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MEASUREMENT OF FERROMAGNETIC TUBE WALL THICKNESS USING PULSED REMOTE FIELD TECHNIQUE

*Darko Vasić, Vedran Bilas, Davorin Ambruš**

Faculty of Electrical Engineering and Computing, University of Zagreb, Zagreb, Croatia
*Brodarski Institute, Zagreb, Croatia

Abstract – Remote field eddy current (RFEC) technique is highly effective electromagnetic method for thickness measurement and assessment of ferromagnetic tube walls corrosion. Measurements in harsh environments can be improved by reducing probe power consumption, simplifying its construction and speeding-up data acquisition. That could be achieved using pulse instead of sinusoidal driving current. Finite element simulations of pulsed RFEC phenomena in ferromagnetic tubes suggested its relevance. We performed measurements of ferromagnetic tube wall thickness with both sinusoidal and pulse excitation. Our first findings confirm applicability of the pulsed RFEC technique. However, significant reduction of exciter power is paid with complex data analysis.

Keywords: wall thickness measurement, pulsed remote filed eddy current technique, ferromagnetic tube.

1. INTRODUCTION

Remote field eddy current (RFEC) technique is a relatively new, highly effective electromagnetic method for measurement of ferromagnetic tube wall thickness and nondestructive quantitative examination of other defects in the structure of the tube [1].

The basic RFEC probe consists of an exciter coil L_E and a detector coil L_D, Fig. 1. The coils are placed coaxially inside the tube at a fixed axial distance, usually two to three coil (tube) diameters R_2.

The exciter coil produces an exciter magnetic field that induces eddy currents within the tube wall. Those two opposite components (the exciter magnetic field $\boldsymbol{B}_C$ and magnetic field from the eddy currents $\boldsymbol{B}_{EC}$) give the resulting magnetic field inside the tube $\boldsymbol{B}_R$.

Fig. 2 shows amplitude and phase of the resulting magnetic field $\boldsymbol{B}_R$ along the tube axis from the exciter coil [1, 2]. In the proximity of the exciter coil (distances less then two coil diameters) the exciter magnetic field presents the dominant component. That zone, characterized with a strong but rapidly attenuating magnetic field, is known as a direct zone. After a transition zone at approximately two coil diameters, where both components are significant, follows a remote field zone where the magnetic field from eddy currents dominates. The transition is also observed as an abrupt change of magnetic field phase, according to Lenz's law. The remote filed zone is characterized with a weak but slowly decaying magnetic field.

Detector coil, being placed in the remote field zone, registers only the variations of the magnetic field from eddy currents, which is affected by material condition, thus greatly improving the sensitivity to wall thickness. Other eddy current non-destructive techniques have difficulties in condition evaluation of materials with high magnetic permeability, since they operate with both coils placed in the direct zone [1].

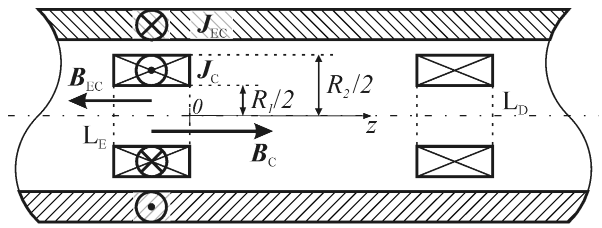

Fig. 1. Arrangement of the coils inside a ferromagnetic tube for RFEC measurement

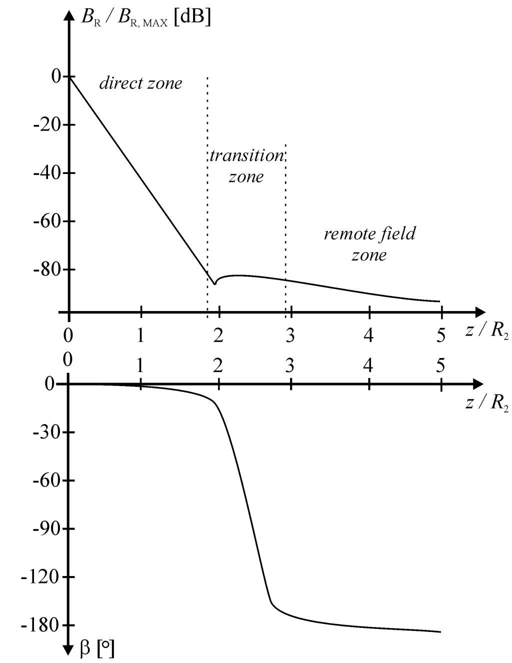

Fig. 2. Amplitude and phase of the resulting magnetic filed along the tube axis from the exciter coil

Commonly, the exciter coil is driven with relatively low frequency sinusoidal current (<100Hz). The amplitude of the voltage induced in the detector coil, as well as the phase between this voltage and the driving current are measured. Wall thickness affects these measurements following the well-known "skin-effect" equation, [2]:

$$B = B_o e^{-c\sqrt{\pi f \mu \sigma}} \sin\left(2\pi f t - c\sqrt{\pi f \mu \sigma}\right). \qquad (1)$$

B is magnetic flux density at any depth of the sample, B_o is magnetic flux density at the surface, c is thickness of the sample, f is frequency of the magnetic field, t is time, μ and σ are magnetic permeability and electrical conductivity of the sample material. According to (1), wall thinning can be observed as an increase of the induced voltage phase or amplitude. There are also well-established methods for interpreting other wall defects from the measured data [1].

To further improve the application of RFEC technique in tubes under extremely harsh environments, such as oil wells, where temperatures are up to 180°C and the power is delivered through a several kilometers long cable, simple and reliable probes with low power consumption are required [3]. Also, it is advantageous to make the data acquisition from the tubing as fast as possible, to reduce losses in production.

Recently, attention has been paid to potential application of pulse instead of sinusoidal driving current. Results of the first finite element simulations of pulsed RFEC phenomena suggested its applicability for detection of wall defects in the ferromagnetic tubes [4]. The total amount of dissipated power for pulsed excitation would be considerably lower. Besides, pulse excitation contains a large number of frequencies enabling acquisition of more information than a single frequency measurement. On the other hand, more complex processing and analysis of the acquired data would be necessary for interpretation.

In this paper we present results of the first experimental study of the application of pulsed RFEC technique for measurement of ferromagnetic tube wall thickness. The measurement with sinusoidal excitation was performed as well and the comparison of the results is given.

2. EXPERIMENTAL SET-UP AND PROCEDURE

Measurements were performed on a 1,46m long ferromagnetic steel tube, with inner diameter R_i=51,4mm and outer diameter R_o=60,3mm. Three axisymmetric external defects were machined with depths d_1=1mm, d_2=2mm and d_3=3mm (tolerances ±0,1mm), each 40mm long and displaced for 32cm.

Exciter coil (N_e=300) and detector coil (N_d=1100) were fixed on a plastic rod that was inserted into the tube, axially centralized and moved along the tube as a unit. During the wall thickness measurement, position of the coils in the tube was measured with the resolution of ±0,5mm.

Measurement set-up is depicted in Fig. 3. The exciter coil was fed from a power amplifier driven by a signal generator. We applied sinusoidal current at 60 and 80Hz and pulsed current with square pulse duration of 4ms and frequency 35Hz.

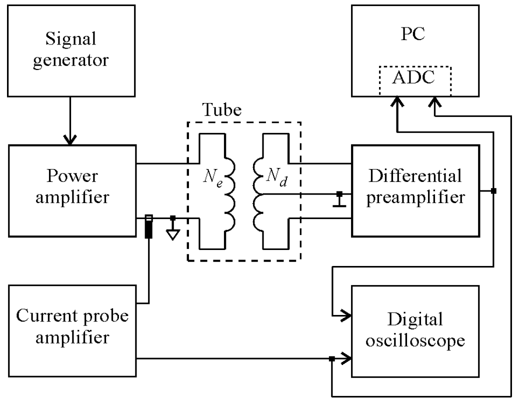

Fig. 3. Block diagram of the tube wall thickness measurement set-up

The driving current was measured with a current probe (*Tektronix,* TM502A). Low-level voltage induced in the detector coil was amplified using a sensitive differential pre-amplifier (A_d=2000, *CMRR*=106dB, f_L=0,1Hz, f_H =1kHz). Both voltages, from the current probe amplifier and the differential preamplifier, were monitored on a digital oscilloscope (*Tektronix,* TEK2440) and digitized using 16-bit A/D converter (PC AD board PCMDAS 16) at sampling rate of 4000Hz for sinusoidal and 50000Hz for pulse excitation. Data processing and analysis were performed on a personal computer using MATLAB software package. Amplitude and phase of sinusoidal response were calculated from several periods of the signal. In the case of pulse excitation, up to twenty responses were averaged and filtered with low-pass digital filter (f_H =3,7kHz) in order to improve signal to noise ratio.

3. RESULTS

3.1. Measurement with sinusoidal driving current

Amplitude and phase of the voltage induced in the detector coil vs. its position along the tube are given in Fig. 4 and Fig. 5. The position of the detector coil is measured from the left edge of the tube. Passing of the detector coil beneath the severest defect (wall thickness c = 1,45mm) is denoted with D and passing of the exciter coil with E.

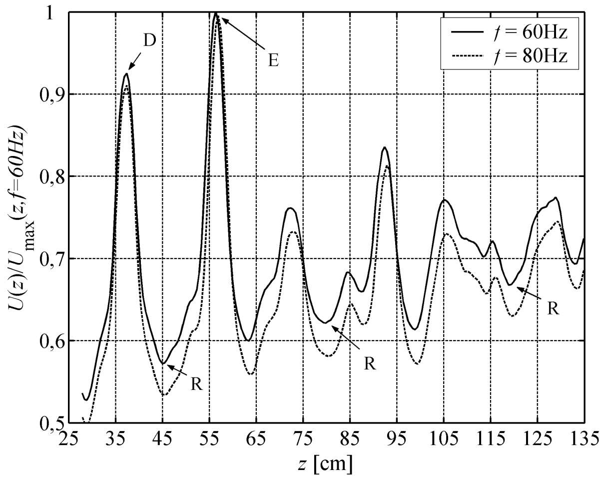

Fig. 4. Amplitude of the voltage induced in the detector coil vs. its position along the tube

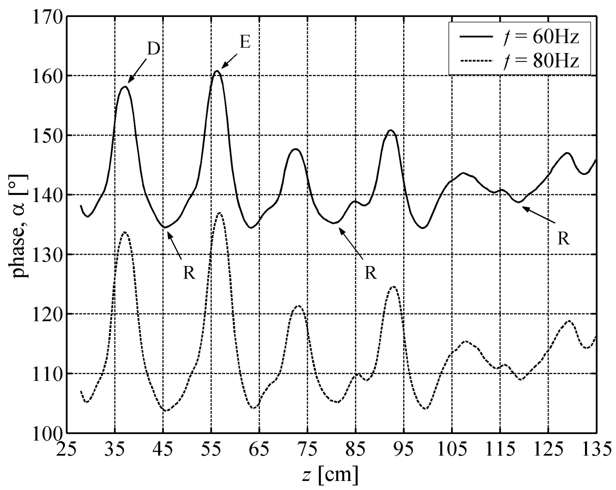

Fig. 5. Phase of the voltage induced in the detector coil vs. its position along the tube

Since proximity of the edges of the tube affects the measurement, phase and amplitude were measured relative to the reference point denoted with R for every defect.

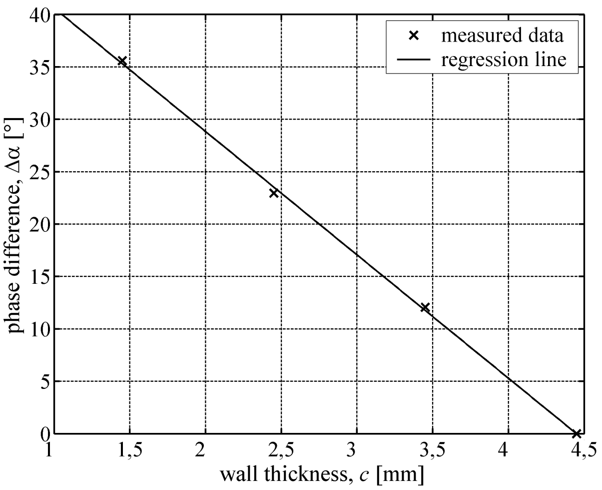

Fig. 6. Relationship between measured phase difference Δα of the induced voltage and wall thickness *c*

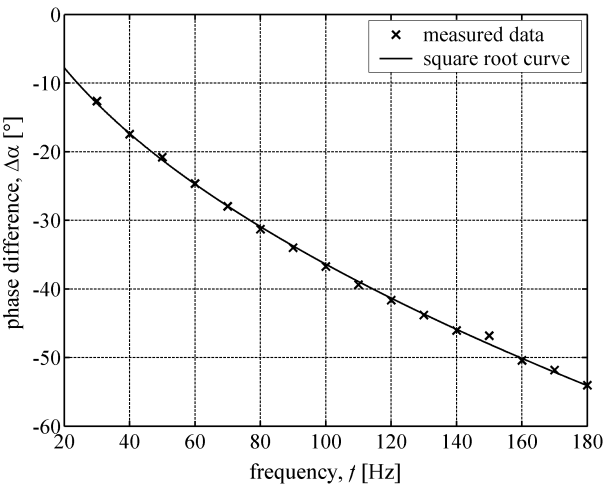

Fig. 7. Relationship between phase difference Δα and excitation frequency *f* (wall thickness *c*=1,45mm)

Fig. 6 shows phase difference $\Delta\alpha = \alpha - \alpha_R$ of the induced voltage vs. wall thickness. The phase difference for wall thickness *c*=4,45mm (wall without any defect) is set to zero. The phase difference for wall thickness *c*=1,45mm (the severest defect) vs. excitation frequency is given in Fig. 7.

3.2. Measurement with pulse driving current

Waveforms of the signals u_d detected with square pulse excitation for three different wall thicknesses are shown in Fig. 8.

Time delay t_d, measured from the start of the current pulse (t = 0) to the zero crossing of the signal waveform, Fig. 8, is used as a characteristic parameter for the measurement of wall thickness [4].

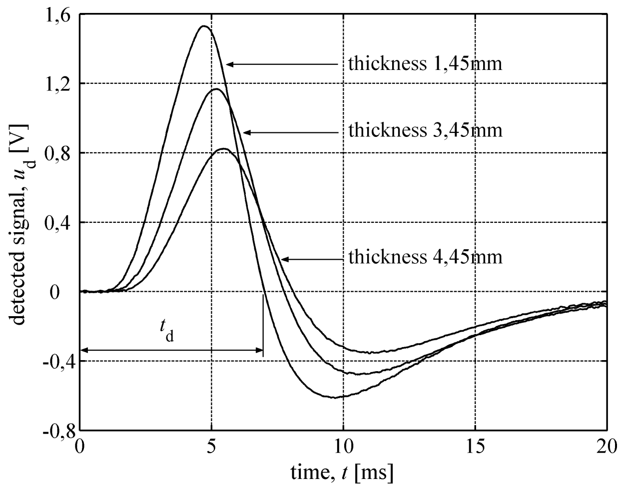

Fig. 8. Induced voltage u_d detected with pulse excitation for three wall thicknesses, definition of time delay t_d

The results of measured time delay t_d vs. wall thickness *c* are given in Fig. 9.

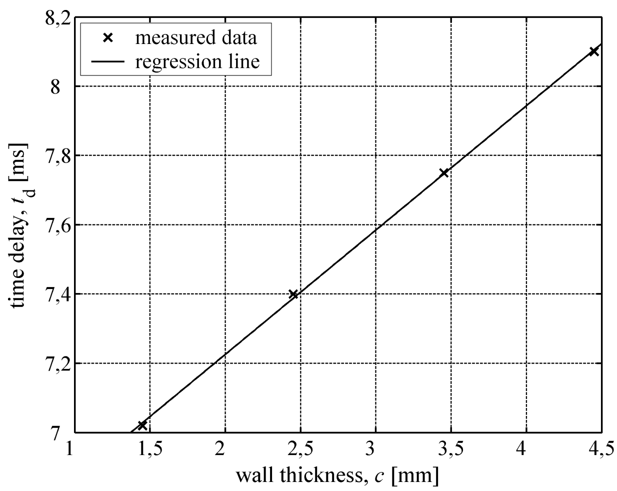

Fig. 9. Relationship between measured time delay t_d and wall thickness *c* of ferromagnetic tube for square pulse excitation

Amplitude and phase spectra of the detected signal u_d (wall thickness *c*=1,45mm and *c*=4,45mm) are shown in Fig. 10 and Fig. 11, respectively.

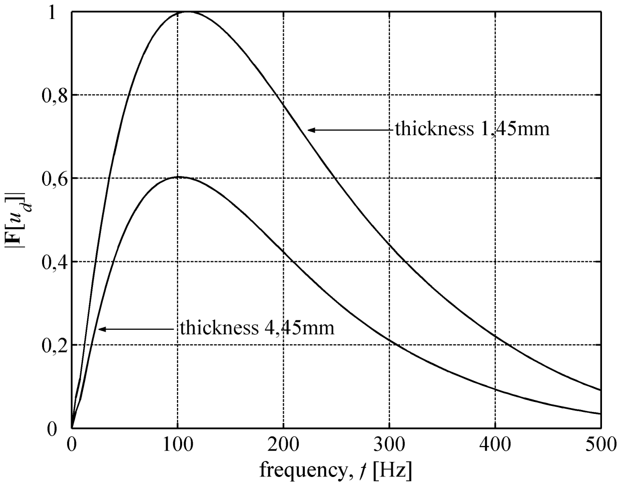

Fig. 10. Amplitude spectrum of the detected signal u_d for wall thickness c=1,45mm and c=4,45mm

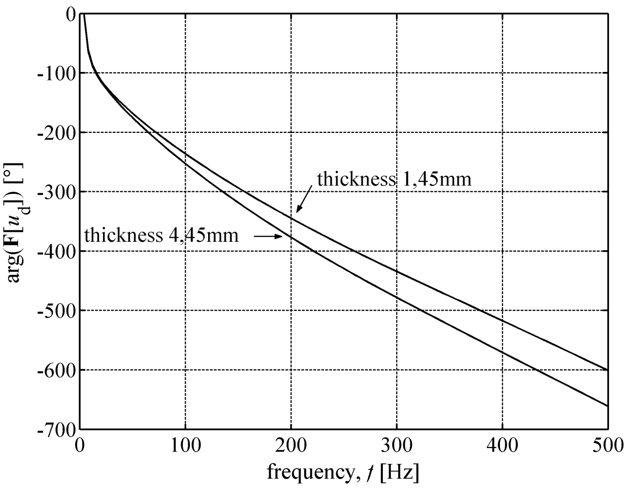

Fig. 11. Phase spectrum of the detected signal u_d for wall thickness c=1,45mm and c=4,45mm

4. DISCUSSION

Maximal driving current in both presented measurements was the same, but rms current for pulse excitation was 10 times lower.

Linear relationship between phase of the induced voltage and wall thickness for sinusoidal excitation, Fig. 6, is in excellent agreement with (1), in spite of its relative simplicity [1, 2]. Phase difference $\Delta\alpha$, shown in Fig. 7, increases with square root of the excitation frequency, as expected from (1).

Time delay t_d of the pulse response follows linear relationship with wall thickness, Fig. 9, same as phase difference $\Delta\alpha$. Fig. 8 shows that maximum and minimum of the signal waveform greatly depend on wall thickness too. The presence of time lag of the signal waveforms in Fig. 8 indicates a diffusion character of eddy currents.

Fig. 12 shows results of finite element analysis of pulsed RFEC phenomena with the same geometry as in presented measurement. Conductivity of the ferromagnetic material was 6MSm^{-1} and relative permeability was 100. The simulation was performed using EMAS (*Ansoft*) software package with 130 time steps in approximately 20000 nodes. Excellent qualitative agreement with Fig. 8 is evident.

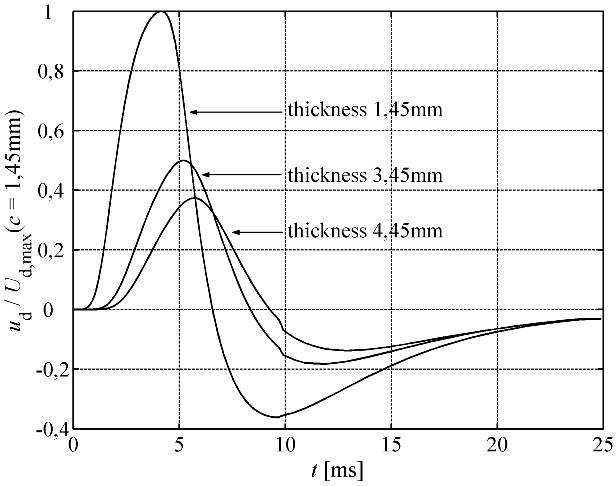

Fig. 12. Results of finite element analysis for different wall thicknesses in case of pulse excitation

The difference between the signal waveforms in Fig. 8 is also visible in the amplitude and phase spectrum in Fig. 10 and Fig. 11, respectively. Although the difference between the phase spectra in Fig. 11 increases with frequency, it is obvious that components around the frequency for which the amplitude spectra have maximum, Fig. 10, have the greatest influence on distinction of the signal waveforms in Fig. 8.

The phase spectrum, Fig. 11, as well as the phase difference in Fig. 7, is proportional to square root of the excitation frequency.

The pulse excitation response contains a large number of frequencies, thus enabling transfer of well-established defect identification techniques from sinusoidal measurement into the frequency domain [5].

5. CONCLUSIONS

Through our experimental results, we verified that pulsed remote field eddy current technique could be successfully applied to wall thickness measurement of ferromagnetic tubes. This type of excitation enables considerable power reduction, potentially simpler construction of the transducer electronics and faster measurements. Because of continuous spectrum of the pulse excitation, more information about material condition could be extracted from the response. However, beside present defect identification techniques, additional data analysis methods are needed for interpretation of the measurement results in order to exploit the full potential of the pulsed remote field effect.

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Authors:
Darko Vasić, student, Department of Electronic Systems and Information Processing, Faculty of Electrical Engineering and Computing, University of Zagreb, Unska 3, HR-10000 Zagreb, Croatia, Tel: (+385 1) 612 9974, Fax: (+385 1) 612 9652, E-mail: darko.vasic@fer.hr
Dr. Sc. Vedran Bilas, Assistant Professor, Department of Electronic Systems and Information Processing, Faculty of Electrical Engineering and Computing, University of Zagreb, Unska 3, HR-10000 Zagreb, Croatia, Tel: (+385 1) 612 9974, Fax: (+385 1) 612 9652, E-mail: vedran.bilas@fer.hr
Davorin Ambruš, Dipl. Ing., Brodarski Institute, Av. Vjenceslava Holjevca 20, HR-10020 Zagreb, Croatia, Tel: (+385 1) 650 4328, E-mail: dambro@hrbi.hr