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Detecting Cracks in Isotropic Plates Using Contact Acoustic Nonlinearity

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Abstract **-** This paper investigates using second harmonic of symmetric Lamb wave (S_0) for detecting cracks in aluminum plates induced by contact acoustic nonlinearity (CAN) experimentally. The generation of nonlinear guided waves around the crack is studied in an aluminum plate. The effects of crack on generation of second harmonic of guided waves are investigated. The data is acquired in time domain and is processed using a signal processing approach consists of several applications in frequency and time-frequency domain. The results show that crack induces CAN which can be observed in form of higher harmonic of guided waves in frequency and time-frequency domain. Also it is shown that crack induces wave distortion with small magnitudes which can be observed in time domain data. However, the magnitude of wave distortion is not large enough to confirm the existence of crack in aluminum plates. The results show that nonlinear wave technique does not require base line data and can successfully detect cracks in aluminum plates.

Keywords**:** symmetric Lamb wave, contact acoustic nonlinearity, damage detection

1. Introduction

Nowadays, plates are widely used in several engineering structures such as aircrafts, buildings, bridges, and cars. However, plates are prone to various types of defects such as corrosion, notch and crack. These defects cause a local reduction in the stiffness and severely reduce the plate's strength and influence its serviceability. The severity of reduction in stiffness depends on the location, the nature and the extension of the damage and if left untreated it may lead to the failure of the structure. Therefore, the early perception of cracks has become a crucial task to ensure the serviceability, reliability, and integrity of engineering structures. Detecting of cracks in metallic plates has been a topic of interest for many years. Several techniques have been studied and proposed to address this issue such as ultrasonic technique, electromagnetic resonance and impedance technique. There have been a number of significant works in these fields concerning metallic plates monitoring. Among these techniques, guided waves technique has shown many advantages over the other techniques such as reliability, ability to inspect large areas, sensitivity to small damages and accessibility to different parts of the structure. Over the past few years, guided waves techniques have been successfully tested and used in various structures such as rods, beams and plates for detection of various types of damages such as notch, crack, delamination and debonding [1-4]. The guided waves techniques are practically divided into two main categories; linear guided waves and nonlinear guided waves. Linear guided waves techniques rely on linear parameters of guided waves such as wave amplitude and wave velocity and attenuation whereas the nonlinear techniques rely on nonlinear parameters of guided waves such as side bands and higher harmonics. The term nonlinear is employed to indicate that the parameters of received signal at frequencies other than the excitation frequency are investigated. Linear guided waves techniques always rely on base line data which may be affected by environmental factors such as temperature whereas nonlinear guided waves techniques usually do not require base line data and rely on nonlinear features of the wave which can provide more information due to its higher sensitivity to defects relative to linear features. However, they are much more difficult to measure because they are subtle. The nonlinear guided waves techniques have attracted many researchers and has been tested in various structures such as beams and plates in both isotropic and anisotropic materials [4-7].

The aim of this study is to investigate detecting cracks using second harmonic of S_0 Lamb wave in isotropic plates. In this study, experimentally obtained data is investigated and verified using analytical data. The sensitivity of the nonlinear guided waves at the crack is also studied. The findings of this study would provide physical insights into the linear and nonlinear Lamb wave scattering phenomena at the cracks, which are important to further advance the Lamb wave-based damage detection techniques and optimize transducer networks for damage detection. The study outcomes could further advance the nondestructive techniques for health monitoring of the structures using nonlinear Lamb wave that can benefit many industries such as oil and gas, aviation, car manufacturing and the construction disciplines.

2. Damage detection methodology

As discussed, most of linear Lamb wave techniques rely on base line data. However, this study proposes to use nonlinear features of Lamb wave such as second harmonic of guided waves (SHG) to detect the cracks, and hence, the assessment process does not require a baseline data. Since symmetric Lamb wave (S_0) has larger in-plane particle motion perpendicular to the crack sub-surfaces plane, the (S_0) Lamb wave was used as the incident wave in this study. The CAN is explained by interaction of an incident guided wave with central frequency of (f_c) with a nonlinear system. The response of the nonlinear system contains higher harmonics of Lamb wave (f_{2c}, $f_{3c}, \dots$) [8,9]. Figure 1 shows a nonlinear system. The sinusoidal wave consists of compressive and tensile parts are crossing through the nonlinear system. The nonlinear system works as a filter when interacting with the sinusoidal wave. In case of a plate with crack, when the incident wave passes through the crack only compressive part of the wave can penetrate and the tensile part is filtered as shown in Figure 1. Therefore the wave length is modified and becomes half cycle. The change in wavelength causes the frequency to change too. That's why the response of the nonlinear system will include the frequencies other than the incident wave frequency.

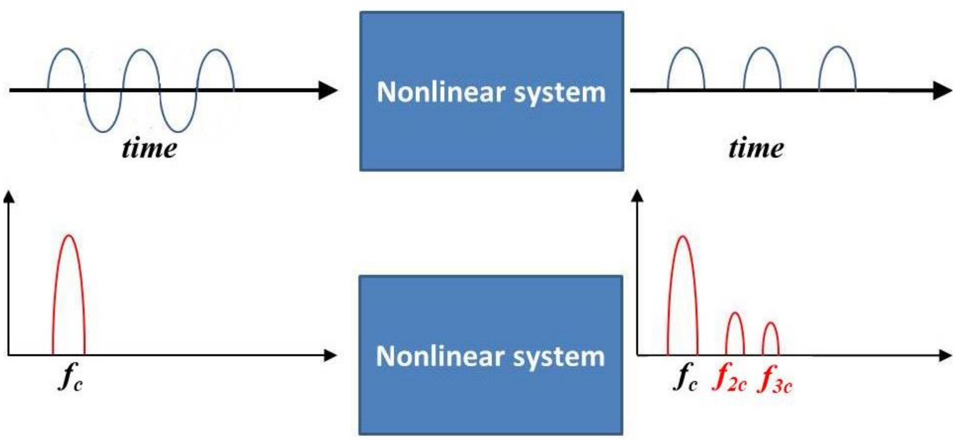

Figure 1 Modification of incident wave after interacting with a nonlinear system

2.1. Signal Processing

The application of advanced signal processing techniques, such as Fourier transform, Hilbert transform, continuous wavelet transform (CWT) and discrete wavelet transform, is an important part of damage detection using guided wave techniques. In general, these signal processing techniques have not been specifically developed for data compression; they are suitable for improving the performance of the optimization approach in damage identification [10, 11].

As discussed in previous section, in this study damage detection and scattering analysis are carried out based on detecting second harmonic of Lamb wave. Therefore, the signal processing task for second harmonic of Lamb wave will be focusing on extracting the nonlinear Lamb wave parameters from the captured data at the receptor sensors. In the present study, a combination of several signal processing approaches is used to process acquired signals. The data is acquired in time domain, Fast Fourier Transform (FFT) is applied to transform the guided wave signals from the time domain to the frequency domain and then a high pass filter is used to extract nonlinear wave data by removing unwanted frequency components.

2.2. Calculation of group velocity

The group velocity is calculated from the energy density spectrum of the guided wave signals using Eq. 1. The group velocity is defined as [12]

$$c_g(f_c) = \frac{\Delta x}{\Delta t} \tag{1}$$

where Δt is the difference of the wave packet arrival times between two measurement points. The time of arrival is determined by calculating the signal envelope using Hilbert transform.

3. Experiment

The experimental study considered an isotropic plate consists of a crack. The specimen is made up aluminum with 500 mm × 500 mm × 2.5 mm dimension and the crack is through thickness with estimated length of 17 mm located in the middle of the plate. The mechanical properties of aluminum plate are shown in Table 1. The size of the specimens is considered relatively large to avoid boundary reflections mix with reflected and transmitted wave. Two circular 20 mm diameter 6 mm thick piezoceramic transducers (transducers 1 and 2) were adhesively bonded to the surface of the plate (Figure 2). The distance between two piezoelectric is 145 mm. The transducers are located on either sides of the crack and thus are in pitch-catch configuration. Transducer 1 (T_1) is used as an actuator while transducer 2 (T_2) is used as a receiver located 50 mm away from the center of the crack.

Table 1: Material properties of the aluminum plate

Young's modulus	70 GPa
Poison ratio	0.32
Density	2700 kg/m^3

An AFG31021 Tektronix arbitrary function generator with 25 MHz Bandwidth and 250 MS/s sample rate was used to generate the excitation signal which is a narrow-band 10-cycle sinusoidal tone burst pulse modulated by a Hann window. The optimum frequency and number of cycles were obtained using trial and error. The number of cycles for excitation signal was swiped from 3 to 10 cycles while the excitation frequency was swiped from 50 kHz to 300 kHz in 5 kHz intervals to find the optimum excitation number of cycles and frequency. It was observed that excitation signal with 10 cycles at central frequency of 140 kHz provides the best signal to noise ratio, and thus, the excitation number of cycle and frequency was set to 10 cycles and 140 kHz respectively. The output voltage of function generator was set to 10 Volts peak to peak and was amplified by a PD-200, 60 watt, PiezoDrive amplifier up to 80 Volts peak to peak before it was applied to the transducer. The distortion rate was calculated to ensure that the CAN is the only source of higher harmonics in captured data. The signal was captured by transducer 2 which was connected to a Tektronix MSO44, 4 Series mixed signal oscilloscope (200 MHZ, 6.25 GS/s and 31.25 M record length) and the quality of measurement was improved by averaging the signals by 50 acquisitions. Figure 2 shows the experimental setup used in this study.

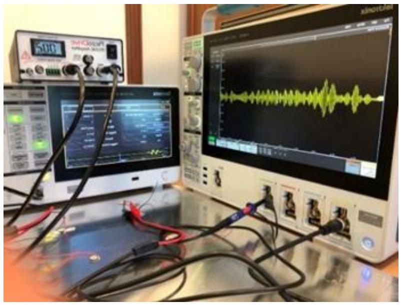

Figure 2 Experimental setup including function generator, oscilloscope, amplifier and aluminium plate

3.1. Experimental results

The data captured at T_2 was captured in time domain and was processed using the approach explained in Sec. 2.1 in frequency and time-frequency domains. Figure 3 shows captured data in frequency domain. The FFT of captured data contains central frequency (140 kHz) and the second harmonic frequency (280 kHz). The third and fourth harmonics at 420 kHz and 560 kHz also exist but can barely be seen in the figure due to their small amplitudes. However, the second harmonics in FFT graph indicates existence of defects in the plate.

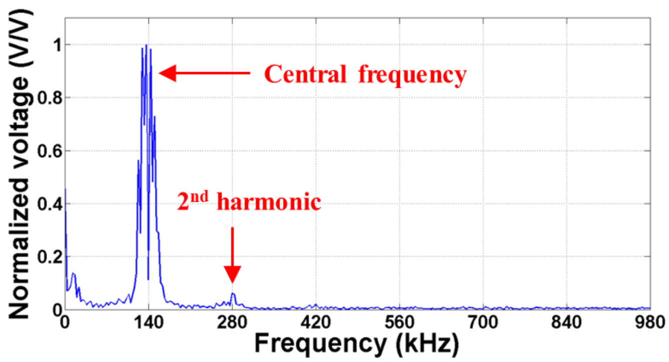

Figure 3 Experimental data captured at transducer 2 in frequency domain

Figure 4a-c shows captured data at transducer T_2 in time domain, the envelope of the signal and data in time-frequency domain using CWT for linear wave at 140 kHz frequency respectively. As can be seen in Figure 4a, the time domain data contains several wave packets and based on this, detecting reflected wave packet from crack is not possible without using a baseline data. Also, the time domain data indicates induced wave distortions with small magnitude which are barely visible and are hard to detect. However, Figure 4c and 4f provide more information regarding the frequency and the time of arrival for each wave packet. Based on these two figures, the time of arrival for linear wave with central frequency of 140 kHz is estimates as 61.2 µs by using signal envelope and the CWT of the signal. In order to verify the time of arrival obtained from the experiment, DISPERSE [7] was used for calculating the group velocity dispersion curve of the plate (Figure 5). According to calculated group velocities, the estimated time of arrival for linear wave with group velocity of 5323 m/s over a distance of 145mm (transducer 1 to transducer 2 center to center) is 62.9 µs which is in a good agreement with the time of arrival calculated from the experimental data.

Although excitation is a narrow band 10 cycle tone burst signal with central frequency of 140 kHz, the captured signal's bandwidth is wider and contains unwanted frequencies and noise. In order to get rid of the unwanted data and consequently to get a clearer signal, a high pass filtering is necessary. Therefore, the filter is applied to the frequency domain data to eliminate the unwanted data followed by an invert FFT to transform the data back to the time domain. The filtered data is presented in Figure 4d-f in time domain, signal envelope and time-frequency domain respectively. Figure 4f shows the nonlinear wave packets with second harmonic frequency of 280 kHz captured at transducer 2. The figure shows several wave packets with second harmonic frequency that attenuate over the time. The first wave packet which is the transmitted wave possesses the largest amplitude whereas the other wave packets are generated nonlinear waves due to interaction of boundary reflections with crack that arrive at transducer 2 with smaller amplitudes. The time of arrival for wave packets with second harmonic frequency was calculated using both signal envelope and the CWT as 61.3µs. This shows that both linear and nonlinear waves are mixed and propagate together. The group velocity for 280 kHz was calculated as 5230 m/s (Figure 5) which is close to the group velocity of incident wave with 140 kHz frequency calculated previously. This shows that both wave packets propagate with the same velocity and thus arrive at transducer 2 together.

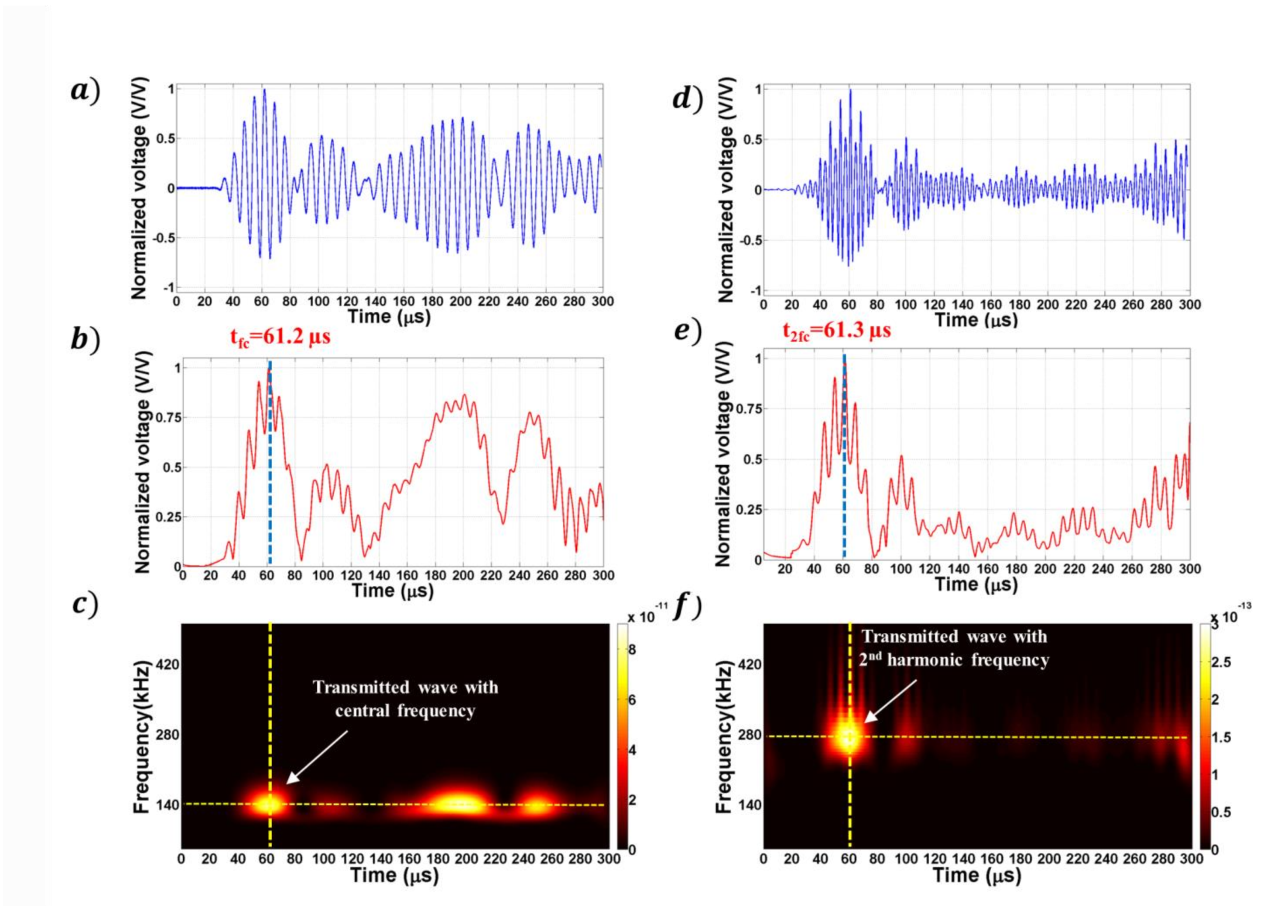

Figure 4 a) Linear wave in time domain b) Linear wave envelope c) Linear wave in time-frequency domain d) Nonlinear wave in time domain e) Nonlinear wave envelope f) Nonlinear wave in time-frequency domain

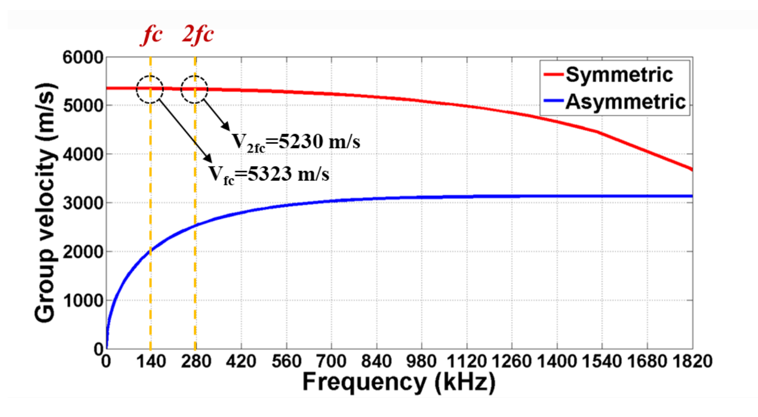

Figure 5 Group velocity dispersion curve for the plate specimen calculated by DISPERSE

The results show a strong match between the experimentally and analytically calculated time of arrival for both linear and nonlinear Lamb wave. Also the experimental result confirms the applicability of CAN and SHG for detecting the crack by proving that crack is the main source for captured second harmonics at transducer 2.

4. Conclusion

This paper studied the feasibility of using S_0 guided waves for detecting crack in isotropic plates experimentally. The guided wave propagation at the crack in aluminium plate was studied using experimentally obtained data and verified using analytical data by the means of group velocity calculation. The study found a good match between analytical time of arrival and experimental time of arrival calculated for nonlinear waves. The results show that CAN is a good indicator for existence of damage in plates. It was shown that the crack induces distortion in response of incident wave. However, the magnitudes of such distortions are very small and may not be a reliable indicator for existence of damage in plates. However the results showed higher harmonics of guided wave when acquired data was processed in frequency domain. Therefore, it is shown that nonlinear parameters of guided waves such as second harmonics are strong indicator for existence of cracks in isotropic plates.

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