Magnetic levitation and rotation of sub-millimetric spherical rotors

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Abstract

To achieve high spinning speed, spherical rotors with less than 1 mm diameter have been levitated. A small device (50 [mm] x 50 [mm]), with a magnetic actuator that controls one degree of freedom of the rotor, an optical sensing system, and a two-phase induction motor has been designed and realized to perform levitation and rotation of small spherical rotors. In order to achieve a high spinning speed, spherical rotors with less than 1 mm diameter have been levitated.

1. Introduction

The experience presented is based on a paper of 1946 entitled "The Production of High Centrifugal Fields" [1]. In this paper, Jesse Beams of University of Virginia has magnetically levitated and spun small spherical rotors down to 0.794 [mm] diameter to their bursting speed. With the smallest rotor tested, they achieved in vacuum a spinning speed of 23'160'000 [rpm]. Afterwards, practically no further research was carried out in this field.

Our goal is, to reproduce these results with actual technologies, to minimize the device for the experience, and to levitate and spin even smaller rotors at very high speed.

The most critical problems are the generation of the very high speed rotating magnetic field to spin the rotor, as well as the detection of the spinning speed. Others challenges are the position sensing of rotor, and its stabilization.

In this paper we present a new, smaller configuration in order to levitate and spin sub-millimetric spherical rotors and first experimental results.

2. Experimental Setup

2.1 Overview

The device is composed of a magnetic actuator and an analog PD controller to stabilize the rotor position, an optical sensing system to measure the rotor position, and a two-phase induction motor. Lateral stabilization is passive. The rotors are steel spheres, as normally used in ball bearings. Two different rotors are considered with diameters of 1 [mm] and 0.5 [mm] respectively. The device for levitating and spinning the two rotors is identical.

2.2 Actuator

The actuator function is to compensate the mass of the rotor, and to stabilize its vertical position. In order to increase the magnetic field generated by the actuator, a ferrite core is placed inside the coil and a half spherical core end is used to facilitate horizontal stabilization of rotors with different diameters (figure 1a and 1b).

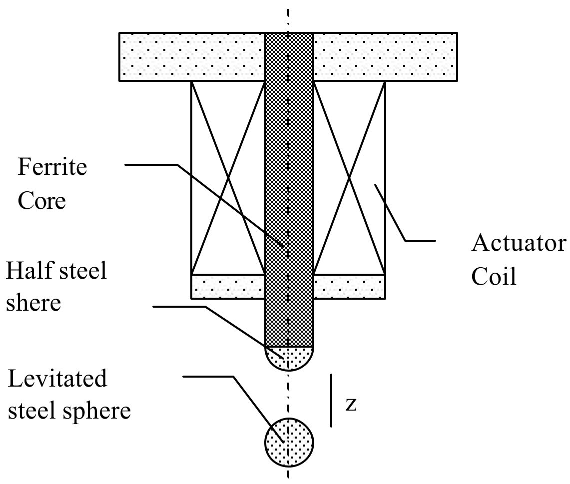


Figure 1a : Schematic view of the magnetic actuator

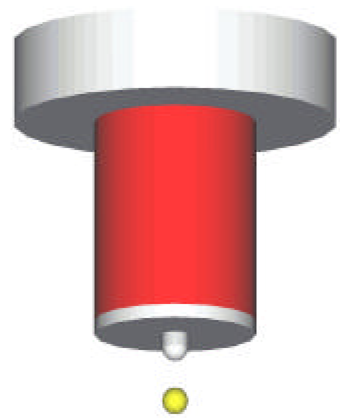


Figure 1b: 3D view of the magnetic actuator

The inductance of the coil is approximated by the following expression:

$$L(z) = L_0 + \frac{\Delta L}{1 + a \cdot z} \tag{1}$$

where z is the distance between the rotor and the end of the actuator, L_0 is the inductance of the coil without the rotor, *DL* is the maximal variation of the coil inductance and a is a fitting parameter.

2.3 Position sensing system

The system to measure the rotor position is composed of a laser source, a lens, and a photodiode (figure 2).

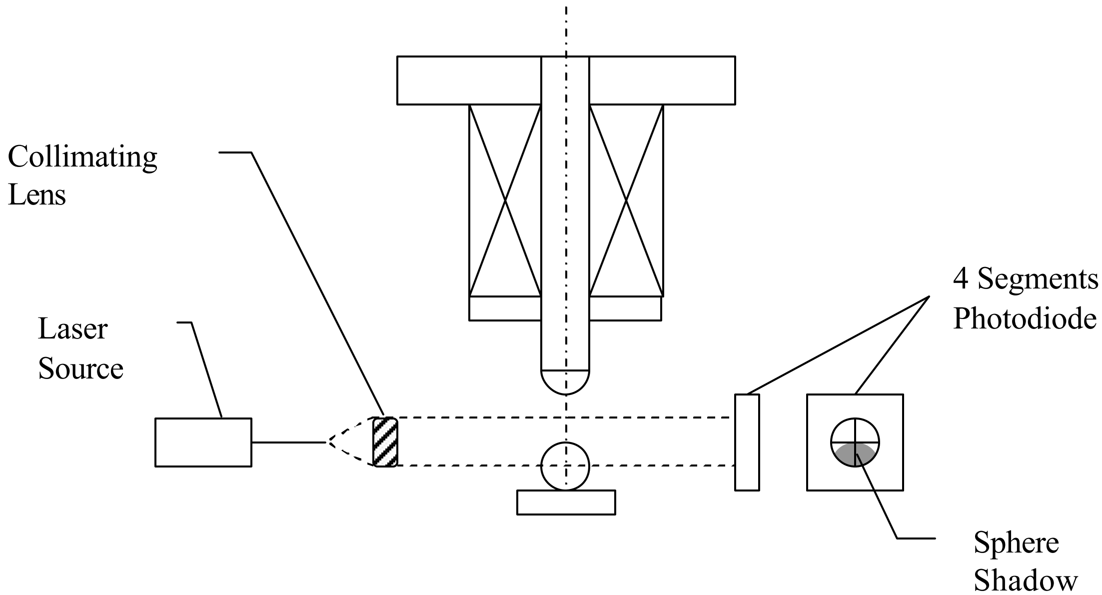
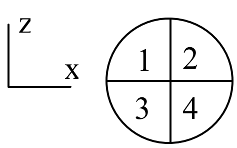


Figure 2: Position sensor principle

Red light, generated by the laser source, is guided to the device by an optical fiber. The laser is collimated with a small lens of 1 [mm] diameter, and illuminates the rotor. The four segments photodiode with a [1 mm] diameter sensing area placed behind the rotor, detects its shadow. Therefore the vertical movement and one horizontal movement, i.e. perpendicular to the laser beam, can be measured. The vertical displacement signal is used for the active control, and it is obtained with the following expression:



$$z = (1+2)-(3+4)$$

So, when the rotor is in the centre of the beam, the output signal of the sensing system is equal to zero.

2.4 Motor

At ultra-high spinning speeds, i.e. beyond 1 million rpm, stator eddy current losses become an important limiting factor in an electrical motor. High resistivity, or non-conductive materials must be considered for the coil cores and the stator, this way eddy current losses will be reduced. For a first try, a two-phase induction motor with a stator without conductive materials is designed with a minimum number of pole pairs, while the rotor must be conductive in order to operate as an induction motor.

Stator

The stator is composed of two coils per phase, that are serially connected (figure 4) and this results in a total inductance of 82 [μH] and a resistance of 3 [Ω]. As the number of the pole pairs is equal to one, the frequency of the stator rotating magnetic field corresponds to the frequency of the currents injected into the motor coils.

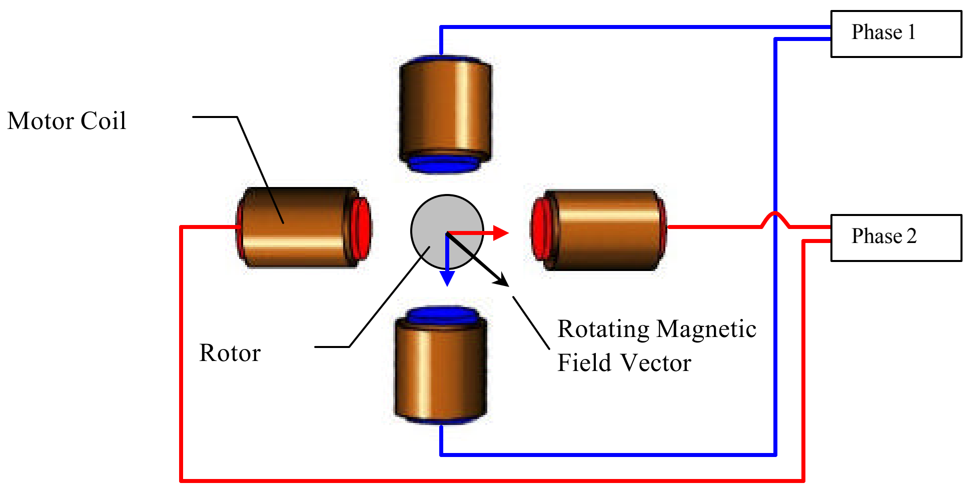


Figure 4: Rotating magnetic field

Figure 5 shows a drawing of the motor support with the four coils and the position sensing system. The coil cores are made out of heat resistant polymer (POM) and the support is made out of transparent polymer (PC). The air gap between two facing coils is 3 [mm], imposed by the crossing of the laser beam.

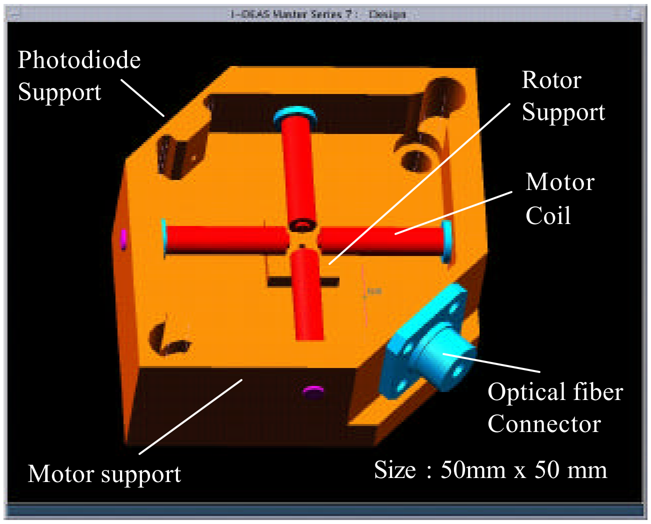


Figure 5: Drawing of the motor support

2.4.1 Rotor

As the rotor is a conductive material, eddy currents are generated in it by the stator rotating magnetic field. Following the principle of an induction motor, a torque is produced to spin the rotor.

2.5 Motor Driver

To create the high speed rotating magnetic field, a driver with an integrated H-bridge is chosen. Supply voltage is up to 50V, maximum output current is 2A and a maximum switching frequency of 250 kHz. With this driver, and a slip equal to zero, the rotor can theoretically achieve a maximum rotational speed of 15’000’000 rpm.

2.6 Speed measurement

The sub-system for the spin speed measure is not yet integrated into the device presented. The principle for the speed measurement is to partially change the reflectivity of the rotor, and to detect reflection variations during spinning of the rotor (figure 6).

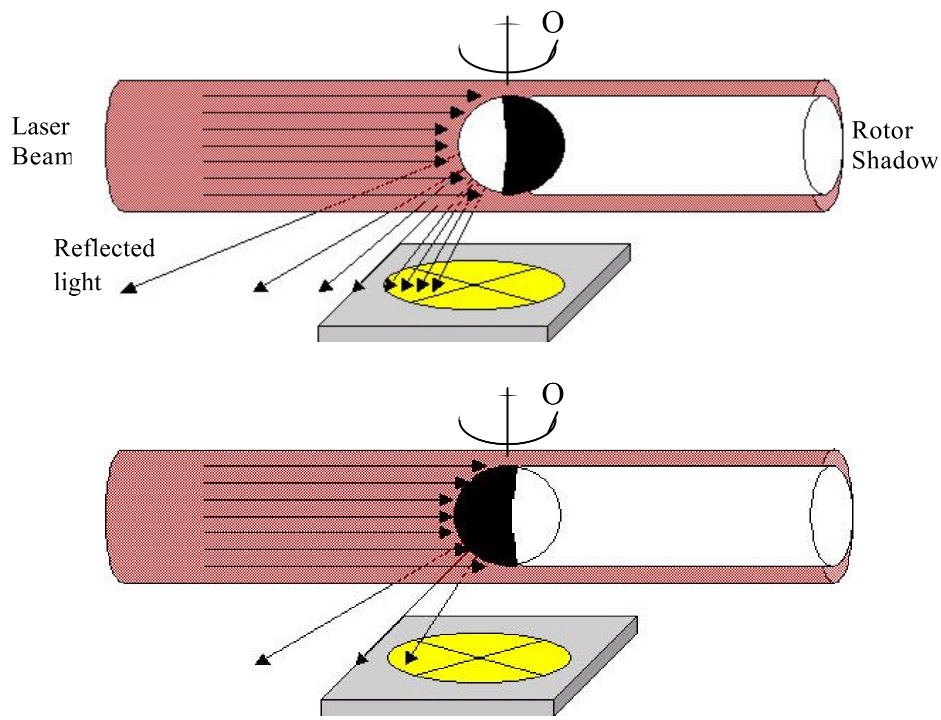


Figure 6: Principle for the speed measure

Reflected light from the rotor will illuminate the photodiode which is placed under the rotor. With one half of the rotor darkened, the frequency of the intensity variations, detected by the photodiode, will correspond to the spinning frequency. In order to have a maximum intensity variation, a well defined rotation axis has to be guaranteed.

3. Results

Levitation of the 1 mm rotor and the 0.5 mm rotor was successfully achieved (figures 7a, 7b and 7c). The starting position of the rotor was on a clean aluminum foil placed at the center of the PC support. At these small dimensions interaction forces between the support and the rotor are not negligible, therefore these elements were frequently cleaned to permit the rotor levitation.

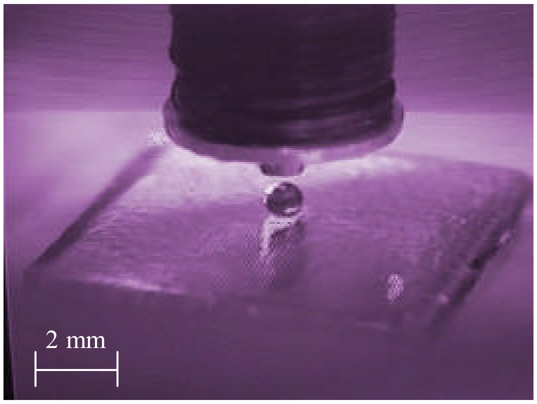


Figure 7a: Levitation of a 1mm rotor

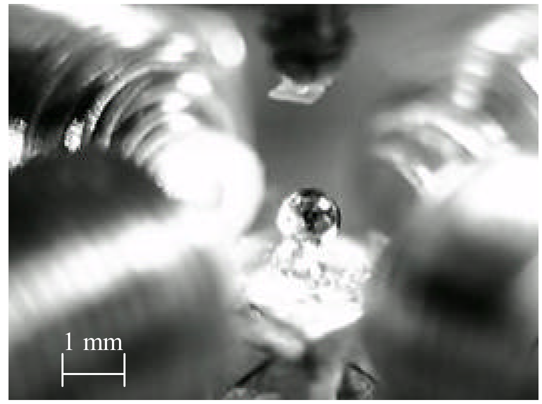


Figure 7b: Levitation and rotation of a 1 mm rotor

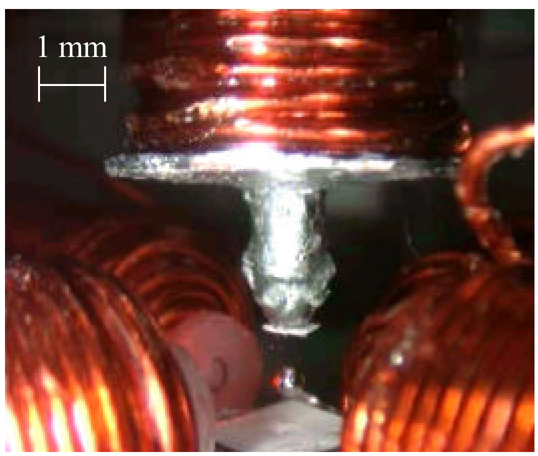


Figure 7c: Levitation and rotation of a 0.5 mm rotor

The motor function was also tested with satisfactory results. The 1 mm and 0.5 mm rotors were stably spinning up to the critical speed. Near this speed, a horizontal vibration occurs and the rotor is radially destabilized. The speed detection system is not yet realized. Table 1 resumes some device characteristics:

	1 mm Rotor	0.5 mm Rotor
Actuator bias current [mA]	543	112
Actuator air gap [mm]	1.5	0.75
Motor coil-Rotor air gap [mm]	1	1.25
Position sensor sensitivity [V/m]	3500	3500
Position sensor working range [mm]	0.6	0.4

Table 1: Device characteristics

4. Conclusions and Outlook

A small device to levitate and spin small rotors (0.5 [mm] and 1 [mm]) was realized with successful levitation and rotation. In order to increase spinning speed, and thus pass critical speeds, radial motion needs more damping (active or passive) [2].

Further improvements of the device will be the design of a new motor with smaller air gaps and ferrite cores, the introduction of an active radial stabilization, and the implementation of the speed measurement.

5. References

[1] J.W. Beams, "The Production of High Centrifugal Fields", Journal of Applied Physics, 1946, pp. 886-890

[2] A. Boletis, H. Bleuler, "Achieving Ultra-High Rotational Speeds", Proceedings of the 8th International Symposium on Magnetic Bearings, Mito, Japan, Aug. 26-28, 2002