (Figure 9) AKIP 4126/2.

Then processing of the pressure \( p_{ch} \) variation curve was processed by a digital filter of Savitskiy-Goley [9]. This is required for filtering electromagnet interferences and increasing stability of calculation of derivative \( dp_{ch}/d\tau \).

Then using the volume balance equation (1) an estimation of the injection rate is carried out for the chamber cavity:

\[
q_{\text{CRI}} = (\mu f) \sqrt{\frac{2}{\rho_{\text{avg}}} (p_{ch} - p_{dr}) - \alpha V_{ch} \frac{dp_{ch}}{d\tau}}
\]  

(1)

where: \( q_{\text{CRI}} \) – fuel flow via injector nozzle holes [ml/ms], \((\mu f)\) – effective cross-section of the jet at the outlet of the chamber, \( p_{ch} \) – pressure into the chamber [Pa], \( p_{dr} \) – pressure at the outlet of the chamber [Pa], \( V_{ch} \) – chamber cavity volume [mm\(^3\)], \( \alpha \) – compressibility [Pa\(^{-1}\)].

The compressibility coefficient \( \alpha \) is calculated by formula [10]:

\[
a_0 = [1053 + 4.7 \cdot (\rho_{\text{amb}} - 850) - 7.82 \cdot (t - 20)] \cdot 10^{-6}, \text{ Pa}
\]

(2)

\[
a_1 = 10.497 + 0.0141(t - 20), \text{ Pa}^{-2}, \quad a_2 = 0.9 \cdot 10^{-10}, \text{ Pa}^{-3}
\]

\[
\alpha = (a_0 + a_1 p + a_2 p^2)^{-1}, \text{ Pa}^{-1}
\]

(3)

where \( a_0, a_1, a_2 \) – empirical coefficients; \( \rho_{\text{amb}} \) – fuel density at 20°C and atmospheric pressure [kg/m\(^3\)]; \( t \) – fuel temperature [°C]; \( p \) – pressure at which the compressibility was calculated [Pa].

Pressure at the outlet from the chamber is maintained constant by the non-return valve. The valve characteristic has hysteresis because the valve rim pressure is a bit higher than the closing pressure which should be taken into account when making calculations by formula (1).

The cross section value \((\mu f)\) may be determined by the method of successive iterations in which the following sequence of actions is realized.

1. The value of injection quantity \( Q_{\text{CRI}} \) is determined by one of traditional methods, for example by weighing a portion of fuel collected during control number of cycles.
2. The value of \( q_{\text{CRI}} \) for \((\mu f)\) is calculated where the cross section of the jet \( f \) is calculated on the basis of its diameter \( d \), and \( \mu \) is assigned equal 0.7.

3. The injection quantity is calculated by formula: 
\[
Q_{\text{CRI}} = \int_0^t q_{\text{sep}} d\tau.
\]

4. If the difference of \( Q_{\text{CRI}} \), determined in item 1 and in item 3 is more than 2.5%, one should return to item 2 having corrected \( \mu \).
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Working with formula (1), one should take into account that the fuel consumption $q_{CRI}$ is determined in [ml/ms]. To recalculate it into mass flow, one should define the fuel density $\rho_f$ [kg/m$^3$]. Taking assumption of the equality of $\rho_f$ in the chamber cavity and at the outlet from it and neglecting the warming of fuel during its throttling in the chamber jet, to determine $\rho_f$, it is enough to measure the temperature of fuel drained into the chamber and determine the dependence $\rho_f$ of the fuel temperature.

4. EXPERIMENTAL CHECK OF THE METHOD OF INJECTION RATE SHAPING BY ACTING UPON IMPULSES OF THE CURRENT

To confirm the efficiency of the proposed method of injection rate shaping of the CRI (8 atomization holes 0.32 mm in diameter), operation modes presented in Table 1 were used. During testing at all the modes, the pressure 100 MPa was maintained in the fuel accumulator 3 (Figure 10).

<table>
<thead>
<tr>
<th>Mode number</th>
<th>$\tau_{imp1}$ [ms]</th>
<th>$\Delta\tau_{imp1-2}$ [ms]</th>
<th>$\tau_{imp2}$ [ms]</th>
<th>$\Delta\tau_{imp2-3}$ [ms]</th>
<th>$\tau_{imp3}$ [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.45</td>
<td>1.1</td>
<td>0.8</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>0.45</td>
<td>0.4</td>
<td>0.8</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>3</td>
<td>0.45</td>
<td>1.1</td>
<td>0.8</td>
<td>2.4</td>
<td>0.5</td>
</tr>
<tr>
<td>4</td>
<td>0.45</td>
<td>0.6</td>
<td>0.5</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>5</td>
<td>0.45</td>
<td>0.28</td>
<td>0.41</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>6</td>
<td>0.34</td>
<td>0.2</td>
<td>0.34</td>
<td>0.32</td>
<td>0.5</td>
</tr>
<tr>
<td>7</td>
<td>0.34</td>
<td>0.15</td>
<td>0.41</td>
<td>0.26</td>
<td>0.5</td>
</tr>
</tbody>
</table>

The following designations are used in Table 1:

$\Delta\tau_{imp1-2}$ – interval between the first and the second control electric impulses;

$\Delta\tau_{imp2-3}$ – interval between the second and the third impulses;

$\tau_{imp1}$, $\tau_{imp2}$, $\tau_{imp3}$ – duration of the first, seconds and the third control electric impulses, correspondingly.

The modes 1 and 2 correspond to supply on the electromagnet of the CRI control valve of the primary (duration $\tau_{imp1}$) and main (duration $\tau_{imp2}$) electric impulses.

At the mode 3, the CRI control valve is supplied with the primary (duration $\tau_{imp1}$), main (duration $\tau_{imp2}$) and following it additional ($\tau_{imp3}$) electric impulses.

The modes 4 … 7 correspond to supplying of two primary ($\tau_{imp1}$, $\tau_{imp2}$) and main ($\tau_{imp3}$) electric impulses.

The obtained integral injection diagrams $Q = f(\tau)$ and injection rate $dQ/d\tau = f(\tau)$ are shown in Figure 11. The diagram $Q = f(\tau)$ determines the mass of fuel supplied from the injection nozzle of the CRI from the injection start to the current time $\tau$.

Table 2 shows the values of the injection quantity $Q_{iq}$ and the fuel quantity supplied during every injection in case of a multiple injection, where $Q_1$ – fuel quantity supplied during the first injection at multiple injection; $Q_2$ – fuel quantity supplied during the second injection; $Q_3$ – fuel quantity supplied during the third injection.
Table 2 Fuel quantities and the amount of fuel supplied by the Common Rail injector during every injection in case of a multiple injection

<table>
<thead>
<tr>
<th>Mode number</th>
<th>( Q_1 ) [mg]</th>
<th>( Q_2 ) [mg]</th>
<th>( Q_3 ) [mg]</th>
<th>( Q_4 ) [mg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>42.7</td>
<td>136.6</td>
<td>—</td>
<td>179.3</td>
</tr>
<tr>
<td>2</td>
<td>42.7</td>
<td>138.3</td>
<td>—</td>
<td>181.0</td>
</tr>
<tr>
<td>3</td>
<td>40.1</td>
<td>127.4</td>
<td>43.6</td>
<td>211.1</td>
</tr>
<tr>
<td>4</td>
<td>41.1</td>
<td>28.9</td>
<td>139.4</td>
<td>209.4</td>
</tr>
<tr>
<td>5*</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>298.7</td>
</tr>
<tr>
<td>6*</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>169.1</td>
</tr>
<tr>
<td>7*</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>224.0</td>
</tr>
</tbody>
</table>

* – injection is considered to be single.

Comparing the values \( Q_1 \) and \( Q_{iq} \) one can see that for the modes 1…4, the value of primary injected fuel portion does not exceed 20 … 25 %.

The results presented characterize the opportunities of the method both for ensuring the multiple injection (Figure 11,a…d) and injection rate shaping (Figure 11,e…g).

Figure 11,b shows the diagram \( dQ/d\tau = f(\tau) \) in which the main injection follows immediately the pre-injection. The similar diagram was obtained during modelling and it is presented in Figure 5 (dotted line).

Diagrams \( dQ/d\tau = f(\tau) \) in Figure 11,e…g were obtained by selecting intervals between the control impulses of current during the three-stage injection.
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As was found in the course of modelling (Figure 6), duration of the first impulse determines the initial period of the CRI needle valve lift. The similar result was obtained experimentally. At mode 5 (Figure 11,e) duration of the primary signal was 0.45 ms. At that, the magnitude of the first peak of the injection rate was 62.6 mg/ms against 44 mg/ms at modes 6, 7 (Figure 11,f, g), where \( \tau_{\text{imp}1} = 0.34 \) ms.

Reduction of \( \Delta \tau_{\text{imp}1-2} \) from 0.28 ms (mode 5) to 0.15 ms (mode 7) stipulated reduction of the fall-off value of the diagram \( \frac{dQ}{d\tau} = f(\tau) \) after the first peak till its full disappearance (Figure 11,g).

Parameters \( \tau_{\text{imp}2} \) and \( \Delta \tau_{\text{imp}2-3} \) have the same influence on the shape of the diagram \( \frac{dQ}{d\tau} = f(\tau) \).

From comparison injection rate shapes (Figures 11,f…g) and \( Q_{\text{iq}} \) values (Table 2) it is seen that the control of the front edge of the \( \frac{dQ}{d\tau} = f(\tau) \) should take into account the required injection quantity. Evidently in case of insufficient response speed of the CRI drive and low control accuracy, it will be difficult to get the desired shape of \( \frac{dQ}{d\tau} = f(\tau) \) at assigned value of \( Q_{\text{iq}} \). In addition, the wave actions which originated in the CRI after the primary fuel injection may influence the consequent injection [11].

Figure 11 Injection rate \( \frac{dQ}{d\tau} \) and integral injection diagram \( Q \) of the Common Rail injector: \( \tau \) – time; 

a – mode 1; b – mode 2; c – mode 3; d – mode 4; e – mode 5; f – mode 6; g – mode 7
5. CONCLUSIONS

1. A method of injection rate shaping by electric impulse which is applied to the electromagnet of the control valve of the Common Rail injector of the Common Rail system was proposed.

2. Selecting duration of the electric control impulses and intervals between them one can obtain the desired shape of the injection rate shape from boot-type to ramp-type.

3. Variation of the injection rate shape by electric control impulses requires balancing with the assigned values of injection quantity.

4. Application of the method of injection rate shaping using acting upon electric impulses is limited by the dynamics of the needle valve, response speed of the control valve and wave actions in the injector.

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