Comparison of Time-Frequency Distributions for Pulse-Echo Ultrasonic Evaluation and Filtering

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Abstract- For a direct evaluation of ultrasonic signals it is necessary to analyse data with an acceptable level of noise. Ultrasonic signals represent a specific category of time domain signals to be analysed. In order to increase difference between the level of noise and the amplitude of the ultrasonic pulse a proper method for data differentiation has to be used. Within this article are discussed and compared two time-frequency distributions. The first approach is via wavelet transform. The second proposed method is S-transform. This transformation has been recently introduced for ultrasonic echo analyses. This tool represents intermediate stage between the Fourier transform analysis and the Wavelet transform analysis. In order to filter ultrasonic signals from Electromagnetic Acoustic transducer with a high level of noise, new, different approach was developed. The result showed complexity of the ultrasonic signal and noise in case of the Electromagnetic Acoustic Transducer. We designed the new adaptive signal processing method, which performs well on studied ultrasonic signals.

Keywords: EMAT, S-Transform, Correlation, Signal Filtering

I. Introduction

Ultrasonic waves are vibrational waves having frequency higher than the hearing range of the human ear, which is typically 20 kHz. The upper range of these waves can be as high as 15 to 30 GHz, but usually the upper bound of the frequency rarely exceeds 20 MHz. The ultrasonic inspection of a material component can be carried out in two ways: active sensing and passive sensing. For active sensing a transducer and a receiver are used in the setup. The transducer transmits the signal and the receiver receives it. If there is any damage in the volume, then the ultrasonic signal is altered by the material inhomogenity. Information about the material structure is gained after the received signal analysis. For a passive inspection no transmitters are used and only receivers are mounted on the component.

There are several possibilities how to arrange transducers on the specimen. Common modes for the transmitter and receiver placement are pulse-echo mode, pitch-catch mode, and through-transmitter mode as it is showed in Figure 1.
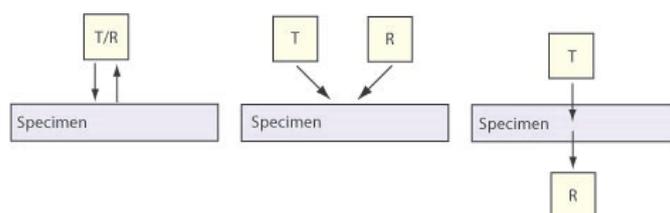

Figure 1: Common modes of transmitter-receiver arrangements

The received signal from an ultrasonic system can be displayed in four different manners known as A-scan, B-scan, C-scan and S-scan also known as Sector-scan.

The typical A-scan record is in Figure 2. This scan consists of full vibratory motion of the receiver which is a function of time for a specific location.

With B-scan the amplitude of received echoes is transformed in to the grey level. When the speed of the movement is constant, the time record corresponds to the position of the probe. With known speed of sound inside specimen, the echo time of arrival is directly proportional to the depth of the reflecting boundary. Wider and darker strip in the record represents stronger signal reflected from the back-wall. Thinner lines in Figure 2 correspond to the local crack.

When the transducer is moved in a plane parallel to specimen surface and the peak value of the received signal is plotted as a function of the transducer position, then the generated image is called C-scan. The image is based on information acquired in the region between the initial echo and the backwall echo. The peak value is plotted as a function of position.

The transducer with selectable angle of the emission could be used to generate S-scan. This method offers virtual cut through specimen. While B-scan is a function of the echo time of the arrival and the record time, S-scan plots echoes values as a function of the received time and angle. The situation is shown in Figure 2.
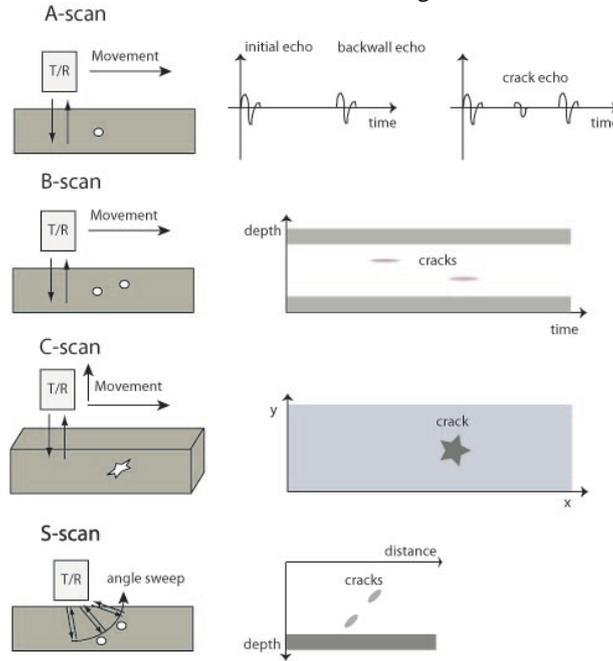
Figure 2: Schematic of A-scan, B-scan, C-scan and S-scan

All the typical ultrasonic visualisations used for the structure analysis are primarily based on the A-Scan data. Within this scope signal processing methods for one dimensional time varying signals are needed.

A. The Electro-Magnetic Acoustic Transducer

Commonly used piezoelectric transducers exhibits widely accepted drawback of a direct mechanical coupling necessary for transmission of the ultrasonic signal, information from transducer to the specimen and back. On the other hand the Electro-magnetic Acoustic Transducer (EMAT) links ultrasonic signal with the probe via changes in dynamic magnetic field and its geometrical configuration relative to the static magnetic field. The laboratory EMAT system is based on "bulk-wave" generation. The permanent magnet produces the biasing, static magnetic field normal to the surface.

There are two types of bulk waves, longitudinal waves and shear waves. When longitudinal waves propagate through an infinite medium only normal stress is generated. The propagation of shear waves generates shear stress. The wave speed of these two wave types are described by:

$$c_L = \sqrt{\frac{\lambda + 2\mu}{\rho}} = \sqrt{\frac{E(1-v)}{\rho(1+v)(1-2v)}} \tag{1}$$

$$c_S = \sqrt{\frac{\mu}{\rho}} = \sqrt{\frac{E}{2\rho(1+v)}} \tag{2}$$

where c_L is the longitudinal wave speed (m/s), c_S is the shear wave speed (m/s), ρ is the density (kg/m³), λ is the Lamé's first parameter (kg/ms²), μ is the Lamé's second parameter or the shear modulus (kg/ms²), E is the Young's modulus (kg/ms²) and v is the Poisson's ratio (-).

Electromagnetic Acoustic forces generate the longitudinal wave and the radially-polarized shear wave. The both waves are propagating in the thickness direction at the same time, for which this is called dual-mode EMAT. If the metal has an orthorhombic elastic anisotropy, due to the texture, the shear wave decomposes into two polarisations along the two principal directions [1].

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B. The Ultrasonic Signal Model

Transducers used for ultrasonic measurement works in impulse stimulation. Impulse transducer operation leads to the wide bandwidth and the factor describing this width is quality factor Q which is defined by

$$Q \doteq \frac{f_r}{f_1 - f_2} = \frac{f_r}{B} \tag{3}$$

where f_r denotes the transducer central frequency, f_1 and f_2 are side frequencies where the amplitude drop about 3 dB in compare to the central frequency and B denotes the bandwidth [2].

Ultrasonic damped oscillations are expressed by

$$a = Ae^{-\beta t} \sin \omega_r t, \tag{4}$$

where $\beta = \omega_r / 2Q$ is the damping factor.

For the pulse ultrasonic evaluation it is required a good resolution with an acceptable sensitivity. Equation 3 denotes contradiction of those requirements. The optimal signal processing transform has to follow the optimal model described by Equation 4 with the discrimination of noise and the ultrasonic pulses.

Following paragraphs will describe Wavelet and Fourier based transforms for time-frequency processing in order to increase the contrast within the ultrasonic signal.

II. Signal Filtering

A. Ultrasonic Digital Filters

The search for an optimal tool for suppressing embedded noise in the ultrasonic evaluation can be traced to [3]. Bilgutay et. al used set of digital filters to split signal and they designed a non-linear technique to reconstruct filtered signal in the time domain. Hoess et. al used Wiener filter to process the signal in frequency domain [4]. After introduction of the Wavelets [5], Wavelet based signal processing improves signal to noise ratio of the ultrasonic signal[6, 7]. We identified two movements in the improvement of the ultrasonic measurement signal to noise ratio. The first one is an introduction of a novel transformation and the second one is invention of a signal processing algorithm suitable for the ultrasonic application and the novel transformation.

B. The Fourier Family Analysis

The Fourier Transform (FT) describes a signal in terms of complex sinusoids series, with varying amplitude and phase. Ultrasonic pulsed signal can be according to Equation 4 described by sinusoid. The sinusoidal basis functions of the Fourier Transform are purely periodic and infinite in extent, and the FT converts entirely signal between the time and the frequency domain, with no direct temporal information remaining after the transform. This represents for ultrasonic pulses imperfect approximation in spite of general recognition of the FT analysis. To allow examination of non-stationary signals, a number of solutions have been proposed, including the Short-Time Fourier Transform (STFT) and more recently the S-Transform (ST). ST is an extension of the STFT which uses frequency-dependent scaling windows in analogy to the Wavelet transform. STFT can use any window function [8] but ST uses Gaussian window which achieves the optimal time and the frequency resolution. The ST of the time signal a(t) is defined in [9] as

$$S(\tau, \upsilon) = \int_{-\infty}^{+\infty} a(t) \frac{|\upsilon|}{\sqrt{2\pi}} e^{-\frac{(\tau-t)^2 \upsilon^2}{2}} e^{-2\pi \upsilon t} dt \tag{5}$$

where τ and υ are the transform time and frequency coordinates.

Equation 5 has the sane form as FT equation, but adds a normalized-area Gaussian window for time localization. The υ parameter causes decrease of the window width with the increasing frequency. This automatically adjust the ST window to provide a progressive trade-off between the time and the frequency resolution for the each frequency, with the improved frequency resolution at low frequencies and better time resolution at high frequencies in compare to FT. Like FT, ST produces a complex spectrum that includes both the frequency and globally referenced phase information [10, 11].

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C. The Wavelet Family Analysis

Wavelets are functions that are used to represent temporal processes. Ultrasonic pulsed signals are usually time and frequency limited. For this reason, the utilization of time-frequency Wavelet analysis was already evaluated [12].
If Wavelet has properties of the compact or the approximate compact support in the time and the frequency domain, it can be treated as a band-pass filter. A bank of band pass filters called Wavelet packets can be obtained with signal processing on different central frequencies and bandwidths by compressing / dilating and shifting a mother wavelet.

Suppose $\varphi(t)$ is an arbitrary mother wavelet, its central frequency and frequency resolution are expressed as

$$w_0 = \frac{\int_{-\infty}^{+\infty} w|\psi|^2 dw}{\int_{-\infty}^{+\infty} |\psi|^2 dw} \tag{6}$$

$$\Delta w = \left(\frac{\int_{-\infty}^{+\infty} (w - w_0)^2 |\psi|^2 dw}{\int_{-\infty}^{+\infty} |\psi|^2 dw} \right) \tag{7}$$

where $\psi(w)$ is the FT of the mother wavelet $\varphi(t)$, $w=2\pi f$ is the angular frequency, w_0 is central frequency of the mother wavelet.
We can define a frequency window of the mother wavelet as: $[w_0-\Delta w/2, w_0+\Delta w/2]$ and with this range is defined band pass region.

D. Correlation Detection

The basic physical observation model that we wish to consider is that of an observed continuous-time waveform that consists of two possible signals ultrasonic echo and noise. Our objective is to decide which of the two possible signals is present, and we wish to do so by processing a finite number (say n) of samples taken from the observed waveform.
This problem can be modelled statistically by the following hypothesis pair for the observed space:

$$H_0: y_i=r_i, \ i=1,2, \dots , n \tag{8}$$

versus

$$H_1: y_i=r_i + s_i, \ i=1,2, \dots , n, \tag{9}$$

where $y = (y_1, \dots , y_n)$ is an observation vector consisting of the samples from the observed waveform, $r = (r_1, \dots , r_n)$ is a vector of noise samples, and $s = (s_1, \dots , s_n)$ is a vector of samples from the possible signal. We are actually trying to detect a signal embedded in noise. For this purpose of this treatment we will assume that noise is independent of the signal under the each hypothesis and that its probability distribution does not depend on which hypothesis is true. This assumption is valid if we assume that the noise part caused by the spurious signal reflection from material boundaries can be neglected.

Optimum procedure for deciding between H_0 and H_1 can be derived if we have models for the statistical behavior of the ultrasonic signal and noise. According to [8] the signal s is classified as one of three basic types. The signal can be completely known (deterministic), it can be known except for a set of unknown (random) parameters, or it can be completely random and thus specified only by their probability distributions.

Suppose that the noise samples $r_1, \dots , r_n$ are independent and identically distributed (i.i.d.) with marginal distribution $N(0,\sigma^2)$ presented in Figure 3b. The structure depicted in Figure 3 is known as a correlation detector or the correlator. This optimum detector can be viewed as a system that inputs the observation sequence $y_1, \dots, y_n$ to a digital linear filter and then samples the output at time n for comparison to a threshold [13].
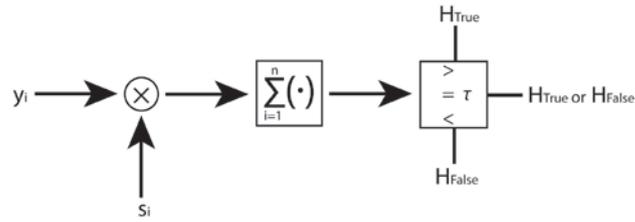
Figure 3: Optimum detector for coherent signals i.i.d. noise

E. Correlation-ST Filtering Algorithm

Preceding signal processing work focused on ultrasonic echo extraction from the signal where the echo has the amplitude smaller than is the noise level failed [14]. Signal processing methods based on ST were studied [15, 16]. The conclusion led to the design of a new signal filtering algorithm. The new Correlation-ST filtering algorithm uses the combined approach from the time and time-frequency domain. The digital filter modifies the signal in the frequency domain by multiplication of the signal and filter frequency characteristic. The Correlation-ST filter modifies the signal in the ST domain by multiplication of the signal and correlation filter time domain characteristic. The S-domain adjusting process is expressed in hypothesis testing as:

$$H = 1 \approx H_{True} \rightarrow c(t,f) \rightarrow c_f(t_i,:) \ = 10 \cdot c(t_i,:), \tag{10}$$

$$H = 0 \approx H_{False} \rightarrow c(t,f) \rightarrow c_f(t_i,:) \ = \ c(t_i,:) \ / \ 10. \tag{11}$$

where $c(t,f)$ denotes ST coefficients described by the time (t) and the frequency (f) location. The detector hypothesis is applied on the transformed signal by the multiplication and adjusted coefficients are transformed back to the time domain via inverse ST.

III. Results

The example of the measured and processed ultrasonic signal is presented in Figure 4. The signal decomposition with ST is in Figure 5.
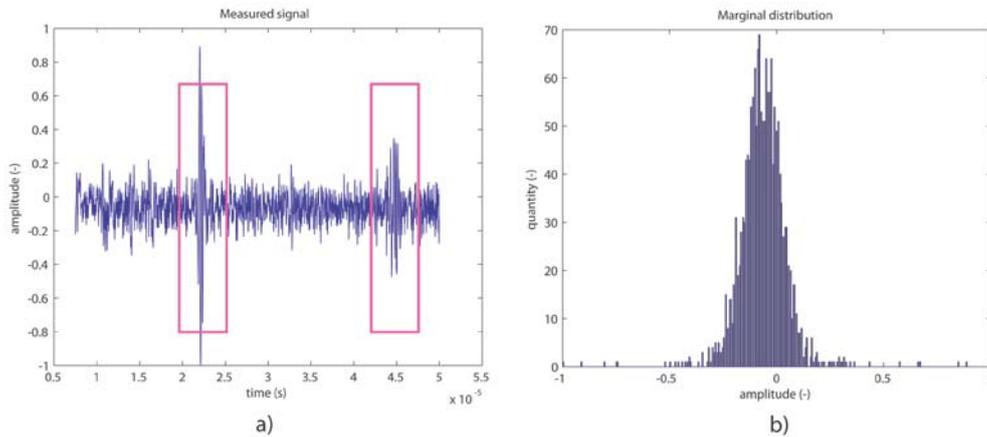

Figure 4: a) Measured signal with ultrasonic backwall echoes, b) Measured signal marginal distribution
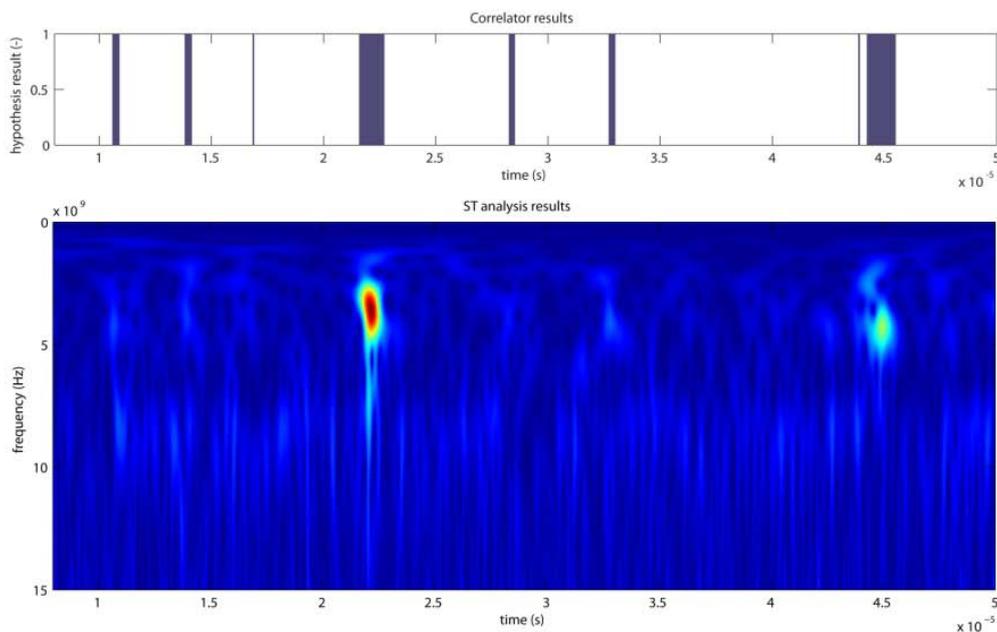
Figure 5: Time and Time-Frequency analysis of the measured signal

For the correlator signal was used the strongest back-wall echo signal. The filtering result presented in Figure 6 is promising. Back-wall echoes have ping colour when the first one is caused by the longitudinal wave and the second one is caused by shear wave. 2mm flat bottom hole made into the aluminium sample cause greenly highlighted ultrasonic echo. Back-wall echoes are repeated with a smaller amplitude caused by material attenuation. It is clear, that the second flaw echo amplitude was small in compare to the level of noise presented in Figure 4. The proposed Correlation-ST filtering (C-ST) algorithm didn't draw it from the noisy input signal. The algorithm is not ideal, because small oscillation is between flaw echo (green) and back-wall echo (ping). From the signal was cut initial echo because it was not important for the flaw detection. After the first shear wave back-wall echo C-ST filter drew the echo (yellow). This doesn't correspond to the neither back-wall echo nor the flaw echo. The assumption is that the condition that the signal noise part caused by the spurious signal reflection from material boundaries can be neglected was violated. This has to be taken as a non-zero error rate of the proposed filtering process. While the filtered echoes contain small amount of high frequency noise the band pass filter was applied. The comparison of signals before and after applying the band pass filter is also presented in Figure 6.
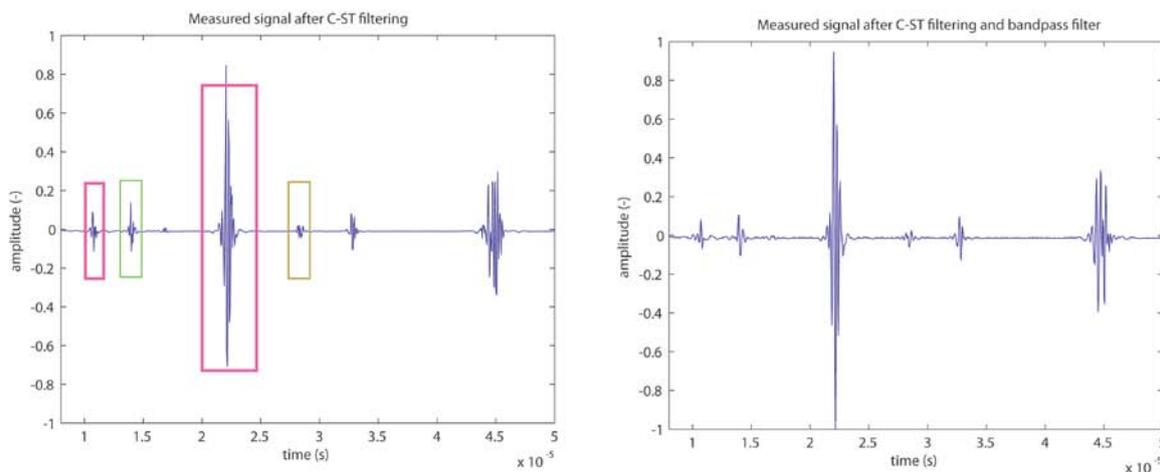

Figure 6: Result of the applied Correlation – S Transform and bandpass filter on the measured signal

IV. Conclusion

The idea of finding the best suited transform for ultrasonic signals resulted in evaluation of two main approaches with different transformation bases. Recently introduced Wavelet Transform exhibits progressive

resolution for time-frequency analysis and its application in ultrasonic signal filtering is widely published. Recently developed the S-Transform in compare to the Fourier Transform improves the time-frequency resolution and therefore its theoretical properties place it between the Fourier Transform and the Wavelet Transform. The direct implementation and application on ultrasonic signals from Electro-Magnetic Acoustic Transducer represents clue, for the study of alternative signal processing to the Wavelet transform. This lead to an improved algorithm for noise and the ultrasonic echo separation compared to commonly used filters. Within this study were introduced all principal aspects of the ultrasonic and EMAT signals. The new alternative Correlation – S Transform (C-ST) algorithm which draws ultrasonic echoes from the noisy signal was derived. The drawback of the developed C-ST algorithm is that for a signal where ultrasonic echoes have the same or smaller amplitude than is the noise level, the C-ST error rate is non-zero. The ultrasonic measurement classification is therefore embarrassed by incorrect ultrasonic findings.

Acknowledgement

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