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Abstract. Magnetic flux leakage testing is one of the most important NDT methods for seamless steel tubes. In order to increase the sensitivity of the inspection, diverse signal processing techniques are already applied. As an alternative to conventional filter techniques, wavelet filtering reveals a higher separation of the signal to the noise level together with an improved adaptation to the signal structure. For the implementation of wavelet filtering into existing third party systems, a multichannel DSP-hardware has been developed, which is capable to filter 32 sensor signals simultaneously. The results show a significant improvement of the signal to noise ratio. Furthermore, it is possible to dispense with the commonly applied differential sensor technique so that a wider range of defect types can be detected.

Introduction

In the production of seamless steel tubes, made of ferromagnetic steel grades, the use of electromagnetic inspection is often favored compared to UT inspections. In addition, certain customer specifications demand EMI as a second NDE method. For seamless pipe production the magnetic flux leakage technique is a good compromise, because flaws at the outside and inside of pipe walls can be detected for DC flux excitation. However, the ability to detect flaws at the pipe-inside is limited and decreases with increasing wall thickness. The demand to shift this limit towards higher walls is essential. Furthermore, seamless pipe production usually leads to significant magnetic background signals, so called seamless pipe-noise, which makes it necessary to implement a more sophisticated filter technique for data processing.

We have researched in this field and developed a wavelet-based technique, which increases the signal to noise ratio and suppresses the background signal reliably. We will discuss several threshold techniques and adaptive threshold methods. Several wavelets (orthogonal and biorthogonal) were tested for this purpose. The selected technique is based on wavelet analysis using a stationary algorithm which omits any data-blocking. The wavelet coefficients are subjected to adaptive thresholds and afterwards subjected to inverse transformation. The denoised signal is fed back into existing installations. The method was implemented on a DSP-based system, resulting in a 32-channel parallel system for real-time evaluation of the signals. The system is installed at existing MFL installations for longitudinal flaw detection at Vallourec&Mannesmann mill in Mülheim, Germany, and a new MFL installation at Vallourec&Mannesmann mill in Düsseldorf, Germany [1].
The testing of the system was done in collaboration with Institut Dr. Foerster, one of the world leading suppliers for magnetic flux leakage inspection systems, using their ROTOMAT system [2]. Foerster also provided an analogue interface for the ROTOMAT system. The 32-channel DSP system has been tested under mill conditions. The aim for the implementation of the wavelet filtering was:
- increase of the signal to noise ratio
- improvement for the detection of inner defects
- substitution of the differential sensor technique by absolute mode detection
- development of methods for defect classification

Overall, the application of magnetic flux leakage should be extended, resulting in significant reduction of costs.

The paper will discuss the system-design and results from the running installations.

Technical Realisation

Wavelet-filtering

In this chapter only a short review of wavelet filtering will be given. For a more comprehensive description see [3-5].

The signals, which are superimposed by noise of different origins, are wavelet transformed into the wavelet domain (see Figure 1). This is similar to a spectral analysis of the signal, but instead of using a sine function, a wavelet (“little wave”) is chosen as a basic function. By a suitable choice of the wavelet an improved resolution for transient signals can be achieved. These types of non-stationary signals are typical for ultrasonic testing, magnetic flux leakage, acoustic emission and others.

After transformation of the signal into the wavelet domain the resulting wavelet coefficients have to be modified to achieve a denoising effect. In this process one has to differ between shrinkage and threshold determination. For shrinkage, several methods are available which cut the wavelet coefficients, which means certain big coefficients are kept while the others are reduced or even set to zero [6]. Which coefficients are finally relevant is decided by the threshold, which can be varied dynamically. For the system discussed in this paper, the threshold is determined by analysing the statistical properties of the wavelet coefficients. The threshold is dynamically corrected. Afterwards the modified wavelet coefficients are inversely transformed back into the time domain. Figure 2 gives the filtering of a typical magnetic flux leakage signal. Another example is given in Figure 3, which shows the 100% inspection (C-scan) of a test tube, in which several artificial defects have been prepared.
Design of the 32-channel system

To realise the wavelet denoising for mill application, the wavelet filtering has been implemented on DSP-based signal processing systems. For this purpose, the filter has been programmed eight times in parallel, so that one single DSP is filtering eight channels. In addition to the DSP, each channel is equipped with an AD and DA converter. The converters are set in parallel, so that delay times due to multiplexing can be excluded. Four of these units are mounted in one 19” rack. The final 32-channel system is shown in Figure 4. Depending on the type of filtering, sampling rates up to 25 kHz can be achieved. This is by far sufficient for most of the MFL applications during seamless pipe production. By slight modifications of the hard- and software higher sampling rates would be possible. The system reveals analogue inputs and outputs to ensure a simple integration into the analogue signal path (black box principle). No change of the existing system control is therefore necessary. The system is parameterized from a PC via an Ethernet connection.

The system presented here has been developed for the ROTOMAT system of the NDT company Institut Dr. Foerster and has been tested intensively in the mill. The ROTOMAT is provided with two sensor shoes, each equipped with an array of 8 induction sensors. The measured signal is fed into analogue bandpass filters and is separated into a high frequency outside channel and a low frequency inside channel. Subsequently, these analogue signals are given to the wavelet filter, which consequently filters inside and outside channel separately. In summary, 32 wavelet filter channels are necessary for the complete system. The effect of the analogue band pass filtering is shown in Figure 5. The ROTOMAT system offers the possibility to perform differential measurements. This is realised on a software basis (right after the wavelet filtering)
where the difference of two channels is calculated and finally evaluated.

**Figure 4:** 32-channel wavelet-signal processing system. The 4 DSP-based systems are clearly visible, each equipped with 8 analogue inputs and outputs.

**Figure 5:** Separation of the stray flux signals in the ROTOMAT system: the upper diagram gives the non-filtered signal. The centre and lower diagram represent the low frequency inside channel and high frequency outside channel respectively.

**System test in the mill**

Below some examples originating from the mill trials are presented. All experimental data have been recorded within the ROTOMAT system, comprising screenshots from the ROTOMAT software or extracts from the ROTOMAT database. All data have been measured under mill conditions.

**Test tube**

During inspection of the first test tube (177.8 x 10.36 mm) only the absolute sensor mode (no differential technique) has been used. The test tube has been inspected several times, while the different parameters of the wavelet filter were tested. The result of optimal filtering is given in Figure 6. The upper part of the diagram (without wavelet filtering) shows a clear separation between the outside defect (5% longitudinal notch) and inside defect (12.5% longitudinal notch). The noise content of the signal becomes quite evident in the inside channel.

After passing the wavelet filter the situation changes: without changing the amplification of the electronics, the signal amplitudes of the indications stay constant while the background signal has been removed nearly completely.

**Natural imperfections**

The next examples show the characteristics for natural imperfections, in this case two small outer defects, shown in Figure 7. The tube dimension was 139.7 x 7.72 mm. The tubes have been inspected five times and the evaluation of the ROTOMAT system has been recorded repetitively, without wavelet filter and with varying wavelet filter adjustments. The result for optimised filter settings is given in Figure 8a and 8b. In contrast to the inspection of the test tube with artificial defects (see above), both...
inspection modes have been used, absolute as well as differential mode. It can be clearly seen, that the outside defect is indicated in the inside channel, which is a typical drawback of conventional band pass filtering defect classification.

For this reason the wavelet filtering works especially in the inside channel. Again the noise is significantly reduced while the indication amplitude stays constant.

In addition, the rather high background signal of the absolute mode result can be reduced to the level of the differential mode, which essentially means that with filtering an absolute mode measurement becomes practically possible.

In the following the measurements will be evaluated statistically. The five runs with identical settings have been averaged and are represented together with results for different wavelet filter settings in Figure 9.
Figure 9a: statistical evaluation of the measurements from example 1. The curves given in the diagram represent the results without wavelet filtering („ow“ blue) and with 3 different setting of the wavelet filtering („w2_5“ green, „w3“ red, „w4“ black, with increasing filter strength in that order). The diagrams given are from top to bottom: differential evaluation of outside channel, absolute evaluation of outside channel, differential evaluation of inside channel, absolute evaluation of inside channel.

Figure 9b: statistical evaluation of the measurements from example 2. For details see caption to Figure 9a.

For the sake of better comparison, all results are normalised to the biggest indication amplitude and are spread in the axial direction of the tube. In each diagram, curves are given in color coding (green, red, black) corresponding to increasing filter strength (in this order) and blue for no wavelet filtering. It can be clearly seen that wavelet filtering is very much effective for the absolute mode measurement. In case of the differential mode measurement a quite strong filter setting has been set in order to obtain a considerable effect. In case of the outside channel of example 2 the filter effect is negligible, probably because the indication amplitude is rather small. On the basis of the results of Figure 9a and 9b the improvements for the signal to noise ratio (SNR) have been quantified (see Table 1 and Table 2).

![Table 1](image)

<table>
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<tr>
<th>Wavelet 2.5</th>
<th>Diff Out</th>
<th>Abs Out</th>
<th>Diff In</th>
<th>Abs In</th>
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<tr>
<td></td>
<td>0</td>
<td>2.81</td>
<td>1.5</td>
<td>2.57</td>
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<tr>
<td>Wavelet 3</td>
<td>0.95</td>
<td>3.67</td>
<td>1.5</td>
<td>4.58</td>
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<tr>
<td>Wavelet 4</td>
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<td>8.03</td>
<td>7.52</td>
<td>10.61</td>
</tr>
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</table>

Table 2: Statistical evaluation of the results for example 2. Improvement of the SNR given in dB relative to the situation without wavelet filtering.

<table>
<thead>
<tr>
<th>Wavelet 2.5</th>
<th>Diff Out</th>
<th>Abs Out</th>
<th>Diff In</th>
<th>Abs In</th>
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<td>n.a.</td>
<td>1.16</td>
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Conclusions

In the scope of the work presented here a multichannel wavelet filter has been successfully adapted to an existing commercial magnetic flux leakage inspection system and has been tested under mill conditions. The filter hardware has been realised on the basis of digital signal processors and has been integrated in the ana-
logue signal path as a black box element. As a consequence, only minor modifications of the regular inspection electronics were necessary. The required space for the DSP-hardware is moderate due to effective programming which allows an 8 channel filtering on one DSP board. The results indicate that a significant improvement of the signal to noise ratio has been achieved. As a consequence, also small indications can be detected reliably. Furthermore, it could be demonstrated, that it is possible to avoid the differential sensor mode, resulting in a higher lateral resolution and a wider range of imperfections which can principally be detected.

References


Author

Dr. rer. nat. Thomas Orth has studied physics at the Ruhr-University in Bochum, Germany until 1994. He researched in the group of Prof. Dr. J. Pelzl in the field of solid state spectroscopy. After subsequently working in the research for the automobile industry dealing with adhesive bonding, he changed in 1998 to the Salzgitter Mannesmann Forschung GmbH (former Mannesmann Forschungsinstitut, MFI). Since 2004 he is the head of department for non-destructive testing, dealing with all conventional and less conventional NDT methods.

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