

Dynamic Stabilization of AC Magnetic Suspension Using Magnetic Resonant Coupling by Transmitted Power

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Abstract

The AC magnetic suspension system using magnetic resonant coupling is dynamically stabilized by a DC suspension mechanism operated by the power transmitted to the floator through the magnetic resonant coupling. The target AC magnetic suspension system has a self-stabilization property; restoring force is produced without any active control. However, it is dynamically unstable because slightly negative damping is also produced when the stator is fixed. Therefore, it is necessary for dynamic stabilization to add positive damping to the floator. A DC magnetic suspension is installed in parallel with the AC magnetic suspension to generate positive damping without any active control. The developed system has a pair of AC electromagnets for positive stiffness and another pair of DC electromagnets for positive damping. First, the coil of the DC electromagnet in the stator is shunted. However, it is experimentally shown that negative damping is produced because the latter pair also has a self-stabilization property; the force increases as the gap increases. Then, a bias voltage is applied to the DC electromagnet on the stator to make the stiffness negative. As a result, stable suspension is achieved without any active control in the developed system.

Keywords : Magnetic suspension, Magnetic bearings, Magnetic resonant coupling, Power transfer, Self-stabilization.

1. Introduction

The alternate-current (AC) magnetic suspension using magnetic resonant coupling has been proposed (Mizuno et al., 2014) and studied extensively (Korikawa et al., 2015) (Mizuno et al., 2016) (Rahman et al., 2000a; 2000b). In this suspension system, the energy transfer technique using magnetic resonant coupling has been combined with the AC magnetic suspension using a tuned LCR circuit. It has a self-stabilizing characteristic that is proper in the tuned LCR circuit levitation (Jayawant and Kaplan, 1971) (Frazier et al., 1974) (Hagiwara, 1978). A restoring force is produced automatically (without control): the attractive force acting on the suspended object (floator) increases as the gap between the stator electromagnet and the floator increases or vice versa. It indicates that the suspension system is statically stable as if the floator is suspended by a normal spring with a positive stiffness. However, it is dynamically unstable because there is slightly negative damping (Korikawa et al., 2015). For dynamic stabilization, direct or indirect damping must be added as in the tuned LCR levitation (Jin et al., 1994).

Meanwhile, the utilization of the power transmitted to the floator has not been discussed sufficiently. In a magnetic levitation system with AC magnets, the current induced in the secondary coil was switched or varied according to the motion of the floator for stabilization (Tsukamoto et al., 1988) (Hirata et al., 1990) (Mizuno et al., 2005). However, active control was necessary in those AC suspension systems. In a magnetically suspended gyro, it was proposed to use the transferred energy to drive a motor (Seito, et al., 2015).

In this work, the transmitted power is used to excite a DC electromagnet in the floator, which constitutes a DC magnetic suspension mechanism installed in parallel with the AC magnetic suspension system using magnetic resonant coupling. The developed magnetic suspension system achieves dynamic stabilization without any active control.

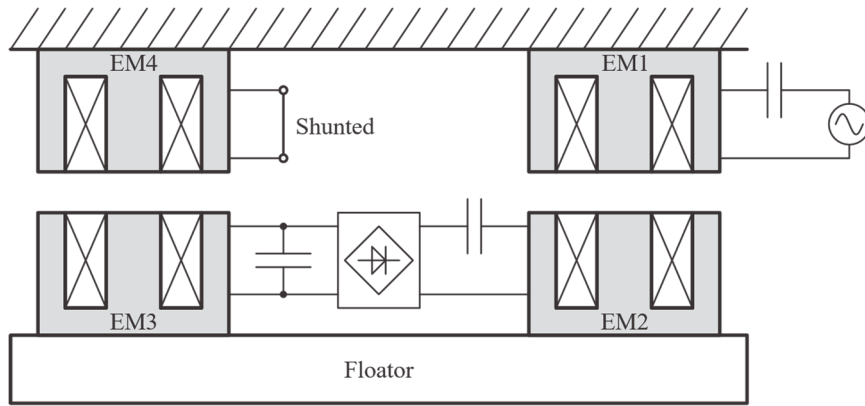


Fig.1 Schematic view of magnetic suspension system proposed to achieve dynamic stabilization. The AC voltage induced in the secondary coil is converted to a DC voltage by a full-wave rectifier and a smoothing circuit with a capacitor. The coil of EM4 is shunted to produce damping-like force.

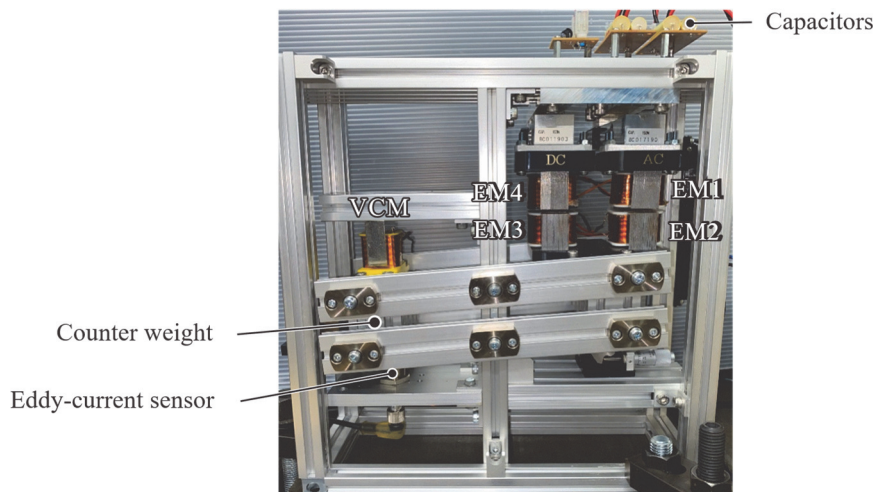


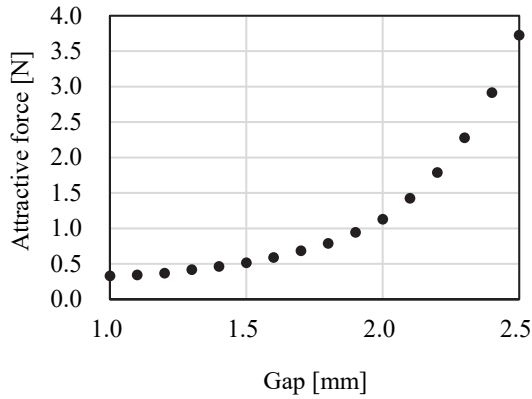
Fig.2 Picture of experimental apparatus

2. Original configuration

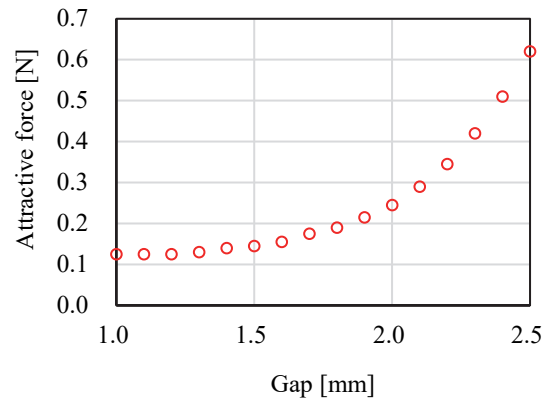
Figure 1 shows a schematic view of the proposed suspension system. There are two pairs of electromagnets. One of them constitutes a magnetic-resonant-coupling AC magnetic suspension. The stator electromagnet E1 is a part of a series-resonant circuit fed by an alternating-voltage source. They constitute the primary circuit. Another electromagnet EM2 is attached to the floator and is also a part of another series-resonant circuit. They constitute the secondary circuit. The two series-resonant circuits are adjusted to have a common resonant frequency. 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 floator due to magnetic resonant coupling. The other pair constitutes a DC magnetic suspension system. An electromagnet EM3 on the floator is excited by the DC source that is produced by converting the AC voltage induced in the secondary coil of E2 with a full-wave rectifier and a smoothing circuit with a capacitor. Another electromagnet EM4 on the stator has a shunted coil that is expected to produce positive damping by the voltage induced by the motion of the floator.

3. Experiments in the first configuration

Figure 2 shows a picture of an experimental apparatus. The apparatus has a seesaw-type floator. An electromagnet for AC suspension (EM2) is fixed at one end of the floator. Another electromagnet for DC suspension (EM3) is fixed



(a) Total force of AC-DC suspension.



(b) Force of DC suspension.

Fig. 3 Relationship between attractive force and gap. The total force of the AC suspension and the DC suspension increases as the gap increases, which indicates the stiffness is positive. It is to be mentioned that the DC suspension also has a positive stiffness.

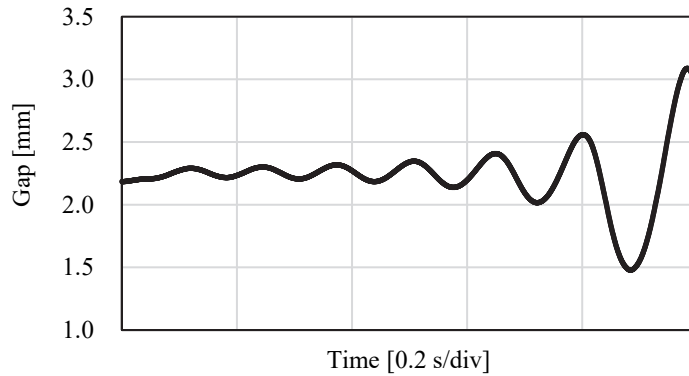


Fig. 4 Displacement of floator when the coil of EM4 is closed. The vibration of the floator diverges, which indicates that the damping is *negative*.

beside EM2. A weight is attached at the other end for the adjustment of static unbalance. The primary electromagnet (EM₁) is attached to a load cell fixed on the frame above EM2. Another electromagnet for DC suspension (EM4) is also attached to another load cell fixed on the frame above EM3. Such structures enable the attractive force of the AC suspension and that of the DC suspension to be measured individually.

Figure 3 shows the measured forces for various gaps. The total force of the AC-DC suspension system increases as the gap increases as shown by Fig.3(a). It indicates that the suspension system has positive stiffness and is statically stable. It is to be noted that the sole DC suspension system has also positive stiffness. If the voltage applied to EM3 were constant, it had negative stiffness and was unstable as the normal DC suspension system. In this system, however, the voltage applied to EM3 is produced from the AC voltage induced in EM2. The excitation frequency is set for the AC suspension system to have a self-stabilizing characteristic, that is, positive stiffness. It indicates that the amplitude of the induced AC voltage increases as the gap increases. Because the DC voltage applied to EM3 is produced from this voltage, the DC voltage also increases as the gap increases as shown by Fig.3(b). In a static point of view, therefore, the DC suspension system improves the stability.

However, the whole suspension system becomes dynamically unstable; the vibration of the floator diverges as shown by Fig.4. The reason is that negative damping is produced by the DC suspension against expectation. If the magnetomotive force in the DC magnet is constant, positive damping were produced as expected. However, in the developed suspension system, the voltage applied to EM3 is the rectified and smoothed voltage of the secondary circuit of the AC suspension (EM2). The DC suspension has a self-stabilizing characteristic (positive stiffness) as mentioned above. When the floator approaches the stator for example, the magnetic flux flowing through the coil of EM4 decreases.

Thereby, the induced back electromotive force tends to increase the flux. It indicates that the motion of the floator is accelerated by the induced force of EM4. As a result, *negative* damping acts on the floator.

4. Modified configuration

Figure 5 shows a schematic view of the modified suspension system. A bias voltage is applied to the DC electromagnet EM4 on the stator to make the stiffness of the DC suspension negative for the voltage induced by the motion of the floator to produce *positive* damping.

Figure 6 shows the total force of the AC-DC suspension for various gaps when the bias voltage is 1.37 V. Comparing it with Fig.3(a), we find that the force becomes larger at small gaps and decreases as the gap increases in the region of the gap where the gap is more than 1 mm and less than 1.55 mm ($1.0 \text{ mm} < \text{gap} < 1.55 \text{ mm}$). Figure 7 shows each attractive force of the AC and DC suspensions for various gaps. The force-to-gap characteristic of the AC suspension is a typical self-stabilizing one; the force increases as the gap increases. In contrast, the force-to-gap characteristic of the DC suspension is an unstable one when the gap is small (less than 1.55 mm) and becomes a self-stabilizing one when the gap is large (remarkable more than 1.8 mm).

Figure 8 shows the stiffness of the combined (AC-DC) suspension and that of the DC suspension for various gaps; the stiffness is calculated from the measured forces. For static stability, the stiffness of the combined suspension must be positive. For dynamic stability (positive damping), the stiffness of the DC suspension must be negative. These conditions

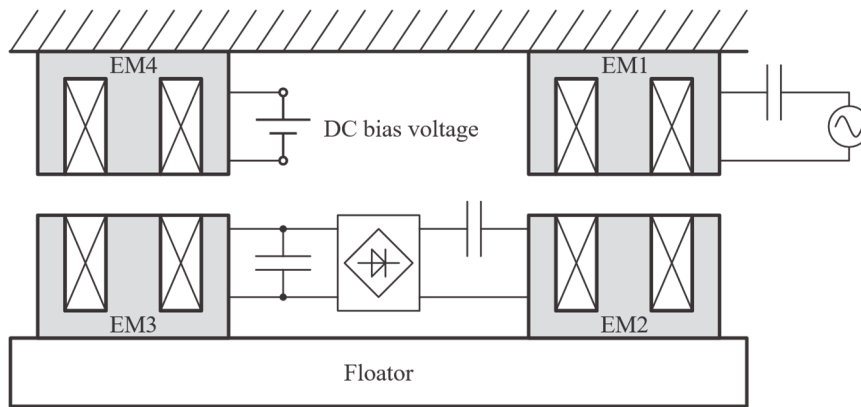


Fig.5 Modified magnetic suspension system. A bias voltage applied to the coil of EM4 to has negative stiffness.

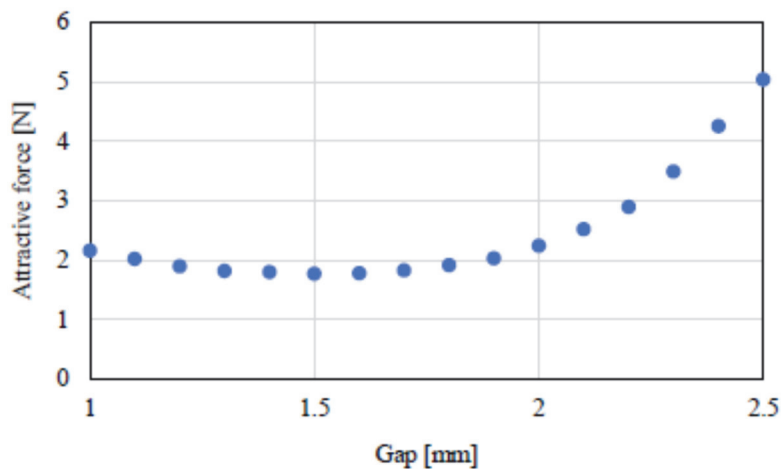


Fig. 6 Relation between the total force and gap in the modified configuration with a bias voltage of 1.37 V. The force decreases as the gap increases in a small-gap region ($1 \text{ mm} < \text{gap} < 1.55 \text{ mm}$) while it increases as the gap increases in a large-gap region ($1.55 \text{ mm} < \text{gap}$)

are satisfied in the region where the gap is more than 1.55 mm and less than 1.8 mm ($1.55 \text{ mm} < \text{gap} < 1.8 \text{ mm}$).

Figure 9 shows the responses of the floator to a disturbance acting on the floator when the equilibrium position x_e is 1.6, 1.7 and 1.8 mm which correspond to the gaps. It is found that the vibrations caused by the disturbance are attenuated

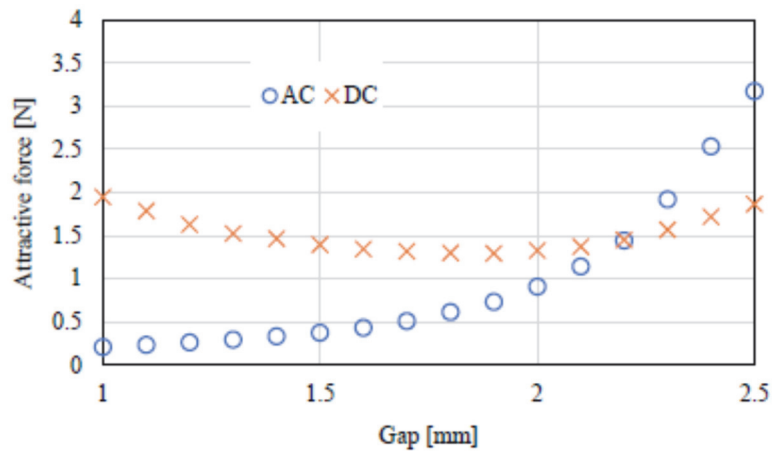


Fig. 7 Each attractive force of the AC and DC suspensions. The force of the AC suspension increases as the gap increases. The force of the DC suspension decreases in a small-gap region ($1 \text{ mm} < \text{gap} < 1.8 \text{ mm}$) and turns to increase in a large-gap region ($1.9 \text{ mm} < \text{gap}$).

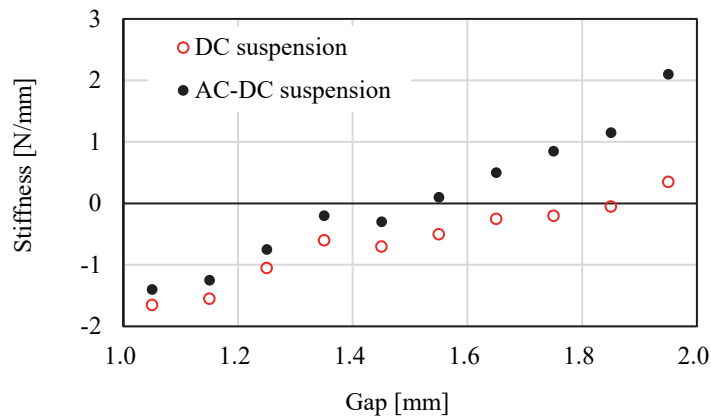


Fig. 8 Stiffness of AC-DC suspension (total stiffness) and that of DC suspension to gap when a bias voltage is applied to EM4. There is a region ($1.55 \text{ mm} < \text{gap} < 1.8 \text{ mm}$) where the total stiffness is positive and the stiffness of DC suspension is negative.

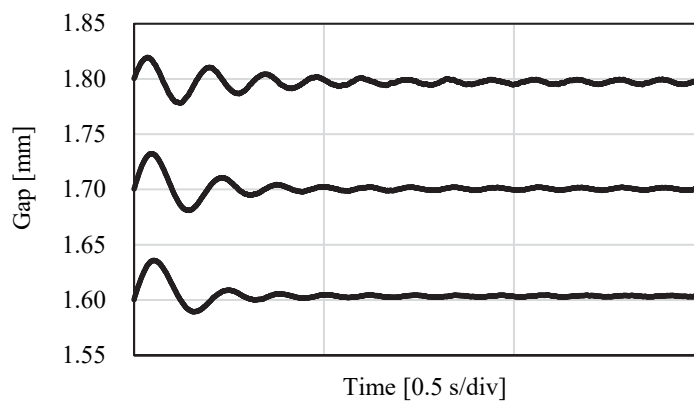


Fig. 9 Responses of the displacement of floator when the bias voltage is applied to EM4 and $x_e = 1.6, 1.7,$ and 1.8 mm . The vibration of the floator is attenuated, which indicates that the suspension system is dynamically stable.

due to positive damping. This result demonstrates that stable suspension is achieved without any active control in the developed AC-DC suspension system.

5. Conclusion

In the AC magnetic suspension using magnetic resonant coupling, dynamic stabilization was achieved by installing a DC suspension driven by the power transmitted to the floator through magnetic resonant coupling. The target AC magnetic suspension system has positive stiffness but slightly negative damping. Positive damping is necessary for dynamic stabilization. To generate such damping, a DC magnetic suspension mechanism was installed in parallel with the AC magnetic suspension and was excited by the power transmitted to the floator through the magnetic resonant coupling. First, the coil of the electromagnet for the DC suspension on the stator was shunted. It was experimentally shown that negative damping was produced because the DC suspension system has positive stiffness. Then, a bias voltage was applied to the DC electromagnet on the stator to make the stiffness negative. As a result, stable suspension was achieved without any active control in the developed system.

A problem of the developed suspension system is the total positive stiffness of the combined suspension decreases because the DC suspension has negative stiffness. Therefore, the operation range of the developed suspension system is limited. This problem can be solved by introducing phase-lead compensation to the DC suspension for producing positive damping without negative stiffness (Kobayashi et al., 2024).

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