Underwater Wireless Power Transfer for Maritime Applications

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***Abstract*—This paper presents the development and implementation of an inductive, underwater wireless power transfer system for use with unmanned underwater vehicles (UUVs). Specifically, the design and fabrication of power transfer coils and power electronics is provided for a system capable of providing 75W to a load. At small standoff distances (<2 inches) and frequencies below 300kHz, it is shown that there is little difference between inductive power transfer in air and seawater. Measured data shows that at power levels of 75W, the system efficiency from the transmitter to a rectifier and resistive load is above 85%.**

I. INTRODUCTION

For unmanned underwater vehicles (UUVs), power is the critical factor that often determines mission lifetime. Unlike many terrestrial vehicles, where batteries can be easily replaced or recharged, UUVs must either surface for battery replacement, or make watertight connections to safely recharge. In both cases, the solution typically requires human interaction, which increases the risk to both the vehicles and operators, as well as raising the total operating cost.

One solution for increasing the operational lifetime of UUVs is the use of inductive power transfer to wirelessly recharge the vehicle batteries while the UUV itself remains submerged. Inductive power transfer uses two electromagnetically coupled coils to transfer power from the transmitter (TX) to the receiver (RX). For terrestrial applications, this type of power transfer is used for inductive stovetops and is currently being developed as a means to charge portable consumer electronics (cellphones, smart watches, etc.) and electric cars. Several groups of industry partners have teamed together to develop standards of wireless power transfer, including the Alliance for Wireless Power (A4WP) [1] and the Wireless Power Consortium (WPC) - developers of the Qi standard [2]. These commercial standards specify system level operation for wireless power transfer, including power levels, operating frequencies, and communication protocols.

While the commercial protocols for wireless power transfer are useful for many consumer applications, there are a number of challenges that limit their use for UUV charging in the maritime environment. For example, the A4WP standard is based upon a power transmission frequency of $6.78MHz$. However, operating in salt water at this frequency leads to high attenuation and low power transfer efficiency. The Qi standard operates at a much lower frequency ($< 250kHz$), but is currently limited to power levels on the order of 10W. To expediently charge a UUV, it is desirable to charge at higher power levels.

The development of a functional underwater wireless power transfer system for charging UUVs is a complex process and requires an examination of many factors, including biofouling, thermal dissipation, power transfer, and communications between the transmitter and receiver. This work focuses specifically on the wireless power transfer portion, and presents the fabrication and characterization of a power transfer system capable of delivering up to 75W to the load.

In this paper, the theory of underwater wireless power transfer is presented first. A high level overview of the system is provided next, followed by a detailed explanation of the coil and electronics design. The experimental setup used to demonstrate power transfer to a resistive load is then presented, followed by a discussion of the measured power transfer efficiency in both air and water. Finally, conclusions and future work are presented.

II. DESIGN OF THE WIRELESS POWER TRANSFER SYSTEM

A functional block diagram of the wireless power transfer system developed for this work is shown in Fig. 1. The transmit side of the system is comprised of a sinusoidal source, TX coil, and tuning capacitor, C_{TX}. For the characterization presented in this work, a function generator and linear amplifier were used to provide power for the transmitter. A more integrated solution of the transmitter circuitry is required for a functional implementation. The receive side of the system is made up of the RX coil, tuning capacitor, C_{RX}, rectification circuitry and a resistive load.

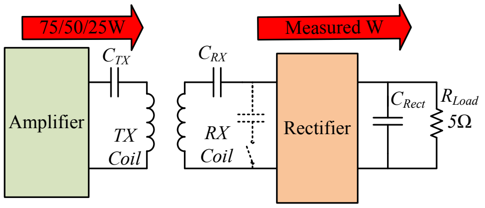

Fig. 1. A block diagram of the wireless power transfer system.

A. WPT Coil Design

For a set of coupled inductive coils, the efficiency of the wireless power transfer from the TX coil to the RX coil is given as,

$$\eta_{WPT} = \frac{k^2 Q_{TX} Q_{RX}}{\left(1+\sqrt{1+k^2 Q_{TX} Q_{RX}}\right)^2}, \qquad (1)$$

where k is the coupling coefficient between the coils, and Q_{TX} and Q_{RX} are the quality factors of the TX and RX coils, respectively. To design a highly efficient system, both the coupling coefficient and quality factors should be maximized. The value of the coupling coefficient is based on the positioning of the coils (spacing and alignment) and the material between them (seawater), while the quality factors are related to the coils themselves (wire resistance, inductance, capacitance). For the planar coils implemented in this design, shown in Fig. 2, it is desirable to align the coils as close together as possible so that the RX coil can capture as many of the flux lines emitted by the TX coil as possible. This means that the efficiency of the power transfer is highly dependent on the quality factors of the two coils.

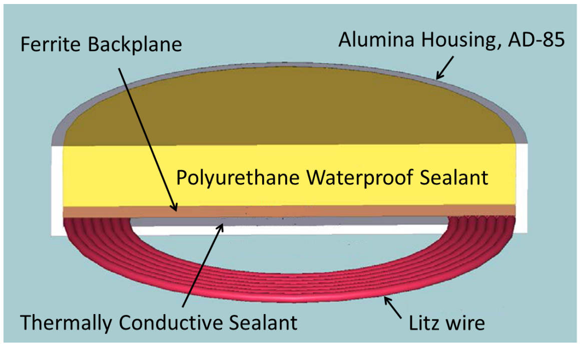

Fig. 2. Planar coils for the wireless power transfer system.

For many terrestrial based systems, inductive power transfer coils are designed with peak Q values to occur in the MHz frequency range. While this practice is acceptable for terrestrial applications where air is the transfer medium, MHz frequencies do not propagate well underwater. Previous work in this area, however, has demonstrated that at short distances ($\leq$ 10cm) frequencies under 300kHz propagate in almost the same manner in water as they do in air [4]. This means that power transfer coils can be designed and characterized to a first order in air with reasonable reliability at low frequencies.

B. WPT Coils

In order to demonstrate the underwater wireless power transfer system, single layer planar coils were fabricated, as shown in 2. The coils were made of stranded litz wire, with a total wire thickness between 10 and 11 gauge. The litz wire was chosen for its low resistance ($< 0.3\Omega$ per coil)and ability to carry high currents ($> 25A$). For both the transmit and receive coils, the litz wire was wrapped on top of an aluminum nitride ceramic disk and potted with a watertight urethane material. The purpose of the ceramic disks were to aid in the heat dissipation of the coils, and therefore the outer surface of the ceramic disks were not potted and open to the environment. The electrical and mechanical parameters of both the transmit and receive coils are given in Table I.

TABLE I
COIL PARAMETERS

	Transmit (TX)	**Receive (RX)**
Number of Turns	13	10
Winding Outside Dia. [$inch$]	5.7	4.8
Winding Inside Dia. [$inch$]	2.0	2.0
Ceramic Disk Dia. [$inch$]	8	6
Ceramic Thickness [mm]	6.35	6.35
Inductance [μH]	18	10

Quality factor measurements of the fabricated coils as a function of frequency are shown in Fig. 3. The top two curves represent the high power transmit (HP TRAN) and receive (HP REC) coils in open air. The third curve shows the high power receive coil inside in air, but mounted inside of an aluminum UUV hull section. The lower three curves show quality factor measurements from a previous iteration of the power transfer coils. These additional measurements are included because they illustrate the small difference between quality factors measured in air and seawater below 250kHz.

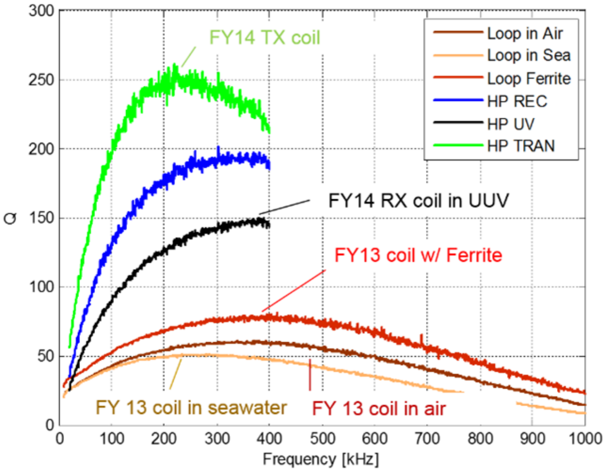

Fig. 3. Coil quality factor measurements.

C. Receiver Electronics

The electronics connected to the receiver coil were comprised of a standard full bridge rectifier circuit and filter capacitor. A diagram of the receiver electronics is shown in Fig. 4. Low loss shottkey diodes were used to realize $D1$ - $D4$, and the rectifying capacitor,C_{Rect}, was realized with a $470\mu F$ electrolytic capacitor.

III. EXPERIMENTAL SETUP

The experimental setup used for this work is shown in Fig. 5. This work focused on the power transfer efficiency through the coils and to a resistive load. Therefore, the transmitter was realized using a bench-top amplifier driven by a function generator. On the TX side, RMS voltage and current output

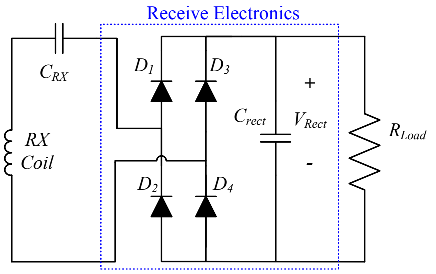

Fig. 4. Electronics on the receiver side of the wireless power transfer system.

by the amplifier were measured using an oscilloscope, and the power was calculated as the product of these times the cosine of phase difference between them using:

$$P_{TX} = V_{RMS} I_{RMS} cos(\theta). \tag{2}$$

On the receiver side, the voltage across the voltage across the resistor was measured using a DC voltmeter, and the output power was calculated using:

$$P_{RX} = \frac{{V_{LOAD}}^2}{R_{LOAD}}. \tag{3}$$

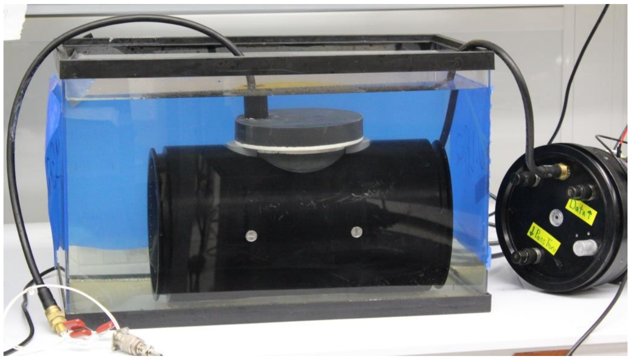

Fig. 5. Underwater test setup used in labratory experiments.

IV. EXPERIMENTAL RESULTS

A characterization of overall efficiency as a function of frequency was first performed, where efficiency, η, is calculated as

$$\eta = \frac{P_{RX}}{P_{TX}} * 100\%. \tag{4}$$

A plot of the efficiency vs frequency for a frequency range of 94kHz to 160kHz is shown in Fig. 6 for several different power levels.

A second test was performed to determine the effects coils spacing on power transfer efficiency. Based on the results of the frequency sweep shown in Fig. 6, a frequency of $118kHz$ was chosen as the power transfer frequency. These tests were first performed in air, with and without the presence of the hull, to determine how the aluminum hull effects the power transfer efficiency. The coils were then tested submerged in salt water, with the hull, to validate the assumption that at low frequencies the power transfer in air and water is nearly identical. Results of this experiment is shown in Fig. 7.

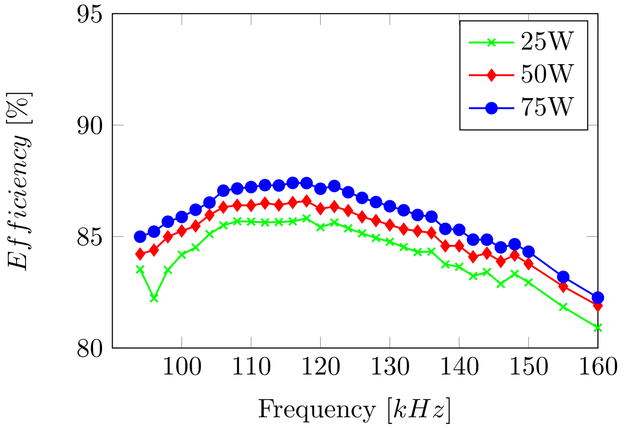

Fig. 6. Power transfer efficiency in water (with hull) at different power levels.

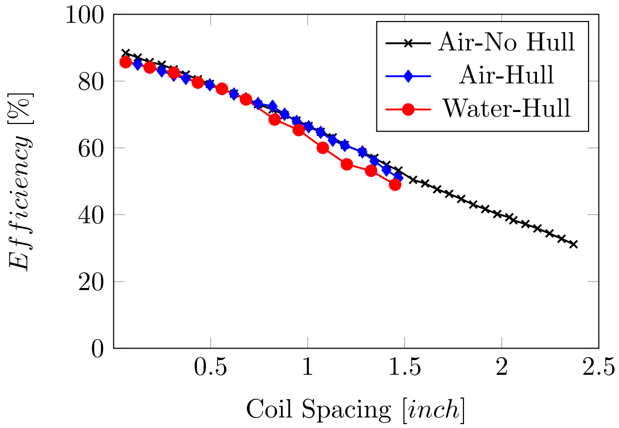

Fig. 7. Power transfer efficiency in water (with hull) at $118kHz$.

Figure 7 shows that the power transfer efficiency ranges from around 90% when the coil spacing is virtually zero, to an efficiency of around 30% at a spacing of 2.5". Additionally, this experiment demonstrated that at low frequencies, there was very little difference between air and water, and that presence of the hull had little effect. It is important to note that in the configuration used for this work, the RX coils were mounted flush with the hull, and that being recessed further within the hull might change the results.

V. CONCLUSION

This paper presented the design, fabrication, and testing of a wireless power transfer system for underwater applications. We have demonstrated the ability to model the transfer of power and shown that at frequencies below 250kHz, there is little difference between transferring power between water and air.

REFERENCES

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[3] [1] J. Zhou, D. Li, and Y. Chen, Frequency selection of an inductive contactless power transmission system for ocean observing, Ocean Eng., vol. 60, pp. 175-185, Mar. 2013.

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