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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.

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

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

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

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).