Research on New Type of Giant Magnetostrictive Precision Flow Pump

Quanguo Lu* , Qin Nie

Institute of Micro/Nano Actuation and Control, Nanchang Institute of Technology, Nanchang, 330099

Abstract. In order to realize the precision flow control and widen the application scope of flow pump, in this article, the giant magnetostrictive material was used as driving source to design a new type of precision flow pump. Adopted I-shaped pump body to simplify the structure, simultaneously, it enhanced the sealing of the system, so that the pump could be more adaptive to the miniaturization volume requirement occasion. The multi-slice magnetostrictive membrane was attached onto the beryllium bronze elastic plate constitute a magnetostrictive vibrator, and thus the magnetic energy could be transformed into mechanical energy by the magnetostrictive vibrator. Combined with the finite element analysis to analyze the magnetic distribution of the whole structure, the influence of different current intensity, different turns of coils, different magnetostrictive membrane structure and size on the maximum deflection of magnetostrictive vibrator. In order to test the performance of the magnetostrictive membrane pump, a test platform was built. The test results showed that when the driving voltage was 3Hz and the driving voltage amplitude was 7V, the maximum output flow rate reached the 0.0952ml/min.

1 Introduction

As one main direction of Micro Electro Mechanical System (MEMS), microfluidic system can accurately detect and control the flow, and has shown a broad application prospects in fields such as the medical detection, computer (CPU cooling), biochemical (genetic screening), environmental monitoring (air pollution), military (fuel injection), industrial control (precision displacement control)[1]. As the core part of the microfluidic system, the precision flow pump has become a hot spot in the domestic and foreign scholars in recent years. Precision flow pump is a kind of hydraulic power device which can precisely control the output flow. It is an energy conversion device. It has the advantages of high precision, wide application range, simple structure and high reliability[2].

At present, most of the international precision flow pump adopt the thin membrane structure, that is, through the reciprocating vibration of the thin membrane to achieve the purpose of pumping fluid[3]. The existing precision flow pump usually uses the piezoelectric material as the driving source[4]. The piezoelectric material mainly refer to the piezoelectric chip type and the piezoelectric stack type[5]. The piezoelectric chip pump can withstand the low voltage, but the driving force is small, the load bearing capacity is relatively weak. The piezoelectric stack pump is driven by high voltage, the displacement is small, resulting in the problem of insufficient pressure[6]. What is more important is that the piezoelectric vibration should work in resonant state, it is very difficult to realize the precise flow control, so the application has been limited strictly[7]. For example, Suzuki Katsuyoshi, a professor at Yamagata University in Japan, produced a piezoelectric chip pump, the optimum frequency was at 2-3Hz, but the driving voltage was 120V, the maximum output flow rate without load was 110ml/min[8]. Investigate its root cause, the driving source material itself characteristic and the drive mode determined its inevitable exist above insufficient aspects. Sweden, Japan has developed a new type of hydraulic pump with Terfenol-D rod as the driving source, the GMM pump developed by Sumitomo Light Metal Co.,

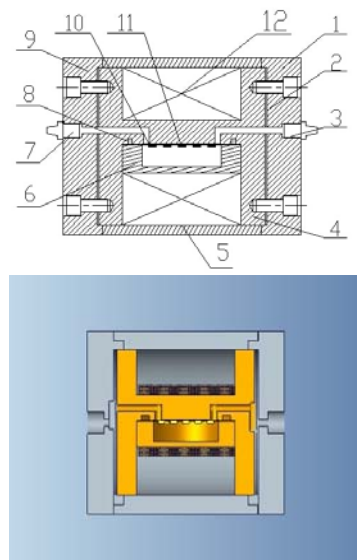Ltd. can be precisely controlled 3mL/min magnitude flow[9].

To improve the response speed and control accuracy of precision pump flow, this article designed a new type of precision flow pump which adopted the giant magnetostrictive material (abbreviated as GMM) as the driving source. the GMM has the characteristic of magnetic field drive(without cable), large deformation and output force, high electromechanical coupling coefficient, fast response speed and low voltage drive[10]. Precise control can be achieved by controlling the input current intensity and frequency[11]. The design provides a better and more effective method for driving the micro-fluid components and improves the output flow of pump[12].

2 Structure Design

2.1 Overall structure design

Giant magnetostrictive material (GMM) is a new type of functional material, which can realize the conversion between electromagnetic energy and mechanical energy. At present, there are two main types of magnetostrictive pump, piston type and membrane type. The piston pump with magnetostrictive rod driving has the characteristic of fast response speed and high precision control flow, but due to the movement of the piston and stick contact, the pump need transmission mechanism and the pre-tight spring. So the output pressure is bigger, but the flow is small, the structure is complex and the volume is larger. Due to the brittleness of magnetostrictive membrane, the range of deflection is subject to certain restrictions, so the output pressure and flow of magnetostrictive membrane pump are smaller[13]. This design used magnetostrictive thin membrane as the driving source, adopted the elastic body instead of the spring to simplify the structure and decrease the pump volume, the elastic membrane can change the volume of the pump chamber, increase the output flow, so that the output flow and pressure can be larger. Instead of the traditional piezoelectric ceramic material[14], this new type of precision flow pump has the

advantages of low voltage driving, high telescopic coefficient and high energy density. The pump need not a high voltage to achieve its function, it can be achieved by changing the driving frequency and the current intensity with high reliability. The structure diagram is shown in the following figure.

1. Inlet end cover 2. Sealing gasket 3. Inlet
4. I-shaped pump body 5. Shell 6. Bottom cover
7. Outlet 8. Sealing groove 9. Outlet end cover
10. Pump chamber 11.GMM membrane 12. Coils

Figure 1. Diagram of Magnetostrictive Membrane Pump

As shown above, the new type of magnetostrictive membrane precision pump used the rare earth GMM as the driving source, pasted multi magnetostrictive membranes onto the beryllium bronze elastic film to compose of a magnetostrictive vibrator. Pass the sinusoidal current through the coil, generating the corresponding alternating magnetic field. When the current increases, the magnetic field strength increases, the GMM membrane elongates in the magnetic field and carry beryllium bronze elastic film move upward. At this time, the pump cavity internal volume decreases while the pressure increases, then, the liquid is discharged from the outlet one-way valve. When the current is reduced, the magnetic field strength decreases. The GMM membrane is gradually restored to normal size and carry beryllium bronze elastic film move downward. At this time, the pump cavity internal volume increases while the pressure decreases, then, the liquid is inhalant from the inlet one-way valve. Through the reciprocating action, the liquid flow continuously. By regulating the driving current intensity and frequency to achieve precise control of output flow. The deformation of concentric elastic film is used as the pre-tightening force, and can be used as the restoring force, so that the structure can be simplified and compact, and it can more efficiently adapt to the small volume occasion. The contact gap between the magnetostrictive membrane and the elastic body is adjusted by the pre-tight spacer, which can effectively prevent the fracture of magnetostrictive membrane.
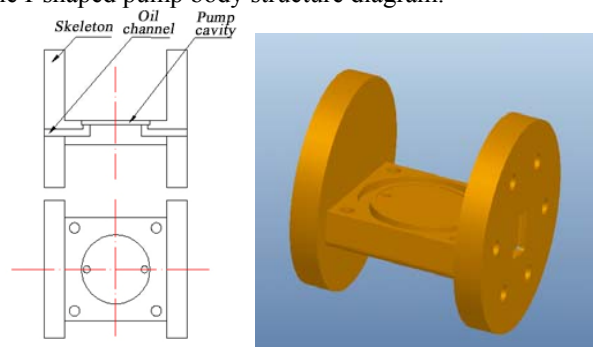
2.2 Design of I-shaped pump body and magnetostrictive vibrator

Taking the performance characteristics of the rare earth GMM and the particularity of flow pump design into account, the design should follow some basic criterion as follows[14].
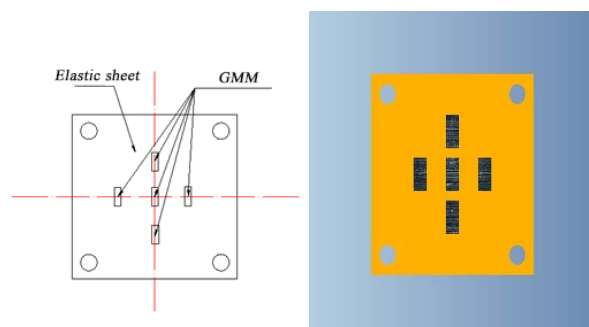
(1) In the magnetic circuit design, the magnetic field generated by the excitation coil should be distributed onto the GMM as much as possible, so the electromagnetic mechanical conversion efficiency can be improved also.

(2) Reasonable solution to the sealing problem of the pump chamber and the flow path. The deflection of the rare earth GMM belongs to the micron level, a good sealing is especially important for the design of the precision flow pump.

The design of the pump chamber and the pipeline will directly affect the sealing performance of the pump. The size of the coil frame directly determines the size of the volume, and the material will affect the magnetic circuit design in the later stage. Based on the above conditions, this article designs a I-shaped pump body. The pump chamber and the inlet pipe and the outlet pipe are integrated in the I-shaped structure, and also can be used as the coil frame. By reducing the number of joints and parts of the pipeline, it can enhance the sealing of the hydraulic system and reduce the leakage. The figure 2 is the I-shaped pump body structure diagram.

Figure 2. Structure Diagram of I-shaped Pump Body

Figure 3. Schematic Diagram of Magnetostrictive Vibrator

In this design, the multi magnetostrictive membrane is attached onto the beryllium bronze elastic plate, which is called the magnetostrictive vibrator. As the power source of the micro pump, the magnetostrictive vibrator is responsible for converting the magnetic field into mechanical energy. The working principle of magnetostrictive vibrator as the micro displacement actuator is the utilization of magnetostrictive affection.

The diagram of the magnetostrictive vibrator is shown in figure 3.

3 Simulation Analysis

3.1 Magnetic field simulation analysis

The magnetostrictive precision flow pump is driven by the magnetic field, and the magnetic circuit design will directly affect the performance of the pump, so the magnetic circuit design is so important in this design. The goal of magnetic circuit design is to distribute the magnetic field onto the magnetostrictive membrane more uniform, reduce the magnetic leakage and improve the electromagnetic conversion efficiency. In here, combined the finite element analysis software ANSYS 12.0 to simulate the magnetic field.
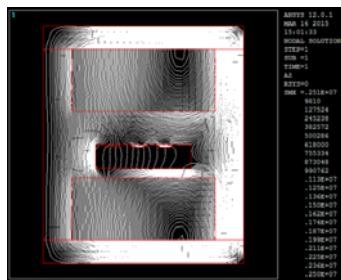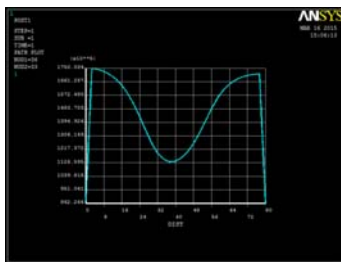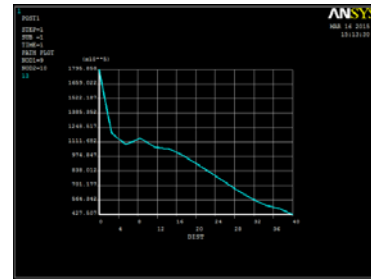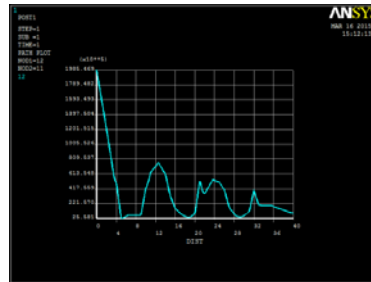

Figure 4. Magnetic Lines Distribution

Figure 5. Edge Magnetic Field Distribution

Figures shown above is the magnetic lines distribution and the edge magnetic field distribution. We can see that the most intensive portion of the magnetic field distribution is the part of the shell which has the largest relative permeability, and the middle part of the magnetic field strength is smaller compared with both ends due to the influence of air area in the middle domain. From the top to down, the magnetic field intensity first decreases, reaches the minimum in the middle air area, then increases gradually, and presents a symmetrical distribution.

In the air field there exists two sides, the side without any magnetostrictive membrane and the side with three pieces of magnetostrictive membranes, the magnetic field strength is shown in the figure 6. It can be seen from the diagram that the magnetic field strength of without any magnetostrictive membrane side is gradually weakened, however, in the side with three pieces of magnetostrictive membranes, the local magnetic field strength is obviously enhanced influenced by the magnetostrictive membranes.

A. without magnetostrictive membrane

B. with magnetostrictive membranes

Figure 6. Magnetic Field Distribution on Both Sides of the Air Area

3.2 Magnetic-Structure coupling simulation analysis

As the energy transducer, magnetostrictive vibrator is the core component of the precision flow pump. In here, utilize the finite element analysis software COMSOL Multiphysics to carry out magnetic-structure coupling simulation analysis.
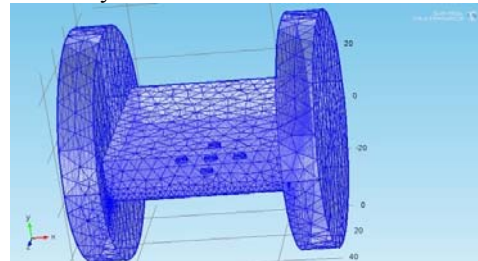

Figure 7. Diagram of Grid Division

The purpose of this magnetic-structure coupling simulation is to obtain the deflection of magnetostrictive vibrator under different current intensity, different turns of coils, different magnetostrictive membrane number and different size.
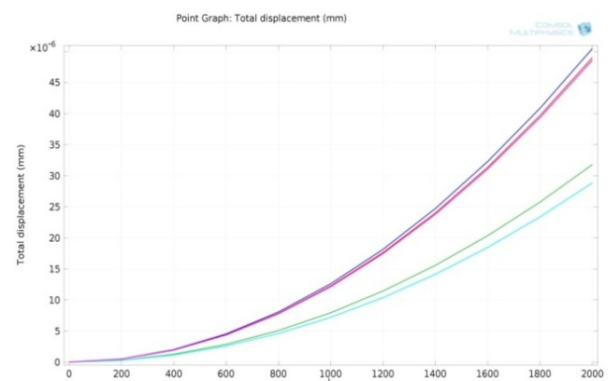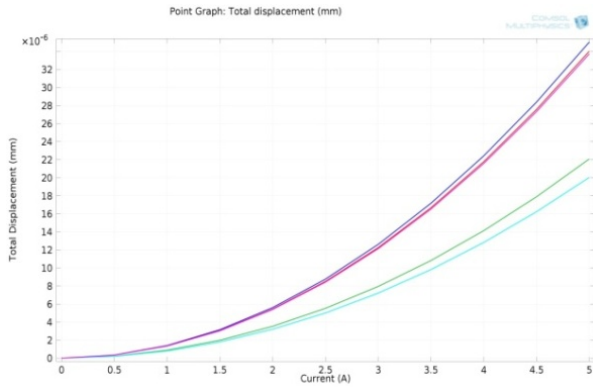

Figure 8. Deflection under Different Turns of Coils

Figure 9. Deflection under Different Current Intensity

From the figures above we can conclude that the deflection of the five magnetostrictive membranes is increased with the increase of the current and the turns of the coil, and considering the horizontal and vertical structure of the coil, The deflection of the center magnetostrictive membrane is the largest and the deflection of the two magnetostrictive membranes in the horizontal direction is comparatively smaller, but the difference is not big.

Table 1. Magnetic-Structure Simulation Results

Number of GMM membrane	size (mm)	Turns of coils	Current (A)	Maximum Deflection (μm)
5	4×2×1	1000	2	10.5
5	4×2×1	2000	2	23.1
5	4×2×1	2000	3	51.9
9	4×2×1	2000	2	23.3

As can be seen from the above table, the current strength and the turns of coils have a bigger influence on the maximum deflection of GMM membrane, the structure size and the number of GMM membrane have a relatively smaller influence.

4 Performance Test Experiment

Through the design, the mechanical machining and assembly, the actual parameters of the magnetostrictive membrane pump are shown in the following table.

Table 2. Actual Parameters of Magnetostrictive Membrane Pump

Coils			Shell		Pump body	
Turns	diameter	Length	external diameter	Length	external diameter	Length
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
500	0.8	60	100	88	80	84

In order to test the performance of the magnetostrictive membrane pump, a test platform was built. The drive signal generated by frequency transducer is connected to the drive coil, generating the driving magnetic field, then the magnetostrictive membrane produces deformation and bring the beryllium bronze elastic film to do reciprocating motion, liquid flow through the oil filter into the pump chamber and then out of the pump cavity thus forming a circle. The test platform is shown in figure 10.
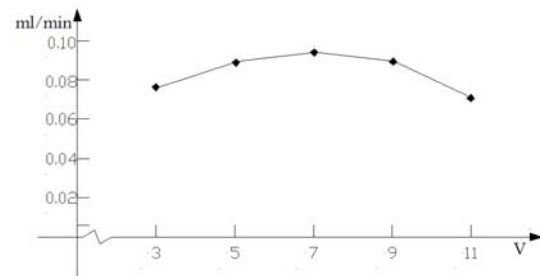

Figure 10. Performance Test Platform

(1) Set the driving frequency as 3Hz, then the variation of the outlet flow with the driving voltage amplitude is shown in the following table.

Table 3. Variation of Outlet Flow with the Driving Voltage

Driving Voltage(V)	3	5	7	9	11
Outlet Flow (ml/min)	0.0731	0.0886	0.0952	0.0840	0.0725

Figure 11. Variation Diagram of Outlet Flow with the Driving Voltage
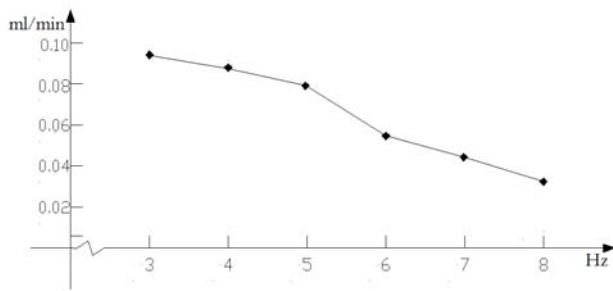
Through the above analysis of the parameters and the diagram, it can be known that when the driving voltage is 3Hz and the driving voltage amplitude is 7V, the maximum output flow rate reaches the 0.0952ml/min. By increasing or decreasing the driving voltage amplitude, it can realize the flow precise control.

(2) Set the driving voltage amplitude as 7V, the variation of outlet flow with driving frequency is shown in the following table.

Table 4. Variation of Outlet Flow with Driving Frequency

Driving Frequency (Hz)	3	4	5	6	7	8
Outlet Flow (mi/min)	0.0952	0.0830	0.0776	0.0524	0.0426	0.0313

Figure 12. Variation Diagram of Outlet Flow with the Driving Frequency

By the diagram above, it can be found that the flow rate decreases with the increasing frequency under the driving voltage of 7V.

5. Conclusions

The pump could realize precise flow control by changing the driving current intensity and frequency, so that this kind of precision flow pump has a broader application prospect especially in the low voltage driving occasions. By combining finite element simulation analysis and the performance test results, we can draw the conclusions as follows.

(1) Under the influence of the magnetostrictive membrane, the local enhancement distribution of the magnetic field strength in the air area is found.

(2) The influence of the coils turns and current intensity on the maximum deformation is relatively bigger, while the influence of structure size and number of the magnetostrictive membrane is comparatively smaller.

(3) The maximum output flow rate reached the 0.0952ml/min when the driving voltage was 3Hz and the driving voltage amplitude was 7V.

Acknowledgments

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