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Wave separation: Application for arrival time detection in ultrasonic signals

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ABSTRACT

A method to detect and accurately measure the arrival time of wave packets in ultrasonic signals using a nonlinear decomposition technique is presented. We specifically address the problem of extracting events that are not well separated in the time, space and frequency domains. Analysis of complex ultrasonic signals, even those composed of poorly separated echoes, provided exceptional estimates of the desired time of arrival, from the media under investigation.

1. Introduction

The ultrasonic pitch-catch technique is one of the common tests for inspecting the quality of materials. Two piezoelectric transducers separated by a certain distance are placed on a free surface of the test object, where one transducer is used to transmit an ultrasonic pulse inside the material while the other sensor captures reflections due to differences in the acoustic impedance between two media. One goal of conducting ultrasonic tests is to measure the thickness of the material under investigation or to locate defects/objects inside the material. Typically, the equation $d = (v \times t)/2$, where v is the ultrasound speed and t is the arrival time is used to determine the distance from the transducer to the target. Thus, distance is related directly to arrival time if velocity is known.

Fig. 1 shows two signals recorded on the same test object. Tracing the signal in time, where the wave typically travels through the material, the recorded amplitude is zero or close to zero. The direct wave (one that travels near the surface of the material when the transmitting and receiving transducers are place close to each other) is usually the first one to reach the receiver as shown by the change in the amplitude in the recorded signal (in the case of Fig. 1 the first arrival time is around 45 μs). However, in ultrasonic tests, this arrival time is occasionally used to get an estimate of the wave velocity since the distance between the transducers is known. The typical ultrasonic signal is composed of multiple modes and reflections with different frequencies. In testing concrete, since the reflections from defects inside the slab are rarely well separated in time, it becomes highly problematic to identify the arrival time from the desired targets. The detection of the arrival times from multiple scatterers inside the medium has been the subject of intense research over many decades. Different methods have been proposed to decompose the recorded ultrasonic waves and measure the associated arrival times. The following is an inventory of the main techniques that have become popular among the nondestructive testing practitioners:

1. Application of the traditional quadrature-demodulation scheme to suitably extract the envelope of the main echo and locate its onset [1].
2. Correlation between input and output for high signal-to-noise ratio waveforms and L2-norm with low noise level [2].
3. Application of the square-root unscented Kalman filter (SRUKF) to identify the shape parameters of an ultrasonic echo envelope [3].
4. Application of Synthetic Aperture Focusing Technique (SAFT) where a constructive interference procedure enhances the lateral spatial resolution and signal-to-noise ratio. The arrival time is estimated from enhanced images of the interior of the medium [4].

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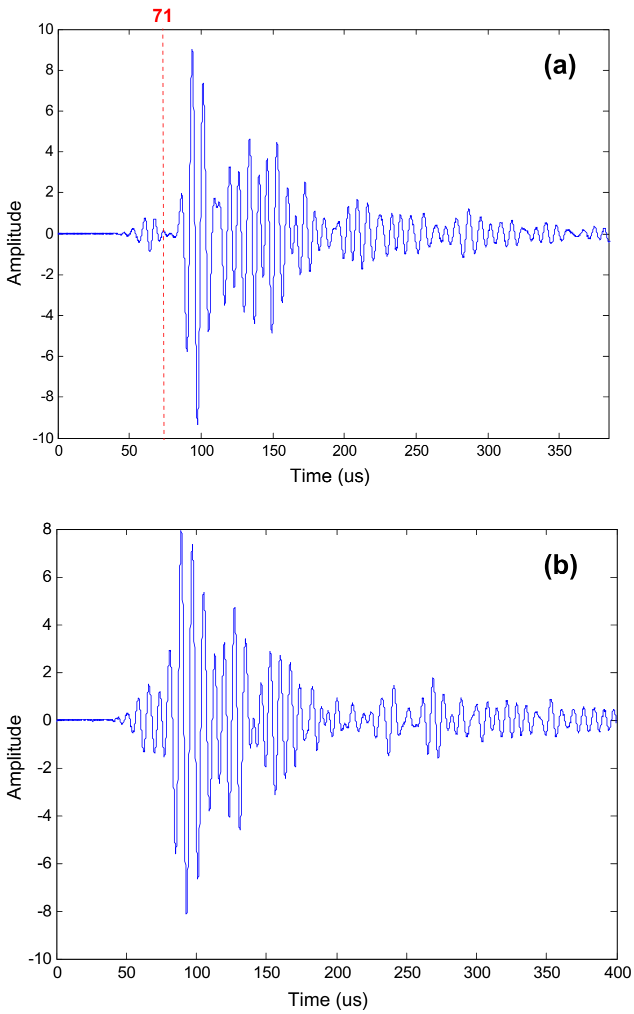

Fig. 1. (a) Well separated ultrasonic signal; (b) mixed ultrasonic signal.

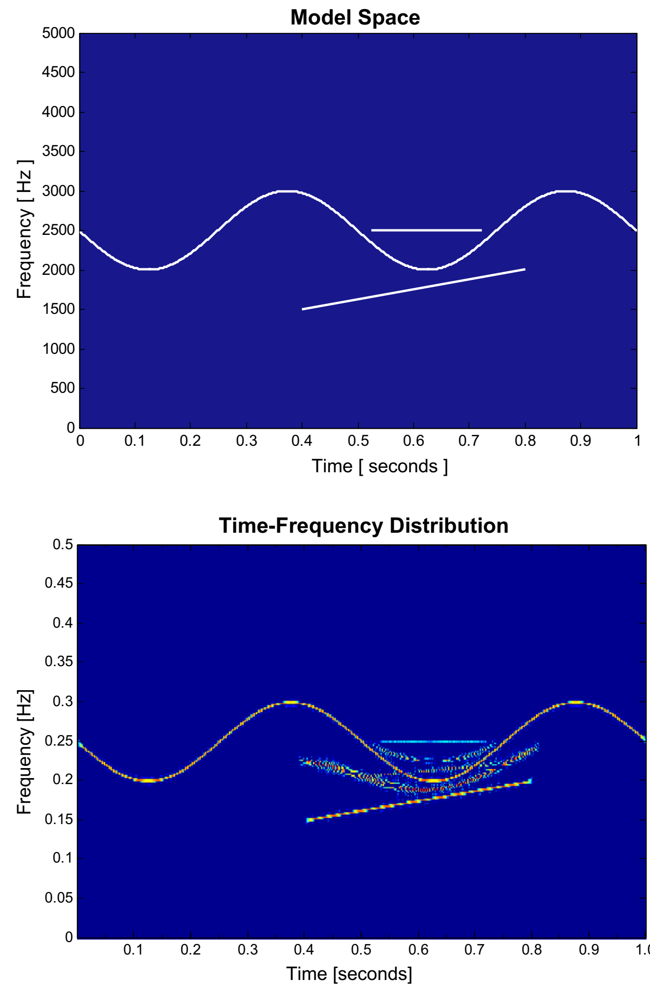

Fig. 2. Model space and the associated Wigner–Ville transform.

5. Separation of non-linear and non-stationary ultrasonic signals by means of the empirical mode decomposition method to obtain the intrinsic mode functions used for signal reconstruction. The arrival time is then obtained from the reconstructed signal [5].
6. Combination of both the improved self-interference driving technique and the optional optimization signal processing algorithms for measuring the arrival time [6].

In some ultrasonic signals, picking the first reflection (arrival time) from the desired target is an easy task since the direct wave and the main reflection are well separated in time (with little or no interference from other sources of ultrasonic scattering), and therefore can be discriminated visually. Fig. 1(a) shows a signal in which the direct wave and the main reflection are relatively well separated and the arrival time was correctly determined by visual inspection. Fig. 1(b) on the other hand, depicts a commonly encountered situation in practice where multiple waves are superimposed, turning the detection of the main reflection into a challenging problem. In these cases, signal decomposition has shown promise and is used in this study to separate the signal into different modes in order to extract the desired reflected wave pack. More specifically, the synchro-squeezed transform (SST), a new signal decomposition method, is shown to provide useful results.

Conventional time–frequency representations, such as the short-time Fourier transform (STFT), the Wigner–Ville transform (WVT), the Wavelet Transform (WT), and the Empirical Mode Decomposition (EMD) method, perform poorly when individual components of the recorded signal are not sufficiently separated in the time–frequency domain. The synchro-squeezed transform builds on the philosophy of the EMD method using a more robust theoretical foundation and employs a different approach for the construction of a signal's constituent components. In fact, synchro-squeezing can be overlaid with many commonly used time–frequency methods [7–10]. SST is a combination of the wavelet transform and reassignment technique [11].

2. Theoretical background

The simplest form of a time–frequency representation is a spectrogram created using a short-time Fourier transform (STFT). This transform employs a short-time window that limits the evaluation of the Fourier transform to some specified region along the time index. It is well-known that STFT spectrograms suffer from the time–frequency resolution trade-off, that is, a shorter window provides better resolution in the time domain, and the larger bandwidth of the window's spectrum affords a poorer resolution in the frequency domain. The Wigner–Ville transform (WVT) takes advantage of the powerful concept of match filtering, effectively employing the time-reversed copy of the signal as the window to carry out a short-time window Fourier transform. A