Wavelet-based Denoising of EMAT Signals – from Development to Industrial Real-time Application

Till SCHMITTE*, Thomas ORTH, Salzgitter Mannesmann Forschung, Duisburg, Germany
Andre GERMES, Stefan NITSCHE, V&M Deutschland, Düsseldorf, Germany

Abstract. EMAT is used whenever a coupling medium like water shall be omitted. However, signal quality sometimes needs improvement, especially if surface quality of the product under test is poor. In this situation wall thickness measurements may be a challenging task. Signal filtering using wavelet based techniques proved to be suited well for improving SNR in situations with pulse-shaped signals. Therefore we developed a system for wavelet-filtering of UT signals in real-time under production situations.

Introduction

In steel tube industry, electromagnetic acoustic transducers (EMAT) are used for ultrasonic testing (UT) of wall-thickness and laminations, whenever the use of a coupling medium like water cannot be accepted, for hot products or in cases where UT is combined with other dry NDT techniques like magnetic flux leakage. However, in some cases the advances are paid with a poor signal-to-noise ratio, especially for rough surfaces and high wall thicknesses.

We present a wavelet-based approach to significantly increase the signal-to-noise ratio (SNR) in these situations. We have researched several wavelet-techniques like adapted wavelets, biorthogonal wavelets, discrete and continuous wavelet-transformations and static and adaptive thresholding techniques. As an outcome of this work we designed and programmed a FPGA-based hardware for adaptive wavelet denoising in real-time of UT-signals. The system, which could not be purchased of the shelf, is running at Vallourec & Mannesmann (V&M) mill in Düsseldorf-Rath in Germany. It comprises 4 channels in parallel and is capable to denoise UT signals at a pulse-repetition rate of up to 5 kHz and sampling rates of up to 125 MHz. The wavelet-denoising uses a well suited wavelet-transform specially adapted to the NDT signals. Additionally, an adaptive thresholding is implemented. The pre-amplified analog EMAT signals are fed into the digital filter electronics, being wavelet-denoised, and subsequently transformed back to analog signals which are transferred into the conventional UT-system. This “black-box” philosophy allows for usage in almost any standard UT-system. The paper describes the basic design of the system and presents results from trials and mill application.

System Design

General

Instead of using a frequency filter, e.g. a band-pass, to reduce the noise, the wavelet filtering enables to filter in the time-frequency domain, thus taking also time aspects (pulse-shaped signals) into account. In addition, mathematics of the
wavelet transformation also allows for using different wavelets which may be adapted to the actual signal shape and thus leads to a better signal discrimination.

The actual wavelet filtering consists of three parts: first the signal in the time domain is transformed into the wavelet domain by the wavelet transformation, in the next step the signals in the wavelet domain are modified (shrinkage) and last the modified signals are transformed back into the time domain by an inverse transformation.

This procedure is very demanding with respect to computing power if the complete filtering should be carried out in real time during the measurement.

In recent years we have gained experience in wavelet filtering for stray flux (MFL) signals [1, 2]. This research resulted in the successful filtering of MFL signals in several installations at V&M mills. Because the MFL signal rate is comparatively slow, the realization could be done with standard DSP techniques. Unfortunately, this could not directly be transferred to UT systems, because the data rate is approximately a factor of 1000 faster. Only a hardware based on modern field programmable gate arrays (FPGAs) will have sufficient computing power for performing the necessary transformations in real time.

**Setup**

The realized wavelet filter programmed on FPGA hardware is mainly optimized for UT wall-thickness (WT) measurement which is a pulse echo method. The hardware enables for a pulse repetition frequency (PRF) of up to 5 kHz. Typically pulses with central frequency around 2 - 10 MHz are used. The reflected signal (an echo from the back wall) is digitized during a limited span of time (window) after the initial pulse. The sampling frequency can be selected up to 125 MHz and the time window has up to 4096 samples. The sampling frequency of the AD and the DA converters are identical.

The time window of the measurement starts with a defined delay time after the trigger. During the recording phase the samples in the time window are recorded and fed into a FIFO (first in - first out buffer). At the same time the filtered data of the previous cycle is passed to the DA converter. During the time between two trigger pulses the data is copied into the FPGA for processing. At the same time the results of filtering of the previous cycle are copied into the output FIFO. The remaining time of the cycle – until the recording starts again – is used for actual filtering the data.

The complete system consists of one circuit board with FPGA, memory, AD- and DA- converter, which is parameterized via PCIe-bus from a standard PC. An additional board stacked upon the first is designed for analog input and output signal conditioning. The system is mounted together with power supply and cooling into a 19’’ rack which can hold up to four channels (10 height units).
Wavelet-Transformation

The mathematics of wavelet transformations is documented in a broad range of books and articles, some of them are given in [3, 4]. Here we concentrate on aspects of the actual algorithm, which we developed for a wavelet based filtering of UT-signals. The wavelet filter consists of a cascading arrangement of finite impulse response filters (FIR filters); also called a filter-bank. By processing the signal through this structure (Figure 1) the signal is transformed into the wavelet domain. This is also called the decomposition. This process can be compared to the Fourier transformation from the time into the frequency domain.

The signal in the wavelet domain consists of wavelet coefficients, which exist in different levels. The number of levels is the number of identical steps in the cascading FIR filter algorithm. After transformation, the wavelet coefficients are modified (shrinkage). This is done by comparing the amplitude of the wavelet coefficients in one level with a threshold value. If the magnitude of the wavelet coefficient is below the threshold the coefficient is set to zero, if it is above the threshold is subtracted in case of positive coefficient and added in case of negative coefficient. This procedure is called soft thresholding. As an alternative to the soft version there is a hard thresholding where the coefficients above the threshold survive unmodified, and those below are set to zero [6]. After the modifications the wavelet coefficients are transformed back into the time domain. This is done with an equivalent FIR filter scheme, see Figure 1. The inverse transform is also called the reconstruction. If all thresholds are zero the wavelet coefficients pass unmodified and the signal is perfectly reconstructed: The output is identical to the input signal.

Instead of using the usual fast wavelet transformation algorithm [5] or the wavelet packet transformation [6], we use the stationary wavelet transform (SWT) algorithm [6]. This algorithm has the advantage that the signal is stationary after filtering and no additional jitter is introduced by wavelet filtering. However, the disadvantage is a higher demand of computing power and memory. The SWT is easily implemented in the scheme depicted in Figure 1. The decomposition is done with \( N \) levels. Therefore the decomposed signal exists in the wavelet domain as details \( d_1 \ldots d_N \) and approximation \( a_N \). The first level set of FIR filters (high pass HP and low pass TP) has \( n \) filter taps. For subsequent levels the number of filter taps increased such that for the \( N \)th level the number of filter taps is \( 2^{N-1}n \). The increase of filter length is done by inserting zeros between the original filter tap values. After decomposition the values in wavelet domain are subjected to shrinkage function \( S_N \). A delay line has to be inserted into the signal path for \( d_N \) for proper phase overlay. The reconstruction is done accordingly. This scheme directly allows for point-by-point filtering of the signals if a signal buffer is associated to each FIR filter. In this manner it is possible to filter virtually endless signals without the need of storing the complete signal and without introducing block-artefacts after filtering. The point-by-point method is thus implemented and the endless signal consists of the A-scans to be filtered.

Shrinkage and Thresholds

As shrinkage function the well explored soft- or hard thresholding is selected. May \( k \) be the index of the discretized signal, \( i \) the number of the level and \( \lambda_i \) the threshold for this level, than e.g. hard threshold is given by

\[
S_i: d_{i,k} \rightarrow \begin{cases} 0 : & d_{i,k} \leq \lambda_i \\ d_{i,k} : & d_{i,k} > \lambda_i \end{cases}
\]

It remains the question of choosing a good threshold value. One strategy may be to use the global threshold level wise, i.e. calculate the threshold using [6]
\[ \lambda_i = \sigma_i \sqrt{2\ln(M_i)} , \]

with \( M_i \) is the number of values in \( i \)th level on which the standard deviation \( \sigma_i \) is calculated upon. The problem here is that the filtering scheme as discussed above, if performing the SWT in a point-by-point manner, has only one wavelet-coefficient in a given level per sampling time interval. Therefore we add an additional memory where the last \( M \) values are to be stored. The threshold is calculated just on this last \( M \) values by performing standard deviation calculation and is valid for the next \( M \) values. This standard deviation is denoted \( \sigma_i^M \) for level \( i \).

Furthermore, the above formula relies on the fact that the noise in the signal to be filtered is white noise, which in most cases in NDT is not fulfilled. Therefore an adjustable number \( f \) is introduced such that

\[ \lambda_i = f \sigma_i^M . \]

The values of \( f \) and \( M \) are adjustable by the user and have to be optimized. It should be pointed out that both parameters are identical for all levels. In this manner a compromise between complete automatic threshold determination on one hand and the necessity of controlling all thresholds manually on the other hand is obtained.

**Figure 2:** Static testing of the wavelet filter at 100 MHz, 4000 samples and 1 kHz PRF at a sample of 14.5 mm wall-thickness. Four a-scans are given for different values of \( f \) as defined in the figure. The red curves show the wavelet-filtered rectified signals and the black curves are non-filtered a-scans. The green curve displays the damping in the filtered (dashed) and non-filtered (straight) case. The green bars display the region of the BWE and the blue straight and dashed bars show the noise level in the filtered and non-filtered case, respectively.
Selected Wavelets

The choice of wavelets is quite important and we performed trials and simulations with a broad variety of different wavelets. Due to performance reasons the first laboratory trials were carried out using Daubechies wavelets with 4 filter coefficients. The mill trials reported here were performed with Daubechies wavelets with 10 coefficients because they proved a better performance than wavelets of shorter length. More complex wavelets were not used because of performance reasons. Other families of wavelets were also tested, but proved less viable for the case of EMAT wall thickness measurements.

Results

All results presented here were carried out at the NDT facilities of the pipe mill of Vallourec & Mannesmann in Düsseldorf-Rath (Germany). This mill is producing large diameter and large wall thickness seamless tubes in the Pilger process. The wall thickness is measured using electromagnetic ultrasonic transducers (EMAT). The system scans the pipe under test in a helical manner. For installation and maintenance purposes a plate or test piece can be placed at the measuring head. Details of the system can be found in [7].

Static measurements

The first presented results were carried out in static operation with a sample tube shell of 14.5 mm wall-thickness. The data was recorded using an oscilloscope. The wavelet-filtering was performed at 100 MHz at a pulse repetition frequency (PRF) of 1 kHz. The lift off of the EMAT head is 1 mm.

Examples of raw and filtered data are presented in Figure 2 for different values of the tuning factor $f$. It can be clearly seen that the noise level, the response in-between the back-wall echoes (BWEs), is reduced. At the same time the damping of the pulse sequence of the BWEs is observed. For usual signal processing only the first or the first and the second BWE is relevant. It can be clearly seen that the increase of $f$ leads to a decrease of noise and also to a stronger damping of the signals.

In order to find a good compromise between optimal noise and minimal signal suppression the signal-to-noise ratio (SNR) is calculated for all recorded situations. The signal amplitude is the maximum of the rectified BWE of a given order. Noise is defined as the maximum rectified amplitude in the region between the BWEs. SNR is given in dB. The time window of the BWE is denoted by green bars, the time between the BWE and the level of noise is denoted by blue lines in Figure 2.

In this manner the SNR is calculated for different $f$ and for different order of BWEs. Obviously, the interesting parameter is the change of SNR for the situation with and without filter. This is expressed by

$$\Delta \text{SNR} = \text{SNR}_{\text{filtered}} - \text{SNR}_{\text{non-filtered}}$$

The values for $\Delta$SNR defined like this are plotted as a function of the order of the BWE for different values of $f$ in Figure 3 and as a function of $f$ in Figure 4.

From the above analysis it can be deduced that the optimal value for $f$ depends on the measurements situation. If one uses only the first BWE for measuring the time of flight and detecting wall thickness it is possible to use up to highest tested values $f < 4$. However, if the wall thickness is deduced from time of flight between first and second BWE, $f \sim 2$ shall be maximum.

![Figure 3: SNR for the same situation as in Figure 2. The change in SNR is plotted as a function of the order of the BWE for several values of $f$.](image-url)
**Dynamic mill test**

One main objective to be proved is if the wavelet filtering may lead to any phase shift or signal deformation and may thereby change the results of wall thickness measurements: All A-scans recorded so far did not show any hint towards such behaviour, if \( f \) is not too high. The values deduced above (\( 1 < f < 4 \)) do not change the shape of the first BWE.

In order to prove this we performed a trial recording all A-scans (filtered and non-filtered) from a wall-thickness measurement with EMAT sensor for one rotation of a pipe. From this data the wall-thickness was calculated utilizing the time of flight between first and second BWE. The filtering was done with a moderate value of \( f \). The result from approx. one half of the rotation is displayed in Figure 5.

This argument can be supported with Figure 6 which displays one example A-scan collected during standard operation of the EMAT wall thickness device in the mill. It is clearly seen that no distortion of the signal takes place. The filtering was performed with \( f = 2 \). From the same measurement a B-scan is constructed and reported in Figure 7. This figure displays a fraction of the rotation of the pipe. From both figures an overall increase in SNR of approx. 10 dB can be concluded which is consistent with the static measurements discussed above. In addition, a more practical approach was performed in order to estimate SNR improvement: During calibration of the UT system first the wall thickness was calibrated using a reference plate of 40 mm thickness without wavelet filtering.

The amplification of the system was adjusted such that noise level is sufficiently low not disturbing the wall thickness measurements. Next, the wavelet filter with \( f = 2.5 \) was switched on and the calibration was repeated with the same objective. In this case the operator could increase the amplification of the system by 12 dB without increasing relative noise level.

**Conclusions**

In this project a real-time wavelet-filtering of UT signals was realized and tested. To
our knowledge this is the first setup which can be operated at technically relevant pulse-repetition frequencies of up to 5 kHz and necessary resolution for wall thickness measurements of 125 MHz sampling. It could be proved that SNR could be improved by 10 to 15 db in different situations, laboratory as well as static and dynamic operation during production. The realized automatic threshold selection works well and an optimum filtering can be found depending on how many back-wall echoes are to be recorded. The algorithm is operating reliably on a FPGA board – also for long term operation. The proposed wavelet filter scheme leads to a linear modification of the damping, depending on the threshold factor \( f \) and the number of detected back-wall echoes and the filtering does not lead to any major distortion of the signal. Thus, the results of wall thickness measurements are not altered.

Main parts of the presented algorithms and techniques have been applied for patent.

References

Author

Dr. rer. nat. Till Schmitte has studied physics at the Ruhr-Universität Bochum, Germany. He researched in the group of Prof. Dr. Dr. h.c. Hartmut Zabel for several years in the field of thin film magnetism and magneto-optics. In 2003 he changed to at that time Mannesmann Forschungsinstitut (MFI) which now is Salzgitter Mannesmann Forschung GmbH in Duisburg, Germany. He specialized on signal processing and evaluation of NDT signals.

email: t.schmitte@du.szmf.de