Software-Defined Ultrasonic Communication System using PPM-EMAT with High Transmission Rate

Xin Huang and Jafar Saniie
ECASP Research Laboratory (http://ecasp.ece.iit.edu)
Department of Electrical and Computer Engineering
Illinois Institute of Technology, Chicago, IL, U.S.A

Sasan Bakhtiari and Alexander Heifetz
Nuclear Science and Engineering Division
Argonne National Laboratory
Lemont, IL, U.S.A.

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***Abstract*— A novel approach to ultrasonic communication systems introduces a software-defined system that utilizes Periodic-permanent-magnet electromagnetic acoustic transducers (PPM-EMATs) as transmitters and receivers. Traditional systems had limitations in adaptability and flexibility. The software-defined system provides enhanced versatility, adaptability, and portability, allowing customization for diverse applications. The use of PPM-EMATs is explored for optimizing energy transfer through metal plate channels, generating shear horizontal waves. Experimental tests validate the efficiency of PPM-EMATs, showing successful communication at a 10-kbps bitrate using ASK modulation with a high signal-to-noise ratio (SNR). The research highlights the potential of PPM-EMAT technology in high-speed software-defined ultrasonic communication systems.**

Keywords—Software-Defined Ultrasonic Communication System, PPM-EMAT, ASK Modulation.

I. INTRODUCTION

In a solid-channel ultrasonic communication system, transducers are utilized to both convert electrical signals into ultrasonic waves for transmission and then back into electrical signals for reception [1][2][3]. These transducers, which are often piezoelectric devices, respond to electrical signals by generating mechanical vibrations. Subsequently, these mechanical vibrations give rise to ultrasonic waves that traverse through the solid medium. The core of the process involves encoding information onto these ultrasonic waves through the application of modulation techniques. However, the conventional signal generators typically employed for producing ultrasonic waves in such systems can exhibit limitations, particularly in terms of their adaptability to swiftly evolving communication requirements and intricate modulation schemes [4][5]. This deficiency in adaptability can especially hinder systems that demand sophisticated modulation techniques or real-time adjustments. Thus, solid-channel ultrasonic communication systems have long been confined by their rigid hardware components and predetermined functionalities. These inherent constraints have impeded their ability to seamlessly adapt to dynamic environments and the ever-evolving demands of communication.

A novel approach to ultrasonic communication systems introduces a software-defined system that utilizes Periodic-permanent-magnet electromagnetic acoustic transducers (PPM-EMATs) as transmitters and receivers [6]. The software-defined ultrasonic communication (SDUC) system presents a compelling array of advantages when contrasted with traditional ultrasonic communication methods [7][8]. These advancements address longstanding limitations and bring a new level of sophistication and adaptability to the realm of ultrasonic communication technology. PPM-EMATs offer a notable advantage in optimizing energy transfer through a distinctive impedance profile [9][10], leading to heightened transmission efficiency and more reliable signal reception. This translates into improved overall communication performance, ensuring effective information conveyance through solid mediums [11]. Additionally, PPM-EMATs stand out for their frequency flexibility, enabling precise customization of communication strategies based on the periodic magnet array structure. Importantly, PPM-EMATs eliminate the need for direct physical contact with the solid medium, simplifying setup and minimizing potential errors due to contact variations [12]. The integration of a software-defined approach adds a new layer of versatility, allowing real-time adjustments to modulation schemes, protocols, and signal processing. This dynamic adaptability empowers the system to perform exceptionally in changing communication contexts.

In this paper, a prototype PPM-EMAT serves as both the transmitter and receiver, generating shear horizontal (SH) waves within the frequency range of 200 kHz to 1 MHz. A software-defined communication platform utilizing amplitude shift keying (ASK) modulation is developed, enhancing signal detection and transmission rates [13].

II. PPM-EMAT TRANSMITTER/RECEIVER

EMATs have been developed to generate both bulk waves and guided waves through the application of Lorentz forces. These EMATs comprise a permanent magnet and a meander coils. Upon application of alternating current to the coil, it induces eddy currents within the material[12][14]. The interaction between these eddy currents and the magnets' static magnetic field generates Lorentz forces, which in turn cause periodic vibrations leading to the production of ultrasonic waves within the material. In Fig. 1, the illustration depicts the orientations of Lorentz forces, influenced by the directions of both the static magnetic field and the current flow.

In Fig 2a, a vital component of the PPM-EMAT is the meander coil, crafted using a flexible printed circuit technique to enable compatibility with varying shape solid channels. The coil's periodicity aligns with that of the magnet array. The PPM-EMAT interfaces with a BNC connector and distinctive impedance profile for optimal performance. The PPM-EMAT prototype shown in Fig. 2b integrates Neodymium Iron Boron magnets, each possessing a surface gauss strength of 7600 Gauss and taking on a rectangular form. These magnets, measuring 0.250" in width, 0.250" in length, and 0.750" in height, are strategically arranged to form the PPM arrays, which corresponds to period of the magnets 12.7 mm.

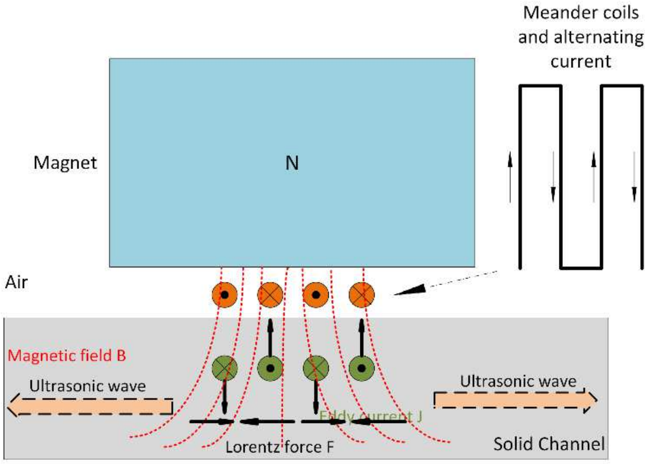

Fig 1. Lorentz force generation of EMAT

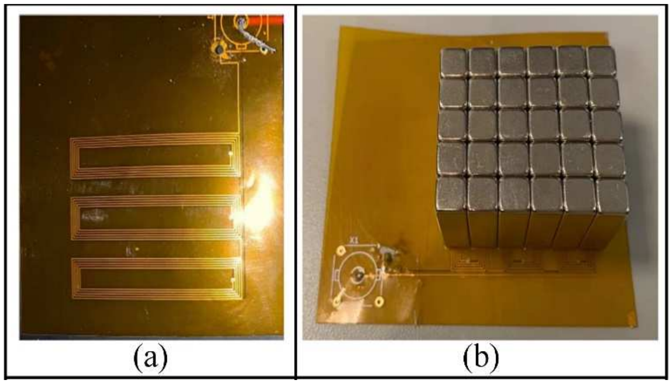

Fig. 2. (a) meander coil, (b) prototype of PPM-EMAT.

III. SDUC System Configuration

The schematic of SDUC depiction is presented in Figure 3. The communication channel employs a stainless-steel plate measuring 169 cm (5.4 feet) in length, 10 cm in width, and 0.95 cm in thickness. The Raspberry Pi platform implement various communication protocols, modulation and demodulation processes, and signal processing techniques. To encode data into ultrasonic signals within a specific frequency range, the Red Pitaya platform, based on a Zynq field-programmable gate array (FPGA), is utilized in conjunction with a power amplifier. The PPM-EMAT transmitter facilitates signal transmission along the solid channels, while the PPM-EMAT receiver, positioned at the opposite end of the channel, is responsible for signal reception. For enhanced clarity, a low-noise amplifier is employed to denoise the received signals. The incorporation of impedance matching networks plays a pivotal role in both the PPM-EMAT transmitter and receiver, contributing to an improved signal-to-noise ratio (SNR) of the ultrasonic signals.

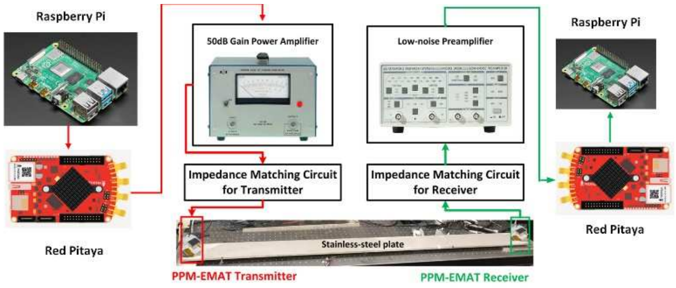

Fig. 3. Schematic of SDUC system

IV. Experimental Test Results

In this section, we undertake an assessment of the different modes of SH waves utilizing PPM-EMAT on the plate channel, executed through a bit pattern test. Amplitude Shift Keying (ASK) is adopted as modulation techniques. Experimental tests are conducted by siting the transmitter and receiver at opposing ends of the plate. To facilitate evaluation, a binary message pattern test employs the sequences '10', '100', '110', '1100', '1110', '11100', and '111000', each repeated six times. A 5 ms interval between transmitted patterns is incorporated to highlight the impact of multipath propagation. The experiments encompass five carrier frequencies: 230 kHz, 279 kHz, 395 kHz, 555 kHz, and 700 kHz, designed to excite the SH0, SH1, SH2, SH3, and SH4 modes of SH-wave. The test bitrates are set at 10 kbps, signifying bit durations of 100 µs for binary information '1' or '0', respectively.

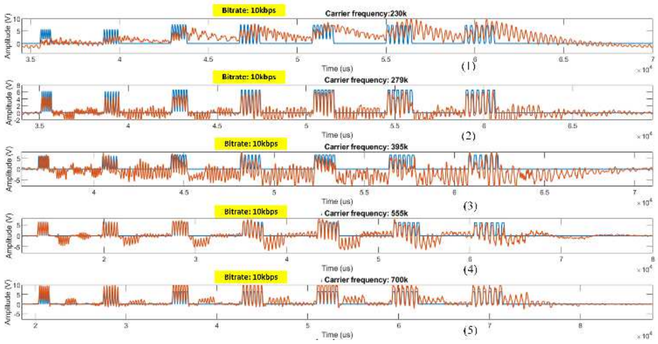

Fig. 4. Bit pattern test on the plate channel, (1) Carrier frequency: 230 kHz, (2) Carrier frequency: 279 kHz, (3) Carrier frequency: 395 kHz, (4) Carrier frequency: 555 kHz, (5) Carrier frequency: 700 kHz,

The results of the bit-pattern test are presented in Fig. 4. Here, the received signals are juxtaposed with the transmitted signals. The anticipated communication bit patterns align with the transmitted signals. In Fig. 4(1), when the carrier frequency is 230 kHz, the received signal distorts within the communication channel. Additionally, the expected pattern intertwines with reflections, rendering the received signal unrecoverable. Similar observations are made across Fig. 4(3) for the 395 kHz carrier frequency, indicating its inadequacy as an information carrier. Conversely, for carrier frequencies of 279 kHz, 555 kHz, and 700 kHz (Fig. 4 (2)(4)(5)), the received bit patterns are distinguishable. Nonetheless, the round-trip reverberations intermix with the bit patterns, manifesting as prolonged reverberation tails. These effects significantly degrade the signal-to-noise ratio (SNR) and impede the performance of EMAT communication. The bit pattern analysis thus provides a concise overview of communication performance across various carrier frequencies and modulation methods. To further illuminate this, SNR calculations are conducted and compared.

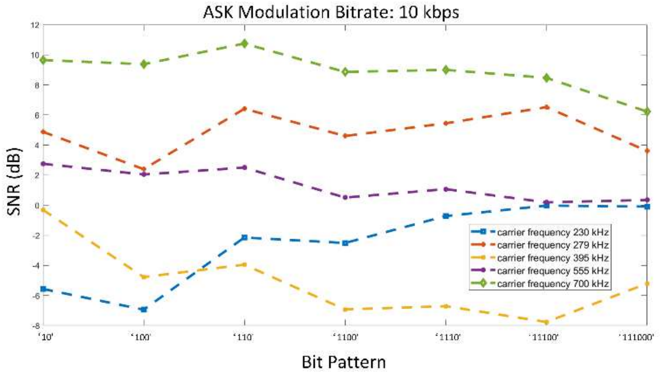

Fig. 5. SNR calculations of bit pattern analysis

Fig. 5. illustrate that the SNR scales of each bit pattern is a frequency-dependent component. Notably, the overall SNR stands out significantly with the 700 kHz carrier frequency compared to the other carrier frequencies. Additionally, the bit pattern associated with the 279 kHz carrier frequency exhibits a favorable SNR. Consequently, the 700 kHz carrier frequency emerges as the preferred choice for excitation, showcasing exceptional performance. Meanwhile, ASK modulation methods prove suitable for utilization.

V. CONCLUSION

Our study delved into the feasibility of integrating PPM-EMAT transmitters and receivers within a software-defined ultrasonic communication framework. The distinct impedance characteristics of PPM-EMAT, intricately linked to excitation frequency, play a pivotal role in optimizing energy transfer during the generation of shear horizontal waves across metal plate channels. The designed PPM-EMAT demonstrated the ability to generate various modes of SH waves through metal plate channels, accompanied by an impressive Signal-to-Noise Ratio (SNR).

In summation, the technology inherent in PPM-EMAT holds substantial promise within software-defined ultrasonic communication systems, facilitating high transmission rates and opening avenues for dynamic applications.

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