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Research Article

Noise Reduction in Ultrasonic Signals for Identification of Weld Defects: A Review

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Abstract: In Ultrasonic Inspection, the first and foremost step to find the defects in welding materials used in industrial applications is Noise Reduction. It is used to improve the detect ability of the weld defects. It plays a vital role in Flaw Detection and Characterization of materials such as Austenitic Stainless Steels etc. This study gives a review of various noise reduction schemes or techniques for reducing the noise to detect the welding defects and aims at the usage of it.

Keywords: LWT, SNR, UT, WPT, WT

INTRODUCTION

Due to stress, fatigue, manufacturing process and environmental changes, the weld defects can occur. Using heat, the similar or dissimilar metals can be joined. This process is known as Metal joining process. Welding is one such method. In welding, two similar metals are joined. During the welding process, defects can be introduced into the material. Different kinds of defects occur in the welding regions. To ensure safety, the presence of defect must be identified in the weldment. The defects can be found using Non-Destructive Testing methods like Ultrasonic Testing. Because of the presence of both noise and fake signals, the quality and reliability of UT of weldments can get affected. Hence, Noise reduction and SNR improvement are the important factors for the flourishing application of ultrasonic NDE and NDT (Yuan and Ma, 2008).

Ultrasonic testing: Based on the frequency, the sound wave can be categorised into the following three types:

- **Infrasonic wave:** Frequency <20 Hz.
- **Audible wave:** 20 Hz≥Frequency ≤20 KHz
- **Ultrasonic wave:** Frequency >20 KHz

In UT, very short pulse-ultrasonic waves are to be launched into the specimen. In the test specimen, the availability and the characteristics of the flaws can be detected using this ultrasonic testing. UT is done on austenitic stainless steels, alloys, concrete and other metals, etc. Ultrasonic testing techniques such as To FD (Manjula *et al*., 2012), Phased Array, etc, have been widely used for detecting and characterizing the flaws in the test specimen. In ultrasonic weld inspection, the most common defects in weld pad are volumetric discontinuities such as porosity, slag and planar discontinuities such as crack and lack of fusion.

Ultrasonic signals are dominated by the various noises such as environmental noise, instrumental noise and material noise, shot noise, thermal noise or Johnson noise etc. Accuracy and precision of the ultrasonic signal can be affected by the unwanted form of energy which is known as noise. Hence, Noise Reduction is an important process in the evaluation of the ultrasonic signals for detection and characterization of the weld defects. To reduce noise in the detected signal i.e., to improve the defect to the background noise i.e., structural noise, many DSP methods proposed and used. These methods include adaptive filtering, correlation technique, median filtering, SSP, ANN, FT, FFT, STFT and WT. Noise reduction is not effective using the simplest and popular methods based on averaging (Matz *et al*., 2009), FIR and IIR (Drai *et al*., 2000a). Now Let us see the formula for finding SNR of a signal.

SNR calculation: The ultrasonic signal can be affected by two categories of noises. One is Coherent random noise (Instrumental noise, etc.,) and another one is Coherent noise (Material noise. etc,). Temporal Averaging can be used to reduce the first category of noise content and more complex techniques are used to reduce the coherent noise content from the received ultrasonic signals. The ratio between the signal strength and noise strength is SNR. Using this SNR, the signal strength can be calculated. The SNR can be calculated using the following ways:

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$$SNR = \frac{Mean}{\text{Standard Deviation}} \quad (1)$$

$$SNR_{rms} = \frac{\text{target peak-to-peak amplitude}}{\sigma_n} \quad (2)$$

(Prasanna and Canelones, 1992)

$$SNR_{RMS} = \frac{Max.\text{ peak-to-peak amplitude}}{\text{RMS value}} \quad (3)$$

(Karpur *et al*., 1987)

Evaluation of SNR improvement can be achieved by:

$$SNRE = 10\log\frac{P_1}{P_2} \quad (4)$$

(Matz *et al*., 2007)

Where P_1 and P_2 - Powers of the noise before and after de-noising:

$$SNR(dB) = 20\log\frac{rms\text{ SIGNAL}}{\text{rms NOISE}} \quad (5)$$

(Bonnie, 2004)

$$SNR_O = 20\log_{10}\left(\frac{STD(\{f(n)\})}{STD(\{f^{'}(n)\text{-}f(n)\})}\right) \quad (6)$$

(Yi and Cheng, 2007).
where, the output SNR is in dB. The input signal and the reconstructed signals are denoted by f(n) and f'(n). Now let us see the various de-noising methods to suppress noise in the signal.

METHODOLOGY

Applying de-noising methods to reduce noise seems to be a promising area. Methods based on STFT, Two dimensional FFT, Hilbert-Huang Transform, Wavelet family, etc., are used in the signal de-noising. We discuss some of the noise reduction methods based on the filter, FT, WT transforms in this section.

Wiener filter: It is a global filter (Xing *et al*., 1993; Izquierdo *et al*., 2002) used to handle the problem of signal estimation in the presence of noise. By minimizing MSE between the estimated signal and uncorrupted signal, the estimation of uncorrupted signal is to be produced. Because of noise, the signal is to be corrupted after de-noising. Fault echo can be measured by Eq. (7):

$$\mathrm{K_c} = R_{A_a A_b}(0)\left(1 - \frac{A_a - A_b}{A_b}\right) \quad (7)$$

where,
A_a = Amplitudes of flaw echo after de-noising
A_b = Amplitudes of flaw echo before de-noising
R = Cross-correlation function the authors (Matz *et al*., 2007) found that the amplitude of flaw echo was reduced.

Advantage:

- Noise suppression is good

VC-based signal de-noising: For signal de-noising and estimation, VC theory was applied by Cherkassky and Shao (Cherkassky and Shao, 2001). To choose an optimal number of fourier coefficients and wavelet coefficients in the signal de-noising applications, a practical must be introduced in VC-bound. In improved VC de-noising method, the noisy signal is over sampled. For different kind of noises and signals, this improved VC-based signal de-noising provides better signal estimation accuracy (Jie and Cherkassky, 2001).

Fourier transform and STFT: Obtained amplitudes and frequencies of the signals are fixed. In STFT, Only the stationary signals can be analyzed and the width of the window is restricted in both frequency and time domains (Jaejoon, 2010).

Split spectrum processing: SSP is a non-linear method based on band pass filters. Based on overlapping Gaussian Pass band filters with different center frequencies and fixed absolute bandwidth, the frequency spectrum of the signal can be divided into a set of narrow band signals to extract the flaw information from the noisy signal by this split spectrum processing (Agostino *et al*., 1997; Rose *et al*., 1988). SSP is used to improve the SNR. Since the proposed SSP algorithms are sensitive to some of the parameters (like number of band pass filters in the filter bank), these SSP algorithms are not robust (Pagodinas, 2002). It used for both suppressing noise and detecting flaws in large-grained stainless steel (Bilgutay *et al*., 1979; Nihat *et al*., 1989; Li *et al*., 1992). In 1970's, SSP was used to suppress the noise and to detect the flaws in the ultrasonic signals based on Fourier transforms and band pass filtering.

Wavelet analysis: It is one of the DSP techniques that involve WT, WPT and LWT.

Wavelet Transform (WT): Wave and Wavelet is similar to Book and Booklet respectively. i.e., wavelet represents small wave or simple wave. Using dilation and translation of a mother wavelet function, some set of wavelet basis functions can be obtained. This is known as wavelet transform. WT (Abbate *et al*., 1994; Kaya *et al*., 1994; Chan 1995; Agostino *et al*., 1997;

Drai *et al*., 2000b) is the most popular method for processing non-stationary signals concurrently in both frequency and time domain. The most important characteristic of WT is its MRA. The information of a signal is decomposed into low and high information at different scales using MRA property. But the performance of WT is dependent on selection of wavelet basis (Jaejoon, 2010). To suppress the noise and then to find flaws, WT is used. Using WT, low and high frequency components of the signal can be found. The high frequency information of the decomposed signal is nothing but noise. The high frequency information i.e., detail components are not to be decomposed continuously. The frequency components are thresholded and the wavelet coefficients are used to reconstruct the de-noised signal. The quantitative measurement of the signal at different scales can be obtained through this WT (Bettayeb *et al*., 2004).

Based on the application, wavelet basis can be selected. This is an advantage of the multi-scale or multi-resolution decomposition. i.e., Wavelet coefficients are used to select the feature vectors. The authors (Louis *et al*., 1997; Lazaro *et al*., 2002; Paul, 2004; Shou-Peng and Que, 2006) concluded that the method based on Discrete Wavelet Transform is popular for noise suppression. For better results, mother wavelet, threshold level and threshold rule must be chosen properly during signal decomposition (Pardo *et al*., 2006). Universal threshold, adaptive threshold, heuristic threshold and minimaxi threshold are known as the four methods of general threshold rule (Yuan and Ma, 2008).

Wavelet packet transform: Since WPT is an extension of DWT, It has better reconstruction process than DWT (Fairouz and Haciane, 2008). The frequency band is to be partitioned into different levels and the detail coefficients are to be decomposed further. Based on the characteristics of the signal analysis, WPT can choose the frequency band and matched with the spectrum of the signal. Hence an improvement is achieved in the processing ability of signal. Computation of WPT in ultrasonic signal de-noising is complex; but it is effective than that of WT (Yuan and Ma, 2008).

Lifting wavelet transform: Unlike classical WT, LWT directly analyses the problems in spatial domain. Split, Predict and Update are the three phases of the lifting scheme of WT. Fast computation, no need of extra memory are some of the characteristics of the de-noising by LWT. It is mainly used in real-time signal de-noising. SNR is similar to WT. But it has flexible design, fast computation, etc., (Yuan and Ma, 2008).

Stationary wavelet transform: SWT or discrete SWT is an undecimated version of discrete wavelet transform. The input signal can be decomposed without decimation to get detail coefficients. The objective of this approach is to average these detailed coefficients. SWT is understood as the repeated application of the standard discrete wavelet transform method for different time shifts.

Threshold de-noising algorithm: (Yuan and Ma, 2008)
This method involves the following steps:

- Obtain decomposition coefficients, by decomposing the noisy signal using wavelet at N levels
- Obtain new detail coefficients from the decomposition detail coefficients by threshold. Any one of the (Hard or Soft or Semi-soft) thresholding functions can be used.
- To produce new de-noised signal by wavelet family, reconstruct the new de-noised detail coefficient with the approximation coefficients.

Wavelet shrinkage algorithm: It involves the following three steps for decomposing the signals using DWT, threshold wavelet detail coefficients and reconstruction using Inverse DWT (Jaejoon, 2010).

- **Decomposition:** Apply DWT to a signal and get the wavelet coefficients
- **Threshold detail coefficients:**
  - Assigns zero to the wavelet coefficients with amplitudes less than a certain threshold.
  - Apply nonlinear soft thresholding operation to do the thresholding operation
- **Reconstruction:**
  - After thresholding, the thresholded wavelet coefficients are to be transformed to reconstruct the signal using IDWT.

Wavelet transform signal processor: An enhanced resolution can be obtained by the self-adjusting window structure of a WT than that of STFT. An improvement is achieved to detect the flaws and suppress the noises in noisy signals by using WT. In this, the relative bandwidth is to be constant. MRA property of WT is used (Agostino *et al*., 1997) to detect the flaw echoes which are embedded in the background noise. Like band-pass filter in SSP, window is used in DWT. A group of scales are denoted as window. The sub-band can also be decomposed in DWT. This window takes the role of band-pass filter in SSP. The authors (Erdal and Saniie, 2004) have shown good results using higher order kernels. Using DWT, the authors (Erdal and Saniie, 2004) obtained 5-12 dB flaw-to-clutter enhancements of ultrasonic signals.

Signal matching wavelet: In WT domain, the energy distributions of the flaw echo signal and the noises are entirely different from each other. The problems concentration and separation must be handled to acquire an optimal energy match in between the flaw echo signal and the wavelet basis function. Echo signal contains both the background noise and the flaw echo signal. i.e., Echo Signal = Noise +Flaw echo signal.

To get a localized energy distribution of the flaw echo signal in wavelet transform domain, the input signal is to be considered as a mother wavelet function. The high frequency information is the noise. The authors (Shi *et al*., 2011) have shown that the efficiency of the flaws detect ability using SMW.

Hilbert-Huang transform (Jaejoon, 2010): HHT is a combination of HT and the EMD algorithm and Huang *et al*., introduced this time-frequency analysis technique. Non-stationary signals are processed by this technique. In HHT, before calculating Hilbert Spectrum of the EMD output IMFs, the decomposition of the signal is to be performed using Empirical Mode Decomposition. An amplitude and frequency-time representation of the signal can be determined from these spectrums. A new PCA method that is used to extract IMFs from high frequency to low frequency is known as EMD. These IMF coefficients concentrate on the most important information of the original ultrasonic signal. Normally, First few scales are used to get the details about noise. The local features of a signal can be emphasized using Intrinsic Mode Function i.e:

- Numbers of both local extrema and zero crossings must be equal or the difference at most one.
- Mean must be determined by the average of the local maxima and minima envelops. It is to be zero.

Hence, based on time-scale characteristics, the signal can be decomposed into sum of intrinsic mode functions:

De-noising algorithm by HHT has the following steps (Jaejoon, 2010):

- Decompose the noisy signal using EMD
- Remove high frequency noises by choosing suitable threshold at every scale
- The proceeded IMF coefficients mainly from the first three scales are to be reconstructed. i.e., the filtered signal can be obtained from this reconstruction process

Advantages:

- Based on EMD process, variable amplitudes and frequencies of the signals can be obtained.
- Due to EMD process, the valuable information can be maintained for feature vectors. Here the noise level is reduced.

The authors (Jaejoon, 2010) achieved better improvements using HHT than that of WT for non-stationary signals.

RESULTS AND DISCUSSION

The author (Pagodinas, 2002) concluded that the usage of SSP is limited because of its computation time for signal decomposition. The authors (Angam *et al*., 2012) concluded that the choice of mother wavelet and threshold values plays a vital role in analyzing and de-noising of the signal. They have shown good SNR improvements using “db4’’ and “coif5” mother wavelets than that of the other mother wavelets. The authors (Aussel and Monchalin, 1989) concentrated on three different basic wavelets namely an autoregressive, binary and Gaussian-shaped wavelets. They (Aussel and Monchalin, 1989) tested both an austenitic steel sample and graphite-epoxy sample using given two decompositions. One is Split Spectrum Processing with conventional Gabor decomposition and another one is generalized with the following wavelets decompositions: an autoregressive wavelet, a binary wavelet and a Gaussian-shaped wavelet. An austenitic stainless steel samples give large background noise; a graphite-epoxy samples give low microstructure noise. They concluded that the Gaussian-shaped and conventional decompositions had about the same performance; but an autoregressive and the binary wavelet decompositions had less performance. But it is more efficient to implement. At last the authors evaluated on synthetic data the application of generalized SSP to deconvolution of noisy ultrasonic data. The authors (Aussel and Monchalin, 1989) had better results on low SNR data with much less computation. For noise reduction in the non-stationary signals, the authors proposed HHT method and achieved good results than that of WT. The authors (Kawashima *et al*., 1996) found that the micro structural changes of the stainless steel can be detected by using the modifications in both backscattered noise and ultrasonic measurement of velocity. The authors (Guilherme and Saniie, 2003) achieved the SNR improvement beyond 30dB. The authors (Bettayeb *et al*., 2004) concluded that the wavelet theory is opting for noise filtering and it is used to improve the test speed with better test validation data bank. Using energetic smoothing procedure, they extracted the noise features and developed the noise analyzing wavelet function and deduced the noise in the spatial domain. They (Bettayeb *et al*., 2004) achieved an easiest ultrasonic signal filtering and a fine flaw detection process by energetic characterization of the noise and useful information. Coifman and Donoho (1995) evaluated the performance of both DWT and SWT with

Coifman wavelet family and obtained good results using translation-invariant property for de-noising. The authors (Agostino *et al*. 1997; Drai *et al*., 2000a) proposed that the signal analysis can be faster in WT than in FT analysis. Lazaro *et al*., 2002 proposed both DWT and Wiener filter using group delay statistics are the best methods for the ultrasonic signal de-noising. The authors (Hasan *et al*., 2002) proposed that the bootstrap method for de-noising signals of different kind. They achieved the better performance using FFT-based de-noising method for stationary sinusoidal signal and WT-based methods for chirp signal. Because of sparse, Maximum Likelihood Estimation (MLE) decomposition is able to compress the ultrasonic signal at high compression rates and signal quality is not affected. Through this MLE, the signal is represented in temporal and spectral domains. Thus the authors (Ramazan and Saniie, 2004) achieved good suppressed noise. Matz *et al*. (2007) found that the DWT is the best noise reduction method than the wiener filter using group delay statistics for ultrasonic signal and they have achieved 35dB of noise suppression for a signal with flaw echo. The authors (Tumšys and Raišutis, 2007) achieved good improvements for removing ultrasonic grain noise from the ultrasonic signals of austenitic stainless steel by using DWT with the mother wavelet Symlet -10 and using Minimax threshold selection rule. The authors (Yi and Cheng, 2007) proposed a noise suppression algorithm using wavelet transform modulus maxima for suppressing noise from the non-stationary signals. They obtained high SNR using this WTMM method than that of sqtwolog method. The authors (Yuan and Ma, 2008) concluded that the computation is complex for LWT but it is fast for WPT. The authors (Fairouz and Haciane, 2008) obtained good results using Debauchee family (especially for db8) in the wavelet packet filtering process. The authors (Chen and Zhu, 2009) found the de-noising signal is closer to the original signal. They got good results than that of the existing de-noising methods by means of RMSE. Hence, using the combination of the existing de-noising methods, many different de-noising algorithms and methods have been introduced and achieved good results.

CONCLUSION

Noise reduction of the ultrasonic signals can be obtained by suppressing unwanted coefficients (noise) of that signal. To do that, many de-noising methods based on averaging, FIR, IIR, WT, WPT, etc can be used. Noise reduction methods must be self adaptive, simple. After de-noising the signal, the amplitude of noise suppressed signal may get attenuation. This is the weakness of the simple filtering (averaging) and some popular filtering methods. In this review, formula for signal-to-noise ratio and various de-noising methods for noise reduction are discussed. For noise reduction in non-stationary signals, HHT can also provide good results. De-noising methods based on Wavelet family produce good results for noise suppression of the ultrasonic signal. Based on the combination of existing de-noising methods, new de-noising algorithms can also be formed and the noise can be reduced from the ultrasonic signals by using that new de-noising algorithms.

ABBREVIATIONS

NDT : Non Destructive Testing
NDE : Non Destructive Examination
SNR : Signal to Noise Ratio
WT : Wavelet Transform
DWT : Discrete Wavelet Transform
WPT : Wavelet Packet Transform
SSP : Split Spectrum Processing
ToFD : Time of Flight Diffraction
UT : Ultrasonic Testing
MSE : Mean-Square Error

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