Novel AC magnetic suspension using magnetic resonant coupling

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Abstract
A novel alternate-current (AC) magnetic suspension using magnetic resonant coupling is proposed and studied both theoretically and experimentally. An AC magnetic suspension with energy transfer function has been developed to achieve magnetic suspension and energy transfer to the suspended object simultaneously. However, the energy transfer efficiency was low in the developed system mainly because there existed a rather wide gap between the primary and secondary circuits. In contrast, the energy transfer technique using magnetic resonant coupling has high efficiency even if there is a wide gap. In this work, this technique is combined with AC magnetic suspension. The fundamental characteristics of the proposed system are studied for a basic model. It is shown analytically that the coupled circuits have two resonant frequencies and attractive force is generated at the lower resonant frequency while repulsive force is generated at the higher resonant frequency. In addition, the self-stabilizing characteristic, which is proper in the tuned LCR circuit levitation, is achievable in the proposed suspension system. A see-saw type experimental apparatus was fabricated for basic experimental study. The theoretical predictions were confirmed experimentally. The self-stabilization was achieved in the fabricated apparatus. It was also shown experimentally that the stiffness and damping characteristics depend on the gap, the amplitude and frequency of the AC voltage source.

Key words: Magnetic bearing, Magnetic levitation, Mechatronics, Electromagnetic actuator, Stability

1. Introduction

There are several methods of suspending a body without contact by using magnetic forces (Jayawant, 1981; Schweitzer and Maslen, 2009). They can be classified in a number of different ways. One classification is based on the principle of stabilization. One category is “active”; stabilization is achieved by feedback control. Active-controlled magnetic suspension using a direct-current (DC) electromagnet has become a maturing technology and have many industrial applications. A typical system consists of the following components:
- object to be suspended (floator)
- DC electromagnet to produce suspension force
- sensor to detect the displacement of the floator
- electronic analog or digital controller
- power amplifier to feed current to the windings of the electromagnet

This system is inherently unstable in the normal direction. Stable action can be achieved by sensing the position of the rotor and controlling the force fields to prevent the rotor from departing from its desired position with sufficient rapidity; increase the current when the air gap is too large, decrease the current when the air gap is too small. The advantages of such active systems are high stiffness and adaptability to environmental changes and low field leakage. The disadvantages are high cost and the penalty of total system weight (Moon, 1994).

The other category is “passive”. Diamagnetic and superconducting levitations belong to this category (Moon, 1994). Another approach is alternate-current (AC) magnetic suspension that uses AC electromagnet instead of controlled DC electromagnet. The tuned LCR circuit levitation was investigated extensively in some period (Jayawant...
and Rea, 1968; Jayawant and Kaplan, 1971; Kaplan and Regev, 1976; Hagiwara, 1978) 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 (Schweitzer and Maslen, 2009).

Other forms of suspension using AC electromagnet have been developed to achieve energy transfer to the suspended object (floator) simultaneously (Tsukamoto et al., 1988; Hirata et al., 1990; Mizuno et al., 2004). 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 (Morishita et al., 1989) 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 (Tsukamoto et al., 1988; Hirata et al., 1990; Mizuno et al., 2004).

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 has been proposed where magnetic resonant coupling is introduced into AC magnetic suspension for improving the energy transfer performances (Mizuno et al., 2014). It is to be noted that the energy transfer method using magnetic resonant coupling has high efficiency in spite of wide gap (Kurs, et al., 2007).

In this work, the principles and basic characteristics of the suspension are studied in a basic single-degree-of-freedom-of motion model. It is shown that the suspension system has a self-stabilization characteristic, that is, the attractive force increases as the gap increases. Therefore, stable suspension without any active control is expected. An experimental apparatus is fabricated for basic study. Several experiments are carried out with the apparatus to study the characteristics of the suspension system experimentally.

2. Principles

2.1 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. They constitute the primary circuit. Another electromagnet 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 angular frequency \( \omega_r \). 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 floator due to magnetic resonant coupling (Kurs, et al., 2007).

Figure 2 shows an equivalent circuit. The electrical dynamics of this circuit are expressed as

\[
L_1 \frac{di_1}{dt} + R_1i_1 + \frac{1}{C_1} \int i_1 dt - L_m \frac{dl_2}{dt} = e
\]

(1)

\[
L_2 \frac{dl_2}{dt} + R_2l_2 + \frac{1}{C_2} \int i_2 dt - L_m \frac{dl_1}{dt} = 0
\]

(2)

Fig.1 Basic configuration of the proposed AC magnetic suspension system using magnetic resonant couplings. The primary circuit on the stator and the secondary circuit on the floator have a common resonant frequency.
where \( i_1 \) is the current flowing through the stator electromagnet, \( i_2 \) is the current flowing through the floator electromagnet, and \( e \) is the voltage source. It is assumed for simplicity that the primary and secondary circuits have the same self-inductance \( L \) and capacitance \( C \) with no loss (\( R_1 = R_2 = 0 \)). The mutual inductance \( L_m \) is given by \( kL \) where \( k \) is the coupling coefficient. To obtain the steady-state solutions, the variables are expressed as

\[
e = E e^{j\omega t}, \quad i_1 = I_1 e^{j\omega t}, \quad i_2 = I_2 e^{j\omega t}\]

where \( \omega \) is the voltage-source angular frequency, and \( E, I_1 \) and \( I_2 \) are complex constants that are referred to as phasors (Cannon, 1967). It is assumed in the following that \( E > 0 \). Substitute (3) to (1) and (2) gives

\[
f \left( \omega L - \frac{1}{\omega C} \right) I_1 - j \omega k L I_2 = E \tag{4}
\]

\[
f \left( \omega L - \frac{1}{\omega C} \right) I_2 - j \omega k L I_1 = 0 \tag{5}
\]

From (4) and (5), each phasor of current is given by

\[
I_1 = -j \frac{\left( \omega L - \frac{1}{\omega C} \right) E}{\left( \omega L - \frac{1}{\omega C} \right)^2 - \omega^2 k^2 L^2} \tag{6}
\]

\[
I_2 = -j \frac{\omega k L E}{\left( \omega L - \frac{1}{\omega C} \right)^2 - \omega^2 k^2 L^2} \tag{7}
\]

From (6) and (7), we get

\[
\frac{I_1}{I_2} = \frac{\omega L - \frac{1}{\omega C}}{\omega k L} \tag{8}
\]

Equation (5) indicates that

\[
\frac{I_1}{I_2} < 0 \quad \text{for} \quad \omega < \omega_r \quad \text{Cumulative coupling} \tag{9}
\]

\[
\frac{I_1}{I_2} > 0 \quad \text{for} \quad \omega > \omega_r \quad \text{Differential coupling} \tag{10}
\]

Fig.2 Equivalent circuit of the AC magnetic suspension system using magnetic resonant couplings.
where the common resonant angular frequency is defined by

\[ \omega_r = \frac{1}{\sqrt{LC}} \]  

(11)

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).

### 2.2 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

\[ LC k^2 - 1 = \omega^2 \]  

(12)

For a fixed given \( \omega_0 \), this value is designated by \( k_0 \). Assume that \( k_0 < k \) and the coupling is cumulative. In these conditions, as the gap increases, \( k \) becomes smaller and approaches to \( k_0 \) (resonant condition) 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.

![Fig.3](image_url) Direction of magnetic fluxes. In the cumulative coupling mode, the force between the stator and the floator while in the differential coupling mode, the force can be repulsive

![Fig.4](image_url) Self-stabilization characteristic. The force increases as the gap increases, and vice versa.
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 (Jayawant and Rea, 1968; Jayawant and Kaplan, 1971; Kaplan and Regev, 1976; Hagiwara, 1978).

3. Experiment
3.1 Apparatus

Figures 5 and 6 show a photograph and a schematic drawing of the fabricated apparatus for experimental study. It

![Figure 5: Photograph of experimental apparatus.](image)

![Figure 6: Schematic drawing of experimental apparatus.](image)

Table 1  Circuit parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1$</td>
<td>Self-inductance of stator electromagnet</td>
<td>9.30 mH</td>
</tr>
<tr>
<td>$C_1$</td>
<td>Capacitance of primary circuit</td>
<td>1.03 µF</td>
</tr>
<tr>
<td>$L_2$</td>
<td>Self-inductance of floator electromagnet</td>
<td>9.37 mH</td>
</tr>
<tr>
<td>$C_2$</td>
<td>Capacitance of secondary circuit</td>
<td>1.04 µF</td>
</tr>
</tbody>
</table>
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 1. It is to be noted that such seesaw-type apparatuses are convenient for basic study mainly because we can focus on a single-degree-of-freedom rotational motion of the floator; on the other hand, friction at the bearing is unavoidable due to damping by sliding (Goodman, 1995).

### 3.2 Resonant frequency

Figure 7 shows the conductance of the primary circuit and that of the combined primary and secondary circuits.

![Conductance vs Frequency](image)

*Fig.7  Resonant frequency of the primary circuit and those of the magnetically coupled circuits with a gap of 1mm.*

![Voltage and Current Waveforms](image)

*Fig.8  Waveforms of the voltage and current of the primary coil and the current of the secondary coil at the first resonant frequency of the coupled circuit; $\omega = 6.41 \times 10^3$ rad/s (corresponding to 1020 Hz).*
with a gap of 1 mm, which were measured with an impedance analyzer. The isolated primary circuit has a resonant frequency of 1600 Hz while the combined circuit has two resonant frequencies below and above the original resonant frequency. This result demonstrates that the primary and second circuits are coupled magnetically, that is to say, resonant coupling is actually achieved.

The voltage and current waveforms at each resonant frequency are shown in Fig.8 and Fig.9. At the first resonant frequency of 1020 Hz, the phase angle between the primary and secondary currents is 180 degrees as shown by Fig.8. In contrast, the phase angle is 0 degree at the second frequency of 1910 Hz as shown by Fig.9. These characteristics coincide with the prediction given by (9) and (10).

![Waveforms](image1)

**Fig.9** Waveforms of the voltage and current of the primary coil and the current of the secondary coil at the second resonant frequency of the coupled circuit; $\omega = 13.0 \times 10^3$ rad/s (corresponding to 1910 Hz)

![Force-frequency](image2)

**Fig.10** Force-frequency characteristics when the gap is 1 mm, $E = 15$ V, and $R_L = 1 \Omega$. 

3.3 Force characteristics

Figure 10 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 1 mm. A load resistance $R_L$ is inserted to short the secondary circuit; it is set to be $1 \Omega$. 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 11 shows a measured force-gap characteristic with $E = 15 \text{ V}$ and $\omega = 6.28 \times 10^3 \text{ rad/s}$ (corresponding to 1000 Hz). It is found that the force increases as the gap increases from 0 to 1 mm; such characteristic is referred to as positive stiffness. This result indicates the possibility of self-stabilization.

![Fig.11 Attractive force as a function of gap when $E=15 \text{ V}$ and $\omega = 6.28 \times 10^3 \text{ rad/s}$ (corresponding to 1000 Hz).](image)

![Fig.12 Force-gap characteristics for various applied frequencies.](image)

![Fig.13 Displacement of floator without any active control ($E = 15 \text{ V}$, $\omega = 6.28 \times 10^3 \text{ rad/s}$, $R_L = 1 \Omega$).](image)
The force-gap characteristics are measured for various frequencies of the voltage source as shown by Fig.12. It demonstrates that the maximum value of attractive force and the range of positive stiffness depend on the frequency. When the frequency is 1000 Hz (lowest), the maximum force is largest and the gap range of positive stiffness is smallest.

3.4 Self-stabilization

Self-stabilization was achieved with $E = 15\ \text{V}$ and $\omega = 6.28 \times 10^3 \text{rad/s}$ (1000 Hz). The counter weight was adjusted for the gravitational force to produce a clockwise torque acting on the floator to counteract the torque produced by the attractive force of the primary electromagnet at an equilibrium state. The gap was 0.8 mm approximately. The floator was kept at the position without any active control. Figure 13 shows the displacement of the floator in such self-stabilization state.

Figure 14 shows transient responses for rectangular-wave disturbance that is generated by a voice coil motor installed in the floator. It shows that the stability is kept even in the presence of disturbance acting on the floator. It is
also found that the response at rise differs from that at decay. Figure 15 shows the frequency responses from the disturbance to the floator displacement when the gap is 1.25 mm and 0.55 mm, which correspond to at rise and at decay. The resonant frequency and damping factor are 7.4 Hz and 0.051 in the former while 5.9 Hz and 0.105 in the latter. These results demonstrate that the stiffness and damping of suspension depend on the gap.

It is to be noted that friction at the bearing generates damping effects because an unstable phenomenon has been observed in a magnetic suspension system without any mechanical contact (Korikawa et al., 2015). It remains an open issue whether completely passive, undamped and noncontact suspension is achievable by the AC magnetic suspension using magnetic resonant coupling.

Stiffness and damping are critical characteristics to stability. They are adjustable by selecting parameters such as the amplitude and frequency of the AC voltage source, inductances, capacitances and resistances in the circuits. The value of stiffness $k_v$ is estimated from measured force-gap characteristics such as those shown in Fig.11. Figures 16 and 17 show stiffness-gap characteristics for various values of the applied voltages $E$, and the excitation frequency $\omega$, respectively. These results demonstrate that the stiffness of suspension can be adjusted with these parameters $E$ and $\omega$. It is found from Fig.17 that the region of gap with positive stiffness tends to be narrower and the gap with the maximum stiffness becomes lower as the excitation frequency decreases.

The damping characteristics also vary depending on these parameters. It was confirmed experimentally that the system became unstable when the stiffness was too high in spite of the friction at the bearing. An indirect measurement using active velocity feedback is conducted here mainly because the direct measurement of damping coefficient is not easy especially when the damping is negative. For achieving velocity feedback, a voice coil motor (VCM) is installed between the floator and the base. It is driven with a power amplifier to produce force proportional to the velocity of the floator. The velocity signal is obtained by differentiating the output of the displacement sensor. To estimate the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig16.png}
\caption{Relation between stiffness and gap for various input voltage amplitudes.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig17.png}
\caption{Relation between stiffness and gap for various frequencies.}
\end{figure}
damping characteristic, a prescribed damping is added to the suspension system with VCM to achieve stable suspension at first. Then, the feedback gain of velocity is decreased until the system falls into instability. The damping just at the boundary is referred to as threshold damping. Figure 18 shows the relation between stiffness and threshold damping. It is found that additional damping necessary for stable suspension increases as the stiffness becomes higher. Meanwhile, negative threshold damping indicates that the suspension system is stable without adding damping when the stiffness is low. It is to be noted again that damping due to friction exists at the bearing even without additional damping.

4. Conclusions

The AC magnetic suspension using magnetic resonant coupling was proposed. In the proposed suspension system, the stator electromagnet is a part of a series-resonant circuit fed by an alternating-voltage source (primary circuit). Another 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 and the two electromagnets face each other across a gap. Such structure leads to magnetic resonant coupling.

The fundamental characteristics of the proposed suspension system were studied both analytically and experimentally. It was predicted that the coupled circuits has two resonant frequencies and attractive force is generated at the lower resonant frequency while repulsive force is generated at the higher resonant frequency. Such characteristics were confirmed experimentally. It was also predicted that the proposed system has the self-stabilization characteristic that is inherent in the conventional tuned LCR circuit levitation. The measured force-gap characteristics supported this prediction. The self-stabilization was achieved in the fabricated apparatus with a see-saw type floator. The measured transient and frequency responses indicated that the stiffness and damping characteristics of the suspension depend on the gap, and the amplitude and frequency of the AC voltage source.

References


