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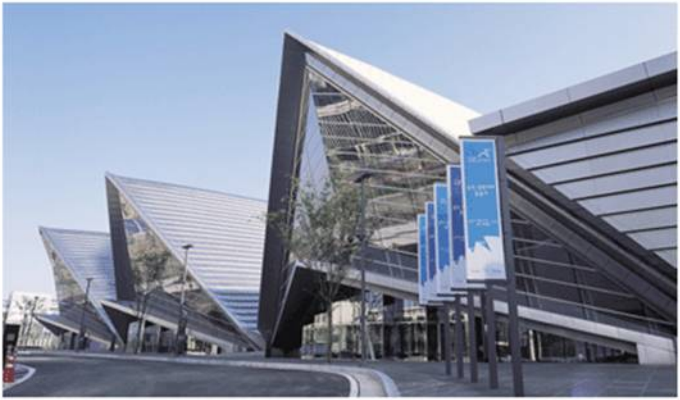
October 18-22, 2009, Songdo Convensia, Incheon, Korea



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Electric Machine and Drives (Poster Presentation) Oct. 21, 2009 (Wed.) 10:30-12:00

10:30-12:00 · PEM-1
Re-acceleration Characteristics of Stationary Discontinuous Armature Permanent Magnet Linear Synchronous Motor by Using Each Control System
Yong-Jae Kim, Kyoung-Pil Cho, Seung-Ho Shin, Youn-Ok Choi, Geum-Bae Cho (Chosun University, Korea)

10:30-12:00 · PEM-2
Development of IPM Synchronous Motor for Diesel Hybrid Electric Vehicle
Ju-Hee Cho, Hong-Seok Oh, Sang-Uk Cho, Deok-Geun-Kim (Komotek Co., Ltd, Korea), Ik-Seong Park (LIGNex1 Co., Ltd, Korea)

10:30-12:00 · PEM-3
The Velocity Control of a Permanent Magnet Type Stepping Motor Using a Self-tuning Theory
Sung-Ho Hong, Soo-Rang Lee, Sung-Hwan Choi (R&D Center CU Medical Systems, Inc., Korea), Young-Tae Kim, Sang-Don Lee (Kangnung Wonju National University, Korea), Cherl-Jin Kim (Halla University, Korea)

10:30-12:00 · PEM-4
Double-layer Rotor Design for Improving Characteristics of Single-phase LSPM Motor
Byeong-Hwa Lee, Fangliang, Jung-Pyo Hong (Hanyang University, Korea), Hyuk Nam (LG Electronics, Korea)

10:30-12:00 · PEM-5
Output Voltage Control of a Synchronous Generator for Ships Using Compound Type Digital AVR
Sang-Hoon Park, Seung-Kyung Lee, Su-Won Lee (Sungkyunkwan University, Korea), Jae-Sung Yu (HYOSUNG Heavy Industries Co., Ltd., Korea), Sang-Seuk Lee (PACTECH, Korea), Chung-Yuen Won (Sungkyunkwan University, Korea)

10:30-12:00 · PEM-6
Optimization of Magnetic Suspension Using Response Surface Methodology
Ho-Kyoung Lim, Jae-Woo Jung, Jung-Pyo Hong (Hanyang University, Korea)

10:30-12:00 · PEM-7
Novel Position Sensorless Starting Method of BLDC Motor for Reciprocating Compressor
Dae-Kyong Kim, Duck-Shik Shin (Korea Electronics Technology Institute, Korea), Sang-Taek Lee (Korea Electronics Technology Institute, Hanynag University, Korea), Hee-Jun Kim, Byung-Il Kwon (Hanynag University, Korea), Byung-Taek Kim (Kunsan National University, Korea), Kwang-Woon Lee (Mokpo National Maritime University, Korea)

10:30-12:00 · PEM-8
Optimal Design for Cogging Torque Reduction in BLDC Motor Using the Response Surface Method
Young-Kyoun Kim, Jung-Moo Seo, Seung-Bin Lim, Se-Hyun Rhyu, In-Sung Jung (Kore Electronics Technology Institute, Korea), Jin Hur (University of Ulsan, Korea)

10:30-12:00 · PEM-9
Core Loss Distribution of Three-Phase Induction Motor Using Numerical Method
Jeong-Jong Lee, Soon-O Kwon, Jung-Pyo Hong (Hanyang University, Korea), Ji-Hyun Kim, Kyung-Ho Ha (POSCO, Korea)

10:30-12:00 · PEM-10
Minimization of Torque Ripple in a BLDC Motor Using an Improved DC Link Voltage Control Method
Jin-soek Jang, Byung-taek Kim (Kunsan National University, Korea)

10:30-12:00
Finite Element Analysis of a Very Large-Scale Permanent Magnet BLDC Motor Considering Two-dimensional Magnetic Properties of Electrical Steels

Optimization of Magnetic Suspension using Response Surface Methodology

Ho-Kyoung Lim, Jae-Woo Jung, Jung-Pyo Hong
Dept. of Automotive Eng., Hanyang University, Korea
E-mail: rosen0825@paran.com

Abstract — Hydraulic system of commercial vehicle is switched electromechanical system for development of next generation vehicle recently. For example electric steering system and electric break system. This paper proposes the structural of magnetic suspension for next generation vehicle and deals with optimization of geometry of magnetic suspension. Two main characteristics are required in design of magnetic suspension. Firstly, magnetic motive force (MMF) by armature winding should have linearity. Secondly, identical magnitude of output force should be produced as direction of MMF for easily control.

In this paper, axis-symmetric finite element analysis is used for analysis of magnetic field analysis. In order to optimize magnetic suspension, response surface methodology combined with experimental design is applied to investigate the characteristics and optimize the magnetic suspension.

I. Introduction

Magnetic levitation system maintains the distance between two parts to be constant without mechanical contact. Due to the non-contacting structure, there is no mechanical friction is occurred and this result in easy maintenance and no friction loss of the system. Therefore, magnetic levitation system is especially suitable for high speed applications such as the magnetic levitation trains and bearings [1]. As an application of magnetic levitation system, magnetic suspension system for vibration-free table is dealt with in this paper. In order to remove vibration in the table, displacement by external force is measured by accelerometer, then internal force is produced by magnetic suspension system to compensate the external force and to maintain constant gap between two parts, one is fixed on the ground and the other is movable when the system is not activated.

Magnetic suspension system is classified into two types by source of force in this paper. One is core type, and the other is permanent magnet (PM) type. The core type of magnetic suspension system consists of core and field coil, therefore magneto-motive force (MMF) by field coil is the only source.

Meanwhile, PM type consists of PM, filed coil, and core. Therefore, PM type has the additional source which is called as reference force in this paper.

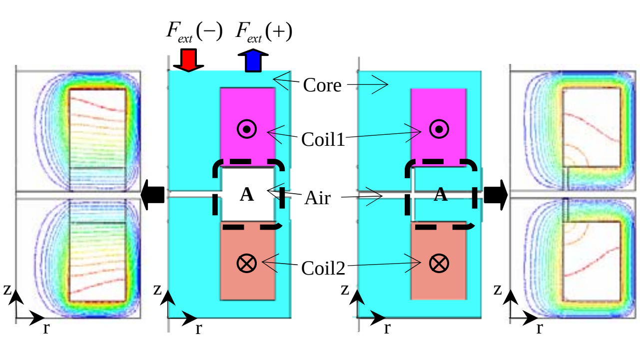
Two kinds of magnetic circuit are considered for both core and PM type, one is air return path and the other is core return path model as shown Fig. 1. According to the type of suspension system and magnetic circuit, characteristics of force production are analyzed. For the easy control, the magnitude of force should be equal when positive or negative current with identical magnitude is applied. To satisfy the characteristic, design of experiments (DOE) and response surface methodology are used with FEA. The optimized designed model is fabricated and analysis results are verified by test [2]..

II. Selection of Base Model for Optimal Design

In the initial design stage, two types of magnetic suspension system are investigated. Fig. 1 shows the axis-symmetric models of core type which have air return path and core return path. Flux lines of each model are described when coil 1 and coil 2 are excited by same direction of current. These systems have symmetrical magnetic flux distribution along circumferential direction as shown in Fig. 1. Therefore, axis-symmetric analysis is applied. The axis-symmetric analysis is possible to consider real flux distribution.

The variation of upper body of magnetic suspension due to external disturbance is monitored by accelerometer, and Coil 1 and Coil 2 are excited to produce compensating force against external disturbance.

When F_{ext}(-) is exerted on the system in Fig. 1, Coil 1 and Coil 2 are excited to generate identical force to F_{ext}(-) with identical current with same polarity. Then, repulsion force is generated. If F_{ext}(+) is exerted on the system, Coil 1 and Coil 2 are excited by identical current with opposite polarity then attraction force is generated and compensate variation. In this system, as shown in Fig. 2, generated force is non-linear to current and attraction and repulsion force differs significantly. Table I shows each of maximum force, repulsion and attraction force during two of coils are exited with sine current that peak value is 1A. Negative signal of the attraction force indicates direction of force. Considering the aspect of generated force, core type of magnetic suspension is not suitable to control.



(a) Air return path model (b) Core return path model

Fig. 1. Core type of magnetic suspension

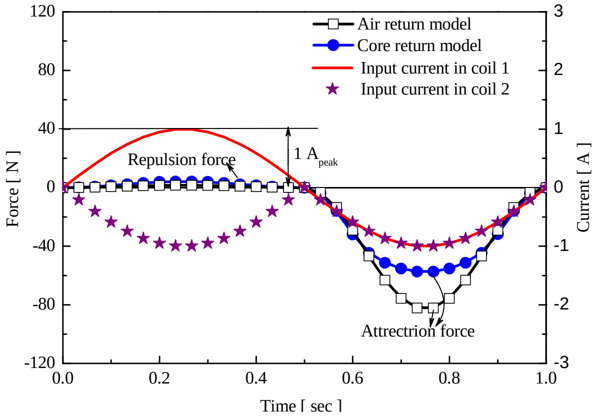


Fig. 2. Current vs. force characteristics of core type magnetic suspension system for input current

TABLE I
MAXIMUM FORCE OF CORE TYPE MAGNETIC SUSPENSION

Model type	Repulsion force [N] (max value)	Attraction force [N] (max value)
Air return path type	1.7	-82.4
Core return path type	4.1	-57.3

Fig. 3 shows the axis-symmetric model of air return path and core return path model of PM type and flux line when the input current is zero. As shown in Fig. 3, the PM type consists of PM, core, coil 1, and coil 2. In the PM type suspension, PM in the suspension face to face each other same pole, therefore repulsive force, F_{REF}, exists basically. When external disturbance, F_{ext}(-), is applied, coil1 and coil2 are excited to magnetizing direction and additional force is generated that defined as F_{INC} and external force is compensated.

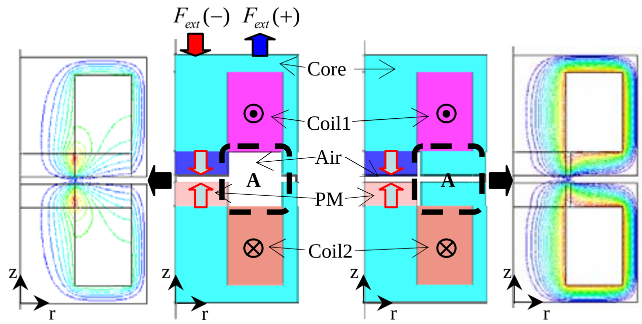
If F_{ext}(+) is exerted on the suspension, coil1 and coil2 are excited to demagnetize the PM, and F_{REF} is decreased as F_{ext}(+) that force named F_{DEC}. Fig. 4 shows output forces of input currents. Output force is nearly proportional to the input current, and the maximum F_{INC} is close to F_{DEC}. F_{INC} and F_{DEC} of core return model have similar values as shown Table II. In conclusion, core return path model of PM type is the suitable for target characteristics. Therefore, core return path model of PM type is chosen for optimization model.

III. DESIGN OF EXPERIMENT

A. Design Variables

Fig. 5 shows the cross section of base model and design parameters. Fig. 6 shows the effect of the parameters on the amplitude and balance that is defined as shown equation (1). From the Fig. 6, the PM length and Main flux path are the most significant parameters to the Balance and the Amplitude respectively. According to change Main flux path(A), PM width is also changed with identical size..

$$Amplitude = F_{DEC} \qquad Balance = \frac{F_{INC}}{F_{DEC}} \tag{1}$$



(a) Air return path model (b) Core return path model

Fig.3. PM type of magnetic suspension

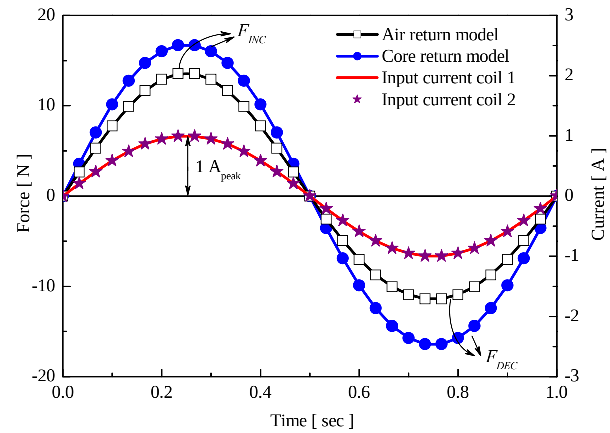


Fig. 4. Current vs. force characteristics of PM type magnetic suspension system for input current

TABLE II
MAXIMUM FORCE OF PM TYPE MAGNETIC SUSPENSION

Model type	F_{INC} [N] (max value)	F_{DEC} [N] (max value)
Air return path type	13.6	-11.4
Core return path type	15.3	-16.7

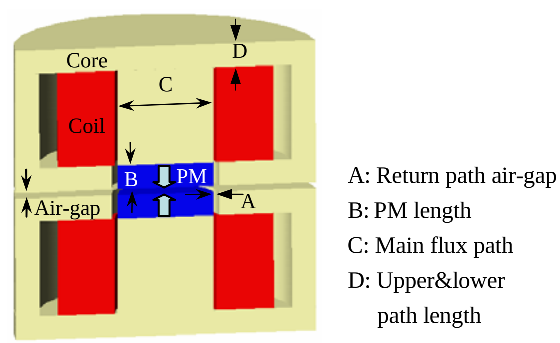
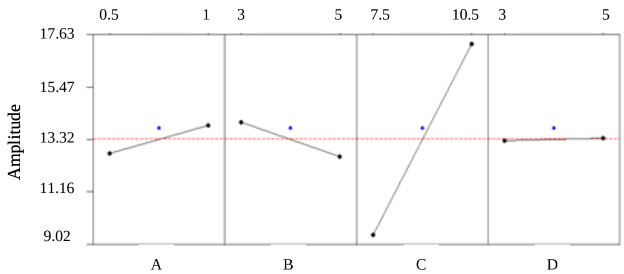


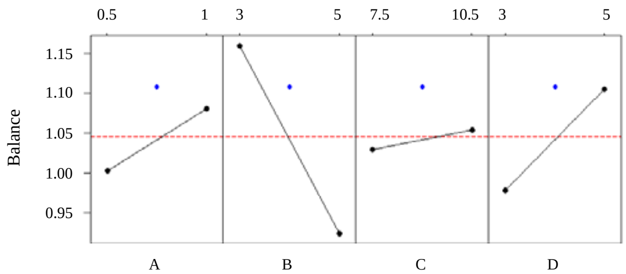
Fig. 5. Cross section and design variable of Magnetic suspension

B. Design Area

Establishment of design area is important. In this paper, 2^4 full factorial design (FFD) is applied to obtain more reasonable and objective design area for response surface method (RSM) [5]. To investigate the effects of the parameters on the object characteristic, Balance and Amplitude FFD is performed [3]. The advantages of FFD are written as follows.



(a) Amplitude



(b) Balance

Fig. 6. Main effect plot of each factor

TABLE III
DESIGN AREA OF EACH FACTOR

Factor	Value	Min.	Max.
B	PM length [mm]	4.5	5.0
C	Main flux path [mm]	9.5	10.5

- •all combinations of design parameters are investigated.
- •all main and interaction effects are evaluated without confounding.

The main effects of all factors are shown in Fig. 6 and it is found that interactions between variables are negligible so this paper does not mention the intersection effects. As shown Fig. 6, Main flux path is the most important factor of Amplitude because PM thickness is also changed according to change main flux path. The other side, variation of PM length highly affects Balance, because PM is also air-gap in magnetic circuit. The effect of other factors, Return air path and Upper&lower path length are insignificant to effects. Therefore, these two factors are ignored in RSM Based on the FFD results, the design areas are determined as shown Table III.

C. Response Surface Methodology (RSM)

RSM is applied to make appropriate response models of Amplitude and Balance. A quadratic approximation function of the models is commonly used to construct the fitted response surface.

In this paper, central composite design (CCD) is employed as the experimental design to estimate the fitted model each response. By adding center point and axial point to 2^k factorial design, the relationship between design variables and output can be considered. After implement of CCD, polynomial models of the response that is amplitude and balance are shown in (2) and (3) respectively.

$$\hat{y}_{Amplitude} = -41.881 - 5.36B - 4.9C + 0.2B^2 + 0.35C^2 + 0.2B \quad (2)$$

$$\hat{y}_{Balance} = -1.6 + 0.262B + 0.455C + 0.026B^2 - 0.021C^2 - 0.001B \quad (3)$$

IV. RESULT OF DESIGN

Fig. 7 showing the change of the responses according to the dimension of PM length and Main flux path is drawn by polynomial model (2) and (3). The area satisfying (4) and (5) is displayed in Fig. 8. In the region, the dot indicates an optimal point.

$$18 \le \hat{y}_{Amplitude} \le 19 \quad (4)$$

$$0.99 \le \hat{y}_{Balance} \le 1.01 \quad (5)$$

The result obtained by RSM is verified by FEA. Fig. 9 shows comparison of force characteristics of FEA results and test results of optimized model.

In order to verify the proposed method in this paper, experiment for characteristic of designed magnetic suspension is conducted. Fig. 10 shows the result of the experiment of magnetic suspension with measurement equipment.

Experiment is conducted using load cell and indicator. Because of friction between Magnetic suspension and guide, measurement value of Amplitude is lower than FEA result. However, amplitude is proportional to input current and almost unit balance is acquired [4], [5].

V. CONCLUSION

In this paper, the design technique of magnetic suspension system by using RSM combined with DOE is presented. Magnetic suspension system enable to active compensation against external disturbance unlike to other mechanical suspension system using elastic material such as spring or rubber pad. In addition, more precise control is possible than suspension system using air pressure. For the precise control ability, generated force should be linear according to input current and when the magnitude of the current is identical, magnitude force should be generated with same amplitude. In this paper, the magnetic suspension has characteristics as mentioned is designed using DOE combined with RSM. The magnetic suspension system is suitable for vibration-free table for precision machines such as electron microscope, optical machine, and semiconductor manufacturing.

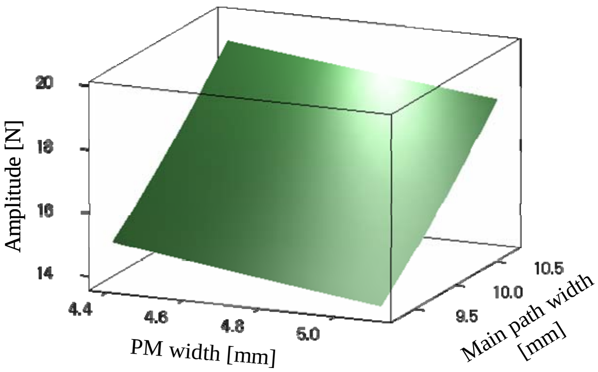
REFERENCES

[1] Masayuki Fujita, Toru Namerikawa, Funtio Matsumura and Kendo Uchida, "μ-Synthesis of an Electromagnetic suspension system", IEEE Trans, Automatic Control, Vol. 40, No 3, PP 530-536, 1995

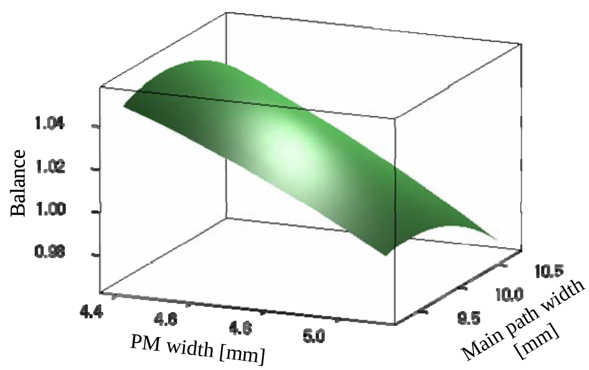
[2] Sung-Il Kim, Ji-Young Lee, Young-Kyoun Kim, Jung-Pyo Hong, Yoon Hur, and Yeon-Hwan Jung, "Optimization for Reduction of Torque Ripple in Interior Permanent Magnet Magnet Motor by Using the Taguchi Method", *IEEE Transaction on Magnetics*, Vol. 41, No. 5, pp. 1796-1799, May. 2005.

[3] Frederic Fillon and Pascal Brochet, "Screening and Response Surface Method Applied to the Numerical Optimization of Electromagnetic

Devices", *IEEE Transaction on Magnetics*, pp. 1162-1167, Vol. 26, No. 4, July. 2000.
[4] D. C. Montgomery, Design and Analysis of Experiments. New York: Wiley, 2001.
[5] Sung-Il Kim, Jung-Pyo Hong, Young-Kyoun Kim, Hyun Nam, Han-Ik Cho, "Optimal Design of Slotless-Type PMLSM Considering Multiple Responses by Response Surface Methodology," in *Transaction on Magnetics,* vol. 42, No. 4, pp. 1219-1222, April. 2006



(a) Amplitude



(a) Balance

Fig. 7. Response surface of each response

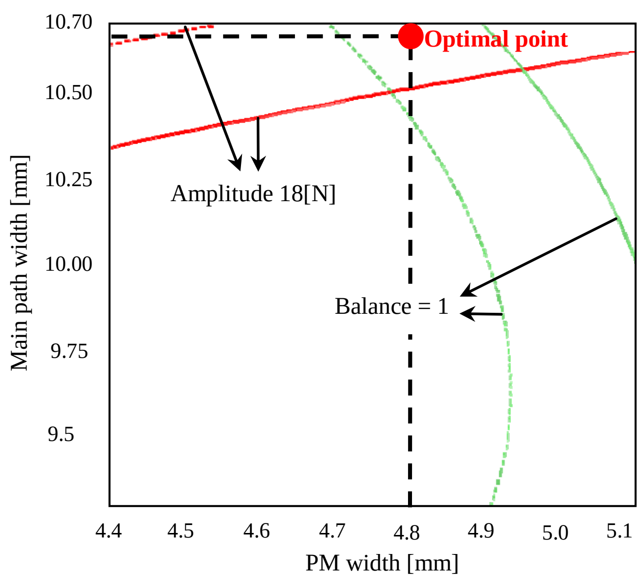


Fig. 8. Multiple responses range and optimal point

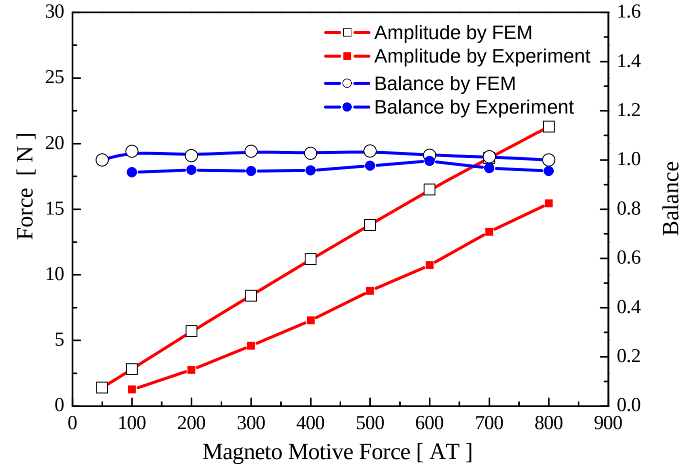


Fig. 9. Characteristic of Magnetic suspension

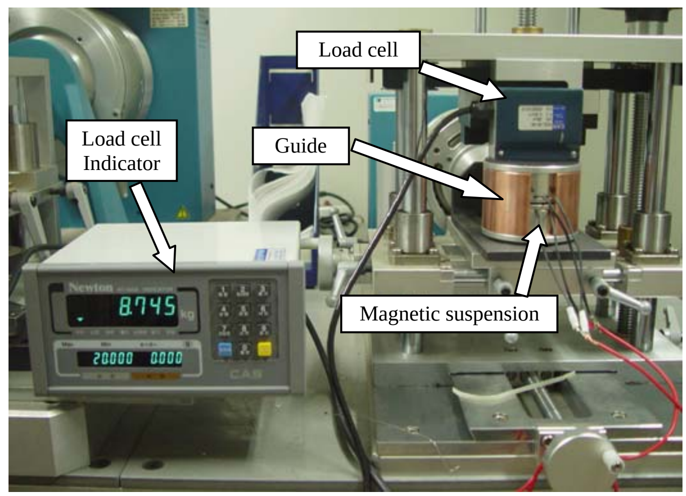


Fig. 10. Experiment of Magnetic suspension