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Split-spectrum processing technique for SNR enhancement of ultrasonic guided wave ☆

Seyed Kamran Pedram [a,b,*], Sina Fateri [b], Lu Gan [a], Alex Haig [b], Keith Thornicroft [b]

[a] Center of Electronic System Research (CESR), Brunel University, Kingston Lane, Uxbridge, Middlesex UB8 3PH, UK
[b] TWI Ltd, Granta Park, Great Abington, Cambridge CB21 6AL, UK

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ABSTRACT

Ultrasonic guided wave (UGW) systems are broadly used in several branches of industry where the structural integrity is of concern. In those systems, signal interpretation can often be challenging due to the multi-modal and dispersive propagation of UGWs. This results in degradation of the signals in terms of signal-to-noise ratio (SNR) and spatial resolution. This paper employs the split-spectrum processing (SSP) technique in order to enhance the SNR and spatial resolution of UGW signals using the optimized filter bank parameters in real time scenario for pipe inspection. SSP technique has already been developed for other applications such as conventional ultrasonic testing for SNR enhancement. In this work, an investigation is provided to clarify the sensitivity of SSP performance to the filter bank parameter values for UGWs such as processing bandwidth, filter bandwidth, filter separation and a number of filters. As a result, the optimum values are estimated to significantly improve the SNR and spatial resolution of UGWs. The proposed method is synthetically and experimentally compared with conventional approaches employing different SSP recombination algorithms. The Polarity Thresholding (PT) and PT with Minimization (PTM) algorithms were found to be the best recombination algorithms. They substantially improved the SNR up to 36.9 dB and 38.9 dB respectively. The outcome of the work presented in this paper paves the way to enhance the reliability of UGW inspections.

1. Introduction

Long range ultrasonic testing (LRUT) is an advanced non-destructive testing (NDT) technique that employs ultrasonic guided wave (UGW) for the inspection of large complex structures such as pipes, rods, cables, and rails. This technique is widely employed for the inspection of oil and gas pipelines. It can screen long lengths of pipelines rapidly and identify defects (*e.g.*, corrosion, erosion) from a single test location [1]. UGW inspection often operates at kHz range (20–100 kHz) to transmit the waves using a ring of dry-coupled transducers around the pipes. These waves propagate within the pipe wall along the pipe's main axis and scattering (reflection and mode conversion) occurs when the waves encounter discontinuities in wall thickness. The transducers are used to record these reflections and mode conversions in order to yield information about the presence and characteristics of features of the pipe [2–4].

Relatively narrowband, short pulses (such as Hann windowed sine wave signals) are usually used for transmission in UGW inspection in order to reduce the effect of dispersion and achieve a good resolution between features. Fig. 1(a) illustrates a 50 kHz 10-cycle Hann windowed sine wave as an excitation signal and Fig. 1(b) shows its frequency spectrum. A synthesized 50 kHz received signal and its frequency spectrum containing some coherent noise are shown in Fig. 1(c) and (d) respectively. In order to minimize the effects of incoherent noise, the received signal is averaged over repeated tests [5]. A UGW response generally consists of a number of peaks that correspond to reflections from structural features under investigation, such as welds, defects, and stands.

The aim of LRUT is to generate an axisymmetric wave mode to promote non-dispersive propagation; however, the interaction of the UGWs with the non-axisymmetric features can cause mode conversion, which results in the generation of dispersive wave modes (DWMs) [6]. If a wave mode is dispersive, the different frequency components in the signal travel at different velocities so

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* Corresponding author at: TWI Ltd, Granta Park, Great Abington, Cambridge CB21 6AL, UK.

E-mail addresses: seyed.pedramrad@brunel.ac.uk (S.K. Pedram), sina.fateri@twi.co.uk (S. Fateri), lu.gan@brunel.ac.uk (L. Gan), alex.haig@twi.co.uk (A. Haig), keith.Thornicroft@twi.co.uk (K. Thornicroft).

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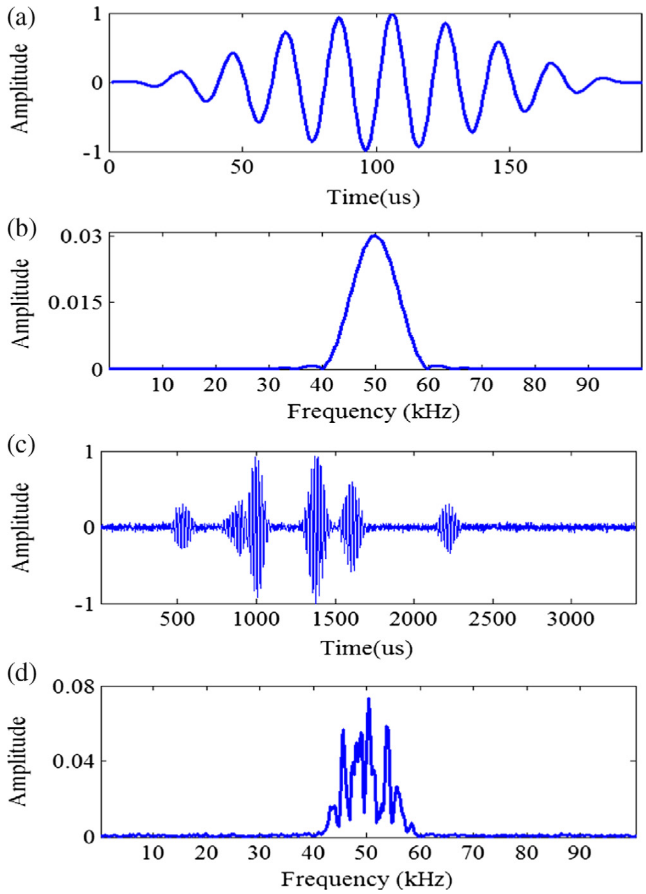

Fig. 1. UGW signal: excitation (a) time domain, (b) frequency domain signals, and received (c) time domain, (d) frequency domain signals.

the energy spreads over space during propagation that compromises the spatial resolution (the ability to distinguish echoes from closely spaced reflectors). The scattering and dispersion of multiple wave modes lead to coherent noise that reduces the sensitivity of UGW testing.

In order to increase the SNR, spatial resolution and specifically defect sensitivity, it is essential to minimize the presence of the DWMs. Dispersion is one of the main sources of the coherent noise which occupies the same bandwidth as the signal of interest as shown in Fig. 1(d). Conventional methods such as bandpass filters and averaging are unable to reduce the effect of DWMs.

Sicard et al. [7] initially studied the effect of dispersion in UGWs to compensate the dispersive behaviour of the signal. Wilcox [8] developed a technique for reversing the effect of dispersion on DWMs. The technique used knowledge of the dispersion characteristics of the wave mode to map signals from the time to the distance domain. Then it reversed the effect of dispersion on a particular wave mode and restored it to an undispersed pulse. The dispersion pre-compensation technique is performed based on the chirp technique by Lin and Zeng [9] on the narrowband excitation signals that managed to compress the time duration of received wave packet during the extracting process. Information of multiple distinct frequency ranges and responses has been extracted for a few narrowband excitations by employing the benefits of broadband chirp excitation. This method utilized a previous knowledge of the dispersion curve and the propagation distance. The dispersion compensation (DC) in multimodal cases is presented by Xu et al. [10] to estimate the plate thickness and propagation distance followed by a self-compensated technique for wave modes that were studied by employing a wideband dispersion reversal (WDR) algorithm [11]. This technique created a single wave mode packet that made the signal interpretation easier, but it was required to have the knowledge of the propagation distance in advance [12]. This was problematic when inspecting over a range of distances.

Toiyama and Hayashi [13] combined the DC algorithm with Pulse compression (PuC) methods by employing chirp waveforms. They investigated a scenario of single wave mode without introducing the quantitative SNR enhancement. Marchi et al. [14] employed a combination of warped frequency transform (WFT)-based DC algorithm with PuC to improve the localization of a steel cylindrical mass in an aluminum plate. However, this technique was tested for a simulated defect only and it was not practical, as the wavelength had to be filtered to reduce the effect of multimodal propagation. They also considered irregular waveguides using a triangular pulse excitation; however, no experimental validation was reported [15]. Yucel et al. [16,17] utilized by combining of DC with PuC employ broadband maximal length sequence (MLS) excitation to improve the SNR of the UGW response for an aluminum rod. The result indicated that the propagation distance was successfully obtained for the highly dispersive flexural wave mode but not that effective for the non-dispersive longitudinal wave mode. It has been claimed that the cross-correlation compared to DC achieves a better result when the wave modes have little dispersion. Mallet [5] considered cross-correlation and wavelet de-noising for reduction of the effect of dispersive wave modes on synthesized and experimental UGW response. It was shown that both techniques were not suitable for the reduction of coherent noise, as both methods have removed the smaller amplitudes regardless of whether or not they were signal or noise.

Split-Spectrum Processing (SSP) technique was initially developed from the frequency agility techniques used in radar [18] and then considered for SNR enhancement in NDT application such as conventional ultrasonic testing (UT) to reduce grain scatter in the UT response [19]. In particular, the SSP technique is applied to the microstructure caused scattering of the ultrasonic signal arising from large-grained materials. The grains only reflect signals with a wavelength that is similar to the grain size such that the response from the grain structure varies with frequency. It is the frequency dependence that frequency agility and later SSP exploits to enhance SNR of the signal response. The frequency agility could reduce the grain scatter in the UT signal [19], to achieve this; the signal's response is split into a set of sub-band signals that is equivalent to the employment of a frequency agility technique where a number of pulses are transmitted with different frequencies.

Karpur et al. [20] presented a theoretical basis for the selection of SSP filter bank parameters and acquired experimental results to verify it. An equation has been defined to predict the SNR enhancement by compounding a number of frequency diverse signals. However, some of these filter bank parameters obtained a larger value than expected. This could be the result of utilizing a Gaussian function for filtering because of its simplicity while the calculation was based on a Sinc function. Shankar et al. [21] considered the use of SSP technique in a number of ultrasonic NDT applications to improve the SNR of signal response. The polarity thresholding (PT) was investigated for the detection of single targets and it was shown how sensitive the SNR enhancement was to the selection of filter bank parameters. It has been mentioned that if "one edge of the plane of the defect is displaced from the other edge by more than three to four times the wavelength with respect to the direction of wave propagation", this technique could not improve the SNR [21].

Aussel [22] investigated the SSP by employing finite impulse response (FIR) filters rather than filtering in the frequency domain, utilizing discrete Fourier transforms that gave a delay, to obtain a real-time response. This method was more efficient for processing