Experimental study on stabilizing range extension of diamagnetic levitation under modulated magnetic field

T C S Chow, P L Wong and K P Liu
Manufacturing Engineering and Engineering Management Department,
City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong, China
E-mail: 50578230@student.cityu.edu.hk, meplwong@cityu.edu.hk, mekpliu@cityu.edu.hk

Abstract. The real energy-free levitation exists with the help of diamagnetic material. Its ultra-high sensitivity to force is particularly attractive to micro/nano force sensing. A key parameter: Levitation Stabilizing Local Range, LR (allowable moving range of the floater) is critical to the load and self-rotating performance. Besides, larger LR reduces the energy loss due to the eddy current and has greater application potential. Recently, an idea of extending the LR by a modulating coil array has been validated using numerical simulation. This paper takes the next move to carry out an experimental study on the shape effect of stacked coil arrays with different currents on LR.

1. Introduction

Micro/Nano-Technology has become a booming research topic in recent years. To reduce friction and energy loss in those micro devices is one of the key concerns. Magnetic levitation provides a feasible solution because of its ‘gravitational free’ characteristics and ultra-high load sensitivity [1-3]. Further, real energy-free levitation can be achieved using diamagnetic materials, which requires no energy input at all [4]. The main drawbacks are its low load carrying capacity and short working range such that it is hardly used in conventional industrial applications although it has been discovered for almost 200 years [1, 4-9]. However, its load capacity and working range are rather practical in the field of micro/nano-technology [10-15]. For example the typical load sensitivity of a diamagnetic levitation system is in micro- or even nano-Newton per mm [1]. Thus, it has attracted significant amount of both fundamental and practical research recently [6, 8-9, 17-19].

The opposing field of diamagnetic materials facilitates stabilized diamagnetic levitation at the point of minimum potential, which is escaped from the Earnshaw theorem [16]. There are two identified levitating configurations, either the floater being a permanent magnet or a diamagnetic material. The latter requires a significant magnetic opposing behavior which can be generated by applying a strong external field or even with a relatively mild external field if a superconducting floater is used. One famous example is the levitation of a frog experiment by a Bitter magnet (~20T) [7]. The former one is manifested with the presence of a diamagnetic material under an external field in either vertically or horizontally setup. Recently, Cazacu et al. [10, 20] have proposed an idea to extend the vertical Levitation Stabilizing Local Range, LR (the gap size between the floater and the diamagnetic plane -- practical vertical moving range of the floater) of a permanent magnet floater by a modulating coil array. The idea has only been validated using numerical simulation. This work takes the next move...
that the effect of different coil array types with different applied electric currents on the stabilizing range is experimentally studied.

2. Experimental Setup

The external magnetic field was provided by electromagnetic coils. Three coil arrays of different shapes namely ascending, descending and center-diverging, were compared, as shown in figure 1. The coil arrays were formed by differential layers that are constructed with elemental coils of a constant number of turns (N=1600, 800, 400, 200). All the elemental coils have the same inner diameter of 40 mm and length of 40 mm. Two configurations for the coil array, namely NI and NNI, were adopted as depicted in figure 2. The former was with differential layers of the same NI (figure 2(i)), and the latter used one elemental coil for each layer i.e. the number of turns for each layer varies (figure 2(ii)).

A NdFeB, Neodymium-Iron-Boron, cubic permanent magnet of weight 0.79 grams and magnetization, \( M \approx 603 \text{K A/m} \) was used as the floater. It was enclosed by two pieces of graphite plates (top and bottom) of dimensions 40mm(W) x 40mm(L) x 9.5mm(H) and magnetic susceptibility, \( \chi = -181 \times 10^6 \) (as measured with VSM -7037 / 9509-P, LakeShore). Each of the stacked coils was connected to an independent power supply for current stability. The field pattern of each coil was first calibrated with the finite solenoid equation [19]. The coil array was formed by inserting elemental coils into the slot fixture as shown in figure 3.

![Figure 1. Coil arrays of three different shapes.](image)

![Figure 2. NI and NNI configurations.](image)

![Figure 3. Test rig setup and specifications](image)
3. Experimental Results

Figure 4. Stacking shape effects on the maximum gap size $D$ at different applied coil currents $I$ (Two differential layer coil array, $N = 1600$, constant $NI$ for each layer).

$D = \frac{12\mu_0 m |x|}{\pi B_z} = D_{\text{Maximum}}$  \hspace{1cm} (1)

where $B_z = \frac{\partial^2 B}{\partial z^2} |_{z=z_0}$, from the finite solenoid equation [19].

$z_0$ is the levitation position and $m$ is the dipole moment of the floater. The differences between the theoretical and experimental data are less than 5%. Figure 4 illustrates that the maximum $D$ decreases with the increase in the applied current and the rate of decrease is about the same for the three different coil array shapes. The good correlation between the experimental and theoretical data validates the theory. Furthermore, the ascending array shape gives the largest working gap size for a given current among the three array configurations.

Figure 5. The maximum $D$ vs number of coil array layer for different shapes, under a constant current $I = 2A$.

Figures 5 (a) and (b) express the maximum $D$ obtained under a constant applied current of 2A with different defined shapes in NI and NNI configurations respectively. Results of standard cylindrical coils, referred to as ‘referred cylindrical coil’, of the same number of turn, $N$, length $L$ and inner diameter of the belonged group are also plotted as reference. The reference coils show no shape effect. Figure 5 shows the results of descending and centre-diverging shapes of 4 layers could not be obtained, due to the size limitation of the test rig. The presented results indicate that only the ascending shape can extend the maximum $D$ from that of a standard coil, but not the others. Furthermore, the more the coil layers, the greater the extension of the $D_{\text{Maximum}}$ is. This could be explained by the increase in the number of layers leading to an increase in length of the stacked coil array. Hence, the source peak...
moves further away from the levitation position of the corresponding simple coil. Conceptually, the ascending shape has the largest number of turns in the 1st and 2nd layer which provide dominating effects on the $D_{\text{maximum}}$. Figure 5(b) shows the similar results with the NNI configuration. Since the centre-diverging shape has different total length from the other two shapes, its results cannot be directly compared and are not shown. Figure 5(b) depicts that for the NNI configuration, none of the tested stacked coil shapes (included centre-diverging) provide any extension of the stabilizing range.

4. Conclusion
The experimental results were well correlated with the theoretical $D_{\text{maximum}}$ for different currents. Thus, the theory of $D_{\text{maximum}}$ is validated. It was found that the ascending shape with NI configurations can extend the maximum $D$ comparing to a corresponding cylindrical coil of the same total NI, length and inner diameter. Although the improvement is marginal (about 7 to 8% increase), it means a lot in saving eddy current loss for a large size diamagnetic levitated flywheel [8-9]. Furthermore, the corresponding increase in load capacity due to the improvement in stabilized range may not be insignificant. Other shapes such as descending and centre-diverging cannot increase the maximum $D$ from that of a uniform coil of the same NI. For NNI configurations, no coil array shape, neither ascending, descending nor center-diverging, can extend the stabilizing range. The current results provide insights into the effective use of coil magnetic field source for diamagnetic levitation.

Acknowledgement
The work described in this paper was fully supported by a grant from City University of Hong Kong [Project No.7002457]. The first author was financially supported by a studentship of City University of Hong Kong.

5. References
[1] Boukallel M, Piat E and Abadie J 2003 Proc. Intl. Conf. on Intelligent Robots and Systems (Las Vegas, Nevada) pp 1062-67
[2] Yamane R, Oshima S and Park M K 2005 J. Magn. Magn. Mater. 289 pp 389–391
[3] Siebert M et al. 2001 A Passive Magnetic Bearing Flywheel 36th Intersociety Energy Convers. Eng. Conf. (Georgia) (NASA Glenn Research Center Project: NASA/TM: 2002-211159)
[4] Moser R, Sandtner J and Bleuler H 2001 J. Micromechatronics 1 2 pp 131–7
[5] Kustler G 2007 Revue Roumaine Des Sciences Techniques – Serie ElectroTechnique ET Ener Getique 52 3 pp 265–282
[6] Simon M D, Heffinger L O, Torrance C A and Geim A K 2001 Amer. J. Phys. 69 6 pp702-13
[7] Berry M V and Geim A K 1997 European J. Phys. 18 pp 301–13
[8] Cansiz A and Hull J R 2004 IEEE Trans. on Magn. 40 3 pp 1636–41
[9] Cansiz A 2008 J. Appl. Phys. 103 034510
[10] Cazacu E and Nemoianu I V 2008 Rev. Roum. Sci. Techn. -Electrotechn. et Energ. 53 1 pp 23-29
[11] Li Q, Kim K S and Rydberg A 2006 Rev. Sci. Instrum. 77 065105
[12] Evrard R and Boutry G A 1967 J. Vac. Sci. and Technol. 6 2 pp 279–288
[13] Lyuksyutov I F, Naugle D G and Rathnayaka K D D 2004 Appl. Phys. Lett. 85 10 pp 1817–19
[14] Chen J Y, Zhou J B and Meng G 2008 Diamagnetic bearings for MEMS: Performance and stability analysis Mech. Res. Commun.(doi:10.1016/j.mechrescom.2008.06.008)
[15] Chetouani H et al. 2006 IEEE Trans. on Magn. 42 10 pp 3557–59
[16] Bassani R 2006 Earnshaw (1805–1888) and Passive Magnetic Levitation (Overviews & Tutorials) Meccanica(2006) 41 pp 375–389 (doi:10.1007/s11012-005-4503-x, Springer 2006)
[17] Cazacu E and Moraru A 2005 Rev. Roum. Sci. Techn. -Electrotechn. et Energ. 50 2 pp 199–205
[18] Cazacu E and Moraru A 2006 Rev. Roum. Sci. Techn. -Electrotechn. et Energ. 51 1 pp 37–44
[19] Cazacu E and Nemoianu I V 2007 Rev. Roum. Sci. Techn. -Electrotechn. et Energ. 52 3 pp 283–290
[20] Cazacu E and Stanculescu A 2006 Annals of University of Craiova, Electrical Engineering series no.30 pp 12–15