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Detailed dynamic modeling of common rail piezo injector  

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Abstract  

A mathematical model of Bosch 3rd generation Common Rail fuel injection system with piezoelectric injector has been created. The numerical calculations for third different accumulator pressures (30, 80 and 160 MPa) and third energizing times ET (0.5, 1 and 2 ms) have been carried out. The results of calculations of total injected mass per cycle have been compared with the experiment with good agreement. The maximum error for ET=0.5 ms is 10.4% and for ET≥1 ms is less than 5 %.

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Keywords: Fuel injection system; Common rail; Piezo injector; Mathematical model.

1. Introduction  

Modern diesel fuel injection systems (FIS) are characterized by complex dynamic hydromechanical processes. Also, an electromagnetic processes on drives of injector's control valves significant influence on fuel injection process.

Optimization of developed fuel injection system design has an important role [1], then, an adequate mathematical modeling, that allows fast and flexible change of varying parameters and get simulation results in optimization criteria form, is very actual.

Now, one of the most perfect of FIS is common rail fuel injection system with piezoelectric indirect-acting injector.

This paper is devoted to modeling of common rail piezo injector from Bosch.

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2. Mathematical modeling

2.1. Bosch Common Rail piezo injector

The design of a piezoelectric injector essentially differs from hydraulic injectors of the previous generations besides that the electromagnetic operating valve has been replaced with the piezoelectric. Developers have refused the locking piston, thereby having excluded the mechanical forces operating on a needle and having reduced moving weights. The management chamber is directly over a needle that, in a compartment with speed of operation of a piezoelement and reduction of moving weights, allows to lower a delay of lifting of a needle to 0.15 ms [2]. The principle of the injector working described in detail in [2-7].

2.2. Mathematical model

For modeling of hydromechanical processes the Astakhov-Golubkov method was used [8,9]. This method consists of a solution of unsteady fuel flow in high pressure line problem by D’Alembert method with boundary conditions in form of volume or mass balance.

The simulation scheme of piezo injector is presented in Fig. 1.

Mass balance equation (for control chamber as an example):

\[
\frac{dp_3(t)}{dt} = \frac{\frac{G_{13}}{\rho_3} - \frac{G_{34}}{\rho_3} + \frac{A_3}{V_3} \frac{dx_n(t)}{dt}}{B_3},
\]

where \( t \) - time; \( p_3 \) - pressure in chamber 3 (control chamber) (see Fig. 1); \( B \) - bulk modulus of fuel; \( \rho_3 \) - current fuel density in chamber 3; \( V_3 \) - initial volume of chamber 3; \( A_3 \) - geometrical area of area 3; \( x_n \) - current lift of needle; \( \sigma_{13} = \text{sign}(p_1 - p_3) \); \( \sigma_{34} = \text{sign}(p_3 - p_4) \); \( G \) - fuel mass flow through orifice, for example:

\[
G_{13} = C_{d13} A_{13} \sqrt{p_1(p_1 - p_3)},
\]

where \( C_{d13} \) - discharge coefficient of orifice 13; \( A_{13} \) - cross-sectional area of orifice 13.

For solution of unsteady fuel flow in high pressure line problem D’Alembert method was used [8,9]. For example, equations for line 1 is written as:

- for inlet:

\[
\begin{align*}
\left\{ p_0 + F_1(t) - W_1(t) e^{-\frac{L_{\text{line}1}}{a}} \right\} &= P_{A1}; \\
\left\{ \frac{1}{a \rho} \left[ F_1(t) + W_1(t) e^{-\frac{L_{\text{line}1}}{a}} \right] \right\} &= u_{\text{lin}};
\end{align*}
\]

- for outlet:
where \( p_0 \) - initial pressure in high pressure line; \( P_A \) - pressure in rail; \( F, W \) - direct and backward pressure waves in high pressure lines respectively; \( A_{line1} \) - cross-sectional area of line 1; \( a \) - fuel speed of sound; \( \rho \) - fuel density; \( L_{line1} \) - length of line 1; \( k \) - friction factor.

Discharge coefficients of orifices was determined by using ANSYS CFX software taking into account the flow regime and cavitation phenomenon [11].

The mathematical model was realised by using of Matlab/Simulink software [12]. The dynamic model of piezoelectric actuator was created as a subsystem in the Simulink environment by using the U. Mezon's thermodynamic condition equations [13].
3. Results of modeling and discussion

For check of adequacy of mathematical model comparison of results of calculation with experiment has been made. Experimental data are taken [3] from work and represent sizes of total injected fuel mass cyclic giving of fuel for three levels of pressure in the accumulator (300, 800 and 1600 bar) and three values of energizing time ET: 0.5; 1 and 2 ms. Results of comparison are presented in Table 1.

Table 1. Comparison results of calculation of injected mass with experiment.

| ET (ms) | 300 (bar) | Calculation | Experiment | 800 (bar) | Calculation | Experiment | 1600 (bar) | Calculation | Experiment |
|---------|-----------|-------------|------------|-----------|-------------|------------|------------|-------------|------------|
| 0.5     | 5.85      | 5.3         | 16.33      | 17.3      | 36.47       | 33.8       |
| 1       | 19.50     | 20.3        | 52.49      | 51.8      | 86.36       | 84.8       |
| 2       | 47.02     | 47.4        | 96.45      | 96.1      | 134.71      | 134.0      |

Maximal error for ET=0.5 ms is 10.4% and for ET≥1 ms - less than 5%.

Feature of the given injector is high lifting of a needle - to 0.9 mm [14], unlike other injectors where courses do not exceed 0.2-0.3 mm [15,16]. Such injector is called ballistic injector [17].

So high lifts of a needle have lacks:

- negatively affects a resource of a spray [18];
- for decrease in fluctuations of a needle and accuracy increase its positioning is necessary to carry out the powerful directing;
- accuracy of dispensing owing to high duration of uncontrollable sites of lifting and needle landing decreases;
- occurrence nonmonotonicity on schedules of dependence of cyclic giving from duration of an operating impulse.

Sites nonmonotonicity on dependence of cyclic giving on duration of an operating impulse at pressure in 800, 1200 and 1600 bar are shown on Fig. 2. At pressure in 300 bar such site is not present, this results from the fact that the needle at such pressure and duration of an operating impulse does not reach against the stop.

On Fig. 2 on the increased fragment of a site nonmonotonicity it is visible that at ET=0.89 ms giving more than at longer ET=0.905 ms, accordingly 82.9 and 81.8 mg.

On Fig. 3 are shown needle lifts, valve lifts, injected masses and injected rates history lines for ET=0.89 and 0.905 ms.
At ET=0.89 ms the needle does not reach against the stop, therefore for change of a direction of its movement it is necessary for more time to extinguish its inertia. At ET=0.905 ms the needle reaches against the stop, its kinetic energy at blow is transferred to an emphasis owing to what, the needle begins movement downwards earlier. However so big courses of a needle have also advantages:

- owing to high lifts of a needle at injection decreases choking fuel under a needle thanks to what pressure of injection increases;
- work ballistic injector assumes absence of a contact of a needle of an emphasis, deterioration of a shaft of a needle therefore decreases;
- ballistic injector in comparison with conventional injector spends fuel for management less, as at identical ET to a needle ballistic injector it is necessary for more time for being closed and consequently will be more injected fuel, thus fuel consumption on the managements, defined ET, it will be identical.

4. Conclusions

Common Rail piezo injector has been studied in this paper and conclusions are obtained as follows:
1. The mathematical model of hydrodynamic processes of fuel system Common Rail of firm Bosch of 3 generations with a piezoelectric injector which can be used for studying and optimization of fuel supply systems of the given type.
2. Comparison of results of calculations with experiment largely changes of pressure in the accumulator and duration of operating impulses has shown satisfactory coincidence that proves adequacy of the developed mathematical model.

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