A Digital Signal Processing Technique for Pulsed Electromagnetic Inspection of Steel Tubes

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Abstract – A pulsed electromagnetic (PEM) technique is an effective method of nondestructive evaluation of steel tube inner diameter and wall thickness. Using time-spatial separation of direct-zone and remote-zone signals, it is possible to determine wall thickness and inner diameter with one receiving coil measuring voltage peak and zero-crossing time simultaneously. However, for fixed coil geometry the zero-crossing time can be recognized only for a limited range of wall thickness. In order to increase wall thickness range and shorten the probe, additional processing of the pulsed-eddy current signal must be applied. In this paper, we present a technique based on integration of the pick-up voltage and measurement of threshold-crossing time. The technique can be easily implemented in the existing PEM tool. We have verified the technique using numerically and experimentally obtained results for a range of tubes specified with API 5CT standard.

I. Introduction

A pulsed electromagnetic (PEM) technique is an effective method of nondestructive evaluation of steel tube inner diameter and wall thickness [1-2]. Proper placement of excitation and receiving coils provides time-spatial separation of direct-zone and remote-zone signals [1-3]. Thus, it is possible to determine wall thickness and inner diameter with one receiving coil measuring voltage peak and zero-crossing time simultaneously [3-4]. In order to accomplish this, coil separation should be between 1 – 1.3 tube outer diameters (OD) [4]. However, this approach limits range of wall thickness and inner diameter that can be measured. Radius of coils should be maximized, within targeted range of tube inner radius, in order to maximize the sensitivity.

If waveform is changed in a way that zero-crossing time feature cannot be recognized, other signal processing technique must be applied. Some signal processing techniques, such as wavelet transform, have been applied to pulsed-eddy current signals [5-6]. However, they are hard to implement for real time applications based on low-end or mid-range microcontrollers. We propose a signal processing technique that can be easily implemented in previously designed tool [3]. Its application enables extension of the tool inner diameter measuring range for approximately 25% with the tool probe shorten for approximately 40%.

II. Methods and materials

Using model based on Dodd and Deeds formalism, vector magnetic potential can be obtained for coil axially placed inside a steel tube [4]. Voltage induced in a pick-up coil can be calculated from the potential equation, for given excitation current. Transfer function is defined as a ratio of induced pick-up voltage and excitation current for given tube and coils parameters. The transfer functions were calculated for fixed geometry of the excitation coil and variable tube wall thickness and inner diameter. The excitation coil had inner radius 40 mm, outer radius 42.5 mm, length 50 mm, number of turns 300. Tube properties were the following: outer diameter OD=139.7 mm (5 1/2 ″), relative permeability μ_r=100 and conductivity σ=4.6 MS/m. Wide range of wall thickness between 6.2 – 22.25 mm are specified for OD=139.7 mm tubes with API 5CT standard [7].

Information about inner diameter is contained in voltage peaks, which are result of rise and fall of excitation current. After excitation is over, only information on tube wall thickness will be contained in the signal. Due to the AC coupling between the coils, the time integral of the pick-up voltage will approach zero as time increases. Because of the linearity of the system, time integral of the higher-frequency band of pick-up voltage (sensitive to the inner diameter) will diminish much faster than the lower frequency band (sensitive to the wall thickness). The first step in proposed signal processing technique is integration of pick-up voltage, implemented in digital domain as voltage samples summation:

$$u_{\mathrm{SUM}} = \sum_{n=0}^{K} u_{\text{pick-up}}\left(t_{\mathrm{n}}\right), \tag{1}$$

where n is sample number, and K is number of samples.

A new feature that we measure, in order to obtain wall thickness, is threshold crossing time t_{tc} defined as:

$$u_{\mathrm{SUM}}\left(t_{\mathrm{n}}\right) > U_{\mathrm{TC}} > u_{\mathrm{SUM}}\left(t_{\mathrm{n+1}}\right) \Rightarrow t_{\mathrm{tc}} \approx t_{\mathrm{n+1}}, \tag{2}$$

where U_{TC} is threshold value.

The method is experimentally verified on a tube with OD=60.3 mm, with three wall thicknesses, *c*: 1.45 mm, 2.45 mm and 3.45 mm. Separation between the coils were 50 mm (approximately 1 OD). Measurement setup is shown in Figure 1. Excitation current was pulse with magnitude of 250 mA, duration of 5 ms and repetition time of 100 ms. Signal was sampled at 80 kHz and 13-bit resolution. Signal-to-noise ratio was improved by averaging 20 consecutive measurements.

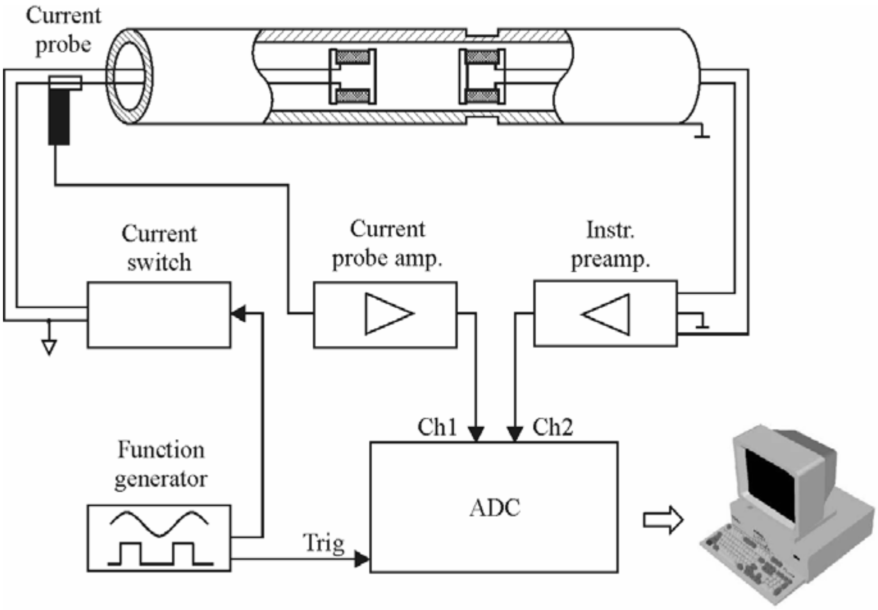

Figure 1. Measurement setup

III. Results and discussion

A. Numerical simulations

Waveforms of pick-up voltages for tube with OD=139.7 mm and coil separation *d*=180 mm, are shown in Figure 2a, whereas detailed view of zero-crossing is shown in Figure 2b. Zero-crossing feature does not exist on waveform obtained for tube with wall thickness *c*=4.85 mm, Figure 2a and Figure 2b.

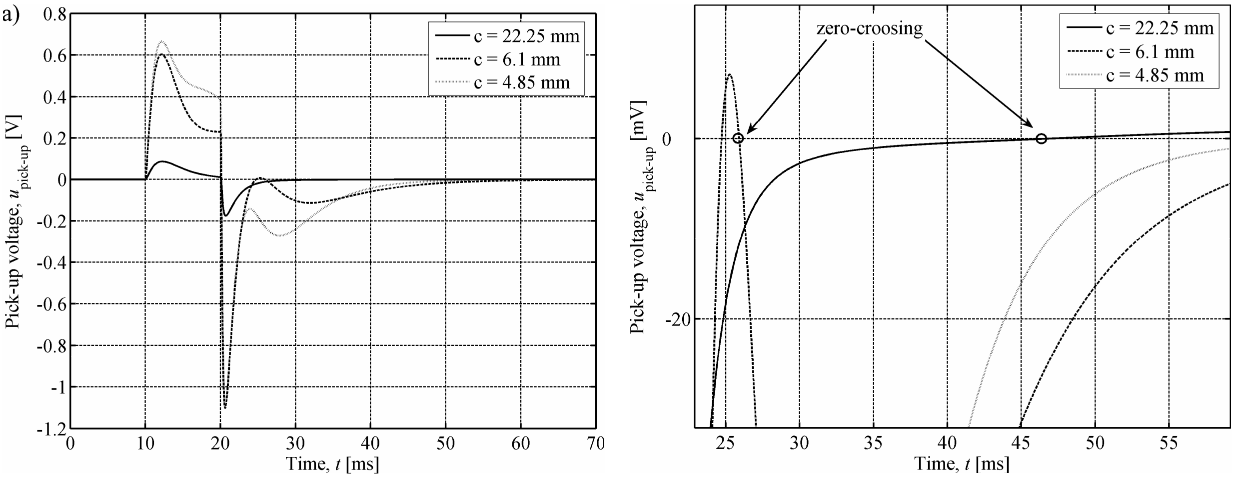

Figure 2. a) waveforms of induced pick-up voltages for tube with OD=139.7 mm, b) detailed view of zero-crossing

Propagation time τ of high and low frequency components, where high frequency components are contained in voltage peaks, are depicted in normalized pick-up voltage shown in Figure 3. Propagation time of high frequency components were measured from excitation start till maximum of pick-up voltage, whereas propagation time of low frequency components were measured from end of excitation till the second minimum of pick-up voltage. Measured propagation times of high frequency τ_{HF} components don't depend on wall thickness, in contrast to propagation time of low frequency components τ_{LF}, Table 1.

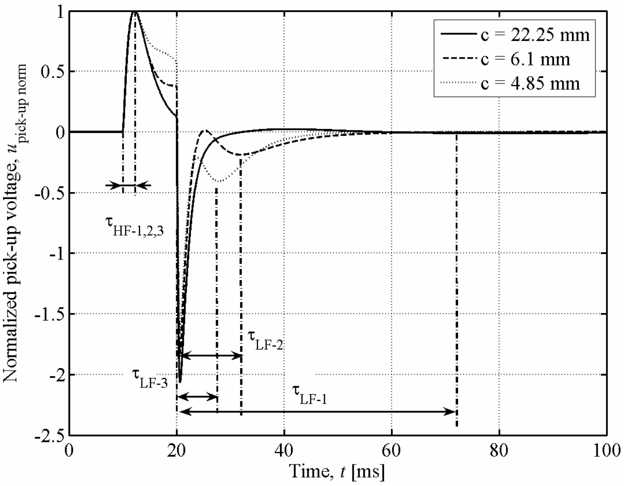

Figure 3. Propagation time of high frequency components $\tau_{\text{HF-i}}$, and low frequency components $\tau_{\text{LF-i}}$, for three wall thickness: c=22.25 mm (i=1), c=6.1 mm (i=2) and c=4.85 mm (i=3)

Table 1. Propagation time of high and low frequency components of normalized pick-up voltage

	Propagation time	
Wall thickness c [mm]	High frequency components, τ_{HF} [ms]	Low frequency components, τ_{LF} [ms]
22.25	2.2	58.6
6.1	2.2	11.9
4.85	2.2	7.9

Sum of pick-up voltage samples (integral), u_{SUM} is shown in Figure 4a, whereas detailed view of threshold-crossing is shown in Figure 4b. To ensure only one threshold-crossing event has occurred, threshold value U_{TC} has to be sufficiently small. It has been found empirically that threshold value, U_{TC} should be around 5% of maximum value of voltage samples sum for tube with the thickest wall in targeted range. Lower U_{TC} improves the sensitivity to wall thickness. However, this is limited with signal-to-noise ratio. For targeted wall thickness, c from 1 mm to 22 mm and outer diameter OD=139.7 mm, AD conversion of at least 14 bits is required.

In case of tube with OD=139.7 mm, chosen threshold value is U_{TC}=1 V. Relation between threshold-crossing time t_{tc} and wall thickness c is shown in Figure 5. It is linear function between 3.6 mm<c<14.225 mm.

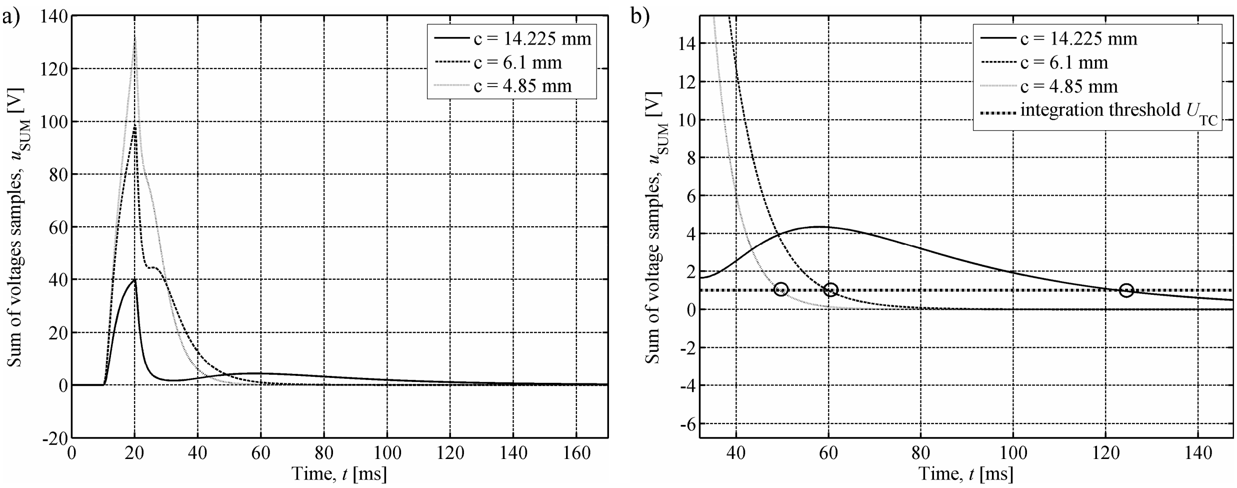

Figure 4. a) sum of pick-up voltage samples, b) detailed view of threshold-crossing

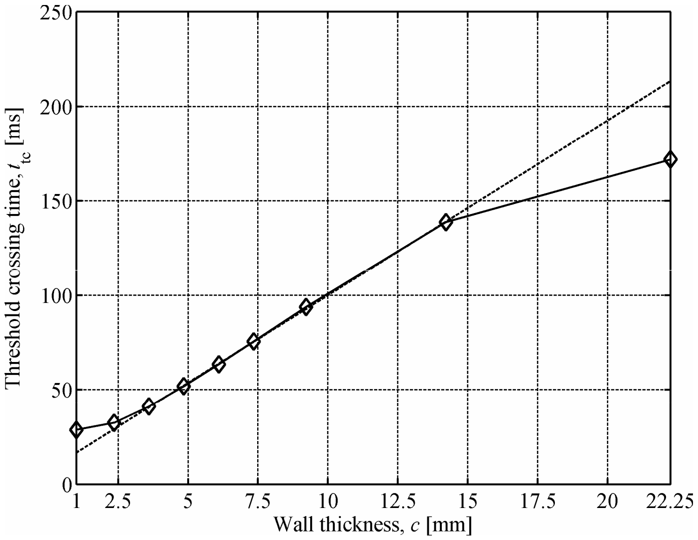

Figure 5. Threshold-crossing time t_{tc} depending on wall thickness c (dashed line – linear interpolation for wall thickness c for range between 3.6 – 14.225 mm)

B. Experiments

Experimentally obtained output waveforms are shown in Figure 6.

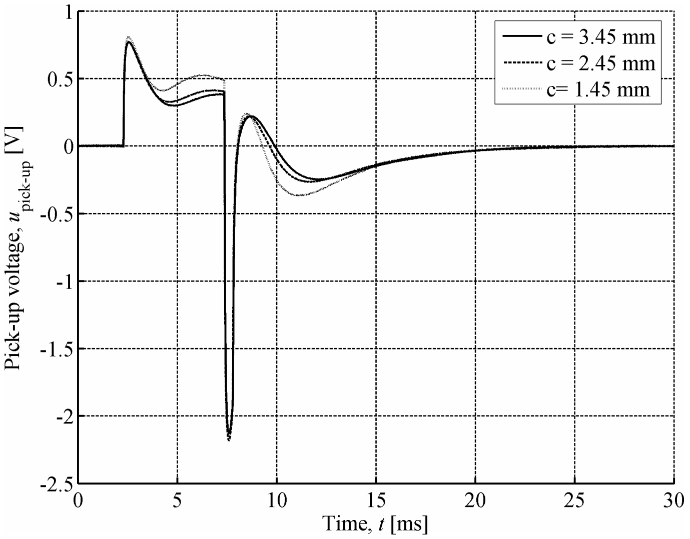

Figure 6. Measured voltage for tube with outer thinning (OD=60.3 mm)

Measured threshold-crossing time, t_{tc} for threshold value U_{TC}=10 V and zero-crossing time, t_{zc} are given in Table 2.

Table 2. Threshold crossing time depending on wall thickness

Wall thickness, c [mm]	Threshold-crossing time, t_{tc} [ms]	Zero-crossing time, t_{zc} [ms]	High frequency component propagation time, τ_{HF} [ms]	Low frequency component propagation time, τ_{LF} [ms]
1.45	18.69	9.28	0.27	3.64
2.45	19.08	9.62	0.27	4.27
3.45	19.41	9.90	0.27	4.8

IV. Conclusion

Using time-spatial separation of direct- and remote-zone signals, it is possible to determine wall thickness and inner diameter of a steel tube with one receiving coil measuring voltage peak and zero-crossing time simultaneously. Since the zero-crossing time can be recognized only for a limited range of wall thickness for a given coil geometry, additional signal processing must be applied to increase the wall thickness range and shorten the probe.

The proposed signal processing technique, featuring signal integration and threshold detection, has been verified using numerical and experimental data. The technique can be easily implemented for real-time operation in the existing mid-range microcontroller based tool. Its application enables extension of the tool inner diameter measuring range for approximately 25% with the tool probe shorten for approximately 40%.

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