Description of operation of fast-response solenoid actuator in diesel fuel system model

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Abstract. The performance of the fast-response solenoid actuator (FRSA) of engine fuel systems is characterized by the response time of less than 0.1 ms and the necessity to take into consideration the non-stationary peculiarities of mechanical, hydraulic, electrical and magnetic processes. Simple models for magnetization in static and dynamic hysteresis are used for this purpose. The experimental study of the FRSA performance within the electro-hydraulic injector of the Common Rail demonstrated an agreement between the computational and experimental results. The computation of the processes is not only a tool for analysis, but also a tool for design and optimization of the solenoid actuator of new engine fuels systems.

1. Introduction

There are many methods for describing magnetization curves, Jiles-Atherton model being popular [1]. However, these models require the choice of parameters; their results may not coincide with the experimental data. Therefore, the models are being continuously improved [2-5]. In addition, excessively sophisticated models are not recommended for the magnetically soft steels which are used in FRSA and Jiles-Atherton models are complex for introducing a large object into the model, such as a fuel system and an engine. FRSA are beginning to be widely used in energy and transport [6-7]. Adequate mathematical models with high computational speed are necessary for successful optimization of complex conjugate processes in modern fuel systems with a fuel pressure of more than 200 MPa and a response time of less than 100 µs [8]. For the models, simple but fairly accurate methods of describing static and dynamic hysteresis curves are required.

The authors propose using the method of computation of the magnetization curves and static hysteresis loops in a logarithmic form. For the initial magnetization line (for the O—A area, Figure 1):

\[
B = \begin{cases}
  a^{-1} \cdot \log^c \left[ H \cdot H_c^{-1} + 2 \right] & \text{for A-C area;} \\
  a^{-1} \cdot \log^c \left[ -H \cdot H_c^{-1} \right] & \text{for C-D area;} \\
  a^{-1} \cdot \log^c \left[ -H \cdot H_c^{-1} + 2 \right] & \text{for D-E area;} \\
  a^{-1} \cdot \log^c \left[ H \cdot H_c^{-1} \right] & \text{for E—A area.}
\end{cases}
\]

(1)

The C and a constants may be determined on the basis of scarce reference data. If the reference data on \( B_m(H_m), H_c, B_r \), are available, the C and a coefficients can be determined as follows:

\[
C = \left[ \log \left( B_m \cdot B_r^{-1} \right) \right], \quad a = b_m^{-1} \cdot \log^c \left( H_m \cdot H_c^{-1} \right)
\]

(2)
If the data on the material contain $B_m(H_m)$, $H_c$, $\mu_{\text{max}}$, then $\mu_{\text{max}}$ is referred to region $B \rightarrow 0$, for example, $\Delta H = 0.25H_c$. In such case:

$$\mu_{\text{max}} = \frac{dB}{dH} = \frac{B}{\Delta H} = \left[ \lg \left( \frac{\Delta H}{H_c} + 1 \right) \right] \cdot (a \cdot \Delta H)^{-1},$$

$$C = \left[ \lg \left( \frac{B_m}{\mu_{\text{max}} \cdot \Delta H} \right) \right] \cdot \left[ \lg \left( \frac{\lg(H_m \cdot H_c^{-1})}{\lg(\Delta H \cdot H_c^{-1} + 1)} \right) \right]^{-1}.$$  \hspace{1cm} (3)

$$a = B_m^{-1} \cdot \left[ \lg \left( H_m \cdot H_c^{-1} \right) \right]^{3}.$$ \hspace{1cm} (4)

The effectiveness of such approximation was proven by the comparison with the known experimental results and authors’ own experiments. It remains possible to use directly experimentally obtained dependence $B=f(H)$. However, using dependences (1)——(4) does not only accelerate counting but also increases the model universalization with respect to the materials for which such detailed information is not available. Approximation (1) provides an agreement with the experimental data for the steels that are used in FRSAs. The ignored curve bend in the event of the initial magnetization in the low value range of the flux density for the FRSA is minor due to a very short period of time and narrow hysteresis loop for the materials used. The applied values of $B_r$, $B_m(H_m)$, $H_c$, $\mu_{\text{max}}$ are ordinary reference parameters of the magnetic material and, therefore, relations (1)——(4) are convenient to be used.

For the FRSA with the response of 0.1 ms and less, specific nonstationary electromagnetic processes become relevant. They include a delayed FRSA action due to remagnetization of the material (magnetic viscosity) and the occurrence of eddy currents in the magnetic core. For the description of dynamic hysteresis, let us use the model of A.I. Kadochnikov [9]. It is a semi-empirical model characterized by a simple and adequate description of the most important nonstationary remagnetization effects. The effective field intensity with the same flux density exceeds the quasi-static one:

$$H_q(t) = H_a(B_{sw}) + \frac{1}{r} \exp(\alpha \frac{B_{sw}}{B_m}) \frac{dB_{sw}}{dt} + \frac{1}{3} \gamma_{\text{eq}} \frac{d}{dt} \delta := \frac{dB_{sw}}{dt},$$

where: $\delta$ - one-half thickness of the strip of the imbricated plates;
$H_a(B_{sw})$ - static remagnetization curve;
$r$ - magnetic viscosity coefficient characterizing dynamic remagnetizing;
$\alpha$ - parameter in the magnetic viscosity equation depending on the material and technology;
$\gamma_{\text{eq}} = \lambda \cdot \gamma$ - equivalent specific conductivity of the magnetic material;
$\gamma$ - real specific conductivity of the magnetic material;
$\lambda$ - characteristic of the domain structure fragmentation degree.

2. Simulation the FRSA operation

If the control system forms known voltage variation law $E_0=f(t)$, current $i$ is calculated on the basis of the models for the capacitor-fed electrical circuits and coil flux density available:
\[
\frac{di}{dt} = \frac{1}{L} \left[ E_0 - \frac{1}{C_0} \int idt - iR - \frac{i}{L} dL \right]
\]  

(6)

where: \( L \) - FRSA flux density; \( R \) - active resistance; \( C \) - capacity of pulse capacitor.

Magnetic flux \( \Phi \) is determined using the magnetic permeability and dependencies (1-5):

\[
\Phi = \frac{iw}{R_{cl} + R_{core}} = iw \cdot \left( \sum_{i=1}^{2} \frac{\delta_{i,j}}{S_{cl,j} \cdot \mu_f} + \sum_{j=1}^{k} \frac{l_{core,j}}{S_{core,j} \cdot \mu_{core}} \right)^{-1}
\]  

(7)

where: \( i \) - current; \( w \) - the number of the winding turns; \( \delta_{i,j} \) - operating clearance; \( \mu_f \) - fuel magnetic permeability; \( l_{core,j} \) - length along the magnetic core median line; \( S_{cl,j} \) - operating clearance cross-section area; \( S_{core,j} \) - magnetic core cross-section area.

The field intensity in the magnetic core and the force acting in the solenoid actuator are as follows:

\[
H = \Phi \cdot \left( S_{core} \cdot \mu_{core} \right)^{-1}; \quad F_{\text{FRSA}} = B_{cl}^2 \cdot S_{cl} \cdot (k_{scat})^{0.5} \cdot \mu_f^{-1}
\]  

(8)

The given FRSA model is used for the description of the forces acting on the control valve of the electro-hydraulic injectors of the Common Rail system. To examine the performance of the fuel system as a whole, the INJECT software is used [10].

3. Study of fast-response solenoid actuator performance within Common Rail injectors

After the identification based on the FRSA static characteristics, the comparison of the computational and experimental results with real-time changes of the control current was of interest to the authors.

Figure 2 shows the executive software window in which the dependences of the current and valve stroke are displayed when the experiment is carried out in the described test bed. There is a possibility of a random shaping of the control diagram for the current within their reasonable limitations.

The computation results of the FRSA processes were compared with the experimental data obtained in the test bed built by the Institute of Electronic Control of Power Plant at Harbin Engineering University. In the operating area of the test bed, the electro-hydraulic injector was installed. The test bed comprises an auxiliary hydraulic system with a high pressure pump, an electronic control system, and a system for measuring electrical, mechanical and hydraulic parameters.

Figure 3 shows the computational and experimental curves for the valve lifting with the FRSA anchor in the time function. The computations were performed when using both the ANSOFT Maxwell software and the described procedure, which is utilized in the INJECT software.

It is obvious that the results of the computations by means of two different software tools are practically identical. An advantage of the ANSOFT Maxwell software is the possibility of more accurate computation of the magnetic core of random geometry. On the other hand, the optimized geometry with constant cross-section along the length of the magnetic flux lines is of interest to the authors. The presetting of the magnetic core as the piecewise-constant areas in the INJECT software satisfies this condition.

However, the main advantage of the INJECT software is an opportunity to analyze the FRSA performance within the whole fuel system and its optimization for the improvement of the fuel injection quality. Therefore, the INJECT software becomes applicable for the optimization and design of the fuel system with the FRSA of the control valve.

Under the conditions of a fast non-stationary process, the FRSA behaviour has its own specific features. The magnetic resistance of the clearance and magnetic core depends on the instantaneous value of the valve position, instantaneous magnetic intensity, and magnetization rate. They include both the current change under an unspecified law and the field intensity considering the dynamic magnetic processes. For these reasons, unlike the resistance ratio under the static magnetization in the fast process, the picture is becoming more complex (Figure 4).
Figure 2. Window of software which controls test bed performance, showing results of current and valve stroke recording

**FRSA process with incomplete demagnetization of magnetic core.** The classical diagram of the FRSA control, which was shaped at the end of the last century, comprises the phase of the forced feed, the phase of anchor holding in operation condition, and a phase of demagnetization. The INJECT simulation of the process enables simple conclusions on the FRSA control law $U=f(t)$ or $I=f(t)$. Thus, after-burning can contribute to the rapid achievement of magnetic saturation and maximum force.

The final phase of the FRSA feed process is usually called demagnetization. The unconditional purpose of this stage is a fast current reduction to zero, and the cessation of magnetic core magnetization. However, in accordance with Figure 1, with zero magnetic field intensity, it is possible to keep the residual magnetization and slow down the closing of the control valve. The slow response of the valve and the injector prevents combustion in the diesel engine.

The description of the complete demagnetization may require all the formulas (1). The optimized process follows the hysteresis trajectory: O-A-C-O (Figure 1). For complete demagnetization, a very insignificant reduction of $H$, less than $(-H_c)$, is possible. However, if the $H$ reduction is limited to zero, it does not ensure remagnetization of the magnetic core and reduces the interval of the force changing from the initial status to the operating condition. A positive feature of incomplete demagnetization may be only the reduced losses of remagnetization and a faster response at the beginning of the process.

Figure 5 compares the FRSA behavior depending on a varied organization of the process completion: with complete demagnetization and without it (in both cases – with complete cessation of the current). The case of movement of the anchor with intensive motion damping from the side of the fuel spreading in the transverse direction along clearance 0.05...0.12 mm is considered. Even with limitation of the magnetization parameter changing rates, the hysteresis loop area considering the effective (dynamic) magnetic field intensity is higher than in the computation of the static hysteresis. It limits the fast response of the valve and the injector.

In a quasi-stationary analysis, the residual magnetization of the actuator leads to a decrease in the response time when the valve is opened, but slightly changes the closing time. In the Common Rail systems, it is especially important to reduce the closing time of the valve, so it is concluded that complete demagnetization is not necessary.

Within the consideration of the dynamic hysteresis, magnetization does not improve the FRSA reaction when the valve opens, but worsens when the valve closes. Therefore, the conclusion is drawn on the importance of complete demagnetization.

The consideration of the dynamic hysteresis has a strong impact on the final results related to the dynamics of the control valve movements (Figure 6). Namely, its response period increases both when
opening and closing (a – h curves). Therefore, it is necessary to take into the consideration the dynamic hysteresis for more accurate prediction of the valve dynamics.

It is especially important to consider the FRSA response delay when calculating a short process, namely, small cycle injections. The situation is characterized with short periods of time when the valve is stopped (in the maximum stroke position). In such event, the main process time is spent on valve lifting and lowering (Figure 6) and their motion computation error changes the process phase and fuel injection characteristics.

A special importance of the accurate computation of small injections is determined by such factors:
– well-known problems of small injection unevenness by the engine cylinders, engine vibrations, increased harmful emissions, and complete cylinder cutouts;
– extended use of multiple injections (Figure 2) with several small injections.

Thus, with respect to the diesel engine of the motor truck with the nominal cycle injection of 165 mg, the pilot fuel batch with the accumulator pressure of 100 MPa has to be 8 mg. In such event, the injector needle does not reach its stop position and the valve may reach or may not reach the stop position. The differences in the computations of the control valve motions with FRSA and fuel injection pressures within different methods of the computational organization in the INJECT software are demonstrated in Figure 7. It should be noted that the cycle injection dispersion in this instance was 168%: from 4.96 mg to 13.3 mg.

Therefore, to make the injector response quicker, it is preferable to organize a complete demagnetization of the magnetic core. In this case, at the end of the process, it is necessary to modulate the negative pulse of both voltage and current. At the same time, when calculating the FRSA, it is recommended that dynamic hysteresis be taken into account.

**Figure 4.** Magnetic resistances of FRSA magnetic core (c) and operating clearance (d) in fast fuel injection process

**Figure 5.** Boundaries of static (a) and dynamic hysteresis with organization of process without complete demagnetization (b) and with demagnetization (c)
Conclusions
- The proposed approximation methods for the static hysteresis curves ensure an agreement with the experimentally obtained curves for the steels used in the FRSA magnetic cores of the engine fuel equipment. At the same time, they are simple for the computations and are based on the parameters available in the reference books for the magnetic materials.

- The proposed integral method for the computation of the processes in the FRSA is much simpler than the calculations involving 3D-simulation, but it is responsible for a sufficient level of the end result accuracy. It is built in the INJECT software for computation of the fuel injection equipment and used for the computational analysis and optimization of the system as a whole.
- The dynamic hysteresis in the fast process of remagnetization in the FRSA is much wider than the quasi-static one. It slows down the process and impedes the actuator fast response. For these reasons, it is mandatory to consider the effects of eddy currents and magnetic viscosity when calculating and designing the FRSA of the engine fuel systems.
- It is especially important to consider the FRSA response delay when calculating a short process, namely, small cycle injections and multiple fuel injections.
- To make the FRSA response faster, it is desirable to provide a complete demagnetization of the magnetic core. To do this, it is not enough to bring the current to zero. A negative current pulse is necessary.
Acknowledgments
This work was supported by the Recruitment Program of High-End Foreign Experts of the State Administration of Foreign Experts Affairs (GDW20162300256), Fundamental Research Funds for the Central Universities (Grant No: HEUCFM170302) and China Marine Low Speed Engine Project: Phase 1 (Grant No: CDGC01-KT0302, CDGC01-KT0802).

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