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# Possibilities of Reliable Ultrasonic Detection of Subwavelength Pipework Cracks

**Ivan Hrabar**
INETEC–Institute for Nuclear Technology Ltd.
Dolenica 28, Lučko, Croatia
ivan.hrabar@inetec.hr

**Antonio Petošić, Petar Frančzek**
University of Zagreb, Faculty of Electrical Engineering and Computing,
Department of Electroacoustics
Unska 3, 10000 Zagreb, Croatia
antonio.petosic@fer.hr, petar.francek@fer.hr

**Marko Budimir**
INETEC–Institute for Nuclear Technology Ltd.
Dolenica 28, Lučko, Croatia
marko.budimir@inetec.hr

## ABSTRACT

An occurrence of cracks in pipework could lead to potentially very dangerous malfunction in some critical engineering systems such as power plants. There is a clear trend of replacing traditional manual testing with non-invasive in-situ methods that should detect crack formation in its early stage. Such as approach would enable replacing of unhealthy pipe components during the regular periodic outages. Ultrasonic testing is known to be a rather mature and reliable technology. However, it suffers from serious problems in detection of the cracks of subwavelength size. This paper attempts to soften aforementioned problems by investigating the influence of a duration of the unipolar excitation signal on the achieved resolution. In addition, the transducer input electrical-impedance of NDT transmitter was measured by using different excitation pulses and their levels and the results are compared with those obtained using traditional frequency sweeping method at low excitation levels. Finally, use of some advanced signal processing algorithms that might lead to the automatic detection of subwavelength voids, in scenarios with low signal-to-noise ratio, is discussed.

***Keywords:*** *ultrasonic testing, NDT, subwavelength, transducer self-impedance*

# 1 INTRODUCTION

Detection of damaged pipelines is a major concern in the power generation industry. Pipeline failure is a serious problem which leads to unpredicted power plant outages and an unplanned increase of operational costs. Therefore, it is important to regularly inspect critical components and to detect cracks in the earliest possible stage. A wide range of non-destructive testing (NDT) techniques can be used for pipe health monitoring (ultrasound, eddy current, surface replication …) [1]. Ultrasonic examination of critical components is a common practice in a variety of applications: aerospace industry, railway industry, quality control, critical nuclear power plant components, etc. In order to be able to detect small defects, in any material, it is needed to transfer as much as possible energy to the ultrasound wave in the component under test. Most commonly, single element ultrasound transducers are used [1]. The same active element is transmitting and receiving the ultrasound signal.

It is needed to design excitation signal in the way that we can get the best possible reflection from the early staged crack. Early stage cracks are small in dimensions and are usually smaller than half of the ultrasound wavelength. Importance of NDT early detection of possible defects in a pipeline is especially visible in nuclear power plant industry [2].

Ultrasound NDT transducers are usually characterized using low voltage (1 $V_{RMS}$) frequency sweeping signals around resonance of interest [3]. Electrical characterization is performed by measuring impedance magnitude and phase at a different frequency or amplitude ranges covering resonance and anti-resonance frequencies. But, on the field, operators most commonly use rectangular or spike excitation pulse signal of around 100 $V_{peak}$ up to 200 $V_{peak}$ with a duration determined from resonant frequencies of NDT transducer (around 200 ns) [1][4].

# 2 EXPERIMENTAL SETUP AND MEASUREMENT METHODS


Figure 1: Part of the experimental setup for testing detection algorithm: Krautkramer 2.25 MHz ultrasound transducer on SS 1018 calibration block

The experimental setup is constructed with commercial NDT Krautkramer 2.25 MHz transducer. Arbitrary waveform generator Keysight 33520b [5] is used for generation of different types of impulse excitation. Signal designed by waveform generator is amplified by E&I 2100L RF Power Amplifier [6]. The current is measured with Tektronix TCP312 current probe (range: 1 mA - 30 A, frequency range up to 100 MHz) [7]. Tektronix TCP312 current probe has integrated its own amplifier TCPA300. The current probe was auto-calibrated, before every measurement session, accordingly to the manual. Voltage is measured using Testec TT-SI9001 Differential Voltage probe.

Voltage probe Testec TT-SI 9001 is connected to coaxial cables right next to the current probe. Testec TT-SI 9001 has a frequency range up to 25 MHz and levels up to 700 $V_{pp}$ [7]. Signals from probes are acquired by Agilent MSO-X 3024A oscilloscope [8]. Acquired signals are analysed in MATLAB by using own developed functions. Signals in experimental setup propagate through coaxial cables except on measuring spot where small modification was made to accommodate current and voltage probe one next to another. Measuring spot is placed as close to the transducer as possible. As sample of material, with the known defect, PH Tool calibration block IIW type 2 reference block made from 1018 steel is used. Repetition frequency is set to a low value to avoid heating of examined ultrasound transducer. Scheme of the experimental system is shown in Figure 2.

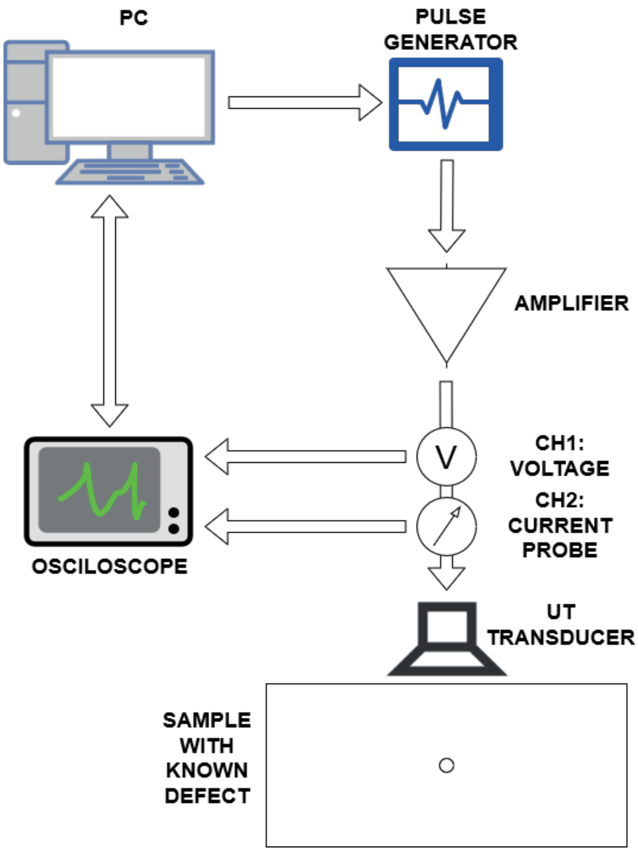



Figure 2: A schematic preview of the experimental setup

Parameters of a pulse generator and oscilloscope can be selected from a computer via standard USB communication. Aforementioned equipment is controlled by MATLAB R2010b programming package [9]. MATLAB script was developed in which computer sequentially sets parameters to pulse generator and acquire data from an oscilloscope. The BODE 100 impedance analyser is used for measuring impute impedance of selected transducer. The BODE impedance analyser is using low voltage (1 $V_{rms}$) frequency sweeping signal. Before every measurement, short, open and load circuit calibration of measurement system was performed in accordance with the manual [10].

## 3 REFLECTION DETECTION ALGORITHM

Algorithm for automatic detection of reflection in low signal to noise ration A-scan was constructed. Acquired A-scans has noticeable quantization noise. A measurement was performed on calibration block with a hole in it (Figure 1.).

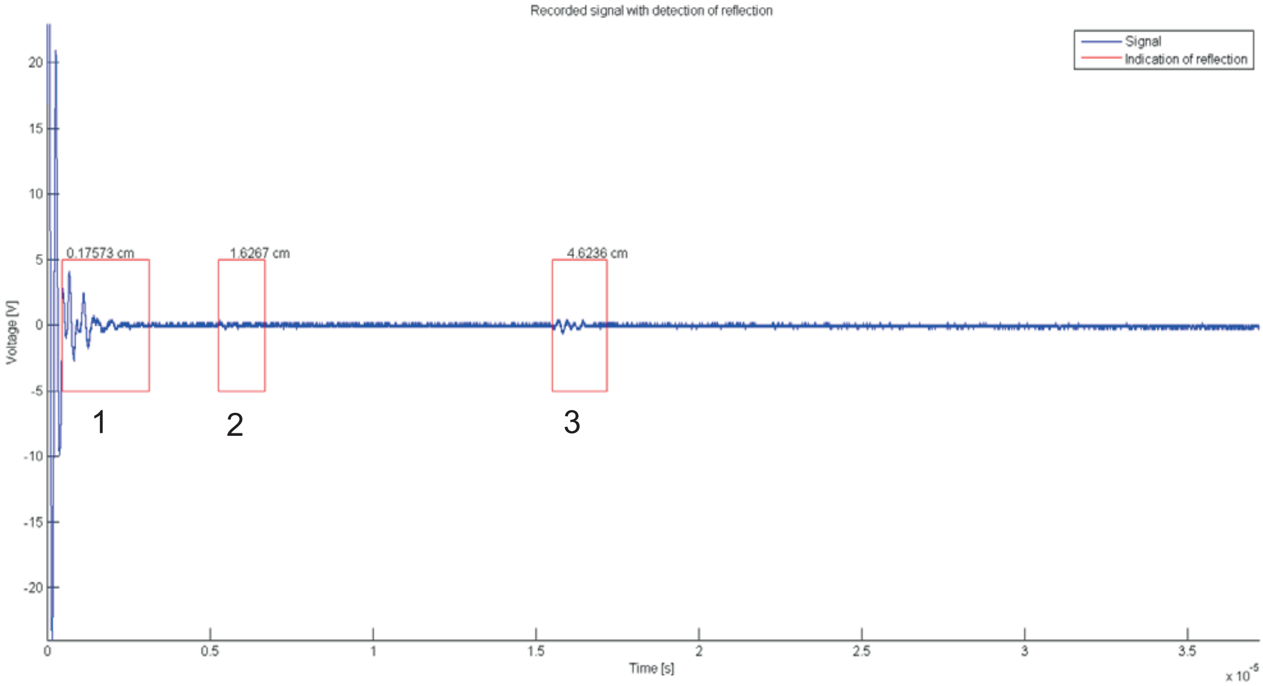



Figure 3: Acquired A-scan with algorithm indicated reflectors (surface reflection, 1 mm hole reflection and bottom reflection)

The diameter of a hole is 1 mm which is below half of the wavelength (1.28 mm) at the declared working frequency of considered transducer at 2.25 MHz of the used ultrasonic wave in calibration block. The hole is placed 1.5 cm from a surface. The algorithm was developed in MATLAB R2010b [9] programming package using built in mathematical and signal processing functions. The bottom surface is placed 4.5 cm from a surface.

Example of acquired A-scan with the result of the algorithm is shown in Figure 3. and part of the setup for algorithm validation can be seen in Figure 1. As it is seen acquired A-scan had high noise presence and reflection from 1 mm hole defect is barely recognizable even for a skilled operator. The goal of the developed algorithm is to soften aforementioned challenge. The amplitudes of both reflections (1 mm hole reflection and bottom reflection) are small. Classical filtering techniques were examined in order to find distinguishing feature which will enable automatically reflection detection in a signal.

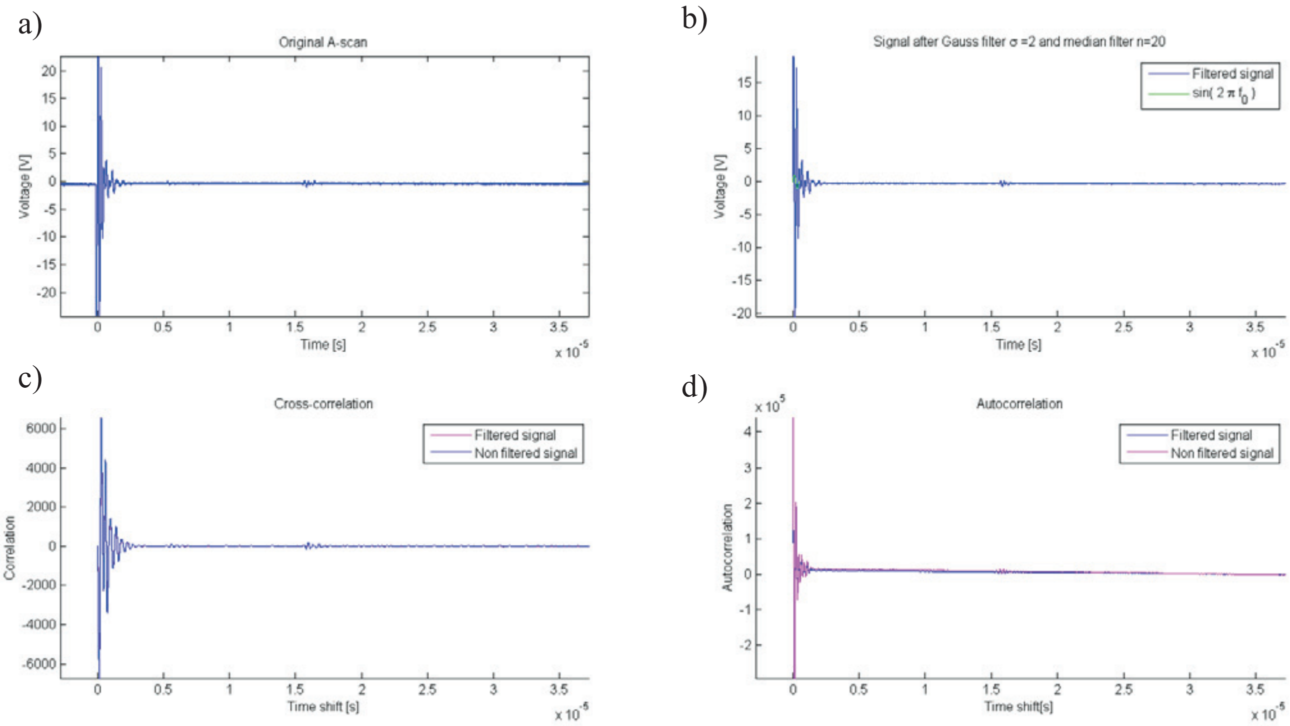



Figure 4: Comparison of classical filtering techniques on acquired A-scan.
a) Original acquired A-scan
b) Signal filtered with low pass Gauss filter ($f_p$= 2.25 MHz, σ=2) and median filter (n=20).
One period of sin signal with frequency 2.25 MHz is plotted for comparison.
c) Comparison of cross-correlation of constructed one period of sine signal (amp=1, f=2.25 MHz) and acquired and filtered signal
d) Comparison of an autocorrelation of a filtered and non-filtered signal

From Figure 4. is seen that best results were achieved with cross-correlation of one period of sine signal, at working frequency of the transducer (2.25 MHz), and acquired signal. Classical filtering did not provide desired information for distinguishing feature of reflection. Hilbert transformation was performed on filtered signal (Equation 1).

$$H(u)(t) = \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{u(\tau)}{t-\tau}d\tau \qquad 1)$$

An absolute value of the result of Hilbert transform is an envelope of the transformed signal [11]: Figure 5a).

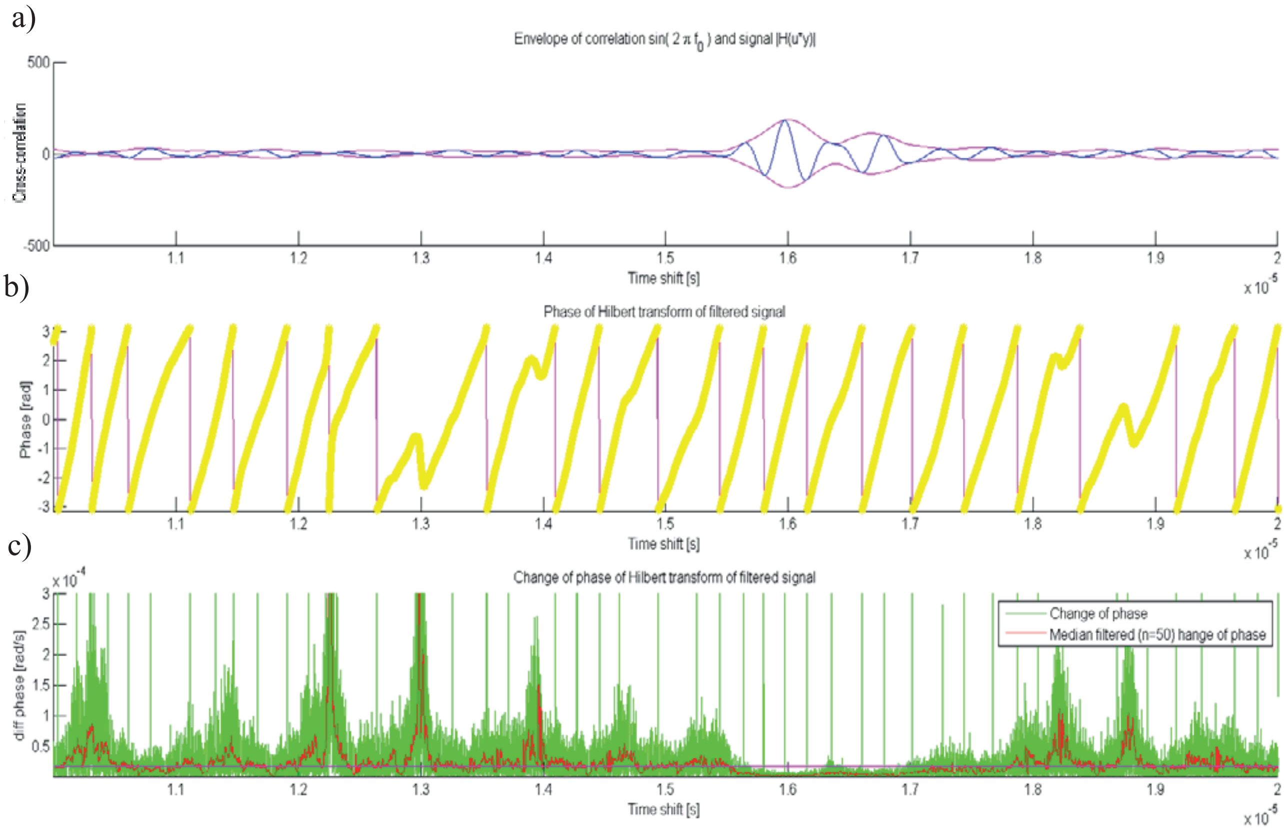



Figure 5: Comparison of part of the signal (1 mm hole reflection) with results of the Hilbert transform

It has been noticed that phase of Hilbert transformation with reflection changes constantly: Figure 5b). In Figure 5c) change of phase of the Hilbert transform is shown. Change of Hilbert transform has frequent, periodic, high pikes caused by phase "jumping" from $+\pi$ to $-\pi$. Other pikes are probably caused by noise. Change of phase of Hilbert transform was filtered by a median filter (n=50) to get rid of all pikes. It is seen, Figure 5c), that after filtering change of phase is almost zero. This showed to be easily distinguishing feature useful for automatic detection of a reflected signal [12]. Criteria of 40% of the mean value of phase change in whole signal and minimal duration of zero phase change (one period, $T = \frac{1}{f}$) were selected for reflection detection.

In Figure 3., the result is shown: red boxes enclosing detected reflections in acquired A-scan. The algorithm had detected and noted three reflections in acquired A-scan. First one is caused by front surface reflection. An ultrasonic gel is applied on ultrasonic transducer before use, to make the transition of ultrasonic waved, to a target material, easier. If a transducer is not firmly placed on the sample, the ultrasonic gel forms a thick layer in between. The second reflection is hard to notice. It is the reflection from subwavelength reflector: 1 mm diameter hole. The third reflection is caused by bottom surface reflection. Based on known sound velocity in used calibration block, the algorithm calculates a position of the reflector in a material. Positions are acceptably correct calculated. Error in position calculation is caused by thickens of the ultrasonic gel layer. Described criteria showed the excellent result of detecting subwavelength reflector in signal with a high signal to noise ratio.

## 4 MEASURING THE INPUT ELECTRICAL IMPEDANCE OF USED TRANSDUCER

Ultrasound transducer from manufacturer Krautkramer, model B 00WT5F with a declared working frequency of 2.25 MHz is used [13]. Ultrasound transducer was characterized in a range from 1.75 MHz to 6.75 MHz. Aforementioned ultrasound transducer was electromechanically characterized using BODE 100. Impedance response of ultrasound transducer can be seen in Figure 6. It is visible that the series resonant frequency of the whole transducer is not on the declared frequency of 2.25 MHz. It is assumed that ultrasound transducers have incorporated impedance matching circuit (RLC circuit to adjust impedance of active element to impedance of cable) inside. Electromechanical characterization of the whole transducer does not necessarily describe behaviour of the active element itself because the resonant frequency of assembled transducer is changed due to added masses (backing and front layers) [1].

Sound speed in used calibration block is 5760 m/s. Calibration block has few through holes that are used as known defects. For frequency of 2.25 MHz and sound velocity of 5760 m/s wavelength in calibration block is 2.56 mm. A hole with the diameter of 2 mm is used in the experiment, which is about 78% of the used wavelength at the declared series resonance frequency ($f_{sr}$) of 2.25 MHz.

$$PW = \frac{1}{2} \cdot \frac{1}{f_{sr}} \tag{2}$$

The input electrical impedance of the used transducer around resonance mode of interest is shown in Figure 6.

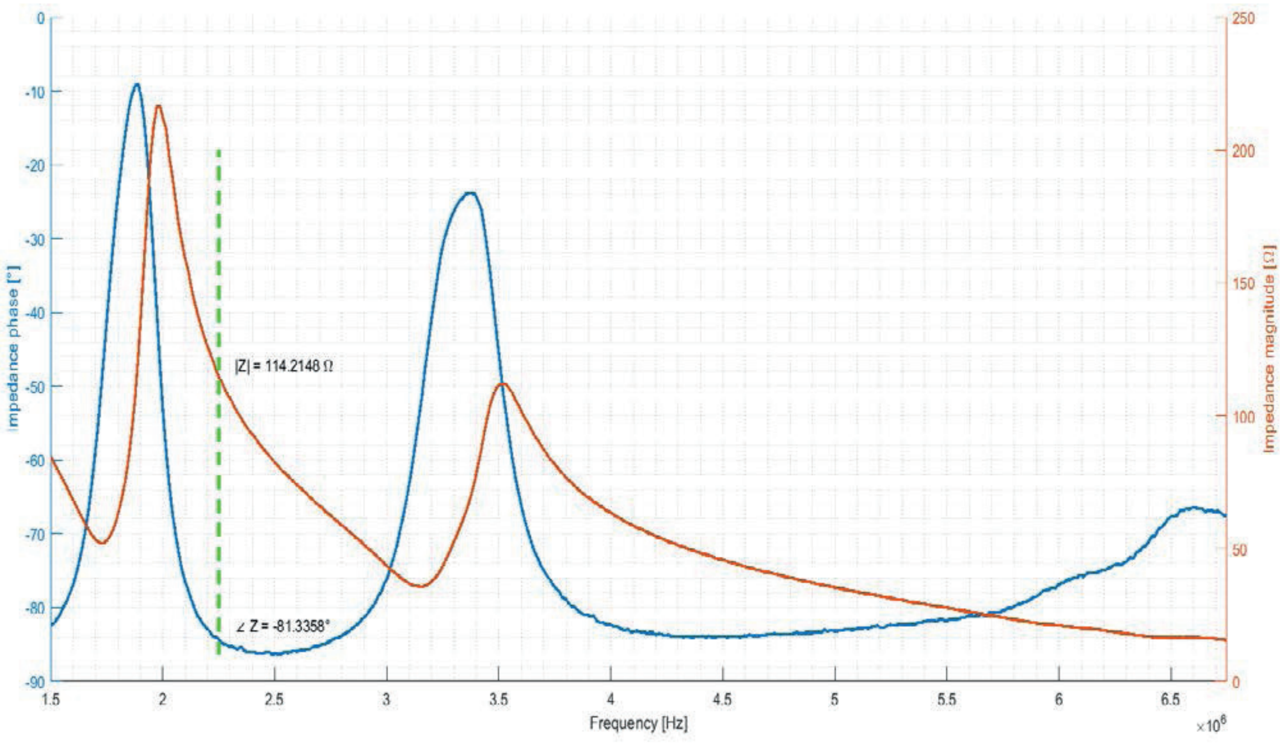
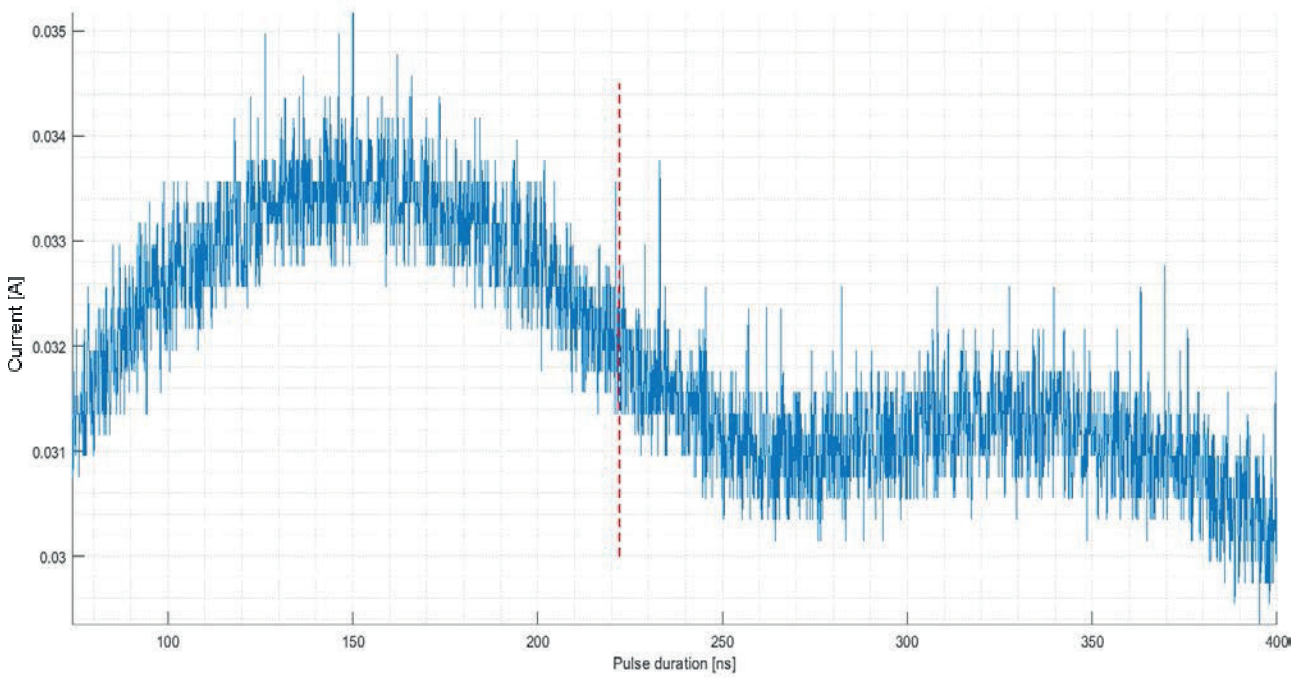



Figure 6: Impedance characteristics of ultrasound transducer Krautkramer B 00WT5F with the specified frequency of 2.25 MHz and accompanying values of impedance magnitude and phase.

In field operations, an ultrasound transducer is excited by a rectangular pulse which duration is determined, in accordance with Equation 2., on declared frequency. The rectangular unipolar excitation signal is constructed in the generator with repetition frequency f=100 Hz. The perfect rectangular signal is not possible to construct on used waveform generator. Minimal feasible rising and falling time of 8.6 ns is used. The duration of the unipolar signal is varied around the declared best duration of excitation signal (222.2 ns) with quantization of 0.1 ns.




It is visible in Figure 7. That better intensity of reflection from known defect, in this case, can be achieved by shortening pulse duration around the 150 ns which gives excitation frequency of 3.33 MHz.

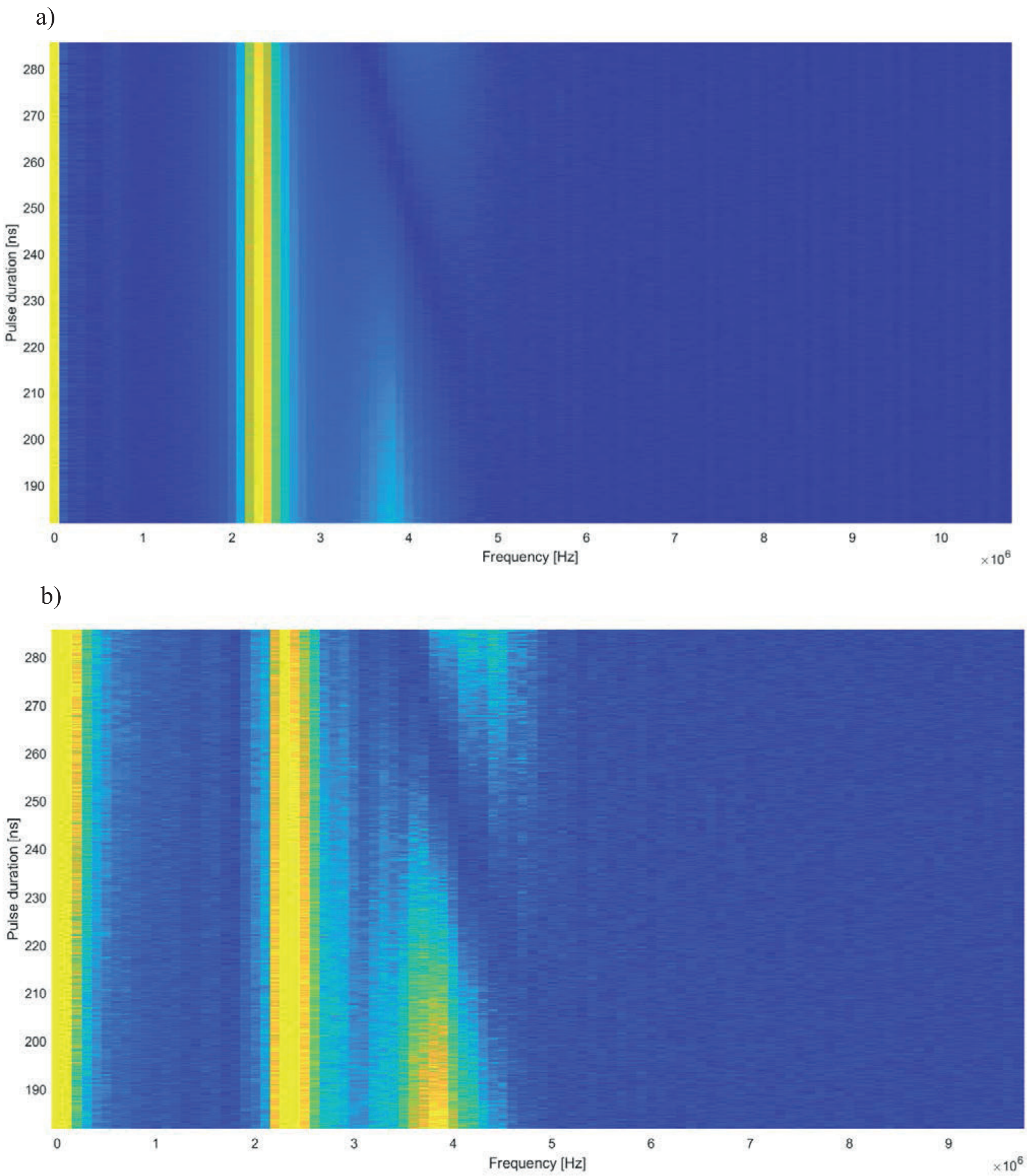



Figure 8. Comparison of lower parts of single side amplitude spectrums of current (a) and voltage (b) of reflection from known defect to the duration of rectangular pulse excitation signal. Warmer colour indicates a higher value of the spectral component.

From Figure 8., it is seen that active element always oscillates on its own resonant frequency of 2.25 MHz and duration of excitation unipolar signal does not make any visible impact on the self-resonant frequency of active element of the examined ultrasonic transducer.

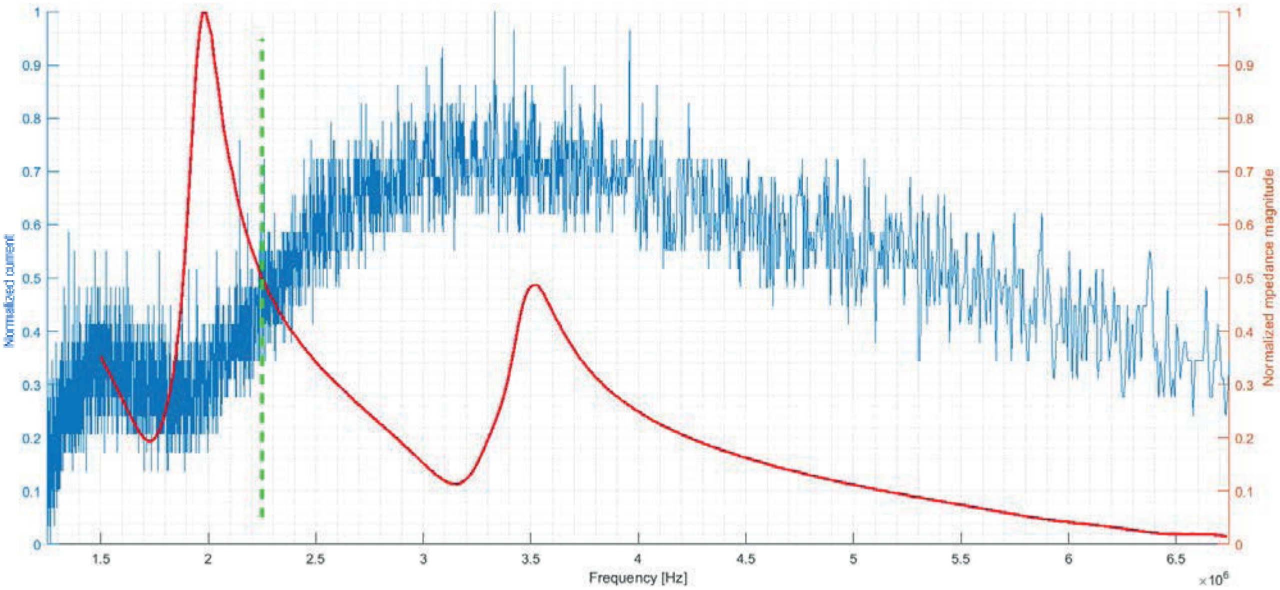



Figure 9: Comparison of the normalized impedance of transducer and normalized intensity of reflection form known defect whit specified declared frequency of 2.25 MHz

From Figure 9. it is seen that shape of the normalized intensity of reflection and shape of normalized impedance magnitude do not match in shape or inverse of shape.

The excitation signal is, by changing the duration of the excitation signal, adjusted not only to the active element but to the impedance of the overall transducer (piezo-electrical element loaded with front and backing layers and) electrical matching network of the transducer as well [1].

## 5 CONCLUSION

The experimental setup for testing the influence of different unipolar pulse duration on the reflection detection is designed by using laboratory setup.

The input electrical impedance of NDT transducer is measured by using BODE 100 Vector/Network analyser and additional electrical characterization of commercial ultrasound transducer was performed with a rectangular unipolar excitation signal before RF amplifier. Dependencies of reflection intensity, form known defect, is measured in dependence with the duration of a unipolar excitation pulse of the same amplitude. Duration of excitation signal was varied around typical duration (Equation 2) determined from the low level series resonance frequency. The intensity of reflection from known subwavelength defect (defect diameter 2 mm, wavelength 2.56 mm, frequency 2.25 MHz) was maximized by shortening duration of excitation rectangular pulse.

Algorithm for automatic detection of subwavelength defects based on the change of A-scan Hilbert transform phase derivation was constructed and experimentally validated. Algorithm showed a very positive result on detection subwavelength reflector (reflector diameter 1 mm, wavelength in material 2.56 mm, Figure 1.).

The input electrical impedance does not depend on the pulse duration when it is determined by using unipolar excitation signals. It is possible to determine the optimal duration of excitation unipolar pulse signal by using pulse excitation, compared with the situation when pulse duration is determined by widely used expression (Equation 2.), when commercial transducer declared series resonance frequency is used as input parameter for optimal pulse width. Described characterization with unipolar excitation pulse of optimal duration enables more reliable early stage crack detection due to higher reflection amplitude.

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