FEM design of proportional solenoid for hydraulic proportional suspension damper

Chin Yi Cheng¹, Jyh Chyang Renn¹, Yi Zhe Xie¹, Yi Kai Huang¹ and Chun Bin Yang²

¹Department of Mechanical Engineering, National Yunlin University of Science & Technology, Yunlin, Taiwan
²Metal Industries Research & Development Center, Kaohsiung, Taiwan

E-mail: zezheng@yuntech.edu.tw

Abstract. In this paper, the FEM simulation package FLUX2D is utilized as a tool to design a proportional solenoid for the hydraulic proportional suspension damper. The hydraulic proportional suspension damper can be used in vehicle semi-active suspension system due to its adjustable output damping force. In addition, the proportional solenoid plays the most significant role to achieve such a variable output damping force. From previous literatures, three different structures of proportional solenoid will be discussed in this paper. The first one utilizes the stepped conical armature design. Its advantages include low cost, easy manufacturing. However, the limited available linear stroke as well as the poor linearity are its major faults. The second structure uses a special tube consisting of three metal rings that are welded together. Between two magnetic steel rings, there is a non-magnetic copper ring serving to guide the magnetic flux and to produce a linear force/stroke relation. Clearly, higher cost and complex manufacturing process are its major disadvantages. However, larger available linear stroke and good linearity are two promising advantages. In this paper, the third design of proportional solenoid is adopted. The construction of the proportional solenoid is divided into several parts. After assembling these parts together, a ring of air gap with a well-designed geometrical shape exists which can be used to replace the non-magnetic copper ring. Without the copper ring, the expensive and complex welding process can be omitted. Meanwhile, the large available linear stroke as well as good linearity are both preserved. Finally, an experimental test device for measuring the force/stroke relation of proportional solenoid is implemented in this study. It is observed that the simulation results agree quite well with the experimental results.

1. Background and Introduction

As shown in Figure 1, the suspension system is classified as a passive, semi-active, and active suspension system, according to its ability to add or extract energy [1]. Among these three systems, the passive suspension is perhaps the most commonly used one and may be found in most vehicles. However, the passive suspension has no means of adding external energy to a system because it contains only passive elements such as a damper and a spring. For the active suspension, the obvious advantage is that it can supply energy from an external source and generate force to achieve the optimal desired performance. However, the inevitable high cost is its major fault. By contrast, for the semi-active suspension, it is possible to continuously vary the rate of energy dissipation using a
controllable damper. Though it can only provide moderate performance, the low-cost configuration is its major advantage. For these reasons, the semi-active suspension using the hydraulic proportional suspension damper is investigated in this study. Figure 2 shows the 2-stage hydraulic proportional suspension damper discussed in this paper. It is observed that a proportional solenoid at the pilot-stage is used to determine the damping force output of the hydraulic proportional damper. Two significant features of the proportional solenoid are the quite linear force/stroke characteristic and the proportionality between the input current and the output armature force. Thus, it is possible to vary the damping force output by changing the input excitation current. In this paper, the FEM simulation package FLUX2D is chosen as a tool to design the proportional solenoid for the hydraulic proportional suspension damper. By surveying some previous literatures [2-4].

![Comparison of Suspension Systems](image)

**Figure 1.** Classification of vehicle suspension system

![2-stage Proportional Damper](image)

**Figure 2.** Scheme of the 2-stage hydraulic proportional damper

## 2. Three Different Kinds of Proportional Solenoid

Three different structures of proportional solenoid will be discussed in this paper. The first one utilizes the stepped conical armature design as shown in Figure 3. Its advantages include low cost, easy manufacturing. However, the limited available linear stroke as well as the poor linearity are its major faults. The second structure uses a special tube consisting of three metal rings that are welded together as shown in Figure 4. Between two magnetic steel rings (No.: 2, 6), there is a non-magnetic copper ring (No.: 5) serving to guide the magnetic flux and to produce a linear force/stroke relation. As the armature (plunger) moving, axial space increase as well as radial space decrease, this will make resultant force keep in same value, Figure 5 shows the relation between axial force, radial force and
resultant force of proportional solenoid [5]. The axial force (Fa) of the base and the radial force (Fr) of the flange work with each other in specific section so that the solenoid force is equal to their sum. Therefore, the proportional electromagnet can be directly controlled, and the solenoid force depends on the operating current in the linear zone. Clearly, higher cost and complex manufacturing process are its major disadvantages. However, larger available linear stroke and good linearity are two promising advantages. In this paper, the third design of proportional solenoid is adopted as shown in Figure 6. The construction of the proportional solenoid is divided into several parts. After assembling these parts together, a ring of air gap with a well-designed geometrical shape exists which can be used to replace the non-magnetic copper ring. Without the copper ring, the expensive and complex welding process can be omitted. Meanwhile, the large available linear stroke as well as good linearity are both preserved. In the following, the FEM design of the proportional solenoid using FLUX 2D will firstly be outlined.

![Proportional solenoid with the stepped conical armature design](image1)

**Figure 3.** Proportional solenoid with the stepped conical armature design [2]

![Proportional solenoid with a tube consisting of three metal rings welded together](image2)

**Figure 4.** Proportional solenoid with a tube consisting of three metal rings welded together [3]

![Radial Force and Axial Force of Proportional Solenoid](image3)

**Figure 5.** Radial Force and Axial Force of Proportional Solenoid [6]
3. Designing the Proportional Solenoid Using Flux2D

![Diagram of a proportional solenoid with the ring of air gap](image)

**Figure 6.** Proportional solenoid with the ring of air gap [4]

**Figure 7.** Construction of the study domain showing different materials

**Figure 8.** Flux distribution diagram of the proportional solenoid

(Input current: 2.0 A, Stroke: 0.5 mm)
In this paper, the commercial FEM software package FLUX 2D is used to design the electromagnetic proportional solenoid. Generally speaking, conventional design approach based on equivalent circuit method and trial-and-error are time-consuming [6]. However, the introduction of FLUX 2D helps to test new ideas quickly and design a successful prototype rapidly. First of all, according to the design dimension of the proportional solenoid shown in Figure 6 the construction of the study domain for the proportional solenoid by showing different materials is shown in Figure 7. Since the geometry of the proportional solenoid is axis-symmetric, a two-dimensional cylindrical coordinate model of the magnetic field is established for the quantitative analysis of the armature’s output force. Then, the FLUX 2D’s automatic mesh points generator accomplishes the meshing in finite elements for the proportional solenoid. Before the simulations, the value of the excitation current as well as the magnetization (B-H) curves for different magnetic or nonmagnetic materials must be given in advance. The former is the known input signal and the latter can be found in the data sheets of corresponding magnetic or nonmagnetic materials. In addition, the boundary condition assuming all the field lines are perpendicular to the boundary is applied throughout the simulations. For the proportional solenoid, the maximal saturation flux density of the Ni-Fe steel permanent magnet is set to be 2.9 Tesla. The number of coil turns is 500 and the maximal external excitation current is set to be 2.0 A. After simulations, as an example, the flux distribution as well as the flux density of the proportional solenoid for the input current of 2.0 A and at the stroke of 0.5 mm can be derived as shown in Figure 8 and Figure 9, respectively. From the numerical table shown in Figure 9, the average flux density can be determined. Consequently, the static force/stroke relation for a given excitation current can be numerically derived. Similar simulations may be repeated for different input currents and at different strokes of the armature (plunger). Figure 10 shows the numerical static force/stroke characteristic curve for the proportional solenoid using four different excitation currents. It is observed that the static force/stroke relation is quite linear within the stroke range from 0.4 mm to 1.4 mm under the error of 15%.

![Figure 9. Magnetic flux density in units of Tesla for the proportional solenoid (Input Current; 2.0 A, Stroke: 0.5 mm)](image-url)
The spool movement in a proportional valve is small; a few mm stroke is typical. The valves are therefore very vulnerable to static friction. In order to make sure that the output flow or pressure is in direct proportion to the input current, we normally take the approximate straight-line part on the characteristic curve as the working range for pressure & current or flow & current. This working range is known as linear range for a proportional valve. When choosing a proportional valve, you should choose the one with narrower linear range.

The corresponding static force/current relation is also shown in Figure 11, in which the good linearity between the magnetic output force and the input excitation current is noticeable.

4. Experimental Test Device
In this study, an experimental test device is developed for evaluating the performances of the proposed proportional solenoid. The scheme is depicted as shown in Figure 12. An open-loop controlled micro-stepping motor is utilized to control the position of armature (plunger) of the tested linear motor. The rotational angle and speed output of the micro-stepping motor can be derived directly from the number of pulses and the frequency of the generated pulse signal sent to the driver, respectively. In addition, the direction of rotation can be easily controlled by sending a Hi- (5 Volt) or Lo- (0 Volt) signal to one
input port of the driver. Besides, this test device provides a position sensor (LVDT) as well as a load cell for the measurement of the stroke and the output force of the armature (plunger). In Figure 12, we set the tested proportional solenoid at position No. 6 and let the micro-stepping motor go right after proportional solenoid excitation. The load cell and LVDT device will measure the force and stroke value and send it to computer. Thus, the most important force/stroke relation can be obtained. Finally, the control of the unit as well as the acquisition and processing of the measured data are all integrated in a PC-based LabVIEW software controller, Figure 13 shows the LabVIEW User Interface of experimental device in this study. After the measuring the sample proportional solenoid with the excitation current of 0.5A to 2.0A, same with simulation, the result is shown in Figure 10 and can compare with the result of simulation.

Figure 12. The static force/stroke test device for the proportional solenoid

Figure 13. User Interface of Experimental Device Constructed by LabVIEW

5. Experimental Results and Discussion
Using the test device shown in Figure 12, the experimental force/stroke relation can be obtained. It is also observed that the range of linear working stroke is from 0.5 mm to 1.4 mm. Therefore, the average output force of the proportional solenoid within this stroke range can be calculated. Table 1. Comparisons between experimental and simulation
shows the comparisons between experimental and simulation average forces for 4 different excitation currents. The minimum error percentage is only 3 % while the maximal error percentage is around 12 %. From engineering point of view, these small deviations are still acceptable.

Table 1. Comparisons between experimental and simulation

| Input Current | Measurement(N) | Simulation(N) | Error(%) |
|---------------|----------------|---------------|----------|
| 0.5(A)        | 7              | 6.2           | 12.9     |
| 1.0(A)        | 18             | 17.5          | 2.8      |
| 1.5(A)        | 28             | 29.1          | -3.9     |
| 2.0(A)        | 38             | 40.4          | -6.3     |

6. Conclusion
In this paper, a proportional solenoid for hydraulic proportional suspension damper is proposed and successfully developed. Three conclusions may be drawn from this research.

1. It is observed that the simulation results agree quite well with the experimental results. The overall percentage deviation between simulation and experimental result is only approximately 6 %.

2. The linear working stroke of the proportional solenoid designed in this paper amounts 0.9 mm. In the real application of pilot-stage design shown in Figure 6, a linear working stroke of 0.5 mm would be sufficient. In addition, the maximal magnetic output force reaches 40 N which meets the design requirement of the pilot-stage. Therefore, it can be concluded that the design of the proportional solenoid proposed in this paper is quite successful.

3. From Figure 10, currently, this study noticeable that the force/stroke relation is not fully satisfactory at the higher excitation current of 2.0A. In the future, however, an optimization study has to be conducted to improve the linearity for the whole range of excitation current. Figure 14 suggests the three most important geometrical parameters for the triangle type control cone. That has to be studied, including the width, W, the length, L, and the angle $\theta$ are cone length, cone thickness, cone depth, cone width, and the gap between plunger and cone, respectively. The attraction force characteristics of the manufactured solenoid actuator were simulation and experimentally calculated. After optimized the geometric shape of the proportional solenoid, the force/stroke relation may become better. [7-8]

Figure 14. Three chosen geometrical parameters for future optimization study

Acknowledgments
The financial supports from the Metal Industries Research & Development Center, Taiwan and the Ministry of Science and Technology under grant number are both greatly appreciated.
References

[1] Renn, J. C. and Chen, H. M., “Design of a Novel Semi-active Suspension for Motorcycles with Fuzzy-Sliding Mode Controller,” J. of the CSME, 26(3), pp. 287-296, 2005.

[2] Backe, W., Servohydraulik, Umdruck zur Vorlesung, RWTH Aachen, 6. Auflage, Germany, 1992.

[3] Backe, W., Steuerungs- und Schaltungstechnik II, Umdruck zur Vorlesung, RWTH Aachen, 4. Auflage, Germany, 1993.

[4] Renn, Jyh-Chyang, Jhan, Cian-Wei, “A Full-Digital Quasi-Proportional Force Output Solenoid,” Proceedings of the 14th International Conference on Automation Technology (Automation 2017), Paper ID: 1006, Kaohsiung, Taiwan, 2017.

[5] He Jen-Yu, Designing the Shape of Poppet for a Proportional Switching Solenoid, National Yunlin University, Master Thesis, Taiwan, 2016.

[6] Renn, Jyh-Chyang, Xu, Zheng-Liang, State-space Modeling and FEM Design of Moving-coil Transducer for Fluid-technical Proportional Valves, “J. of the CSME, Vol. 24, No. 2, pp. 119-125, 2003.

[7] So-Nam Yun, Young-Bog Ham, Jung-Ho Park, Attraction force improvement strategy of a proportional solenoid actuator for hydraulic pressure control valve, 12th International Conference on Control, Automation and Systems, Engineering, 2012.

[8] So-Nam Yun, Young_Bog Ham, and Jung-Ho Park, New Approach to Design Control Cone for Electro-Magnetic Proportional Solenoid Actuator, IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Taiwan, 2012.