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## Wireless communication combined damage detection using Lamb waves through healthy and damaged plates with symmetrical notches

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Ultrasonic guided waves such as Lamb waves have been widely studied in Non-Destructive Testing and Structural Health Monitoring applications for damage detection. Recently, the use of those waves in communication through solid metallic channels has gained popularity due to the huge need in some industrial sectors such as nuclear, railway, aerospace and smart vehicles. This paper aims to combine the concept of wireless communication with the damage detection while using Lamb waves through healthy and damaged aluminum plates with Symmetrical Notches. For this sake, the finite element software Elmer is used to simulate the propagation of guided waves in healthy and damaged aluminum plates with symmetrical notches having depths varying from 1 to 5 mm. The concept of wireless communication using ultrasonic guided waves combined with damage detection is launched based on two concepts. The first one is the modes separation of the first wave-packet for  $S_0$  mode selection. The second one is the cross-correlation algorithm combined with Binary Phase Shift Keying modulation using only the  $S_0$  mode for the first binary digit. Simulated results have proven that the binary message is fully recovered simultaneously with the detection of symmetrical notches. The detection is represented as a slight linear drop in the similarity percentage while increasing the damage depth to reach a bit rate of 200 kbits/s.

## 1 Introduction

The use of ultrasonic guided waves such as Lamb waves for wireless communication through solid metallic channels has recently gained popularity in some industrial sectors. Different applications such as nuclear, aerospace, railway and smart vehicles require wireless solutions due to the attractive benefits that can be added to the system. Traditional wired connections used for information transmission, will result with an increase of the structures' weight and lead to additional power and fuel consumption. In addition to this, wires detachment accidents due to their integrity near rotating devices can be also considered as an additional maintenance problem. Wireless solutions may be also challenging for these industrial applications due to many reasons. The use of electromagnetic waves as an information carrier for wireless transmission is unlikely due to their attenuation near metallic components caused by Faraday shielding effect. Furthermore, wireless transmission problems related to power consumption, data security and interference still exist and highly decrease wireless communication efficiency. Ultrasonic guided waves seems to be a good candidate to replace electromagnetic waves as an information carrier since it can propagate through long distances in metallic structures like plates. Furthermore, since those waves are used in Non-Destructive Testing (NDT) and Structural Health Monitoring (SHM), they can provide interesting and important information about the health of the structure. Despite off the benefits that can be added to the system, the use of Lamb waves for communication is challenging. Those waves are dispersive, reverberate and scatters while propagating in the structure [1]. Therefore, they require special signal processing treatments to be used for telecommunication applications.

Wireless communication using ultrasonic guided waves in solid structures has been proposed at first during the first decade of this century [2–6]. Primerano et al. proposed an echo cancellation algorithm based on pre-distortion filtering for transmitting digital data through metal barriers. Pulse Amplitude Modulation (PAM) was used for coding the desired information [7, 8]. After this, a Time Reversal-Pulse

Position Modulation (TR-PPM) has been proposed by Jin et al. [9, 10] to solve the dispersion problem of Lamb waves that affects the wireless data transmission. Steel pipes are used as communication channels opening new boundaries for new industrial applications. The same method has been used by Mirajez et al. [11] and Trane et al. [12, 13] using sub-oil rigs steel tubes and a corrosion resistant multi-wire as communication channels, respectively. Another concept for wireless communication based on cross-correlation from signal processing for dispersion effect compensation has been proposed by Kexel et al. [14, 15] and Moll et al. [16] using On-Off Keying (OOK) modulation for aluminum plates structures. Peaks in the cross-correlation between the signal measuring the acoustic response of the channel and the multi-bit sequence indicate the similarity and are considered as binary ones digits during demodulation. Another concept based on Code Division Multiple Access (CDMA) and dispersion compensation was simulated for multiple transducers using Binary Phase Shift Keying (BPSK) modulation [17, 18].

Few and recent publications has treated the same problematic of this paper to use ultrasonic guided waves for wireless communication and damage detection simultaneously. Mälzer et al. [19] uses an aluminum plate channel for communication and inspection. Two frequency ranges are used, one for inspection and the other for communication. High frequencies (between 400 and 616 kHz) are used for communication and low frequencies (between 70 and 180 kHz) are used for inspection. A network of distributed nodes is used to maximize the inspected area and communicate the health state to the processing unit in the form of a Damage Indicator (DI). This parameter is calculated as a standardized Root-Mean-Square-Deviation (RMSD) based on the difference between two data measured successively. Another publication by Zonzini et al. [20] uses Direct Spread Spectrum (DSS) modulation based on CDMA multiplexing technique in a metal beam to ensure communication and channel inspection simultaneously.

This work aims to study the feasibility of using Lamb waves for wireless communication and damage detection simultaneously through healthy and damaged

aluminum plates with Symmetrical Notches (*SN*). A finite element simulation using Elmer software is used to simulate the propagation of Lamb waves in healthy and damaged transmission channels. At first, the finite element simulation setup is shown for the healthy and damaged plates with a symmetrical depth increase from 1 to 5 mm. Then, a wireless communication concept based on BPSK modulation technique and cross-correlation is introduced and validated as well.

The novelty of this paper is with the simultaneous communication and damage detection concept considering the reference case as the healthy state of the aluminum plate using one fundamental mode. It is based on modes separation of the first wave-packet for selecting the  $S_0$  mode using arithmetic operations. The choice falls for the symmetric fundamental mode since it is less dispersive. The data packet is decomposed into inspection and communication binaries. The first digit is considered for inspection separated by a time space of the remaining binaries used for communication. The comparison between *SN* plates with different depth is based on the first binary similarity percentage comparison with respect to the healthy state of the plate.

This paper is divided into four sections. Section 2 presents the finite element setup of the healthy and damaged plates with the geometries, meshing and parameters. The description of the wireless communication concept based on BPSK modulation and cross-correlation is given. Results for the healthy and damaged plates with *SN* varying from 1 to 5 mm are shown as well. Section 3 combines the communication and damage detection while decomposing the data-packet into inspection and communication binaries. Modes separation of the first wave-packet as well as the comparison of the similarity percentage with respect to healthy state of the plate are shown. Finally section 4 draws a conclusion to this work.

## 2 Simulation of Lamb waves for wireless communication

### 2.1 Finite element simulation

A finite element simulation is used to simulate in 2D the propagation of Lamb waves through healthy and damaged aluminum plates. Gmsh and Elmer software are used for meshing and computations, respectively. Figure 1 show the finite element simulation model for the healthy and damaged plates.

A one cycle sinusoidal burst excited at 200 kHz frequency is used as the excitation signal  $E(y, t)$  located at  $x = 112.5$  mm following the normal direction to the plate surface. The simulated structure have a length and width of  $L = 500$  mm and  $t = 6$  mm, respectively. Gmsh software is used for the mesh of the structure and square quadratic element of 8 nodes each are taken into account for accurate

computations. Since the wavelength of the Anti-symmetric fundamental mode  $\lambda_{A_0}$  is equal to 12.08 mm at 200 kHz frequency, the elements size are chosen as  $\Delta_x = \Delta_y = 0.5$  mm to be at least four time less than the smallest wavelength generated.

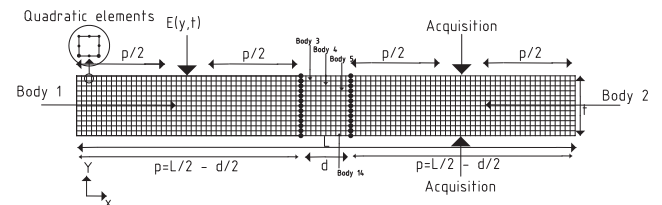


FIGURE 1 – Finite element simulation model.

The sampling frequency is equal to 10 MHz which corresponds to  $0.1 \mu\text{s}$  time step duration and the total simulation time is  $200 \mu\text{s}$ . Normal and tangential displacements are computed and saved at the top and bottom sides of the right half of the plate for each simulation.

The geometry shown in figure 1 is decomposed into 14 separated bodies. Bodies 1 and 2 are the undamaged parts in the geometry. The upper and lower acquisitions are located at the center of those bodies, respectively. The damage is introduced in the form of small bodies (Body 3 to 14) having a length  $d = 50$  mm and a thickness of 0.5 mm located at the center of the plate ( $p = 225$  mm). To simulate the healthy plate, bodies 1 to 14 are taken into account in the simulation. Otherwise, for the case of symmetrical discontinuities, one body from the upper and lower side, respectively, is removed, representing a 1 mm decrease in depth. Five damage thicknesses are tested going from 1 to 5 mm. The emission and reception are separated by a distance of 275 mm. The same sampling and excitation frequencies, mesh size, time step intervals and total propagation time are used in all simulations.

### 2.2 Cross-correlation demodulation

#### 2.2.1 Demodulation algorithm

A demodulation algorithm based on cross-correlation discussed in a previous communication by the authors is used [21]. It is based on measuring the channel impulse response of the aluminum plate since communication through damaged plates is taken into account. This algorithm uses also Binary Phase Shift Keying (BPSK) modulation scheme that consists of phase shifting by 180 degrees while passing from binary one to zero and vice versa.

To recall, a one burst sinusoidal signal is sent at first to measure the impulse response of the transmission channel at 200 kHz frequency. After this, the bit sequence is constructed

at the receiver as shown in figures 2a to c according to the BPSK modulation concept. The acquired signal of the one cycle sinusoidal burst represents the binary one digit (Figure 2a). For the following bits, the same signal is shifted in time with a period of  $\frac{1}{f_c}$  from its previous binary digit. Binary zero is represented by the inverse of this signal while keeping the same time shift (Figure 2c).

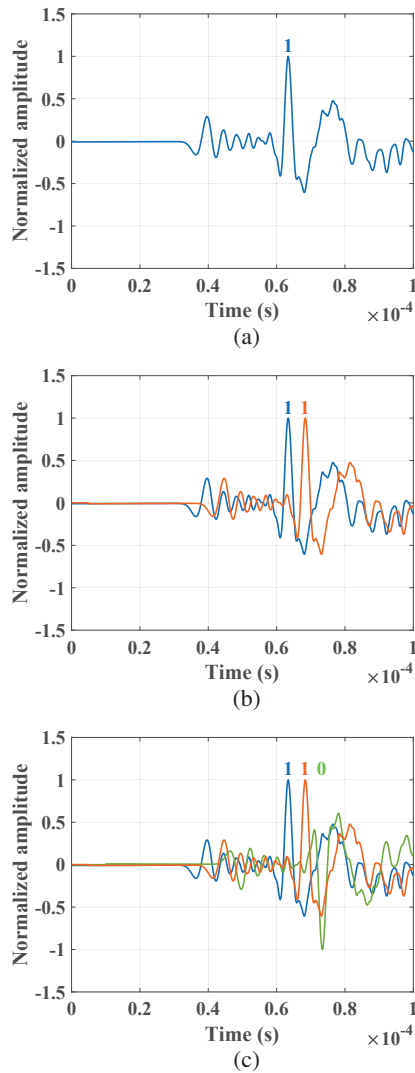


FIGURE 2 – Bit sequence construction process : (a) First bit, (b) First two bits and (c) First three bits.

A ten bits binary sequence is used since it is sufficient to represent a sensor information in binary digits. The linear characteristic allows to sum up all the previous signals shifted in time to get the correct ten bits binary sequence at the receiver. Figure 3 shows the summation result of the binary sequence "1101001110". The cross-correlation is applied between this signal and the one shown in figure 2a that measures the acoustic response of the plate. This binary construction process is repeated for each damage depth of *SN*. Positive peaks in the cross-correlation are detected as binary one values and negative peaks as binary zeros.

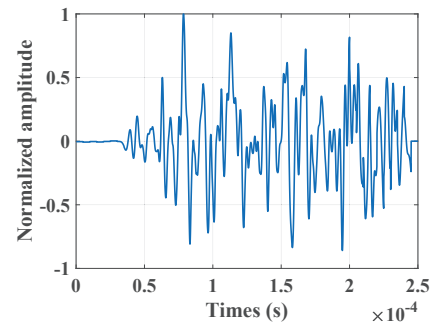


FIGURE 3 – Bit sequence construction.

### 2.2.2 Simulation results

Figures 4a and b show an example of the demodulation results for the binary sequence "1101001110" of the healthy plate and with *SN* with 5 mm notch depth, respectively. It can be noticed that the message is fully recovered even in the presence of a huge damage in the transmission channel.

To compare between the demodulated results, a reference case must be taken into account. The choice falls for the healthy plate since the propagated wave is not influenced by any discontinuity. Furthermore, separating the Lamb wave fundamental modes  $A_0$  and  $S_0$  will highly reduce the complexity of the signal processing. For this sake, the next section is going to deal with Lamb wave mode separation for wireless communication purposes to compare later on with the reference case of the healthy plate.

## 3 Combined communication and damage detection

The combined communication and damage detection is based on two concepts. The first one is the cross-correlation demodulation algorithm presented in the previous section. The second one is the fundamental Lamb mode separation that will be discussed in the following sub-section.

### 3.1 Fundamental Lamb mode separation

As mentioned previously, the normal and tangential displacements of Lamb waves are recorded at the upper and lower surfaces of the aluminum plate. In fact, the use of a simple arithmetic operation allows to double the amplitude of a selected mode or to cancel it. The summation of normal displacements of the upper and lower surfaces of the plate allows to double the amplitude of  $A_0$  (equation 1). Contrariwise, subtraction of those displacements cancels the  $A_0$  and doubles the amplitude of the  $S_0$  mode (equation 3). The same operations works for tangential displacements but



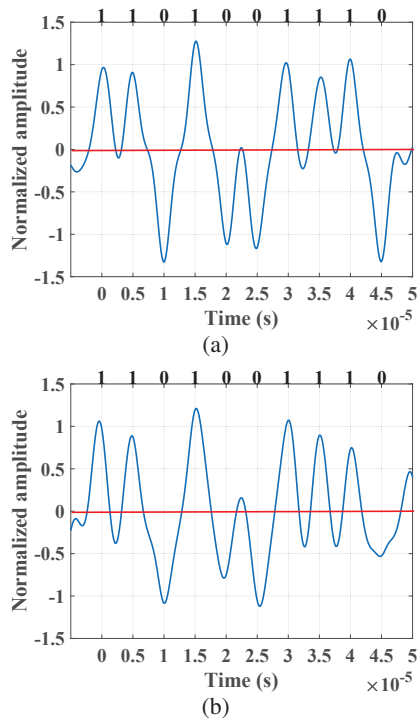


FIGURE 4 – Demodulation results for the (a) Healthy plate and (b) SN with 5 mm notch depth.

in an opposite way (equations 2 and 4) [1].

It is important to mention that those operations works only at low frequency range where  $A_0$  and  $S_0$  modes are the only ones excited. The following equations can be used for fundamental Lamb wave modes separation.

$$2U_{NA_0} = U_{N_{upp}} + U_{N_{low}} \quad (1)$$

$$2U_{TA_0} = U_{T_{upp}} - U_{T_{low}} \quad (2)$$

$$2U_{NS_0} = U_{N_{upp}} - U_{N_{low}} \quad (3)$$

$$2U_{TS_0} = U_{T_{upp}} + U_{T_{low}} \quad (4)$$

Figures 5a show the separated  $S_0$  mode for  $SN$  with damage depth varying from 1 to 5 mm, respectively. It can be noticed that there is small phase shift for the  $S_0$  mode with respect to the healthy plate. This will probably allows to use the BPSK demodulation technique with the referenced case considered as the undamaged plate without facing any problems. Those presented signals are going to act as the probing signal used to measure the acoustic response of the solid metallic channel.

Figure 5b show the  $A_0$  mode separated for  $SN$  with damage depth varying from 1 to 5 mm, respectively. A big delay in time domain is noticed while increasing the damage depth. This delay in time leads to a phase shift if

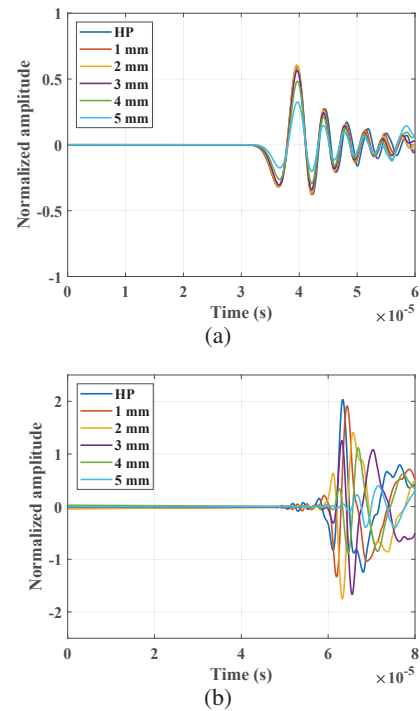


FIGURE 5 – (a)  $S_0$  and (b)  $A_0$  mode separation.

the undamaged plate is considered as the reference case and highly affects the quality of demodulation. Therefore, the binary message will be affected while compared with the undamaged state of the plate and the information will be modified at the receiver.

### 3.2 Simultaneous communication and damage detection algorithm

Figure 6 shows the demodulation combined damage detection process. At first a one burst sinusoidal wave is driven through the healthy plate to measure the channel impulse response (step 1). The modes are separated using the recordings at points A and B and the  $S_0$  mode is selected (step 2). This measurement is considered as the reference for all the following cases and saved in the data base as the undamaged state of the aluminum plate.

To simulate the presence of a damage in the transmission channel, the same one burst sinusoidal signal is driven through the damaged channel with  $SN$  (step 3). The signal is acquired and recorded as well (step 4).

After this, the binary sequence modulated using BPSK is driven through each damaged channel separately (step 5). The first binary digit is driven at first to represent the inspection binary separated by a time space of one bit period of the nine following communication binaries. The time separation between the first bit and the following is mandatory to avoid that the cross-correlated function overlaps with the following bits.

At the reception (step 6), the  $S_0$  mode is extracted from the first inspection binary only and cross-correlated with the acquired signal in step 2 to measure the similarity percentage with respect to the healthy state of the plate. The remaining part of the acquired signal after time space representing the communication binaries are demodulated by cross-correlation with the recorded signal in step 4.

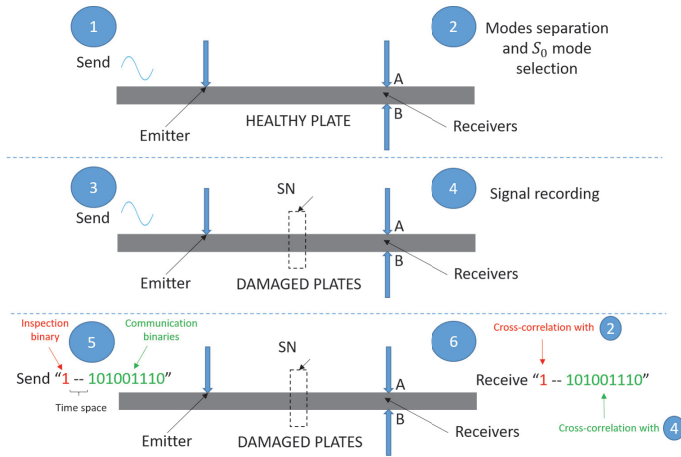


FIGURE 6 – Demodulation combined damage detection process.

### 3.3 Simulation results

Figures 7a and b show the results for the cross-correlation demodulation combined with damage detection for  $SN$  damage with depth variation from 1 to 5 mm and its zoom, respectively. It can be noticed that the similarity percentage is slightly decreasing with the increase of the damage depth from 1 to 5 mm for the inspection binary. Furthermore, the cross-correlation function shape is similar to the healthy plate since no mode conversions occurs while considering a symmetrical damage. This drop in the similarity percentage is explained in the  $SN$  due to the modification of the transmission channel.

Results have shown for the inspection binary that the percentage of similarity with respect to the healthy plate is decreasing with the increase of damage depth. The use of  $S_0$  for damage detection gives a proportional decrease in the similarity percentage with respect to the reference healthy state of the plate. A maximum detection for the first binary can easily recognize this drop and compare it with the reference case to determine whether the tested specimen is intact or damaged. For the communication binaries, the message is fully recovered.

## 4 Conclusion

This paper was concerned with the simultaneous wireless communication and damage detection using ultrasonic

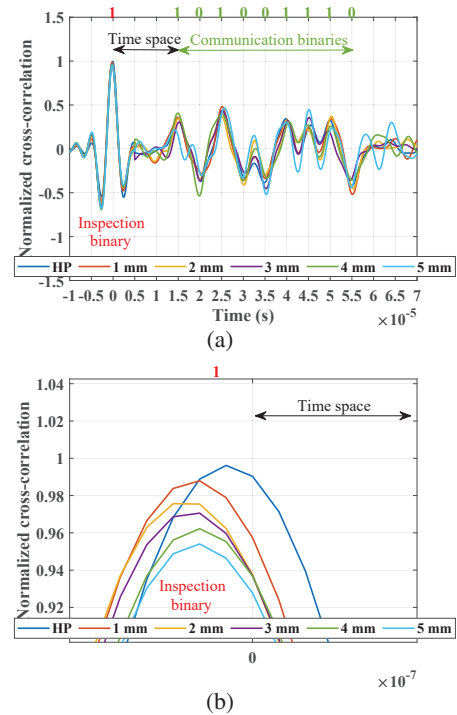


FIGURE 7 – (a)  $SN$  damage results for the communication combined damage detection and (b) the first bit zoom.

guided waves in aluminum plates. At first, a finite element model is developed for healthy and damaged aluminum plates with 500 mm long and 6 mm thick. Gmsh and Elmer are used for meshing and finite element calculations, respectively.

The demodulation algorithm based on Binary Phase Shift Keying (BPSK) and cross-correlation is presented using the simulated displacement values. Results show that the message can still be recovered even in the presence of a huge damage in the transmission channel. Therefore, the effects of multiple reflections caused by the presence of a Symmetrical Notch ( $SN$ ) is compensated.

Then, a simultaneous communication and damage detection strategy is introduced. The reference case is considered as the healthy state of the aluminum plate. The first bit driven through the channel is observed and considered as the damage inspection binary. The amplitude of the cross-correlation function normalized to the maximum of the healthy plate represents the damage detection information. Results for communication has proven that the message is fully recovered. For damage detection, the similarity percentage of the first bit with respect to the healthy state of the plate shows a proportional decrease with the increase of the damage depth.

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