Structure and Vibration Analysis of Solenoid Pump for Two-way Hydraulic Control

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Abstract

A solenoid pump is a reciprocating piston pump that moves linearly by the aid of a piston cylinder attached at the linear motor axis which carries out a reciprocating motion. Generally, a solenoid pump is a pump utilizing a magnetic plunger of magnetic substance and an electric induction coil. A solenoid pump model for the hydraulic pressure that can control bi-directionally and can generate a high pressure is proposed in this study. The design parameters for the parts of the solenoid pump used for hydraulic pressure are studied using a numerical analysis method. After selecting an adequate solenoid model, the magnetic force and magnetic density on the model are estimated by electromagnetic force analysis. Based on the obtained magnetic force and magnetic density, a structural analysis of the model is performed. Also, design parameters are obtained for the robust design by vibration mode analysis to avoid resonance effect on the key parts of the system. The results of the vibration mode analysis and FFT analysis are proposed in the design of new products.

Keywords: Solenoid Pump; Magnet; hydraulic; Oil pressure; Hydraulic Control

1. Introduction

Automotive and robot industries are demanding more compact and lightweight products today. The existing hydraulic system is constructed with rotating motor, hydraulic pump and cylinder, solenoid value, and piping. Because this system has many parts, the manufacturing process becomes more difficult and expensive. It requires a huge space and high labor charges. Recently, researches about solenoid hydraulic pumps that can solve these problems have been conducted [1-2]. A solenoid hydraulic pump is a component used as a small-size actuator in the mobile robot field and as a part of cars [3-4]. A solenoid pump is a reciprocating piston pump that moves linearly by the aid of a piston cylinder attached at the linear motor axis which carries out a reciprocating motion [5]. Generally, a solenoid pump is a pump utilizing a magnetic plunger of magnetic substance and an electric induction coil. When power is transmitted into the induction coil, a magnetic force is generated in it. Accordingly, a reciprocating motion from the magnetic material plunger is induced to suck and discharge the fluid. Burkhard Horstkotte et al. performed a research about the characteristics of a solenoid pump suiting the gas supply [6]. Choi et al. evaluated the experimental performance of the proposed low pressure pump which could be applied in the water pressure pump [7-8]. However, these pumps supply fluid toward only one direction.

Therefore, a separate solenoid valve should be attached in order to control the pumps. Further, the discharge pressure of these pumps is low which makes it difficult to be used in the hydraulic power equipment. Therefore, a solenoid pump model for the hydraulic pressure that can control bi-directionally and can generate a high pressure is proposed in this study. The design parameters for the parts of the solenoid pump used for hydraulic pressure are...
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2. Solenoid Pump Model

The model which has been used for the analysis in this study has a structure with a bidirectional control or two-way direction. The implemented hydraulic model in this study is proposed by Y. J. Jang and the author [9]. Figure 1 shows the proposed model having a symmetrical structure and table. The operation method of a two-way solenoid pump model is shown below. When a hydraulic pump coil (⑥) at the center is ON, a magnetic force is generated between the coil and the hydraulic pump magnet (⑦), and this generated force will push the hydraulic pump piston to make fluid flow through. The flowing direction is decided according to the polarity (+ and −) of the power input in the coil. The magnet part arranged symmetrically at the right and left sides plays a role as a solenoid valve. Same as the pump movement, once power is input in the solenoid coil (②), a magnetic force between coil and solenoid valve magnet (③) is generated and its force pushes the solenoid plunger (⑩) to move the valve (④). With this movement, the route through which fluid flows is opened. Figure 1(a) shows a route through which hydraulic fluid flows towards the left side, while figure 1(b) shows a route through which hydraulic fluid flows towards the right side.

![Figure 1. Configuration of the model](image)

![Figure 2. Application in the three-dimensional model](image)
3. Magnetic Analysis Results

A three-dimensional model is designed with an integrated mechanism to make hydraulic pump, hydraulic cylinder, and symmetrical solenoid valve perform the functions shown in Figure 1. The result is illustrated in Figure 2. A magnetostatic analysis is also performed to examine the magnetic force which is generated between hydraulic pump coil (⑤) and the internal energy of the magnet (⑦). This magnetic force is converted into a force that pushes the fluid. The commercial code used in the analysis is Maxwell 14.0. After analysis, the piston pressure generated through electricity input, magnetic power, and internal energy distribution are drawn. Copper of almost pure grade is used as a coil material. Meanwhile, the magnet used in the commutator is NdFe 48.

The physical properties of the used materials in the model are tabulated as in Table 1. The analysis range is set until 40 mm from the solenoid pump surface. The input current in the coil is set to 2A and voltage is set to DC 12V. Winding is 500 turns. Magnetization of the magnet is set to cylindrical. Triangulation of the elements is performed as in Figure 3, and magnetostatic analysis for the line of magnetic force and magnetic induction, as well as transient analysis to determine the plunger force, is carried out.

Figure 4 shows the magnetic flux density distribution result and detailed macrograph thereof. The analysis results show that the strongest magnetic force is generated near the center of the magnet. Magnet force almost does not affect the main body and plunger. Since the magnetic force at the center of the system is converted to a force which pushes the fluid, it is an important design parameter which decides the size of the hydraulic pressure. Figure 5 shows the magnetic energy density distribution. The largest density is created from both ends of the magnet and the maximum energy level is 3.057 MJ/m$^3$. With this energy level, hydraulic pressure is sufficiently generated. In the next stage, a transient analysis is carried out to examine the magnetic force generation from the initial stage of the power input. The physical properties, analysis conditions, and mesh are set similarly as those for magnetostatic analysis. The analysis result is obtained from a magnetic force received by the plunger surface. Figure 6 illustrates the result of the size of a magnetic field and the magnetic force analysis. From the figure, it is clear that the size of magnetic field generated from the magnet is larger than that from the coil. An average energy loss of 4.475 MJ/m$^3$ occurs from the coil indicating that the model is designed without generating a large energy loss.

As a result, the area of plunger is 0.000113 m$^2$. When this area is converted into a pressure, the maximum pump pressure of the plunger becomes 39.5 MPa. Therefore, this design can be possibly used in the hydraulic system operated at a lower pressure which is below 30 MPa.

<table>
<thead>
<tr>
<th>Table 1. Magnetic properties</th>
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<tbody>
<tr>
<td>Name</td>
</tr>
<tr>
<td>Relative Permeability</td>
</tr>
<tr>
<td>Bulk Conductivity</td>
</tr>
<tr>
<td>Magnitude</td>
</tr>
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4. Structure and Vibration Analysis Results

The structure and vibration analysis are carried out by selecting a spring which can generate a resonance with the body which is a key part during hydraulic pump operation. The used materials for the analysis are Al 6061 for the body and SUP4 for the spring. The mechanical properties of the parts are tabulated in Table 2. The commercial code ANSYS 13.0 is used as software for the analysis. The analysis results are displayed for the equivalent stress, total deformation, and strain which are generated when load is imposed. After modeling the key parts, triangle elements mesh with 47,091 nodes, and 26,751 elements are
created. The input pressure which is obtained from transient magnetic analysis is applied in the model. Also, a maximum inner pressure of 60 MPa is implemented considering the safety factor. The stress, strain, and total deformation of the body under the maximum pressure condition are illustrated in Figure 7. Firstly, the equivalent stress analysis result is displayed in Figure 7(a) which indicates that stress around 35 - 40 MPa is generated at the wall of the cylinder. With this stress value, the adopted model is proven safe. Figure 7(b) shows the maximum strain rate at the bottle neck where the inner tube becomes narrower. At the bottleneck, though strain becomes the maximum, the value is less than 0.0007 mm/mm and the maximum deformation shown in Figure 9(c) also is less than 0.015 mm. The strain in the design standard is less than the allowance in the processing and assembly of the products which confirms that the implemented design is safe. The vibration mode analysis is carried out for the robust design suited to control the repeated agitation. The vibration mode shapes and natural frequency modes of body from the first mode until the sixth mode are displayed in Figure 8. Vibration mode shapes are analyzed with FFT and the result is presented in Figure 9. Here, resonances are generated between 2,090 and 2,600 Hz in the first mode and second mode, 6,835 Hz in the third mode, and 9,000 Hz after the fifth mode. It could be confirmed that the vibration mode is out of the resonance zone of the system during pump rotation. In the next stage of the analysis, the vibration of the compression coil spring (⑤) which pushes the solenoid valve is analyzed. During the analysis, modeling is carried out with a rectangular mesh with 46,929 nodes and 8,584 elements as in Figure 10. Total strain analysis on the spring under the load which has been obtained previously shows the value on an average of 0.4 mm/mm from the inner side where breakage of the spring occurs with the highest possibility as in Figure 11. The vibration mode shapes and natural frequency modes of spring from the first mode until the forth mode are displayed in Figure 12. The vibration mode FFT analysis result shows that a vibration between 199.7 Hz and 1532 Hz is generated in the first and second mode, 1,743 Hz in the second mode, and 2,082 Hz during the fourth vibration in Figure 13. The results indicate that the resonance does not match either the natural frequency of body or the rotation speed of motor, thus, the model displays safety.

<table>
<thead>
<tr>
<th>Name</th>
<th>Al</th>
<th>Spring wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comp. Ultimate Strength</td>
<td>0.0 MPa</td>
<td>2530 MPa</td>
</tr>
<tr>
<td>Comp. Yield Strength</td>
<td>395.0 MPa</td>
<td>2150 MPa</td>
</tr>
<tr>
<td>Density</td>
<td>7.20x10^-6 kg/mm^3</td>
<td>7.8888x10^-6 kg/mm^3</td>
</tr>
<tr>
<td>Poisson's Ratio</td>
<td>0.33</td>
<td>0.35915</td>
</tr>
<tr>
<td>Tensile Yield Strength</td>
<td>395.0 MPa</td>
<td>1280 MPa</td>
</tr>
<tr>
<td>Tensile Ultimate Strength</td>
<td>405.0 MPa</td>
<td>1505 MPa</td>
</tr>
<tr>
<td>Young's Modules</td>
<td>69160 MPa</td>
<td>193,000 MPa</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>26 GPa</td>
<td>71 GPa</td>
</tr>
</tbody>
</table>
Figure 7. The analysis result of the structure

Figure 8. The analysis result of the natural frequency mode shape for body
Figure 9. The natural frequency of modes

Figure 10. The model & mesh

Figure 11. Total deformation

Figure 12. The analysis result of the natural frequency mode shape for spring
5. Conclusion

This study is conducted to obtain design parameters by magnetic field analysis and vibration mode analysis for a small-sized solenoid pump with a two-way discharge control. The results of the structure and vibration are as follows.

1. A three-dimensional modeling is carried out for the proposed mechanism and then magnetostatic analysis and magnetic transient analysis are performed to investigate the lines of magnetic force and magnetic induction phenomena and to obtain a force generated from the piston in the pump. The generated maximum energy from the model is $3.057 \, MJ/m^3$ at the center of coil and the pressure generated under the maximum energy condition is $39.5 \, MPa$. This result could be implemented in the hydraulic system for small products used under a pressure less than $30 \, MPa$.

2. A structure analysis is carried out for the proposed pump mechanism. The results show that an equivalent stress around $35$- $40 \, MPa$ is generated from the inner wall of the cylinder which confirms safety of design. Also, the maximum strain occurs at the bottleneck where inner tube diameter becomes narrower, but the value is less than $0.0007 \, mm/mm$ and the maximum deformation is also low with value less than $0.015 \, mm$. Therefore, the strain and total deformation in the design standard are less than the allowances adopted in the processing and assembly of the products which implies that the implemented design secures the safety.

3. By vibration mode analysis, a robust design standard is well-complied by avoiding the resonance points of the vibration and other body parts.

4. In the future, products matching the present model would be fabricated and the actual vibration values would be compared with the experiment’s results. The pump proposed in the present study is an integrated fluid pump and it could be implemented in the pump for small actuators in the aeronautic field and mobile robots field.

Acknowledgements

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References


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