Detection and Visualization of Flaws in Ultrasonic Defectoscopy

Václav Matz, Marcel Kreidl, Radislav Šmíd

Czech Technical University in Prague
Faculty of Electrical Engineering
Department of Measurement

Abstract - In ultrasonic defectoscopy it is very difficult to detect flaws in materials with coarse-grain structure. Measured ultrasonic signal contains echoes from flaw and echoes from grains included in material. These echoes characterized noise have to be cancelled. A common source of noise is electronic circuitry, which is used for processing of the ultrasonic signal, and scattering at the inhomogeneities in the structure of a grainy material. For reduction of noise efficient methods for suppression of noise have to be used. In this case the most efficient method for noise reduction is method based on discrete wavelet transform. This method gives the best results for filtering of ultrasonic signal in A-scan. In this work method based on neural networks for flaw detection in B-scan is used. Proposed methods are efficient used for separation of flaw from undesirable echoes. For visualization of flaw volume construction was created. The 3D volume visualization characterizes volumetric depiction of measured material. By using 3D volume visualization of ultrasonic signal it is possible to determine character and place of flaws in ultrasonic defectoscopy.

Keywords: Ultrasonic testing, discrete wavelet transform, 3D visualization, neural networks

1. INTRODUCTION

Ultrasonic non-destructive testing is used for flaws detection in materials. Ultrasound uses the transmission of high-frequency sound waves in a material to detect a discontinuity or to locate changes in material properties. The most commonly used ultrasonic testing technique is a pulse echo, where sound is introduced into a test object and the reflections (echoes) are returned to a receiver from internal imperfections or from the geometrical surfaces of the part. The highest signal-to-noise ratio (SNR) can be assumed by the optimum frequency selection of an acoustic wave appropriate for detecting specific discontinuity. There are many centers in coarse-grain materials, which can generate echoes that seem to be randomly distributed in time. These echoes are usually defined as background noise. Noise, formed from scattering of inhomogeneous micro-structures has to be cancelled. Several techniques have been proposed to reduce noise from signal. Split spectrum processing, FIR filtering and discrete wavelet transform were studied and the best method for filtering of ultrasonic signal were searched [1, 2]. Among them discrete wavelet transform (DWT) gives very good results.

This paper introduces an experimental study involving measurement of ultrasonic signals with consequent analysis and signal processing. Proposed processing of ultrasonic signals allows efficient filtering, it is possible to reduce the noise from scattering and electronic circuitry.

For measurement of an ultrasonic signal a system for data acquisition was created. Data acquisition system is described in the first section. Device for precise movement of ultrasonic transducer was used. The software part of the system consists of the signal processing and filtering of ultrasonic signal. Mathematical morphology is also used for visualization of flaw and obtaining the smooth shape of flaw.

In the next section a method for detection of a flaw based on the neural networks is described. A feature is based on extraction of the neighborhood area of central pixel in B-scan data.

In final section construction of 3D volume visualization of measured material is introduced. By means of 3D visualization it is possible to study the structure of flaw.

2. DETECTION OF FLAWS

2.1 Data acquisition

An ultrasonic system was created for measuring of ultrasonic signals using the ultrasonic transducer with frequency of 20 MHz. The system consists of units for measurement of ultrasonic signals and device for precise positioning of ultrasonic transducer. The system is described in Fig.1.
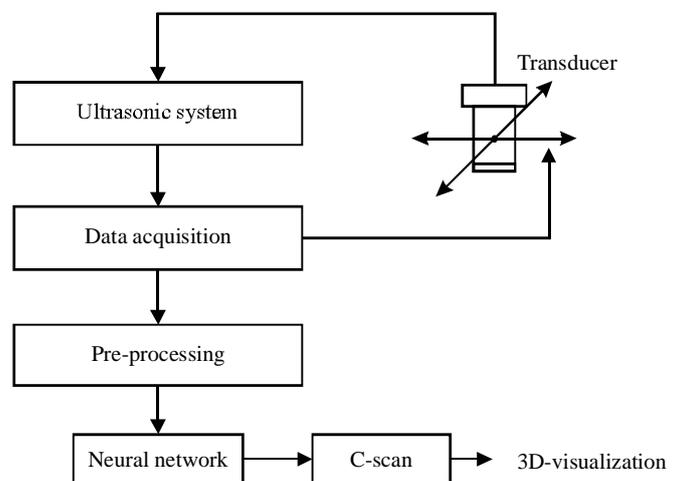

Fig. 1. Block diagram of the complete system

The transducer was moved by steps 250 μm along the material and signals in time domain (A-scan) were measured and recorded. With the recorded A-scans a C-scan was created. By means of the C-scan a 3D volume visualization of the measured material was created. For measurement of ultrasonic signals materials with artificial flaw were used. In the first material a circle-shaped flaw was created. In the another material (which is used for construction of airplane engines) artificial flaws were created. 3D volume visualization of the material with the circle-shaped flaw is in Fig. 2.
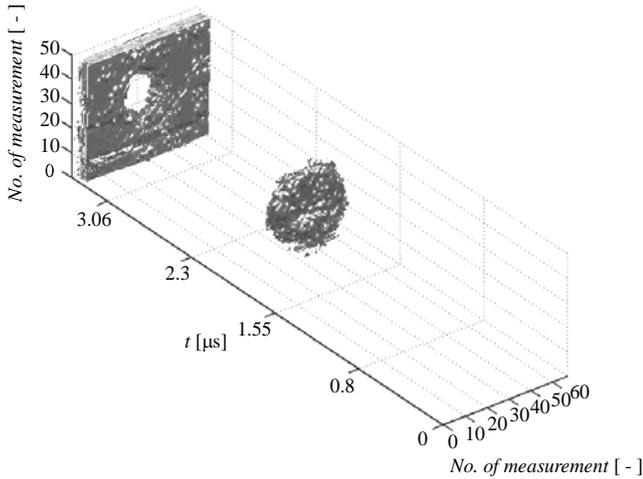

Fig. 2. Volume visualization of material

2.2 Pre-processing of ultrasonic signal

Pre-processing of ultrasonic signals contains the amplitude normalization and filtering. For filtering of ultrasonic signal a method based on the discrete wavelet transform (DWT) is used. This method is very efficient in the time domain. The ultrasonic signal in A-scan is measured and DWT is used for the improvement of the signal-to-noise ratio. The wavelet transform is a multiresolution analysis technique that can be used to obtain the time-frequency representation of the ultrasonic signal.

The discrete wavelet transform [3] can be used as an efficient filtering method for families of signals that have a few nonzero wavelet coefficients for a given wavelet family. This is fulfilled for most ultrasonic signals. The standard filtering (also called de-noising) procedure affects the signal in both frequency and amplitude, and involves three steps. The basic version of the procedure consists of:

a) decomposition of the signal using DWT into N levels using bandpass filtering and decimation to obtain the approximation and detailed coefficients,
b) thresholding of detailed coefficients,
c) reconstruction of the signal from detailed and approximation coefficients using the inverse transform (IDWT).

DWT [4] analyzes the signal by decomposing it into its coarse and detail information, which is accomplished by using successive high-pass and low-pass filtering operations, on the basis of the following equations:

$$y_{high}(k) = \sum_n x(n) \cdot g(2k-n),$$
$$y_{low}(k) = \sum_n x(n) \cdot h(2k-n), \tag{1}$$

where $y_{high}(k)$ and $y_{low}(k)$ are the outputs of the high-pass and low-pass filters with impulse response g and h, respectively, after sub sampling by 2. This procedure is repeated for further decomposition of the low-pass filtered signals. A global threshold is usually used in wavelet filtering. In our study for comparison a local thresholding was used instead of global thresholding. The threshold is computed from detail coefficients at each level of decomposition. Then the computed threshold is applied for thresholding detail coefficients in the same level. For examination of quality filtering signal-to-noise ratio is computed:

$$FNR = 20 \cdot \log\left(\frac{F_{ef}}{N_{ef}}\right) \text{ [dB]}, \tag{2}$$

where

N_{ef} is the root mean square value of the noisy part of the raw signal.

F_{ef} is the root mean square value of an adequate part of the filtered signal.

2.3. Mathematical morphology

Mathematical morpholog*y* offers a broad set of signal processing operations that can process signals based on their shapes. Morphological operations [5] apply a structuring element to an input signal, creating an output signal of the same size. The most basic morphological operations are dilatation and erosion. In a morphological operation, the value of each sample in the output signal is based on a comparison of the corresponding sample in the input signal with its neighbors. By choosing the size and shape of the neighborhood, one can construct a morphological operation that is sensitive to specific shapes in the input signal.

Dilatation is defined as follows:

$$A \oplus B = \{c \,|\, c = a+b \ \exists \ a \in A \text{ and } b \in B\}, \tag{3}$$

where A is an input signal and B is structuring element. The value of the output sample is the maximum value of all the samples in the input sample's neighborhood.

Erosion is defined as follows:

$$A \oplus B = \{x \,|\, x+b \in A \ \forall \ b \in B\}, \tag{4}$$

where A is an input signal and B is structuring element. The value of the output sample is the minimum value of all the samples in the input sample's neighborhood. We use a composed morphological operation closing, which fills in all places where the structuring element will not fit in the signal background. In morphological operations the method closing was used, because the final C-scan of the flaw contains loose places. The function closing consists of dilatation followed by erosion with the same structuring element. As structuring element line vector with dimension three was used.

2.4. Neural network

For detection of flaw a neural network with the backpropagation algorithm [6, 7] was used. The backpropagation (BP) algorithm is one of the simplest and most general methods for supervised training of multi-layer neural networks (NN). The multi-layer neural networks consist of one input layer, one output layer and more hidden layers. Each hidden unit computes the weighted sum of its inputs to form its scalar net activation:

$$net_j = \sum_{i=1}^{d} x_i \cdot w_{ji} + w_{j0} , \qquad (5)$$

where i indexes units in the input layer,
  j in the hidden layer,
  w_{ji} denotes input to hidden layer weights at the hidden unit j.

Networks have two primary modes of operation: feed forward and learning. Feedforward operation consists of presenting a pattern to the input units and passing the signal through the network in order to yield outputs from the outputs unit. Supervised learning consists of presenting an input pattern and changing the network parameters to bring the actual outputs closer to the desired teaching or target values. For learning the training patterns have to be known. The first in learning is to start with untrained network, present a training pattern to the input value, pass the signal through the net and determine the output. Here these outputs are compared with the desired target values; any difference corresponds to an error.

2.4. Feature Extraction

For neural network classification it's very important feature extraction stage. In this study for training of BP neural network the neighborhood area of pixel in B-scan was used. Defect detection in a given image requires identification of region with the uniform texture. An exhaustive evaluation of potential features sets for the characterization of texture is difficult. Every pixel from the acquired image is characterized by a feature vector. A simplified characterization of texture based on relations between the pixels in restricted neighborhood is used. B-scan as an input matrix used for training of BPNN was splitted into sub matrixes. These sub matrixes with marked pixel which was in the middle of sub matrix were used as input to BPNN. Pixel was marked if considered as a flaw. In other cases wasn't marked. Dimension of each sub matrix was 3×5 (see Fig. 3).
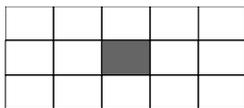

Fig. 3. 3×5 neighborhood area

3. EXPERIMENTAL RESULTS

Evaluation of the proposed algorithms on real data is presented. Measured signal in A-scan (see Fig. 5. bottom) without any signal processing was used for construction of

C-scan (see Fig. 4.). For filtering of the ultrasonic signal in A-scan DWT with threshold *Thr* based on standard deviation is used:

$$Thr = k \cdot \sqrt{\frac{1}{N-1} \cdot \sum_{i=1}^{N} (Dc_i - \overline{Dc})^2} , \qquad (6)$$
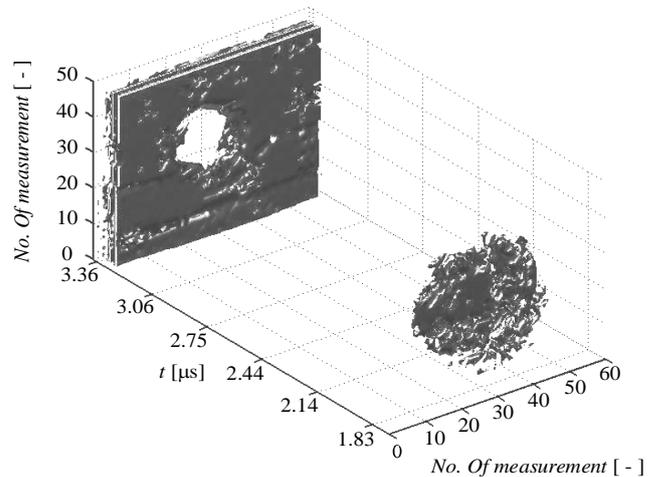

Fig. 4. Detailed visualization of material – measured signal

where N is the length of each set of detailed coefficients, k is a crest factor and Dc is a vector of detailed coefficients at each level. Example of application of DWT for signal filtering is in Fig.4.
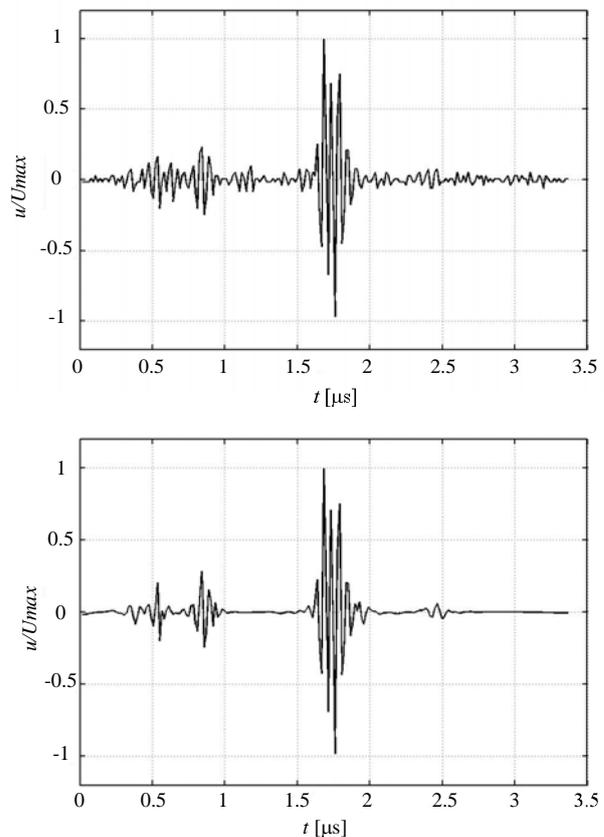

Fig. 5. Raw signal - top and filtered signal - bottom

Noise reduction in the depicted case for DWT is *FNR=17* [dB]. In filtered signal false echoes were suppressed. The results of closing of filtered ultrasonic signal with fault and back-wall echo is in Fig. 6.
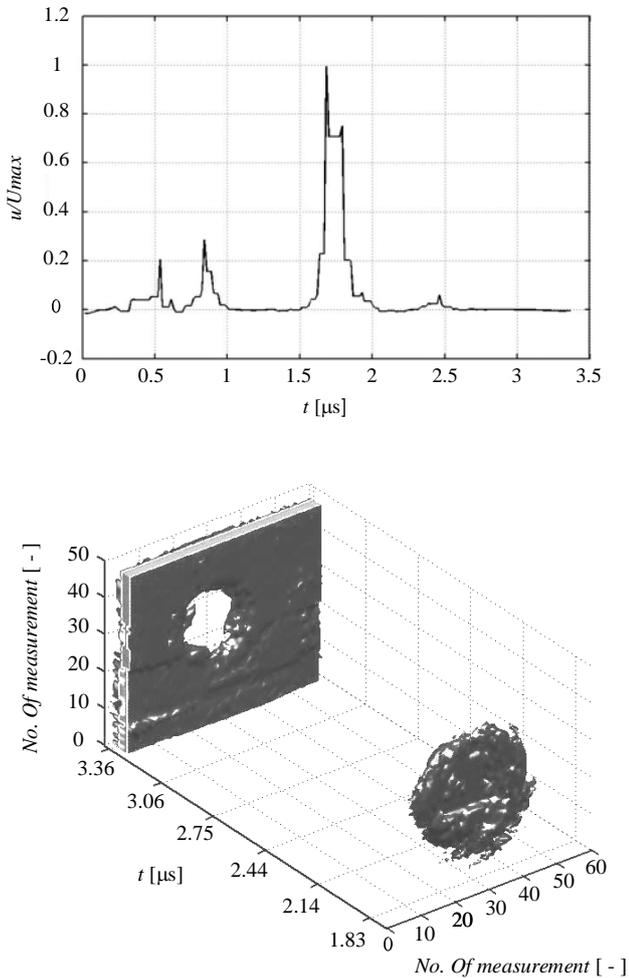

Fig. 6. Operation closing, A-scan – top, C – scan bottom

By mathematical morphology was reached the recovery of flaw shape in final 3D volume visualization.

For detection of flaw a neural network with the backpropagation algorithm is used. Neural network was applied to B-scan, where places with flaw were manually marked. In this study training based on Levenberg-Marquardt backpropagation (LMB), gradient descent backpropagation (GDB), resilient backpropagation (RB) and gradient descent with momentum (GDMB) backpropagation were used for comparison. In the Tab. 1 performance of all used functions are shown.

Tab. 1: Performance of different training function

Function	Epochs	Deviation
LMBP	41	0.04
GDBP	Goal wasn't met	1.03
RBP	198	0.05
GDMBP	Goal wasn't met	0.83

Evaluated neural network BP contains four layers. Fifteen neurons were in the input layer, first hidden layer had five neurons and another had three neurons. The output layer had one neuron, indicating the flaw in the input 3×5 neighborhood area consider places with flaw. By marking these places the final volume visualization was obtained. The result contains circle shaped place, which more accurately corresponds to the real flaw. The final 3D-volume visualization is in Fig.7.
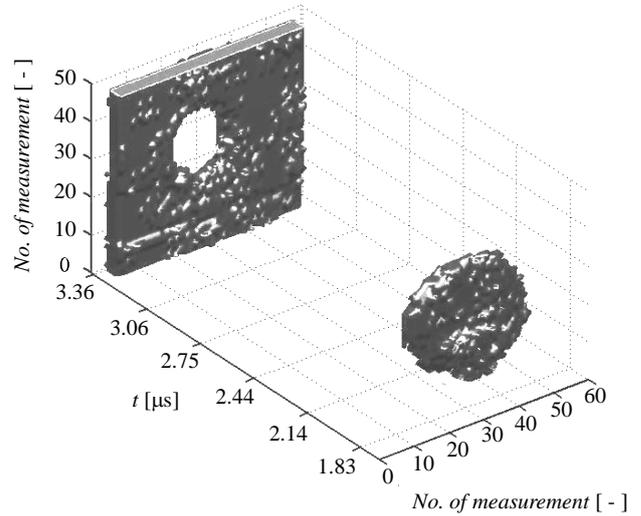

Fig. 7. Final 3D-volume visualization of material

For comparison the material used for construction of airplane engines was used. This material is coarse grained and measured signal contains echoes from grains with data falsification. The application of proposed method in this material which contains the flaw is in Fig.8.
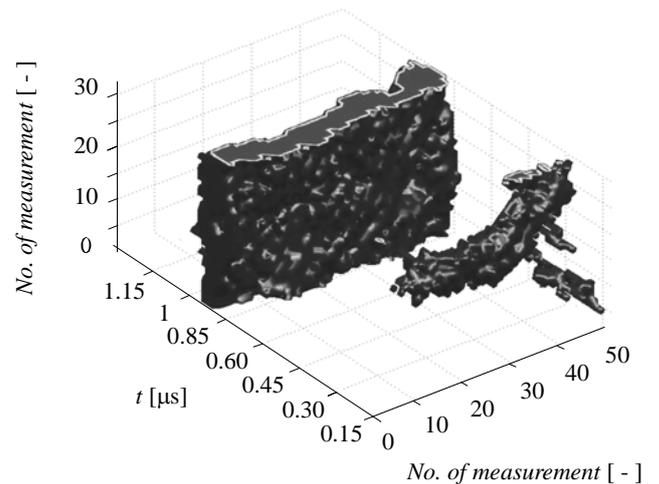

Fig. 8. 3D-volume visualization of grainy material with unknown flaw

By 3D volume visualization as is shown in previous picture it is possible the regard the shape of flaw.

4. CONCLUSION

In this paper a new system for ultrasonic flaw detection has been proposed. The system for detection of flaw consists of data acquisition, filtering, morphologic processing and the neural network. For detection of flaw a material with artificial circle shaped flaw was used. By mathematical morphology the C-scan sketches the shape of flaw. With application of neural network it is possible to characterize the shape of the flaw exactly. For the comparison a material with coarse grained structure where detection of flaw is difficult was used. Filtering of ultrasonic signal is useful for suppressing echoes from grains. In the future using the 3D volume visualization of ultrasonic signal it will be possible to determine the character and place of a generation of flaws in ultrasonic defectoscopy.

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Ing. Václav Matz
CTU, FEE, Department of Measurement
Technická 2, Praha 6, 16627
e-mail: vmatz@email.cz
Phone: +420-22435 2346

Doc. Ing. Marcel Kreidl, CSc.
CTU, FEE, Department of Measurement
Technická 2, Praha 6, 16627
e-mail: kreidl@feld.cvut.cz
Phone: +420-22435 2117

Ing. Radislav Šmíd, Ph.D.
CTU, FEE, Department of Measurement
Technická 2, Praha 6, 16627
e-mail: smid@feld.cvut.cz
Phone: +420-22435 2131