SNR Enhancement of Ultrasonic Pulse-Echo Signals using 1-D Anisotropic Diffusion Filter

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Abstract: Ultrasonic pulse-echo techniques for flaw/defect detection have been widely used for the industrial non-destructive evaluation (NDE). The backscattering noise of the highly scattering materials and/or instrumentation system noise may cause peak value of ultrasonic signal higher than the inspected flaw echoes. Thus, it is essential to enhance the signal-to-noise ratio (SNR) for proper detection of flaw signals by utilizing efficient noise filtering algorithm. In this paper, we have presented the one-dimensional (1-D) anisotropic diffusion filtering technique for the SNR enhancement and echo detection of the ultrasonic amplitude based pulse-echo signal. The anisotropic diffusion filtering algorithm has been examined, evaluated and developed for the filtering of 1-D ultrasonic signals. The stopping criterion for the iteration has been proposed for the efficient echo detection. For the experiment, a single channel ultrasonic pulse-echo measurement system has been developed. The capability of de-noising filtering method is evaluated in terms of SNR improvement. The results show that this approach is more applicable to the processing of noisy ultrasonic signals.

Keywords: Ultrasonic, NDT, Noise suppression, Echo detection, Anisotropic diffusion

1. INTRODUCTION

Ultrasonic testing is extensively used non-destructive testing (NDT) technique. It employs high-frequency (0.5-20 MHz) acoustic waves to detect defects/discontinuities in metallic objects, as well as variations in the metallurgical properties within the materials that could lead to failure of the object. One of the most well-known ultrasonic testing is a pulse-echo technique. In this mode, a transducer connected to an ultrasonic pulser transmits sound waves into the component being examined. In that mode, the acoustic waves propagate through the substance and get reflected back to the same transducer. When defects/discontinuities are present, some fraction of the sound energy will be reflected back. The reflected waves are converted to electrical signals by the transducer (called A-scan signal) and are displayed on the GUI screen.

In the practical industrial applications for materials with a non-homogeneous or coarse-grained structure, the ultrasonic energy is lost due to scattering, so it is challenging to detect and identify small defects in such materials. This noise is time-invariant and produces a frequency band particularly in the range of the echo-signals. Thus, this noise cannot be eliminated by traditional de-noising techniques such as time averaging or hardware filtering. Additionally, the ultrasonic instrument also introduces the noise due to many reasons such as impedance mismatch between several hardware boards, over-amplification of the acquired signal, AC power-line interference, ADC quantization error, electromagnetic interference, cross-talk between analog channels and high-frequency interference. As ultrasonic echo is non-linear and non-stationary, to process this type of signal, numerous signal processing techniques have been used. But every
technique has some drawbacks like cross-correlation is the simple method for implementation but it is not effective to reduce the noise because if the noise and signal have an equal amplitude in the corresponding frequency range then it would be difficult to distinguish among them [1]. The wavelet transform [2] is the most accepted technique due to its time and frequency localization properties. But it needs the selection of the mother wavelet function and scale of it for signal enhancement. The empirical mode decomposition [3] based data-driven technique is also utilized for the signal analysis and processing in the time domain. But it requires many mathematical computations and iterations for the processing.

Formerly, the anisotropic diffusion filtering technique was extensively used for the 2-D image processing application such as image smoothing, image enhancement, edge detection, and image segmentation [4], [5], [6]. Perona and Malik [7], developed the anisotropic diffusion algorithm especially for image processing application that smooths the images without blurring the edges. Subsequently, this filtering technique is also applied for the speckle removing of ultrasonic 2-D images [8]. In this study, we have outlined a one-dimensional (1-D) anisotropic diffusion filtering approach for the noise suppression and echo detection of the amplitude based ultrasonic pulse-echo signals.

2. ANISOTROPIC DIFFUSION FILTER

The anisotropic diffusion filtering scheme is mathematically defined as a smoothing process that governed by the knowledge about the statistics about the noise degradation and the edges strengths [9]. The anisotropic diffusion filter has the following form [7]:

\[
\frac{\partial}{\partial t} I(x, t) = \text{div} \left[ G(|\nabla I(x, t)|) \nabla I(x, t) \right]
\]  

(1)

where \( I(x, t) \) represents the strength (intensity) of the noisy signal at a specific time \( t \) and \( \text{div} \) denotes the divergence operator. The \( \nabla I(x, t) \) is the gradient of the signal at time \( t \) and \( G(\cdot) \) is called the conduction function. The conduction function depends on the magnitude of the gradient of the signal amplitude and it is monotonically positive decreasing function \( G(x, t) = F(|\nabla I(x, t)|) \). Therefore, in the edges where the gradient magnitude is large, the conduction function is small and as appearing, the smoothing effect is negligible. Similarly, in the smooth region where the gradient magnitude is small, the conduction function is large and consequently the softening effect is considerable. The following two common conduction functions have been proposed for the anisotropic diffusion [7].

\[
G_1(x, t) = \exp \left( - \left( \frac{|\nabla I(x, t)|}{K} \right)^2 \right)
\]

(2)

\[
G_2(x, t) = \frac{1}{1 + \left( \frac{|\nabla I(x, t)|}{K} \right)^{1+\alpha}}, \quad \alpha > 0
\]

(3)

where \( K \) is the gradient threshold parameter. If \( |\nabla I(x, t)| \gg K \), then sharpening arises, if \( |\nabla I(x, t)| \ll K \), then it results in Gaussian filtering. The discrete form of (1) is expressed by

\[
I^{t+1}(s) = I^t(s) + \frac{\lambda}{|\eta_s|} \sum_{p \in \eta_s} G(|\nabla I_{s,p}|) \nabla I_{s,p},
\]

(4)

where \( I^t \) is the discretely sampled signal, \( t \) denotes the iteration step, \( s \) is the sample position in a discrete one dimension and \( G \) is the conduction function. Constant \( \lambda \in (0, 1] \) determines the time step size of neighborhood samples and \( \eta_s \) represents the spatial neighborhood of the sample \( s = \{L, R\} \), where \( L \) and
\( R \) are the left and right neighbors of the sample \( s \). Thus, the direction differences of the samples are as follows:

\[
I^t_L(x) = I^t(x - 1) - I^t(x) \\
I^t_R(x) = I^t(x) - I^t(x + 1)
\]

The anisotropic diffusion process is remarkably sensitive to the number of iterations as it is an iterative method. Because the emphasis of the stopping time \( T \) may lead to blurring the original edges while undervaluing it may allow the unfiltered noise. The overall problem on stopping criteria was performed in [10], [11] using the statistics of each filtered version of the image specifically for the 2-D image processing applications such as decorrelation criteria that minimizes the correlation between filtered and noisy images [10] and maximum SNR criteria that requires the variance of noise [11]. Here for 1-D signal processing applications, we have proposed the maximum pulse-echo SNR based scheme by checking the quality of the echoes of the definite signal. The stopping time \( T \) is selected such that it maximizes the SNR.

\[
T = \arg \max_t \left[ SNR^t(dB) \right]_{BW}
\]

where we have adopted the SNR of only back-wall (BW) echo signal because it is settled and constantly presents at the same position. The other major reason to prefer the SNR of BW echo is that it is totally independent of the other echo signals acquired from the flaws/defects.

3. RESULTS AND DISCUSSIONS

Fig.1 describes the overall block diagram of the developed single-channel ultrasonic imaging system, especially for the pulse-echo measurement and imaging purposes. The system comprises high voltage pulser which generates negative HV spike pulse in response to the positive low voltage trigger pulse generated by the external device (FPGA). The spike pulse excites the ultrasonic transducer and produces the ultrasonic wave of its center frequency [12]. The output of ultrasonic pulser is connected to the ultrasonic receiver amplifier board through a limiter to amplify echo signals. The output of the three-stage cascaded receiver amplifier with a maximum gain of +40dB is connected to the analog multiplexer amplifier. For the analog-to-digital conversion, 8-Bit, 100 MSPS, low power ADC is used. ADC is interfaced with the Spartan-6 (XC6SLX9-3CSG324) FPGA. All the control signals are generated by the FPGA which provides clock and power-down signal to the ADC. The 8-Bit output of the ADC is stored in on-chip FIFO of FPGA for further processing of data. The reconfigurable data controller architecture has been developed in FPGA using VHDL code. Read clock domain of FPGA FIFO is entirely controlled by the external USB controller which has a system clock of 400 MHz. The controlled signals are provided by the GPIO bus of the USB device. A USB 3.0 peripheral controller with an on-chip 32- bit, 200-MHz ARM926EJ-S core CPU has been used as a controller between FPGA and PC. The USB application firmware has been developed using C++ language. The GUI software has been developed in Visual Studio platform using Visual C# language [13].

Fig.1 also shows the aluminium object with three artificial holes \( H_1, H_2 \) and \( H_3 \) one below another. The height of the block is 153 mm. For measurements, the experimented pulse-echo signal has been acquired from the artificial holes of the aluminium block via a contact transducer of 2.2 MHz frequency and 25 mm diameter. The sampling rate of 16 MHz with 8-bit resolution is adopted for the data acquisition.

The amplitude-based (A-scan) waveform has been captured using the GUI based software for the post-processing. Fig. 2 displays the noisy signal as well as a processed output signal by the anisotropic diffusion
filter. From the Fig.2, it can be observed that four echoes $H_1$, $H_2$, $H_3$ from the holes and $BW$ from the back-wall surface are precisely identified and visualized with high SNR.

The modified SNR function is used to analyze the enhancement of the pulse-echo signal $x(t)$ using anisotropic diffusion filtering [14]. The $SNR(dB)$ function is:

$$SNR'(dB) = 10 \cdot \log_{10} \left[ \frac{\sum_{x=L-W/2}^{L+W/2} I_t^2(x)}{\sum_{x=1}^n I_t^2(x) - \sum_{x=L-W/2}^{L+W/2} I_t^2(x)} \right]$$  \hspace{1cm} (7)

where $L$ is the location of flaw/hole and $W$ is the pulse width of the echo signal. These parameters can be obtained manually through visual examination. The same $SNR$ function is used for raw noisy input and its anisotropic diffusion processed output. The Table I shows the enhancement in the pulse-echo signals for the all echoes. The total SNR enhancement is $+6.09dB$, $+5.52dB$, $+2.54dB$, and $+10.30dB$ for the $H_1$, $H_2$, $H_3$, and $BW$ echo, respectively.

**TABLE I. SNR ENHANCEMENT BY 1-D ANISOTROPIC DIFFUSION FILTER**

<table>
<thead>
<tr>
<th>Echo locations</th>
<th>SNR (Noisy Signal)</th>
<th>SNR (Processed Signal)</th>
<th>SNR Increment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_1$</td>
<td>$-11.9233$</td>
<td>$-5.8319$</td>
<td>$+6.0914$</td>
</tr>
<tr>
<td>$H_2$</td>
<td>$-12.9925$</td>
<td>$-7.4688$</td>
<td>$+5.5237$</td>
</tr>
<tr>
<td>$H_3$</td>
<td>$-17.3115$</td>
<td>$-14.7718$</td>
<td>$+2.5397$</td>
</tr>
<tr>
<td>$BW$</td>
<td>$-8.6344$</td>
<td>$+1.6665$</td>
<td>$+10.3009$</td>
</tr>
</tbody>
</table>
The stopping time $T$ is calculated by applying the (6) and (7). For the BW echo signal, the sample number $L = 828$ and the sample width $W = 50$ have been considered for the calculations. The $SNR(dB)$ versus the number of iterations ($t$) plot (Fig. 3) illustrates that the maximum $SNR(dB)$ is obtained at the $T = 23$ iteration.

Fig. 2. A-scan of experimented noisy signal and its processed signal by anisotropic diffusion filter

Fig. 3. The measured $SNR$ value in every iterations for the $BW$ echo signal
4. CONCLUSION

It has been demonstrated and experimentally validated an anisotropic diffusion filtering based new approach for the SNR enhancement and echo identification of ultrasonic pulse-echo signals. For that purpose, 1-D anisotropic diffusion based numerical algorithm has been accordingly implemented for the post-processing of ultrasonic pulse-echo signals. We also have proposed the stopping criteria that consider the level of embedded noise as well as preserves the quality of the echo signal. A complete single channel system has been developed for the A-scan signal acquisition. Experimental results demonstrate that the 1-D anisotropic diffusion filtering algorithm provides SNR enhancement and improves echo detection. Numerical results show the SNR enhancements of about 10 dB for the BW echo. Thus, this approach is very effective for canceling noise and improving the detectability of the ultrasonic echo signals.

REFERENCES