DESIGN OF A 3 DOF DISPLACEMENT STAGE BASED ON FERROFLUIDS

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Abstract:
This paper presents the design of a 3 DOF (Degrees Of Freedom) displacement stage. This stage is composed of a mobile platform in suspension on three ferrofluid *bubbles* as an hydrostatic suspension. Bubbles stay *attached* to the platform thanks to three permanent magnets fixed on this platform. The actuation is obtained by fixing and controlling three coils on the support near the magnets. The dynamical characteristics of the stage are tuning by choosing appropriate volumes and properties for the ferrofluid and permanent magnets. The control in open loop permits a resolution of 50 nm but unfortunately a lower repeatability. The stage will be improved in the future by using a position feedback control.

Keywords: micro-robotic, ferrofluids, displacement stage

Introduction

Ferrofluids are colloidal fluids composed of ferromagnetic nanoparticles in suspension in a liquid carrier. Due to the nanometre size of the particles, these suspensions don't settle out and give to the fluid the properties of giant paramagnetism [1]. These fluids can conveniently be used to create sensors or actuators. To design actuators, the motion of the fluid can be controlled with a temperature gradient in a constant magnetic field as in micro pumps [2] or with a magnetic field gradient at a constant temperature [3] [4].
The use of a fluid and magnetic actuation permits the creation of a motion without any solid contact between the stator and the rotor as it is the case for conventional actuators (electric motors) that require the use of bearings. If very different applications can be found in the literature concerning ferrofluids [5], very few are dedicated to micro-motion control. This paper presents the design of a three DOF displacement stage based on ferrofluids.

Presentation of the device

The basic principle of the device can be understood with the help of the Fig. 1.

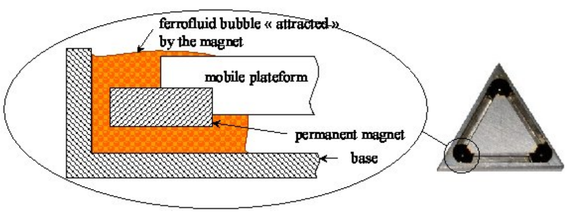

Fig. 1: *Basic principle of the 3 DOF displacement stage.*

Three permanent magnets are attached to the corner of a mobile platform. A ferrofluid bubble surrounds each magnet and therefore acts as an hydrostatic suspension for the platform.

The stiffness and the damping of the platform can be assigned according to the volume and properties of the ferrofluid and magnets. Two different ferrofluids were tested, the main difference being the viscosity of the fluid (Ferrotec APG-32: 1200 mPA.s and Ferrotec APG-027n: 175 mPa.s). Two different stages with two different magnets were also designed, the first one (T1 stage) is equipped with three ϕ 1.5 mm $\times$ 2 mm cylindrical NeFeB magnets (IBS magnet company NE152) and the second one (T2 stage) is equipped with three ϕ 4 mm $\times$ 1.5 mm cylindrical NeFeB magnets (IBS magnet company NE415) (see Fig. 2).

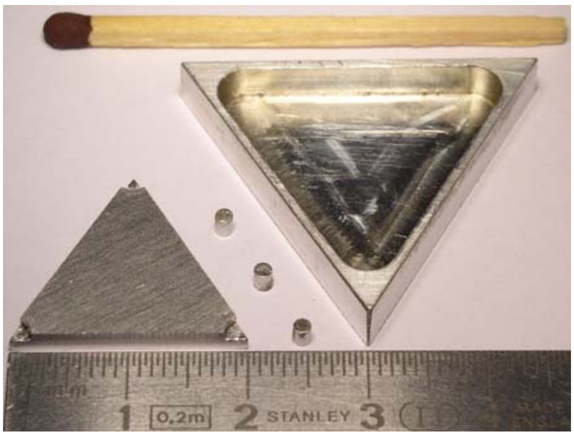

Fig. 2: Description of the different parts of the T1 stage.

Mechanical characteristics of the stage in the z direction

The influence of the design parameters (size of magnets, volume and type of ferrofluid) were studied in an experimental bench at our laboratory. Static measurements of the z stiffness were conducted. As expected, only few differences in the stiffness are noticeable according to the viscosity of the fluid for a great range of motion (70% of the full range of motion: Fig. 3).

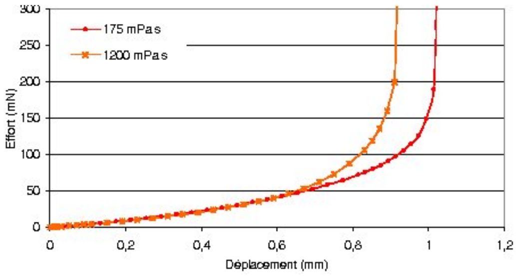

Fig. 3: Static measurements of the z stiffness (force vs. displacement) according to the viscosity of the ferrofluid.

Nevertheless, the volume of the bubbles of ferrofluid and the size of the magnets have a strong influence on the stiffness of the stage (Fig 4).

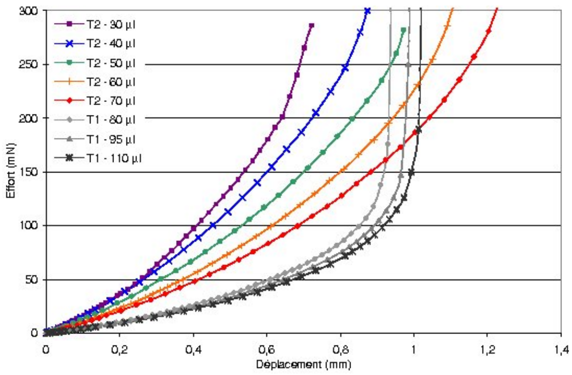

Fig. 4: Static measurements of the z stiffness according to the volume of ferrofluid and size of the magnets.

These measurements show that the rigidity of the stage decreases with the volume of the ferrofluid and increases with the size of the magnets. A constant z stiffness coefficient (linear relation between the displacement and the force: $F = K \cdot z$) is acceptable only for approximately 10% of the maximal range of motion. This displacement corresponds to 100 µm for a total range motion of 1 mm in the z direction.

Dynamical tests were also carried out on our bench. Free motions (natural motions) were recorded with a laser sensor from an initial z position to the final stable position. These experiments enable to estimate the viscous damping of the stage in the z direction. The dynamical behaviour of the stage was shown to be strongly non-linear. Nevertheless, for a small initial displacement (less than 100 µm) and a high viscosity of the fluid (1200 mPa.s), the natural motion of the stage in the z direction can be approximated by a linear mechanical second order model. In this case, the stage moves as a mass/spring/dashpot system. An ARX identification procedure was then adopted to extract an equivalent mass/stiffness/damping model of the stage for the z direction. ARX models of the first and second order were identified using a least square method:

$$\begin{cases} z(k) = -a_{11} \cdot z(k-1) \\ z(k) = -a_{12} \cdot z(k-1) - a_{22} \cdot z(k-2) \end{cases} \quad (1)$$

where k is the index of time. We have to notice that logically, the model must be of the second order because the Newton law is a second order law between force and displacement. Nevertheless, a first order model can be sufficient for our stage because of the high viscosity of the fluid (no overshot in the step response). The results given by the second order model for the high viscosity fluid are quite good for a range of 100 micrometers (Fig. 5) but the results given by the first order model are less accurate.

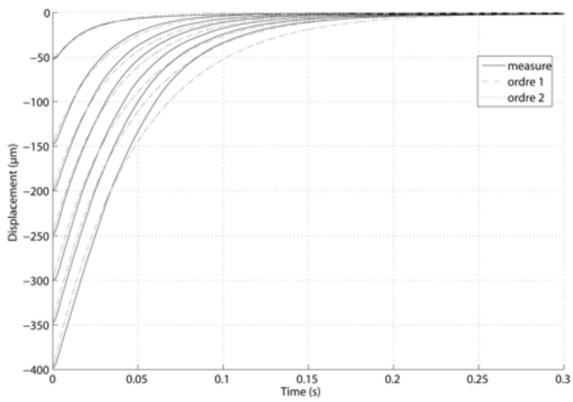

Fig. 5: ARX model and experiments for the T2 stage with the high viscosity ferrofluid.

For the stage using the low viscosity fluid, the identification procedure is not appropriate because of the strong non-linearity of the stage motion in the z direction (Fig. 6).

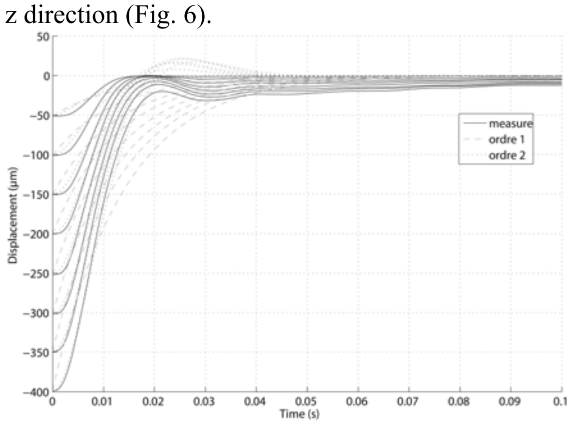

Fig. 6: ARX model and experiments for the T2 stage with the low viscosity ferrofluid.

Other identification procedures will be conducted in the future to extract the mechanical parameters (stiffness and damping coefficients) in the other directions (x and y).

Actuation of the device

The actuation of the platform is realized by putting coils near the three corners of the stage. The force is obtained according to the magnetic force:

$$\vec{F} = \mu_0 \nabla\left(\vec{M}\cdot\vec{H}\right) \qquad (2)$$

Where $\vec{H}$ is the magnetic field of a coil and $\vec{M}$ the magnetisation of a magnet. The direction of the coil is chosen parallel to the magnetisation then the direction of the force can only be change according to the direction of the current in the coil. The actuation principle is explained on the Fig. 7.

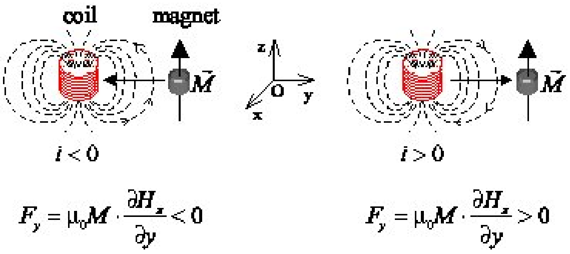

Fig. 7: Force creation on one magnet of the device.

The disposition of the coils around the platform is reported on the Fig. 8.

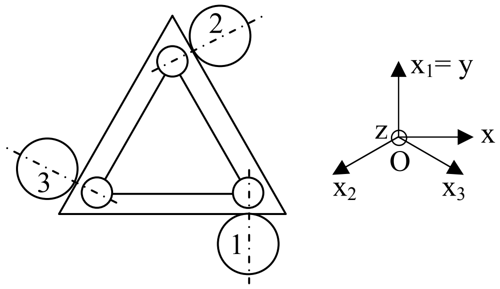

Fig. 8: Disposition of the coils around the platform.

The sum of the three forces on the three magnets creates a resultant force and a resultant torque on the platform in suspension on the ferrofluid. The three degrees of freedom (x, y translations and z rotation) can be controlled *via* the three coil currents. With the configuration of the Fig. 8, we obtained the following scheme for the control:

Translation in the x direction:

$$\begin{cases} F_3 = -F_2 \\ F_1 = 0 \end{cases} \Rightarrow \begin{cases} F_x = \sqrt{3}\cdot F_2 \\ F_y = 0 \end{cases} \qquad (3)$$

Translation in the y direction:

$$\left\{ F_2 = F_3 = -\frac{F_1}{2} \right. \Rightarrow \begin{cases} F_x = 0 \\ F_y = 1.5\cdot F_1 \end{cases} \qquad (4)$$

Rotation about the z direction:

$$F_1 = F_2 = F_3 \Rightarrow C_z = \frac{3}{2}\cdot F_1 \cdot l \qquad (5)$$

Coils are feeding with three current amplifiers and driving by a Digital Signal Processor board (dSpace) connected to a personal computer. The motion of the platform is measured through a laser sensor as depicted on the Fig. 9.

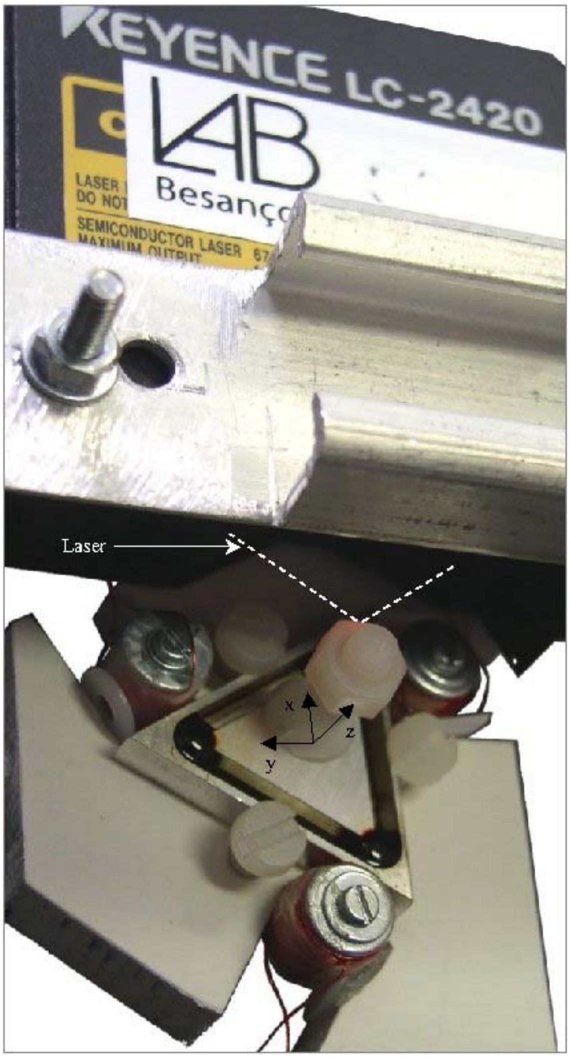

Fig. 9: *Photograph of the stage and laser measurement system.*

The ADC of the board is a 16 bits converter and with the laser sensor, the system permits to measure a 10 nm displacement. Nevertheless, the noise on the transmission line reduce significantly this precision to around 100 nm. We then designed analog and digital filters to improve the precision of the measurements. The dynamic of the stage is reported on the Fig. 10 for different digital filters for a step input. A good compromise between precision and dynamic is then adopted for the signal processing: it gives a measurement precision of around 25 nm for a time constant of 80 ms. This filter reduces the dynamic range of the stage but it stays sufficient for the first control laws.

Currently, only open loop controls were tested. The DAC of the board is a 12 bits and associated to the power electronic (current converters), the smallest current step size that can be obtained is 0.06 mA. With this resolution, it is possible to obtain displacement step size of around 50 nm.

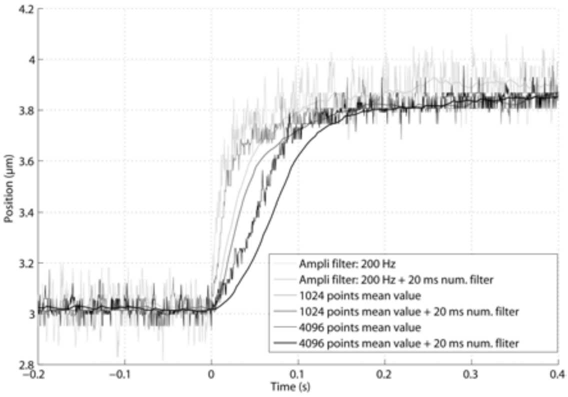

Fig. 10: *Choice of the digital filter to improve the precision/dynamic compromise of the position measurement.*

With a parallel mounting of two coils, it is also possible to increase the resolution to a position step size of 25 nm (Fig. 11 and 12) but as it is noticeable at the end of the Fig. 12, environment perturbations limit the precision of the stage to approximately the value of 25 nm.

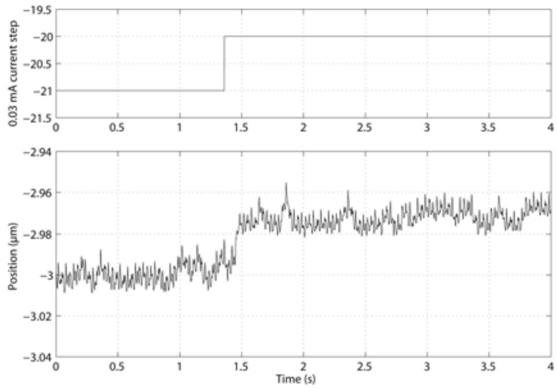

Fig. 11: *Step response of the stage for an input command of 25nm in the x positive direction.*

To improve the precision to a step smaller than 25 nm, it would be necessary to put the stage inside a controlled environment space.

Other tests have shown that a drift of the rest position is also present. It is probably due to the *rearrangement* of the ferrofluid around the magnets. In the near future, we will improve the device by using a feedback control of the stage and modelling the behaviour of the fluid around the magnets. The use of a feedback control will greatly improve the repeatability of positioning and a better modelling of the fluid behaviour will increase the quality of the tuning for the feedback control.

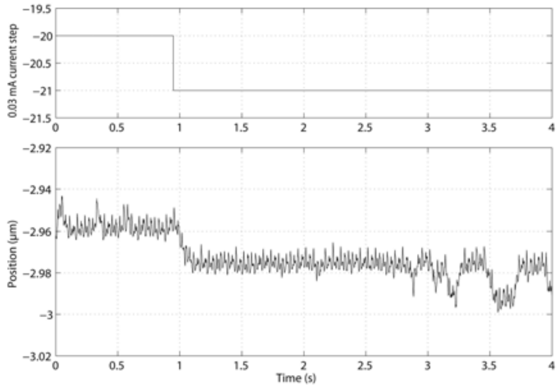

Fig. 12: *Step response of the stage for an input command of 25nm in the x negative direction.*

Conclusion

This paper presents a new micro positioning stage based on ferrofluids. This stage permits to control three degrees of freedom with a minimal step motion of 50 nm. Currently the stage is controlled in open loop but a feedback control would be added to increase the repeatability of motion. Experiments show that it would be necessary to put the stage inside a controlled environment space if we want to increase the precision to a step motion smaller than 50 nm.

References

[1] R.E. Rosensweig, *Ferrohydodynamics.* Cambridge University Press,1985.

[2] L.J. Love, J.F. Jansen, T.E. McKnight, Y. Roh, T.J. Phelps, L. Yeary and T. Cunningham, Ferrofluid field induced flow for microfluidic applications, *IEEE/ASME Transactions on Mechatronics*, 10:68-76, February 2005.

[3] A. Hatch, A.E. Kamholza, G. Holman, P. Yager and K.F. Böhringer, A ferrofluidic magnetic micropump. *Journal of Microelectromechanical Systems*, 10:215-221, June 2001.

[4] S. Sudo, S. Segawa, S. Tsuda and H. Nishiyama, Micro-actuator using magnet and magnetic fluid, In Abstracts of 10th International Conference on Magnetic Fluids, 2004

[5] G. Millet, Study of the possibilities of using ferrofluids for microrobotic applications (in French). Master thesis, University of Franche-Comté, Besançon France, 2005.