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# Ultrasonic Signal De-noising Using Dual Filtering Algorithm

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**Abstract**

This paper describes the proposal of dual filtering algorithm used for ultrasonic A-scan signal de-noising. In ultrasonic non-destructive testing the signals characterizing the material structure are evaluated. The sensitivity and resolution of typical ultrasonic systems is commonly limited by backscattering and electronic noise level commonly contained in acquired ultrasonic signals. In ultrasonic non-destructive testing area it is really difficult to detect flaw in materials with coarse-grain structure. In this paper, the main goal was to efficiently suppress the undesirable noise level and successfully detect the fault echo that is hidden under the noise level. The dual filtering algorithm, presented in this paper, is based on application of efficient de-noising algorithms as Wiener filter and discrete wavelet transform. The Wiener filter based group delay statistics is presented and the best parameters are searched. The discrete wavelet transform algorithm with different mother wavelets, threshold levels and threshold rules is also presented. Both algorithms are evaluated using two parameters, signal-to-noise ratio and fault echo corruption. The proposed dual filtering algorithm is performed on both simulated and real ultrasonic signals acquired on grainy material used for constructing airplane engines.

**Keywords**: Ultrasonic testing, De-noising algorithms, Noise reduction.

## 1. Introduction

Ultrasonic non-destructive testing (UT) is commonly used for flaw 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 [1]. Ultrasonic wave propagation in tested materials is essentially influenced by the tested material structure. In general, due to material structure the acquired ultrasonic signal can be corrupted with relatively high noise level, commonly called backscattering noise. Besides backscattering noise level, another source of noise is usually caused by the electronic circuitry. These sources of noise components are generally contained in all acquired ultrasonic signals together with the flaw and back-wall echoes. Back-wall echo characterizes the reflection of ultrasonic wave from the end of material (surface) and fault echo is caused by the reflection of ultrasonic waves from the cracks or defects.

In present, the most desired task is to detect the fault echo in ultrasonic signal; it means to locate the cracks or defects in tested materials. The flaw detection efficiency is mainly influenced by the noise level and on this account the efficient signal processing techniques used for noise reduction and signal separation are proposed. In past, many methods have been proposed and evaluated [2], [3], [4], [5], [11] for efficient noise reduction in ultrasonic signals.

This paper presents and evaluates methods used for ultrasonic signal de-noising as discrete wavelet transform and Wiener filter with appropriate settings. First of all, these methods are

evaluated in terms of signal-to-noise improvement and flaw detection efficiency and consequently combined to get better results.
This paper is structured as follows. Firstly, the basic theoretical descriptions of used de-noising methods are briefly described. In third section the evaluation of methods with different parameters setting is performed. Based on the theoretical analysis, in section four, new proposal of combination both methods are applied. For the evaluation, the samples of materials used for airplane engines construction were used. Finally, the results are discussed and the future work is indicated.

## 2. De-noising methods

### 2.a. Discrete wavelet transform

The wavelet transform [3], [6], [7] is a multiresolution analysis technique that can be used to obtain the time-frequency representation of the ultrasonic signal. Discrete wavelet transform (DWT) analyzes the signal by decomposing it into its coarse and detail information, which is accomplished by using successive high-pass and low-pass filtering and subsampling operations, on the basis of the following equations:

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

where $y_{high}(k)$ and $y_{low}(k)$ are the outputs of the high-pass (HP) and low-pass filters (LP) with impulse response $g$ and $h$, respectively, after sub sampling by 2 (decimation). This procedure is repeated for further decomposition of the low-pass filtered signals.
Starting from the approximation and detailed coefficients the inverse discrete wavelet reconstructs signal, inverting the decomposition step by inserting zeros and convolving the results with the reconstruction filters.
The DWT can be used as an efficient de-noising 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 common 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: decomposition of the signal using DWT into $N$ levels using filtering and decimation to obtain the approximation and detailed coefficients, thresholding of detailed coefficients, reconstruction of the signal from detailed and approximation coefficients using the inverse transform (IDWT). For decomposition of the signal it is important to choose a suitable mother wavelet, threshold rule and threshold level.

### 2.b. Wiener filter based group delay statistics

The Wiener filter [9], [10] is a global filter and produces an estimation of the uncorrupted signal by minimizing the mean square error between the estimated and the uncorrupted signal in a statistical sense. Process representing the received signal consists of signal and noise, both uncorrelated zero-mean wide-sense-stationary random process.
By filtering $y(t)$ we estimate $s(t)$ using time-invariant linear system with transfer function $H(f)$. Resulting mean-square error then will be

$$e = \int_{-\infty}^{\infty} \left|1 - H(f)\right|^2 S(f)df + \int_{-\infty}^{\infty} \left|H(f)\right|^2 N(f)df\,, \tag{2}$$

where $N(f)$ and $S(f)$ are power spectral densities of noise and signal. Error $e$ is minimized over $H(f)$ for fixed $S(f)$ and $N(f)$. The transfer function can be estimated by means of group delay target signal has a deterministic phase delay over the working frequency. The following techniques are based on using the discrete group delay. It can be calculated by

$$T(k) = -\frac{N}{2\pi}[\phi(k+1) - \phi(k)] \ , \tag{3}$$

where $\phi(k)$ is the phase component of the discrete Fourier transform, $k$ is the frequency index and $N$ is the total number of points. For minimizing the edge effect different windows for received time sequence are applied. To obviate discontinuity in the group delay phase unwrapping techniques are used. Two useful variants based on the group delay statistics are group delay moving standard deviation

$$\sigma_k = [\frac{1}{M-1}\sum_{m=k}^{M+k}\{\Delta T(m) - \Delta\overline{T}_k\}^2]^{\frac{1}{2}} \tag{4}$$

and group delay moving entropy

$$H_k = -\sum_{j=k+1}^{M+k} f(T_j)\log_2[f(T_j)] \, . \tag{5}$$

Both estimates are computed within a moving window $M$. The window $M$ is set to a small compared data length, and reflects a trade off between resolution and estimation error.

**3 Theoretical results**

First of all, for the detail analysis and de-noising methods performance the simulated ultrasonic signal has to be generated. The signal is simulated based on the amplitude and frequency analysis of set of acquired ultrasonic signals. Based on this analysis and physical analysis of ultrasonic wave propagation, the signal was generated based on simple clutter model using the equation [11]:

$$H_{mat}(\omega) = \sum_{k=1}^{K_{tot}} \beta_k \frac{\omega^2}{x_k} \exp(-2\alpha x_k \omega^4) \exp(-i\omega \frac{2x_k}{c_l}) \cdot H(\omega) \cdot H(\omega) \, , \tag{6}$$

where $\alpha$ is the material attenuation coefficient, $c_l$ is the velocity of the longitudinal waves, $x_k$ is the grain positions of $k = 1...K_{tot}$ number of grains and $\beta_k$ is a random vector depending on the grain volume. The example of generated ultrasonic signal can be seen in fig. 1. The signal consists of noise (backscattering, electronic), fault echo and back-wall echo.

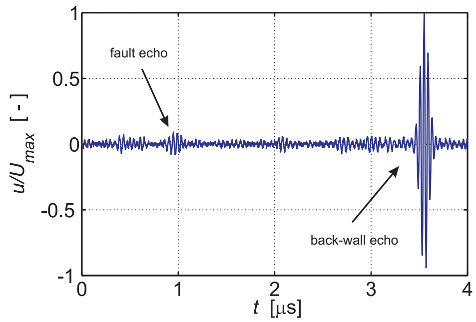


Fig.1: Simulated ultrasonic signal

First of all, the Wiener filter method using the group delay statistics was used. The Wiener filter based group delay moving entropy and group delay moving standard deviation were used and the best parameters were searched for the efficient ultrasonic signal noise reduction. The main idea of using the group delay statistics is that the useful signal has the constant group delay in a certain frequency range. This frequency range depends on frequency response of used ultrasonic transducer. By using an appropriate window with frequency bandwidth and threshold level the de-noising efficiency can be increased. In our evaluation only the Hamming window was used.

In the case of threshold level and frequency bandwidth we changed the threshold level within 1 – 80 % of maximal amplitude of Wiener filter transfer function and frequency bandwidth within 5 – 15 MHz. The Wiener filter was evaluated by using parameter SNRE as in the case of DWT.
The proposed methods we evaluated by the calculation of two parameters. The first parameter evaluates the signal-to-noise ratio enhancement and can be expressed as

$$SNRE = 10\log\frac{P_1}{P_2} \tag{7}$$

where $P_1$ and $P_2$ are the power of noise before and after de-noising. Another parameter evaluates the fault echo changes and amplitude decreasing and can be expressed as

$$Dx = \mathrm{E}[A_b(\mathrm{n})A_a(\mathrm{n+r})].\left(1-\frac{A_a - A_b}{A_b}\right) \tag{8}$$

where E is the mean value, $A_b$ and $A_a$ are the fault echo amplitudes before and after de-noising.
The evaluation of Wiener filter based group delay statistics is in fig. 2. The ultrasonic signal with different fault echo amplitude was also generated. The best results were obtained with the threshold level of 40 % and frequency bandwidth corresponding to 9 MHz. With this setting, the highest SNRE = 14.7 dB. In the comparison of both algorithms the values of SNRE for Wiener filter based standard deviation are higher.

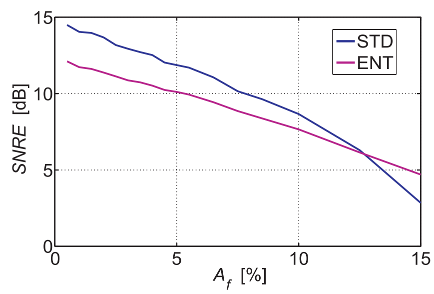


Fig. 2: Wiener filter evaluation

The next evaluated method is based on the DWT de-noising algorithm was used. For the efficient noise reduction, the shape of mother wavelet, threshold level and threshold rule have to be selected. The shape of the mother wavelet has to be very similar to the ultrasonic echo. It has to fulfill the following properties: symmetry, orthogonality and feasibility for DWT. A group of mother wavelets was tested: Haar's wavelet, the discrete Meyer wavelet, Daubechie's wavelet and Coiflet's wavelet. In the proposed procedure, only local thresholding of detailed coefficients was used. In case of thresholding rule, the soft and hard thresholding can be used. From literature [6], [7] it has been known that the soft thresholding is not a good alternative for noise reduction in ultrasonic signals because the noise level and amplitude of fault echo is decreased by threshold level. Other options for thresholding rules can be the modification of the hard thresholding rule using the following equations:
Compromise thresholding rule can be defined as

$$\hat{T}_{ij} = \begin{cases} sign(T_{ij})(\left|T_{ij}\right| - \alpha T), \left|T_{ij}\right| \geq T \\ 0, \left|T_{ij}\right| < T \end{cases}, \tag{2}$$

where $T_{ij}$ is a threshold level for sample $i$ at level $j$ and $\alpha$ is the coefficient meaning the compromise of the hard and soft thresholding. The custom thresholding rule is defined as

$$\hat{T}_{ij} = \begin{cases} T_{ij} - sign(T_{ij})(1-\alpha)T, \left|T_{ij}\right| \geq T \\ 0, \left|T_{ij}\right| \leq \tau \\ \alpha T \left( \frac{\left|T_{ij}\right| - \tau}{T - \tau} \right)^2 \left\{ (\alpha - 3) \left( \frac{\left|T_{ij}\right| - \tau}{T - \tau} \right) + 4 - \alpha \right\} \end{cases} \quad (3)$$

where $\tau$ is the coefficient characterizing the sample level from where the thresholding is valid. We evaluated common thresholding methods implemented in the Matlab Wavelet toolbox [7] (rigsure, sqtwolog, heursure, minimaxi) and due to the unsatisfactory results we proposed a new method based on standard deviation $V_1$ and mean value together with standard deviation $V_2$. The local thresholds at each level of decomposition are given by

$$V_1 = k \cdot \sqrt{\frac{1}{n-1} \cdot \sum_{j=1}^{n} (cD_j - c\bar{D})^2} \quad (4)$$

and

$$V_2^k = \sqrt{(\mu + V_1)} \quad (5)$$

where $n$ is the length of vector detail coefficients, $k$ is the constant (crest factor), $cD$ is the vector of detailed coefficients and $\mu$ is the mean value.

Many combinations have been processed with the different threshold levels, threshold rules and mother wavelets and to the simulated ultrasonic signal the fault echo within 1 – 100 % of initial echo amplitude was added. In case of threshold rule evaluation, the parameters $k$, $\alpha$ and $\tau$ were changed within appropriate range. The best achieved results for the hard, custom and soft thresholding are stated in tab.1, tab. 2 and tab. 3.

Tab. 1: Evaluation of hard thresholding

| threshold level | *V1* | | | | *V2* | | | |
|---|---|---|---|---|---|---|---|---|
| mother wavelet / parameter | db2 | db4 | db6 | dmey | db2 | db4 | db6 | dmey |
| max. *Dx* (-) | 0.994 | 0.989 | 0.978 | 0.981 | 0.967 | 0.976 | 0.966 | 0.984 |
| max. *SNRE* (db) | 25.97 | 37.76 | 35.18 | 37.59 | 24.70 | 24.59 | 19.33 | 19.72 |
| min. *Af* ( % ) | 9 | 7 | 9 | 5 | 13 | 9 | 20 | 2 |
| min. *k* (-) | 1.35 | 2 | 1.1 | 1.4 | 1.35 | 4.5 | 1.4 | 1.4 |

Tab. 2: Evaluation of compromise thresholding

| threshold level | *V1* | | | | *V2* | | | |
|---|---|---|---|---|---|---|---|---|
| mother wavelet / parameter | db2 | db4 | db6 | dmey | db2 | db4 | db6 | dmey |
| max. *Dx* (-) | 0.991 | 0.991 | 0.989 | 0.991 | 0.959 | 0.967 | 0.982 | 0.976 |
| max. *SNRE* (dB) | 26.76 | 32.88 | 31.09 | 31.83 | 26.70 | 32.98 | 30.34 | 30.81 |
| min. *Af* ( % ) | 8 | 6 | 9 | 5 | 13 | 10 | 20 | 10 |
| min. *k* ( - ) | 1.35 | 2 | 1.1 | 1.4 | 1.35 | 4.5 | 1.4 | 1.4 |
| min. *αv* ( - ) | 0.16 | 0.22 | 0.18 | 0.2 | - | - | - | - |

Tab. 3: Evaluation of custom thresholding

| threshold level | *V1* | | | |
|---|---|---|---|---|
| Mother wavelet / parameter | db2 | db4 | db6 | dmey |
| max. *Dx* ( - ) | 0.869 | 0.820 | 0.887 | 0.820 |
| max. *SNRE* ( dB ) | 26.88 | 35.72 | 29.38 | 32.23 |
| min. $A_f$ ( % ) | 9 | 7 | 11 | 6 |
| *k* ( - ) | 1.35 | 2 | 1.1 | 1.4 |
| *αv* ( - ) | 0.16 | 0.22 | 0.18 | 0.2 |

| | | | | |
|---|---|---|---|---|
| $\tau_v$ ( - ) | 0.03 | 0.04 | 0.03 | 0.03 |

It can be seen from tab. 1 that in case of hard thresholding the best results were obtained using discrete Meyer mother wavelet and threshold level based on standard deviation. The value *SNRE* = 37.59 dB and the fault echo with amplitude of 5 % of initial echo amplitude was detected. Other thresholding rules and mother wavelets do not bring better results. The noise was suppressed and the fault echo with amplitude equal to noise level was efficiently detected.
Based on achieved results with DWT de-noising algorithm and Wiener filtr based group delay statistics, the mentioned methods were used in combination to get better results. It can be seen, using DWT de-noising algorithm the noise is efficiently suppressed and the minimal amplitude of fault echo that can be detected has to correspond to minimal 5% of initial echo amplitude. This value characterizes that fault echo amplitude has to be higher than noise level contained in acquired ultrasonic signal. On the other hand, the Wiener filter efficiently suppressed only the noise level corresponding to electronic circuitry noise. The SNRE values are lower than in the case of DWT. This can be caused because the Wiener filter has the shape similar to band pass filter suppressing only the frequencies out of the frequency range of proposed filter. By these considerations, the following de-noising algorithm was proposed. First of all, it is useful to suppress electronic noise part (Wiener filter) and in the following to use DWT de-nosing algorithm to suppress another part of noise. This filter consequence can be called dual filtering. By this dual filtering method, it is possible to detect fault echo amplitude which is lower than noise level measured during the testing. The principal of the proposed dual filtering method is schematically shown in fig.3.

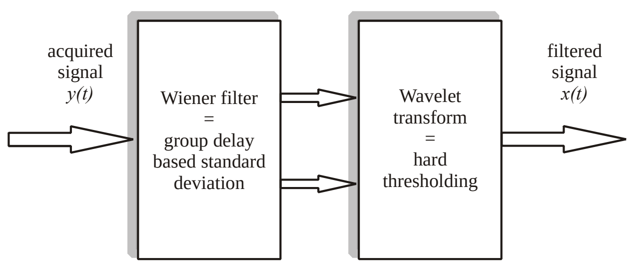

Fig. 3: Principal of dual filtering algorithm

In both methods, the parameters with the best achieved results were used. The following fig.4.represents signal-to-noise ratio enhancement evaluation based on fault echo amplitude. It can be seen that the SNRE values are higher than using DWT or Wiener filter only.

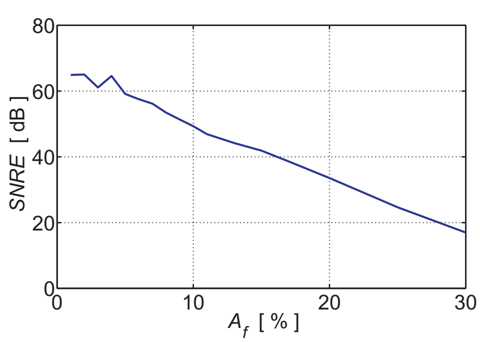

Fig.4a. Dual-filtering algorithm evaluation in terms of noise suppression

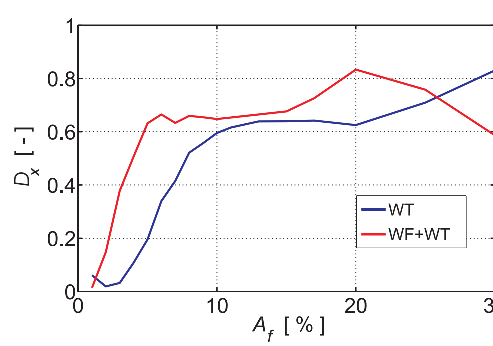

Fig.4b. Dual-filtering algorithm evaluation in terms of noise suppression

For the successful noise level suppression the minimal fault echo amplitude detection has to be specified. It is evaluated by parameter *Dx.* If the parameter *Dx* is higher than 0.1, it means that

fault echo amplitude was detected. As can be derived from fig. 6b, the minimal fault echo amplitude that was detected corresponds to 2% of initial echo amplitude. The achieved results are much more better than previous individual methods and by using the dual filtering algorithm we are able to detect fault echo that is hidden under the noise level.
In fig. 5, it can be seen the ultrasonic noise suppression on simulated ultrasonic signal using dual filtering algorithm (see fig. 5a). In fig. 5b only the Wiener filter was used. As can be seen, only the electronic part noise was suppressed. Fig. 5c demonstrates the dual filtering method. Noise was successfully suppressed and fault echo amplitude corresponding to 2% initial echo amplitude was detected.

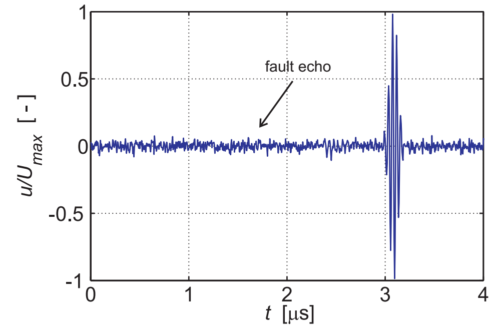

Fig.5a. Simulated ultrasonic signal with 2% fault echo amplitude

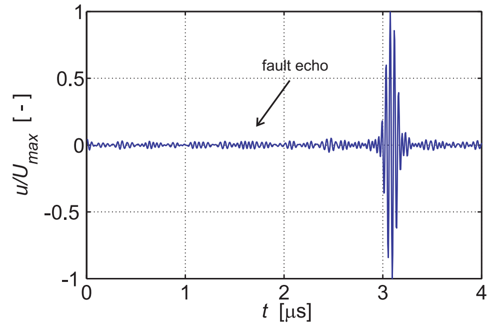

Fig.5b. Filtered ultrasonic signal using Wiener filter

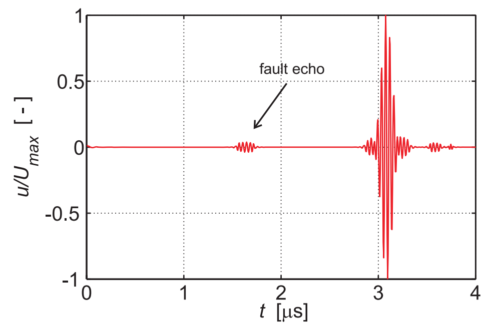

Fig. 5c. Filtered ultrasonic signal using dual filtering algorithm

## 4 Experimental results

Based on achieved result in section 3, the proposed dual filtering algorithm was used on the real ultrasonic signal measured on the coarse-grained material used for airplane engines construction. The signal (see fig. 6) was measured on the place with artificial flaw. The flaw was drilled with laser technology and has a diameter 0.4 mm.

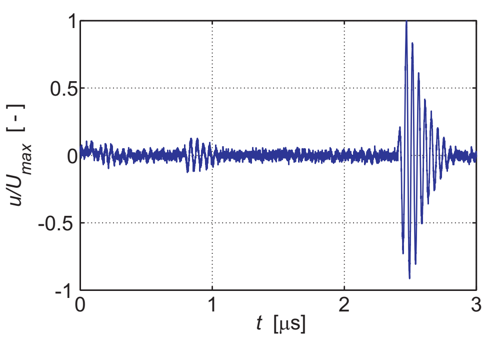

Fig. 6a. Measured ultrasonic signal

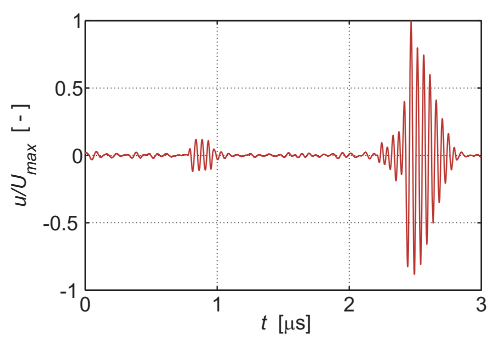

Fig. 6b. Filtered real signal using dual filtering

## Conclusion

This paper performs an evaluation of the proposed dual filtering algorithm, which is based on combination of two methods, the discrete wavelet transform and Wiener filter based group delay statistics. First of all, these methods are separately evaluated on a simulated ultrasonic signal with different sizes of fault echo. The discrete wavelet transform can be used for efficicent de-noising in case the fault echo amplitude is higher than noise level. Wiener filter based group delay statistic can suppress only the noise caused by electronic circuitry influence. Based on achived results, new algorithm called dual filtering was proposed. This proposed algorithm combine both mentioned methods. With proposed algorithm is noise efficiently suppressed (SNRE is within 17 to 70 dB) and the fault echo relative amplitude corresponding to 2% of initial echo amplitude is safely detected. The proposed method was evaluated on both simulated and measured ultrasonic signal.


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