Characterization of Coupled Coils in Seawater for Wireless Power Transfer

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***Abstract*—This paper presents the electrical characterization of coupled electromagnetic coils in saltwater for an undersea wireless power transfer system. The resonant frequency of the system, as well as the separation gap between coils was varied, in both air and seawater, in order to study the effects of saltwater on the energy transfer process. The results indicate that wireless power transfer can be achieved for *in situ* charging of unmanned vehicles in the ocean.**

Keywords—wireless power transfer; coupled coils; input impedance

I. INTRODUCTION

A key challenge to undersea unmanned vehicle (UUV) operations is the finite mission duration times which result primarily from limitations in power storage. Due to the autonomous nature of these vehicles, UUVs are power limited by both space constrains and physical distance from external energy sources. Consequently, UUVs must constantly be extracted from the ocean, serviced (e.g., battery replaced), and then re-deployed resulting in unwanted lapses in operations. To increase the longevity of these systems, the vehicles need to be recharged *in situ*. The two techniques currently used to recharge UUV's without extraction implement either an electric socket or rotary transformer [1, 2]. Unfortunately, both of these techniques require precision mating for the transfer of electrical energy. For the electrical socket configuration, any physical misalignments can lead to shorting or corrosion of the conductors used in the power transfer. While the rotary transformer approach addresses issues with exposed conductors, alignment on the order of millimeters is required for efficient power transfer. In practice, this degree of alignment is difficult to achieve for deployed underwater systems.

An alternative approach to the electrical socket and rotary transformer is to adopt wireless power transfer technology being developed in the commercial sector and adapt it to the underwater maritime environment. There are several key advantages to implementing this types of wireless power transfer (WPT). First, WPT is designed to transmit power over larger distances (> cm's) without having to be in direct contact, and transfer efficiency is relatively high (>75%). However, there are several open ended questions that must be answered in order to transfer power in an underwater operational environment. Eddy current losses, for example, caused by inductive power transfer through a conductive medium (i.e. the ocean), will have detrimental effects on the efficiency of the power transfer. Additional losses associated with the skin effect will also reduce efficiency.

In order to better understand these and other issues associated with wireless power transfer through seawater, this work investigates the electromagnetic properties of coils that will be exposed to the ocean. First, the impedance of a single coil in seawater is analyzed and compared to the impedance of a coil in air. An analysis is then presented for the mutual inductance between two coils in seawater. Input impedance measurements are then performed on single coils submerged in saltwater. From these impedance measurements, the resistance, inductance and quality factor Q for the single coil systems are extracted. The change in these electrical properties for coils in air versus seawater is also examined. Input impedance measurements are then made for coupled sets of two coils, in both air and seawater. The coupling coefficient is extracted from these measurements. The studies performed here provide an understanding on the effects the saltwater channel would have on coil's electrical properties and coupling mechanics. The analysis will show there is an upper frequency bound of operation in seawater. Finally, it is demonstrated that the operating frequency of coil system in seawater around is approximately 100 kHz, which is comparable in performance to power transfer through air.

II. UNDERSEA WIRELESS POWER TRANSFER SYSTEM

A wireless power transfer system can be represented schematically by the circuit diagram [3, 4] illustrated in Figure 1(a). The coils, both the transmit and receive, can be represented by an inherent inductance, *L,* and inherent resistance, *R*. In order for the coil to resonate at the desired frequency of operation, ω, a capacitor, *C,* is placed in series with the coil. Finally, the coil coupling is represented by the mutual inductance, *M*.

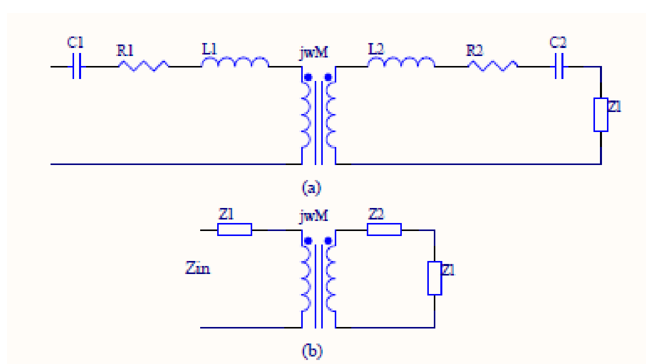

Figure 1. Circuit diagram for two coil wireless power transfer system, (b) an equivalent input impedance model.

The two-coil WPT system can be further simplified, and is characterized by an equivalent input impedance model, shown in Figure 1(b). The input impedance as seen by the transmit coil, Z_{in}, is given by

$$Z_{in} = Z_1 + \frac{\omega^2 M^2}{Z_2 + Z_L} . \quad (2)$$

The input impedance expression captures the system coupling (M), load impedance (Z_L) and the impedances of each coil (Z_1 and Z_2), where Z_1 is the impedance of the transmit coil, and Z_2 is the impedance of the receive coil. The impedance for each coil is given by

$$Z = R + j\omega L + 1/j\omega C , \quad (3)$$

In this work, it is assumed that saltwater will modify the electrical characteristics of the coils. In order to test this assumption, single coil and coupled two-coil systems are examined. Any additional losses (resistances) or changes in reactance (inductance), as a result of the saltwater, are recorded.

A. Impedance of a Single-Coil in Seawater

The impedance of a single loop in a conductive medium has been studied by many different authors [6, 7]. For instance, Kraichman developed expressions for the change in radiation resistance and reactance for a thinly-insulated circular loop in a conductive medium. Here, these formulas are examined for coils immersed in seawater and compared it to coils in air.

The total resistance of a coil in air or seawater is

$$R = R_{DC} + R_{AC} + R_{rad} ,$$

where R_{DC} and R_{AC} are the DC and AC contributions of the resistance, respectively, and R_{rad} is the radiation resistance. The DC and AC resistances for a coil in air or saltwater will be similar in magnitude , since these resistance are based on the type of wire and how it is wound. The radiation resistance for a loop in a conductive medium was derived by Kraichman [5] and is given by

$$R_{rad}^{sea} = \omega\mu a \left[\frac{4}{3}(\beta a)^2 - \frac{\pi}{3}(\beta a)^3 + \frac{2\pi}{15}(\beta a)^5 - ... \right]$$

where a is the radius of the loop in meters, μ is the permeability of medium, ω is the frequency in radians, σ is the conductivity of medium, and $\beta = (\mu\omega\sigma/2)^{1/2}$. In comparison, the radiation resistance of the coil in free-space is given by the well-known formula [6]

$$R_{rad}^{air} = \frac{\pi}{6} \frac{\omega^4 \mu a^4}{c^3}$$

Fig. 2 shows a comparison of the DC and AC resistances of a coil used for experimental tests. Also included are plots of the radiation resistance of a coil in both air and saltwater. The coil is 6 cm in radius with 15 turns. The permittivity and conductivity of the ocean is approximated as $\varepsilon_r = 72$ and $\sigma = 4$ S/m. The radiation resistance of the coil in air is negligible. By comparison, the radiation resistance of the coil in seawater, at frequencies greater than 150 kHz, increases more rapidly with frequency than the AC resistance, which normally dominates the losses in air.

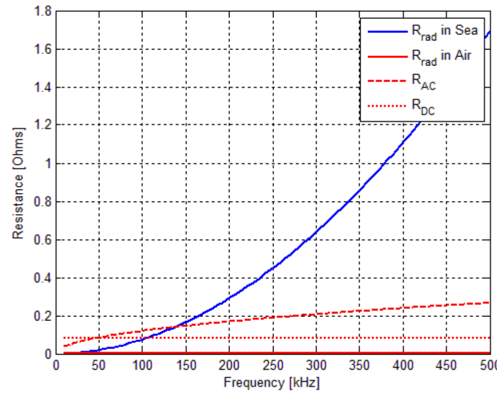

Figure 2. Comparison of the resistances for a coil in air and saltwater. The red dashed line (--) and dotted line (:) is the AC and DC resistance, respectively. The solid red line (-) is the radiation resistance of the loop in air. The solid blue line is the radiation resistance of the loop in seawater.

Kraichman also derived an expression for the reactance of a loop in seawater [6].

$$X = \omega\mu a \left[K(k) - 2 - \frac{\pi}{3}(\beta a)^3 + \frac{4}{15}(\beta a)^4 - ... \right],$$

where $K(k)$ is the complete elliptic integral of the first kind. In comparison, the reactance of a single-turn coil in air is given by

$$X_{air} = \omega\mu a [K(k) - 2].$$

Substituting the reactance in air into the reactance of the coil in the conductive media yields,

$$X = X_{air} - \omega\mu a \left[\frac{\pi}{3}(\beta a)^3 - \frac{4}{15}(\beta a)^4 - ... \right].$$

Fig. 3 shows a comparison of the inductance for the same coil located in air ('red') and in seawater ('blue) as a function of frequency. The inductance is determined from the above expressions for reactance. Also, included is Grover's inductance calculation for a circular loop [7]. A key finding of this study is the difference in inductance of a coil in air or submerged in seawater from 10 kHz to 1 MHz is less than 4%.

The present analysis shows seawater has an effect on the resistances of a coil. This is dependent on coil geometry, size and frequency of operation. Higher frequencies lead to worse losses. In contrast, the inductance of the coils changes very little over the frequency of operation.

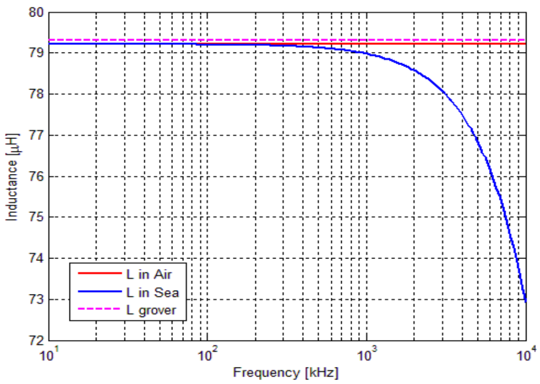

Figure 3. Comparison of the inductance for a coil in air and saltwater. The red solid line (-) and dotted line (:) is the inductance of a coil in air given by the above formula and Grover's equation. The solid blue line (-) is the inductance of the coil is seawater.

B. *Mutual inductance between coils in seawater*

For a two-coil system, the mutual inductance between two tightly wound, thin circular coils co-axial located and separated by a distance, *d,* is given by Grover's formula [7]

$$M = \mu N_1 N_2 \sqrt{R_1 R_2}\left\{\left(\frac{2}{k}-k\right)K(k)-\frac{2}{k}E(k)\right\}$$

where μ is the permeability of the medium, N_1 and N_2 are the number of turns of the two coils, $k = 4R_1R_2/((R_1+R_2)^2+d^2)$, d is the spacing between coils and $K(k)$ and $E(k)$ are the elliptical integrals of the first and second kind. The relative permeability of air or free-space is the same for saltwater (μ_r = 1). Therefore, the mutual coupling between coils is not going to change significantly, whether in air or saltwater. because the permeability remains the same.

The mutual inductance is derived assuming the medium is dissipative. While this is true at lower frequencies, this approximation is not satisfied in seawater at higher frequencies. To understand the high frequency cutoff of coils in seawater, we can remove the quasi-static approximation to Neumann's original formula. Starting with Neumann's formula and including fullwave affects [8], the mutual inductance is given by

$$M_{21} = \mu \oint_{Loop2} \oint_{Loop1} \frac{e^{-jk|\mathbf{r}-\mathbf{r}'|}d\mathbf{l}_1 \bullet d\mathbf{l}_2}{4\pi|\mathbf{r}-\mathbf{r}'|}.$$

Figure 4 is a comparison of the mutual inductance between two coils versus frequency in air using Grover's formula ('solid') and seawater ('dash') using the above expression. Two different coil cases were considered. The first case was for coil geometry and spacing $R_1 = R_2 = d$ = 6cm. The second case was for $R_1 = R_2 = d$ = 15cm. In the 6cm case, there was little variation in mutual inductance over frequency from 30 kHz to 1MHz. However, there was greater variation in mutual inductance in seawater versus air for the 15cm case. For instance, there was an 11% variation in mutual inductance at 400 kHz. For different coil geometries and spacing, there can be considerable disparity in the mutual inductance between coils in seawater versus air.

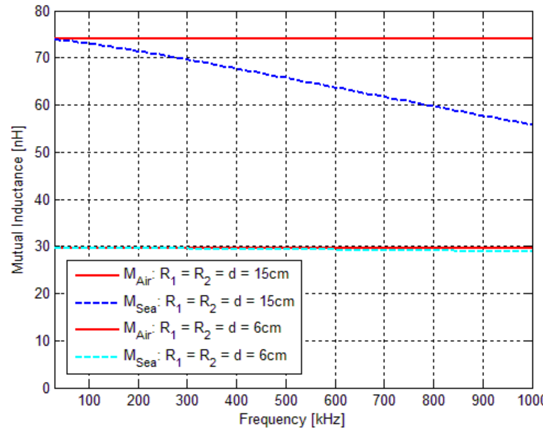

Figure 4. Mutual inductance of a coil in a conductive medium Comparison of the mutual inductance for a coil in air and saltwater. The red solid lines (-) are the mutual inductance of a coil in air given by Grover's equation. The dashed lines (-) in blue are the mutual inductance of the coil in seawater.

III. Design of RF Coils

A number of different RF coils were investigated to determine the topologies best suited for integration into unmanned vehicles. Short, tightly wound cylindrical coils were designed with 18 (AWG) wire gauge, N = 18 turns, and radius a = 6.0325 cm. This diameter of the coils and number of turns was determined to meet the spacing requirement for a UUV. The estimated inductance based on these parameter values was 80 μH. To achieve the desired frequency of operation at 100 KHz, a C = 33nF capacitor was placed in series with the coil. The designed coils needed to be potted to protect the copper wire from the saltwater environment. A clear urethane potting material, previously used on hydrophones with a permeability of 1, was used as the potting material. A thermal epoxy was also applied to the coil to aid in dissipating the thermal load from the applied current. An example of one of the tethered cylindrical coils is shown in the Fig. 5(a).

Solenoid coils were also designed and fabricated. The receive coil was designed to be inserted inside the transmit coil as shown in Fig. 5(b). The receive coil was filled with a ferrite powder to increase its inductance and also increase its weight. The transmit coil was a tightly wound, single layer solenoid with 5.715cm diameter, length 2.54 cm and 16 turns of Litz wire. The calculated inductance for the transmit coil with these dimensions was 46.5 μH, and using an LCR meter, the measured inductance was 53 μH. The receive coil's radius was slightly smaller and hade 8 turns of Litz wire. Its measured inductance was 9 μH when air-filled. Both transmit and receive solenoids were potted. The receive coil was potted with iron powder to add weight when submerged underwater.

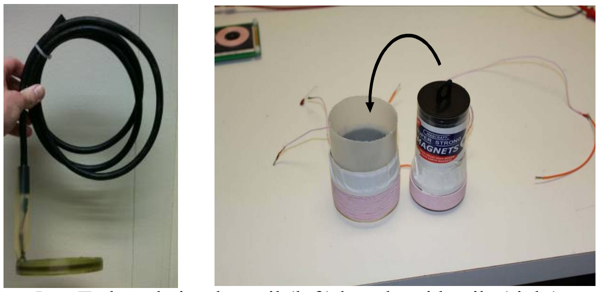

Figure 5. a. Tethered circular coil (left) b. solenoid coils (right).

IV. Input Impedance Measurements

Input impedance measurements were conducted to characterize the various coil designs. Single coil measurements were performed on the un-potted, potted and coated coils, with the goal of understanding whether the potting process would change the impedance or add any additional loss into the system.

Figure 6. Experimental setup for two coil measurements in seawater.

Figure 6 shows the experimental set-up for the input impedance measurements in seawater. The S-parameters were first measured using an Agilent E5071C network analyzer. The measurements were performed from 10 kHz to 1 MHz. The S-parameters were then converted to input impedance using the formula

$$Z_{in} = Z_o \frac{1 - S_{11}}{1 + S_{11}}$$

where Z_o is 50 ohms. Once the input impedance was measured, the resistance and the inductance of the coil could be extracted from the real part of the impedance and its reactance.

A. Single Coil Measurements

Single coil measurements were performed on the tethered circular coils and solenoids in air and in the saltwater aquarium. In air, the resistance of the circular coil was about 1 ohm. The inductance in air for the different designed circular coils varied between 77µH to 80µH around the operating frequency of 100 kHz. The tethered coil was then submerged into a tank of ocean saltwater. Fig. 7 compares the resistance and reactance of the coils in air versus saltwater. As can be seen, there is very little discrepancy between the two different mediums when operating below 100 kHz. Above this frequency, the resistance of the coil in seawater begins to increase. Also shown is a result for a coil placed on top of a ferrite plate. In comparison, the coil placed on the ferrite plate resulted in much higher reactance and the resistance compared to the coil in air.

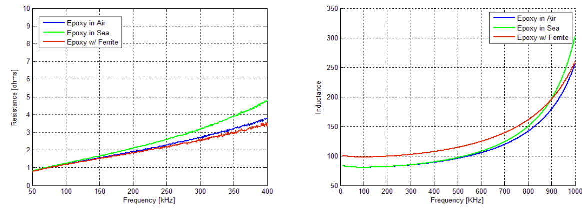

Figure 7. Input impedance measurements versus frequency for a single cylindrical coil in air and seawater, (a) resistance, and (b) reactance.

The quality factor, Q, can be determined from the measured resistance and inductance of each coil. The Q of a single coil is given by

$$Q = \frac{\omega L}{R_{Tot}}.$$

The Q for the different coil configuration is shown in Fig. 8. The higher resistance from the coil in seawater diminished the Q of the coil significantly.

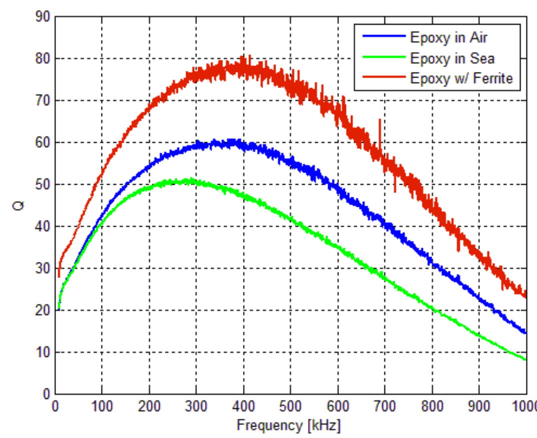

Figure 8. Quality factor of the coils in air, seawater and atop a ferrite plate.

The input impedance for the single layer solenoid was measured next. Fig. 9 shows a comparison of the resistance and inductance versus frequency for the transmit solenoid coil in air and saltwater. The resistance of the coil below the operating frequency of 100 kHz was 0.25 ohms in air and in seawater. But above 100 kHz, the resistance of the coil in seawater increased rapidly with frequency. The reactance for the solenoid in air or seawater showed little variation. The coil was tuned to 100 kHz with a capacitor value of $C = 47$nF.

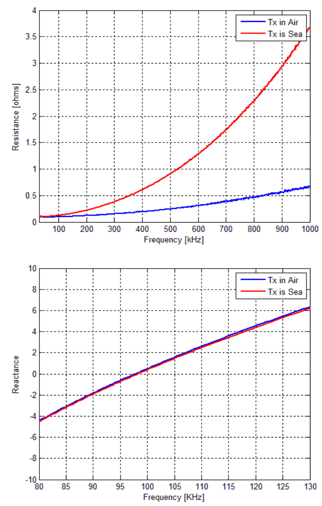

Figure 9. Input impedance measurement versus frequency for the transmit solenoid in air and seawater, (a) resistance, and (b) reactance.

B. *Coupled Two Coil Measurements*

Input measurements were performed on the coupled cylindrical coils and solenoids. For both cases, the load was a 1 ohm resistor. Both sets of coils were tuned to 100 kHz. For the cylindrical coils, `the spatial separation varied from 2.54cm to 20.32 cm. Fig. 10 shows a comparison between the two-coil systems in air and saltwater. For this work, the frequency range of interest was around 100 kHz. There is little difference in input impedance between the coils operating in air or seawater. The resistance was as high as 200Ω at resonance for 2.54 cm spacing and then quickly fell off to 20Ω for 5.08cm spacing. The reactance, however, shows much greater variability over the range of coil spacing.

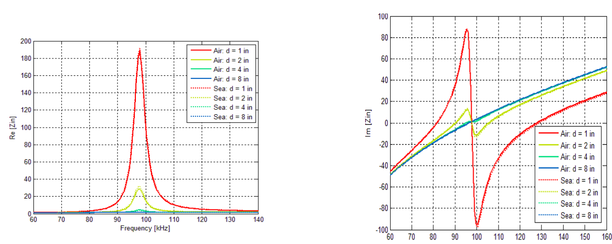

Figure 10. Comparison of the input impedance versus frequency for coupled cylindrical coils in air versus saltwater. Measurements are conducted for difference spacing between coils.

Figure 11 shows the input impedance measurements versus frequency for the coupled solenoids in air and seawater. These coils were designed so that the receive coil would fit closely *inside* the transmit coil. The spacing between the two coils was on the order of mm's. Again, near an operating frequency of 100 kHz, the two measurements in air and seawater are in good agreement. For frequencies greater than 300 kHz, the resistance increased for the coil in saltwater. In comparison, the reactance varied very little whether the coils were in air or seawater.

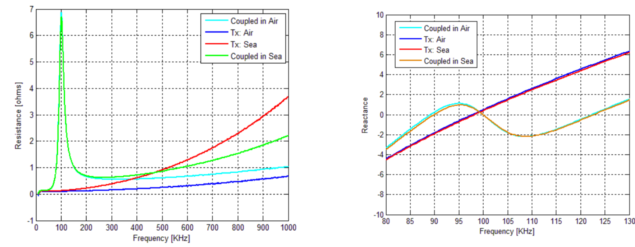

Figure 11. Comparison of the input impedance versus frequency for the coupled transmit and receive solenoid in air versus saltwater. Measurement was performed for the receive coil slotted inside the transmit coil.

The final analysis of the electrical properties for the coupled coils was to provide an estimate of the separation coefficient k_{12} or mutual coupling between the coils. The separation coefficient is given by the expression

$$k_{12} = \frac{M}{\sqrt{L_1 L_2}} .$$

The separation coefficient k_{12} can range in value from 1.0 (good coupling) to 0.0 (poor coupling). The k_{12} coefficient is extracted from the two-coil impedance measurements using the method described in [9]. Fig. 12 is a summary of the estimated k_{12} versus spacing for the different designed coils setups. For the solenoids, where the receive coil fit snugly inside the transmit coil, the k_{12} value was approximately 0.7. The cylindrical coils k_{12} ranged from 0.4 to 0.15 with respect to coil spacing. The solenoid coils appeared to provide better coupling. So, two final coils were designed based on the transmit solenoid. The extracted k_{12} values for this final coupled solenoid are shown in green below. They show slight improvement in k_{12} value over the cylindrical coils.

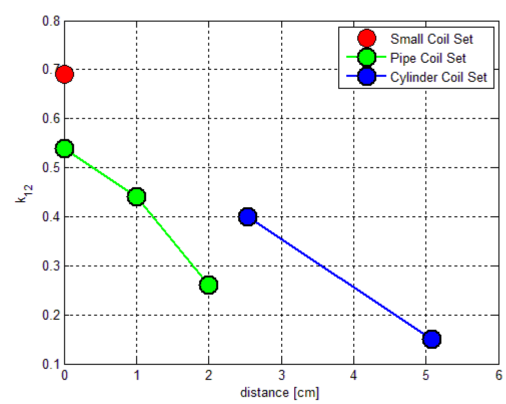

Figure 12. Separation coefficient for cylinderical coils ('blue'), Quality factor of the coils in air, seawater and atop a ferrite plate.

V. CONCLUSION

Using two port network analysis, key parameters of an underwater wireless power system were measured. Preliminary results indicate that at frequencies below 100 kHz, the electrical properties of coils and their mutual coupling were almost identical whether in air or in saltwater. Above 100 kHz, seawater began to have a detrimental effect on the resistance of the coil and their coupling performance. Future work will use coils made with larger and higher frequency Litz wire and increase the resonance frequency to determine when saltwater will affect the power transfer.

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