Design Optimization for Nonlinear Dynamic Response of the Electromechanical Actuator

Seok-Heum Baek, Hui-Eun Bae, Sangmo Kang, Chan-Woo Ahn, Hyun-Su Kim*
Department of Mechanical Engineering
Dong-A University
840 Hadan2-Dong, Busan 604-714
KOREA
*Corresponding author: kimhsa@dau.ac.kr

Abstract: This paper describes the design optimization of core for automatic transmission solenoids. A solenoid actuator is a key component of hydraulically control in automatic transmissions. Control pressure of the solenoid operates clutch on transmission system, and the pressure has linear property to prevent shock by gear shift. The solenoid has electromagnetic force (EMF) by electrical signal with 0 mA to 1100 mA typically. This study tries to find the reason of low EMF response for the dynamic characteristic of solenoid actuator and to improve the dynamic response. The optimization problem is formulated to minimize the variation of EMF at every moving displacement of the mover for fast and easy control. The core design of solenoid actuators have been investigated to obtain the required EMF proportionality, and the fast speed of response. The orthogonal array, analysis of variance (ANOVA) techniques and surrogate model approximation, are employed to determine the main effects and their optimal design variables. The methodology is demonstrated as a optimization tool for the core design of solenoid actuator.

Key-Words: Electromagnetic analysis, Finite element analysis, Variable force solenoid valve, Surrogate model approximations

1 Introduction
The solenoid valve for the automobile transmission is composed of the hydraulic unit which controls the oil pressure and the actuator which controls valves. The solenoid valve generates control pressure during automatic transmission and is closely involved with the transmission performance and quality. Hence, it is necessary to have a precise estimation for the control characteristics and ranges about the behavior of the actuator when designing a solenoid actuator. Solenoid actuator is capable of linear movement for small displacement and has a simple structure that it is reliable and convenient to produce. The actuator can control linear behavior with the magneto-resistive characteristic of the material according to the movement of the plunger [1-3].

Fig. 1 shows the composition of the solenoid actuator for automatic transmission used in this study. The solenoid actuator is composed of the core, yoke, case, coil and plunger. The electromagnetic force affecting the plunger changes due to the change in the flux density following plunger movement, making it move in the direction of the core. For the plunger behavior performance, it is most important to obtain the same electromagnetic force for the entire stroke of 0 mm-1.7 mm. The valve can display the same performance for the same stroke regardless of the initial position of the plunger when a solenoid actuator has a linear characteristic. The Plunger behavior has enormous impact on the transmission performance and durability of the clutch for automatic transmission.

In this paper, developed and optimum design for the core shape of the solenoid actuator using analysis of variance and orthogonal polynomial based approximate model [4,5]. For the optimum design of the efficient core for nonlinear electromagnetic characteristics of the plunger, the approximate model for each response was constructed using the orthogonal polynomial at the test point using the table of orthogonal arrays [6-8]. This approximate model manifests the same electromagnetic force for the plunger stroke at the typical plunger positions; 0.1 mm, 0.8 mm, and 1.5 mm, and is integrated into the optimum design loop considering the goal of design, the minimization of core weight. The optimum core shape was suggested from the result of optimum design, and the performance enhancement for the dynamic response of the plunger and its effectiveness were presented.
2 Electromagnetic Analysis of Solenoid Actuator

2.1 Calculation of electromagnetic force
The electromagnetic field analysis for solenoid valve considers the eddy current generated inside the electric conductor, a soft magnetic material, unlike the static analysis where the input current is fixed. Maxwell equation is presented in Eqs. (1) and (2) and the magnetic equation for time-varying system which takes magnetic vector potential \( A \) as the system variable, in Eq. (3)

\[
\nabla \times \vec{H} = \vec{J} \quad (1)
\]
\[
\nabla \times \vec{B} = 0 \quad (2)
\]
\[
\nabla \cdot \left( \frac{1}{\mu_0} \nabla \times \vec{A} \right) = \left( \vec{J}_0 + \vec{J}_e + \vec{J}_m \right) \quad (3)
\]

where \( H \) represents the magnetic field intensity, \( B \) the magnetic flux density, and \( \mu \) the relative permeability. The magnetic flux generated inside the solenoid is the combination of the magnetic flux generated with current density \( J_0 \), the magnetic flux generated with eddy current density \( J_e \), and the magnetic flux generated with the magnetization of the soft magnetic material, \( J_m \). The components of the eddy current in the electromagnetic field become more important for the solenoid actuators requiring fast response [9,10].

The magnetic force in the plunger is generated by the Hamilton's principle similar to the force generated between two permanent magnets [11]. The equation for the force generated here can be represented with the force active in the magnetic circuit \( F \) and magneto-motive force \( U \). Here, \( S \) is the sectional area of the pole face and \( d \), distance between pole faces. By substituting Eq. (5) into Eq. (4), the electromagnet force to the plunger can be obtained through Eq. (6)

\[
F = B^2 \times \frac{S}{2\mu_0} \quad (4)
\]
\[
U = B \times \frac{d}{\mu_0} \quad (5)
\]
\[
F = \frac{1}{d^2} \times \frac{\mu_0 \cdot S \cdot U^2}{2} \quad (6)
\]

2.2 Finite element analysis
Table 1 shows the properties of the materials for each part of solenoid actuator. Fig. 2 represents the method of analyzing the boundary condition of the analysis model using commercial electromagnetic analysis program, Maxwell [12]. For the precision of analysis, a grid system was generated by using the automatic adaptive meshing feature of Maxwell and the Dummy. The analysis model is the axial symmetric model compatible with 2D analysis. The analysis area was set sufficiently not to interfere with the flow of magnetic flux since the magnetic flux generated with input current does not exist inside the model only.

Fig. 3 shows the result of flux intensity and flux density for static magnetic analysis. The conditions for analysis were 510 coil turns, 0 mA-1100 mA of input current, and 1.7mm of permeability of plunger stroke. For the solenoid valve of automatic
shows that it is difficult to control the oil pressure or (flux) precisely for the operating range of the solenoid actuator and the range of use is limited. Therefore, an optimal design is required in order to obtain the behaviour maintaining a certain level of electromagnetic force which is more stable for the plunger stroke.

3 Structural Optimization of Core Shape

3.1 Optimization formulation and design objective

This study considered the shape of the core as the major influence for the enhancement of solenoid actuator performance, set the design variable for the core shape as follows: inner diameter ($x_1$), tip length ($x_2$), cone angle ($x_3$), and tip thickness ($x_4$). Fig. 4 represents the design variables of the selected core shape, and Table 2 shows design variables and their levels.

The goal of design was to determine the minimization of the core weight while obtaining the electromagnetic force range of 12 N-13 N which is required at typical sections; 0.1 mm, 0.8 mm, and 1.5 mm concerning the entire plunger stroke, 0 mm-1.7 mm. If the material density of the core is assumed to be consistent, Eq. (7) can be obtained by minimizing $y = w x_i$ of the axial symmetric section and formulating the optimal design which satisfies the electromagnetic range required at the typical position of plunger stroke.

Find $x_1, x_2, x_3, x_4$

to minimize $y_{area} = w x_i$

subject to $12 \leq y_{stroke0.1} \leq 13$  
$12 \leq y_{stroke0.8} \leq 13$  
$12 \leq y_{stroke1.5} \leq 13$  
$x_i^{lower} \leq x_i \leq x_i^{upper}, i = 1, 2, 3, 4$  (7)

where $y_i(x_i)$ is the approximate model for each response. The optimal solution for the approximate model was calculated with feasible direction method in connection with the optimal design module of ANSYS V.11 [13,14].

3.2 Optimization process and result

Table 3 shows the design matrix of L16 table of orthogonal arrays for 4 design variables for the core and their analysis result. For the selection of design...
Table 2 Design variables and their levels

<table>
<thead>
<tr>
<th>Design variable</th>
<th>Description</th>
<th>Unit</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_1$</td>
<td>Inside diameter</td>
<td>mm</td>
<td>7.5</td>
<td>8</td>
<td>8.5</td>
<td>9</td>
</tr>
<tr>
<td>$x_2$</td>
<td>Tip length</td>
<td>mm</td>
<td>0.3</td>
<td>0.5</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td>$x_3$</td>
<td>Conical angle</td>
<td>Deg.</td>
<td>10</td>
<td>25</td>
<td>40</td>
<td>55</td>
</tr>
<tr>
<td>$x_4$</td>
<td>Tip thickness</td>
<td>mm</td>
<td>0.2</td>
<td>0.4</td>
<td>0.6</td>
<td>0.8</td>
</tr>
</tbody>
</table>

The entire plunger stroke is attributed to the difference in the rate of contribution of design variable at each position. This feature of ANOVA provides the insight for the design and issue in obtaining the same electromagnetic force. The approximate model of electromagnetic force for core area and plunger position considering significant difference in number and reciprocal action of the design variable based on ANOVA can be represented by Eqs. (8)-(11).

$$y_{core} = 72.24 - 4.596x_1 + 0.1237x_1^2 + 6.545x_1 - 4.752x_1^2 + 0.1486 - 0.001514 + 4.092 - 1.192$$

$$+ 0.82885 + 3.092x_1^2 + 0.004$$

$$y_{stroke0.1} = -350 + 87.52x_1 - 5.43x_1^2 + 0.92x_1 + 1.4x_1^2 + 0.0789x_1 - 0.003195x_1^2 + 70.88x_1 - 79.44x_1^2 - 0.1486 - 0.001514 + 0.0789 - 0.003195$$

$$+ 0.004 - 0.001514$$

$$y_{stroke0.8} = -257.3 + 65.32x_1 - 3.994x_1^2 + 188.7x_1 + 8.391x_1^2 - 0.9899x_1 - 0.006516x_1^2 + 3.511x_1 + 2.881x_1^2 - 49.81x_1x_2 - 0.03607x_1x_2 - 0.362x_2x_3 - 0.82885x_1x_3 + 3.092x_1^2 + 0.004922x_1x_3^2$$

$$- 0.1486 - 0.001514$$

$$y_{stroke1.5} = -52.94 + 19.851x_1 - 1.259x_1^2 + 15.594x_2 + 11.006x_2^2 + 0.11952x_1 + 0.000747x_2^2 - 20.618x_1 + 9.475x_1^2$$

Fig. 4 Design variable of core shape for solenoid actuator

variables and disparities for the response surface model of each response, the term determined to be significant in ANOVA was selected and Chebyshev orthogonal polynomial coefficient was used. In the Chebyshev orthogonal polynomial, the coefficient was estimated one after another in the order of low to high nominal even when the coefficient of the high nominal is unknown or there is a large difference in the coefficient as each nominal which gives priority to low nominal is independent. The reciprocal action of the design variable can be qualitatively evaluated in the same procedure.

Table 4 shows ANOVA result on core of cross-sectional area. ANOVA evaluates the sensitivity of each design variable on response by orthogonally analyzing it as polynomial term. The design variable which has dominant influence on core area is $x_3$ which is 76%. In ANOVA result for the electromagnetic force at each plunger position, the design variable that has great effect on electromagnetic force at the plunger position of 0.1 mm and 1.5 mm is $x_4$, and the influence at each position is 51% and 48.7%, respectively. The design variable has the largest effect as $x_3$ is 22.1% when plunger is at 0.8 mm. The influence of reciprocal action is approximately 56% which is very large when the plunger is in the middle position. In particular, the reciprocal action between the cone angle and tip thickness toward the core, $x_3x_4$, is 47%. The non-linearity of the electromagnetic force for

Fig. 5 compares the results of analyzing electromagnetic fields using orthogonal polynomial oriented approximate model and table of orthogonal arrays in Eqs. (8)-(11). The approximate values do involve errors but show that the position of estimated value and the value of function are effectively approximated. Table 5 and Fig. 6 shows the result of optimized design developed based on approximate model and feasible direction method. The optimized design has linear characteristic for major plunger stroke compared with the initial design and manifests enhanced electromagnetic force. Since the optimal solution was obtained through the approximate model, the reanalysis was conducted with the actual model. According to the result of reanalysis concerning the optimal solution,

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Table 3 DOE Layout and FEA results for L16 orthogonal array

<table>
<thead>
<tr>
<th>Exp.</th>
<th>$x_1$</th>
<th>$e$</th>
<th>$x_2$</th>
<th>$x_3$</th>
<th>$x_4$</th>
<th>Area (mm$^2$)</th>
<th>Magnetic force $y_i$ (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1 mm</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>50.058</td>
<td>10.601</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>53.433</td>
<td>15.247</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>54.405</td>
<td>16.074</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>54.987</td>
<td>15.609</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>50.391</td>
<td>9.991</td>
</tr>
</tbody>
</table>

Table 4 Analysis of variance for core area

<table>
<thead>
<tr>
<th>Design variable</th>
<th>Sum of squares</th>
<th>DOF</th>
<th>Variance</th>
<th>F-ratio</th>
<th>Effective ratio(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_1$ Linear</td>
<td>32.6210</td>
<td>1</td>
<td>0.0775</td>
<td>0.69</td>
<td>1</td>
</tr>
<tr>
<td>$x_1$ Quadratic</td>
<td>0.0153</td>
<td>1</td>
<td>0.0153</td>
<td>0.14</td>
<td>0.2</td>
</tr>
<tr>
<td>$x_2$ Linear</td>
<td>0.568</td>
<td>1</td>
<td>0.7449</td>
<td>6.6</td>
<td>9.6</td>
</tr>
<tr>
<td>$x_2$ Quadratic</td>
<td>0.578</td>
<td>1</td>
<td>0.578</td>
<td>5.12</td>
<td>7.4</td>
</tr>
<tr>
<td>$x_3$ Linear</td>
<td>11.3877</td>
<td>1</td>
<td>4.0654</td>
<td>36</td>
<td>52</td>
</tr>
<tr>
<td>$x_3$ Quadratic</td>
<td>1.8557</td>
<td>1</td>
<td>1.8557</td>
<td>16.43</td>
<td>24</td>
</tr>
<tr>
<td>$x_4$ Linear</td>
<td>6.7286</td>
<td>1</td>
<td>0.4154</td>
<td>3.68</td>
<td>5.3</td>
</tr>
<tr>
<td>$x_4$ Quadratic</td>
<td>0.0364</td>
<td>1</td>
<td>0.0364</td>
<td>0.32</td>
<td>0.46</td>
</tr>
<tr>
<td>Error</td>
<td>0.7904</td>
<td>7</td>
<td>0.1129</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5 Relation between electromagnetic analysis and run number in DOE

(a) core area
(b) stroke 0.1 mm
(c) stroke 0.8 mm
(d) stroke 1.5 mm
Table 5 Optimal solution

<table>
<thead>
<tr>
<th>Step</th>
<th>Area (mm$^2$)</th>
<th>$F_{stroke0.1}$ (N)</th>
<th>$F_{stroke0.8}$ (N)</th>
<th>$F_{stroke1.5}$ (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>50.6</td>
<td>10.83</td>
<td>15.32</td>
<td>11.99</td>
</tr>
<tr>
<td>Optimal</td>
<td>49.5</td>
<td>12.01</td>
<td>12.98</td>
<td>12.08</td>
</tr>
<tr>
<td>Reanalysis</td>
<td>49.8</td>
<td>11.54</td>
<td>12.9</td>
<td>12.55</td>
</tr>
</tbody>
</table>

Fig. 7 Initial design vs. Optimal design

Fig. 8 shows the electromagnetic force measuring equipment and it is comprised of the measuring table for fixing the solenoid, load cell, stroke display, force display, and measuring pin behavior unit. The current (1100 mA) was applied to the coil in the optimized model and the plunger was moved at an interval of 0.1 mm and the result was compared with the result of FEA.

Fig. 9 compares the result of the optimal design for electromagnetic force and the test result of the product prepared in this study. The performance of electromagnetic force considering the increase of stroke is similar to the result of FEA. The difference in electromagnetic force between analysis and test was less than approximately 1 N which is translated into approximately 10% of error.

4 Conclusions

This study conducted the optimal structural design to enhance the performance of the solenoid actuator for automobile transmission using the orthogonal polynomial based approximate model. For efficient optimal design, the approximate model for each response was constructed using ANOVA and the orthogonal polynomial at the test point using the table of orthogonal arrays. According to the comparison of performances in each plunger position in the optimal design, the force increased by 0.7 N in 0.1 mm section which is 6.5% increase compared with the initial model, decreased by 2.4 N in 0.8 mm section which is 15% decrease, and increased by 0.6 N in 1.5 mm section which is 4.7%
increase. As shown in Fig. 6, the electromagnetic force carries linear behavior throughout the entire plunger stroke, and the optimal design was developed through analysis so that approximately 12 N is maintained throughout the entire section. A product was prepared by applying the optimum solution to evaluate the accuracy of the analysis on the optimal design. The electromagnetic force of the solenoid produced was measured and compared with the analysis result. According to the comparison of the analysis and the test result, the electromagnetic force manifests the same trend for the plunger stroke. The difference in electromagnetic force between analysis and test was less than approximately 1 N which is translated into approximately 10% of error. UNICK Co. Ltd. registered patent for the core shape in this paper (No.10-2010-0082043).

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References: