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DESIGN, MODELING AND FABRICATION OF A NOVEL ELECTROMAGNETIC MICRO-ACTUATOR FOR A NEW CONCEPT OF VALVELESS MICROPUMP

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Abstract: *In this paper, a novel electromagnetic micro-actuator prototype has been designed, analyzed and fabricated using conventional elements for a novel working principle of valveless bidirectional micropump. The proposed micro-actuator includes two unfixed permanent magnets placed in opposite polarities between two fixed coaxial coils. The novel electromagnetic actuating concept depends on moving the two unfixed permanent magnets vertically in a cylinder channel via the interaction of their magnetic fields and that resulting from both coils. Therefore, the actuation of magnets is produced with a periodic movement and controlled by the current of the coil. The finite volume method (FVM) is used to analysis the electromagnetic and mechanical behavior of the proposed micro-actuator and to give the dynamic characteristic of the actuation. The proposed micro-actuator shows a large displacement and a high electromagnetic force.*

Keywords: *electromagnetic micro-actuator, FVM, magnets, dynamic characteristic, valveless micropump.*

1. Introduction

According to their association to micropumps for biomedical use, several micro-actuators studies have been elaborated [1]. Regarding some research papers, micro-actuators based on the electromagnetic or piezoelectric phenomenon are the most proposed and fabricated [2], [3]. By the way, two major factors must be considered, the economic one and the fabrication one [4], [5]. Micro-actuators based on electromagnetic phenomenon offer an attractive choice according to many advantages appropriate for various applications thanks to their relatively large displacement and higher force development. They also present the possibility of reducing power consumption by using an appropriate excitation coil [6]-[8]. Mainly, in the electromagnetic actuator, the mechanical force is

produced by means of the interaction of magnetic fields of both excitation coil and a permanent magnet. For example, in the micro-actuator designed by [9], which is consisting of a Nd-Fe-B permanent magnet, a silicon membrane, and an electroplated copper coil, the produced electromagnetic force is used to acting on the diaphragm membrane. Here, the deflection of the membrane attained 14.18 μm whereas the coil is supplied with a current of 1A. Based on the membrane deflection different prototypes of electromagnetic micro-actuators are proposed and designed for micro-pump applications [10]-[13]. However, these micro-pumps are typically limited to 100 μm of membrane deflection and the use of valves is necessary for pumping. According to the biomedical applications area, valveless micro-pump design is required. Such a micropump takes as advantage its simple structure. It offers an excellent alternative in comparison with those utilizing valves. One can notice that two major categories of valveless design have been discussed in bibliography. The first is based on the peristaltic motion of more than three reciprocating membrane pumps [14][15]. The working principle for peristaltic micropumps based on reciprocating membrane is appropriate to the condition of large compression ratio. This is described as the ratio between the stroke volume of the membrane deflection and the dead volume of the pump chamber. So the high compression ratio is attended when the volume of the chamber is obstructed by the moving membrane completely [16]. In addition the use of more than two micro-actuators leads to complicate the driving signals control. Another type of peristaltic motion, consisting of a micro channel formed around a circular hole in the center of the microchip housing a miniature motor is provided

[17]. In contracts the need of motor drive limits its applications and is complicated to fabricate. The second is based on rectifying fluid flow by utilizing diffuser and nozzle elements [18]. However, a few novel designs of valveless micropump have been proposed. In [19], Al-Halhouli proposed and fabricated a novel gentle valveless micropump which includes twelve coils and two permanent magnets. The pumping concept is based on rotating both magnets in an annular channel by controlling the electric current in coils. As the number of coils is large and must be supplied with a specific driving current mode, the required control circuit seems complicated.

In this paper, a novel electromagnetic micro-actuator has been designed, analyzed and fabricated for a new concept of valveless bidirectional micropump. This micro-actuator contains two unfixed permanent magnets placed in opposite polarities between two fixed coaxial coils. The actuating concept depends on moving both magnets vertically in a cylinder channel via the interaction of their magnetic fields and the magnetic field resulting from coils. The magnets move with a periodic movement that is controlled by the electric current of coils. A prototype of the proposed micro-actuator is fabricated and evaluated. The finite volume method based in-house software is used to give the electromagnetic and mechanical behavior of the fabricated micro-actuator, and in particularly the dynamic characteristic of the actuation. In addition, a measurement setup is realized especially to record the experimental dynamic characteristic of the actuation. Both experimental and numerical results are compared.

2. Novel micropump design and working principle

The novel electromagnetic valveless micropump design is presented at Fig. 1. It contains mainly of a cylindrical channel as a pump chamber that houses two discs with opposite holes. The pump chamber is covered by two lids including inlet and outlet ports as shown Fig. 2.

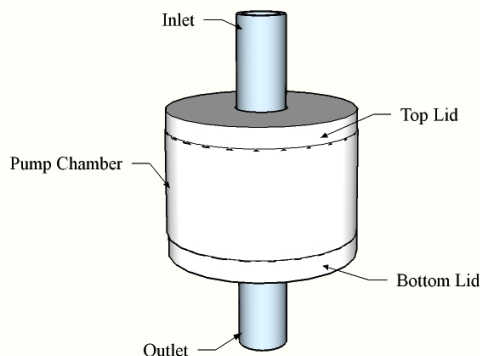


Fig. 1. Valveless micro-pump design

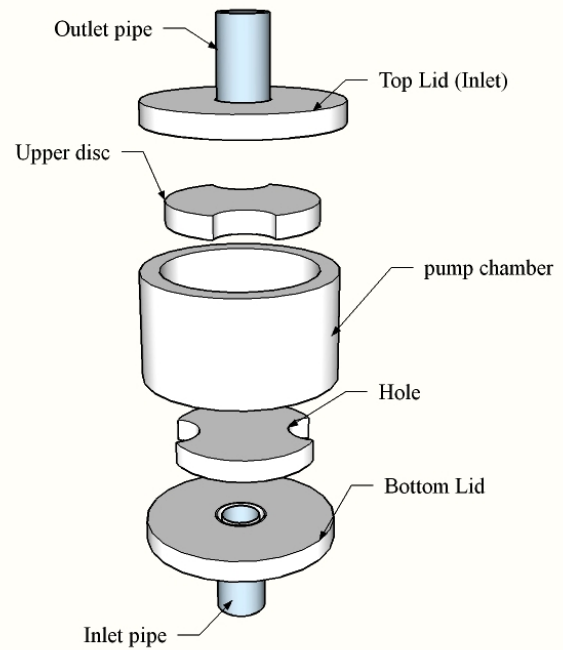


Fig. 2. Valveless micro-pump components

The working principle of the valveless micro-pump is presented in Fig. 3. It based mainly on moving the two discs with opposite holes inside a cylindrical channel with specific motion that provide pressure difference and by consequence a fluid pumping without using valves.

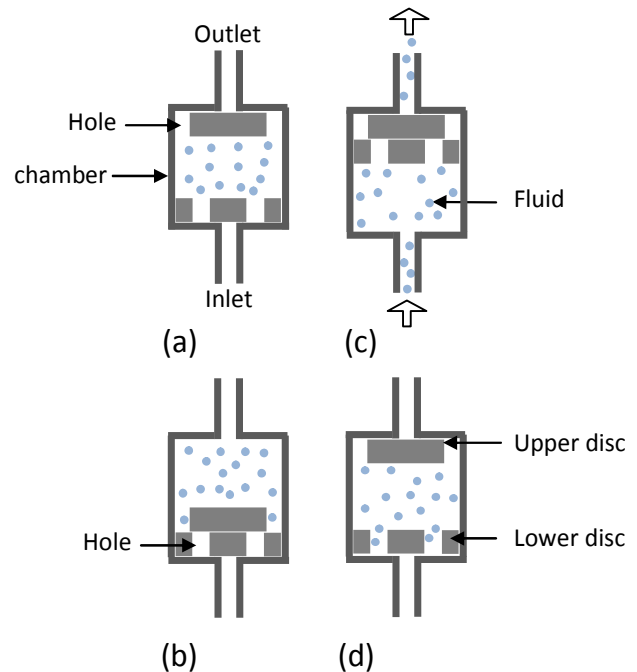


Fig. 3. Working Principle of micro-pump

Let consider at the initial state that the pump chamber is filled by fluid and the inlet and outlet ports are closed by discs positions as shown in (Fig. 3.a). When the upper disc moves toward to the lower disc the fluid inside the chamber is flowing through the holes of the upper disc due to the closed inlet, and stabilizes up of the assembled discs (Fig. 3.b). The simultaneously displacement of the assembled discs as a one without holes; *i.e.* due to the opposites holes, at this state the fluid is pumping out through the outlet and in the same time the chamber is filled by fluid flowing from the inlet as shown in Fig. 3.b. At this state the discharging and suction operations are performed at the same time. (Fig. 3.c) shows how we back to the initial state by moving the lower disc toward to close the inlet, here the fluid is flowing through the holes of the moving disc to stabilize between the closed inlet and outlet. Thus, one pumping cycle is achieved, and as it is a valveless the pump is able to pumping in both directions by reversing the discs movement. In order to evaluate this pumping concept a novel electromagnetic micro-actuator has been proposed.

3. The proposed electromagnetic micro-actuator

The design of the proposed electromagnetic micro-actuator is shown in Fig. 4, it requires two identical coils fixed to upper and bottom extremities of a cylindrical channel, and two permanent magnets. Each magnet is bonded to a non-magnetic material disc as a magnet support. In addition the magnets are placed in opposite polarities.

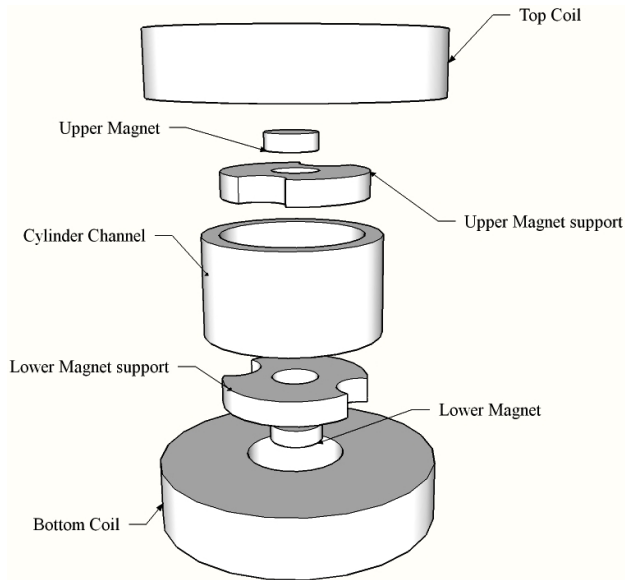


Fig. 4. Design of electromagnetic micro-actuator

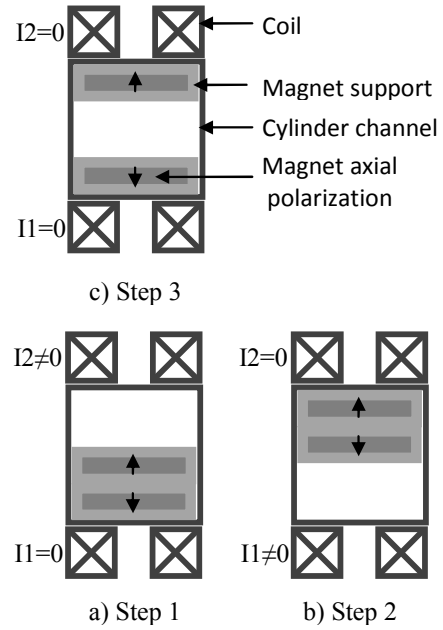


Fig. 5. Working principle of micro-actuator suitable to the pumping concept

The actuating desired mode for the novel valveless micro-pump concept is consisting of moving vertically both magnets inside the cylindrical channel, by means the interaction of magnetic fields generated by the magnets and the coils. In that way, the actuation is produced with a cyclic movement, where one cycle can be subdivided into three main actuation steps Fig. 5. The first actuation step occurs by supplying only the top coil ($I_1=0$, $I_2 \neq 0$). As a result, the upper magnet is repulsed downward inside the cylindrical channel to reach the lower magnet (Fig. 5.a). The second actuation step happens when, at the same time, turning off the top coil and supplying the bottom coil ($I_1 \neq 0$, $I_2=0$) as shown in (Fig. 5.b). In such situation, both magnets repulsed upward simultaneously as they form one piece to reach the top extremity of the cylindrical channel. Finally, the third step happens by turning off both coils ($I_1=0$, $I_2=0$), and due to magnets polarities disposition, a natural repulsive force is produced between them so as each magnet reaches the extremity (Fig. 5.c). The driving currents supplying mode of coils for this actuation cycle are shown in Fig. 6.

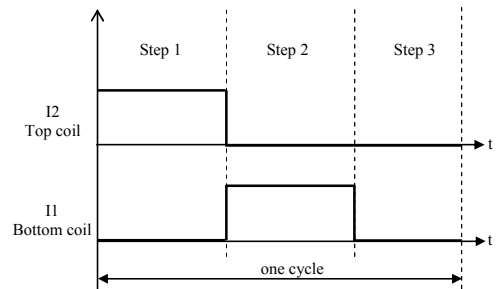


Fig. 6. Driving currents mode for one actuation cycle

4. Fabrication and experimental characteristics

A prototype of the proposed micro-actuator has been fabricated using available elements (Fig. 7 and Fig. 8), two 1.3T NdFeB magnets with 5mm diameter and 1mm height, and two identical copper coils with an outer diameter of 36mm, an inner diameter of 22mm and height of 20mm. Each magnet is bonded to an Aluminum disc. It has 2.5mm height, 15mm diameter drilled in its center to house magnets. The cylindrical channel is retrenched from a prefabricated plastic one, with dimensions of 10mm height and 15mm diameter. To maximize the magnetic field, a cylindrical iron core of 4mm of diameter is inserted in the center of each coil. Because the aim is to test the functioning of the proposed micro-actuator, we are not interested here by dimensional optimization. For this reason, we have taken preliminary dimensions of the micro-actuator which are chosen according to commercially available elements.

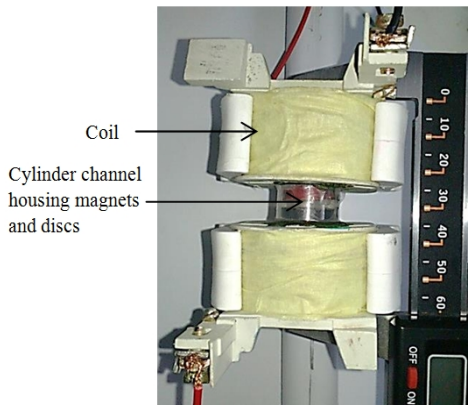


Fig. 7. Photograph of the fabricated micro-actuator

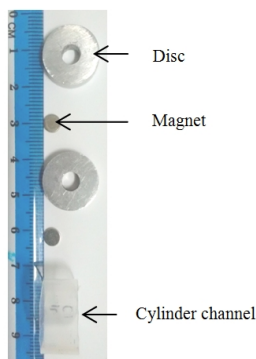


Fig. 8. Photograph of the components of the micro-actuator

The experimental dynamic characteristic of the actuation, i.e. magnet displacement versus time, is measured by using an opto-electronic displacement sensor as described in Fig. 9. The output voltage of the sensor is a function of its illuminating surface, and hence once the magnet moves, the output voltage (Volts) of the sensor is recorded through a data acquisition board (DAQ) and translated into displacement (mm) using an appropriate LabVIEW application. In addition, the developed LabVIEW application controls the electric power supply of coils through a power amplifier. Here, only the dynamic characteristic of the actuation of the upper magnet is measured, and hence only the top coil will be supplied.

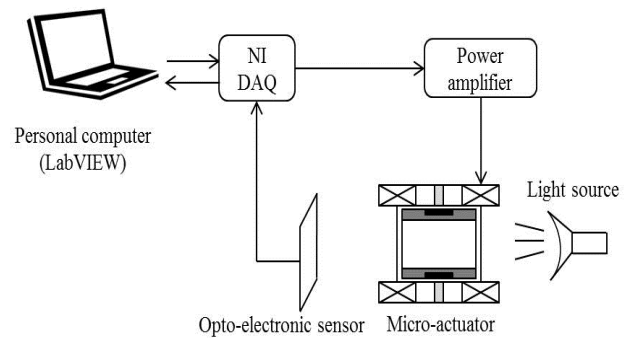


Fig. 9. Measurement of the dynamic characteristic of the upper magnet

The experimental dynamic characteristic of the actuation of the upper magnet is shown in Fig. 10. From 0 to 6ms, when the top coil is supplied with a current of $I_2=1.65A$, the upper magnet is repulsed downward from 7mm to 4mm to reach the lower magnet. Here 0mm is referenced to the lower face of the lower magnet. From 6ms to 17ms, the top coil is turned off, that is why the upper magnet moves back due to the opposite polarities to reach its initial position which is the upper extremity of the cylindrical channel.

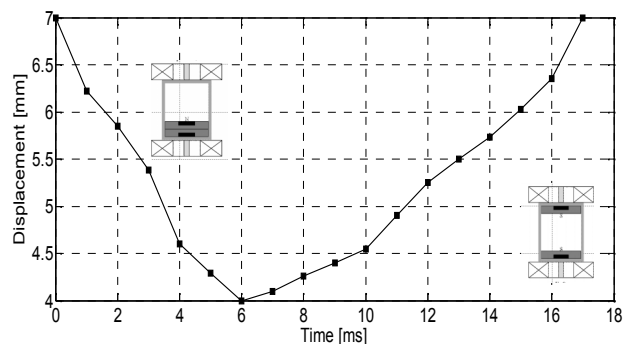


Fig.10. Experimental dynamic characteristic of the actuation of the upper magnet

5. Modeling and numerical characteristics

As described previously, both magnets move next to the action of the electromagnetic forces produced via the interaction of magnetic fields resulting from coils and magnets. In order to evaluate the numerical dynamic characteristic of the actuation, an electromagnetic numerical model has been developed. The governing electromagnetic equations are given by the following set of equations, written in the axisymmetrical case. In (1), A is the magnetic vector potential, J_s is the source current density of coils and ν is the magnetic reluctivity. Once the magnetic vector potential is calculated, the magnetic flux density B is obtained from equation (3). According to the amperian current model a cylindrical permanent magnet whose axial polarization is B_r in Tesla, can be represented by a thin coil whereas its equivalent current is given by equation (2). In this equation, n is the normal unit, and μ_0 is the permeability of the vacuum [20]. Then, based on Lorentz force, equation (4) is used to compute the electromagnetic force F_z along z which is only related to the radial component B_x .

$$\frac{\partial}{\partial r} \left(\nu \frac{\partial A}{\partial r} \right) + \frac{\partial}{\partial z} \left(\nu \frac{\partial A}{\partial z} \right) = -J_s \quad (1)$$

$$\vec{J}_a = \frac{\vec{B}_r \times \vec{n}}{\mu_0} \quad (2)$$

$$B = \nabla \times A \quad (3)$$

$$F_z = \int J_a \times B_x \quad (4)$$

The dynamic characteristic of the actuation, which is the magnets displacement versus time, has to be evaluated by coupling the previous set of equations to the mechanical one (5). In this equation, m and z are respectively the mass and the displacement of the moving magnet along z -axes and g is the gravity. The magnet displacement is considered ideal *i.e.* frictions are not taken into account.

$$m \frac{\partial^2 z}{\partial t^2} = F_z + m \quad (5)$$

To solve the electromagnetic equations, the finite volume method FVM is used. In order to validate the experimental dynamic results, let consider the geometrical model and its triangular discretization of Fig. 11.

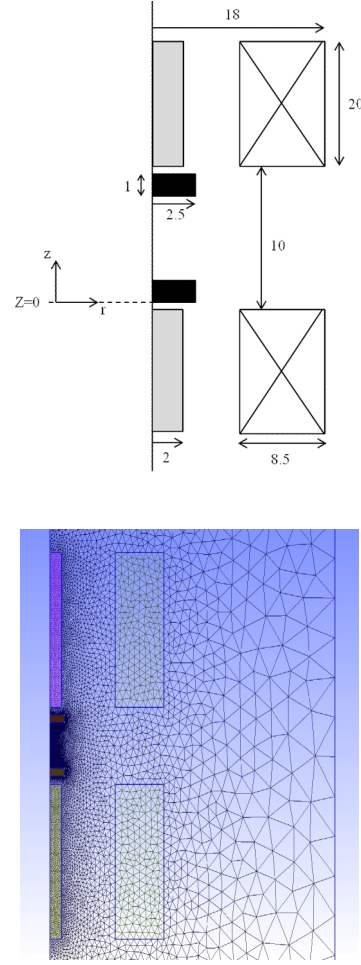


Fig. 11. FVM mesh of the geometrical model of the micro-actuator

The numerical results obtained by the FVM method, show that the upper magnet takes 5.1ms to move downward from its initial position at 7mm to attain its final position at 4mm, and takes about 7.5ms to move upward from 4mm to reach its initial position (Fig. 12). Since frictions are not taken into account in the mechanical equation, the elapsed time in the numerical characteristic is less than in the experimental one with a difference of 4ms. However, what interests us is the device actuation dynamics, *i.e.* the traveled distance of the magnet between its initial position and final position. Both experimental and numerical characteristics of the actuation show that the electromagnetic force applied to the magnet is sufficient for the operation of the micro-actuator that requires a force strong enough to push the magnet until it being in contact to the lower magnet which is placed in opposite polarity. At this position the total force applied on the magnet is about -0.035N. When the coil is turned

off the force between magnets is equal to 0.14N as shown in Fig. 13. Indeed, this first result has given us an idea on the value of the eclectic current of coils that ensures the desired operation mode. This current is 1.65A. This value will be used thereafter to determine the full dynamic characteristic of the actuation.

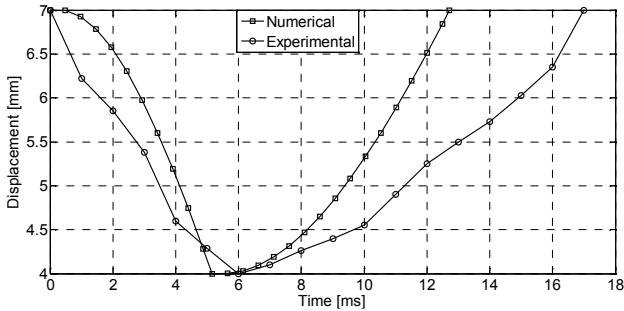


Fig. 12. Numerical dynamic characteristic of the actuation of the upper magnet

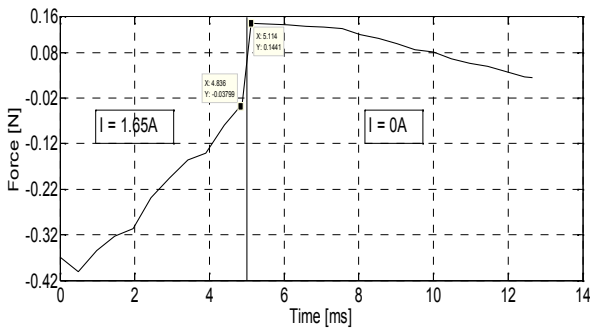


Fig. 13. Electromagnetic force of the actuation correspond to experimental

At this point, only the dynamic characteristic of the actuation of the upper magnet is evaluated. The full dynamic characteristic of the actuation, *i.e.* the dynamic of both magnets according to the previous described three-actuation steps, is also evaluated.

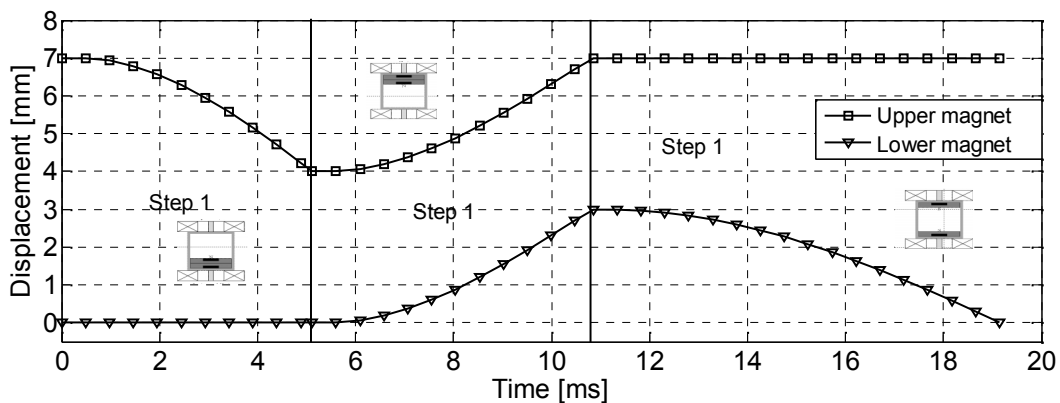


Fig. 14. Full dynamic characteristic of the one actuation cycle

Fig. 14 shows the full dynamic characteristic of the actuation for one cycle. From 0ms to 5.1ms, the top coil is supplied and the upper magnet is repulsed downward from its initial position at 7mm to reach the lower magnet. When assembled, both magnets are separated by their non-magnetic supports with a distance equal to 3mm, *i.e.* 1.5mm for each support. Note that the magnet is of 1mm height, that is why the distance between magnets appears corresponding to 4mm at 5.1ms in Fig. 14. At the end of step 1, the top coil is turned off and the bottom coil is simultaneously supplied, therefore assembled magnets move upward to reach the top extremity of the cylindrical channel, from 5.1ms to 10.9ms. After that both coils are turned off, so at 10.9ms both magnets are starting separated by their natural repulsive force. At time 17.2ms, each magnet attains its initial position and hence one actuation cycle is completed. The computed electromagnetic force of this actuation cycle is shown in Fig. 15. Take for example the second step, the applied electromagnetic force on the assembled magnets is positive and it decreases from 0.33N to about 0.03N when the force between magnets is negative which means that the repulsive force results from bottom coils is bigger than the repulsive that results from top magnets. In addition, the opposite polarities between magnets ensure the separation of discs. By this, one can conclude that the desired operation mode of the proposed electromagnetic micro-actuator previously described is established, a vacuum of 3mm higher and 15mm diameter is swept by the assembled magnets and the elapsed time for one cycle was about 19ms which in other hand a maximum frequency to swept a vacuum of 3mm is 52Hz. and according to the driving current angles as shown in Fig. 6. It is relatively easy to control actuation frequency also to control the time of each step of the actuation. As the components of the fabricated device are not imposed then the micro-actuator is capable of being highly optimized according to a given specification for pre-defined applications taking into account as an example the swept vacuum, the applied forces.

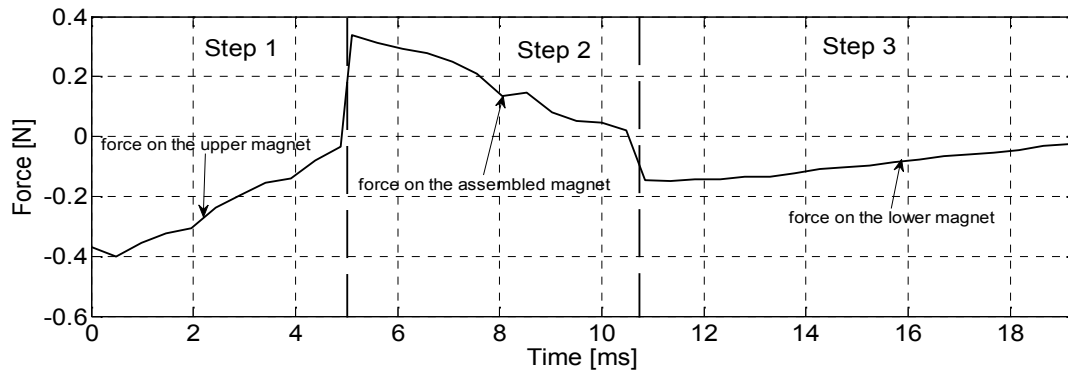


Fig. 15. Electromagnetic forces through one actuation cycle

Fig.16 shows the magnetic force between the two magnets that corresponding to the size of the suitable pump chamber.

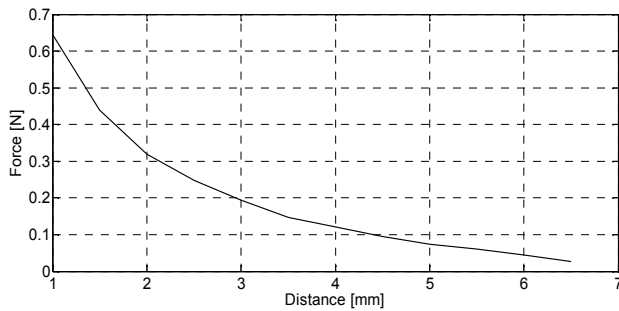


Fig. 16. Electromagnetic forces between magnets in function of distance

Where Fig. 17 shown the radial component of the magnetic field result from the upper coil along x-axes with different positions of the upper magnet along z-axes, where the B_x decreased as the upper magnet position is increased. When $z=1.5\text{mm}$ the a two maximums value of B_x are in limits of the coil and near to limits of magnet due to the iron core that has been inserted in the center of the coil and its influence decreases as the magnet moves away from the coil.

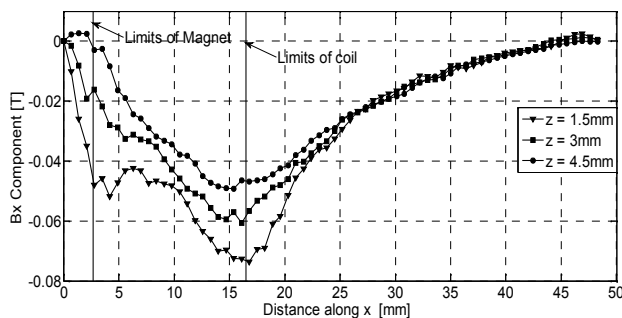


Fig. 17. B_x component of coil along x axes with different positions of the upper

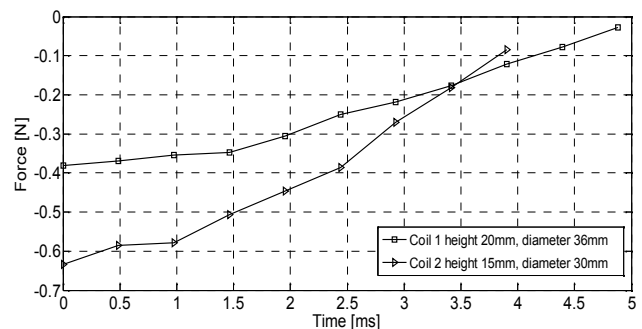


Fig. 18. Electromagnetic forces with different coils

Thus, since the force along z-axes is proportional to this component B_x , which gives us an idea about the suitable diameter of permanent magnet so that we get a large force as possible. Then, the value of B_x can be elevated by changing the coils dimensions as shown in Fig. 18. The electromagnetic force is applied on the upper disc during the first step with different coils.

6. Conclusion

In this paper, an electromagnetic micro-actuator is proposed. It consists of moving two hard disc magnets placed in opposite polarities inside a cylindrical channel, between two fixed coaxial coils. The electromagnetic analysis of the proposed micro-actuator has made use of the FVM method to determine the dynamic characteristic of the actuation of the magnets. According to the primary results, the electromagnetic device shows many advantages such as large displacement of the magnet, about 3mm, and a frequency of 52Hz can be attended. These results can be optimized by changing the supply mode of coils and by adjusting The magnets and coils dimensions. The proposed micro-actuator has shown its suitability to use it for the design of a novel linear valveless micro-pump. Future work will focus on employing the micro-actuator as a bidirectional valveless micro-pump.

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