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Wavelet based signal analysis of pulsed eddy current signals

***Abstract**. This paper deals with response signals processing in eddy current non-destructive testing. Non-sinusoidal excitation is utilized to drive eddy currents in a conductive specimen. The response signals due to a notch with variable depth are calculated by numerical means. The signals are processed in order to evaluate the depth of the notch. Wavelet transformation is used for this purpose. Obtained results are presented and discussed in this paper.*

***Streszczenie.** Praca dotyczy sygnałów wzbudzanych przy nieniszczącym testowaniu za pomocą prądów wirowych. Przy pomocy symulacji numerycznych wyznaczono sygnały odpowiedzi dla niesinusoidalnych sygnałów wzbudzających i defektów o różnej głębokości. Celem symulacji jest wyznaczenie zależności pozwalającej wyznaczyć głębokość defektu w zależności od odbieranego sygnału. W artykule omówiono wykorzystanie do tego celu transformaty falkowej. (**Analiza falkowa impulsowych prądów wirowych**)*

Keywords: non-destructive evaluation, eddy currents, pulse excitation, wavelet transform.
Słowa kluczowe: badania nieniszczące, prądy wirowe, analiza falkowa.

Introduction

Eddy current testing (ECT) is an effective technique for non-destructive inspection of conductive materials. Conventional ECT employs harmonic driving with single or multiple frequencies. Multi-frequency systems usually utilize two or three frequencies with very complex mixing system requirements for the signal analysis. In contrast to harmonic driven eddy currents, pulsed eddy current (PEC) testing utilises a short electrical pulse to obtain similar results as in the multi-frequency ECT technique. The main advantages of PEC system are that it can possibly generate a wider band of frequencies and it allows deeper penetration of eddy currents through a metal sample when compared to the conventional harmonic driven ECT. The driving pulse can be very short with a high voltage which potentially allows the generation of higher power pulses that can be used without overheating the probe. This can help to momentarily produce magnetic saturation in a ferromagnetic part and allows the subsequent detection of subsurface flaws in ferromagnetic materials, [1, 2].

Most of the information in a signal is carried by its irregular structures and its transient phenomena. Finding of small fluctuations in the time-domain is rather difficult task. However, these difficulties can be overcome by transformation into the frequency domain. Conventional method used for converting a signal into the frequency domain is the Fourier transform. Still a certain instance may vary in time and/or space over the frequencies. In such cases it is preferable to decompose the signal with spatial localization of the variations in spectral composition of the signal. This alternative can be achieved by using the Short Time Fourier transform (STFT) and the Wavelet transform (WT). Due to the decomposition of a signal into elementary building blocks that are well localized in both time and frequency, the Wavelet Transform is capable of defining the local irregularity of a signal.

Methods

The PEC technique uses a non-sinusoidal voltage to excite the probe. The advantage of using such a driving voltage is that according to Fourier theory it can be decomposed into a sequence of harmonic signals. Hence, the electromagnetic response to several different frequencies can be measured within a single step and information from a range of material depths can be obtained all at once. To improve the strength and simplify the interpretation of the signal, a reference signal from area without defects is usually collected and is compared with other signals. Flaws, conductivity, and dimensional changes produce a change in the signal and a difference between the reference signal and the measured signal is then displayed. The distance of the flaw and other features relative to the probe will cause the signal to shift in time. [2]

Continuous Wavelet Transform

The continuous wavelet transform (CWT) was developed as an alternative approach to the STFT. The CWT analysis is similar to STFT. The signal is multiplied with a function similar to the window function in STFT and the transform is computed separately for different segments of the time-domain signal. In the WT the window function is replaced by a function ψ - the wavelet function. The wavelet function is a function with zero mean well localized in both frequency and time. There are several functions satisfying the properties of a wavelet, e.g. the Morlet, which is defined as

$$\psi_0(\eta) = \pi^{-\frac{1}{4}} e^{j\omega_0\eta} e^{-\frac{1}{2}\eta^2} , \tag{1}$$

where ω_0 is dimensionless frequency and η is dimensionless time. The Morlet wavelet provides a good balance between time and frequency localization.

The CWT applies the wavelet as a bandpass filter to the time series. For one-dimensional discrete time signal $x(n)$, the CWT is calculated as its convolution with scaled and translated function ψ - mother wavelet, which is stretched in time by varying its scale a, so that $\eta = a \cdot t$, and shifted along the time axis by varying its location parameter b

$$W(a,b) = \sum_{n=0}^{N-1} x(n) \psi^* \left(\frac{(n-b)\delta t}{a} \right), \tag{2}$$

where * denotes a complex conjugate. By varying the wavelet scale a and translating along the time by means of location index b, it is possible to construct a picture showing both the amplitude features versus the scale and amplitude variations in time. In practice it is faster to implement the convolution in Fourier space and the wavelet transform is then the inverse Fourier transform of the product of the Fourier transforms of $x(n)$ and ψ

$$W(a,b) = \sum_{k=0}^{N-1} X(k)\, \Psi^*(a\omega_k) e^{j\omega_k b \delta t} , \tag{3}$$

To ensure that the wavelet transforms (3) at each scale a are directly comparable to each other and to the transforms of other time series, the wavelet function at each scale a is normalized to have unit energy [6]. After the transform is computed the wavelet power spectrum is estimated as $|W(a,b)|^2$.

Cross-wavelet spectrum

For two time series x and y with wavelet transforms $W_x(a,b)$ and $W_y(a,b)$ the cross-wavelet spectrum is defined as $W_{xy}(a,b) = W_x(a,b)W_y^*(a,b)$. In general, the cross-wavelet spectrum of two complex wavelet transforms is also complex, and hence the cross-wavelet power (WCPS) is $|W_{xy}(a,b)|$. Confidence intervals are shown in all WPS figures (solid black line) in order to compare the peaks in a wavelet power spectrum against the mean background. The confidence interval of 95% corresponds to the desired significance p = 0.05. The confidence interval is defined as the probability that the true wavelet power at a certain time and scale lies within a certain interval around the estimated wavelet power. Confidence levels for the cross-wavelet power can be derived from the square root of the product of two chi-square distributions [6].

Results

The PEC signals applied for wavelet analysis are obtained from numerical simulations. The probe used in the simulations is a simple absolute pancake probe with number of turns N=40 and dimensions (in mm) shown in Fig. 1a). Probe is driven by non-sinusoidal current I = 1A of 'Peak' type built in Vector Fields Opera. At first the probe is placed over the plate over the area without defect and then over the area with defect, Fig. 1b), with a lift off d=1mm.

The probe is of the absolute type, thus it serves as exciter and pickup at the same time. Numerical simulations are performed for several driving pulse periods and results for two of them are presented in this paper; $T_{d1} = 1$ ms and $T_{d2} = 10$ ms. The PEC signal response is computed for 5 different flaw depths shown in Table 1.

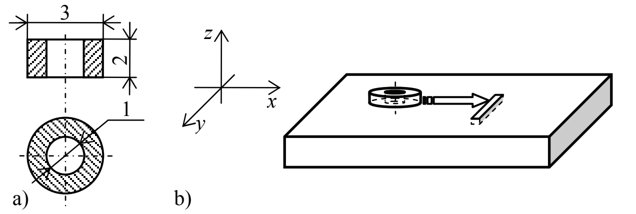

Fig.1. Probe and specimen arrangement

Table 1. The dimensions of the defects

Defect	Width [mm]	Length [mm]	Depth [mm]
#1	0.2	10	1
#2	0.2	10	3
#3	0.2	10	5
#4	0.2	10	7
#5	0.2	10	9

Time domain representation of first 0,1ms of time series for driving pulse periods $T_{d1} = 1$ ms and $T_{d2} = 10$ ms and all five defect depths are shown in Fig. 2.

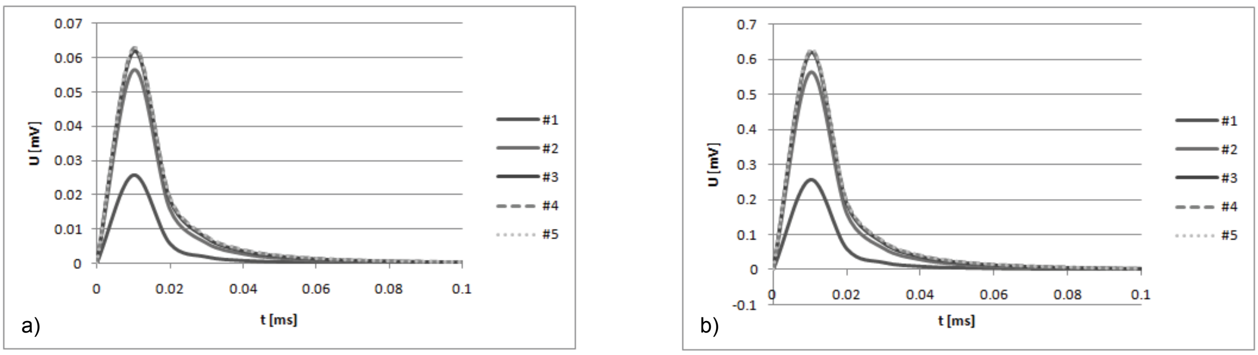

Fig.2. Differential voltage response of: a) T_{d1} = 1ms, b) T_{d2} = 10ms

Increasing amplitude is in correlation with the growing depth of defect. The duration of transient phenomena is independent of the pulse period and is constant in all simulated cases; it depends on the time constant of circuit. Fig. 2 also shows that increasing depth of defect causes saturation of signals thus it is difficult to recognize deeper defects according to their responses in time domain.

For time-frequency representation of differential current response of simulated flaws CWT is performed and wavelet power spectrum (WPS) is computed. All transforms are computed using Morlet wavelet. Results of CWT for defects #1, #5 are shown in Figs. 3, 4. A sequence of flaw signals from #1 to #5 is shown in Fig. 5. for better illustration of changes in the time-frequency representation of signal.

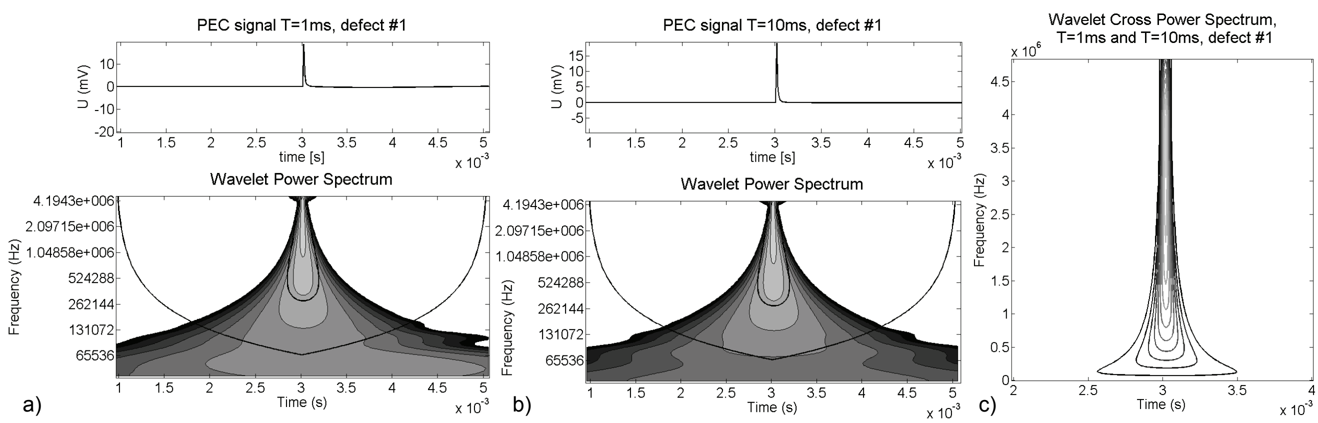

Fig.3. Differential voltage response and its WPS for defect #1 of a) T_{d1} = 1ms, b) T_{d2} = 10ms, c) WCPS

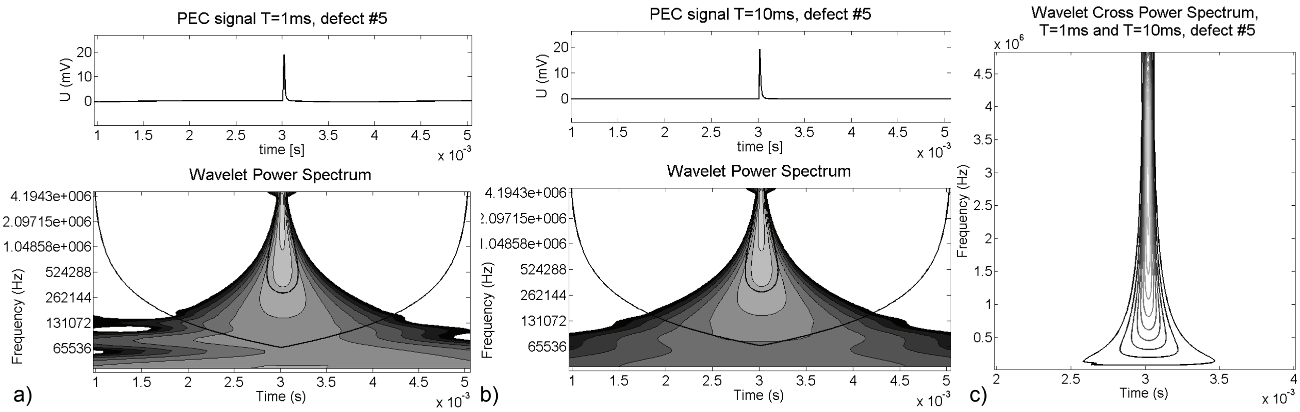

Fig.4. Differential voltage response and its WPS for defect #5 of a) T_{d1} = 1ms, b) T_{d2} = 10ms, c) WCPS

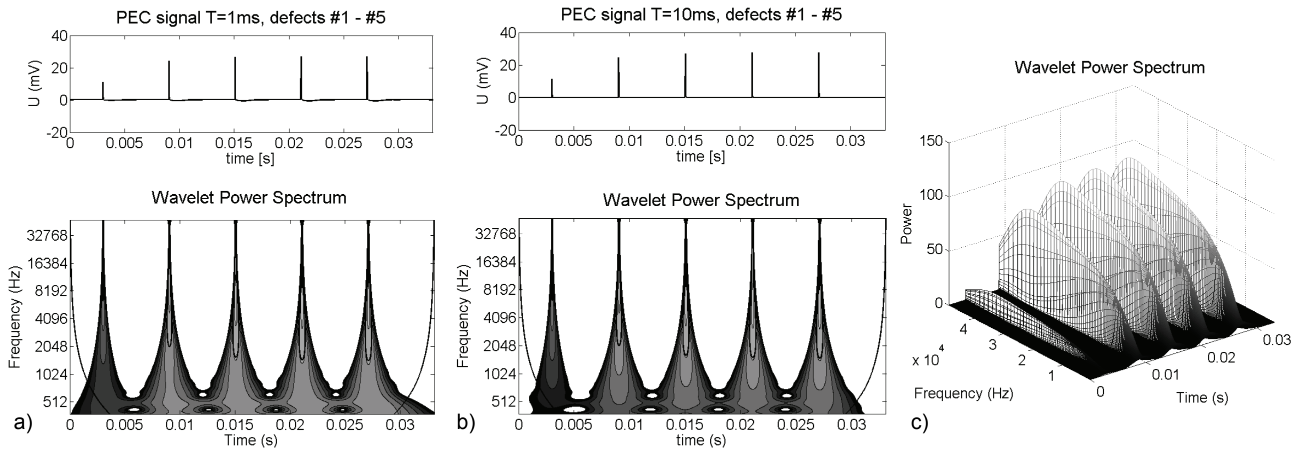

Fig.5. Differential voltage response and its WPS of sequence: a) T_{d1} = 1ms, flaws #1-5, b) T_{d2} = 10ms, flaws #1-5, c) WCPS

Results shown in Fig. 3 and Fig. 4 depict in more detail the effect of flaw depth and driving frequency on WPS. Overall representation of depth effect for all 5 depths of flaw and both the driving pulse periods is shown in Fig. 5. From the cross wavelet power spectrum, Fig. 5 c), it is possible to determine the flaw depth.

Conclusion

The pulsed eddy current testing method is a useful tool for non-destructive evaluation of conductive materials. Extraction of information carried in a response signal in the time-domain is rather difficult. Wavelet analysis is a useful tool for transformation of the time series from time domain into the time-frequency domain. The simulations were carried out for two driving pulse periods and five flaw depths in order to create data for further feature extraction. The data was processed using continuous wavelet transform and presented results show good resolution of flaw depth effect in time-frequency domain.

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