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Lamb Wave Wireless Communication in Healthy Plates Using Coherent Demodulation

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Abstract—Guided ultrasonic waves are used in Non-Destructive Testing and Structural Health Monitoring for inspection and damage detection. Recently, wireless data transmission using ultrasonic waves in solid metallic channels has gained popularity in some industrial applications such as nuclear, aerospace and smart vehicles. The idea is to find a good substitute for electromagnetic waves since they are highly attenuated near metallic components due to Faraday shielding. The proposed solution is to use ultrasonic guided waves such as Lamb waves as an information carrier due to their capability of propagation for long distances. In addition to this, valuable information about the health of the structure could be extracted simultaneously. In this work, the reliable frequency bandwidth for communication is extracted experimentally from dispersion curves at first. Then, an experimental platform for wireless communication using Lamb waves is described and built. After this, coherent demodulation algorithm used in telecommunications is tested for Amplitude Shift Keying, On-Off Keying and Binary Phase Shift Keying modulation techniques. Signal processing parameters such as threshold choice, number of cycles per bit and Bit Rate are optimized. Experimental results are compared based on the average bit error percentage. Results has shown high sensitivity to threshold selection for Amplitude Shift Keying and On-Off Keying techniques resulting a Bit Rate decrease. Binary Phase Shift Keying technique shows the highest stability and data rate between all tested modulation techniques

Keywords—Lamb Wave Communication, wireless communication, coherent demodulation, bit error percentage.

I. INTRODUCTION

WIRELESS communication using ultrasonic guided waves in solid metallic structures is gaining popularity recently in different industrial applications such as nuclear, aerospace and smart vehicles. In the classic wireless communication theory, the electromagnetic wave represents the modulated signal which propagates through air as physical medium to reach a receiver for demodulation and information extraction. In one hand, the use of electromagnetic waves as a carrier near metallic components is subjected to many propagation difficulties especially in the transportation industry. Faraday shielding effect [1] causes a huge attenuation during propagation and leads to signal loss at the receiver. In addition to this, the data transmission is in action next to electrical parts, therefore, it creates high electromagnetic noisy region leading also to data disruption at the receiver. Furthermore, problems like high power consumption and data security still exist and support the need to find an alternative solution for communication. In the other hand, using cable connections for data delivery is not a tactical solution for many reasons that can badly influence the industrial sectors. For example, adding extra cables in the transportation sector leads to an increase of the structure's weight, and therefore, a negative impact on the fuel consumption. Also, more cable connections will expand the design complexity causing maintenance difficulties and increases detachment accidents next to rotating and movable devices.

Due to the previous mentioned obstacles, the use of ultrasonic guided waves, such as Lamb waves, as an information carrier and metallic structures as a transmission medium becomes attractive. Those wave type are usually used for Non-Destructive Testing (NDT) and Structural Health Monitoring (SHM) applications and can propagate through long distances. For this sake, using them for communication may come up with important information about the health state of the metallic transmission channel. The problematic of wireless communication in solid metallic structures has been treated differently using various techniques. Time Reversal Pulse Position Modulation (TR-PPM) has been used to solve the problem of channel dispersion while using Lamb waves. Different communication channels has been studied such as steel pipes by [2], [3] and multiple layers of different materials by [4]. Another concept for compensating the dispersion effect inside the aluminum plates channels based on OOK modulation and cross-correlation is proposed by [5], [6] and [7]. Another concept based on Code Division Multiple Access (CDMA) from telecommunications was simulated also for communicating through aluminum plates [8], [9]. A back propagation dispersion compensation method is used before demodulating the received BPSK signal.

The objective of this work is to test and compare experimentally the coherent demodulation algorithm used in telecommunications, for amplitude and phase modulations, on a healthy aluminum plate. For this sake, an experimental setup is built for wireless communication using Lamb waves and MATLAB software is used for coherent demodulation signal processing. Experimental results of three modulation techniques are compared: On-Off Keying (OOK), Amplitude Shift Keying (ASK) and Binary Phase Shift Keying (BPSK). The comparison will be based on the Bit Error Percentage (BEP) for different Bit Rates (BRs).

The following section is going to describe the experimental platform used for communication. Section III will explain the coherent demodulation algorithm used for ASK, OOK and BPSK. The fourth section will show the experimental results for a healthy aluminum plate of 6 mm thickness. Finally,

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Section V draws a conclusion to this work.

II. ULTRASONIC LAMB WAVE COMMUNICATION EXPERIMENTAL SETUP

The experimental setup for wireless communication is built from a computer used as a signal processing and instrumentation control unit. MATLAB Graphical User Interface (GUI) is used to control an Arbitrary Waveform Generator (AWG, RIGOL DG4162) and to define the amplitude (20 V) and frequency of the modulated binary information. A 200 kHz frequency is chosen to excite only the fundamental Anti-symmetric mode A_0. This is verified experimentally using a device that calculates the two dimensional Fourier Transform. The binary information ”1101001110” is used to include various transitions between binaries and a Hamming window is applied on the signal. The number of cycles vary from 4 to 1 allowing the Bit Rate (BR) to vary from 50 to 200 kbits/s. The modulated signal excites an ultrasonic transducer (Panametrics), the acoustic wave propagates through an aluminum plate (500 x 300 x 6 mm^3) and picked up by the receiver.

The emitter and receiver are separated by a distance of 8 cm at the center and acoustic gel is used to ensure a good power transfer between the transducers and the plate to minimize the effect of boundary reflections. After this, the acoustical signal is converted back to an electrical one, amplified (Mistras) and driven to an oscilloscope (Lecroy Wavepro 960) that is connected by GPIB bus to the computer and synchronized with the AWG. Fig. 1 shows a photo of the ultrasonic Lamb wave communication experimental setup [10].

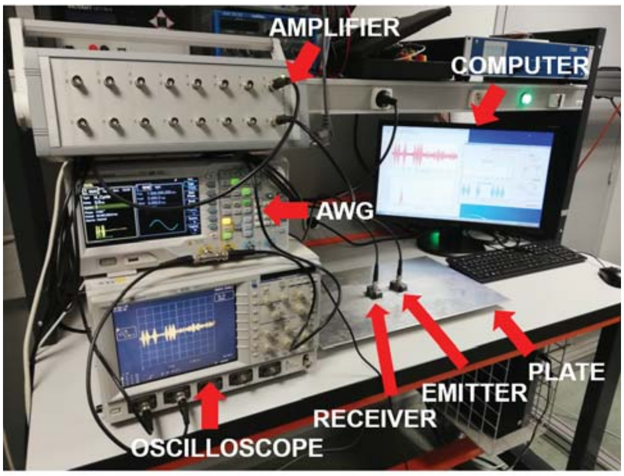
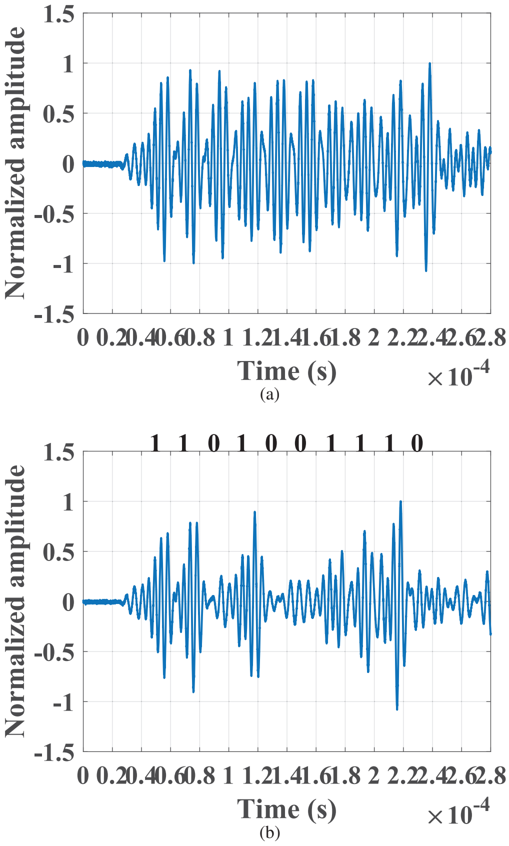


Fig. 1 Ultrasonic Lamb wave communication experimental setup

III. COHERENT DEMODULATION ALGORITHM

Coherent demodulation is the process where a synchronous carrier is mandatory at the receiver. At first and before demodulation, a continuous sinusoidal probing carrier is driven through the channel to measure the acoustic response of the aluminum plate. After this, the amplitude or phase modulated message is sent also representing the binary information. Both acquired signals are saved and denoted as $P(t)$ and $A(t)$ respectively. An example for OOK modulation for the probing sinusoidal signal and the acquired modulated one is shown in Figs. 2 (a) and (b), respectively. The Time Of Flight ($ToF = \frac{D}{C_g(f_c)}$) is eliminated for both signals before demodulation with D the distance between the emitter and receiver, $C_g(f_c)$ the group velocity at the carrier frequency 200 kHz.



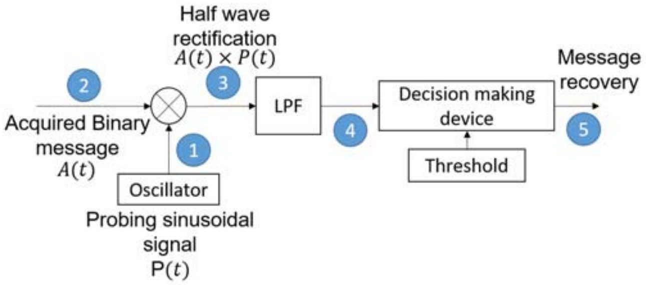
(a)

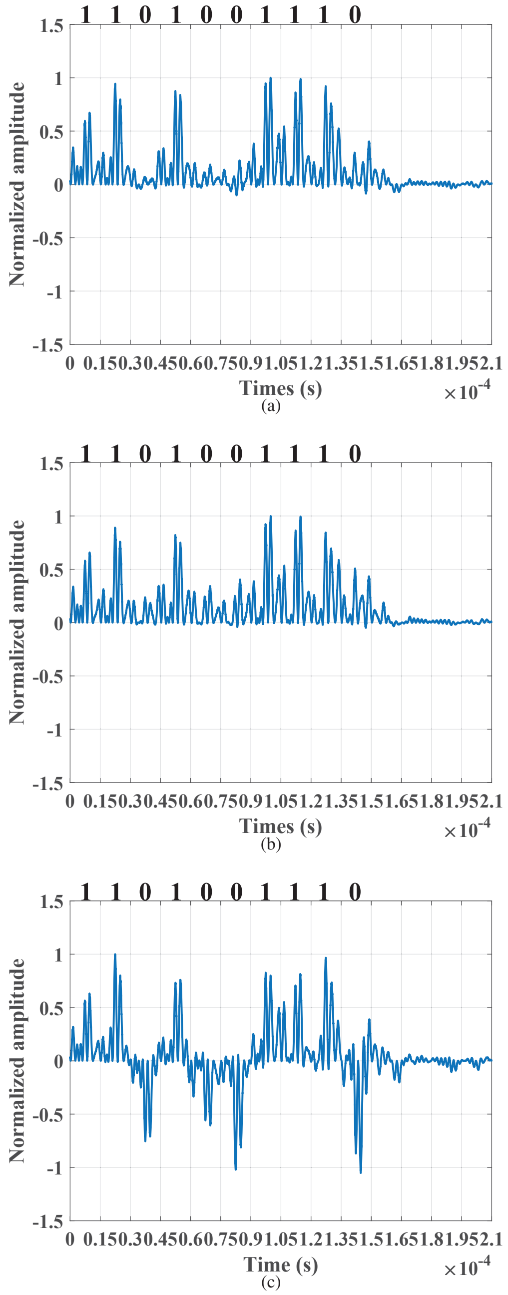
(b)

Fig. 2 (a) Probing $P(t)$ and (b) Binary modulated $A(t)$ acquired signals

Fig.3 shows the bloc diagram of coherent demodulation. In the beginning, the modulated acquired binary message $A(t)$ is multiplied by the probing acquired signal that is usually generated from an oscillator or extracted from the sender. The frequency of the oscillator is the same of the modulated carrier. After this, the half wave rectification is obtained by multiplying both signals (Step 3).

Figs. 4 (a)-(c) show the half wave rectification process of OOK, ASK and BPSK, respectively. It can be noticed that at binary zeros, a negative value is obtained in the case of BPSK due to the phase shift between binaries transition. After the multiplication, the signal is ready to enter the Low Pass Filter (LPF) which acts as an integrator. The area under the curve is calculated by integrating for each bit duration (Step 4). Finally, The decision making device will pick up a binary one for all values above the threshold and a binary zero for the ones below. The threshold is fixed at zero for BPSK and optimized for ASK and OOK as shown in the following section.





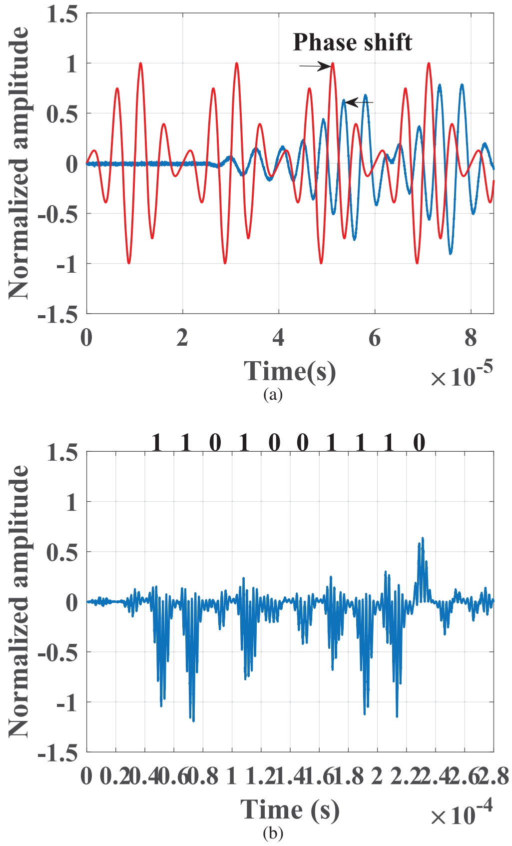
(a)

(b)

(c)

Fig. 4 (a) OOK, (b) ASK and (c) BPSK half wave rectification

Since the coherent demodulation is based on multiplying the acquired signal at the receiver by the extracted sinusoidal carrier at the sender, dispersion causes by Lamb waves may highly affect the results. An example of phase shift and its effect on demodulation is shown in Figs. 5 (a) and (b), respectively. The red curve represents the Hamming windowed 4 cycles tone burst extracted from the sender and the blue curve the acquired signal after traveling 8 cm at the receiver. It could be seen while zooming in figure 5a that a phase shift caused by dispersion will affect the multiplication process and changes the results of demodulation.



(a)

(b)

Fig. 5 (a) Phase shift between the carrier wave and the message signal and (b) the demodulated phase shifted results

IV. EXPERIMENTAL RESULTS

A. *OOK and ASK*

Experimental results for OOK and ASK coherent demodulation for the healthy 6 mm aluminum plate are shown in Figs. 6 (a) and (b) respectively. The multiplication of the acquired sinusoidal carrier transmitted through the channel, and the binary acquired message at the receiver gives a high positive amplitude for binary one and barely zero amplitude for binary zero. The threshold is increasing from 0 to 0.7 with a step of 0.01 for each BR. For OOK, the total average Bit Error Percentage BEP is calculated to be 31.91% showing a high sensitivity of the threshold choice. This value can be minimized if only taking into account values below 0.35. This value is considered since the decision making device can only fully recover few cases above. The highest BR reached is

133.33 kbits/s. Since the OOK is an amplitude modulation technique, the phase shift compensation helps to improve the demodulated signal quality but cannot be considered as a fully dispersion compensation method since the amplitude variation still exists and affects the quality of signal recovery.

For ASK, the total average BEP is 35.64% which slightly higher than the same case for OOK. Both maps highly resemble due to phase shift compensation applied during demodulation. Regions with zero error are reduced due to the presence of a non-zero small amplitude for binary zeros. All values above 0.4 can be neglected for a better average BEP. The highest BR reached is also 133.33 kbits/s. It can be noticed that higher amplitude values are obtained for the blue curve representing ASK for binary zeros time interval. Therefore, the threshold choice became more critical in this case which is the main reason of the increase of the average total BEP.

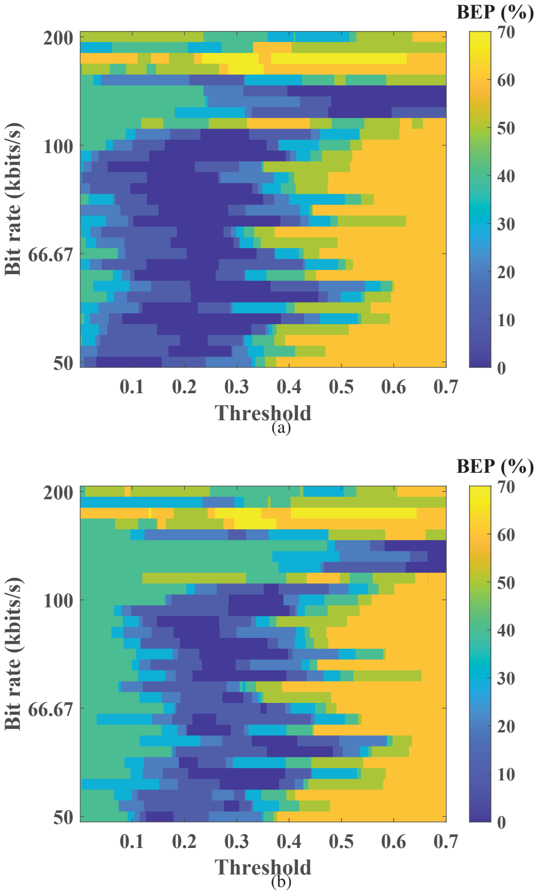


Fig. 6 (a) OOK and (b) ASK coherent demodulation results

B. BPSK

The same coherent algorithm used for ASK and OOK is repeated for BPSK. The only difference is within the threshold choice which is fixed at zero. It is important to mention that the BPSK technique depends on the phase change for binary detection. Therefore, the phase shift compensation is highly useful combined with this technique and may give promising results. Furthermore, the gap between a normalized negative and a positive value is much bigger than the gap between two positive ones. After multiplication positive amplitude values correspond to binary one and those negative to binary zero. This technique shows a high stability in terms of threshold choice since the comparison is applied only relative to the zero value. The average BEP calculated is 3.87% giving the best result between all previous cases. The average BER is very low in this case since a phase shift dispersion method is applied in the algorithm and the BPSK is based only on phase shift for binary change detection. The highest BR reached is 153.85 kbits/s which is also the highest between all previous cases.

V. CONCLUSION

Experimental results of coherent demodulation for OOK, ASK and BPSK are presented in this paper. Detailed steps for demodulation are shown and described. Signal processing was based on the phase shift compensation combined with coherent demodulation to avoid phase inversion of the acquired signal caused by dispersion. This method is based on testing the acoustic channel response by driven through the channel the sinusoidal carrier wave extracted from the sender.

The Bit Error Percentage BEP is calculated for OOK and ASK to be 31.91% and 35.64% respectively. Those values show higher sensitivity of threshold choice. The highest Bit Rate BR for both cases are 133.33 kbits/s. Numerical results has shown that the threshold value is more critical in the ASK due to the present of non-zero amplitude for zero binaries.

For BPSK, the threshold value is fixed at zero for the decision making device. This unique choice gives also an important advantage in terms of time processing reduction since the threshold does not need optimization anymore. Experimental results give an average total BEP of 3.87% and a maximum BR of 153.85 kbits/s which is the best between all previous cases.

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