Lamb Wave generation with an air-coupled piezoelectric array using square chirp excitation

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ABSTRACT
This paper describes a new inspection technique using Lamb waves induced by square chirp signals (595 kHz-890 kHz, 50Vp-p) for inspection of thin materials in a NDT system. The excitation system is based on an air-coupled ultrasonic plane array transducer with 15 active elements. A square chirp signal has been used to provide a waveform that allows pulse compression techniques, cross-correlating the received signal with a reference. The advantage of using a chirp is that being a complex coded waveform, it improves the accuracy for time of flight measurements. Moreover, the signal could be detected although the received chirp level was under the noise, because the cross-correlation improves the signal-to-noise ratio (SNR). The proposed square chirp excitation technique has been used to measure the Lamb wave propagation characteristics of 1 mm and 2 mm-thickness-aluminium plates.

INTRODUCTION
In this work a new excitation technique for an air-coupled piezoelectric array transducer is proposed. The whole system is designed to inspect on-line plate materials, such as paper, using air-coupled Lamb waves. This paper studies the use of a square chirp signals as input signal. Air coupled ultrasound allows to test and evaluate materials where couplants like water, sprayed water or gels can not be used [1], [2]. Moreover, the absence of any couplant makes easier the inspection procedures. Unfortunately, the attenuation and the insertion losses make the air-coupled ultrasound especially complicated. The ultrasound attenuation in air can be approximated as $1.64f^2(10^{-10}$ dB/m), where $f$ is the frequency in hertz [3], [4]. The insertion losses in air are so high due basically to the extremely low acoustic impedance of air (427 Rayls at 1 atm and 20 °C [4]) compared with the typical acoustic impedance of piezoelectric materials (Up to 36 MRayls). This huge mismatch makes very difficult to transfer energy from the transducer to the air and vice versa. The usual way to improve the energy transfer is to use matching layers in the transducer [5], [6]. Nevertheless, these matching layers only work properly within a reduced range of frequencies and the materials with suitable characteristics for efficient matching are difficult to obtain. There is a need to improve the signal to noise ratio (SNR) further. This paper describes a new inspection technique that can achieve this, using pulse compression with chirp signals.

Chirp signals are being introduced in the last years in medical applications to increase the resolution and penetration [7], [8]. Penetration is improved due to its greater temporal duration and resolution is improved using pulse compression technique, despite chirp signals are much longer than the standard pulsed signals. The pulse compression technique consists in correlate the received signal with a reference waveform [9].The correlation increases the signal to noise ratio and the accuracy in calculating signal delay. Moreover, this modulation scheme also leads to a side-lobe level reduction of the compressed pulses [18]. These advantages have also been used in other ultrasonic applications [10], [11] and in air-coupled ultrasonic NDT [12].
Lamb waves are dispersive and contain multiple modes. To generate only the desired Lamb wave mode is necessary a good bandwidth control [13]. When exciting dispersive Lamb waves modes, as greater bandwidth as greater the dispersion effect would be. However, the advantage of using a broadband chirp excitation is that the full air-coupled spectral response of a material with multiple resonances can be obtained simultaneously.

SIGNAL DESCRIPTION

The typical chirp signal is a linear frequency sweep of a sinusoidal signal. The equation that defines this signal is presented in Eq. (1), where \( f_1 \) and \( f_2 \) are the starting and the final frequencies respectively, and \( T \) is the duration of the pulse. The length of the chirp waveform presented in Fig. 1(A) is 20 \( \mu s \), and \( f_1 \) is at about 600 kHz and \( f_2 \) at about 900 kHz. Fig. 1(B) corresponds to the frequency spectrum of the Fig. 1(A) signal, obtained via FFT.

\[
c(t) = \sin \left( 2\pi f_1 t + \frac{\pi(f_2 - f_1)}{T} t^2 \right) ; 0 \leq t \leq T
\]  

(1)

Fig. 1: (A) Sinusoidal linear chirp with \( f_1 = 600 \) kHz, \( f_2 = 900 \) kHz and \( T = 20 \mu s \). (B) frequency spectrum of (A)

The usual way to excite an ultrasonic inspection system is using sinusoidal signals. But when working with array systems, as in our case, these signals are difficult to generate, due to their complexity and the number of channels to be implemented. We need to generate up to 15 different chirp signals at the same time. We propose to use the square chirp, a signal similar to the sinusoidal chirp that can be generated using digital techniques, which reduces the complexity of signal generation hardware [18].

Square chirp can be defined as a frequency sweep of a square-wave. Fig. 2 shows the temporal parameters of a square chirp, which are the amplitude \( V_{DD} \), the initial frequency \( f_1 \), the final frequency \( f_2 \) and the total duration \( T \).

\[
s(t) = \begin{cases} 
V_{DD} & 1/f_1 \leq t \leq 1/2f_1 \\
0 & 1/2f_1 < t < 1/f_1
\end{cases}
\]

\[
s(t) = \begin{cases} 
V_{DD} & 1/f_2 \leq t \leq 1/2f_2 \\
0 & 1/2f_2 < t < 1/f_2
\end{cases}
\]

Fig. 2: Time parameters of the square chirp signal

A FPGA seems the most feasible method to generate several square chirp signals at the same time. Being a digital system, the frequency resolution is limited by the system’s clock frequency. With a 50 MHz clock it can be generated the square chirp shown in Fig. 3 (A), with
\[ f_1 = 595.24 \text{ kHz} \] that corresponds to 42 clocks cycles, \( f_2 = 892.86 \text{ kHz} \) that corresponds to 28 clocks cycles and \( T = 21.01 \mu\text{s} \). So we form a square chirp signal of 15 pulses subtracting one clock to each period from \( 1/f_1 \) until \( 1/f_2 \). Fig. 3 (B) shows the frequency spectrum Fig. 3 (A) signal.

The main drawback of using square chirp signals are the energy losses, which are due to the energy out of the transducer bandwidth. A characteristic of the spectrum of the square chirp is its behaviour between \( f_1 \) and \( f_2 \). In contrast with the sinusoidal chirp that is flat in this band, the square chirp power spectrum decays with the frequency. This behaviour can be estimated if the square chirp is decomposed in several square pulses where the spectrum amplitude of each one depends proportionally on its temporal duration [14]. Therefore, the higher frequency periods of the square chirp have less power than the lower frequency ones.

\[ \begin{align*}
\text{Fig. 3: (A) Square chirp with } V_{DD} &= 1, f_1 = 595.24 \text{ kHz}, f_2 = 892.86 \text{ kHz and } T = 21.01 \mu\text{s}. \\
\text{(B) frequency spectrum of (A)}
\end{align*} \]

**CHARACTERIZATION OF THE AIR-COUPLED ARRAY**

The Fig. 4 shows the experimental setup implemented to characterise the transducer response when the square chirp is used as excitation. The experimental setup consists of a square chirp generator, a linear array, a hydrophone to measure the ultrasonic field at a distance of 0.9 cm, an amplifier to condition the input signal, and an oscilloscope. The array is composed of 15 identical piezoelectric elements with an active surface area of 15 mm\(^2\) and the resonance frequency at 800 kHz. The square chirp generator drives the transducer and the signal is received by a PVDF-Z44-1500 hydrophone, from Onda Corp, with a diameter of 1.5 mm. The square chirp has 15 cycles, \( f_1 \) equal to 595 kHz, \( f_2 \) equal to 892 kHz and \( V_{DD} \) equal to 50 V. The amplifier has 57-dB gain and 5-MHz bandwidth. The amplified signal is recorded and displayed with a Tektronix TDS 2024B oscilloscope. The signal captured by the oscilloscope is shown Fig. 5. The signal envelope is clearly affected by the transducer frequency response, where the low frequency components have lower amplitude than the higher ones.

\[ \begin{align*}
\text{Fig. 4: Setup used to measure the emitted signal by the piezoelectric transducer}
\end{align*} \]
Fig. 5: Received signal using the experimental setup presented in Fig. 4, and $f_1 = 595$ kHz, $f_2 = 892$ kHz and $V_{DD} = 50$ V

LAMB WAVE GENERATION AND RECEIPTION

In this section, results obtained when square chirp waveform is used to generate Lamb waves in different aluminium plates will be presented. The block diagram of the measurement setup is presented in Fig. 6. To detect and generate the airborne waves, two air-coupled piezoelectric transducer arrays are used. The emission array is a 15-elements linear array. The Lamb waves are excited using the linear array characterized in the previous section. Received signal is detected using a concave array described in detail in [16]. The reception array has a circular concave profile with a radius of 35 mm. Concave array geometry facilitates beam-steering. Both arrays have the resonance frequency at 800 kHz.

The inspection system core is a personal computer which controls both the excitation and the reception subsystems. This computer controls the square chirp generator (an Altera EP1C20F324C7 FPGA) that excites simultaneously 15 elements of the array creating a plane wave front. The airborne wave impacts in the aluminium plate and generates a Lamb wave. The plate vibration generates airborne ultrasonic waves that are detected by the piezoelectric elements of the reception array. The signal generated by each element is amplified by a 10-MHz bandwidth and 80-dB gain custom-made amplifier [17]. The amplified signals are acquired by an analog-to-digital board Gage Compuscope 12100 (PCI 12 bit, 100 Msps). A 32 to 1 custom-made analog multiplexer board controlled by the personal computer is used to select the output signal of the element to be acquired. Recorded signals are processed by the personal computer. Afterwards, once the signal is processed, the pulse compression technique is applied.

Fig. 6: Block diagram of the measurement setup used to generate Lamb waves
Aluminium plates of 1 and 2 mm were measured to evaluate the usefulness of using square chirp signals to generate Lamb waves. This material has been chosen for its well-known mechanical properties and its low attenuation.

The measurements presented in this section has been obtained using a square chirp signal consisting of 15 cycles, \( f_1 \) equal to 595 kHz, \( f_2 \) equal to 892 kHz and \( V_{DD} \) equal to 50 V. The generated Lamb wave mode in all plates is the lowest asymmetric order, A0. Fig. 7 (A) shows the acquired signal in 1-mm aluminium and Fig. 7 (B) presents the result of the pulse compression using Fig. 3 (A) signal. In the same way, Fig. 8 (A) and (B) presents the same measurements but using 2-mm aluminium plate. Table 1 presents the signal-to-noise ratio of the received Lamb waves and the obtained pulse compression signals. No average was used to obtain these measurements.

<table>
<thead>
<tr>
<th>Material</th>
<th>Not compressed signal SNR (dB)</th>
<th>Compressed signal SNR (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mm aluminium</td>
<td>12.99</td>
<td>25.28</td>
</tr>
<tr>
<td>2 mm aluminium</td>
<td>12.26</td>
<td>26.33</td>
</tr>
</tbody>
</table>

Table 1: Results of the measurements

As can be seen in Table 1, after transmission through the system and pulse compression, the SNR of the compressed signal is more than 12 dB higher than the SNR of the received signal. This demonstrates that square chirp and compression technique can be used to improve the SNR. The figures Fig. 7 and Fig. 8 also show that the peak of the compressed signal could be use to detect the time-of-flight.
Conclusions

A square chirp signal has been used to excite air-coupled piezoelectric arrays in order to generate Lamb waves in aluminium plates. The excitation and reception have been successful generating A0 Lamb mode.

The amplitude of the excited signal are clearly modified by the transducer frequency response as can be seen in Fig. 7 (A) and Fig. 8 (A), where the amplitude of input signals was constant. The received signals contain all the frequency components corresponding to pass band of the transducer, as a result pulse compression techniques can be applied.

The measurements demonstrate that the compression pulse technique has been very useful to improve the time resolution. Additionally, square chirp and pulse compression technique has been demonstrate extremely useful to increase the signal to noise ratio, which has been increased more than 4 times (>12dB). Moreover, the use of square chirps instead of sinusoidal chirps leads to less signal generation hardware requirements. These three advantages are of great utility in air-coupled ultrasound systems, where SNR is usually poor and speed propagation calculation is important to characterize the inspected materials.

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REFERENCE