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Pulsed ultrasonic comb filtering effect and its applications in the measurement of sound velocity and thickness of thin plates

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ABSTRACT

An analytical and experimental study of the pulsed ultrasonic comb filtering effect is presented in this work intending to provide a fundamental tool for data analysis and phenomenon understanding in pulsed ultrasonics. The basic types of comb filter, feedforward and feedback filters, are numerically simulated and demonstrated. The characteristic features of comb filters, which include the formula for determining the locations of the spectral peaks or notches and the relationship between its temporal characteristics (relative time delay between constituent pulses) and its spectral characteristics (frequency interval between peaks or notches), are theoretically derived. To demonstrate the applicability of the comb filtering effect, it is applied to measuring the sound velocities and thickness of a thin plate sample. It is proven that the comb filtering effect based method not only is capable of accurate measurements, but also has advantages over the conventional time-of-flight based method in thin plate measurements. Furthermore, the principles developed in this study have potential applications in any pulsed ultrasonic cases where the output signal shows comb filter features.

1. Introduction

A comb filter refers to a filter whose frequency spectrum consists of a number of equally spaced elements resembling the tines of a comb [1]. As a physical tool, it has been used to improve the signal-to-noise ratio in pulsed radar systems [1], video signal transmission systems [2,3] as well as in biological signal detection [4] and speech transmission [5,6]. It has also been applied to designing gas sensors [7] and multi-wavelength fiber lasers [8–11]. In the auditory physiological and psycho-physical studies, it is even applied for generating noises [12]. As an algorithm of signal processing, its application for separating mixed signals [13], tracking slow changes in system frequencies [14,15], improving sensor performance [16] and GPS code tracking performance [17] have been investigated. The most recent research is focused on its application in optics [18], electronics [19] and photonics [20].

Within the scope of acoustics the comb filtering effect has been mostly investigated in room acoustics such as its role in the sound coloration of orchestra and opera halls [21], in musical acoustics such as its application in musical sound representation [22] and in speech acoustics such as speech enhancement [23] and pitch detection [24]. In audio engineering, the comb filtering effect, which normally results from the interference of sound with its delayed duplicates, is either deliberately avoided to eliminate undesired colored sound, or used to create flanging effects. All these acoustic investigations are performed in the low frequency regime, and to the authors' knowledge no investigation has been done in the high frequency regime such as in ultrasonics.

In ultrasonic applications, the comb filtering effect occurs in various cases such as the reflection and transmission of the pulses normally incident unto thin plates (which is studied in this work). If this effect can be well understood, it will definitely be helpful for extracting desired information from ultrasonic measurements or properly interpreting experimental observations.

The current work serves as a fundamental study of the comb filtering effect in pulsed ultrasonics. The theoretical investigation of the pulsed ultrasonic comb filtering effect starts with a numerical model of a pulse with a Gaussian spectrum. Two basic forms of comb filter, namely feedforward and feedback, are first theoretically described using a block diagram and the difference equation; and are then numerically simulated based on the defined pulse. The important features of the comb filtering effect in pulsed ultrasonics, namely the locations of spectral amplitude enhancing and reducing effects and the relationship between the temporal and spectral characteristic features, are analytically derived. Then, a special case of the feedback comb filter, in which all the pulses overlap in the time domain, is introduced to demonstrate the comb

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filtering effect in extreme situations. The pulsed ultrasonic comb filtering effect is further demonstrated experimentally based on a series of pulse-echo and through-transmission measurements on thin plate samples.

In addition to the theoretical analysis and experimental demonstration, and in order to show its practical usefulness in ultrasonics, the characteristic relationship of the comb filtering effect is applied to measuring the sound velocity and thickness of thin plate samples as the solution of a common problem in pulsed ultrasonics. For sound velocity measurement, the method based on the comb filtering effect not only is capable of simultaneously obtaining both longitudinal and shear velocities, but is even capable of doing so in cases where the conventional time-of-flight (TOF) based ultrasonic method fails in the case of very thin plates where an overlap of ultrasonic echoes occurs in addition to the inherent reduction in temporal resolution [25].

Furthermore, the same principle derived from the comb filtering effect appears even applicable to acquire thickness measurement of thin plates with high accuracy.

The rest of this paper is outlined as follows. The comb filtering effect in pulsed ultrasound is theoretically described in Section 2 and experimentally demonstrated in Section 3. Section 4 shows the application of this effect in measuring the sound velocity and thickness of thin plate samples as a case study of potential application of the study presented in this work. Section 5 provides the concluding remarks.

2. Pulsed ultrasonic comb filtering effect

There are two basic types of comb filters: feedforward filter and feedback filter [26]. In this section, we will first define an ultrasonic pulse commonly appearing in pulsed ultrasonic technology, and then numerically demonstrate these two types of comb filters in both the time domain and the frequency domain. Together with the relationship for determining the frequencies of the peaks/notches, the relationship between the time domain characteristics (relative time delay between pulses) of the output of these filters and their frequency domain characteristics (distance between the spectral peaks/notches) will be analytically derived. A special case, in which the output pulses of these filters overlap in the time domain, will also be demonstrated.

2.1. Defining a pulse

In most cases of ultrasonic testing the spectra of ultrasonic pulses are not exactly Gaussian per se, but they are to a good approximation Gaussian-like. For the convenience of theoretical analysis a Gaussian spectrum is assumed for all the ultrasonic pulses in this study. The amplitude of the Gaussian spectrum is defined as

$$A(f) = A_0 e^{-\frac{(f-f_0)^2}{2\Delta^2}} \tag{1}$$

in which A_0 is the maximum amplitude, f_0 the center frequency, and Δ the width deviation of the spectrum. An ultrasonic pulse corresponding to this spectrum is defined by the following Fourier series,

$$x(t) = \frac{1}{K} Re\left(\sum_{n=1}^{K} A_n e^{i(2\pi f_n (t-t_0)+\varphi_0)}\right) = \frac{1}{K} Re\left(\sum_{n=1}^{K} A'_n e^{i2\pi f_n t}\right) \tag{2}$$

in which $x(t)$ is the pulse waveform, K the total number of component harmonics, A_n the complex amplitude, f_n the frequency, φ_0 the pulse phase, i.e. a phase offset of all the harmonic components representing the given pulse, and t_0 is the time delay of the pulse. Unless otherwise clearly stated, in what follows, the 'amplitude' of an amplitude spectrum means the absolute value of a complex amplitude A'_n and the 'phase' of the phase spectrum refers to the angle of the complex amplitude obtained in the fast Fourier transform (FFT) calculation. An example of a Gaussian amplitude spectrum and the resultant pulse waveform as well as its phase spectrum is shown in Fig. 1. If more than one pulse is defined in one wave, their phase difference is realized by choosing a proper pulse phase φ_0 for each pulse in addition to a relative time delay t_0.

2.2. Feedforward comb filter

The block diagram and difference equation of the feedforward comb filter are shown in Fig. 2 and Eq. (3), respectively. It is easy to see that the output of this filter is a linear combination of the direct and delayed input signals. From the perspective of pulsed ultrasonics, this filter is the physical model of the reality in which a pulse is superposed onto a delayed and attenuated version of itself. The reason of delay can be either extra distance or different materials that the input pulse propagates through, or both. And the source of the attenuation can possibly be absorption, diffraction or spherical spreading loss.

$$y(n) = b_0 x(n) + b_M x(n-M) \tag{3}$$

To demonstrate the effect of this feedforward comb filter in pulsed ultrasonics, a wave containing a pulse defined in Section 2.1 and its delayed and attenuated version is assumed as shown in Fig. 3(a). Compared with the first pulse, the second pulse is delayed by 1 μs and attenuated to 80% of the amplitude. Because the second pulse is the delayed and attenuated version of the first pulse,

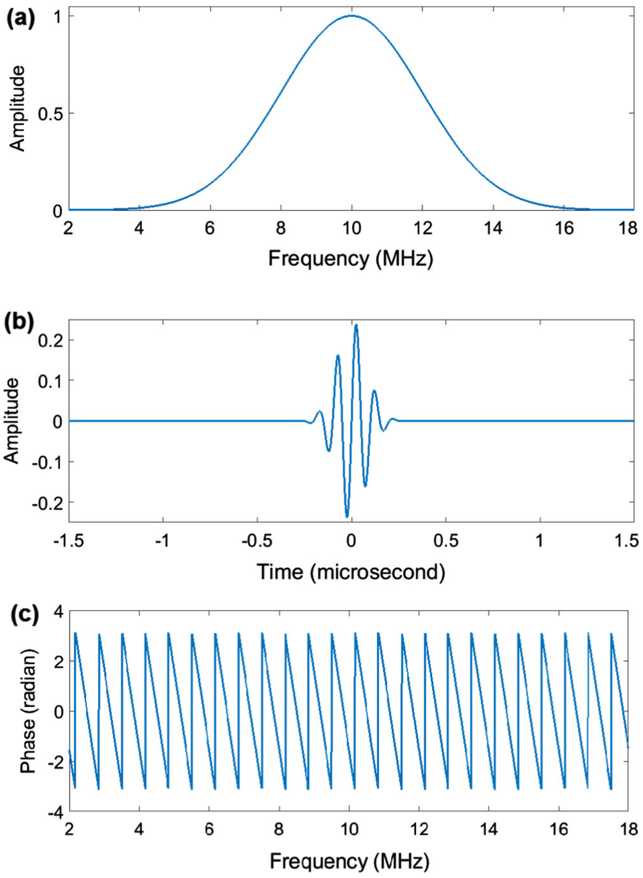

Fig. 1. (a) A Gaussian amplitude spectrum with unity maximum amplitude, center frequency of 10 MHz and width deviation of 2 MHz, (b) the resultant ultrasonic pulse defined on this spectrum and (c) the phase spectrum of the defined pulse. Zero phase offset and zero time delay are chosen for all the component harmonics in this pulse.