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Research Article

Experimental Study and Simulation Analysis on Electromagnetic Characteristics and Dynamic Response of a New Miniature Digital Valve

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In order to get the better electromagnetic characteristics of the micro digital valve, the larger electromagnetic force should be obtained in the smaller electromagnetic structure. The electromagnetic force directly determines the electromagnetic properties of the miniature digital valve. The electromagnetic force test is studied in the paper. The results of electromagnetic simulation results are basically consistent with the experimental results. The simulation model is reliable and accurate. The dynamic simulation results show that the dynamic characteristics of the miniature digital valve meet the requirements of the digital hydraulic technology. Design of the new micro digital valve is reasonable.

1. Introduction

Digital hydraulics technology has a potential to replace the proportional technology and the servo technology because of their superior properties, such as low cost, reliability, and insensitivity to contamination [1, 2]. Because the digital hydraulic system is composed of many digital valves, the size of the system is bigger than that of the proportional system and the servo system. Therefore, the size of a single valve should be designed to be smaller to solve the problem. In addition, the micro high-speed digital valves are the key components of the digital hydraulics system. Fast response performance of the micro high-speed digital valves directly influences the control precision of the whole system. Electromagnetic force decides the response performance of the micro high-speed digital valves. How to obtain largest electromagnetic force in a smaller size is a key problem, which should be given more attention.

A large number of working mechanisms of electromagnetic characteristics of the high-speed valves have been studied [3–5]. Through selection of different soft magnetic materials and structure parameters, larger magnetic force and lower power losses have been achieved by Tao et al. [6]. Effects of electronic circuit on the magnetic field of a solenoid valve were studied by Angadi [7]. The dynamic behavior of two different micro valves was measured by Luharuka et al. [8]. The dynamic response and power losses of high-speed solenoid injector were studied by Cheng et al. [9] by using a simplified model. The multiphysics modelling of a solenoid valve was established, and the multiphysics network simulation was done by Mutschler et al. [10]. The dynamic response and the static electromagnetic characteristics of the solenoid valve were studied by Wang et al. [11] by using the simulation method. The effects of current on speed response of a high-speed valve were developed by Topcu et al. [12]. The integrated numerical-experimental approach which can be used to examine both the mechanical and hydraulic performance of the pilot valve was proposed by Ferrari et al. [13]. The key factors of electromagnetic force of the solenoid valve were researched by Liu et al. [14]. The highly accurate method for prediction of dynamic characteristics of a solenoid fuel injector was presented by Ando et al. [15]. Energy consumption of the solenoid

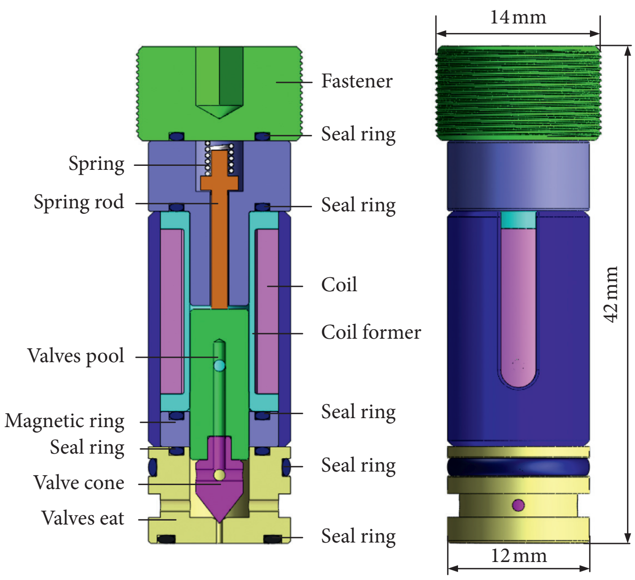


Figure 1: Novel micro high-speed digital valve.

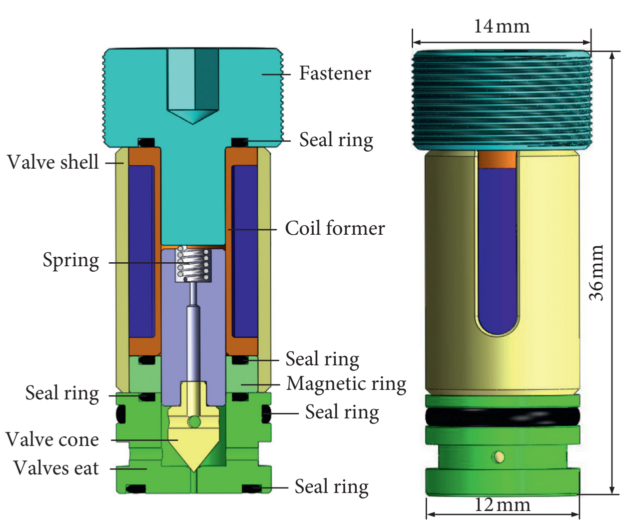


Figure 2: Traditional micro high-speed digital valve.

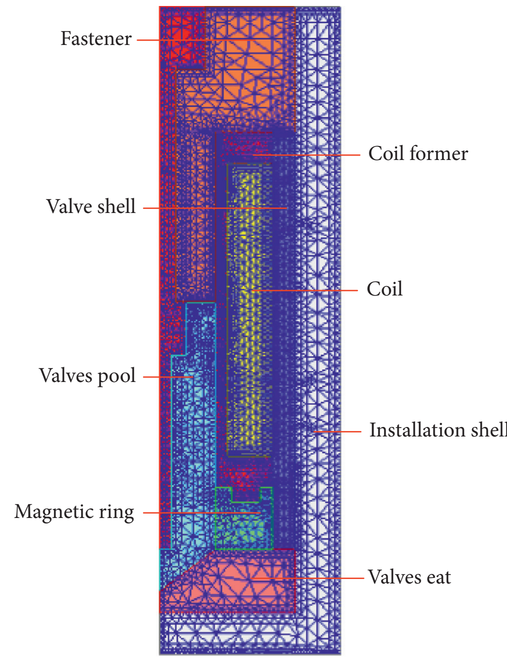


Figure 3: Mesh model of the traditional valve.

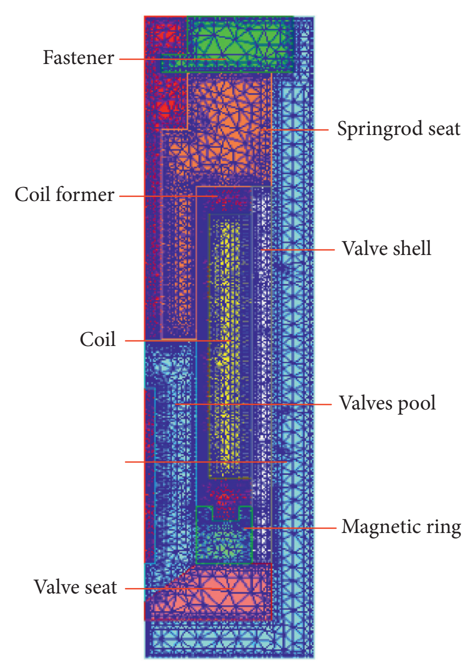


Figure 4: Mesh model of the novel valve.

actuator and the influence of different structure parameters on the response time were studied by Lantela et al. [16].

According to the above literatures, it can be concluded that electromagnetic force plays a key role in the micro high-speed digital valve. Structure parameters are crucial to the electromagnetic force. Although the researchers have done a lot of research work on electromagnetic force, they only focused on different driving parameters and structure parameters. The objective of this paper is to research electromagnetic characteristics and dynamic response of the new miniature digital valve. The effects of different parameters on magnetic properties and dynamic response are analyzed in the paper.

2. Miniature Digital Valve and Testing Rig

2.1. The Novel Micro High-Speed Digital Valve. Unlike the traditional digital valve, the new micro digital valve adopts the spring top arrangement, as shown in Figure 1. Compared with the traditional valve (as seen in Figure 2), this new design increases the magnetic flux area and effectively improves the electromagnetic force. The more detailed parameters can be obtained in [17].

Table 1: Detailed information of Maxwell computation.

Item		Classification	Setting
Physical properties	Armature	Material property	DT4
		Outer diameter	5 mm
		Air gap	0.1 mm
	Coil	Material property	Copper
		Winding type	Standard
		Turns	Variable
		Height of coil	14 mm
		Inner diameter of coil	7.5 mm
		Outer diameter of coil	10 mm
	Other components	Material property	Al or 316 L
	Motion field	Material property	Air
	Solving domain	Material property	Air
Initial boundary	Driven condition	Direct current	Variable

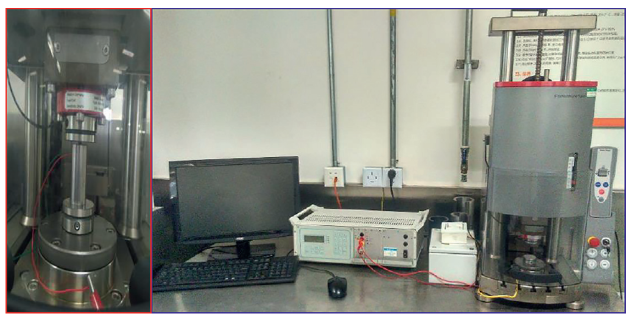
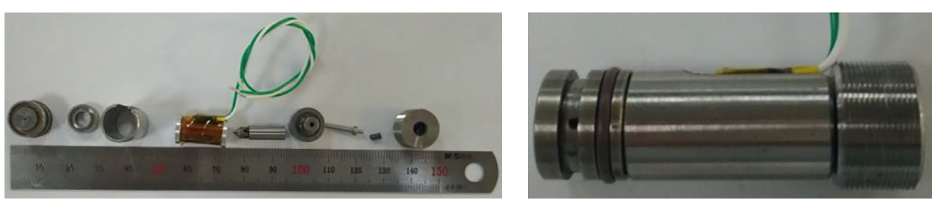


Figure 5: Testing platform of electromagnetic force.



(a) (b)

Figure 6: Micro high-speed digital valve.

2.2. Simulation Setting. Accurate simulation models can make our calculation more accurate. In order to verify the accuracy of the model, we have adopted the verification method between experiment and simulation. In the simulation, we use the finite element method in [11, 18]. The simulation software of ANSYS Maxwell has been adopted to the simulation study [11, 19]. The grid models of the traditional valve and the novel valve are shown in Figures 3 and 4. In order to get more accurate simulation results, we use the more refined grid. The more detailed information and parameters of the simulation are obtained in Table 1 [17].

2.3. Testing Platform. The testing platform of electromagnetic force was made up of the industrial personal computer, the current controller, the current collector, the control panel, force transducer, and the host computer, as is seen in Figure 5. Figures 6(a) and 6(b) show all the components and the whole structure of the micro high-speed digital valve. Electromagnetic force was transmitted from the valve spool to the force transducer through the guide rod [17].

The dynamic and static characteristics of the solenoid valve are related to the magnitude of the electromagnetic force, the greater the electromagnetic force, the better the characteristics of the micro digital valve. Using the electromagnetic force test platform, the test conditions can be adjusted by changing the magnitude of excitation current and air gap stroke. In order to verify the correctness of the simulation model and settings, the electromagnetic force of the miniature digital valve with 0.9 A test current, 400 coil turns, and 0.1 mm air gap stroke is tested. The simulation and test results are shown

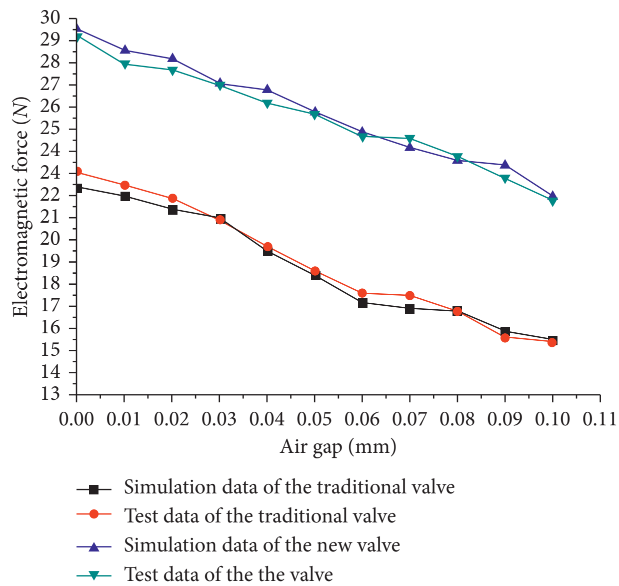


Figure 7: Simulation and testing comparison of electromagnetic force of the two valves.

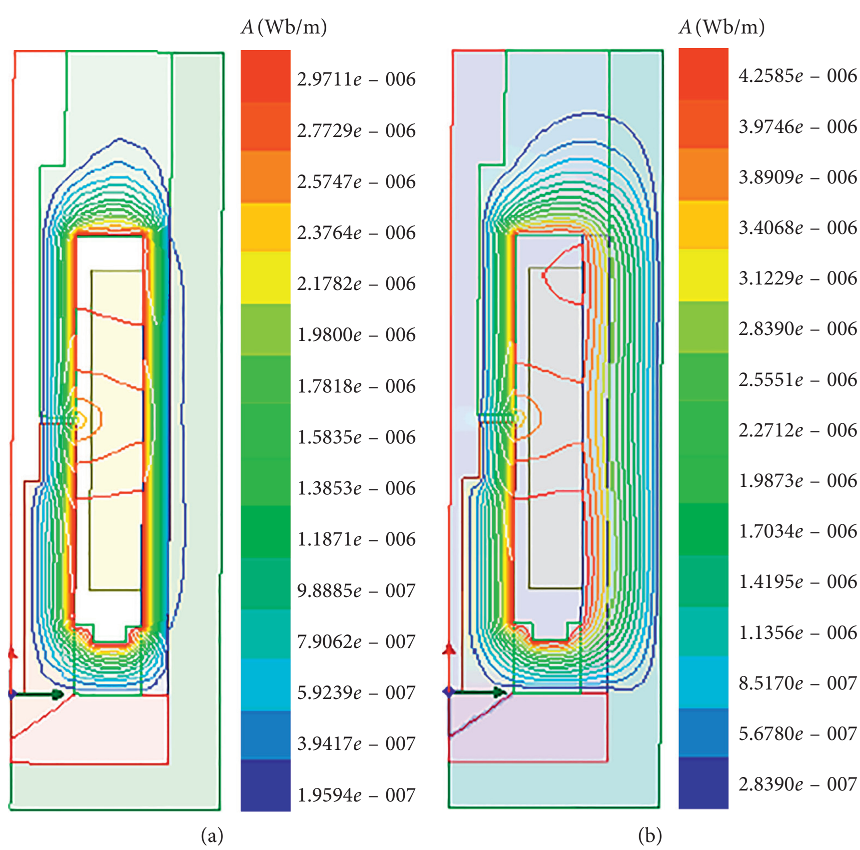
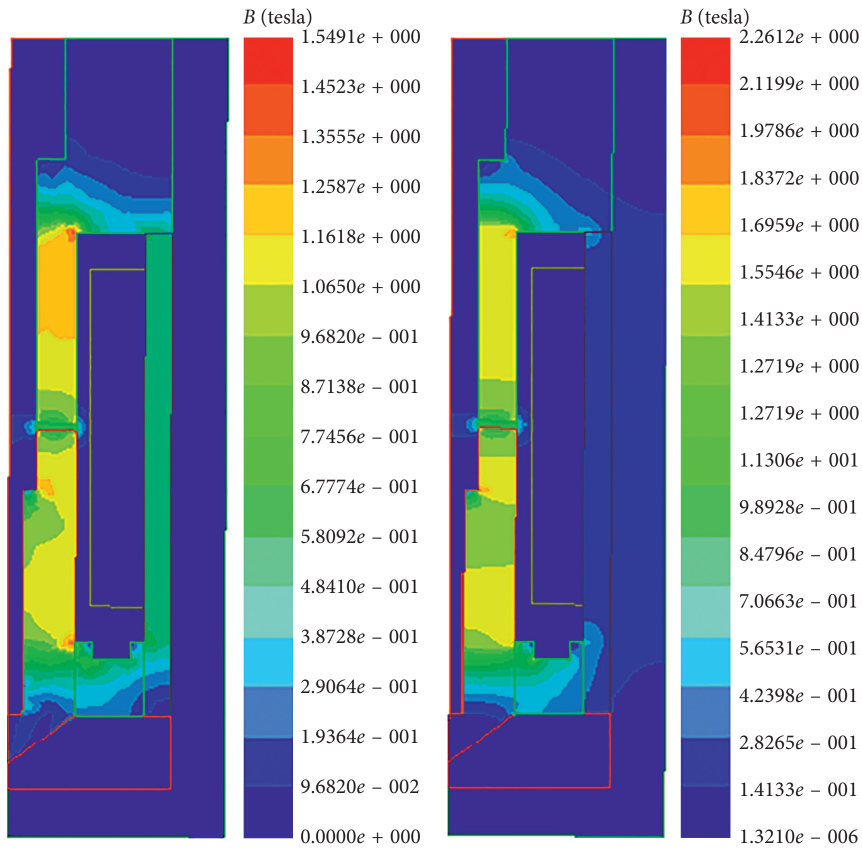


Figure 8: Distribution of magnetic lines of force. (a) 0.8 A. (b) 1.2 A.

in Figure 7. From Figure 7, it can be concluded that electromagnetic force rises along with the reduction of the air gap. The error between simulation and experiment is very small and less than 4 percent. Therefore, the simulation is in agreement with the actual results, and the simulation model is reasonable and correct.



(a) (b)

Figure 9: Magnetic induction intensity. (a) 0.8 A. (b) 1.2 A.

3. Simulation Results and Analysis of Multiparameters

3.1. Influence of Different Currents. The characteristics of electromagnetic field determine the magnitude of electromagnetic force. The greater the magnetic field line density of electromagnetic field, the greater is the intensity of electromagnetic field. The variation of magnetic line density and electromagnetic field intensity under different excitation currents is studied in this paper. As shown in Figure 8, the excitation currents of 0.8 A and 1.2 A are taken, respectively, and the magnetic field lines of force are shown in Figures 8 (a) and 8(b); the magnetic induction intensity nephogram of the electromagnetic field is shown in Figure 9. The ohmic loss of the electromagnetic field of the two micro valves under the same current is shown in Figure 10. As can be seen from Figures 8 and 9, the magnetic line density and magnetic induction of the electromagnetic field rise with the increase of the excitation current. The ohmic loss of the new valve is smaller than that of the traditional valve.

3.2. Dynamic Characteristics. The current rising speed of the electromagnet determines the dynamic characteristics of the micro solenoid valve. The faster the current rising speed, the better the dynamic characteristics. The rising speed of the current depends on the inductance of the electromagnet, and the inductance is related to the number of coils. As shown in Figure 11, as the number of coils increases, the inflection point of current rise appears more slowly, and when the current is stable, the currents are the same. This is because as the number of coils increases, the inductance of the electromagnet increases, impeding the rate of current change, thus reducing the rate of current rise. In order to obtain a higher current rising speed, the number of coil coils should be reduced appropriately.

The motion speed, displacement, and electromagnetic force of different coil loops are shown in Figures 12–14. Taking 1300 turns as an example, at 2.78 ms, the electromagnet begins to move with speed and displacement. At 3.61 ms, the speed reaches the maximum value, about 1.02 m/s. Since then, the velocity has decreased, and the velocity has decreased to 0 at 3.74 ms. Accordingly, the displacement has reached the maximum value of 0.3 mm.

4. Conclusion

In this paper, the simulation results are in good agreement with the experimental results of the miniature digital valve, and the simulation model is accurate. The electromagnetic characteristics and dynamic response are studied in the paper. The smaller the coil number and the smaller the

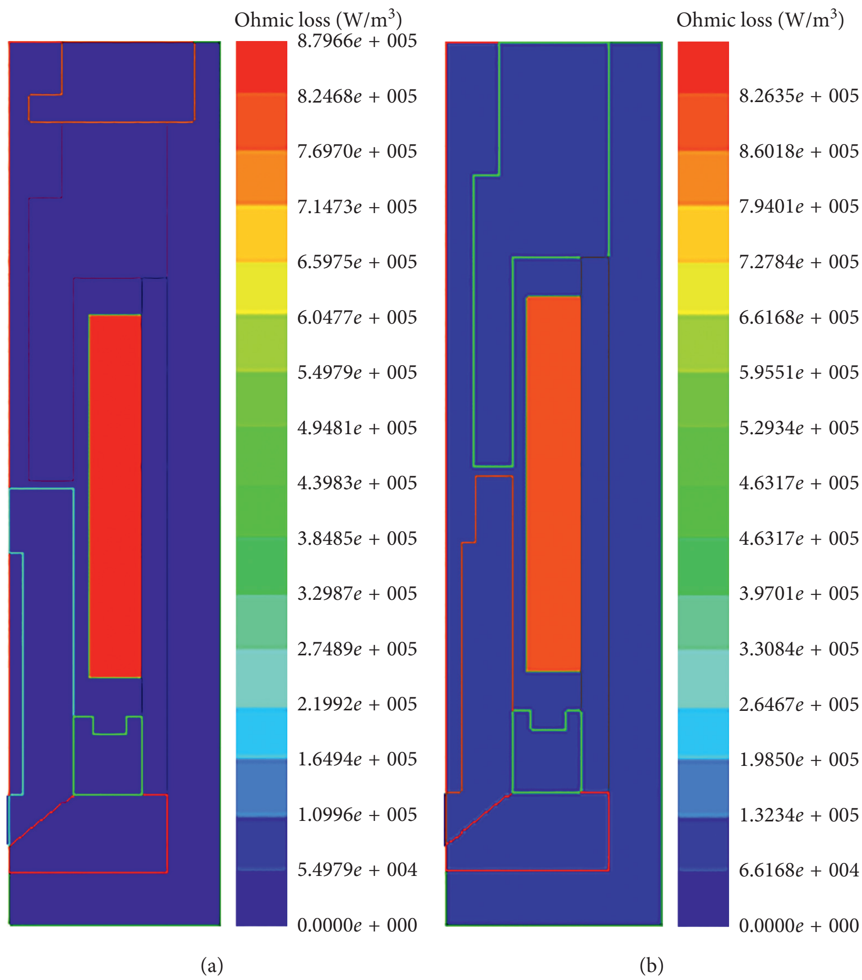


Figure 10: Energy nephogram. (a) 0.8 A. (b) 0.8 A.

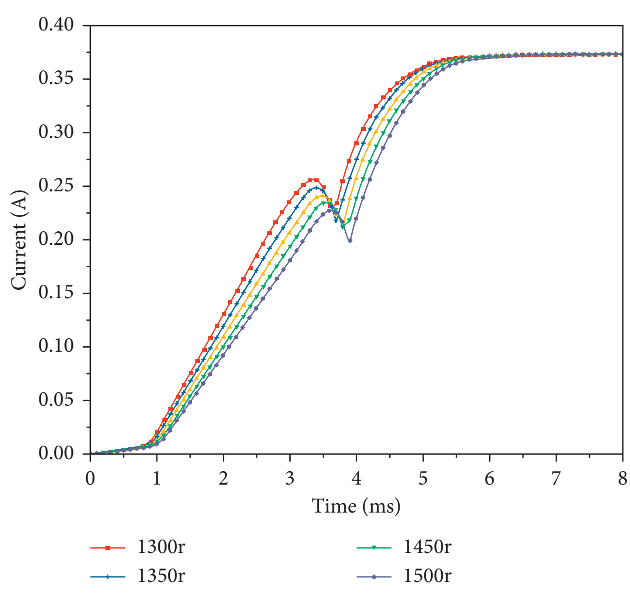


Figure 11: Current under different coil turns.

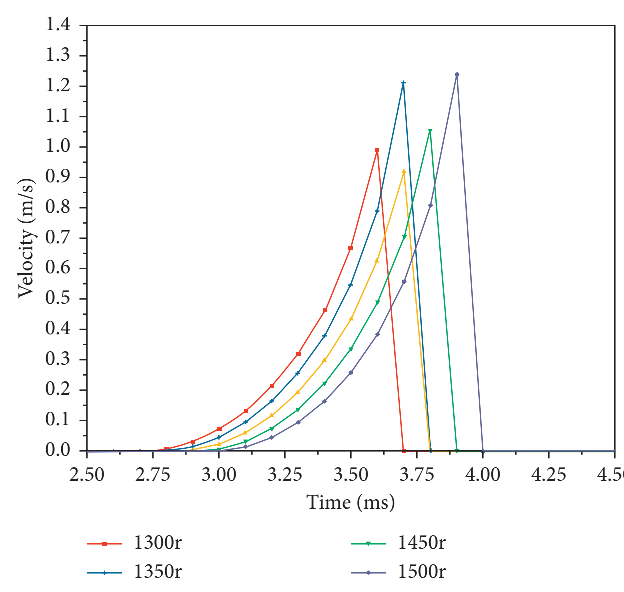


Figure 12: Velocity under different coil turns.

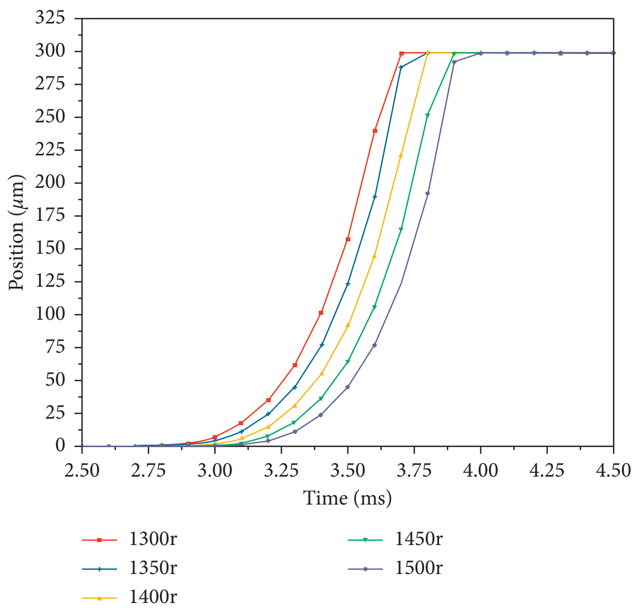


FIGURE 13: Position under different coil turns.

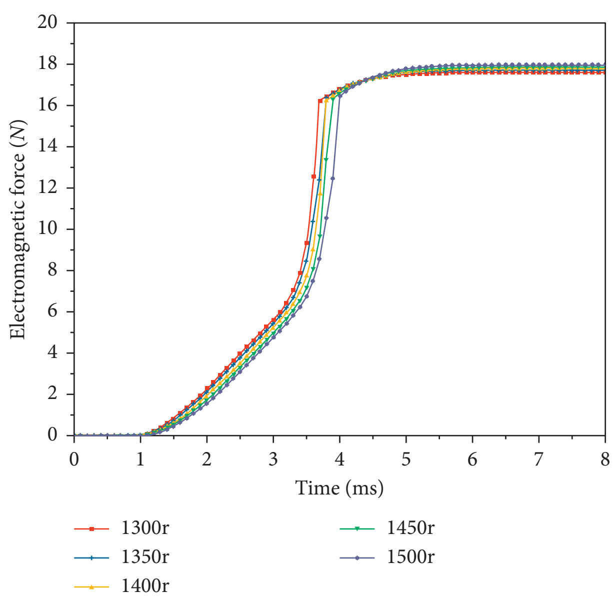


FIGURE 14: Electromagnetic force under different coil turns.

inductance, the faster the current response of the electromagnet. Correspondingly, the faster the speed, the greater the displacement. Therefore, under the same conditions, the coil turns should be reasonably reduced to improve the dynamic characteristics of the micro digital valve.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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