Concept of Displacement Sensor Using Resonant Inductive Coupling

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Abstract

This paper presents the concept of a novel displacement sensor based on resonant inductive coupling. Resonant inductive coupling uses two coils or LC circuits similarly to an electromagnetic induction. The electromagnetic induction, that is the principle of transformer, is also an interaction of magnetic fields in usually a kilohertz-range. It is used for power transfer and operated with a small gap. A power transmission with rather larger gap is possible by using a megahertz-range resonance. Resonant inductive coupling is actively studied in the field of wireless power transfer recently. Meanwhile, some AMB systems need a displacement sensor operating with a large air gap. Thus, the resonant inductive coupling is applied to a displacement sensor. It can achieve high resolution (sub-mm) over a very large distance (10cm). In this paper, the principle of resonant inductive coupling is explained. Several basic results are shown, and these results are evaluated as a displacement sensor.

1 Introduction

Wireless power transfer techniques with resonant inductive coupling are impressively progressing. These techniques have been very popular topics of research (mostly about its efficiency) since the report in 2007 [1]. In recent years, many portable devices have batteries, and wireless power transfer is convenient to charge such devices. In conventional noncontact charge, wireless power transfer uses electromagnetic induction. It can keep high efficiency in a short range (centimeter-order); however, efficiency falls dramatically out of the range. On the other hand, the feasibility of higher-efficiency and middle-range transfer was indicated [2, 3], and several methods such as WiTricity and WREL have been developed.

Sensors using resonance are studied for detecting a small change. When a capacitance or inductance changes, its impedance and resonant frequency change. Such sensors achieve high sensitivity and high resolution by using high quality factor Q.

In this paper, we propose a displacement sensor based on resonant inductive coupling for certain AMB applications that require large air gaps (decimeter-order). These applications include wind tunnels, and also art works, e.g. a free floating skateboard. In this project, an artist asked for a skateboard-type object (called hoverboard) floating about 10 cm above a basis, with no visible technical artifacts. The proposed solution includes permanent magnets in both, floator and stator, to obtain a roughly indifferent equilibrium at nominal position and then additional coils for active stabilization in at least 2 DOF (the front and back lateral positions). The other 4 DOF may be stable without active control. Such systems are known and even commercially available. One of the challenges is the sensing system, given the requirements (no conventional optical light barrier). For this challenge, we present a novel resonant inductive sensor concept adapted for this kind of systems, using an inductance and a capacitance.

A new resonant inductive sensor is therefore proposed. As described above, it is inspired by wireless power transmission systems [1]. The air gap may go up to the stator coil diameter [4]. The resonance frequency and the nominal air gap are adjusted in such a manner as to have a single resonance peak in the center position. The height of this resonance peak will vary with the lateral position. In addition, proposed sensor system may be treat as a

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method on extension of the electromagnetic induction. Therefore, to discriminate the two lateral directions, two additional large coils of a few windings are hidden in the stator table, aligned with the hoverboard, connected in differential manner. From the reported characteristics of the resonant inductive coupling, displacement can be measure as change of efficiency at the resonant frequency. This paper includes measurement results on these sensing concepts, with the purpose of getting high resolution (sub-mm) over a very large distance (10cm).

2 Hoverboard based on AMB

The skateboard-type magnetic suspension system is shown in Fig 1. Both suspension systems are same. Each one has 4 electromagnets (EMs) and 12 permanent magnets (PMs) on stator and 9 PMs on the disk floator as shown in Fig. 2. EMs have laminated steel cores, and two opposite EMs are utilized in a differential manner. Each coil size is 80 mm in width, 120 mm in depth and 60 mm in height. The inductance is 0.4 mH, the resistance is 8 Ω and the current to force coefficient is 1.35 N/A. The PMs are neodymium magnets with a diameter of 30 mm and a height of 60 mm. The disk floator is 120 mm in diameter and 20 mm in height with neodymium magnets. The poles of all magnets are the same in direction. The floator, the PM holders and the base are made of synthetic resin. This system controls x- and y-direction translations and rotation about z-axis of the hoverboard. The others are passively controlled, whose position is determined by the alignment and intense of PMs. A displacement sensor has to detect at least x- and y-direction displacement separately from the z-axis position. This system is developed for display as an artwork so that the load to be suspended is only gravity. It is 20 N.

Figure 3 shows a magnetic field simulated based on FEM using software titled JMAG. Repulsive force between the stator and the floator can be recognized when all PMs are aligned in the same pole direction. Each stiffness in x- or y-axis direction is negative, which is −98 N/m. When the disk floator displacements are too large, z-directional magnetic force will be attractive.

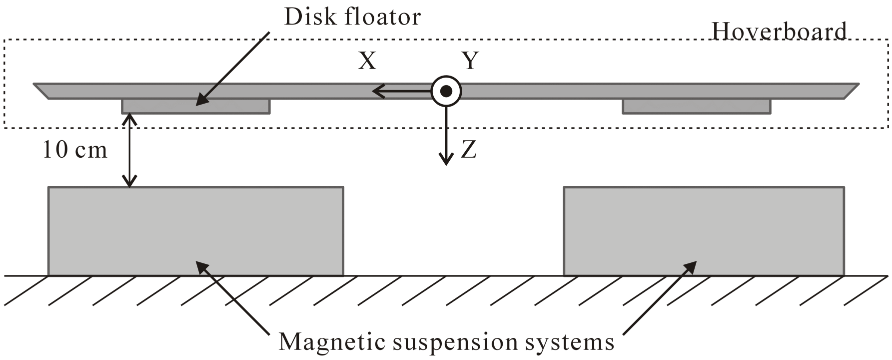

Fig. 1 Hoverboard-type active magnetic suspension system.

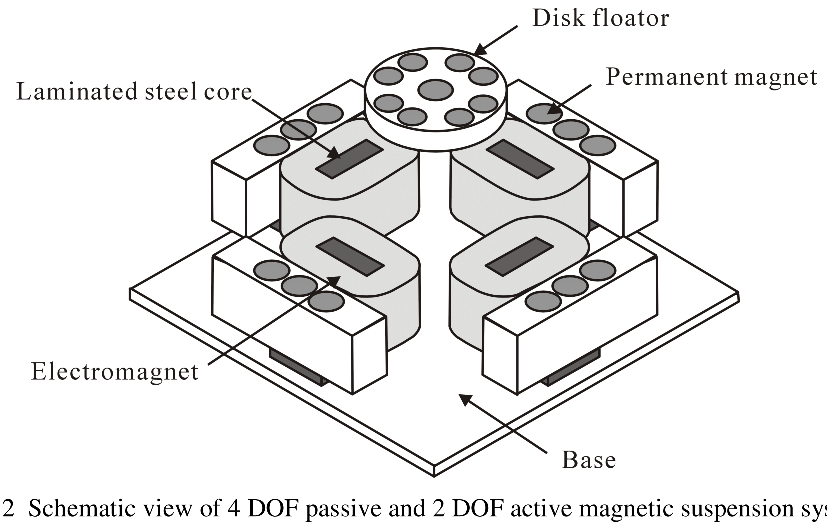

Fig. 2 Schematic view of 4 DOF passive and 2 DOF active magnetic suspension system.

3 Resonant Inductive Coupling

3.1 Transmission and reflection coefficients

Resonant inductive coupling, otherwise called as resonant electromagnetic coupling or magnetic resonance, is applied to wireless power transfer. Inductive coils are used as a resonator in such an application. In this session, resonant inductive coupling with coils is explained. Coils with compensation capacitors compose a resonant LC circuit as shown in Fig. 4. We shall discuss near-field characteristics. Note that the near field means within $\lambda/2\pi$ where λ is a wavelength. Actually, realized wireless power transfer is operated in a nearer field.

Resonance means that the reactance of a circuit becomes zero. The resonance frequency is given by

$$f_r = \frac{\omega_r}{2\pi} = \frac{1}{2\pi\sqrt{LC}}, \tag{1}$$

where ω_r is a resonance angular frequency. In the case of low frequency-range operation, each, the inductor and the capacitor must be large. On the other hand, when the f_r is high, components are even small. Therefore, high frequency operation is desirable. Meanwhile, the intensity of resonance is given by a quality factor indicated as

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}}. \tag{2}$$

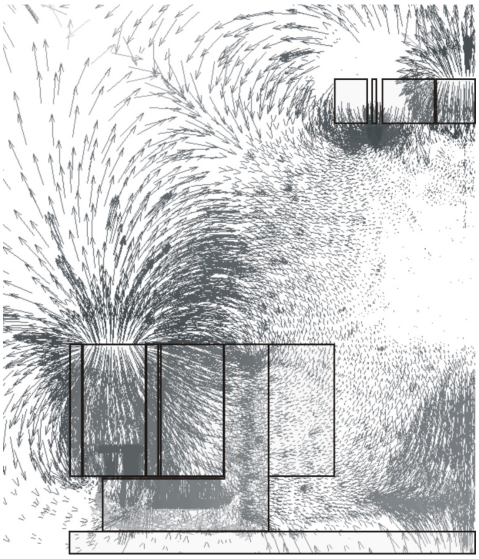

Fig. 3 Simulated magnetic field of the suspension system.

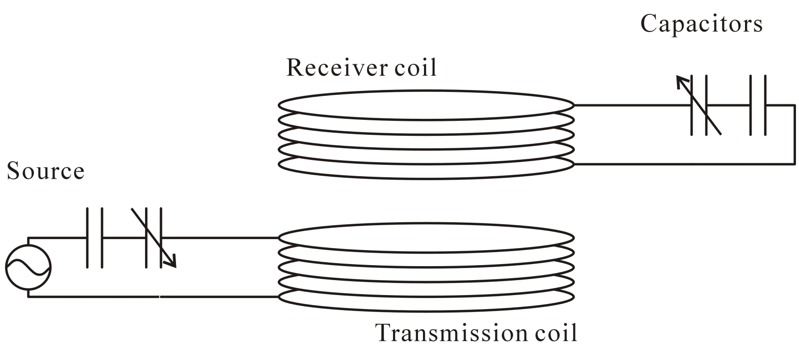

Fig. 4 LC circuit with resonant inductive coupling.

Equation (2) indicates that a large L is required to obtain a high Q.

The efficiency of power transmission or reflection is calculated from S parameters that are defined by

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}, \tag{3}$$

where a_1 and a_2 indicate input powers of the ports 1 and 2, respectively, and also b_1 and b_2 indicate the output powers. S_{11} and S_{21} represent reflection coefficient and transmission coefficient, respectively. Reflection power efficiency and transmission power efficiency can be calculated from these parameters. Here, a two-terminal pair network shown by Fig. 5 is considered. Figure 6 shows an equivalent circuit of the LC circuit shown by Fig. 4. This circuit satisfies the following equation.

$$\begin{pmatrix} V_1 \\ I_1 \end{pmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{pmatrix} V_2 \\ I_2 \end{pmatrix}, \tag{4}$$

where V_1 and I_1 are voltage and current of port 1, V_2 and I_2 are voltage and current of port 2. The other parameters are given by

$$A = \frac{V_1}{V_2} = \frac{(\omega L - \frac{1}{\omega C})}{\omega L_m} - j\frac{R}{\omega L_m}, \tag{5}$$

$$B = \frac{V_1}{I_2} = \left\{ R + \frac{1}{j\omega C} + j\omega(L - L_m) \right\}(A+1), \tag{6}$$

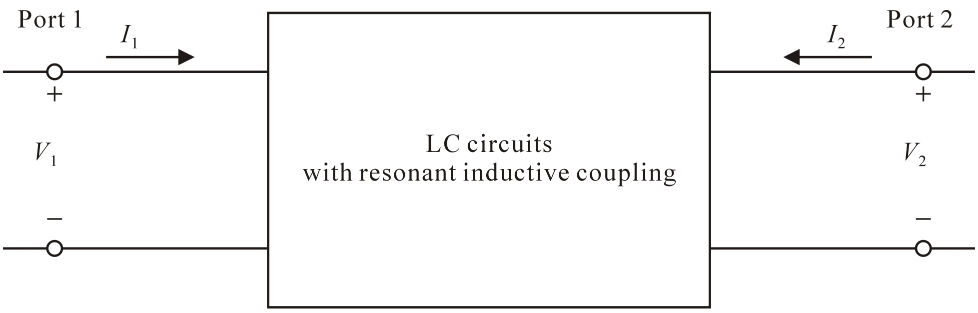

Fig. 5 LC circuits with resonant inductive coupling treated as two-terminal pair network.

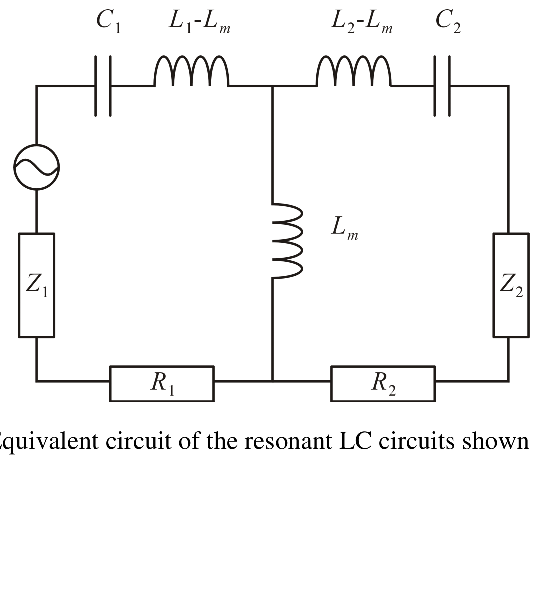

Fig. 6 Equivalent circuit of the resonant LC circuits shown in Fig. 4.

$$C = \frac{I_1}{V_2} = \frac{1}{j\omega L_m} = -j\frac{1}{\omega L_m}, \tag{7}$$

$$D = \frac{I_1}{I_2} = \frac{(\omega L - \frac{1}{\omega C})}{\omega L_m} - j\frac{R}{\omega L_m} = A, \tag{8}$$

where $L_1 = L_2 = L$, $C_1 = C_2 = C$. The reflection coefficient is given by

$$\begin{aligned} S_{11} &= \frac{\sqrt{\frac{Z_2}{Z_1}}A + \frac{B}{\sqrt{Z_1 Z_2}} - \sqrt{Z_1 Z_2}C - \sqrt{\frac{Z_1}{Z_2}}D}{\sqrt{\frac{Z_2}{Z_1}}A + \frac{B}{\sqrt{Z_1 Z_2}} + \sqrt{Z_1 Z_2}C + \sqrt{\frac{Z_1}{Z_2}}D}, \\ &= \frac{Z_2 A + B - Z_1 Z_2 C - Z_1 D}{Z_2 A + B + Z_1 Z_2 C + Z_1 D} \end{aligned} \tag{9}$$

where Z_1 and Z_2 are impedances. When $Z_1 = Z_2 = Z$,

$$S_{11} = \frac{\frac{B}{Z} - ZC}{2A + \frac{B}{Z} + ZC}. \tag{10}$$

In resonance,

$$\begin{aligned} S_{11} &= \frac{Z^2 + R^2 - \omega_r^2 L_m^2}{(Z+R)^2 + \omega_r^2 L_m^2} \\ &= \frac{Z^2 + R^2 - \omega_r^2 k^2 L^2}{(Z+R)^2 + \omega_r^2 k^2 L^2}, \end{aligned} \tag{11}$$

$$S_{21} = 2j\frac{(\frac{Z}{kL\omega_r})}{(\frac{Z}{kL\omega_r})^2 + 1}. \tag{12}$$

Therefore, the reflection coefficient S_{11} is determined by the frequency ω_r, coupled constant k, and inductance L. Even k is very small, high frequency and a large inductance make the reflection coefficient low. This is one of techniques to obtain high efficiency of wireless power transfer. When the resonant inductive coupling is applied to displacement sensor, these S parameters vary according to the coupling constant k in a wide air gap, and can be amplified by ω_r and L. Slight change of k can be detected through the S parameters.

3.2 Coupling constant

In general, electromagnetic resonators have two resonant frequencies when the resonators are strongly coupled. Coupling constant shows intensity of coupling as given by

$$k = \frac{f_h^2 - f_l^2}{f_h^2 + f_l^2}, \quad (13)$$

where f_h is the higher resonant frequency given by

$$f_h = \frac{1}{2\pi\sqrt{(L-L_m)(C+C_m)}}, \quad (14)$$

and also f_l is the lower resonant frequency given by

$$f_l = \frac{1}{2\pi\sqrt{(L+L_m)(C-C_m)}}. \quad (15)$$

L_m and C_m indicate mutual inductance and mutual capacitance, respectively. The inductive coupling constant k_m is given by

$$k_m = \frac{L_m}{L}. \quad (16)$$

On the other hand, the electric coupling constant k_e is given by

$$k_e = \frac{C_m}{C}. \quad (17)$$

These values of coefficients k_m and k_e are influenced by the horizontal displacement and vertical gap of resonators. From Eqs. (14) – (17), Eq. (13) is transformed to

$$k = \frac{k_m}{1-k_m k_e} - \frac{k_e}{1-k_m k_e}. \quad (18)$$

When $k_m k_e << 1$,

$$k \approx k_m - k_e \quad (19)$$

Therefore, when inductive coupling is actively used, electric coupling should be small for getting a high coupling constant. Generally, the dominant coupling constants are depends on the type of resonator.

4 Proposed Displacement Sensor

4.1 Resonant frequency

The resonant frequencies of the resonators are changed by several quantities. One is the gap between the two coils. When the gap is smaller than the coil diameter, two resonant frequencies exist. We measured the conductance of the resonators as shown in Fig. 7. In this experiment, each coil has a diameter of 155 mm and 20 turns whose wire diameter is 1 mm. The inductance is 73 μH and the resistance is 0.5 Ω. The individual resonant frequency is adjusted to 1 MHz. The two resonant frequencies vary to 1 MHz as the gap between two coils increases. When the resonant frequencies are two, the transmission efficiency is kept high at either resonant frequency of the two. On the other side, when the resonant frequency is only one, transmission efficiency decreases gradually as the gap increases. The lateral displacement is also related to the resonant frequency and efficiency. In this case, the threshold is the half of the coil diameter [5].

4.2 Concept

In this session, a displacement sensor using resonant inductive coupling is proposed and explained as an extension of conventional electromagnetic induction. The setup is shown in Fig. 8. There are two coils. One of them is a receiver coil and another is an oscillator coil. Each coil constructs a LC resonant circuit with a capacitor element. Each LC circuit has the same resonance frequency that is in MHz range. Our new proposal is that the sensor detects a lateral displacement from the change of efficiency. The efficiency can be calculated from *S* parameters; and these coefficients are usually measured with a vector network analyzer (VNA). In the case of noncontact suspension, the floator should be wireless. Therefore, the reflection coefficient is suitable as the variable to be detected. The terminals of stator-side LC circuit give two signals: a traveling wave and a reflected wave from the oscillator coil. One of the methods to obtain the reflection coefficient is to measure VSWR (voltage standing wave ratio). The magnitudes of traveling wave and reflected wave can be estimated by using directional couplers. Attenuators adjust the levels of these signals and impedances. The circuit with AD8302 can calculate the gain and the phase of these signals so that VSWR can be measured. When this measurement is used, the coil diameter is adjusted to equal the nominal gap. In addition, x- and y-direction displacements should be separate from each other and also from the z-direction displacement. When differential mode as same as electromagnetic induction coil array is useful, however, much interaction is expected.

Here, we can mention another possibility of measurement. When the gap is smaller than the coil diameter, two resonant frequencies are expected. These frequencies vary according to the change of gap and also displacement.

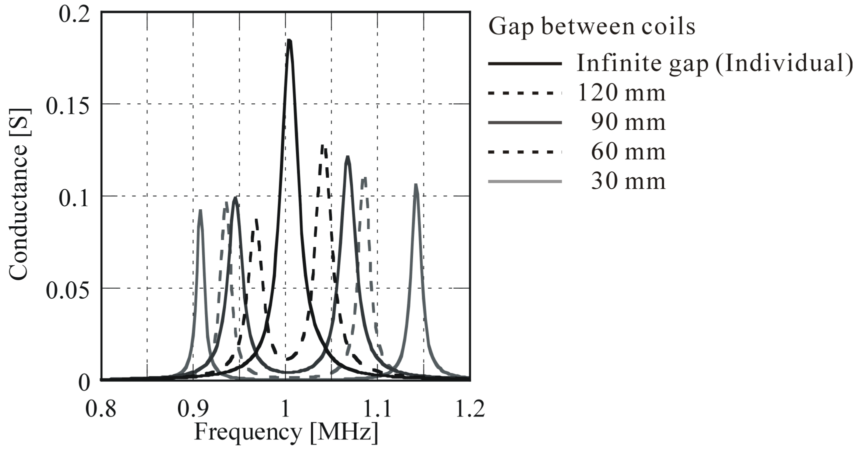

Fig. 7 Resonant frequencies of inductive coupling depending on the gap.

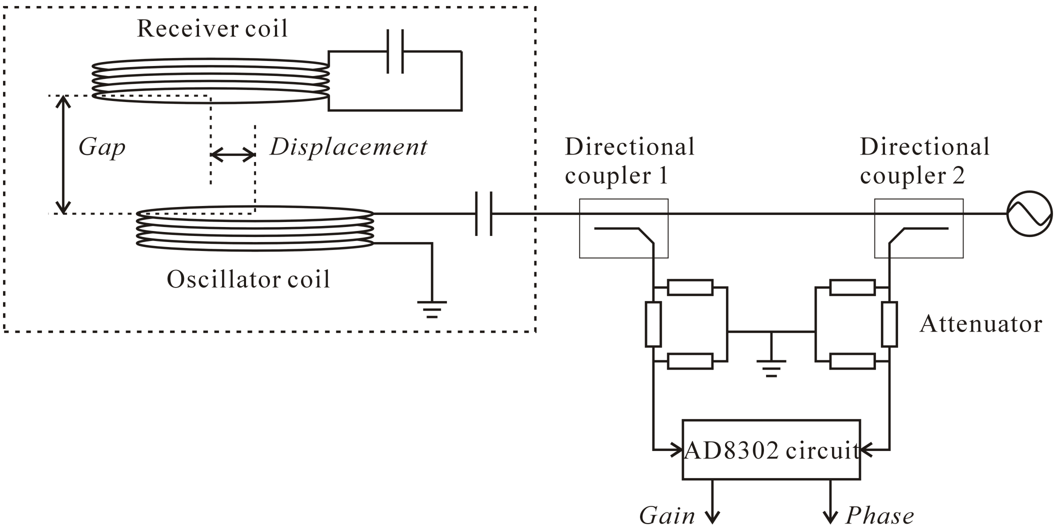

Fig. 8 Proposed displacement sensor setup.

When one of the parameters can be restricted, measuring the varying of the resonant frequency gives high resolution. It is caused by high operating frequency. Resonant frequency follow-up device [6] is applicable to trace the resonant frequency.

5 Conclusion

The concept of a displacement sensor with a wide gap was proposed. It was inspired from wireless power transfer techniques, and explained as expansion of conventional electromagnetic induction. The proposed sensor is based on resonant inductive coupling. The transmission and reflection coefficient of the resonant inductive coupling is shown. One of the sensor setup for the measurement of the reflection coefficient was explained. In addition, we mentioned the possibility that the detection of the resonant frequencies is valid, when the gap is smaller than coil diameter.

In prospective applications of AMB, suspended objects will be smart objects or electric devices such as a self-spinning floator, unit-type multiple floators with electromagnets. These floators will need wireless power transfer. At that time, sensing can be achieved using coils for power transfer or additional coils.

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