Proposal of AC Magnetic Suspension Using Magnetic Resonant Coupling

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Abstract— **A novel AC magnetic suspension using magnetic resonant coupling is proposed and studied both theoretically and experimentally. The conventional AC magnetic suspension with energy transfer function has a problem that energy transfer efficiency is very low because it has a gap. In contrast, even if it has a gap, the energy transfer method using magnetic resonant coupling has high efficiency. In this paper, this method is combined with AC magnetic suspension. An experimental apparatus is fabricated for basic study. The floator was successfully suspended without control, and the self-stabilization characteristic is confirmed.**

I. INTRODUCTION

There are several methods of suspending a body without contact by using magnetic forces [1], [2]. One of them uses AC electromagnet instead of controlled DC electromagnet. The tuned LCR circuit levitation was investigated extensively in some period [3]-[6] mainly because it can be stable without a control loop. However, this characteristic has lost significance recently because powerful controllers are available at rather low cost [2].

Other forms of suspension using AC electromagnet have been developed to achieve energy transfer to the suspended object (floator) simultaneously [7]-[9]. When energy is consumed in the floator, either wire connection between the suspended object and ground facilities or the installation of a battery on the object [10] is necessary in suspension systems using controlled-DC electromagnet. However, the former breaks the noncontact property. In the latter, exchanging or recharging a battery is unavoidable. Such problems can be solved by using AC electromagnet not only for suspension but also for energy transfer [7]-[9].

However, the conventional AC magnetic suspension with energy transfer function has a problem that energy transfer efficiency is rather low because of a rather wide gap. To overcome this problem, a novel AC magnetic suspension using magnetic resonant coupling is proposed. It is to be noted that the energy transfer method using magnetic resonant coupling has high efficiency in spite of wide gap [11].

In this work, magnetic resonant coupling is introduced into AC magnetic suspension for improving the energy transfer performances. It is also demonstrated that the proposed suspension system has a self-stabilization characteristic so that stable suspension is achieved without any active control. An experimental apparatus is fabricated for basic study. Several experiments carried out with the apparatus are presented to demonstrate the fundamental properties of the proposed magnetic suspension system.

II. PRINCIPLES

A. Force Generation

The principle of suspension is illustrated in Fig.1. The stator electromagnet is a part of a series-resonant circuit fed by an alternating-voltage source (primary circuit). An electromagnet is attached to the floator and is also a part of another series-resonant circuit (secondary circuit). The two series-resonant circuits are adjusted to have a common resonant angular frequency ω_r. The two electromagnets face each other across a gap. Even if the gap is rather wide, a high-efficiency energy transfer is expected from the stator to the

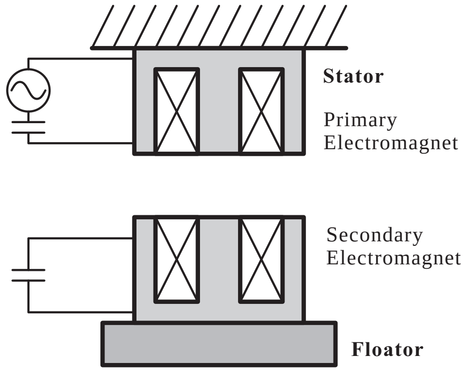


Figure 1. Basic structure of AC magnetic suspension using magnetic resonant coupling

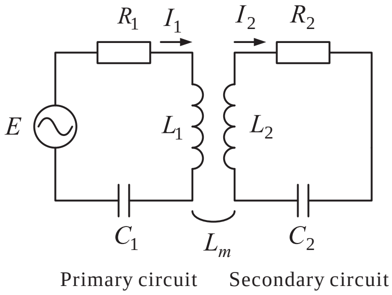
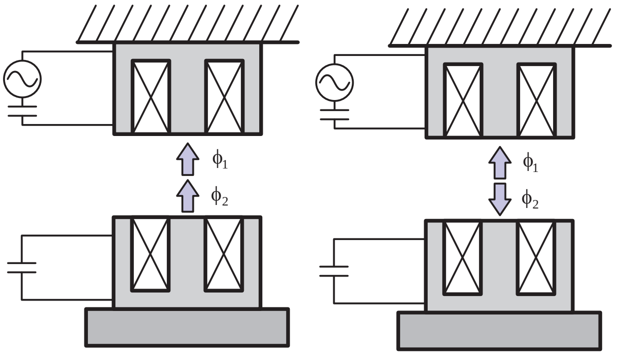
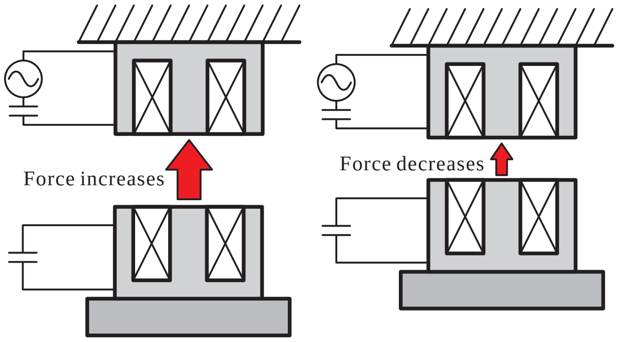


Figure 2. Equivalent circuit



(a) Cumulative coupling (b) Differential coupling

Figure 3 Direction of magnetic fluxes



(a) Gap increases (b) Gap decreases

Figure 4. Self-stabilization characteristic

floator because of magnetic resonant coupling.

Figure 2 shows an equivalent circuit. It is assumed for simplicity that the primary and secondary circuits have a same self-inductance L and a same capacitor C with no loss ($R_1=R_2=0$). The mutual inductance L_m is given by kL where k is the coupling coefficient. The circuit equations are given by

$$j\left(\omega L-\frac{1}{\omega C}\right)I_1-j\omega kLI_2=E\ , \tag{1}$$

$$j\left(\omega L-\frac{1}{\omega C}\right)I_2-j\omega kLI_1=0\ , \tag{2}$$

where ω: voltage-source angular frequency, I_1: amplitude of current flowing through the stator electromagnet, I_2: amplitude of current flowing through the floator electromagnet, and E: amplitude of voltage source. From (1) and (2), each amplitude of current is given by

$$I_1=-j\frac{\left(\omega L-\dfrac{1}{\omega C}\right)}{\left(\omega L-\dfrac{1}{\omega C}\right)^2-\omega^2k^2L^2}E\ , \tag{3}$$

$$I_2=-j\frac{\omega kL}{\left(\omega L-\dfrac{1}{\omega C}\right)^2-\omega^2k^2L^2}E\ . \tag{4}$$

From (3) and (4), we find that

$$I_1I_2<0 \text{ for } \omega<\omega_r \qquad \textit{Cumulative coupling}, \tag{5}$$

$$I_1I_2>0 \text{ for } \omega>\omega_r \qquad \textit{Differential coupling}. \tag{6}$$

Figure 3 illustrates the direction of force between the electromagnets. In the cumulative coupling mode, the flux generated by the stator electromagnet is reinforced with the flux generated by the floator electromagnet so that the force between them is attractive as shown in Fig.3(a). In contrast, the force can be repulsive in the differential coupling mode as shown in Fig.3(b).

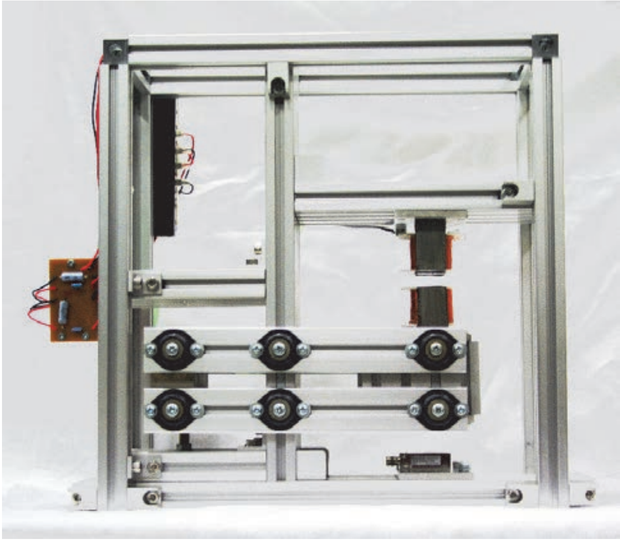


Figure 5. Photograph of experimental apparatus

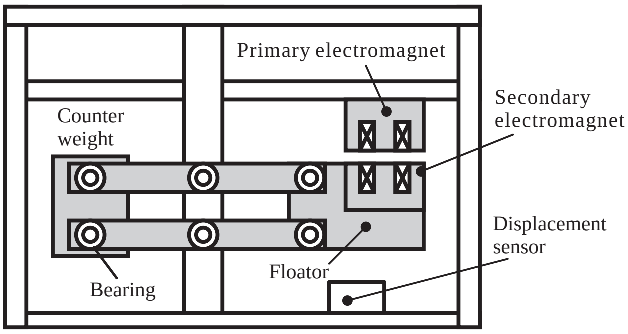


Figure 6. Schematic drawing of experimental apparatus

B. *Self-Stabilization*

It is assumed for simplicity that only the coupling coefficient k is a function of the gap between the stator and the floator. Generally, the coefficient increases as the gap decreases. The resonant condition of the whole circuit shown in Fig.2 is given by

TABLE I. CIRCUIT PARAMETERS

	Parameter	Value
L_1	Self-inductance of stator electromagnet	9.30 mH
C_1	Capacitance of primary circuit	1.03 μF
L_2	Self-inductance of floator electromagnet	9.37 mH
C_2	Capacitance of secondary circuit	1.04 μF

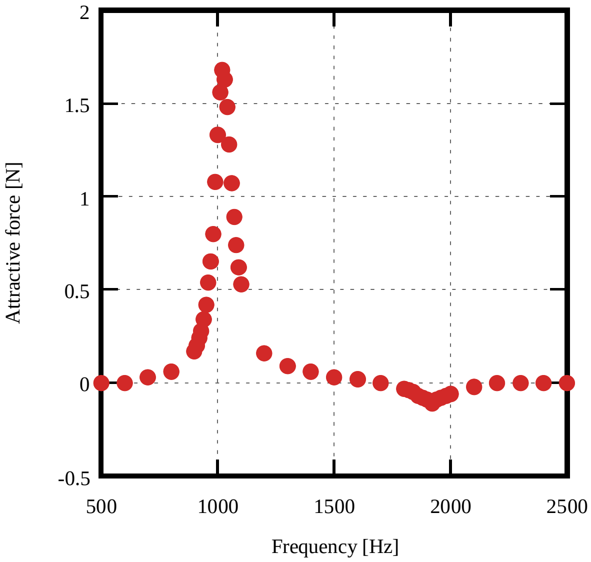


Figure 7. Force between the electromagnets as a function of frequency
($E = 15\text{V}$, Gap: 1mm, $R_L = 1\Omega$)

$$k = 1 - \frac{1}{\omega^2 LC}. \tag{7}$$

For a fixed given ω, this value is designated by k_r. Assume that $k_r<k$ and the coupling is cumulative. In these conditions, as the gap increases, k becomes smaller and approaches to k_r so that the amplitude of current and the attractive force increase as shown in Fig.4(a). Inversely, as the gap decreases, the attractive force decreases as shown in Fig.4(b). It indicates that this suspension system has a self-stabilization characteristic that was proper to the conventional AC magnetic suspension using a tuned LCR circuit [3]-[6].

III. EXPERIMENT

A. Apparatus

Figures 5 and 6 show a photograph and a schematic drawing of the fabricated apparatus for experimental study. It has a seesaw-type floator. An electromagnet for suspension is fixed at one end of the floator while a counter weight is attached to the other end for the adjustment of static unbalance. The stator electromagnet is fixed above the floator electromagnet. Under the floator, an eddy-current gap sensor is installed to measure the displacement of the floator. The parameters are listed in Table I.

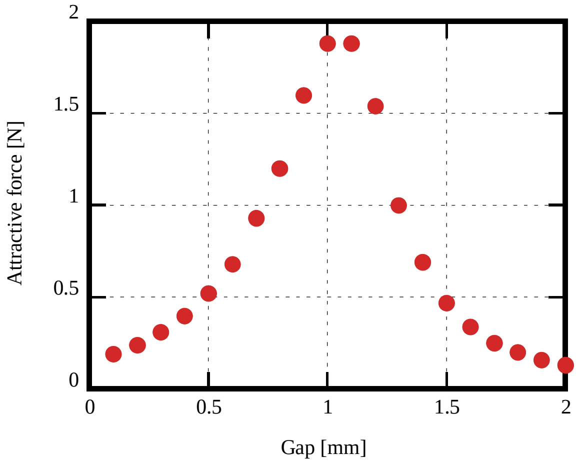


Figure 8. Force as a function of gap
($E = 15\text{V}$, $\omega = 6.28\times10^3$rad/s, $R_L = 1\Omega$).

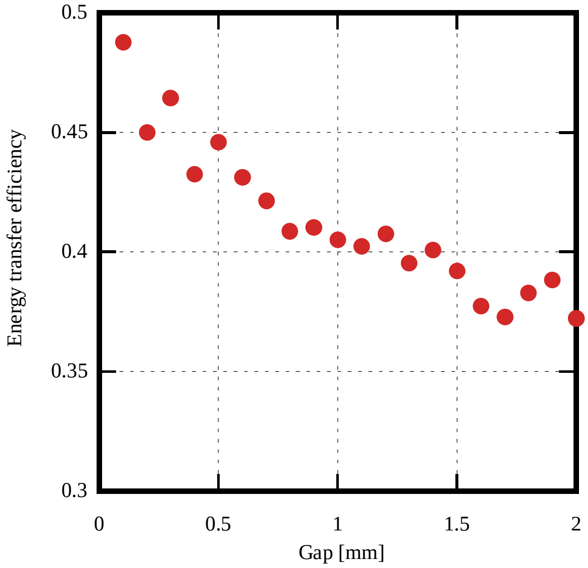


Figure 9. Energy transfer efficiency
($E = 15\text{V}$, $\omega = 6.28\times10^3$rad/s, $R_L = 10\Omega$).

B. Force characteristics

Figure 7 shows a measured force-frequency characteristic. During the measurement, the floator is fixed to a load cell installed below the floator and the gap is kept to be 1mm. A load resistance R_L is inserted to short the secondary circuit; it is set to be 1 Ω. The amplitude of the applied voltage E is 15 V. It is found that the maximum attractive and repulsive forces are obtained at 1020 Hz and 1910 Hz, respectively. Not only attractive force but also repulsive force were generated as predicted in Fig.3.

Figure 8 shows a measured force-gap characteristic with E=15 V and $\omega = 6.28\times10^3$ rad/s (correponding to 1100 Hz). It is found that the force increases as the gap increases from 0

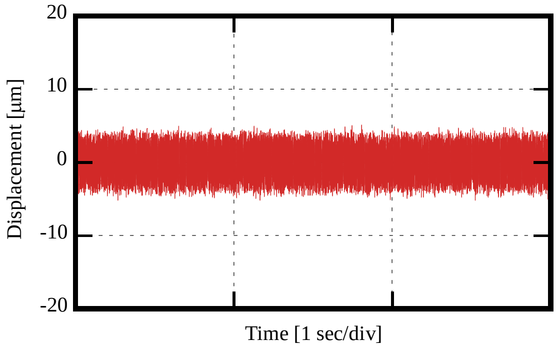


Figure 10. Displacement of floator during levitation ($E = 15\,\mathrm{V}$, $\omega = 6.28\times10^3$rad/s, $R_L = 1\Omega$).

to 1 mm. This result indicates the possibility of self-stabilization.

C. *Energy transfer characteristics*

Figure 9 shows a measured energy transfer efficiency as a function of the gap under the conditions where $E = 15\,\mathrm{V}$, $\omega = 6.28\times10^3$ rad/s (1000 Hz) and $R_L = 10\,\Omega$. It is found that the efficiency decreases as the gap increases but the ratio of decrease is not so large as that in the conventional AC magnetic suspension system [9].

D. *Suspension without control*

Self-stabilization suspension was achieved with E=20 V and $\omega = 6.28\times10^3$ rad/s (1000 Hz). The gap was 0.8 mm approximately. The displacement of the floator during suspension is shown in Fig.10. The floator is kept at a position without any active control.

IV. CONCLUSIONS

The AC magnetic suspension using magnetic resonant coupling was proposed. The fundamental characteristics of the proposed suspension system were studied both analytically and experimentally. It is demonstrated that the proposed system has the same characteristic of self-stabilization as the conventional tuned LCR circuit levitation. The self-stabilization suspension was achieved successfully in the fabricated apparatus.

REFERENCES

[1] B. V. Jayawant, "Electromagnetic Levitation and Suspension Technique," pp.1-31., Rdward Arnold, London, 1981.

[2] G. Schweitzer and E. H. Maslen (Ed.), "Magnetic Bearings," pp.10-15, Springer, 2009 .

[3] B. V. Jayawant and D. P. Rea, "New electromagnetic suspension and its stabilisation," Proc. IEE, Vol.115, No.4, pp.549-554, 1968.

[4] B. V. Jayawant and B. Z. Kaplan, "The development and stabilization of a new electromagnetic suspension," Journal of Physics E: Scientific Instruments, Vol.4, pp.301-306, 1971.

[5] B. Z. Kaplan and D. Regev, "Dynamic stabilization of tune-circuit levitatiors," IEEE Trans. on Magnetics, Vol.12, No.5, pp.556-559, 1976.

[6] S. Hagihara, "Performance and stability of a magnetic suspension device using a tuned LCR circuit," Proc. IEE, Vol.125, No.2, pp.153-156, 1978.

[7] O. Tsukamoto, K. Yasuda and J. Z. Chen, "A new levitation system with AC magnets," IEEE Trans. on Magnetics, Vol.24, No.2, pp.1497-1500, 1988.

[8] T. Hirata, T. Hikihara and Y. Hirane, "Susepension characteristics of magnetic suspension system bylinear induction motor," Trans. IEE Japan, Vol.110-D, No.10, pp.1091-1099, 1990.

[9] Mizuno, T., Kishita, D., Takasaki, M. and Ishino, Y., "PM-biased AC magnetic suspension having energy transfer function," Proc. 9th International Symposium on Magnetic Bearings, 70, 2004.

[10] M. Morishita, T. Azukizawa, S. Kanda, N. Tamura and T. Yokoyama, "A new Maglev system for magnetically levitated carrier system," IEEE Trans. on Vehicular Technology, 38, No.4, pp.230-236, 1989.

[11] André Kurs, et al., "Wireless Power Transfer via Strongly Coupled Magnetic Resonances," Science Express, Vol. 317, No.5834, pp. 83-86, 2007.