MODELING AND CONTROL OF ELECTROMAGNETIC FUEL INJECTOR SOLENOID VALVE

Anmoldeep S. Sidhu¹ and S. S. Dhami²
¹²Mechanical Department, NITTTR Chdg., India

Abstract- Electronic Fuel Injectors (EFIs) are used to inject gasoline into the intake manifold in a very short interval of time i.e. in the range of milliseconds. This necessitates excellent dynamic response of the EFI valve stem. In the present work a control system is proposed, for optimizing the transient and steady state response of the EFI, with the objective of injecting precise amount of gasoline during the minuscule time available for fuel injection, particularly at high engine speeds. The values of the performance indicators obtained, indicate a highly suitable transient response with a settling time of less than 2ms. The values of rise time, settling time, overshoot and steady state error, obtained with the tuned controller for step inputs, covering the entire stroke of the armature, indicated optimum response of the EFI valve.

Keywords – Electronic Fuel Injector, Simulation, Modeling, optimize, armature

I. INTRODUCTION

Spark Ignition Engines are equipped with Multi Point Fuel Injection (MPFI) systems in which fuel is injected, using Electronic Fuel Injectors, into the intake manifold just upstream of each cylinder's intake valve. The rate of gasoline to be delivered, by the injector, during the intake stroke is a function of driving conditions which include throttle position, engine rpm, ambient conditions etc. Therefore the electronic fuel injectors must deliver accurate amount of gasoline within milliseconds. This necessitates precise control of electronic fuel injection. This is further necessitated by the stringent emission laws being applied, to control the increasing level of pollution due to the vehicular emissions. However, a limited literature, in the public domain, is available on design and operation of EFIs. Passarini and Pinotti [1] proposed a non-linear mathematical model of EFI. The model comprised of electrical subsystem and electro-mechanical subsystem. The output of this model was validated with experimental data. Passarini and Nakajima [2] proposed a method for investigating the effect of armature mass on the EFI performance. A range of armature mass was proposed for the given EFI, to improve the dynamic response which is very critical in view of the minuscule time available for fuel injection particularly at high engine speeds.

II. EFI VALVE CONSTRUCTION AND WORKING

An EFI injects fuel into the intake manifold during the intake stroke, mixing it with the intake air and forming a homogenous air-fuel (A/F) mixture, ready to be burned. A schematic diagram of EFI solenoid valve with its sectional view, clearly representing the armature, return spring, solenoid coil etc., is shown in Fig. 1.

An electrical signal is given to the terminals to energize the coil of EFI solenoid valve. This energized coil attracts the armature, pressed against the valve seat. The movement of the armature causes the valve to open and allow a metered quantity of fuel from fuel inlet, connected to fuel pipe, into the intake manifold. The moment the current signal stops and the coil gets de-energized, the valve is closed by the return spring, acting in the opposite direction [3]. It can be said that the quantity of fuel released is a function of the amount of opening which depends upon the magnitude of the current applied to the solenoid and the time for which injection takes place.
Figure 1 EFI valve schematic diagram

Most automobile engines operate at an average rpm of 2000 during cruising but at lower gears the engine rpm can go up to 7000 to 8000. In a four cylinder engine, the time for every intake stroke can thus range from 7.5ms to 60ms. The opening and closing time of EFI valve lies between 0.5 and 1ms. The ECU calculates the appropriate injection timing for each cylinder. The angle of rotation for intake valve opening ranges from 200° (low speed) to 250° (high speed) [4]. Taking 225° as the average angle of intake valve opening, the time for fuel injection at various rpms is given in the Table 1.

Table 1. Varying time of fuel injection

<table>
<thead>
<tr>
<th>RPM</th>
<th>Time for Fuel injection (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>37.50</td>
</tr>
<tr>
<td>2000</td>
<td>32.81</td>
</tr>
<tr>
<td>3000</td>
<td>28.22</td>
</tr>
<tr>
<td>4000</td>
<td>23.43</td>
</tr>
<tr>
<td>5000</td>
<td>18.75</td>
</tr>
<tr>
<td>6000</td>
<td>14.06</td>
</tr>
<tr>
<td>7000</td>
<td>9.37</td>
</tr>
<tr>
<td>8000</td>
<td>4.68</td>
</tr>
</tbody>
</table>

As the EFI has to operate in time period of milliseconds, its transient and steady state responses are critical for the accurate delivery of fuel. Response is affected by number of mechanical factors [2]. The collision of the armature at the ends of course, (also called armature rebound) significantly affects how much fuel is delivered by the EFI. Others important effects are the delays in effective opening and closing times which cause the EFI to be opened longer.

III. OBJECTIVE

In order to regulate the fuel to the intake manifold, the current supplied to the solenoid valve in injector has to be controlled for the optimum transient and steady state behavior of EFI. Therefore, an EFI control system is proposed in this work. For this purpose, an EFI valve stem movement was modeled. A virtual model was developed in the Simulink module of MATLAB and a PID controller was developed to control the EFI valve stem dynamics for regulating fuel injection.
IV. EFI VALVE MODELING

EFI valve modeling consists of an electrical subsystem and an electromechanical subsystem. [1]

4.1 EFI valve Electrical Subsystem

A solenoid control valve is the commanding element of the EFI system. A voltage signal (V) generates a current (i) in the coil while overcoming the resistance (R) and inductance (L) of the coil in the solenoid valve. The equation for generation of current in the coil according to the input voltage is as follows:

\[ L \frac{di}{dt} + iR = V \]  

(1)

Taking Laplace of (1):

\[ LsI(s) + RI(s) = V \]  

(2)

\[ I(s) = \frac{1}{Ls + R} V(s) \]  

(3)

4.2 EFI valve Electromechanical Subsystem

The current (i) applied to the coils of the control valve produces a force (fc), which acts on the armature thereby producing an armature displacement (x). The force (fc) acting on the armature may be expressed as:

\[ fc = Gi \]  

(4)

Where G is the coil force coefficient

i is the current applied to the valve coil
The relationship between the current applied to the solenoid coil and the resulting force acting on the armature is shown in Fig.3. [5]

Figure 2 magnetic force vs. current graph

The curve in Fig.2, as seen, is far from linear, particularly for low current values (duty). It should be remembered that solenoids not only have resistance, but also reactance. This parameter is responsible for a deviation from linearity at low duty factor signals at low mean currents (PWM signal). However, solenoid valve driven actuator is equipped with a return spring; to move the actuator from rest, the initial force must exceed a threshold, substantially higher than zero. Hence, by taking the curve as linear, the constant slope will give the value of coil force coefficient, G.

The parameters, which relate the armature displacement to the force acting on it, are the armature mass (m), the viscous friction coefficient (b) and the stiffness (k) of the springs. Thus the equation of motion for the armature can be written as:

\[ m \frac{d^2x}{dt^2} + b \frac{dx}{dt} + kx = f = Gi \]  

(5)

Where \( x \) is the armature displacement
\( \dot{x} \) is the armature velocity
\( \ddot{x} \) is the armature acceleration
\( m \) is the armature mass
\( b \) is the viscous friction coefficient
\( k \) is the spring stiffness coefficient

Taking Laplace of (5):

\[
ms^2X(s) + bsX(s) + kX(s) = F
\]

\[
X(s) = \frac{1}{ms^2 + bs + k} F(s)
\]

V. OPEN-LOOP RESPONSE OF SOLENOID VALVE LIFT ‘x’

By using (3), (4) and (7), the block diagram for the solenoid valve can be constructed as follows:

Combining the cascading blocks:

The armature displacement ‘x’ comes out to be:

\[
x = \frac{G}{Lm^3 + (Lb + Rm)s^2 + (Rb + Lb)s + Rk} V
\]

At the steady state:

\[
x = \frac{G}{Rk} V
\]

Accordingly, the steady state values of lift (displacement) with varying input voltage can be found. This has been tabulated in TABLE 2.

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Displacement(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.52</td>
</tr>
<tr>
<td>0.19</td>
<td>1</td>
</tr>
<tr>
<td>0.5</td>
<td>2.62</td>
</tr>
<tr>
<td>1</td>
<td>5.24</td>
</tr>
<tr>
<td>1.5</td>
<td>7.86</td>
</tr>
<tr>
<td>2</td>
<td>10.48</td>
</tr>
</tbody>
</table>

The simulations for the EFI response are run for a time period of 5ms since at higher engine rpm the available time of EFI operation is only 4.68ms (TABLE 1). The transient and steady state of the EFI armature for different input voltages (TABLE 2) are shown in Fig.3.

![Figure 3 open-loop response](image-url)
For all input voltages, the rise time of 2.1ms and settling time of 3.8ms is unacceptable since the operating time is usually between 1ms and 4.68ms (TABLE 1). The steady state value of the lift can be accurately measured, according to the given voltage signal (V), coil resistance (R), coil force coefficient (G) and spring stiffness coefficient (k). But this does not give us any control over the transient state.

To improve the transient response and attain desired steady state value as early as possible, a controller can be used which will regulate the voltage input to the solenoid as a function of positional error of the armature. For this there is need for a feedback mechanism. A closed-loop control model, generated in the MATLAB in the Simulink module [6][7], is shown in Fig.5.

![Simulink model of closed-loop solenoid valve](image)

**Figure 4 Simulink model of closed-loop solenoid valve**

Where \( x_r \) is the reference input
\( x - x_r \) is the error signal

**VI. SIMULATION OF THE WORKING OF EFI**

PID control algorithms are most common and tested algorithms for different working environments and purposes. The total displacement of armature of the EFI considered in the present work is 10mm. The simulations were carried out for an armature displacement of 1, 3, 5, 7.5 and 10mm. The simulation results for these reference inputs are shown in Fig. 5.

![Closed-loop response with default values of P, I and D](image)

**Figure 5 Closed-loop response with default values of P, I and D**

The armature response (shown in Fig.5), with default values of 1, 1 and 0 of Proportional(P), Integral(I) and Derivative(D) respectively, gives very undesirable results as compared to the reference inputs. MATLAB provides algorithms for optimizing the transient and steady state response. By applying these algorithms, the values of control parameters (P, I and D) obtained are:

\[
P = 427.8244 \\
I = 467363.982 \\
D = 0.092705
\]

The dynamic response with the above values is shown in Fig.6.
To further understand the response at the given reference values, the dynamic characteristics of the closed-loop response has been tabulated in TABLE 3.

**Table 3. Characteristics of a closed-loop response**

<table>
<thead>
<tr>
<th>Reference input (mm)</th>
<th>Rise Time (ms)</th>
<th>Settling Time (ms)</th>
<th>Settling Min (mm)</th>
<th>Settling Max (mm)</th>
<th>Overshoot (%)</th>
<th>Undershoot (%)</th>
<th>Peak (mm)</th>
<th>Peak time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.69</td>
<td>1.8</td>
<td>.9</td>
<td>1.0</td>
<td>4.47</td>
<td>0</td>
<td>1.0</td>
<td>1.4</td>
</tr>
<tr>
<td>3</td>
<td>0.69</td>
<td>1.8</td>
<td>2.7</td>
<td>3.1</td>
<td>4.47</td>
<td>0</td>
<td>3.1</td>
<td>1.4</td>
</tr>
<tr>
<td>5</td>
<td>0.69</td>
<td>1.8</td>
<td>4.5</td>
<td>5.2</td>
<td>4.47</td>
<td>0</td>
<td>5.2</td>
<td>1.4</td>
</tr>
<tr>
<td>7.5</td>
<td>0.69</td>
<td>1.8</td>
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<td>7.8</td>
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<td>9.0</td>
<td>10.4</td>
<td>4.47</td>
<td>0</td>
<td>10.4</td>
<td>1.4</td>
</tr>
</tbody>
</table>

It is observed from Fig.6 and TABLE.3 that an optimum transient and steady state response is achieved with PID control. A setting time for all the reference inputs is found to be 1.8ms. The overshoot is observed to be negligible with a zero steady state error.

Since we have the characteristic values of both open- and closed-loop response, a comparison between the outputs of the two systems can be better understood from the TABLE 4.

**Table 4. Comparison between open- and closed-loop responses**

<table>
<thead>
<tr>
<th>Reference input (mm)</th>
<th>Rise Time (ms)</th>
<th>Settling time (mm)</th>
<th>Overshoot (%)</th>
<th>Peak time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open-loop</td>
<td>Closed-loop</td>
<td>Open-loop</td>
<td>Closed-loop</td>
<td>Open-loop</td>
</tr>
<tr>
<td>----------------------</td>
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<td>0.69</td>
<td>3.8</td>
<td>1.8</td>
</tr>
<tr>
<td>10</td>
<td>2.1</td>
<td>0.69</td>
<td>3.8</td>
<td>1.8</td>
</tr>
</tbody>
</table>

The feedback system (closed-loop) and the PID controller give a better settling time (1.8ms) than the open-loop response (3.8ms). So is the case with rise time and peak time. Though the overshoot
comes as a drawback with this response but this negligible overshoot can be overlooked for the much improvement in rise, settling and peak time.

VII. CONCLUSIONS

A Control System for optimum transient and steady state response of EFI is proposed with the objective of injecting precise amount of gasoline during miniscule time available for fuel injection, particularly at high engine speeds. The open-loop transfer function of a high speed solenoid valve is used to obtain the steady state relationship between the armature displacement and the voltage applied to the solenoid coil. A PID controller was used in closed-loop system to regulate the voltage to the coil for reference displacement spanning the entire stroke of the armature. The controller parameters were tuned to optimize the transient and steady state response of the EFI valve. The values of the performance indicators obtained, indicate a highly suitable transient response with a settling time of less than 2ms. The values of rise time, settling time, overshoot and steady state error, obtained with the tuned controller for step inputs, covering the entire stroke of the armature, indicated optimum response of the EFI valve.

APPENDIX

Values of various parameters used in the simulation model of EFI are given below:

- Mass of the armature (m) = 460mg
- Viscous damping coefficient (b) = 2.47 Ns/m
- Spring stiffness coefficient (k) = 3313 N/m
- Resistance of Coil(R) = 0.9348 ohms
- Inductance of Coil (L) = 0.5057 mH
- Coil Force Coefficient (G) = 16.25 (from the graph in Fig. 2)

REFERENCES