Linear nano-positioning stage using ferrofluid bearings

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Abstract

A ferrofluid bearing is a type of hydrostatic bearing, containing a magnetisable fluid which is pressurized by a magnetic field and held in place by the same field. Advantages of these bearings over other hydrostatic bearings are compactness, no stick-slip, absence of pumps & sealing, and higher damping for shock loads [1].

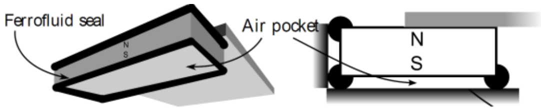
In this paper ferrofluid is used in magnetic fluid bearings, which can be a cheaper alternative for a high precision application with low loads, such as sample scanning in microscopy. A 1-DoF linear precision positioning stage was built with a Lorentz actuator and an Arduino microcontroller.

1. Properties of a ferrofluid bearing

Ferrofluids, known as magnetic colloids, are suspensions of magnetic nanoparticles in a base fluid [2]. When exposed to a magnetic field, these particles are attracted and the fluid is pressurized. The induced pressure can carry a load, which will be discussed later in this section. Ferrofluid bearings can work over a long range without friction. They have some advantages as following: ferrofluid bearings are used completely passively, so no additional bearing related actuators or controllers are needed; the cost of ferrofluid (S12N [3], which was used) for the bearing discussed in this paper is only about €0.1; ferrofluid has very low evaporation pressure; it doesn't require a fine-machined surface.

When a ferrofluid is directly applied on a permanent magnet, it will collect on the edges (Figure 1a), where the magnetising field gradient is the highest. When the translational ferrofluid bearing moves, however, part of the ferrofluid sticks to the bearing surface, leaving behind a trail. This ferrofluid interacts with the moving magnets by pulling them back, resulting in a spring-like force in the direction opposite to the movement. During large strokes, this may result in changing the stage height, and thereby also the mechanical damping, which was taken into account when designing the controller.

The air pocket enclosed by the ferrofluid gives additional stiffness to the bearing (Figure 1b). The maximum pressure inside a ferrofluid collected at the edge of our magnet (32mm×10mm×5mm, Br=1.2T) is 200mbar.



(a) (b)

Figure 1: A photo of the ferrofluid collected on the edges of a permanent magnet (a), a schematic of an air pocket sealed by ferrofluid (b) and a ferrofluid bearing with an enclosed air pocket. When a vertical load is applied to the bearing, the pressure inside the air pocket will increase, thus, increasing the stiffness and load capacity of the bearing.

Once the pressure distribution in a ferrofluid bearing is known, its load capacity F can be calculated by integrating the pressure p at point (x,y,z) over the bearing surface A, $F = \int_A p dA$. The air pocket is not used in the final design of the bearing because it gives rise to additional non-linearity and high load was not needed in our application.

2. The 1-DoF linear stage based on ferrofluid bearing

The 1-DoF stage can be used for low-load applications such as microscopy which requires being small and fast. The range of operation is ≥ 1.5 cm; precision in actuation direction is ≤ 1 μm (σ); the glass sample surface dimension is 2.6 cm × 7.6 cm, and 5 gram mass.

To make a ferrofluid bearing more effective in terms of load capacity, the magnetic field lines should be shaped to maximize the flux density. The higher flux density is, the bigger gradient is, which increases the pressure inside the ferrofluid. As a result, higher load capacity can be obtained. To make the actuator more effective in terms of actuation force, the coil should be placed where the flux density is the highest. Therefore, 2 iron plates were placed both on top of and at the bottom of the magnets (Figure 2) to guide the flux and lower the reluctance in the magnetic circuit, thus higher flux density was achieved.

The final stage is designed and built as in Figure 3. The main stator block is CNC-milled in aluminium EN5053. The mover is held together by magnetic forces, although gluing is recommended for future applications. The ferrofluid was applied with a precision pipette equally on both sides of the stage to guarantee the symmetry of the stage to keep the force in the centre. The motion straightness is dependent on the straightness of the housing and ferrofluid makes the motion smooth. It has been proved to be easy to be assembled by hand in the lab. The stage is 107mm×110mm.

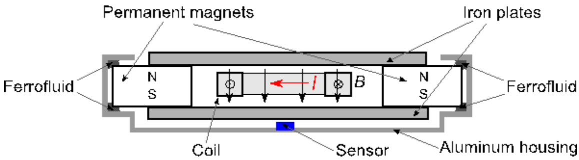


Figure 2: Concept design of the 1-DoF stage. The bearing and actuator use the fields from the same magnets. Two iron plates increase the flux density in-between and make the field more homogeneous. It has been built first to prove the basic concept.

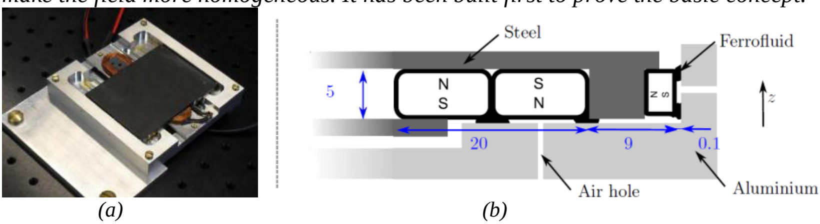


Figure 3: Overall photo of the final stage (a) and half of the cross section of the stage (b). Three magnets were used on both sides to increase the load capacity of the bearing.

3. Actuator, sensor and controller

A Lorentz actuator was chosen because it has long range, and the force is linearly dependent on the current and not dependent on the position [4]. A Lorentz actuator consists of a coil carrying a current and magnets to create a magnetic field. In our stage, the bearing already has magnets in it so no additional magnets were required for the actuator, which makes the stage more compact. The Lorentz actuator has a motor constant of 0.63*N/A*.

The position is sensed with a *MicroE Mercury 3500Si* encoder with a resolution of 5nm. For microscopy application, the position of interest is the middle of the top plate of the mover. The sensor was placed at the bottom of the stage to have the top surface free, causing a small Abbe error. The sensor position is indicated in Figure 2. This linear stage was equipped with both long-stroke and short stroke sensors for two experiments. First, the 5nm-resolution encoder, an Arduino microcontroller and PWM current amplifier with a PID feedback controller were implemented in the stage which can be positioned with a precision of σ=10*nm* over a range of 20*mm*. A control bandwidth of 100*Hz* was achieved. Second, a capacitive sensor with 0.7nm resolution was placed according to Abbe's principle. A precision of σ=1.6*nm* and a control bandwidth of 300*Hz* with a phase delay of only 3.6° at 300*Hz* were achieved using a 16bit D/A converter and an analogue current amplifier with 15*kHz* sampling frequency. The step responses are shown in Figure 4.

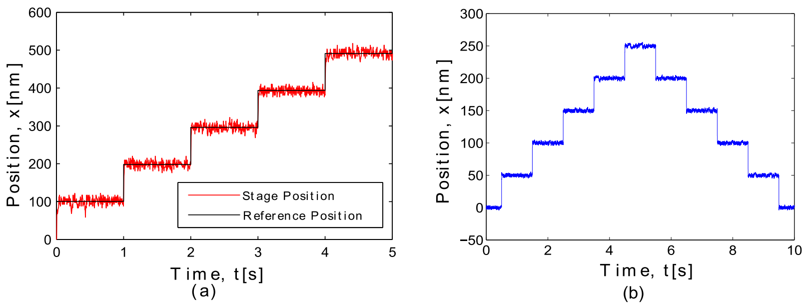


Figure 4: Step response: (a) with a 5nm-resolution encoder, an Arduino microcontroller and PWM current amplifier, rise time is 8ms. (b) with a 0.7nm-resolution capacitive sensor, 16bit D/A converter and an analog current amplifier, rise time is 1.3ms.

4. Conclusions

A 1-DoF linear nano-positioning stage was realized using a ferrofluid bearing. Such a bearing provides a hydrostatic bearing without pumps and seals, which is cheap, easy to implement. The magnets have double functions for both the bearing and the actuator. The best performance had 300*Hz* bandwidth. The load capacity of the bearing in our setup is 300*g*.

Acknowledgement

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