FUNDAMENTAL STUDY OF MAGNETICALLY LEVITATED CONTACT-FREE MICRO-BEARING FOR MEMS APPLICATIONS

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Abstract- In this paper, the authors introduced a new approach to realize a contact-free micro-bearing for MEMS (Micro-Electro-Mechanical-Systems) applications. In the proposed idea, the mechanism of magnetic repulsion by eddy current was employed. Numerical analysis and experimental research was performed. In the proposed structure having a ringed magnetic circuit having a circularly-arranged gap (gapped-core), the generated magnetic flux was concentrated with high density and showed precipitously gradient in the magnetic field and also showed a larger of repulsive force comparing to the general electromagnetic (iron-core). Advantage of the proposed method and its viability as a contact-free Micro-bearing was discussed.

Index terms: **Micro-bearing, magnetic levitation, eddy-current, contact-free, MEMS**

1. INTRODUCTION

In recent years, according with the development of semiconductor technology, MEMS research attracts lots of attention. But, at the present stage the processable bearings in MEMS field are mainly sliding type [1]. Sliding type bearing has the advantage of simple structure and low cost, but, in the micro scales of size, because of the distinguished effect of surface tension and the friction problem, the durability of the rotating machinery is poor. This makes it difficult to build up a rotating machinery system in MEMS filed like the micro turbine [2].
Bearings processable by traditional machining technology can be divided into the following three types: (a) rolling bearing, (b) sliding bearing, and (c) magnetic bearing. Rolling type and sliding type have been widely used in many kinds of implements including the transportation equipments. But, when it is microminiaturized for the application of micro-machine systems, the viscous force effect from lubricating oil become dominantly obvious, so that the rotor will

be unable to work.

Magnetic bearing can realize non-contacting suspension. Magnetic bearing can support a rotating body by means of the magnetic levitation. It has been used in rotating equipments that require specific environment like turbo molecular pump, centrifugal compressor and flywheel for the electric power storage. Because of the non-contacting suspension by the magnetic levitation, there will be non-wearing, no need of lubricating oil, and the operating life is semi-permanent. However, the magnetic bearing is generally high cost and large sizes, make its practical realization become only in a limited field.

For the purpose to build up a rotating machinery system in MEMS filed, the authors focused on the mechanism of non-contacting magnetic bearing. Generally, in order to realize stable control in the magnetic bearing, 5-degree-of-freedom is need to be controlled from opposed direction. Considering the microminiaturization and the fabrication process, simple structure that can generate attraction and repulsive force from the same one direction is desirable. In this paper, the authors proposed a novel magnetic levitation system using the eddy current repulsion mechanism [3~5]. In the proposed method, it was confirmed that by making precipitous magnetic gradient at z axis direction, linear repulsion force can be generated using less of electric current. It was also confirmed that a larger of effective spring constant between the coil and levitated metallic conductor is formed, so that much higher precision of control could be possible. Based on the proposed idea, an optimized design for the magnetic circuit configuration was performed to fabricate a prototype, and the availability of effective levitation by precipitous magnetic field at z axis direction was investigated.

2. MECHANISM OF CONTACT-FREE MAGNETIC LEVITATION

The diagrammatic sketch of proposed non-contacting magnetic levitation system is shown in figure 1. In order to miniaturize the whole bearing system, such a magnetic levitation structure that could be controlled only by one direction is desirable. To realize such a system, it is necessary to generate the attraction and repulsion force on the same one direction. Generally, it is relatively easier to get an attraction force comparing to the repulsion force. The authors formulated and realized the repulsion force by means of magnetic force. The levitation method using magnetic repulsion is favorable to realize a stable levitation where the complex control is not necessary. According to Earnshaw's theorem, it is impossible to get a stable levitation by a permanent magnetic repulsion. The possible methods to get a stable levitation are limited in the use of superconductive diamagnetic repulsion, or an eddy current repulsion with a magnetic field [6-15]. As an applicable method, the authors attempted to get the repulsion force by means of an eddy current which generated by electromagnetic induction and ingenerate repulsive levitation and damping force. However, this method will be associated with heat generation in principle, so that it is important to minimize the generating heat as can as possible when achieve the necessary repulsive levitation. The attraction force can be generated by applying direct current to the coil and relatively easy to be realized. The most important issue is to get the repulsion force efficiently. As the solution of this issue, the authors proposed a novel magnetic circuit configuration by which the magnetic field gradient generated from the coil at z axis direction will be precipitous and the generated repulsion force will become easier to control. Prototype was fabricated based on the magnetic circuit design, and an evaluation was performed by experiment to demonstrate the proposed levitation mechanism.

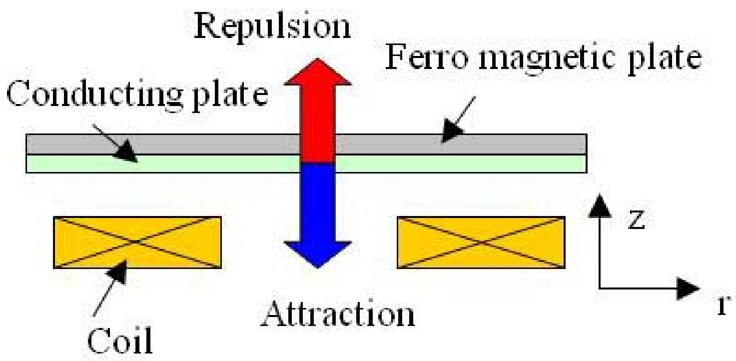

Figure 1. Concept of magnetic levitation

3. FINITE-ELEMENT APPROACH FOR THE MAGNETIC FIELD ANALYSIS

As a generating source of the magnetic field, such a magnetic circuit is desirable which can increase the springing at the z axis direction and at the same time can generate a big of suspension force with precipitous magnetic gradient at the same z axis direction. Figure. 2 shows the designed magnetic circuit structure having circularly-arranged gap. By means of such a magnetic circuit, a localized magnetic field could be formed at the void part (circularly-arranged gap). A pole type electromagnet (iron-core structure) that has the same diameter with the central yoke of designed magnetic circuit (gapped-core) was also fabricated as a comparing candidate to evaluate the effectivity of the proposed idea.

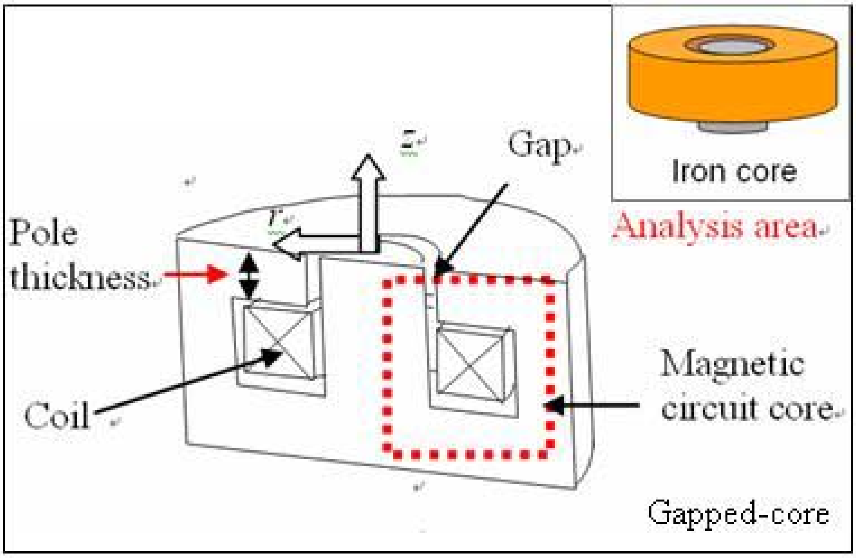

Figure 2. Designed magnetic circuit structure having circularly-arranged gap (gapped-core), and general electromagnetic (iron-core)

3.1 RELATIONSHIP BETWEEN THE MAGNETIC GAP WIDTH AND THE MAGNETIC GRADIENT AT Z AXIS DIRECTION

Based on the magnetic circuit structure as shown in figure 2, the magnetic field analysis was performed with the magnetic gap width (circularly-arranged gap) as the parameter to evaluate the magnetic field gradient at z axis direction associated with the increased distance from the magnetic pole surface. In this analysis, the thickness of the magnetic pole was 0.8-mm with an electromagnetic soft iron as the magnetic circuit material whose relative permeability was 2000. In the coil, the cross-sectional area was 4×10^{-6}-m^2, electrical resistivity was 1.8×10^{-8}-Ω・m, and the frequency of applied alternating current was 50 kHz, current density was 2.5×10^{6} A/m^2, and magnetomotive force (MMF) was 10A. Figure. 3 shows the relationship between the strength of the magnetic field at z axis direction associated with the increased distance from the magnetic pole surface on the horizontal position of circularly-arranged magnetic gap (0.8-mm outside from the center) at the condition of different width of the gap sizes. From figure 3, it was known that when the gap becomes narrower, stronger of magnetic field can be generated, further, when the width of ringed gap size was 0.2-mm, the generated magnetic field was strongest and the magnetic field gradient at z axis direction was most precipitous. It supposed to be that with the narrowed gap, less of the magnetic field leakage was occurred in the area of the ringed gap. Further more, there might be exist an optimum ratio of about 4:1 between the width of gap size and the magnetic pole thickness.

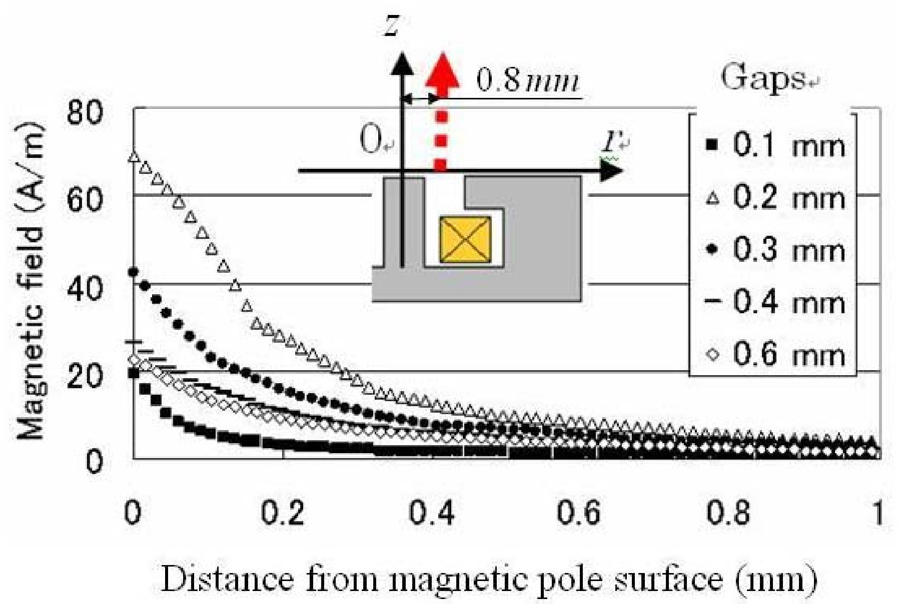

Figure 3. The strength of magnetic field vs. the increased distance on *Z* axis from the magnetic pole surface (horizontal position: on the center of circularly-arranged magnetic gap at 0.8-mm outside from the center) at the condition of different width of the gap sizes

3.2 RELATIONSHIP BETWEEN MAGNETIC POLE THICKNESS AND MAGNETIC GRADIENT IN *Z* AXIS DIRECTION

Based on the magnetic circuit configuration of figure 2, analysis was performed with the magnetic pole thickness as the parameter and to search the corresponding magnetic field gradient in z axis direction. The analysis condition was same with section 3.1, and the analyzed results of relationship between the magnetic pole thickness and the magnetic field intensity was shown in figure 4. From the analyzed results, it was known that the thinner the magnetic pole, the more precipitous of magnetic field gradient at the z axis direction.

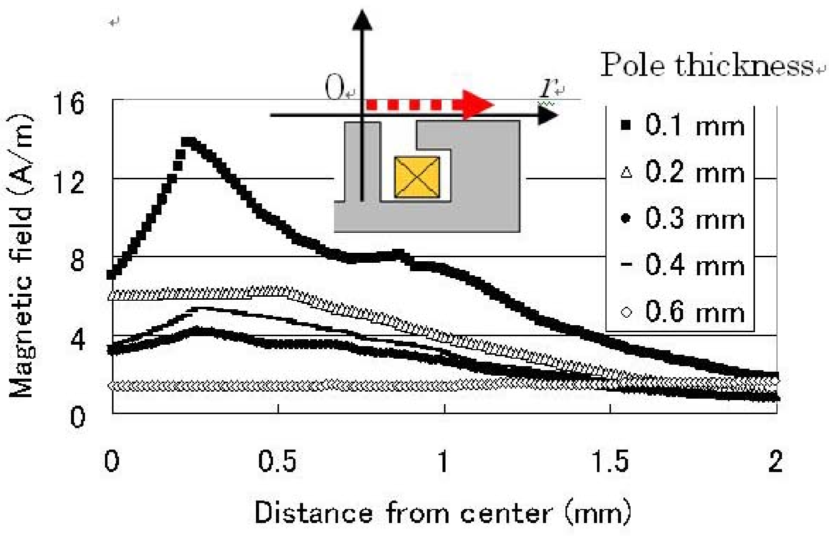

Figure 4. The strength of magnetic field vs. the increased distance from the magnetic circuit center (vertical position: on the magnetic pole surface)

4. EXPERIMENTAL EVALUATION OF PROPOSED MAGNETIC CIRCUIT

The proposed magnetic circuit having 0.2-mm width of ringed gap and 0.8-mm thick of magnetic pole was fabricated with the material of permendur (Fe49-Co49-V2) as the magnetic circuit and an amorphous of Co series as the magnetic pole. The inside and outside diameter of the coil was 2-mm and 5-mm respectively with the turned total number of 80-turns, and the wire diameter was 0.14-mm. A pole type electrical magnet (iron-core structure) was also fabricated as a comparing candidate using 1.6-mm diameters of electromagnetic soft iron bar by setting it into the inside of the coil hole.

4.1 MEASUREMENT OF MAGNETIC FIELD DISTRIBUTION

In this research, it was impossible to measure the magnetic field distribution by using a commercially available hall element because of its large size and insufficient spatial resolution problem. The magnetic field distribution generated from the coil surface was measured by using a thin-film magnetic head having a micro magnetic pole as the measuring gauge of the magnetic potential difference. The measured data is represented as a voltage signal that got from the temporal differentiation of the flux which generated by the magnetic potential differences. When a 50 kHz of alternative current was applied to the coil, the voltage signal from the magnetic potential gauge was measured. The measured results are shown in figure 5. From figure 5, it was confirmed that the proposed magnetic circuit having circularly-arranged gap shows much precipitous magnetic field gradient at the z axis direction comparing with the iron-core structure.

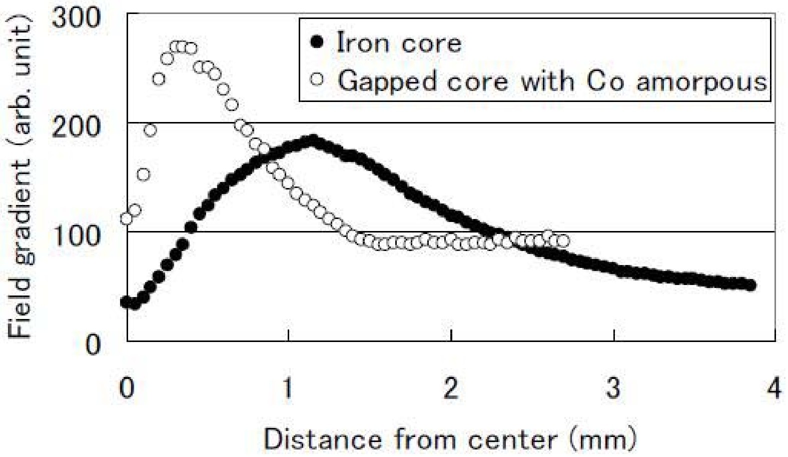

Figure 5. Experimental results of magnetic field distribution at 50-kHz

4.2 MEASUREMENT OF MAGNETIC REPULSION

The relationship between the magnetic field gradient and the repulsion force on the metallic conductor was measured experimentally. Experimental method was as below (see figure 6).

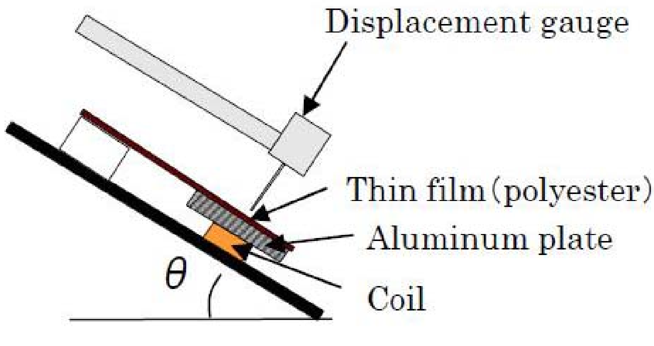

Figure 6. Schematic illustration of measuring method for the magnetic repulsion

The coil was fixed on a stage, and an aluminum plate with the dimension of 0.3-mm thick, ϕ6-mm in diameter, and 23-mg in weight was set up on to the coil. The aluminum plate was restricted other than the perpendicular direction to the coil surface with a 6-μm thick stretched polyester film. And then, an applied load on the aluminum disc whose direction is vertical to the aluminum disc surface was changed by inclining the inclination angle of the stage because of the vertical component of the aluminum plate gravity. By adjusting the input current on the coil, the levitated distance of the aluminum disc from the magnetic circuit surface can be controlled to the same value at every different load by making the load and the input current get counterbalanced. The repulsive force was measured from the input current at the state of the counterbalance between the load at the vertical direction and the input current. The measured results were shown in figure 7. From figure 7 it was known that at the same input current, the repulsive force on the gapped-core type was much bigger than that of the magnetic circuit having an iron-core. Further, it was known that by drawing an approximate line from the measured data, a dead zone will be generated due to the magnetic field gradient from the limited magnetic gap. The zero force point was got by an extrapolating method because it could not be got experimentally. From the zero force point shown in figure 7, it was known that on the gapped-core type, a linear repulsive force was generated by less of input current comparing to the iron-core. It is supposed to be that because of the extensively extended magnetic field, much of loss was generated in the case of the iron-core comparing to that of gapped-core. Further more, the ringed magnetic circuit (gapped-core) will be much more befitting with a feedback control system due to the less of a dead zone than the case of iron-core type.

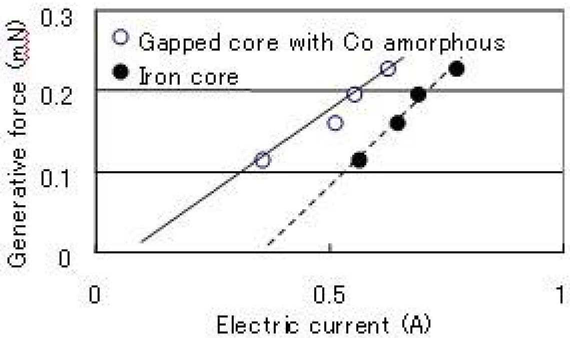

Figure 7. Generative repulsion force vs. input current at 50-Hz

4.3 MEASUREMENT OF MECHANICAL CHARACTERISTIC

The effective spring constant between the coil and the levitated metallic conductor was measured where the coil was fabricated to make the magnetic field gradient at z axis direction to be precipitous. Experiment was performed with the same method as used in section 4.2, but, setting the stage horizontally. In the experiment, the amount of displacement on the aluminum plate was measured by detecting the displacement of the aluminum plate by using an optical displacement meter, where 50-kHz of alternative current was input to the coil and output signal was taken with the frequency of 1-Hz by switching. The experimental result was shown in figure 8.

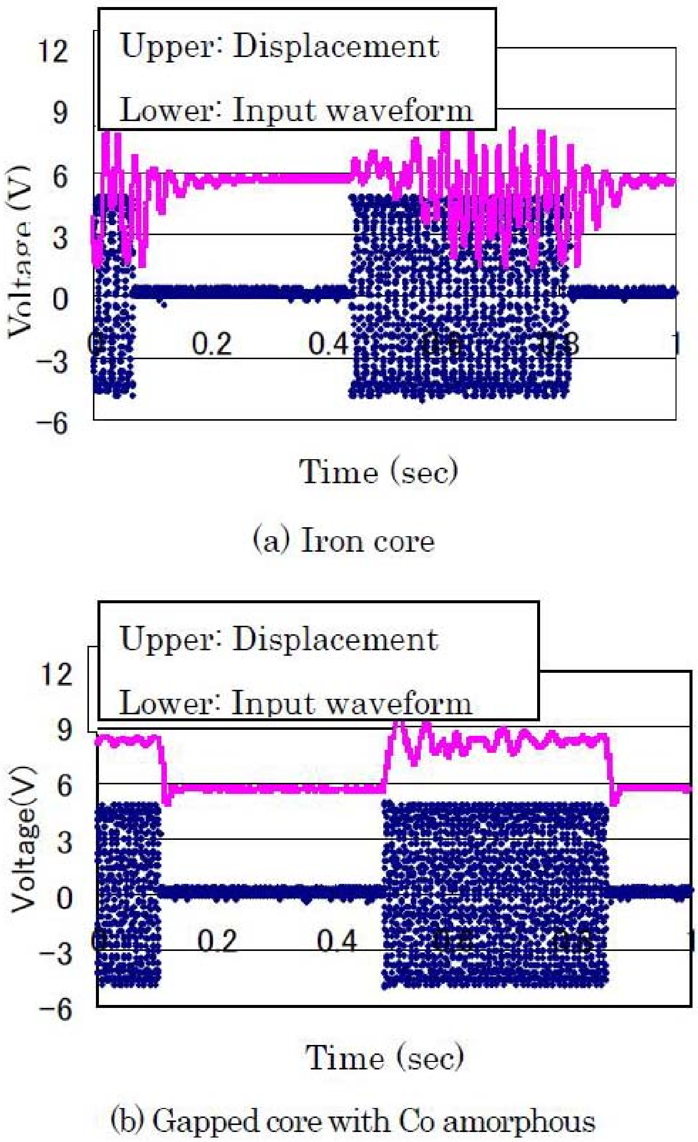

Figure 8. Experimental results of mechanical characteristics (effective spring constant)

In the case of iron-core magnetic circuit, there occurred a roll vibration on the levitated plate so that the average time constant was enlarged. While, in the case of ringed magnetic circuit with a circularly-arranged gap (gapped-core), there the vibration was converged and the time constant was about 52-ms and a stable levitation was confirmed on the levitated aluminum plate. From the results mentioned above, it was known that by generating a precipitous magnetic filed gradient on the magnetic circuit at z axis direction, it is possible to create a higher value of effective spring constant between the coil and the levitated metallic conductor, and at the same time, it is also possible to create a higher responsive control systems.

4.4 MEASUREMENT OF ATTRACTION FORCE

The attraction force was measured on the fabricated bilayer metallic sheet that consists of an aluminum plate and Ni-Fe film. The schematic view of the experimental set up was shown in figure 9.

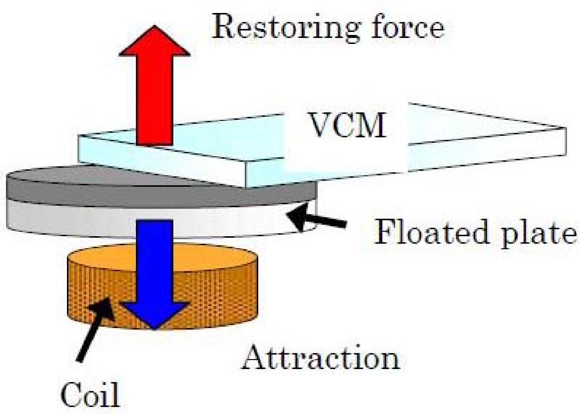

Figure 9. Schematic illustration of measuring method for the magnetic attraction force

Due to the small generating force, it is difficult to measure the attractive force by using a load cell. In the experiment, a voice of coil motor (VCM) was used. By applying 1mA of current, a 0.11-mN of load can be generated in this VCM. In experiment, the fabricated bilayer metallic plate was fixed on to the VCM, and a direct current was applied to the coil, so that an attractive force could be worked to the bilayer metallic sheet and make it to be attracted to the coil. The attractive force was calculated from the input current on the VCM by applying a restorative force to the VCM and make the bilayer metallic sheet return to the original position. Figure 10 is the analyzed and experimental results using the ampere-turn as the horizontal axis and the attractive force as the vertical axis where the distance from the coil surface to the bilayer metallic plate is constant. The experimental results showed the same trend with the analyzed one, although the attractive force from the experimental result was less than the analyzed one. The difference between the analyzed and experimental results might be generated from the lower value of magnetic permeability in the fabricated bilayer metallic conductor comparing to the analyzed one. From the experimental results, it was known that at the same ampere-turn it shows stronger of attraction force in the gapped-core compared with that of the magnetic circuit having an iron-core, and the attraction force difference will be increase with the number of ampere-turn.

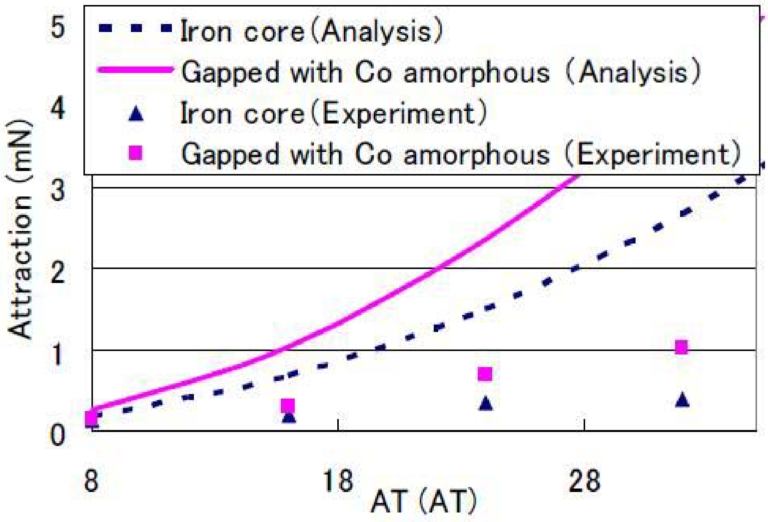

Figure 10. Attraction force vs. ampere-turn (AT)

4.5 MEASUREMENT OF TEMPERATURE CHARACTERISTIC

The levitation mechanism of eddy current repulsion used in this study is the same with the method of induction heat in principle, and when the levitated metallic conductor get heated, its repulsion force will be declined, so it is necessary to understand the heated level. For this purpose, the temperature of levitated metallic conductor was measured by applying a 50-kHz and 1 A of alternative current to the coil. In the experiment, an infrared thermometer (made in CENTER 350 series) having Distance:Spot=8:1 and 0.5°C of resolution was used and the distance from the thermometer to the surface of the levitated metallic conductor was 1-cm. The experimental result was shown in figure 11. From figure 11 it could be confirmed that comparing with the structure of iron-core, the case of gapped-core shows less of temperature rise (about 10°C). It is supposed to be that in the case of iron-core, the generated heat in coil will be directly radiated to the levitated metallic conductor, while in the case of gapped-core, due to the Co serial amorphous of the magnetic pole between the coil and the levitated metallic conductor, the Co serial amorphous worked as the heat-proof layer so that there was less of the temperature rise in the gapped-core comparing to the iron-core. Even with the same material on the elevated plate, the radiation ratio will be greatly changed according with the surface roughness and the oxidized layer, so, it will also be possible to control the temperature rise by means of a heat treat on the levitated metallic conductor.

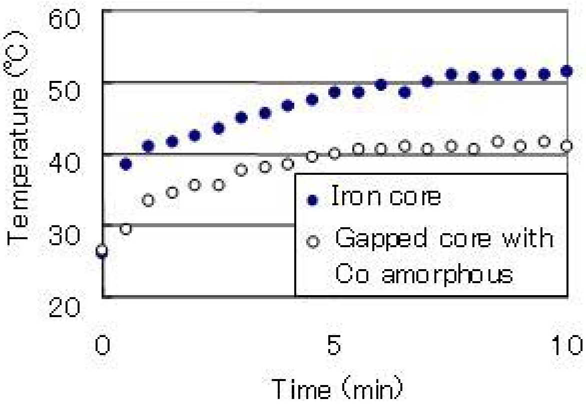

Figure 11. Measurement of temperature characteristic (temperature rise vs. past time)

5. SUMMARY

Advantages of the proposed approach and its viability as a contact-free Micro-bearing were discussed. As a key technology of contact-free Micro-bearing for MEMS applications, the authors proposed a novel type of micromagnetic bearing which can generate attraction and repulsive force at the same one direction. Numerical analysis and experimental research was performed. The approach was demonstrated to be useful as the method of contact-free Micro-bearing. The following conclusions can be summarized:

(1). Comparing to the iron-core, the proposed magnetic circuit having circularly-arranged gap (gapped-core) was proved to generate much concentrated magnetic flux with high density and much precipitous magnetic field gradient at the z axis direction.

(2). By using the gapped-core magnetic circuit, a stronger of repulsion and attraction force, a less of the dead zone and less of temperature rise could be realized.

(3). In the proposed magnetic circuit, the thinner the magnetic pole, the more precipitous of magnetic field gradient could be generated at the z axis direction. But, there exist an optimum ratio of about 4:1 between the width of gap size and the magnetic pole thickness. At this optimum ratio, the generated magnetic field was strongest and the magnetic field gradient at z axis direction was most precipitous.

(4). By making precipitous magnetic gradient at z axis direction, linear repulsion force can be generated using less of input electrical current. It was also confirmed that a larger of effective spring constant between the coil and levitated metallic conductor is formed, so that much higher precision and responsive control could be promising.

Further research to get stable suspension at lateral direction is going on in our Lab. and the detailed work will be reported in the near future.

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