

# Preliminary experimental study on new contact-free linear drive system using diamagnetic material

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**ABSTRACT:** Technology of passive magnetic levitation using diamagnetic materials is very important in various industry fields. Recently, we discovered an interesting phenomenon for the driving on passive magnetic levitation of diamagnetic graphite plates at room temperature. In this paper, we shall report preliminary experimental result about a novel contact-free linear drive technique based on Halbach PM arrays, diamagnetic levitation and small pieces of Permanent Magnets.

## 1 INTRODUCTION

Passive magnetic levitation is a very important technique in various industrial fields. However, in the case of magnetic levitation using superconductive materials, it is necessary to use a big amount of electrical energy to cool down the system below 77[K].

In the recent years, there are some interesting reports about magnetic levitation using the diamagnetism of some substances in conjunction with strong magnetic fields at room temperature. Eur. J. Phys. in 1997, magnetic levitation of a frog in stable zone of a 16T magnet was reported by the group of Univ. of Nijmegen, the Netherlands<sup>(1)</sup>. Also on the Nature in 2001, the experimental research on passive magnetic levitation of a permanent magnet piece in the special magnetic field gradient constituted with the bismuth cylinder or human finger was reported by the group of UCLA<sup>(2)</sup>.

Especially, it seems that the magnetic levitation using graphite plates is a very important technique in the field of micro factories (see Fig.1). The EPFL-LSRO1 group (co-authors) has already reported about the magnetic levitation characteristic of a graphite plate on some two-dimensional permanent magnet arrays<sup>(3)</sup> and about prototypes of non-contacting rotors<sup>(4)</sup> and linear conveyors using the diamagnetic levitation of graphite plates<sup>(5)</sup>.

Recently, the authors of this paper discovered an interesting phenomenon that can be used, in conjunction with diamagnetic levitation, to move graphite plates without any contact with the use of small magnets<sup>(6-8)</sup>. In this paper, we shall report preliminary experimental results about a novel contact-free

linear drive system using graphite plates and small piece magnets.

## 2 PASSIVE MAGNETIC LEVITATION OF DIAMAGNETIC MATERIALS

### 2.1 Magnetic levitation of diamagnetic graphite

Figure 1 shows the passive magnetic levitation of diamagnetic material (Pyrolytic Graphite : PG) plate on a two-dimensional permanent magnetic array. We can see that the stable magnetic levitation with about 250 micron air gap was carried out by the PG plate of about 1mm thickness.

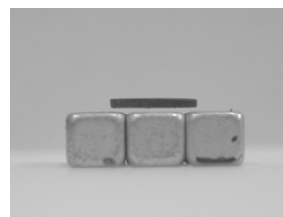


Figure 1: Magnetic levitation of diamagnetic graphite(PG) plate at room temperature. (Photo by EPFL-LSRO1)

The thrust force of a graphite plate is very weak, and the levitation of graphite is more unstable than the levitation using magnetic flux pinning of bulk superconductors. On the other hand, the passive magnetic levitation of graphite plate on PM arrays does not need coolant such as liquid nitrogen. This fact, passive levitation on a wide temperature range including room temperature, is the great advantage for the development of contact-free devices for industrial applications.

In the case of a simple levitation system such as shown in Fig. 1, it seems that the thrust force for

diamagnetism depends on the magnetic flux density above the PM array and the magnetization of the diamagnetic material. In general, thrust force of the above system may be expressed as equation(1).

$$\vec{f} = \frac{1}{2\mu_0} \chi_m \overrightarrow{grad} (B^2) \quad (1)$$

The magnetization of some typical diamagnetic materials is shown in Table 1. The magnetization of a graphite plate shows the value of about 2 to 3 times as compared with bulk material of bismuth and graphite, and graphite plate can be called the good key material for the passive magnetic levitation system.

Table 1: Magnetic susceptibility of diamagnetic material

Materials	Magnetic Susceptibility $-\chi_m (\times 10^{-6})$
Water	8.8
Bismuth	170
Graphite rod	160
Pyrolytic graphite	450

## 2.2 Magnetic levitation of a graphite plate on a Halbach permanent magnets array

The magnetic levitation characteristic of a graphite plate clearly depends on the magnetic field above the surface of the permanent magnets array. From two points of view, magnetic thrust force and stability, we made a Halbach permanent magnets rail array with Nd-Fe-B permanent magnet rods (3x3x100mm, abt. 0.4T on surface) as shown in Fig. 2. We then carried out an observation of the magnetic levitation of a graphite (PG) plate and started some initial experiments of a non-contact drive.

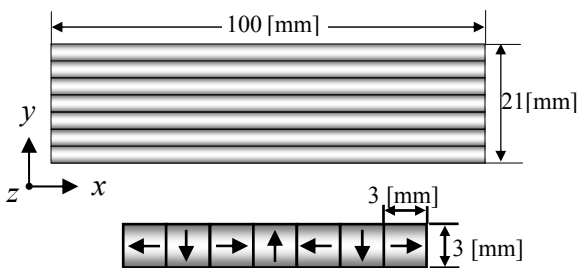


Figure 2: Structure of the test rail with Halbach PM array

Figure 3 shows the graphite (PG) plate which carries out stable magnetic levitation on the constituted Halbach PM array rail. This graphite sample plate with 1.05mm thickness and 0.47g weight is stably levitated with an air gap of about 0.95mm.

By the unique magnetic field distribution of the test PM rail caused by the Halbach array (see Fig.4), we could achieve wide air gaps as well as a magnetic guide of graphite (PG) plate. In this condition, a magnetic guidance occurs in the direction of  $y$ , and

a contact-free run is realized in the  $x$  direction on the rail.

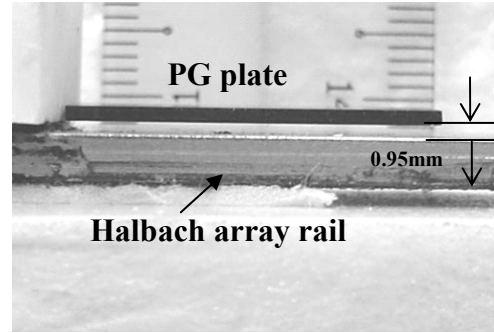


Figure 3: Stable magnetic levitation of a graphite plate on the test rail with Halbach PM array

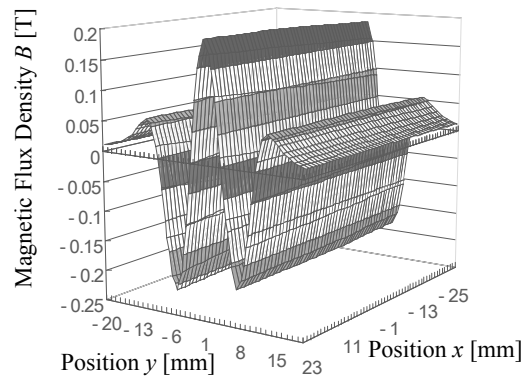


Figure 4: Distribution of magnetic flux density on the test rail with Halbach PM array

## 3 MAGNETIC LEVITATION DRIVE WITH GRAPHITE PLATE

### 3.1 Motion of a graphite plate using a PM piece

We discovered by experiments an interesting phenomenon to drive a diamagnetic graphite plate subjected to passive magnetic levitation. Figure 5 shows the setting of the experiments with the graphite plate over the permanent magnets. The acceleration motion ( $x$  direction of the rail) of the graphite plate is performed by approaching a small piece of permanent magnet near the graphite plate (see Fig.6). The moving direction of the graphite plate depends on the magnetic pole relation between the permanent magnet piece and the Halbach array.

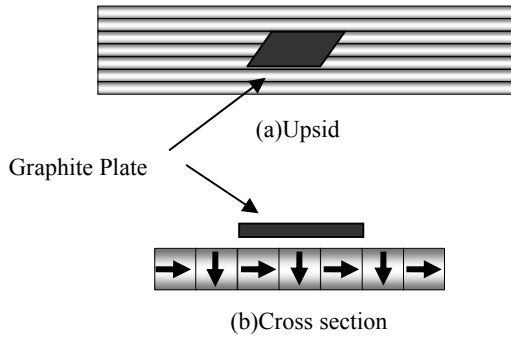


Figure 5: Layout of graphite (PG) plate on the test rail with Halbach PM array

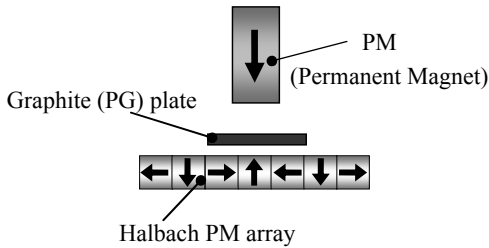


Figure 6: Pattern layout of the approaching magnet, used to drive a graphite plate levitated on the test rail with Halbach PM array. (N-N magnetic polar arrangement)

For example, if the polarity of a permanent magnet as shown in Fig.6 (N-N magnetic polar arrangement) is given to the left end of the graphite plate (arrow position) shown in Fig.7, the graphite plate will accelerate in the left direction in Fig.7. Figure 8 shows the motion of the graphite plate towards the left side using this novel technique.

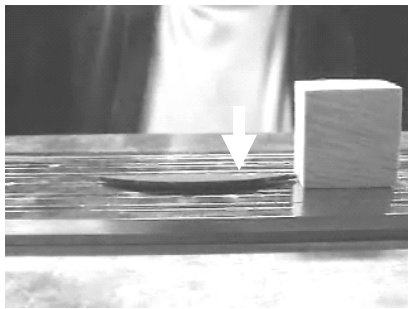


Figure 7: Approaching a graphite (PG) plate by a PM

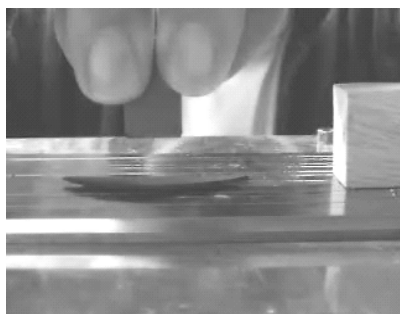


Figure 8: Motion of a graphite (PG) plate with an approaching PM

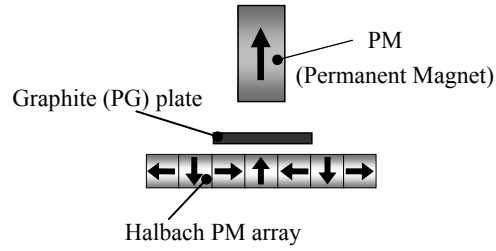


Figure 9: Pattern layout of the approaching magnet, used to drive a graphite plate levitated on the test rail with Halbach PM array. (N-S magnetic polar arrangement)

On the other hand, as shown in Fig.9, if we approach the graphite plate with a magnet of opposite polarity, a rightward acceleration will take place.

### 3.2 Magnetic field by the novel arrangement of Halbach array and PM piece

Figure 10 shows a simulation result of the magnetic field distribution in the case of the N-N magnetic polar arrangement (Fig.6) between the center of the Halbach array and the PM piece.

In Fig.10, a blank portion exists between the center of the rail of Halbach array and a small permanent magnet: this portion shows the magnetic flux density  $B=0$ [T].

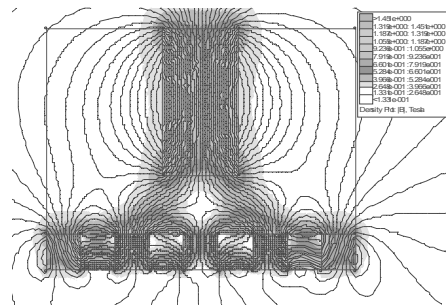


Figure 10: Simulation result of the magnetic flux distribution between Halbach PM array and PM piece

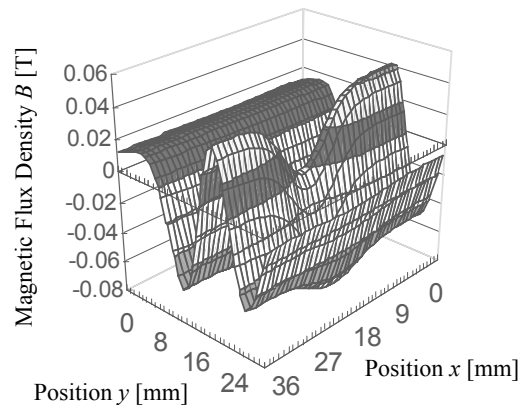


Figure 11: Measurement result of the magnetic flux density distribution between the test rail with Halbach PM array and the approaching PM piece

Figure 11 shows the measurement of the magnetic flux density distribution resulting from the Halbach array and the approaching small magnet.

As a result of the simulation and the measurement, we can see that the acceleration of the graphite plate is caused by the magnetic field gradient.

### 3.3 Characteristic of the magnetic levitation drive

When the parameters of the permanent magnet (size and magnetism) are constant, we observed that the acceleration depends on the form of the graphite plate. It seems that the characteristic of a magnetic levitation drive is particularly determined by the edge shape of the graphite plate. Using samples with the same volume as shown in Fig.12, we can show that the acceleration of the PG plate depends on the edge angle of PG plate sample. It is important to show the relation between the edge shape and the acceleration of the PG plate for the development of a contact-free micro-actuator with diamagnetic material.

In addition, Fig. 13 shows a schematic illustration of the motion of the PG plate in the N-N polarity conditions shown in Fig.6. Depending on the relative position of the PG plate and the approaching permanent magnet, as shown in Fig.13(a) and (c), we observe acceleration motion of the PG plate in opposite directions.

When positioning a permanent magnet above the PG plate, an oscillation motion occurs. Of course, when this motion is observed in air or another gas atmosphere, the amplitude is clearly decreasing with time. However from a scientific point of view, it is very interesting to observe this oscillation motion under special conditions. We have set up experiment equipments for this special phenomenon observation, and are taking the preliminary data now.

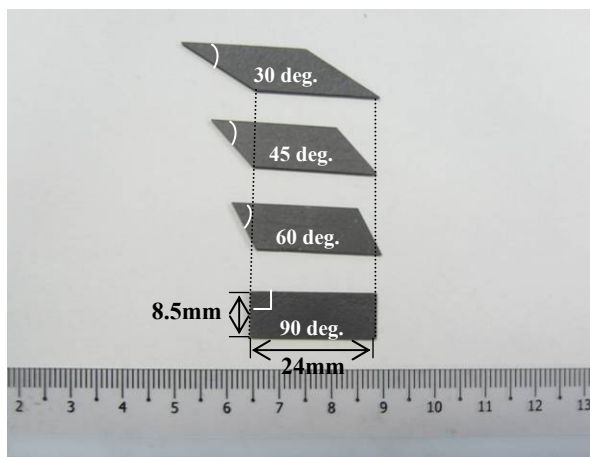
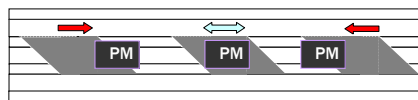


Figure 12: Several samples of graphite (PG) plate with different edge angles.



(a) (b) (c)  
Figure 13: Schematic illustration of the oscillation motion of graphite (PG) plate.

## 4 CONCLUSION

The advantage of this experimental research is to enable the magnetic levitation drive control of graphite (PG) plate using only the energy of a permanent magnet, without using irreversible energy such as electric and electrostatic energy used in a general actuator and a linear motor. It seems that the method of the contact-free linear drive that uses permanent magnet and graphite plate, which we showed in this paper, is a high potential technique to construct micro-actuators and micro-factories.

On the other hand, it cannot be said that the electromagnetic physical properties of this diamagnetic graphite (PG) plate is understood enough. Therefore, the electromagnetic physical properties of PG plate will be clarified by conducting some more experiments about this research.

## 5 ACKNOWLEDGEMENT

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