Design of a misalignment-resistant capacitive coupler for wireless power transfer under fresh water

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Abstract: In this study, we describe the design of a misalignment-resistant capacitive coupler under fresh water. The two main issues discussed in this study are: the relation between misalignment and efficiency when using a typical capacitive coupler, and the design of a misalignment-resistant capacitive coupler. Theoretical calculation and analytical results show no relation between misalignment and transmission efficiency in terms of monotonic reduction. Further, the relation between misalignment and transmission efficiency is discussed with respect to the coupling coefficient. Finally, we establish the design guideline using coupling factors that take into account misalignment and design a misalignment-resistant capacitive coupler.

Keywords: wireless power transmission, underwater technology, Q-factor, coupler, coupling circuit

Classification: Transmission Systems and Transmission Equipment for Communications

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1 Introduction

Presently, the diagnosis of infrastructure deterioration using an autonomous underwater vehicle (AUV) is attracting research attention[1]. Underwater wireless power transfer (U-WPT) to an AUV through a charging station has been proposed as a solution to improve the charging efficiency.

A majority of the currently investigated U-WPTs employ inductive coupling methods. However, the AUVs are equipped with sensors and precision instruments for data recovery, and these instruments may be affected by magnetic field leakage. It is difficult to construct a shielding structure in water because metal shielding or ferrite is required. In addition, the weight of the power transmission and reception system will increase considerably[2].

Electrical flux lines are confined between the electrodes in capacitive coupled systems, thus, the problem of electromagnetic leakage is solved. Also, capacitive couplers have a very simple structure and are much lighter than inductive couplers. In capacitive WPT, there is a deterioration of transmission efficiency when wireless power is transmitted to an AUV. This is because of the misalignment of couplers, and this issue needs to be addressed. Fine control of AUVs is difficult because they move in a three-dimensional manner in viscous fluids. Therefore, it is expected that only a few electrodes will land on the location completely and be opposite to each other.

Misalignment problems between the receiver and the transmitter are a serious concern in other WPT-based applications besides AUVs. Much research on misalignment in inductively coupled systems has been conducted, where
couplers resistant to horizontal misalignment [3, 4], vertical misalignment[5], and rotational misalignment[6] have been studied. In addition, antennas resistant to horizontal misalignment have been studied in radio emission systems[7]. Also, in capacitive-coupled stems, couplers that are resistant to rotational misalignment have been studied[8, 9], but the relationship between horizontal misalignment and efficiency has not been clearly understood.

In this study, the effect of horizontal misalignment on efficiency is quantitatively measured and discussed. In addition, a misalignment-resistant electrode is designed and fabricated, and clarify its effect by simulation.

2 Relation between misalignment and power transfer efficiency

\[ \eta_{\text{max}} \quad \text{when the position of the coupler is displaced with respect to the horizontal direction was analyzed using the CST electromagnetic simulation software. The coupler was used with a frequency of 50 MHz a spacing of 20 mm and an efficiency of approximately 90% as shown in [10]. The analysis intervals were 20 mm for both x and y axes. Fig. 1(a) shows the model in CST, and Fig. 1(b) shows the analysis results. The analysis results show that a misalignment in the y-axis direction equal to the electrode length results in an efficiency of approximately 80%, indicating a small decrease in efficiency. In contrast, the efficiency was only approximately 20% when it was displaced by 60 mm in x-axis direction. The efficiency behavior did not} \]
monotonically decrease, and poles could be observed at approximately 100 mm. These can be confirmed from Fig. 1(c), which focuses on the x-axis displacement characteristics at y = 0 mm.

To verify the above analysis, we measured the efficiency of the coupler for varying horizontal misalignment using a vector network analyzer. A balun with an efficiency of 89.1% was used for the two-port measurement, and the measurement interval was 20 mm on both x and y axes. Fig. 1(d) shows the measurement results. When comparing Fig. 1(b) and (d), the analysis and measurement results generally agree with each other. The measurement indicates that a pole exists in relation to the x-axis direction.

3 Considerations using the coupling coefficient

\( \eta_{\text{max}} \) can be estimated based on the coupling coefficient \( k \) and the Q-factor of water \( Q \). \( \eta_{\text{max}} \) is represented by Eq. (1) [11]. The Q-factor is represented by Eq. (2), where the angular frequency is \( \omega \) (rad/s), dielectric constant is \( \varepsilon_r \), dielectric constant in vacuum is \( \varepsilon_0 \), and electrical conductivity is \( \sigma \). Since the frequency is constant at 50 MHz, the change in \( \eta_{\text{max}} \) because of horizontal misalignment can be attributed to the change in the \( k \). In particular, we discuss the notable dip in efficiency with respect to the x-axis misalignment results.

\[
\eta_{\text{max}} = 1 - \frac{2}{1 + \sqrt{1 + (kQ)^2}} \\
Q = \frac{\omega \varepsilon_r \varepsilon_0}{\sigma} 
\]

The value of each element must be obtained from the equivalent coupler circuit to calculate the \( k \) associated with each position. CST was used to calculate these element values. Fig. 2(a) shows a discrete port (50 \( \Omega \)) connected to an electrode pair, and Fig. 2(b) shows S11 and the expected equivalent circuit of the electrode pair. The analysis frequency was 0–100 MHz. From Fig. 2(b), the electrode pair is considered to be an RC parallel circuit with L connected in series. \( Z \), as seen from the discrete port connected to the electrode pair, it can be represented by Eq. (3).

\[
Z = \frac{R}{1 + (\omega CR)^2} + j \left[ \omega L - \frac{\omega CR^2}{1 + (\omega CR)^2} \right] 
\]

First, \( R \) is derived from Eq. (4) using Eq. (3). \( \omega_0 \) is the resonance frequency, \( \text{Re}(Z_0) \) is the resistance, and \( \text{Im}(Z_0) \) is the reactance at the resonance.
\[
\begin{align*}
\omega_0 L - \frac{\omega_0 CR^2}{1 + (\omega_0 CR)^2} &= 0 \\
\Rightarrow L &= \frac{CR^2}{1 + (\omega_0 CR)^2} \\
\text{Im}(Z) &= \omega L - \frac{\omega CR^2}{1 + (\omega CR)^2} \\
&= \frac{CR^2}{1 + (\omega CR)^2} + \frac{\text{Im}(Z)}{\omega} \\
CRR\text{Re}(Z_0) &= CRR\text{Re}(Z) + \frac{\text{Im}(Z)}{\omega} \\
CR &= \frac{\text{Im}(Z)}{\omega(\text{Re}(Z_0) - \text{Re}(Z))} \\
R &= \text{Re}(Z) \left\{ 1 + \left[ \frac{\text{Im}(Z)}{\text{Re}(Z_0) - \text{Re}(Z)} \right]^2 \right\}
\end{align*}
\]
The values of $C$ and $L$ can be derived using Eqs. (3) and (4). Each electrode-to-electrode capacity obtained by solving these equations is shown in Fig. 2(c). $C_{13}, C_{14}, C_{23},$ and $C_{24}$ are the mutual capacities of each electrode pair. Fig. 2(c) shows that $C_{13}, C_{24}, C_{14}$ is monotonic with respect to the misalignment in the x-axis direction. $C_{23}$ increases and decreases after becoming maximum at 80 mm. This may be due to the fact that the diagonal electrode pairs became opposed at 80 mm, which increased the capacity. The capacitance value of each electrode pair is monotonic with respect to the distance between each electrode. It is difficult to formulate the capacitance-position characteristics between the electrodes; therefore, we conduct our discussion based on the values obtained by CST. Fig. 2(c) shows that $C_{13}, C_{24}, C_{14}$ is monotonic with respect to the misalignment in the x-axis direction. $C_{23}$ increases and decreases after becoming maximum at 80 mm. This may be due to the fact that the diagonal electrode pairs became opposed at 80 mm, which increased the capacity. The capacitance value of each electrode pair is monotonic with respect to the distance between each electrode. It is difficult to formulate the capacitance-position characteristics between the electrodes; therefore, we conduct our discussion based on the values obtained by CST. Fig. 2(d) shows that the inductance of each electrode pair varies linearly with the distance between the electrodes. $L_{13}, L_{14}, L_{23},$ and $L_{24}$ is considered to be the parasitic inductance of the discrete port. Therefore, the next $k$ can be obtained without considering the inductance. Fig. 2(e) shows an equivalent circuit of the coupler shown in Fig. 2(a) using an admittance box, where $Y_{12}, Y_{34}, Y_{13}, Y_{14}, Y_{23},$ and $Y_{24}$ are the mutual admittances. The circuit shown in Fig. 2(e) is transformed into Fig. 2(f) using Kirchhoff’s current law. The $Y_m, Y’m$ and $Y’’m$ shown in Fig. 2(f) are represented by Eq. (5).

$$Y_m = \frac{Y_{13}Y_{24} - Y_{23}Y_{14}}{Y_{13} + Y_{24} + Y_{23} + Y_{14}}$$

$$Y’m = \frac{(Y_{13} + Y_{14})(Y_{24} + Y_{23})}{Y_{13} + Y_{24} + Y_{23} + Y_{14}}$$

$$Y’’m = \frac{(Y_{13} + Y_{23})(Y_{24} + Y_{14})}{Y_{13} + Y_{24} + Y_{23} + Y_{14}}$$

The ratio of current $I_1$ in port 1 to current $I_2$ when port 2 is shorted is defined as the $k$. Eq. (6) shows the expression for each admittance of the $k$.

$$k = \frac{I_2}{I_1} = \frac{Y_{13}Y_{24} - Y_{23}Y_{14}}{(Y_{13} + Y_{14})(Y_{24} + Y_{23}) + Y_{12}(Y_{13} + Y_{24} + Y_{23} + Y_{14})}$$

Fig. 2(g) shows a plot obtained after substituting the parameters obtained via Eqs. (3) and (4) into Eq. (6).

The $k$ exhibits a local minimum value around 50 mm before increasing and decreasing again. This is in general agreement with the characteristics of the $\eta_{max}$ shown in Fig. 1(c). We explain the reason for this in terms of Eq. (6). The denominator of Eq. (6) is the difference between the products of the mutual admittance of opposing electrode pairs and the mutual admittance of diagonal electrode pairs, i.e., $Y_{13}Y_{24} - Y_{23}Y_{14}$. The $Y_{13}Y_{24}$ decreases monotonically as the electrode position is displaced. Further, Either $Y_{23}$ or $Y_{14}$ was monotonically reduced. However, the other mutual admittance of diagonal electrode pairs increases and then decreases. Therefore, when the electrode position is displaced, the $k$ becomes zero at the point at which $Y_{13}Y_{24}$ and $Y_{23}Y_{14}$ balance each other. After the $k$ becomes zero, it increases and decreases again because $Y_{14}Y_{23}$ is temporarily dominant.
4 Coupler resistance to horizontal misalignment

Our coupler is designed to keep the condition of $Y_{13}Y_{24} > Y_{23}Y_{14}$ with a wide range of the electrode allocation. Since the electrodes on the receiving side are mounted on the AUV, it is difficult to change the size of the electrodes. To satisfy the above conditions, it is necessary to increase $Y_{13}Y_{24}$ and decrease $Y_{23}Y_{14}$ compared to conventional couplers. To increase $Y_{13}Y_{24}$ under the condition of x-axis misalignment, the width of the transmission electrodes can be extended in the x-axis direction. This is because the distance between the transmission and receiver electrodes in the misalignment direction becomes shorter. The next step is to reduce $Y_{23}Y_{14}$. As the width of the transmission electrodes is increased, $Y_{23}Y_{14}$ increases compared to the conventional coupler. This is due to the increase in the bonding area of the transmission electrodes. Therefore, the width between the electrodes is increased while maintaining the width of the transmission electrodes to reduce the $Y_{23}Y_{14}$. Although this operation reduces $Y_{13}Y_{24}$, it increases the distance between diagonal electrode pairs, and thus, $Y_{23}Y_{14}$ can be greatly reduced.

Based on the above design guidelines, an asymmetric coupler having the distance between its transmission electrodes increased from 40 to 160 mm was designed and analyzed by CST. Fig. 3(a) shows the model diagram of the asymmetric coupler and Fig. 3(b) shows the capacitance between the electrodes of the asymmetric coupler. Fig. 3(c) shows the $k$ of the asymmetric coupler. From Fig. 3(b), the opposing capacitance $C_{24}$ is observed to be dominant over a wide range. In addition, from Fig. 3(c), the point at which the $k$ becomes zero moves far away from $Y_m$. However, the maximum value of the $k$ is degraded compared to that in Fig. 2(g). This is because $Y_{13}$ and $Y_{24}$ are smaller than that of conventional couplers even when there is no horizontal misalignment. Finally, the $\eta_{\text{max}}$ of the asymmetric coupler

![Image](image-url)

Fig. 3. Coupler resistance to horizontal misalignment
is shown in Fig. 3(d). The range of high-efficiency (>60%) transmission is approximately 90% larger than that in Fig. 1(b).

5 Conclusion
In this study, we presented a misalignment-resistant coupler design. The electromagnetic field analysis and equivalent circuit analysis revealed that this can be attributed to the equilibrium between $Y_{13}Y_{24}$ and $Y_{23}Y_{14}$. Further, a design guideline was established to intentionally change the balance between them in terms of the $k$, and a coupler was designed based on this guideline. The asymmetric coupler successfully increased the efficiency over an extended range.

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