Experimental Investigation of Transfer Characteristics of Midrange Underwater Wireless Power Transfer

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Abstract: - The transfer characteristics of an underwater Wireless Power Transfer (WPT) system with a resonant frequency of 460kHz are studied experimentally. The coils have an outer diameter of 22.5 cm. Through this study, it was found that when the transfer distance is small, the transmission effect of WPT system in seawater is similar to that in air; when the transfer distance is larger than 20 cm, the load voltage of the WPT system in seawater is 4 times higher than that in air, and the transmission efficiency in seawater can reach 17 times of that in air on average. The experimental results in this paper are compared with studies published, and a circuit model is proposed to explain and predict the experimental phenomena, but the specific model still needs further work. Finally, the underwater WPT system has a low transfer efficiency of only 20% at midrange, so the findings of this research may be used for distance first scenarios.

Key-Words: - Midrange, underwater wireless power transfer, transfer characteristics, planar coils.

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1 Introduction

With the continuous development of ocean resources, various underwater devices are applied more frequently, which brings about the demand for safe and efficient power transfer technology. At this time Wireless Power Transfer (WPT) technology with its unique power supply, begins to receive extensive attention. It has been widely used in transportation, medical treatment, entertainment, communication and other aspects [1-7]. It has also a wide application in underwater environments [8-9], such as underwater autonomous vehicles [10-12], and underwater sensors [13].

Two main problems facing WPT system are to improve transfer efficiency and increase transfer distance. Based on these two points, many solutions have been proposed. A method for designing high quality spiral resonators with transmission efficiency up to 95% is suggested in [14]. In [15], targeting the two main problems of seawater attenuation and resistance, a lightweight self-locking coupling structure on the receiving side is proposed to improve the coupling coefficient to resist ocean current interference. [16] proposes a coil structure composed of two transmitting coils and one receiving coil, and the eddy current loss is reduced by half while the transmission efficiency is improved by about 10%. [17] designs a wireless magnetic resonance-based power transfer system with multiple coils using bandpass filter (BPF) theory. The results confirm that the wireless power transfer distance in the seawater environment is more than 10 meters. [18] confirms underwater WPT over 10 meters through multi-coil experiments. The above researches are all methods to improve transfer efficiency and increase transfer distance by different methods at present, and certain achievements have achieved, however, these two issues cannot be resolved simultaneously.

Underwater WPT system has developed well, however transfer characteristics of WPT system working at non-resonant frequency is blank. And according to existing studies, it is generally believed that the transfer efficiency in seawater is lower than that in air due to eddy current losses in seawater. [19] suggests that the transfer efficiency in seawater is lower due to eddy current losses, and the general law of eddy current loss is summarized based on electromagnetic field calculation, and it is found that the eddy current effect is proportional to the quadratic power of resonant frequency, the fourth power of coil radius, and the quadratic power of magnetic induction intensity. This study gives a general expression of eddy current loss, but this method is based on magnetic field and is not easy to understand.

For the frequency splitting problem, [20] systematically studied the frequency splitting phenomenon in the series tuned contactless power transfer system by circuit theory. [21] explores the frequency splitting mode and analyzes the frequency splitting mode of the low order wireless power relay transmission system with the coupling mode theory.

[22] and [23] show that when the WPT system works below 100 kHz, the transmission characteristics in air are basically the same as that in sea water; when the WPT system works above 1 MHz, the transmission efficiency is basically zero. Therefore, this paper compares the transmission characteristics in sea water and air when the system works between 100 kHz and 1 MHz. It is found that the WPT system has a much better transfer ability in seawater than air at midrange [24] (The midrange mentioned in this study refers to the distance at least greater than the outer diameter of the transmitting and receiving coils.), the average transfer efficiency in the sea water can be up to 17 times in the air. The experimental results in this paper are compared with studies published, and a circuit model is proposed to explain and predict the experimental phenomena, but the specific model still needs further work. Finally, the underwater WPT system has a low mid-range transmission efficiency of only 20%, which can be used for distance first scenarios.

This paper is mainly divided into five parts. The first part presents previous research. Part 2 describes the experimental methods and procedures. The third part describes the experimental results. The fourth part discusses the experimental results. The fifth part summarizes the work.

2 Methods

2.1 Experimental WPT Systems

Due to the existence of air gap between coils, the leakage inductance between loosely coupled transformers is large, leading to the transfer loss between coils, so it is necessary to add capacitor for reactive power compensation to reduce the loss. At present, there are four compensation topologies most commonly used: series-series (SS), parallel-parallel (PP) serial-parallel (SP) parallel-series (PS). Among them, SS compensation topology is the most widely used.

So, to explore the midrange transfer characteristics, a series-tuned two-coil WPT system with a 460 kHz resonant frequency is built.

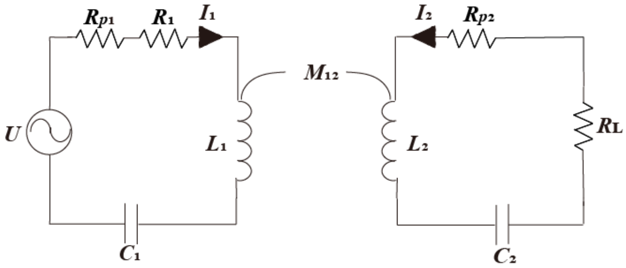


Fig. 1: Topology of the experimental WPT system in air.

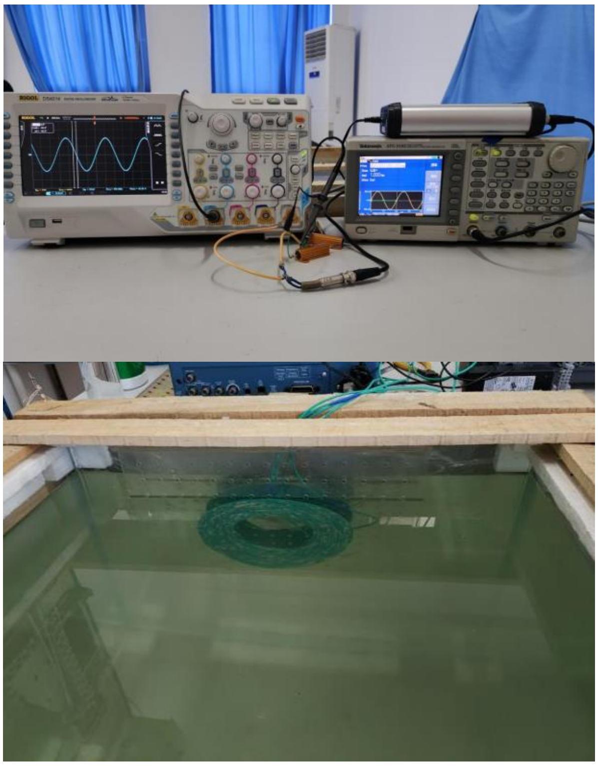


Fig. 2: Underwater WPT system experimental platform.

The topology of the experimental WPT system in air is shown in Fig. 1, where, U is the excitation voltage source; I_1 is the primary current; R_1, C_1 and L_1 are the primary resistance, capacitance, and inductance, respectively; I_2 is the secondary current; C_2 and L_2 are the secondary capacitance, and inductance, respectively; M_{12} is the mutual inductance between the two coils; R_L is the secondary load resistance; R_{p1} is the internal resistance of primary coil, capacitor and output resistance of power amplifier; and R_{p2} is the internal resistance of secondary coil, and capacitor.

2.2 Experimental Procedures

The underwater WPT experimental platform is shown in Fig. 2 [26], the planar primary and secondary coils have 17 turns wound with the

AWG16 wire, their inner diameter is 12 cm, and their outer diameter is 22.5 cm. The water tank has a size of 120 cm × 70 cm × 70 cm, and the water depth is 65 cm. 19.6 kg salt is added to make the seawater salinity reach 3.5%, and the conductivity measured by the conductivity meter (Shanghai Lichen Bangxi: LC-DDB-1A) is 3.6 S/m. The system parameters in air are shown in Table 1.

Table 1. Experimental WPT parameters in air

Symbol	QUANTITY	Value
L_1	Primary coil inductance/ μH	67.5
L_2	Secondary coil inductance/ μH	67.5
C_1	Primary capacitance/nF	1.8
C_2	Secondary capacitance/nF	1.8
R_1	Primary resistance/Ω	44.4
R_L	Secondary load resistance/Ω	44.4
f_{01}	Primary resonant frequency/kHz	460
f_{02}	Secondary resonant frequency/kHz	460
R_{p1}	Internal resistance of primary coil, capacitor and output resistance of power amplifier/Ω	1.1
R_{p2}	Internal resistance of secondary coil, capacitor/Ω	0.5

The sinusoidal wave output by the signal generator (Tektronix: AFG3102) is amplified by a 10 W power amplifier (Rigol: PA1011). The power amplifier output with a peak-peak value of 20 V is fed to the primary coil of the WPT system.

The peak-to-peak load voltage in the secondary coil is measured by an oscilloscope (Rigol: DS4014) for analysis. The frequency characteristics in the range of 240-700 kHz are explored at a 10 kHz step at 20 different coil distances. The minimum coil distance is 27 mm and the maximum coil distance is 527 mm.

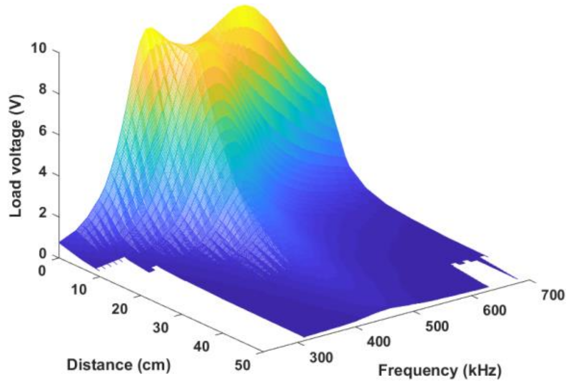
The two coils are placed in the air and water tank respectively, the operating frequency of the input voltage and the distance between the two coils are changed, and the load voltage is measured.

3 Experimental Results

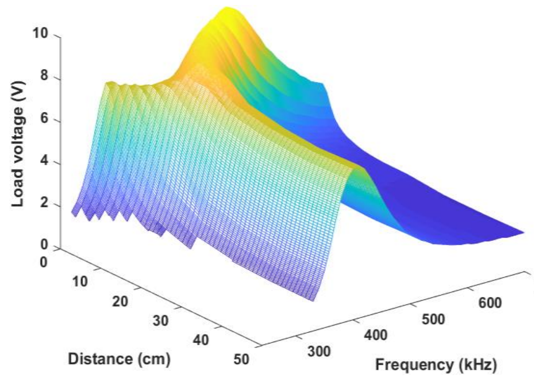
3.1 Voltage Transfer Characteristics

Load voltages of the experimental WPT system measured in seawater and air are shown in Fig. 3.

From Fig. 3a, when the transfer distance is less than 20 cm, the load voltage of the WPT system in the air is large near the resonant frequency (bright yellow), and frequency splitting phenomenon occurs. When the WPT system operates at midrange, that is, transfer distance greater than 20 cm, the load voltage of the system in the air is very low at most frequency (deep blue). From Fig. 3b, when the transfer distance is less than 20 cm, the load voltage of WPT system in seawater is also large near the resonant frequency (bright yellow), and frequency splitting phenomenon occurs. When the WPT system operates at midrange, there is a substantial load voltage in seawater at midrange (bright yellow) around 500 kHz. That is, at close range, the WPT system has similar transfer ability in seawater and air, while at midrange, the WPT system has a much better transfer ability in seawater than air.



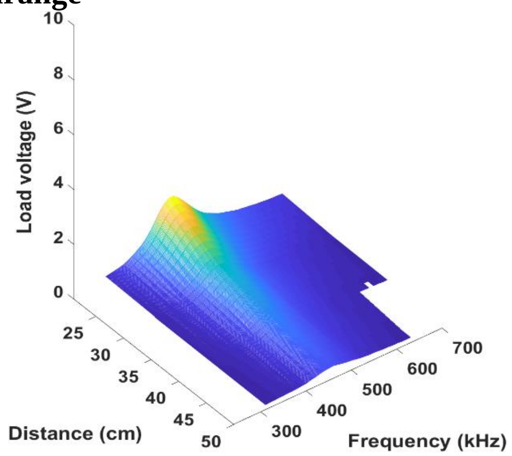
(a)



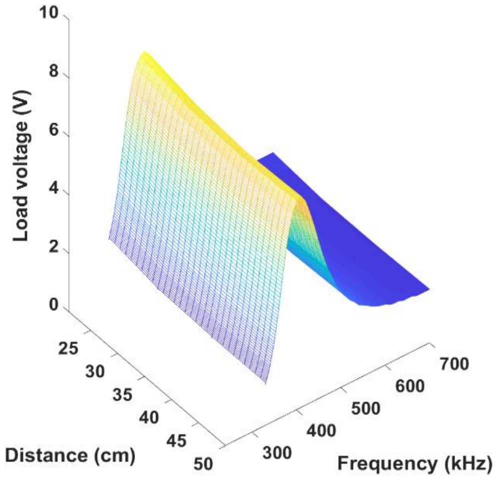
(b)

Fig. 3: 3D diagram of the secondary load voltage of the experimental WPT system. (a) Air; (b) Seawater

3.2 Voltage Transfer Characteristics at Midrange



(a)



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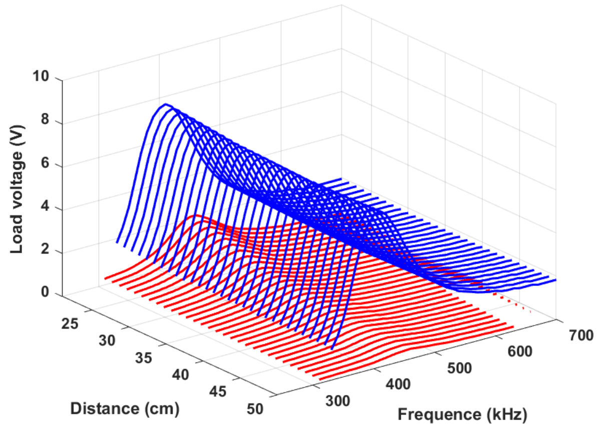


(c)

Fig. 4: 3D diagram of the secondary load voltage of the experimental WPT system at midrange. (a) Air; (b) Seawater; (c) Air (red lines) and seawater (blue lines)

Load voltages measured at midrange in seawater and air are shown in Fig. 4.

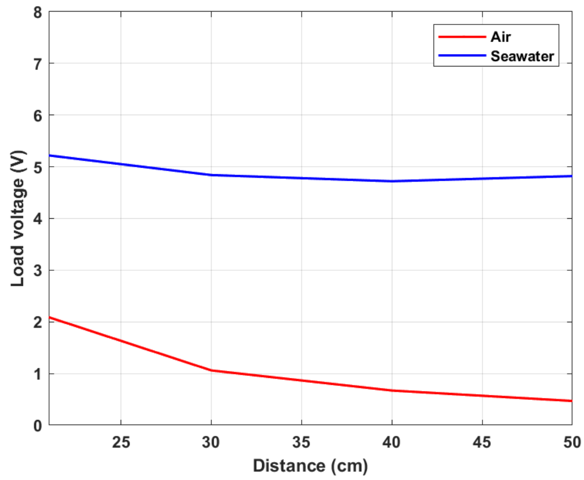
From Fig. 4, it can be seen more clearly that the transfer ability of the WPT system is much better in seawater than in air at midrange.

3.3 Comparison of Transfer Characteristics at Resonant Frequency

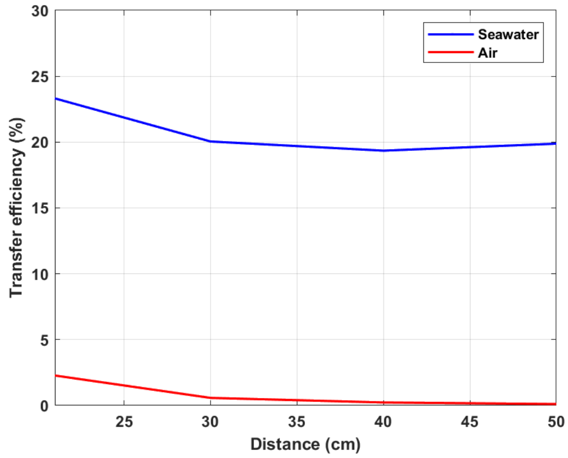
The transfer efficiency of a symmetric two-coil WPT system is [25]

$$\eta = 2\times\frac{U_{R_L} I_2}{UI_1 \cos\theta}\times 100\% \qquad (1)$$

where, U_{R_L} is the secondary load voltage, and θ is the phase difference between primary voltage and current.



(a)



(b)

Fig. 5: Comparison of transfer ability of the midrange WPT system in air and seawater at 460kHz. (a) Load voltage; (b) Transfer efficiency.

Fig. 5 shows the load voltage and transfer efficiency of the midrange WPT system in air and seawater at the resonant frequency of 460 kHz. The load voltage in seawater maintains at about 5 V, and the load voltage in air has an average value of 1.27 V, with a maximum of 2.09 V and a minimum of 0.45 V. That is, the WPT system has a 4 times load voltage improvement in seawater than air at midrange. The transfer efficiency in seawater is about 20%, while in air, the average efficiency is 1.2%, with a maximum of 2.28% and a minimum of 0.11%. That is, the WPT system has 17 times transfer efficiency improvement in seawater than air at midrange.

4 Discussion

The planar coil WPT system with the outer diameter of 22.5 cm has frequency splitting phenomenon in both seawater and air when working near the resonant frequency of 460 kHz in this study.

However, in [26], when the frequency characteristics of underwater WPT system are studied through similar experiments, it is found that when the transfer distance is relatively close, there is the frequency splitting phenomenon of secondary load voltage in air, while the frequency splitting phenomenon disappeared in fresh water and seawater. The reasons discussed in [26] are the high frequency and high eddy current losses in seawater. The differences between [26] and this study may be due to the experimental temperature, water quality, salt and other environmental factors.

From Fig. 3, it can be seen more clearly that when the transfer distance is small, the transfer ability of the WPT system in seawater is similar to that in seawater. However, the transfer efficiency in seawater is much higher than that in air at midrange. In [26], when the transfer distance is greater than 20 cm, the load voltages in seawater and freshwater are much bigger than those in air, similar to the findings in this study. In [27], the transfer characteristics in seawater are consistent with that in air, mainly because of the small size of the coils, a 12cm outer diameter, much smaller than the 22.5cm outer diameter in this study.

Fig. 6 shows the secondary load voltage in air and seawater when the transfer distance is 30 cm. The resonant frequency in air is about 460 kHz, and in seawater it is about 420 kHz. The resonant frequency shifts to the left. In [28], however, the resonant frequency shifts to the right in seawater. The deviation may be due to the coil winding mode, the coil size, and the seawater volume. In [27], the resonant frequency also shifts to the right in seawater. The differences may be due to operational frequency and the ferrite core.

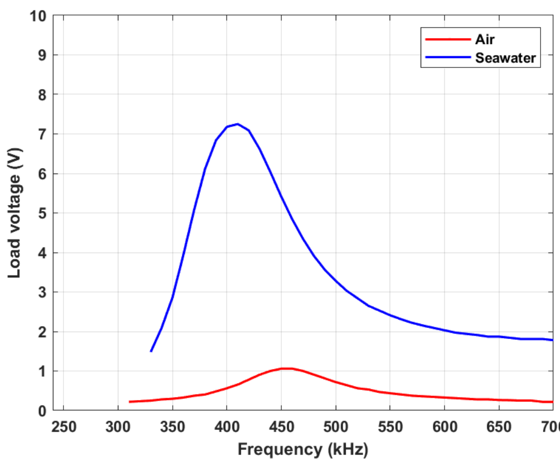


Fig. 6: Resonant frequency shift at a 30 cm transfer distance.

The shift of resonance frequency indicates that seawater brings about the change of inductance, while the change of secondary side load voltage indicates that seawater brings about the change of resistance. [28] calculates the inductance variation is about 5 μH according to the resonant frequency migration. In [29], after analyzing the magnetic field in seawater, the eddy current loss is calculated, and it is found the resistance variation is proportional to the square of the working frequency. [27] finds that the resistance variation is also proportional to the working frequency with a smaller 12 cm coil.

A circuit model of an underwater WPT system in which the inductance and resistance changes, similar to [27], [28] and [29], might be built to explain the experimental findings in this study.

To sum up, this paper has mainly two observations on transfer characteristics of underwater WPT system: first, frequency splitting still exists; second, underwater transfer efficiency is higher than that in air at midrange. Primary analysis shows that the experimental phenomenon may be explained by a circuit model, but the model needs further study.

5 Conclusion

In this study, it is found experimentally that the secondary load voltage in seawater is much higher than that in air in the midrange WPT. However, the 20% seawater transfer efficiency is relatively low, and the midrange underwater WPT may be used in a transfer distance priority scene.

Based on the analysis of this phenomenon, it is suggested that a circuit model may be used to explain the experimental findings in this study, which should be further improved in the follow-up work. The circuit model, which get rid of the complex electromagnetic field computation, is easier to understand and easier to calculate. In addition, the experimental conditions of the phenomenon in this paper might be extended in the follow-up work.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)
-Weiting Zhang carried out the experiment, data analysis and original draft preparation.
-Wangqiang Niu did the conceptualization, methodology and revision.
-Wei Gu supervised the study.