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# Ferrofluid-Based Shape-Controllable and Fast-Responsive Micro-Pumping and Valving Actuation

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***Abstract*—Micro-pumping and valving based on ferrofluid is a promising research area that offers novel solutions in many potential engineering and biomedical applications. In this paper, a novel electromagnetic actuated valve design based on ferrofluid action is presented. To date, traditional mechanical pumps and valves is replete with limiting features such as low on-off frequency limit, contact wear losses, and bulky size. However, due to the superparamagnetism and the high magnetic susceptibility of the ferromagnetic nanoparticles, ferrofluid can be actuated by magnetic field to perform fast-responsive, shape-controllable and small-scale valving actions. In this study, finite element models are built to analyze various design parameters including valve shape, valve dimensions, electromagnetic characteristic of ferrofluid and applied magnetic fields. An electromagnetic actuated ferrofluid valve is then designed and implemented. The valves are tested with switching frequency up to 250 Hz, and the valve's diameter can be scaled down to 1 mm and beyond.**

***Index Terms*—Ferrofluid, micro-valve, micro-pump, electro¬magnetic actuation.**

## I. Introduction

Miniaturization of actuating devices has been of immerse interest for their potentials in many biomedical and industrial applications. Miniaturized actuators such as those based on piezoelectric materials have dominated the field. Most of these devices are designed by scaling down their mechanical counterparts, and therefore deplete with limiting features such as low on-off frequency limit, contact wear losses, and bulkiness. However, recent advances in nanotechnologies and nanomaterials have opened up new design opportunities that are based on very different actuation mechanisms. Since its discovery by National Aeronautics and Space Administration (NASA) in 1963 [1], ferrofluid has been used to form micro-channels in a range of applications, such as in heat transfer [2]–[5], chip cooling system [6]–[9] and drug delivering [10]–[14], with varying degrees of success. Although ferrofluid has been used for micro-pumping by Evrim and Arzu [15], [16],they use a mechanical means to generate rotating magnetic flux to actuate the ferrofluid valves. Thus, the method is very cumbersome and bulky. Besides, it cannot control the valve's shape. Meanwhile, miniaturized electromechanical pumps based on scaled-down mechanical structures using piezoelectric materials have been widely reported with much success. Piezoelectric actuation designs by Spencer [17] and Van Lintel [18] demonstrate their potentials in miniatured pumping and valving. Izzo has carried out a modelling method and experimental validation of piezoelectric micro pumping [19]. In Ma [20] and Park's [21] work, different applications of piezoelectric pump have been analysed such as cryogenic and diaphragm micro-pump applications [20], [21]. However, significant challenges remain for these electromechanical micropumps and valves, such as the limitation of on-off action frequency, contact wear loss and limitation of materials and sizes of the valve. These intrinsic limitations present design challenges for piezoelectric-based valves, in particular in micro/nano scaled applications, and thus incentivize the search of nanomaterial-based solutions.

In recent researches, ferrofluid has been widely investigated for microfluidic pumping applications. The main actuation method for the microfluidic pumping is rotary permanent magnet. A various of rotary magnet designs were introduced in the recent research works carried out by Doganay, Liu. [22], [23]. In Doganay's and Liu's work, the ferrofluid is actuated by a rotary magnetic field sources generated by rotating magnets. However, this actuation method requires a large space for the external rotating magnetic source comparing to the small size of the micro-valve. Furthermore, it is hard to control the shape of the ferrofluid valve by a rotating permanent magnet system.

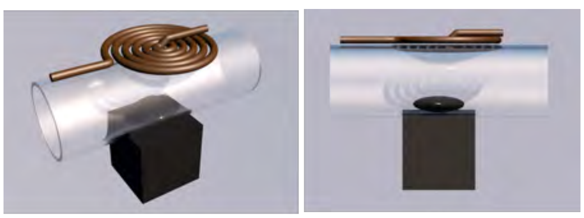
This study aims to explore the full potentials and viability of a ferrofluid-based shape-controllable and fast-responsive nano/micro pumping and valving actuation. In this simulation empirical study, an electromagnetic actuated ferrofluid valve design is proposed. Due to the superparamagnetism characteristic of the ferrofluid and the high magnetic susceptibility of the ferromagnetic nanoparticles, the speed and manner of the formation of the shape of the ferrofluid can be readily manipulated by externally controlled magnetic field. The weight of the nanoparticles will be negligible in the models, and their distribution will be predicted by magnetic flux pattern rather than gravity. To verify this assumption, a various of different finite element models have been built to predict the distribution of magnetic flux density and the simulation results are verified with experimental results.

## II. Methodology

### A. Mechanism of ferrofluid valve

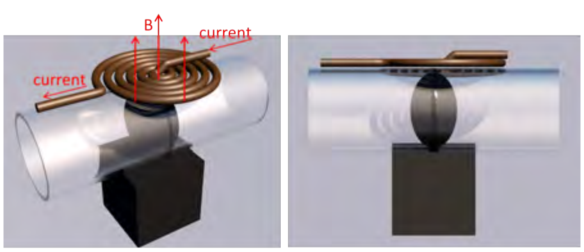
In this work, the proposed ferrofluid valve is actuated by an applied external magnetic field. The schematic model of how the ferrofluid valve works is shown in Figure 1 and Figure 2. The electromagnetic actuator and the permanent magnet are put on the top side and bottom side of the test tube respectively. The ferrofluid is put inside the tube and adsorbed by the permanent magnet. As shown in Figure 1(a) and Figure 1(b), there is no current excitation in the coil and the coil generates no actuation. So the ferrofluid is fully adsorbed by the permanent magnet and the valve action is "on" which allows the fluids to flow through the valve. While there is a current excitation in the coil as shown in Figure 2(a), the coil generates a magnetic field which is the external actuation for the ferrofluid. The actuated ferrofluid forms into a barrier and blocks the fluid flowing through the valve, as shown in Figure 2(a) and Figure 2(b). So with current excitation, the ferrofluid valve action is "off" which blocks the fluid flow.

Therefore, by controlling the current excitation, the ferrofluid valve can be manipulated to form as an effective on-off switching valve. Furthermore, the shape of the ferrofluid valve can be controlled to generates different flow patterns by manipulating the magnetic actuation field.



(a) (b)

Fig. 1: (a):Schematic model of ferrofluid valve (valve on, excitation off), (b): Side elevation .




(a) (b)

Fig. 2: (a):Schematic model of ferrofluid valve (valve off, excitation on), (b): Side elevation.

### B. FEM simulation

In this study, two different sources for magnetic fields, permanent magnets and field electromagnets, are firstly analysed and then used as the actuation sources to apply electromagnetic field.

For the fields generated by electromagnets, the magnetic vector potential is solved by equation (1).

$$\nabla \times (\mu^{-1} \nabla \times A) = j_c \tag{1}$$

where $\mu$ is the magnetic permittivity, $A$ is the magnetic vector potential, $j_c$ is the current density of the applied current. Accordingly, the magnetic field $H$ and the magnetic induction intensity $B$ can be expressed as:

$$B = \nabla \times A \tag{2}$$

$$H = \mu^{-1} B \tag{3}$$

For the fields generated by permanent magnets, the magnetic field $H^{'}$ at the non-current region satisfies the following conditions:

$$\nabla \times H' = 0 \tag{4}$$

The magnetic scalar potential $V_m$ can be expressed as:

$$H' = -\nabla V_m \tag{5}$$

It is homologous to the definition of the electric potential in an applied static electric field. The magnetic induction intensity $B^{'}$ at the non-current region can be derived as:

$$B' = \mu_0 (H' + M) \tag{6}$$

$$\nabla \cdot B' = 0 \tag{7}$$

where $M$ is the magnetization factor, $\mu_0$ is the permeability of vacuum. By substituting equation (5) and (6) into (7), $V_m$ can be rewritten as:

$$-\nabla \cdot (\mu_0 \nabla V_m - \mu_0 M) = 0 \tag{8}$$

Due to the characteristic of superparamagnetism material, the ferrofluid behaves like a paramagnet with a large magnetic moment in the absence of the external magnetic field. However, the ferrofluid becomes ferromagnetic and magnetized when applied with external magnetic field. The magnetic force on the ferrofluid can be calculated by integrating the surface stress tensor over the entire boundaries of the ferrofluid region. The stress tensor can be expressed as [24]:

$$n_1 T_1 = -\frac{1}{2}(H \cdot B) n_1 + (n_1 \cdot H) B^T \tag{9}$$

where $n_1$ is the boundary normal pointing out from the ferrofluid, $T_1$ is the stress tensor of air.

The finite element model is meshed using the COMSOL software and the magnetic equations and field are solved by the Multiphysics 5.6 COMSOL software. The finite element simulations were performed in the workstation with Intel 2.80$GHz$ processor and 64$GB$ RAM. The value of the simulation parameters are shown in Table I.

### C. *Experimental set-up*

The experimental set-up for building and testing the ferrofluid valve is shown in Figure 3. The size of the test tube for designing the shape of ferrofluid valve are selected to be 1.5 $cm$ and 1 $mm$. The permanent magnet are put under the test tube to adsorb the ferrofluid and to work as a magnetic fixation for the ferrofluid. The excitations for the ferrofluid valve are the electromagnet and permanent magnet putting on the top side of the test tube.

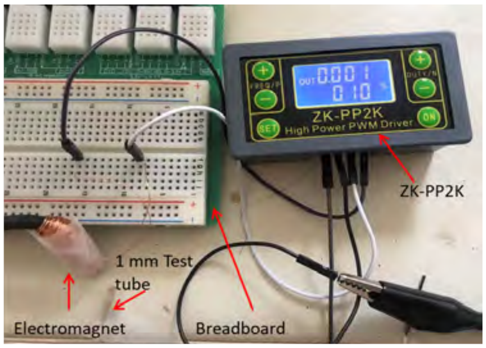



Fig. 3: Experiment set-up.

The electromagnet is winded using copper wire with diameter of 0.1 $mm$. There are two types of iron cores selected in this study to build two electromagnets with different diameters. The diameters of larger and smaller electromagnets are 2 $cm$ and 2 $mm$ respectively. Each iron core is winded with 500 turns of copper wires and the wires are connected to a ZK-PP2K PWM generator, which works as a signal generator generating DC voltage signal and square wave signal with frequency ranging from DC to 150 $kHz$. The ZK-PP2K PWM generator is powered by a DC power supply with voltage output ranging from 0 $V$ to 30 $V$.

The shape control experiment of the ferrofluid is carried out by putting the permanent magnet in the exactly same position and orientation (north pole pointing direction). The magnetic flux inside the test tube is determined by the position and orientation of the external permanent magnet. The shape of the ferrofluid can be controlled by manipulating the magnetic flux flowing through the ferrofluid.

The on-off switching frequency experiment is carried out by putting the electromagnet on the top of the test tube. A square wave excitation for the electromagnet is generated by the ZK-PP2K PWM generator. The excited electromagnet actuates the ferrofluid to form an on-off switching valve action with frequency referring to the excitation signal. A fluid pumping system was built to measure the flow rate of the system to validate the effectiveness of the ferrofluid valve. The flow rate is measured by a flow rate sensor with a electronic meter. As shown in Figure 4, the flow rate measurement system consists of a water pump, a water tank, a flow rate meter and a digital reading screen connected to the flow rate meter. The maximum capacity of the water tank is 2.5 $L$. The water pump is working under 5 $V$ to 12 $V$ and it can generate a water flow with

TABLE I: Parameters and power system terminology

| Symbol | Parameter | Value | Units |
|---|---|---|---|
| $\rho_f$ | density of ferrofluid | $1,212$ | $kg/m^3$ |
| $\rho_p$ | density of $Fe_3O_4$ | $5,240$ | $kg/m^3$ |
| $\emptyset$ | volume fraction ratio | 0.05 | – |
| $\rho_w$ | density of water | $1,000$ | $kg/m^3$ |
| $\mu_w$ | viscosity of water | $1 \times 10^{-3}$ | $Pa \cdot s$ |
| $\mu_r$ | relative permeability of ferrofluid | 1.05 | – |
| $\mu_f$ | viscosity of ferrofluid | $1.13 \times 10^{-3}$ | $Pa \cdot s$ |
| $\mu_{r,m}$ | relative permeability of water | 1 | – |
| $\mu_{r,p}$ | relative permeability of $Fe_3O_4$ | 2.46 | – |

flow rate up to 1 $L/min$. The flow rate meter is DigiFlow 6710M connected to a digital reading screen which can read the flow rate and the total amount of fluid flowing through the meter. The diameter of the pipe is 4 $mm$ and a ferrofluid valve was built inside the pipe with the same diameter of 4 $mm$. The effectiveness of the on-off switching ferrofluid valve is validated by the result of flow rate test based on PWM controlling.

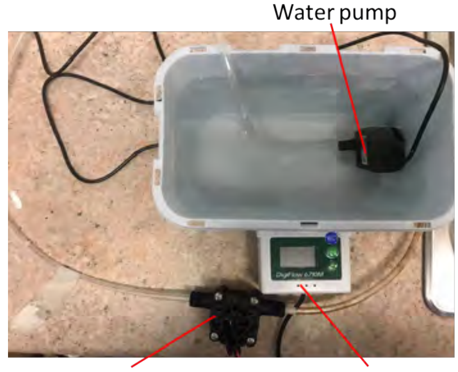



Fig. 4: Flow rate measurement system.

## III. Result and discussion

### A. *Shape control of ferrofluid*

The FEM simulation results are validated by experimental results of ferrofluid valve actuated by applied external magnetic field. The shape of the ferrofluid under different applied external magnetic field can be predicted by calculating the distribution of magnetic flux density based on finite element models and the results are in good agreement with the experimental results. The simulation results are compared for different meshing accuracy to maintain the convergence and independence of the number of element for the numerical solutions. Since the size of the valve is significantly small, the influence of the gravity of ferrofluid is negligible comparing to the influence of the magnetic force in this study.

The magnetic flux is generated by the permanent magnets and the coils. The distribution density of the magnetic flux is determined by the orientation and position of the permanent magnets and coils. By calculating the distribution density of the magnetic flux, the shape of the ferrofluid can be predicted and plotted. In this study, finite element based simulation models have been carried out and verified with experimental results.

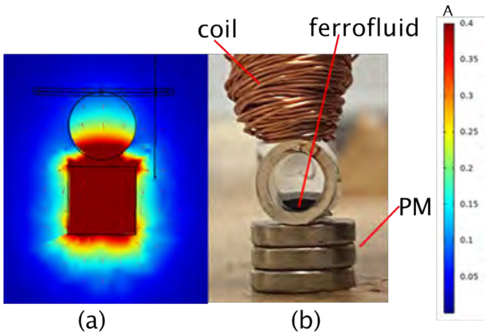



Fig. 5: Shape prediction of ferrofluid (a) FEM model (b) Experimental with non-optimised coils.

Figure 5(a) shows the simulation result of magnetic flux density distribution without excitation from the coil. The tube is put in the middle of the model shaped as a circle. The coil and the square permanent magnet are put on the top side and bottom side of the tube model respectively. The diameter of the tube and the length of side of the permanent magnet in Figure 5 (a) are 1 $cm$. The magnetic flux density mainly distributed on the permanent magnet and the lower part of the tube as shown in Figure 5(a). The ferrofluid is adsorbed by the permanent magnet with magnetic force 0.5 $N$ which makes the ferrofluid capable to withstand a pressure of $1.8 \times 10^4$ $Pa$. In the verification experiment, a permanent magnet was put on the bottom side of the test tube and 1 $ml$ ferrofluid was put in the tube and adsorbed by the permanent magnet. The size parameters of the experiment are set to be the same with the simulation model, and the permanent magnets are put in the same position and orientation with the simulation models. Since the ferrofluid is superparamagnetism, the shape of the ferrofluid is conformed to the magnetic flux density distribution as shown in Figure 5(b).

To verify the assumption that the ferrofluid shape is determined by the magnetic flux density distribution, several groups of simulations and experiments with different combination of permanent magnets have been carried out. As shown in Figure 6 (a) and Figure 7 (a), the distribution of the magnetic flux density is determined by the position and orientation (north pole of the permanent magnet pointing to the orientation direction) of the applied permanent magnet. In Figure 6 (a) there are two permanent magnets put on the top and bottom side of the tube with the same vertical orientation. In Figure 7 (a) the bottom permanent magnet is oriented to the horizontal level which significantly altered the distribution of the magnetic flux density. The experiment results validated that the shape of the ferrofluid is conformed to the distribution of the magnetic flux density, as shown in Figure 6 (b) and Figure 7 (b). Figure 6 (b) shows the front view inside the test tube, the ferrofluid formed into the same shape with the high magnetic flux density region (red region) shown in Figure 6 (a), which is caused by the superparamagnetism characteristic of the ferrofluid. The shape of the ferrofluid in Figure 7 (b) is also in good agreement with the shape of the high magnetic flux density region in Figure 7 (a). There is a little distortion on the shape of the experimental result of ferrofluid comparing with the simulation result. This can be caused by the error of the magnetization and flux direction of permanent magnet in the experiment. However, the shape of the ferrofluid is still in high correlation to the shape of the magnetic flux density distribution regions. Similar results are shown in Figure 8 (a) and (b) that the shape of the ferrofluid is in good agreement to the distribution of the magnetic flux density. Various combinations of permanent magnet position and orientation have been carried out for more valve shape design and the simulation results are verified with experimental results as shown in figure 9.

Based on comparing the simulation and experimental results, the assumption can be validated that by controlling the position and orientation of the permanent magnet, the magnetic flux density distribution can be controlled and thus the shape of the ferrofluid can be manipulated.

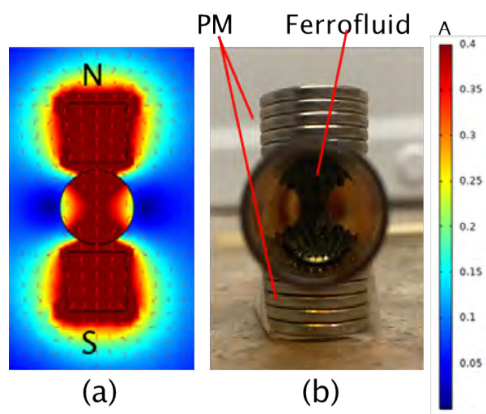



Fig. 6: Fig. 8: Shape prediction of ferrofluid (a) FEM model (b) Experimental

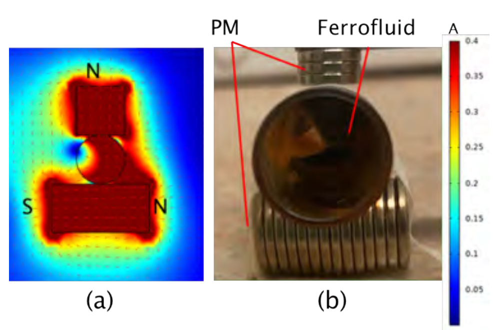



Fig. 7: Fig. 8: Shape prediction of ferrofluid (a) FEM model (b) Experimental

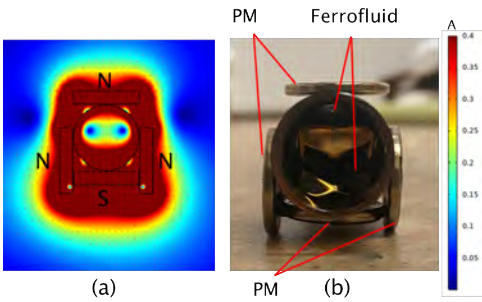
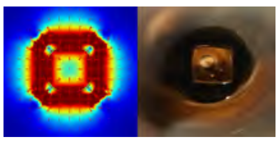
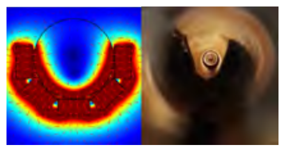


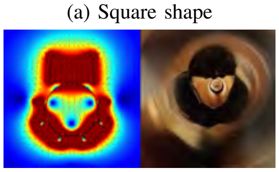

Fig. 8: Fig. 8: Shape prediction of ferrofluid (a) FEM model (b) Experimental



(a) Square shape



(b) U shape



(c) Triangle shape

Fig. 9: Valve shape design

### *B. Ferrofluid valve*

As the shape of the ferrofluid can be manipulated by controlling the distribution of the magnetic flux density, the ferrofluid can be formed into various shapes to act as a valve. The main challenge of designing the ferrofluid valve is the power efficiency and performance as an on-off switch valve. In this study, the ferrofluid valve is designed as a on-off switching valve and the effectiveness of the ferrofluid valve is validated by measuring the flow rate of the fluid flowing through the ferrofluid valve. In addition, a flow rate against PWM duty cycle test is carried out to verify the performance of the designed ferrofluid valve at higher frequency. The experimental set-up for implementing an on-off switching ferrofluid valve and measuring the flow rate are shown in Figure 3 and Figure 4 respectively.

The simulation and experimental results of valve action ”on” are shown in Figure 5. There are no excitation generated from the coil and the ferrofluid is adsorbed by the permanent magnet on the bottom side of the test tube. The ferrofluid action is ”on” and the measured flow rate is 130 $ml/min$ under the pressure of 4.8 $kPa$. To form a valve action ”off”, a 0.9 $A$ current is injected into the 500 turns copper coil with a 2 $mm$ iron core. The simulation and experimental result is shown in Figure 10. The ferrofluid is actuated by the magnetic field generated by the coil and formed as a barrier to block water flow. The flow rate is reduced to 0 $ml/min$ when applying a current excitation and the valve action is ”off”. The result shows that the closed valve can block the entire water flow and the ferrofluid can behave as an effective on-off switching valve. Furthermore, a PWM duty cycle controlling test for the ferrofluid valve is carried out to validate the effectiveness of the valve. According to Miha [25], the solenoid can not fully respond to the input current when the frequency is too high. Therefore, the frequencies of the PWM test are chosen to be 150 $Hz$, 200 $Hz$ and 250 $Hz$ in this study.

The PWM input controlling result is shown in Figure 11. The duty cycle is defined as the duration of valve action ”on” over the whole duration of a single cycle. The flow rate are normalized to zero when the duty cycle is under 10%. Then the flow rate curve shows a steep increasing trend with the duty cycle ranging from 10% to 30%. According to Miha [25], this phenomenon is caused by unstable dynamic equilibrium under low pressure and the initiation of the valve opening action. From duty cycle 30% to 100%, the flow rate increase linearly to 130 $ml/min$ which is 100% of the flow rate when the valve is fully open. This result is in a good agreement with published works carried out by Miha and Taghizadeh [25] [26]. In Miha's work, the flow rate at low pressure 0.1 $bar$ shows the same trend that it increase dramatically at lower duty cycle from 10% to 20% and then the flow rate becomes relative linear from duty cycle 20% to 100% [25]. The work carried out by Taghizadeh shows the similar trend at lower pressure and frequency range. Therefore, the effectiveness of the proposed ferrofluid valve is validated by flow rate measurements and the published results [25], [26].

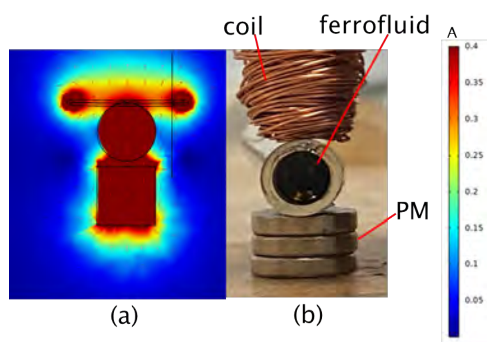



Fig. 10: Simulation and experimental result with coil excitation (a) FEM model (b) Experimental with non-optimised coils.

## IV. Conclusion

A novel non-contact shape-controllable ferrofluid valve is proposed in this paper. The shape control of the ferrofluid is simulated by FEM models and verified with experimental results. It can be concluded that the shape of the ferrofluid is obedient to the applied external magnetic flux density. By controlling the shape of the ferrofluid, a fast react and effective on-off switching valve is implemented. The effectiveness and performance of the proposed ferrofluid valve is validated by flow rate measurements and PWM duty cycle controlling tests. The measurement results are in good agreement with published works. Therefore, the proposed ferrofluid valve is validated

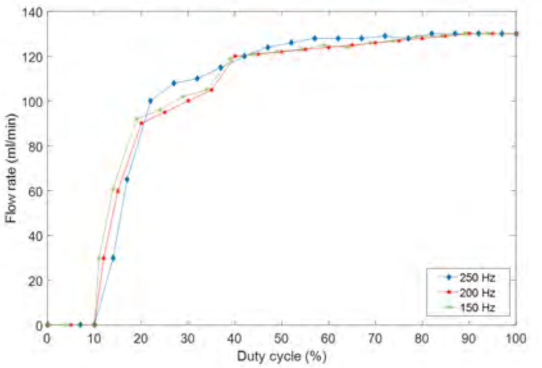



Fig. 11: Result of PWM duty cycle control.

to work effectively at frequency up to 250 $Hz$. Moreover, the FEM models show the ferrofluid-based valve can readily be scaled to nano-pumping and valving applications, thus opening up a new research theme of versatile nanomaterial-based actuations. Further work will be reported in the full paper and our future research.

## ACKNOWLEDGMENT

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