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Mechanical Strain Monitoring in Plates Using Wavelet Coherence Based Filter of Wideband Ultrasonic Guided Waves

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Abstract

Time reversal or cross-correlation technique can be applied to monitoring the strain in metallic plates by observing the decrease on the time reversal signal's peak. In order to analyze the sensitivity to mechanical strain, the wavelet coherence is applied to wide band guided waves signals. A new time reversed reference signal is obtained by applying a filter based on the continuous wavelet transform. This filter removes the stationary modes, synthesizing a highly sensitive signal which is used as a reference for cross-correlations of the received signals at different strain levels. Experiments revealed that this filter led to a tenfold increase in the sensitivity to longitudinal strain.

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Keywords: strain measurement; acoustic wave guide; wavelet, time-reversal

1. Introduction

The interpretation of the ultrasonic signals is complex when the propagation occurs in mechanical structures that behave as waveguides, as the case of a simple metallic plate due to the appearance of various Lamb wave modes [1]. Moreover, Lamb waves may be dispersive, hindering the use of conventional signal processing techniques. Ultrasonic waves can also be used for strain measurement at bulk [2] or guided waves [3]. When the plate is subjected to external stress, each guided wave mode presents a different delay on the time-of-flight compared to a reference no-stress state. This delay is a function of both geometric deformation and velocity changes [4].

The most common usage of this phenomenon for strain measuring considers only single mode guided waves [3, 4]. The use of many propagation modes to measure strain becomes complicated due to the difficulty of measuring the time-of-flight shift of each mode. This analysis can be even more difficult if edge reflections are present. The use of the time-reversal technique [5], or cross correlation between the signals read at different strain condition, on Lamb

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waves can ease the strain evaluation by looking at the peak amplitude [6]. The use of the time reversal peak amplitude can be technologically easier to analyze than the propagation time-of-flight. When using a single propagation mode, there is no relevant amplitude difference and for meter-length samples the time-of-flight delay is about some nanoseconds [3], requiring high sampling rates to be detectable.

The main objective of this work is to synthesize a new reference signal to be used as a reference instead of the raw time reversed signal of the impulse response. This new signal must improve the strain sensitivity in the peak amplitude.

The wavelet coherence was used on multi-mode guided wave wideband signals in order to analyze the wavelet coefficients phase shift due to longitudinal strain. Then a continuous wavelet transform based filter was designed aiming to filter out the stationary modes, related to those wavelet coefficients that presented the lowest phase shift. The use of this filtered signal as a reference for time-reversal monitoring process increases the amplitude sensitivity.

2. Continuous wavelet transform and wavelet coherence

Wavelet transform is a common time-frequency transformation [7]. It uses a sliding and dilating window to process many bandpass filters of a desired signal. This way the signal can be represented in both time (corresponding to the sliding parameter) and scale (corresponding to the dilating parameter).

The continuous wavelet transform (CWT) of a signal, x(t), is defined as.

$$W_x(t,s) = \int_{-\infty}^{\infty} \frac{1}{\sqrt{s}} \Psi^* \left(\frac{\tau - t}{s}\right) x(\tau) d\tau \,, \tag{1}$$

where,$(\cdot)^*$ represents the complex conjugate, ψ(t) is the mother wavelet, that is dilated by the scale parameter s and translated in time by t [7]. In this work it is used the complex Morlet mother wavelet, that is often used in ultrasonic dispersion analysis [8]. The wavelet coherence (WCH) is a tool for analyzing how two signals are correlated in the time-frequency space [9]. WCH is a complex entity having unitary absolute value, its phase indicates the relative phase shift between two signals, say x(t) and y(t), in the time-scale space. It is defined as

$$WCH_{xy}(t,s) = \frac{W_x^*(t,s) W_y(t,s)}{|W_x(t,s)| |W_y(t,s)|} \,. \tag{2}$$

3. Wavelet coherence analysis and filtering of ultrasonic signal

It is considered that multi-mode Lamb waves are received for two different strain conditions, x_0 (t) at zero strain and x_ε (t) at strain ε. If the wavelet coherence is operated into these two signals, one can identify how they are correlated and the time-scale zones more affected by strain. As the predominant effect of applied strain in the propagating wave is introducing phase changes [4, 6], the phase of the WCH between these signals is analyzed aiming to detect the most sensitive wavelet coefficients to longitudinal strain. The regions in the time-scale plane that present higher wavelet coherence phase are supposed to be more sensible to strain than the regions of lower or null phase. This idea is used to design a filter in order to synthesize a signal that presents only the wavelet coefficients with high phase shift due to strain.

For the filtering procedure, it is established a threshold in the phase angle of WCH for considering the associated wavelet coefficient as phase sensitive or invariant. The filter design is organized as follows. Initially it is computed the CWT for null strain, W_{x0}(t, s) (see Fig. 1.a), and the coherence between null strain and full strain signals, WCHoε (t, s) (see Fig. 1.b). Then an angle threshold (φ) is chosen in order to build a coefficients mask, Mφ,oε (t, s). This mask is one-zero map in the time-frequency space that is responsible for filtering out the less sensible modes. Mφ,oε (t, s) is one for those coefficients whose WCHoε (t, s) angle are above the threshold and zero otherwise. The actual filtering is then performed by multiplying the mask by the original spectrum, W_{xfilt} (t, s) = Mφ,oε (t, s) × W_{x0} (t, s), allowing only the wavelet coefficients of the original signal with high phase sensitivity to be preserved. Finally the synthesized signal is addressed in time domain by the inverse continuous wavelet transform applied to the filtered spectrum (see Fig. 1.c).

This new signal is used in order to monitor the strain state in the real system. This is done by transmitting the time reversed version of the synthesized signal at the ultrasonic actuator. As the synthesized signal retains the phase of the original signal for the preserved coefficients, the received time reversal signal due to this excitation is still focused, i.e., it presents a main peak, as can be seen at Fig. 2.a. The observation of the peak amplitude is used for monitoring the strain. For the unloaded system the time reversal signal produces the best focalization, or the higher peak amplitude. As expected, when the plate is strained, the peak amplitude decreases [6]. If the synthesized signal is used as reference, it is expected a higher decrease rate than the obtained by using a non-filtered signal.

4. Experimental results

Experiments were performed in a 3-mm thick, 800-mm long and 100-mm wide aluminum plate. The plate is mounted on a bridge structure where a variable traction can be applied allowing to impose strain in the up to 150 µm/m. The actual strain value is measured by a resistive strain-gauge placed on the center of the plate. Three different experiments are conducted using 2-2 piezocomposite transducers, with 500kHz, 1MHz and 2MHz nominal frequencies, for emitting and receiving the waves. A set of these three transducers are bonded on each extremity of the plate. One set is used as emitter and the other set as receiver. A collection of received signals for the whole strain range were acquired for offline analysis and the time-reversal process was done numerically, by cross correlating the signals.

Figure 1.a. shows a signal received by the 500kHz transducer for null strain in time and frequency domain and the correspondent wavelet spectrum. The wavelet spectrum represents the time-frequency distributions of the wave-packets in a color chart where the blue color coefficients are null amplitude and the red color is the highest amplitude. The wavelet coherence between the signal at null strain (Fig. 1.a) and at 150µm/m is calculated and shown in Fig. 1.b. The zones where the phase is around zero (green color) represent the coefficients that are immune to the external strain condition, this indicates that these coefficients do not present phase difference as a function of the applied strain. On the other hand, the coefficients that show a high phase in the coherence spectrum (red or blue color) are more sensible to traction. One can observe that there are zones where the wavelet coherence phase present values away from null and reach up 180°, as show in Fig. 1.b, around the time of 320µs and the frequency of 200kHz, for example.

Figure 1.c shows the synthesized signal when using a 50° phase threshold. It is observable that this signal presents much less echoes than the raw signal, because only the echoes that have coherence phase higher than this threshold were preserved. The signal shown in Fig. 1.c is used as reference for time reversal monitoring. The time-reversal signals for null strain, using the signals of Fig. 1.a and Fig. 1.c as reference, are shown in Fig. 2.a.

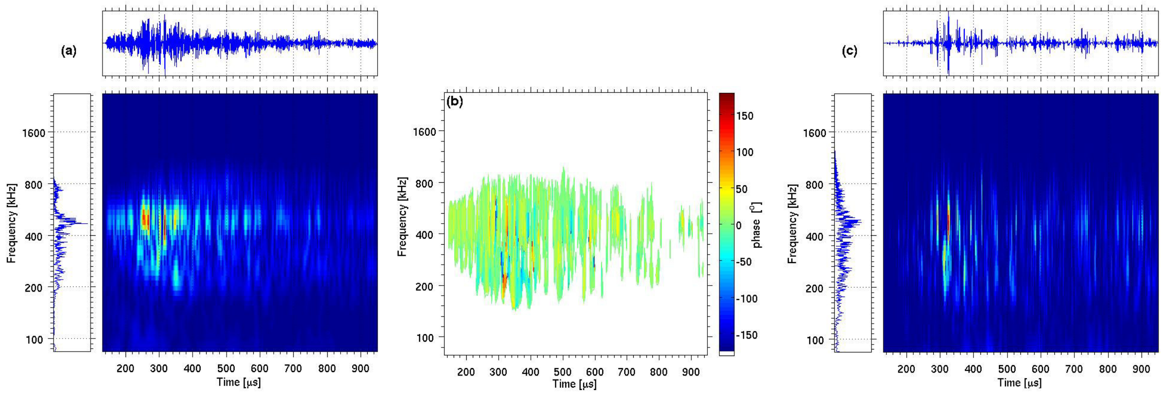

Fig. 1. Experimental spectra for 500kHz transducer. (a) Raw signal for null strain condition, top: time domain; bottom: CWT spectrum; left: Fourier transform absolute value. (b) Wavelet coherence phase between null and full strain condition. It is used a contour mask to exhibit only the phase for those coefficients whose absolute wavelet transform values are above 1/10 of the maximum. (c) Synthesized signal for 50° threshold, top: time domain; bottom: CWT spectrum; left: Fourier transform absolute value. For better interpretation, the spectra are plotted according to a frequency axis, instead of the scale of the dilated mother wavelet.

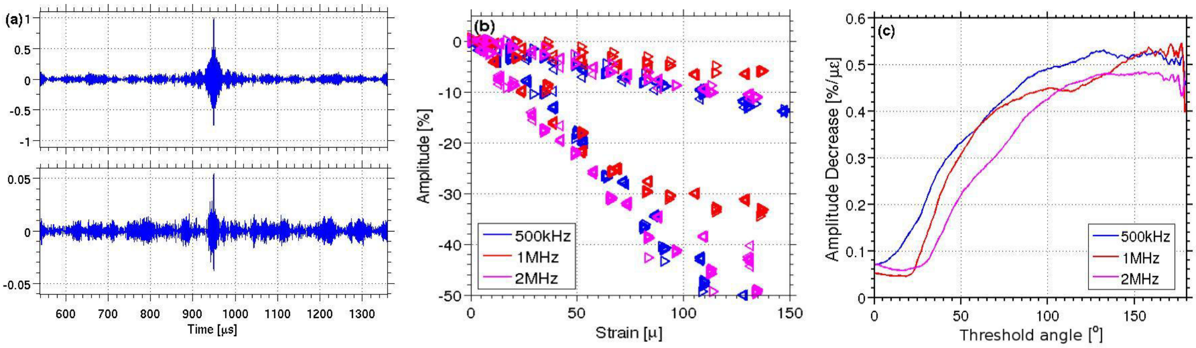

Fig. 2. (a) Focused signals at null strain state for 500kHz transducer. Top, raw signal excitation and bottom, filtered signal excitation. Scales are normalized for unitary peak. (b) Experimental peak amplitude behavior, top curves stand for raw signal excitation, bottom for filtered at 50° threshold. (c) Amplitude sensitivity versus phase threshold.

It is possible to observe that the signal shape is distorted because the reference is altered, from the raw signal (Fig. 1a) to the filtered one (Fig. 1.c)

The peak amplitude of the time reversal when using the raw and filtered signal as reference is used to monitor the strain during the tensile test. The sensitivity of amplitude to the applied strain is higher at all transducer pairs when using the synthesized signal obtained by the wavelet filter. This behavior is shown at Fig. 2.b for 50° phase threshold, where the top curves stand for the time reversal peak decrease when using the raw signal as reference, and bottom curves using the filtered signal as reference.

A threshold analysis is performed in order to observe its influence on the amplitude behavior. Figure 2.c shows the amplitude sensitivity versus threshold value. One can observe that, for the three transducer pairs, as higher the threshold angle higher the amplitude sensitivity.

5. Conclusions

The wavelet coherence analysis was used for identifying the most sensible coefficients to the longitudinal strain. A new filtering procedure based on the wavelet coherence was proposed in order to synthesize a signal that presents only the relevant spectral content. The mechanical strain sensitivity is increased using the synthesized signal obtained by the proposed wavelet filter as reference for time reversal strain monitoring.

Three transducer pairs were used with nominal frequency of 500kHz, 1MHz and 2MHz. The sensitivity using the synthesized signal as reference depends on the phase threshold. The sensitivity could be increased for all the experiments and the maximum sensitivity value obtained was about 0.5%/μ-strain, using the synthesized signals as reference, against the sensitivity of less than 0.08%/μ-strain when using the raw signal. The filtered signal of the 1MHz transducer, when using a 179° threshold, produced a sensitivity ten times higher than when using the correspondent raw signal as reference.

The methodology based on wavelet coherence filter proposed in this work showed to be useful to improve the strain sensitivity for the time reversal monitoring technique.

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