Analysis of Magnitude-/Phase-Only vs Combined Readings for Joint Effusion Detection

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Note: This report is a modified version of the authors' paper entitled "Wearables for Joint Effusion Detection: An Analysis for Magnitude-/Phase-Only vs. Combined Readings" that appeared in the Proceedings of the 2021 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting

Abstract—**Joint effusion is the buildup of synovial fluid on a joint. Detecting and monitoring joint effusions can be invasive and costly to the patient. Previously, we introduced a seamless wearable system for detecting and monitoring joint effusion using 2 loop antennas worn around the limb placed on either side of the joint. This system required the monitoring of phase and magnitude measurements at separate frequencies. In this report, we describe a simplified design which can monitor both phase and magnitude at a single frequency while eliminating the need for lumped elements. We provide a design operating at 1485.2 MHz that is robust to frequency fluctuations of up to 30 MHz.**

***Index Terms*— bioelectromagnetics, wearable technology**

I. INTRODUCTION

Injuries or chronic conditions can lead to a build up of synovial fluid within a joint, known as joint effusion [1]. Individuals with joint effusion may have difficulty moving the joint, or pain with movement [1]. The diagnosis process for joint effusion is often time consuming and costly, requiring physical examinations, imaging, and extraction of synovial fluid [1],[2].

In previous work, we have reported a wearable system for joint effusion detection [3]. The system consists of two loops, one transmit loop and one receive loop, wrapped around a limb, and placed symmetrically across the joint in question as seen in Fig. 1. In our first reported work, the magnitude and phase of the transmission coefficient (S_{21}) between the two loops were individually monitored to determine synovial fluid build-up [3]. Two distinct operating frequencies and corresponding lumped element configurations were required to optimally monitor the phase and magnitude [3]. This system was then refined to monitor phase and magnitude simultaneously without the use of any lumped elements to simplify fabrication and operation of the sensor [4]. The refinement of the system will be the primary subject of this scholarship report.

II. DESIGN APPROACH AND METHODOLOGY

Four criteria were used to optimize the sensor performance when determining the frequency of operation and lumped element configuration: (1) the ability to obtain a monotonic trend in magnitude and phase with increasing synovial fluid size, (2) the minimum change in synovial fluid size that can be captured via the S_{21} magnitude and phase measurements (ideally small), (3) the dynamic range of the sensor (the difference between the maximum and minimum S_{21} values for all synovial fluid sizes for both magnitude and phase which is ideally large), and (4) the bandwidth around the operating frequency where the sensor is still operational (ideally large).

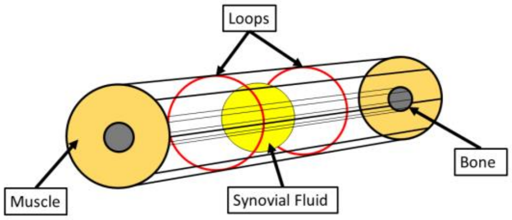

Fig. 1. Wearable electromagnetic loop system to monitor joint effusion on a cylindrical limb model.

All simulation results were created using CST Microwave Studio® [5]. Fig. 1 shows a diagram of the simulation setup. Two loops (radius = 4 cm) were placed equidistance from the center of two concentric cylinders (6 cm apart). The large cylinder of radius 3.9 cm emulated muscle while the small cylinder of radius 1 cm emulated bone. To simulate joint effusion, a sphere emulating synovial fluid was placed in the center of the limb. The sphere size was varied from 1 cm to 3 cm in steps of 0.5 cm. The three lumped element configurations in [4] were used: (1) no lumped element, (2) 1 pf capacitor, (3) 820 nH inductor.

For all three designs, frequencies between 200 MHz and 2000 MHz with monotonic trends in phase and magnitude were identified separately. Frequencies corresponding to the best sensitivity and dynamic range for all three designs were then obtained for magnitude and phase separately. Finally, the optimal setups for magnitude sensitivity and dynamic range, and phase sensitivity and dynamic range were determined and compared to the proposed design that monitors both phase and magnitude at a single frequency.

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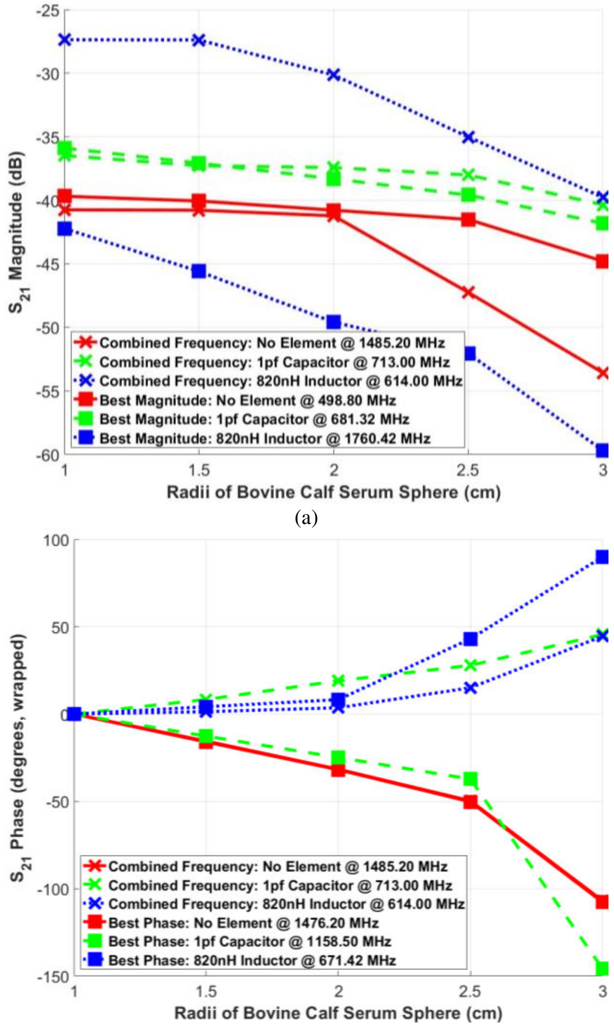
III. SIMULATION RESULTS

Fig. 2 shows the trends in both magnitude (Fig. 2(a)) and phase (Fig. 2(b)) for all designs optimized for sensitivity and dynamic range. Table I contains the identified configurations for optimal performance along the metrics described above, as well as the comparison of the optimal single measure designs with the proposed design. The best performance when examining both phase and magnitude at a single operating frequency was obtained by operating the loops with no lumped elements at 1485.2 MHz. At this operating frequency, the loops are slightly larger than one full wavelength and are operating in the antenna mode.



(a)

(b)

Fig. 2. Trends for (a) S_{21} magnitude and (b) S_{21} phase (wrapped) for three designs optimized at independent frequencies for phase and magnitude and at proposed combined frequency.

As seen in Table I, the convenience of operating at a single frequency for both phase and magnitude monitoring does not come free. Both percent changes presented are an average of the phase percent changes and the linear magnitude percent changes and as such the values represent the change from both the optimal phase and optimal magnitude designs. Finally, we note that the proposed design is robust to frequency fluctuations of at least 15 MHz, giving an operational bandwidth of 30 MHz centered at 1485.2 MHz.

TABLE I SUMMARY OF SIMULATED RESULTS

Parameters	**Values**	**Frequency (MHz)**	**Design**
Best Magnitude Sensitivity (dB)	2.45	1760.42	820nH inductor
Best Magnitude Dynamic Range (dB)	17.48	1760.42	820nH inductor
Best Phase Sensitivity (degrees)	15.90	1476.2	No Element
Best Phase Dynamic Range (degrees)	145.74	1158.5	1pF capacitor
% Change in Sensitivity (from best)	-22.75%	1485.2	No Element
% Change in Dynamic Range (from best)	-46.25%	1485.2	No Element

IV. CONCLUSION

We reported an improvement on a previous design for wearable joint effusion detection that utilizes S_{21} phase and magnitude measurements. The new proposed design does not rely on lumped element components and can monitor both the phase and magnitude at a single operating frequency (1485.2 MHz) at the cost of 22.75% reduced sensitivity versus the ideal, and 46.25% reduced dynamic range versus the ideal. By eliminating lumped element components, this design can be implemented exclusively using e-textiles which allows for seamless integration in clothing and other garments. In the future, we will validate the design upon tissue-emulating phantoms.

V. FUTURE PLANS AND MTT-S IMPACT

Without the MTT-S Scholarship, my decision to pursue graduate school would have been made much more difficult. It is thanks to the work I have conducted as a part of this program that I am happily conducting research as a PhD student at Ohio State and intend to pursue research as my career path. I would like to thank the MTT-S community for their support. At the time of this writing, I am planning on attending the 2022 International Microwave Symposium in Denver, CO. I look forward to learning about a wide range of topics and hopefully bringing the inspiration and creativity back with me to my own research.

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