Performance Evaluation of Antennas for Underwater Applications

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Abstract—The capability of an Autonomous Underwater Vehicle (AUV) or Remote Operated Vehicles (ROVs) to communicate with underwater sensor nodes or a docking station, for the exchange or transfer of data gathered during a survey mission, requires an high-speed short-range communication link. This is important because of the global attention to the underwater communication applications. To this end, underwater antennas will play a significant role in ensuring good data rates and propagation distances for these applications.

In this paper, the performance of three antennas, specifically, loop, dipole and J-pole is assessed through simulation for usage in fresh and sea water operating in the High Frequency (HF) band. The antennas were designed in FEKO, an electromagnetic simulation software and their performance is assessed in terms of bandwidth and directivity. The results obtained shows that the J-pole antenna has significant advantages in term of the measured parameters over the other antennas. Experimental results of the reflection coefficient of the J-pole antenna in fresh water are given that agree well with the simulation results.

Index Terms—Autonomous Underwater Vehicle; Underwater Antennas; loop; dipole; J-pole; directivity; bandwidth.

I. INTRODUCTION

There has been a growing demand for high speed wireless communication links for underwater applications, which include: oceanographic data collection which will require data exchange between two or more Autonomous underwater vehicles (AUVs) and other underwater sensors, coastline protection and surveillance, underwater environmental observation for exploration and off-shore oil and gas field monitoring. In these regards, there are three established technologies through which underwater communications have been considered, they are: acoustics and ultrasonic signals, optical signals, and Electromagnetic (EM) signals [1]. Each of these technologies has its merits and demerits in their usage for underwater communications. For instance, acoustic and ultrasonic systems are typically good for long range communications (up to tens of kilometers), but this technology is unfit for real-time and broadband underwater wireless sensor networks because of poor immunity to noise, low data-rates and high channel latency [2]. Optical communication systems on the other hand deliver high data-rates and low latency, which are major advantages over acoustic systems, but at the same time it requires very good alignment and are also affected by suspended particles in water and marine fouling [2]. On the other hand underwater EM transmission can deliver data rates up to 10 Mbps though at very short distances and their propagation is not limited by water conditions (clean or dirty), and neither require strong alignments [1]. Unfortunately, this technology suffers greatly from attenuation as it increases with increasing operating frequency, which imposes limits on its usage for underwater communications [3]. Thus, this paper present the design, simulation and comparison of three antennas in underwater for maximum directivity and bandwidths, which are important parameters that can affect the propagation distance and the achievable data rates.

II. OVERVIEW OF THE DESIGNED ANTENNAS

The antennas investigated in this paper are Loop, Dipole and J-pole Antennas. These are simple to design from either a crop of wires or tubing and can also be printed on a desirable substrate.

A. Loop Antenna

The Loop antenna has drawn a lot of attention from radio frequency (RF) engineers across the globe; due to its simplicity in design, ease of fabrication, versatility, low cost, as well as ease of integration to other electronic components and devices [4]. Indeed various shapes like rectangular, triangular, circular, ellipse and other configurations have been designed but circular loop is believed to be the most popular and more work has been done on this than in any other shapes, because of the simplicity in analysis and construction [4]. In [5], a three-turn Electrically Coupled Loop Antenna (ECLA) was developed for underwater applications, but the antenna was placed in an air-filled box, thereby altering what should have been the operating frequency of the antenna in water. In addition, the work does not discuss the achievable bandwidth of the antenna in the medium.

B. Dipole Antenna

A dipole antenna is made up of two identical conductive elements or rods, which is fed at the center by a balanced transmission line, with equal and opposite flowing currents [6], [7]. It has been used in several applications for many decades because of the simplicity in its design, flexibility and is very effective for a wide range of communication needs, including underwater applications [8]. Dipole antennas also come in several types and shapes, which include short dipole, half-wave dipole, folded dipole, bow-tie, V-shaped and other configurations [4]. Efforts have been made to use these antenna
for underwater applications. In [9], three dipole antennas were developed for underwater applications, but the antennas were designed to operate at frequency of 150 MHz. Yet at this frequency, the attenuation is very high as shown in Fig. ??.

C. J-Pole Antenna

The third antenna presented in this paper is the J-pole antenna, otherwise known as J antenna. This antenna typically got its name from its shape (J-Shape), which resembles the letter J. It is comprised of two arms (long and short) with a difference of half wavelength at the operating frequency and the base [2]. This antenna also has other configurations or variations which include the slim Jim antenna, Super-J antenna and Collinear J antenna [11]. In [2] experiments on the performance of the double loop and the J-pole antennas for operation in underwater, were conducted at the operating frequency of 7 MHz and 30 MHz respectively. The received voltages at the two bands were measured but the bandwidth of the antennas was not presented in the paper.

III. DESIGNING OF THE ANTENNAS

The models of these antennas, as designed in FEKO software, are shown in Fig. 1 and based on the analysis presented in [8] and [11], both the permittivity of the water ($\epsilon_r=81$) and its conductivity will determine the final dimensions of the antennas. The antennas are designed to operate at the frequency of 40 MHz. Different configurations of the antennas are required for each medium since the desired operating frequency actually depends on the conductivity of the medium. The physical dimensions of the dipole and J-pole antennas were calculated in a similar way. The dimensions of the antennas for fresh and sea water are given in Table I. The thickness of the wires used in the design of the antennas is 3 mm, the wires are covered with insulating material with thickness of 50 $\mu$m and relative permittivity of 3.

### TABLE I

<table>
<thead>
<tr>
<th>S /No.</th>
<th>Parameters (mm)</th>
<th>Fresh Water ($\sigma=0.05$ S/m)</th>
<th>Sea Water ($\sigma=4$ S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Radius of Loop Antenna</td>
<td>155.75</td>
<td>74.55</td>
</tr>
<tr>
<td>2</td>
<td>Dipole Antenna Arms</td>
<td>217.00</td>
<td>115.50</td>
</tr>
<tr>
<td>3</td>
<td>Short Arm of J-pole Antenna</td>
<td>161.13</td>
<td>42.50</td>
</tr>
<tr>
<td>4</td>
<td>Long Arm of J-pole Antenna</td>
<td>402.26</td>
<td>121.80</td>
</tr>
<tr>
<td>5</td>
<td>Base of J-pole Antenna</td>
<td>80.00</td>
<td>80.00</td>
</tr>
</tbody>
</table>

### TABLE II

<table>
<thead>
<tr>
<th>S /No.</th>
<th>Parameters</th>
<th>Loop</th>
<th>Dipole</th>
<th>J-pole</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bandwidth (MHz)</td>
<td>15.76</td>
<td>12.84</td>
<td>26.41</td>
</tr>
<tr>
<td>2</td>
<td>Directivity (dB)</td>
<td>3.80</td>
<td>2.22</td>
<td>7.69</td>
</tr>
<tr>
<td>3</td>
<td>Impedance (Ohm)</td>
<td>34.90</td>
<td>19.40</td>
<td>-</td>
</tr>
</tbody>
</table>

IV. SIMULATION RESULTS

A. Fresh Water

Simulation results corresponding to the bandwidth, input impedance and directivity characteristics of the three antennas are given in Table II. Similarly, the reflection coefficient as a function of frequency for the antennas is presented in Fig. 2. It is clearly seen that the J-pole antenna has a higher bandwidth and directivity, hence higher data rates and propagation distance will be possible, than with the loop and dipole antennas. The bandwidth is measured at -10 dB of the reflection coefficient, when the input impedance of the antennas are matched to the source. The results shows that the J-pole antenna has both a higher bandwidth and directivity than the loop and the dipole antennas. This is an important result when considering the data rates and the directivity required for successful underwater communications.

The 3D radiation pattern of the three antennas are presented in Fig.3. Here, it is seen that the three antennas exhibit three distinct behaviors in the medium. The Dipole antenna exhibits an omnidirectional pattern at the operating frequency, the loop antenna on the other hand has a bi-directional pattern which is at right angles to the wire and the J-pole antenna is highly directional towards the short arm of the antenna.

B. Sea Water

Again the antennas were designed with the parameters defined in Table I associated with the sea water and the results obtained are tabulated in Table III. The results obtained for the reflection coefficient as a function of frequency are presented in Fig. 4, while the 3D radiation pattern for the antennas in sea water are shown in Fig. 5. In this medium, the loop antenna exhibits a higher bandwidth than in the previous case, but the J-pole antenna still has a higher directivity. In addition, the maximum directivity is towards one direction only as the pattern changes direction in this medium to the long arm, whereas the loop and dipole antennas show a maximum in the opposite directions. An important result here is that the radiation pattern of the antennas changes significantly with conductivity. When going from fresh to sea
water, the maximum directivity direction of the loop antenna changed 90°. Moreover, the dipole antenna which in fresh water exhibited an omnidirectional radiation pattern, now it became bi-directional. In turn, the J-pole antenna radiation pattern shows a maximum in the radiation pattern only in one direction. Therefore, the three antennas exhibit noticeable transition in their respective radiation pattern, when compared with the results obtained in fresh water. These changes is the effect of the different conductivity in fresh water and sea water. In addition it is also understood from Section III that sea water behaves as conductor at the operating frequency of the antennas, whereas fresh water operates as an insulator. Hence, it can be concluded that it is important to take into consideration the conductivity of the medium in the design of the antennas, because the major radiation parameters may change significantly with change in the conductivity. Thus, knowledge of the antenna characteristics in air or low conductivity mediums is not sufficient to design the antennas for operation in sea water.

V. EXPERIMENTAL RESULTS

The three antennas were fabricated using the dimensions for each of the antennas as presented in Table I; thickness of copper wires used is 3 mm and current baluns were added to the antennas to reduce undesired radiation on the coaxial cables that could change some of the characteristics of the antennas by interfering with the measured parameters. Based on the achievable bandwidth and directivity of the antennas, and other previous work in this group [12], emphasis was laid on the J-pole antenna that has the best simulation results among the three antennas.

Thereafter, measurements of the J-pole antenna was set up in a freshwater pool located at INESC TEC, with the antennas at a depth of 2.5 m from the surface and placed on the centre of the tank (which has dimensions of $10 \times 6 \times 5.5$ m and the conductivity of water was 0.0487 S/m at 25°C). Thus, the J-pole antenna was manufactured and when the antenna is measured in the water are presented in Fig. 6. The simulation results of the reflection coefficient are compared with the measured results in Fig.7. The measured reflection coefficient agrees well with the simulation: the location of the minimum occurs at the desired frequency of 40 MHz in spite of a larger bandwidth. The difference between the simulated and the measured results can be due to the cable loss or attenuation through the cable.

In addition, the E-plane of the radiation pattern of the antenna was also measured experimentally in the water and the results obtained for the 2D radiation pattern in the plane in fresh water is compared with the simulation results and are presented in Fig. 8. The measured radiation pattern is also in good agreement with the simulation results.

VI. CONCLUSION

Performance of three antennas namely, loop, dipole and J-pole antennas have been analyzed in this paper. In fresh water, the J-pole antenna has a higher bandwidth and directivity and is, thus, desirable for applications in this medium. The radiation pattern of the dipole antenna is omnidirectional, while that of the loop antenna is bi-directional at right angles to the wire and that of the J-pole antenna is directed towards the short arm. In sea water, the loop antenna has slightly higher bandwidth than the other antennas but the J-pole still has a higher directivity, with the maximum directivity only in one direction unlike the other antennas that show bi-directional patterns. The experimental results obtained for the

<table>
<thead>
<tr>
<th>S /No.</th>
<th>Parameters</th>
<th>Loop</th>
<th>Dipole</th>
<th>J-pole</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bandwidth (MHz)</td>
<td>13.94</td>
<td>11.89</td>
<td>10.43</td>
</tr>
<tr>
<td>2</td>
<td>Directivity (dB)</td>
<td>5.20</td>
<td>3.61</td>
<td>7.69</td>
</tr>
<tr>
<td>3</td>
<td>Impedance (Ohm)</td>
<td>12.20</td>
<td>6.69</td>
<td>6.36</td>
</tr>
</tbody>
</table>
J-pole antenna are in good agreement with the simulation results. In conclusion, it is seen that the designed antennas inevitably have different dimensions, input impedances and radiation patterns in both fresh and sea water, due to the huge difference in their conductivity. Of the three antenna analyzed the J-pole one would be the natural choice for operation in either fresh or sea water, due to its better performance in terms of bandwidth and directivity. Similarly, the beam of the J-pole antenna is wider in sea water, which is an added advantage when considering usage of the antennas in this medium. Finally, the J-pole radiation pattern with its maximum of radiation in one direction, is of interest to be fitted within an AUV in the scenario of communication with a docking station. Further work will also include measurement of the antennas characteristic in sea water.

VII. ACKNOWLEDGEMENT

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REFERENCES