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ANALYSIS OF THE MAGNETIC FLUX LEAKAGE SIGNAL DETECTED BY A PIPELINE INSPECTION GAUGE WITH THE HELP OF THE CONTINUOS WAVELET TRANSFORM

Leszek Piotrowski* — Marek Chmielewski*

The paper discusses the new possible ways of magnetic flux leakage (MFL) signal analysis with the help of the wavelet analysis. It describes the advantages of such approach taking into account its potential in using standard wavelets for the flaw detection, as well as the possibility of adapting the custom designed wavelet function. The possibility of detection and quantitative evaluation of material defects is considered. In the paper, the abovementioned issues are dealt with on the basis of the results of the measurements performed with the help of a prototype device that is intended to be a part of a presently designed high resolution pipeline inspection device (PIG).

Keywords: magnetic flux leakage, nondestructive testing, wavelet transform

1 INTRODUCTION

Nondestructive evaluation of oil and gas pipelines integrity is an ever important issue. Such a task can be dealt with using a pipeline inspection gauge (PIG) travelling inside the pipeline. There are two main types of such devices - containing either ultrasonic transducers (UT) [1] or magnetic flux leakage (MFL) detectors [2]. In the latter case, which will be the topic of the present paper, the leakage is enforced by the set of permanent magnets, coupled with the help of a magnetic yoke, moving along the pipeline. The leakage signal is measured with the help of Hall effect sensors. The physics behind the method is relatively simple, yet there are many factors that have to be taken into account while considering such devices. The crucial parameters are magnetisation level inside the inspected material, flaw location and orientation (surface/subsurface crack, parallel/perpendicular to the flux lines direction) and the PIG's travelling speed. In the present paper we will not deal with the PIG's technical parameters, concentrating mainly on the analysis of the experimental results. There are several procedures that can be applied for the flaw detection such as *eg* artificial neural networks [3] or wavelet analysis [4]. We propose to adopt the second approach. The increase in computational power during the last years has been so significant that the high resolution, multi channel, multi scale continuous wavelet transform can be performed using an arbitrarily chosen wavelet on a standard PC in a very short time (of order of several seconds per meter of inspected section).

There are known several commercial applications of pipeline inspection devices, in this paper however we describe the results obtained during tests of one section of a PIG device that is currently being constructed by CDRiA Pipeline Services Ltd. in cooperation with Gdansk University of Technology. It is designed as a very high resolution, fully autonomous device suitable for both gas and oil pipelines inspection (while only the latter type can be inspected with the help of UT inspection devices).

2 WAVELET TRANSFORM

A wavelet is an oscillation-like function (see Fig. 1 for an example), which in contrast to sine/cosine functions used in the Fourier analysis is localized in time [5,6].

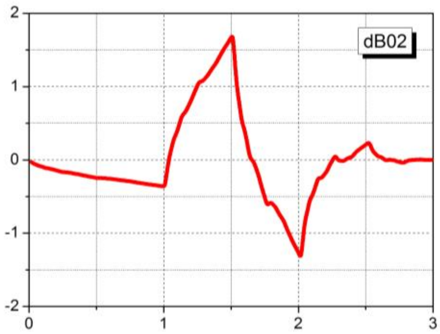

Fig. 1. An example of a wavelet—Daubechies

Being so it is much better suited to analysis of the signals that are not periodical, such as for instance pulsed noise signals [7] or (at the other end of frequency range) single oscillation events (such as for instance signals detected during the passage of the Hall probe over a crack). In a continuous wavelet transform (CWT) the procedure of CWT coefficient determination consist in calculation of the integral:

$$CWT(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} s(t) \psi\left(\frac{t-b}{a}\right) dt, \qquad (1)$$

where *a* determines the scale of the wavelet (the higher the scale the wider the time span of the wavelet). Once the integral is calculated, the wavelet is shifted in time and the procedure is repeated. The *b* parameter determines the translation of the function and gives the time domain localization of a given CWT coefficient. The

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CWT is in principle irreversible and does not allow to recreate the signal after modification of the CWT coefficient. Being so all the conclusions are to be drawn on the basis of the analysis of the coefficient matrix.

3 ANALYSIS OF EXPERIMENTAL RESULTS

In the investigated device, the MFL is characterised with the help of three Hall probes per channel - one of them measures magnetic induction in the direction parallel to the movement direction (*Bx*) and two others measure its normal component (*Bz*) and on that basis determine its spatial derivative $\partial Bz/\partial x$ - *ie* gradient of *Bz* along *x* axis. The tests were performed on the set of steel plates (length L = 1,2m, width w = 0,5m, thickness h = 10mm), containing artificially prepared flaws simulating cracks, corrosion pits, etc. As it turned out, in the case of shallow "cracks", and particularly in the case of smooth dips simulating corrosion pits, detection is not so straightforward. There are two main reasons for that. Firstly the signal is somewhat noisy, the second reason arises from the fact that the magnetic flux leakage is velocity dependent - the overall leakage strongly increases with the increase of the device speed. The signal originating from the flaw is superimposed on the background leakage signal the changes of which can, to some degree, mask the interesting signal.

There are several methods of denoising signals that could be applied, there are also known algorithms that can be used for baseline tracking and deduction. However both problems can be dealt with simultaneously by applying the wavelet analysis. The wavelet functions are particularly suited for the analysis of non-harmonic signals as they are localized both in time and frequency domains. We have performed continuous wavelet transform of the measured signal, with the help of a dedicated software working in the LabVIEW environment. As a result we have obtained denoised, zero background level signals for which flaw location detection is very straightforward. It can be done *eg* with the help of peak detection tools. In addition to that, by analysing the CWT coefficient obtained for different scales one can obtain the information on the flaw size. There are many wavelet functions suitable for different induction component, *eg* in order to analyse the B_x component the Daubechies db02 wavelet is appropriate, whereas for the derivative the better suited are either Mexican Hat or Morlet wavelets. In Fig. 2 - Fig. 4 there are presented the results of the CWT analysis (CWT coefficients absolute values) obtained for the plate with simulated "cracks" of increasing depth (from left to right - 20 to 80 % of thickness) for the Mexican Hat (Fig. 2,3) and Morlet wavelet (Fig. 4). In these pictures 5000 points is approximately equivalent to the sample length L. In both cases the derivative component has been taken into account. As can be seen the overall amplitude of CWTs increases with the increase of the scales of wavelets, yet the increase is higher for deeper "cracks". An important benefit of CWT analysis is that the obtained coefficient are very close to zero in the regions without flaws. Being so the peak detection analysis is very straightforward to apply for the flaws localisation - there is no need to trace the baseline

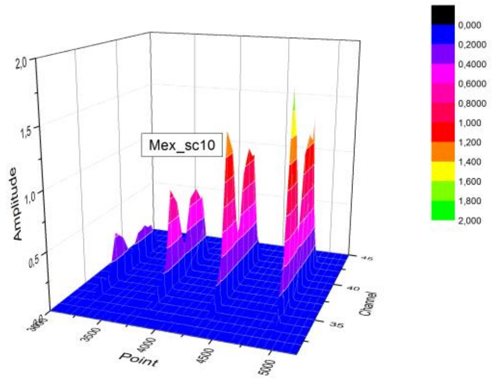

Fig. 2. Mexican Hat CWT coefficients for small scales (scale 10)

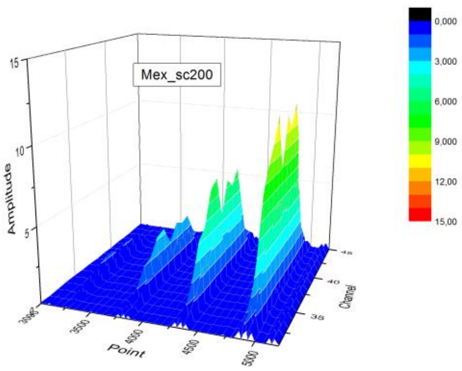

Fig. 3. Mexican Hat CWT coefficients for large scales (scale 200)

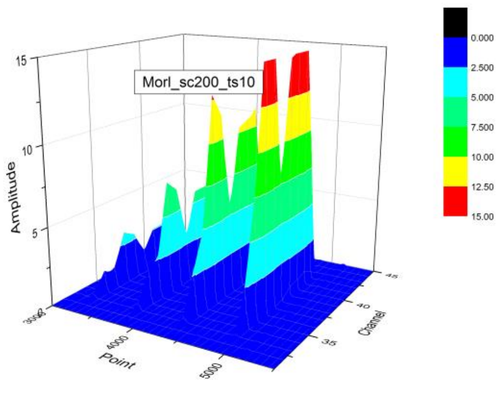

Fig. 4. Morlet CWT coefficients for large scales (scale 200)

of the signal. Such an attempt was made and the LabVIEW based software was created. On the basis of CWT coefficient matrix the best wavelet scale (for which the flaw signals are the most pronounced) is chosen. For this scale the peak detection algorithm seeks for the flaws position. The character of CWT coefficient close to the flaws is oscillatory, so the algorithm regards the peaks within the user defined range as a one flaw. Once the flaws are detected, the analysing software determines the profiles of the flaws in the scale domain, which is related to the physical size of the leakage region. In Fig. 5 one can see profiles obtained for the B_X component using Mexican Hat wavelet. The X value is proportional to the position of the flaw. As can be noted the bigger flaws (X = 296 and X = 366) are easily discernible from the other two. This is however not the case for the two smaller flaws, which is a result of an oscillatory character of CWTs. The problem may be dealt with by averaging CWTs obtained for the points close to the flaw. The results of such procedure are shown in Fig. 6. In this case all the flaws are clearly discernible.

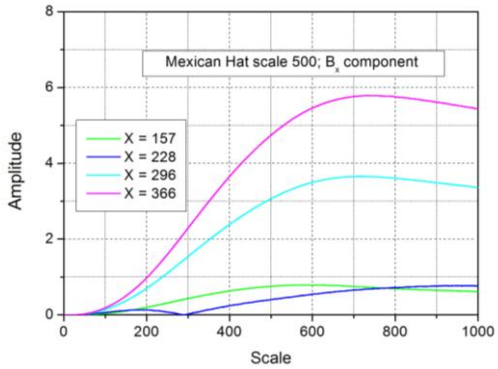

Fig. 5. Flaw profiles (scale domain) obtained for the Mexican Hat wavelet and the B_X component of the signal

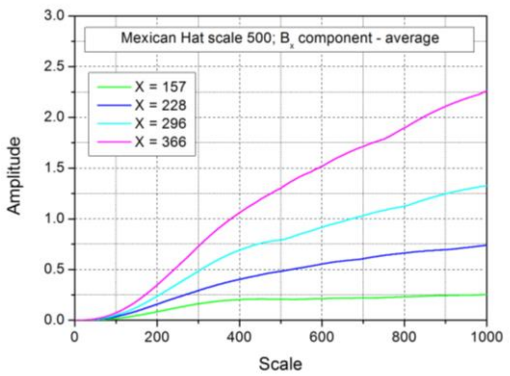

Fig. 6. Flaw profiles (scale domain) obtained for the Mexican Hat wavelet and the B_X component of the signal - space averaged

The results of such analysis for the derivative component of the signal are shown in Fig. 7. In this case there is no need to average signals - the profiles of the flaws are clearly separated and in a correct order. In addition to that one can observe that for bigger flaws the maxima of the profiles are observed for bigger scales what suggest that the flux leakage in those cases starts farther from the flaw edge. Such behaviour is probably due to the fact that the profile of the derivative component of the flux leakage from a crack is very similar to the Mexican Hat wavelet. Being so one can conclude that the best choice is to use gradient signal and Mexican Hat or Morlet wavelet and discard the other components. One can however seek for wavelets better suited to the B_X signal analysis. An obvious choice might be the Daubechies db02 function (see Fig. 1) - which is somewhat similar to the observed signal. But there is another possibility, *ie* one can use a measured signal as a model function and on its basis create a user-defined wavelet.

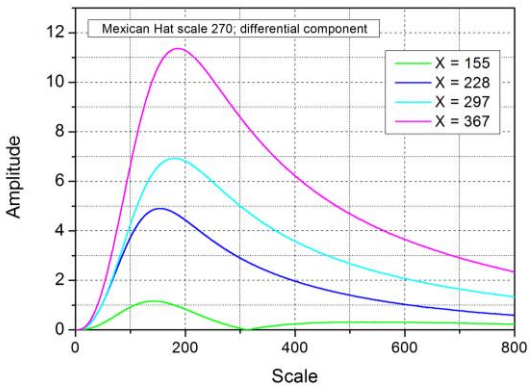

Fig. 7. Flaw profiles (scale domain) obtained for the Mexican Hat wavelet and the derivative component of the signal

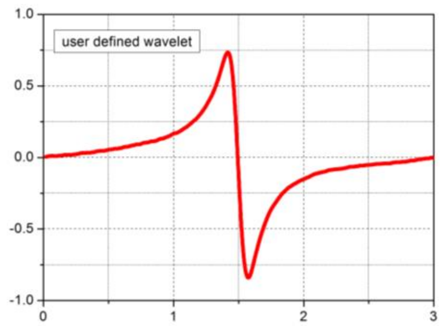

Fig. 8. User defined wavelet for the B_X component analysis

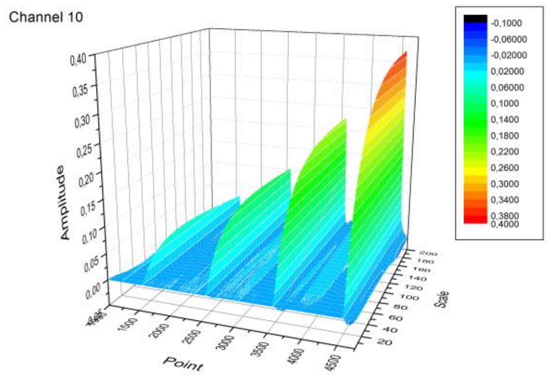

Fig. 9. CWT coefficients obtained with the help of the user defined wavelet

It is relatively easy if we realize that the numerical integration (CWT coefficient determination) performed by the LabVIEW procedures is in fact done using the wavelet stored as an array of points.

Being so one can interpolate the experimental data to fit the size of LabVIEW based wavelets and substitute it for the original. An example of such a wavelet is shown in Fig. 8, the experimental results used in that case were obtained during the movement of magnetizing rig with a very small velocity. The results of the CWT analysis for the created wavelet are shown in Fig. 9. All the flaws are easily discernible and the background level is practically equal to zero. In this picture the actual values (not the absolutes) are pictured and yet there are almost no negative coefficients - it is a result of a very strong similarity of the wavelet function to the signal. What is important for analysing the B_X component signal, is the fact that it is strongly dependent on the velocity of the magnetizing set movement, due to the eddy current driven concentration of the flux in the subsurface area. The example of results obtained for two velocities are shown in Fig. 10, the background signal in the case of the fast run (about 3 m/s) is significantly higher than for the slow (about 1 m/s) one. The positions of two strong signals at the start and end correspond to physical dimensions of the investigated plate. The results of the wavelet analysis are free from such a drawback, see Fig. 11. The wavelet coefficients obtained in the case of both runs are very similar, the small spatial shift of the signals is a consequence of a small mismatch of the starting point. In both cases however the peak positions can be easily determined with the help of an automated software.

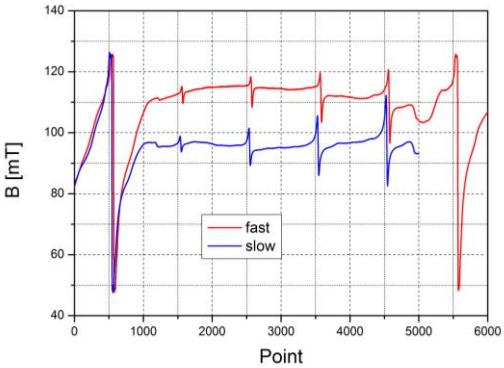

Fig. 10. B_X component of the MFL signals obtained for two runs with different velocities

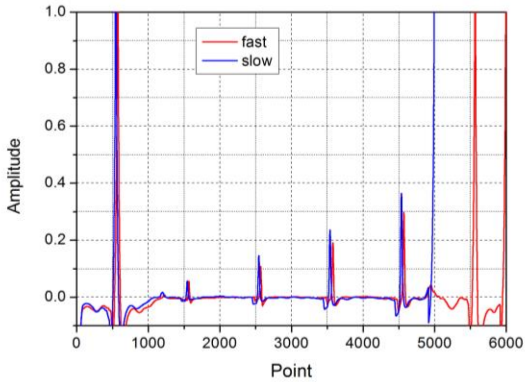

Fig. 11. CWT coefficient for two runs with different velocities - user defined wavelet

4 CONCLUSIONS

Magnetic flux leakage signals are very useful for the flaw detection in ferromagnetic materials. There are some problems connected with background noise level and signal dependence on the inspection device velocity. They can be dealt with by applying the wavelet analysis of the measured signals. By analysing the CWT coefficient obtained for different scales one can not only find the location of the flaws but also obtain the information on the flaw size. There are many wavelet functions suitable for different induction component, *eg* in order to analyse the B_x component the Daubechies db02 wavelet is appropriate, whereas for the derivative the better suited are either Mexican Hat or Morlet wavelets. It is also possible to design custom wavelet function on the basis of experimentally obtained signals. The wavelet tool undoubtedly is a very powerful tool for the MFL signal analysis.

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