Comparison of De-Noising Methods used for EMAT Signals

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Abstract. The electromagnetic acoustic transducer (EMAT) method is emerging non-contact ultrasonic method for wide range of applications. This method allows couplant-free detection of the defects and voids in conductive materials. Due to low transduction efficiency the raw EMAT signal is degraded by noise and interferences. The resulting low signal-to-noise ratio (SNR) presents the main performance limitation. One of the potential approaches to SNR improvement is filtration of EMAT signal. In this paper we compare both linear and non-linear filtering methods as anti-causal FIR and IIR filters and discrete wavelet transform (DWT) de-noising and propose a modified threshold computation for DWT. The design of de-noising algorithm is based on both coherent and incoherent noise analysis. The performance of algorithms is compared on simulated and real EMAT signals.

Introduction

Electromagnetic acoustic transducers [1] are emerging as a mainstream Non-Destructive Evaluation (NDE) technique. Electromagnetic acoustic transducer (EMAT) is commonly used for the non-contact generation and detection of ultrasonic signals in metals for some time. EMAT consist of a coil and a magnetic field, applied to a conducting substrate. The transmitter coil is conventionally driven with a transient current pulse. The characteristics of electromagnetic acoustic transducers as an ultrasonic source depend on the direction of the applied magnetic field and eddy current density induced at a conducting surface. The presence of a Lorenz force on the substrate causes an elastic wave to propagate into the volume of the material, or along the surface. EMAT detection works via an inverse process, where motion of the surface induces an electromagnetic field into the coil. EMAT offer several distinct advantages over traditional piezoelectric transducers for many inspection applications requiring novel solutions. These advantages include: operation without a coupling fluid, non-contact operation, high temperature operation, and the ability to utilize shear horizontal (SH) waves. EMATs are also ideally suited to launching and receiving Rayleigh waves, Lamb waves, and shear horizontal (SH) plate waves. The primary disadvantage of EMATs when compared to piezoelectric transducers is poor transduction efficiency. One of the most useful EMAT applications [2, 3] is flaw detection in metallic materials. In this case the efficiency is very important factor. The received EMAT signal contains back-wall echo, fault echo and reflections of ultrasonic waves from structure of the tested material. These reverberations are commonly called as backscattering noise (coherent noise). Another source of noise can be caused by influence of electronic circuitry and this noise is called electronic noise (incoherent noise). Both backscattering and electronic noise have to be considered as a part of received EMAT signal. In the case of coarse grained structure of materials the noise can sometimes totally mask the echoes from flaw and must be suppressed. A lot of methods for noise reduction have been proposed.

This paper is focused on comparison of both linear and non-linear filtering methods as anti-causal FIR and IIR filters [4] and discrete wavelet transform de-noising methods [5]. The advantages and disadvantages of compared methods are mentioned and evaluation by signal-to-noise ratio is performed.

In the first section our data acquisition system is presented. In this study we used transducer with central frequency of 3.6 MHz. For the measurement of EMAT signals calibration gauge was proposed. Next section describes short theoretical background of proposed filtering methods based on the anti-causal IIR filters, discrete wavelet transform and wavelet packets [5, 6]. All methods are relatively good alternative for noise reduction of EMAT signals. In third section all methods are performed and the settings of important parameters for efficient filtering of each method are described. For the verification of the proposed methods the artificial EMAT signal that reflects the real frequency response of EMAT probe and propagation of ultrasonic waves through the material was created. Comparison of methods is evaluated by signal-to-noise ratio enhancement. In the last section the verification of the best filtering method on real measured signal is referred. The discussion of implementation to digital signal processor is also mentioned.

1. Data Acquisition

EMAT system was created for the measurement of EMAT signals using the electromagnetic acoustic transducer with central frequency of 3.6 MHz. The system consists of pulser for generating of high frequency peaks, system for measurement of EMAT signals and EMAT preamplifier. The system is described in Fig.1.

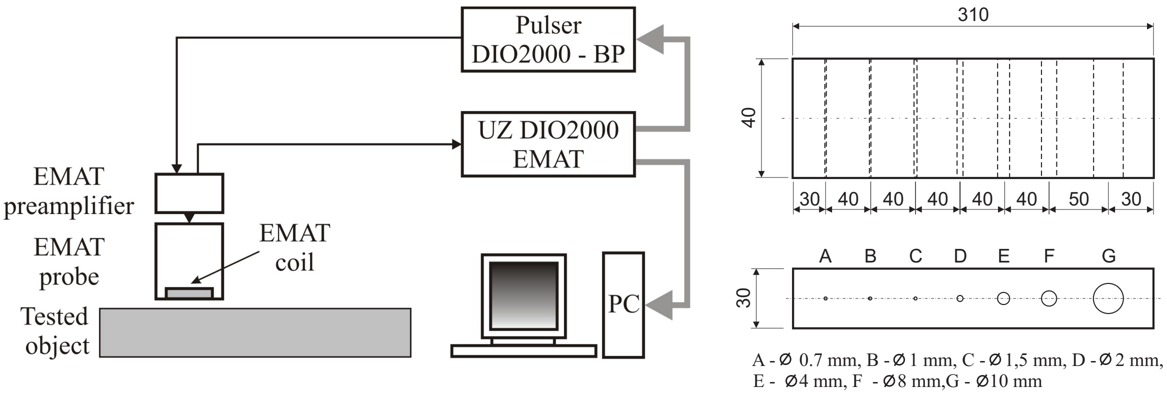

Fig. 1. Block diagram of EMAT system (right), EMAT gauge (left).

For measurement of EMAT signals we proposed and created EMAT gauge with different size of flaws. The artificial flaws are circle shaped and size is within 0.7 – 10 mm. The drawing is in Fig. 1. (left). The examples of measured signals on 2 mm flaw and 4 mm flaw are in Fig. 2.

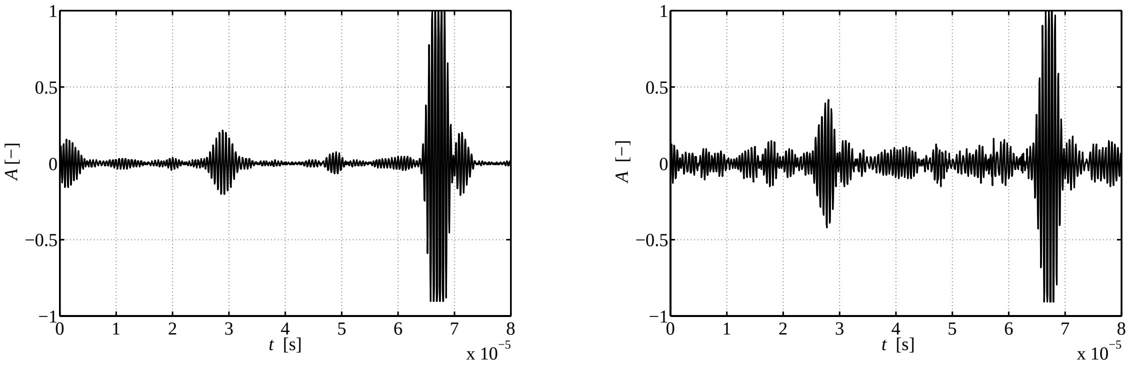

Fig. 2. Measured EMAT signals – on circular flaw - 2 mm (left) and 4 mm (right)

In Fig. 2. there can be seen the signals with undesirable level of noise that should be suppressed with efficient filtering method.

2. Filtering Methods

2.1 Anti-causal IIR and FIR Filter

Zero-phase digital filtering can be realized using non-casual filtering method. This method is based on processing the input data in both the forward and reverse directions. After filtering in the forward direction, the filtered sequence is reversed and fed back through the filter. The resulting sequence has precisely zero-phase distortion and double the original filter order. The used implementation [4] minimizes transients at beginning and at end of signal by matching initial conditions (DC component). This method is suitable for both FIR and IIR filter structures. In the case of FIR filtering, the time delay can be also adjusted by simple processing. For initial experiments we use the FIR band-pass filter designed by the Parks-McClellan algorithm. This design method uses the Remez exchange algorithm. In the case of IIR filtering, the Chebyshev approximation to design filters with optimal fits between the desired and actual frequency responses is used. The resulted filters minimize the maximum error between the desired frequency response and the actual frequency response (also called minimax filters). Filters designed using this method exhibit an equiripple behavior in their frequency response, and hence are also known as equiripple filters. This method has limitation to non-real-time processing of acquired signal.

2.2 Discrete wavelet transform

The discrete wavelet transform [5] can be used as an efficient filtering method for families of signals that have a few nonzero wavelet coefficients for a given wavelet family. Filtering procedure is based on decomposition of signal using DWT in *N* levels using band pass filtering and decimation to obtain the approximation and detail coefficients. Next step is thresholding of detail coefficients and reconstruction of signal from detail and approximation coefficients using inverse transform (IDWT). One of the most important properties is to choose the suitable mother wavelet and propose threshold level.

2.3 Wavelet packets

The WP method [5, 6] is a generalization of wavelet decomposition that offers a larger range of possibilities for signal analysis. In wavelet analysis, a signal is split into an approximation and detail coefficients. The approximation is then itself split into a second-level approximation and detail, and the process is repeated. In WP analysis, the detail coefficients as well as the approximation coefficients can be splited.

3. Theoretical simulations

The comparison of proposed method is described in this section. For the evaluation of all used de-noising methods we create the set of simulated EMAT signals. These signals were created based on known central frequency and frequency bandwidth of used electromagnetic acoustic transducer [7]. The central frequency is 3.6 MHz. The frequency response of EMAT burst is in Fig. 3. (left). To the simulated signal we also add the fault echo corresponding to the circle flaw which signal is in Fig. 2. (left). Noise with Gaussian distribution was added within $SNR = 1 – 60$ dB. The simulated signal with fault echo, back-wall echo and noise with $SNR = 15$ dB is in Fig. 3. (right).

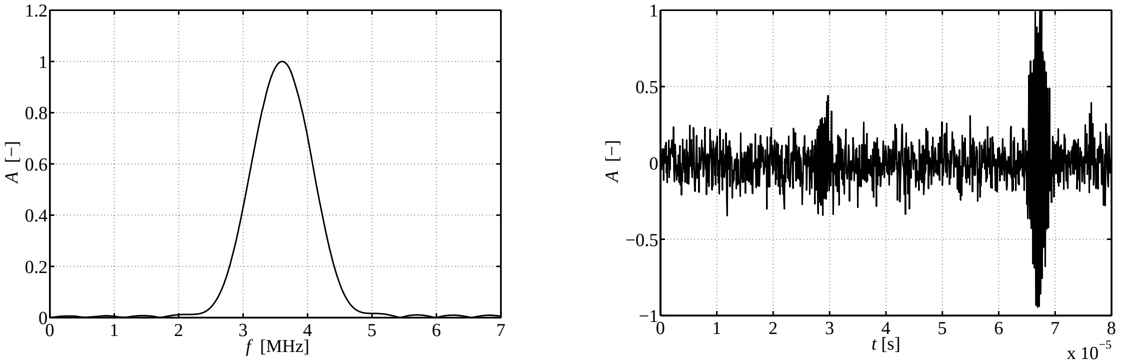

Fig. 3. Frequency response (left) and simulated EMAT signal (right)

The discrete wavelet transform filtering techniques and anti-causal IIR filter were used for de-noising of EMAT signals. In the case of WT methods the different properties as suitable proper mother wavelet, level of decomposition, threshold rule and properties of thresholding have to be chosen. The shape of the mother wavelet has to be very similar to the ultrasonic echo. It has to fulfill the following properties: symmetry, orthogonality and feasibility for DWT. A group of mother wavelets was tested: Haar’s wavelet, the discrete Meyer wavelet, Daubechie’s wavelet and Coiflet’s wavelet. The best results were obtained with the discrete Meyer mother wavelet. In the following study, only this mother wavelet is used. Hard thresholding is used for thresholding detailed coefficients. Hard thresholding can be described as the process of setting to zero the elements whose absolute values are lower than the threshold. In the proposed procedure, local thresholding of detailed coefficients was used [6]. We calculate the threshold at each level of decomposition from the detailed coefficients, and this value was used for thresholding in the same level. We evaluated common thresholding methods implemented in the Matlab Wavelet toolbox [8] (rigsure, sqtwolog, heursure, minimaxi) and due to the unsatisfactory results we proposed a new method based on standard deviation. The local threshold at every level of decomposition is given by

$$Thr = k \cdot \sqrt{\frac{1}{N-1} \cdot \sum_{i=1}^{N} (Dc_i - \overline{D}c)^2} \ , \qquad (1)$$

where k is coefficient related to crest factor of filtered signal (crest factor is the ratio of the peak value to the RMS value),

Dc are detail coefficients at each level,

N is length of each set of detail coefficients.

Usually global threshold is used in DWT and WP filtering. In our study for comparison of both methods (DWT and WP) local thresholding was used instead of global thresholding. For comparison both of methods signal-to-noise ratio enhancement (SNRE) is used:

$$SNRE = 20 \cdot \log\left(\frac{N_{ef,rand}}{N_{ef}}\right) \quad [dB], \tag{2}$$

where

$N_{ef,rand}$ is root mean square value of noise, which was added to signal (noise with normally random distribution),

N_{ef} is root mean square value of noise which was recovered from signal.

The performance of all proposed filtering methods is shown in Fig. 4. The best results were obtained with wavelet packet filtering technique. The signal-to-noise ratio enhancement is for the highest level of noise about 27 dB. In comparison with DWT filtering technique the WP has a better result that is based on better decomposition and richer analysis of the signal. In the other hand the filtering methods based on IIR and FIR filters has *SNRE* only about 11 dB and 5 dB. The important property in the case of filtering is the suppressing of noise without magnitude suppressing of back-wall echo and fault echo. This property with all filtering methods was observed.

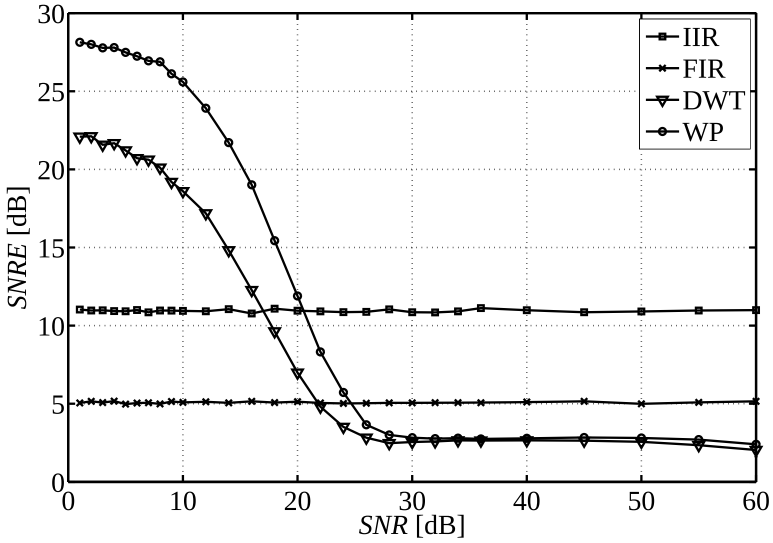

Fig. 4. SNRE evaluation for filtering methods

The WP filtering technique as the best filtering method was used for further de-noising of EMAT signals. In Fig. 5 is the filtered EMAT signal which was simulated. The level of noise corresponds in this case signal-to-noise ration equal to 15 dB. Simulated EMAT signal is in Fig. 3.

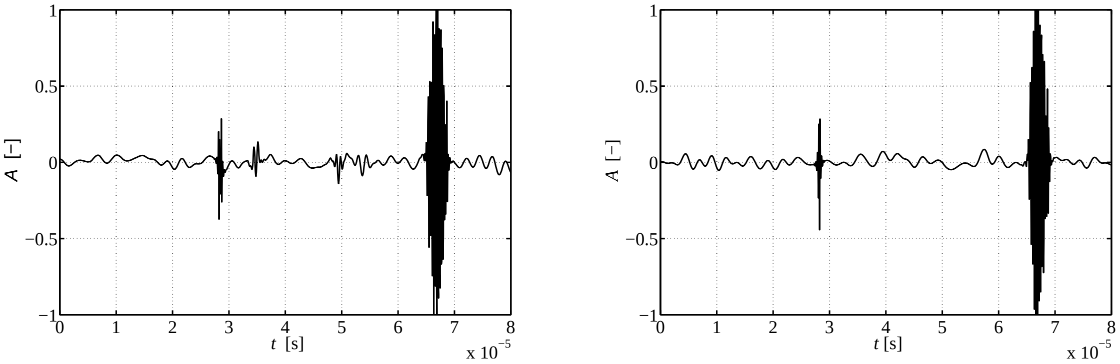

Fig. 5. Filtered EMAT signal – DWT (left), WP (right)

3. Experimental results

The wavelet packet filtering technique was used for the filtering of measured EMAT signals. The signals were measured on the EMAT gauge with different artificial circle shaped flaw. Filtered EMAT signals that are measured above the 2mm and 4mm circle shaped flaw are in Fig. 6. In both cases the signal has higher level of noise and the noise has been successfully suppressed. Both measured signals are in Fig. 2.

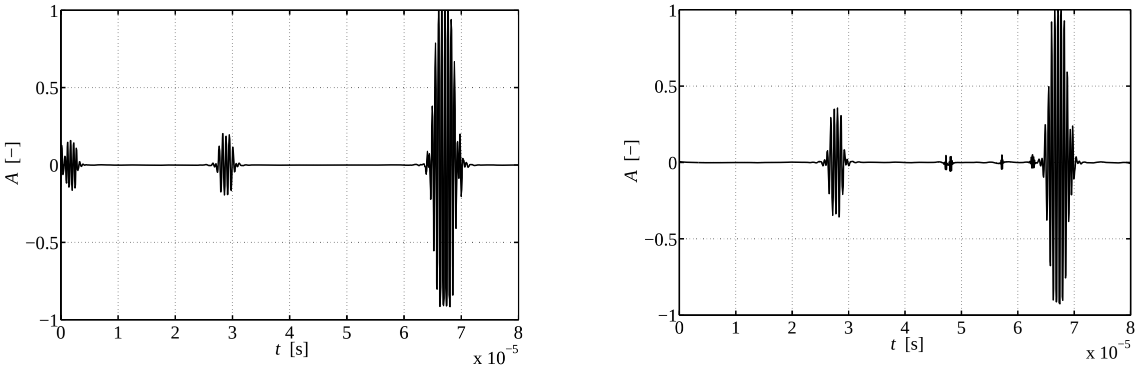

Fig. 6. Filtered EMAT signals with fault echo– flaw 2mm (left), flaw 4mm (right)

In previous case the fault echo has been above the level of noise. In 1mm circle shaped flaw the flaw echo has similar magnitude as noise. In Fig. 7. there can be seen the measured and filtered EMAT signal on 1 mm circle shaped flaw with wavelet packet filtering technique. For thresholding the threshold based on standard deviation was used.

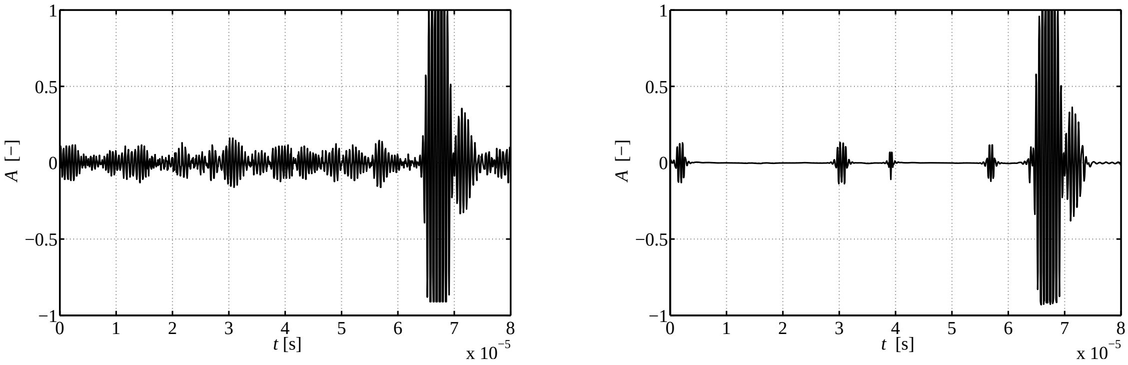

Fig. 7. Measured EMAT signal (left) and filtered EMAT signal (right)

The method based on DWT called WP is good alternative for filtering of EMAT signals and can be implemented to the EMAT systems. A fast algorithm for WP computation using standard DSP operations (FIR filtering, up/down-sampling) is available. For this reason the WP technique can be used in real time digital signal processors used in EMAT systems.

Conclusion

Digital signal-processing methods for EMAT signals have been presented. It compares linear and non-linear de-noising methods based on DWT and anti-causal IIR and FIR filters. The performance of all methods have been assessed both through a number of numerical tests on simulated EMAT signals and signal-to-noise ratio enhancement. The methods have shown valid alternative for filtering of EMAT signals with relatively higher level of noise. The best method is wavelet packet with highest signal-to-noise ration enhancement about 27 dB. For the comparison the EMAT gauge with different circle shaped flaws has been proposed and created. Wavelet packet filtering technique is good alternative for efficient filtering of EMAT signals in real time applications.

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