Maximum nongaussianity principle for ultrasonic flaw detection*

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Abstract: The noise suppression techniques with wavelet transform (WT) are widely used in non-destructive testing and evaluation (NDT&E). In this paper, we have analyzed the non-gaussian statistical properties of the ultrasonic echoes. The distribution of the sum of the M-superimposed Gaussian echoes and WGN is closer to gaussian distribution than that of the M-superimposed ultrasonic Gaussian echoes. The smaller the signal to noise ratio of the M-superimposed Gaussian echoes, the weaker the nongaussianity of the ultrasonic Gaussian echoes. In this paper, a technique for improving the signal to noise ratio of ultrasonic signals using optimal frequency-to-bandwidth ratio wavelet transform (OWT) is presented. We address the design of this wavelet using maximum nongaussianity principle. Experimental results have been presented to evaluate the effect of the optimal wavelet transform filtering on ultrasonic flaw detection. All results showed that the optimal wavelet has best effect of the noise suppression and in much improved detection of the signals.

Key words: Ultrasonic, NDT, Maximum nongaussianity, Defect inspection

1 Introduction

The ultrasonic pulse echoes reflected from inhomogeneities or discontinuities in tested materials or specimen contain a large amount of information of the reflectors. These signals are also contaminated by noise originating from both the measurement system and specimen. The noise embedded in useful signals, sometimes even very heavy, places a fundamental limit on the detection of small defects and the accuracy of measurement. The amplitude of the flaw echo can be quite small, and buried in coherent noise, leading to some difficulty in detecting them with an acceptable signal to noise ratio (SNR). It is essential, therefore, to employ advanced signal enhancement techniques to extract useful diagnostic information from the measured ultrasonic NDE signals [1-2]. The WT is defined in terms of basis functions obtained by compression/dilation and shifting of a mother wavelet [3]. It acts as a mathematical microscope which allows one to zoom in on the fine structure of a signal, or, alternatively, to reveal large scale structures by zooming out. Its property of self-adjusting the analysis windows according to the signal frequency makes it more suitable for the analysis of transient non-stationary ultrasonic

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signals. In ultrasonic NDT&E, using wavelet based signal processor to remove the noise is not a new concept. Zhang et al. [4] proposed a method of using the filter with optimal frequency- to-band ratio of wavelet to de-noise the ultrasonic signals under the assumption of both the wavelet and the ultrasonic signal possessing a same function envelope of Gaussian function. Yang et al. [5] analyzed the orthogonality of the ultrasonic signal acted as base wavelet. And another scholar, Fan et al. [6] apply stationary wavelet transform together with kurtosis and universal de-noising to analyze ultrasonic signals in an attempt to identify the weak signals encountered in testing of metallic materials.

In pulse-echo ultrasonic testing of pipeline, the ultrasound radio-frequency signal is typical super-gaussian random variables [7-8], the density is contained in some limited intervals with high probabilities, but the distribution of the ultrasound echoes contaminated by noise is closer to Gaussian distribution, as the SNR worsens, the value of kurtosis coefficient of the ultrasound radio-frequency signal will descend. This property is highly useful, making it possible to increase super-gaussian for improving the SNR of the ultrasound RF signal.

The remainder of this paper is organized as follows. In Section 2 We address the choice of the optimal scale of a daughter wavelet using the maximum nongaussianity principle. In Section 3, results obtained from actual ultrasonic signals are presented. Conclusions are presented last.

2. Optimal scale wavelet transform

In the ultrasonic NDT&E, the ultrasonic signal is usually a broadband signal pulse modulated at the central frequency of the transducer. Therefore the transient signal is usually time-and frequency-limited [9-10]. For this reason, the utilization of time–frequency wavelet analysis can be more appropriate. Ultrasonic pulse detection consists of determining the presence or absence of a pulse and estimating its amplitude and arrival time. In ultrasonic testing, the measured ultrasonic signal $f(t)$ can be expressed as the sum of two components:

$$f(t) = s(t) + n(t) \qquad (1)$$

Where $s(t)$ is the acoustic signal embedded in the noise $n(t)$. The signal $f(t)$ is thus band-limited, corrupted, and distorted by white Gaussian or random noise $n(t)$. The purpose of this work is to obtain a signal $f_w(t)$ as close as possible to $s(t)$, thus minimizing the effect of $n(t)$. The ability of adapting the window size in frequency domain makes the WT a natural candidate for the analysis of transient ultrasonic signals with a wide spectral range.

Suppose $\psi(t)$ is an arbitrary mother wavelet, its central frequency and frequency resolution are expressed as,

$$\omega_0 = \frac{\int_{-\infty}^{\infty} \omega |\hat{\psi}(\omega)|^2 \, d\omega}{\int_{-\infty}^{\infty} |\hat{\psi}(\omega)|^2 \, d\omega} \tag{2}$$

$$\nabla\omega = \left(\frac{\int_{-\infty}^{\infty} (\omega - \omega_0) |\hat{\psi}(\omega)|^2 \, d\omega}{\int_{-\infty}^{\infty} |\hat{\psi}(\omega)|^2 \, d\omega} \right)^{\frac{1}{2}} \tag{3}$$

where $\hat{\psi}(\omega)$ is the Fourier transform of the mother wavelet $\psi(t)$, ω is the angular frequency, ω_0 is central frequency of the mother wavelet.

We can define a frequency window of the mother wavelet as: $[\omega_0 - \Delta\omega/2, \omega_0 + \Delta\omega/2]$. The analyzed signals whose frequency falls into this window will pass through. In order to cover the entire interest frequency band, a set of daughter wavelets $\psi_{s,u}(t)$ is generated from the mother wavelet $\psi(t)$ by dilation s and shift u operations. The function is given by

$$\psi_{s,u} = \tfrac{1}{\sqrt{s}} \psi(\tfrac{t-u}{s}) \tag{4}$$

The Fourier transform of the daughter wavelets has the following form:

$$\hat{\psi}_{u,s}(\omega) = \sqrt{s}\hat{\psi}(s\omega) e^{-j2\pi u\omega} \tag{5}$$

It has support on $[\omega_0/s - \Delta\omega/2s, \omega_0/s + \Delta\omega/2s]$.

Let us consider an ultrasound RF signal $f(n)$, and the DWT of the signal can be obtained by:

$$c_s(n) = \sum_k f(k) h(k - 2n) \tag{6}$$

$$w_s(n) = \sum_k f(k) g(k - 2n) \tag{7}$$

$h(k)$ and $g(k)$ are the impulse response of low-pass and high-pass filters of the corresponding daughter wavelets $\psi_{s,u}(t)$ with the scale s, called quadrature mirror filters. $c_s(n)$ and $w_s(n)$ are discrete scaling coefficients and wavelet coefficients on the scale s.

The signal recovered by the reconstructing filter only using the scaling coefficients is

$$f_w(n) = \sum_k c_s(k) \tilde{h}(n - 2k) \tag{8}$$

Where $\tilde{h}(n)$ is dual low-pass filter (the reconstructing filter).

If the central frequency the ultrasonic pulse $s(t)$ is equal to that of the daughter wavelet $\psi_{s,u}(t)$, and the frequency band of the ultrasonic pulse is within but as close as possible to the support of the daughter wavelet, that is to say, majority of the interest frequency components can pass through. Meanwhile the noise beyond this range is well cut down. The recovered signal $f_w(n)$ will be as close as possible to the ultrasonic pulse $s(n)$. It also indicates that one filter is enough to maintain the useful information of the ultrasonic signal. In practice, it is very difficult to select the scale s of the daughter wavelet.

In pulse-echo ultrasonic testing of pipeline, the ultrasound radio-frequency signal is typical super-gaussian random variables [7-8] , as the SNR worsens, the value of kurtosis coefficient K_u of the ultrasound radio-frequency signal will descend. The kurtosis coefficient K_u of the ultrasound RF signal y can be expressed as

$$kurtosis = \frac{E(y^4)}{[E(y^2)]^2} - 3 = \frac{E(y'+n)^4}{[E(y'+n)^2]^2} - 3$$

$$= \frac{E[(y')^4] - 3[E(y')^2]^2}{[E(y')^2]^2 + [E(n^2)]^2 + 2E(n^2)E(y')^2} \qquad (9)$$

Where $y' = \sum_i^M h(\theta_i;t)$ is the superimposed Gaussian echoes. The random variable $y(t)$ here has zero mean and been normalized. It can be shown that the value of K_u in the presence of noise is greatest when the SNR is the greatest ($E(n^2)$ is the smallest). Here the ultrasound RF signal is deterministic. In this case, the standard criterion to maximize K_u is to maximize the SNR.

The above results indicate that we can address the choice of the optimal scale $\hat{s}$ of the daughter wavelet using the standard criterion to maximize the kurtosis of the DWT coefficients:

$$J(c_s(n)) = kurt(c_s(n))^2 \qquad (10)$$

$$\hat{s} = \arg_s \max(J(c_s(n))) \qquad (11)$$

Once the optimal scale $\hat{s}$ has been computed using the kurtosis maximization algorithm, in the next step, the DWT of the ultrasound RF signal can be performed by the optimal scale daughter wavelet, then, the noise in the ultrasound RF signal will be well cut down.

3. Experimental results

In order to verify the efficiency of this method in actual ultrasonic flaw detection, an offshore pipeline spacemen is applied in which a man-made crack is fabricated. The experiments were done inside the pipe. The ultrasonic probe with 5 MHz central frequency and 6mm diameter wafer is used and water as couplant. The flaw echoes were recorded in the format of A-scan with a sample frequency of 100 MHz. Fig. 1 (a) shows the original ultrasonic signal received from a flaw near the outer wall, and the flaw size is $10\times0.5\times1.5mm^3$. Three ultrasonic echoes reflecting from the inner wall, outer wall and the flaw are expected in the ultrasonic signal. It can be seen that the ultrasonic signal is contaminated by noises, there only two distinct pulses can be identified: the inner wall echoes and outer wall echoes, there are on obvious flaw echoes existing between the inner wall echo and outer wall echo. The analyzed wavelet is the guass3 wavelet. Using the maximum nongaussianity method, the optimal scale can be computed as 3. Fig. 1 (b) shows the spectra distribution of the Gaussian mother wavelet, the Gaussian daughter wavelet and the ultrasonic signal. It can be seen from Fig. 1 (b) that the spectra distribution of the Gaussian mother wavelet does not match the spectra distribution of the ultrasonic signal, but the Gaussian daughter wavelet of order 3 does so. Fig. 1 (c) shows the de-noised ultrasonic signals processed by the daughter wavelet of order 3, it can be seen from Fig. 1 (c) that the optimal scale daughter wavelet has the best effect of the noise suppression, the flaw echo present a clear waveform.

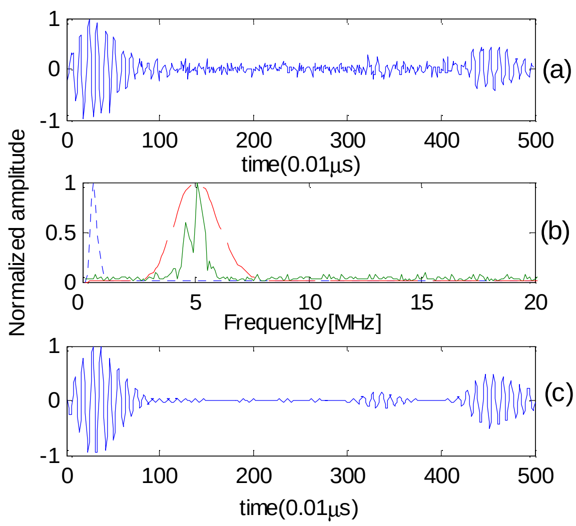

Fig. 1 the de-noised ultrasonic signals processed by the daughter wavelet of order 3: (a) time domain waveform of ultrasonic signals. (b) the spectra distribution of the Gaussian mother wavelet(dashed line), the Gaussian daughter wavelet (dot dash line) and the ultrasonic signal (solid line) (c) the de-noised ultrasonic signals.

4. Conclusion

A method of identification of weak ultrasonic signals based on the optimal scale wavelet transform is proposed in this paper. We address the choice of the optimal scale of a daughter wavelet using the maximum nongaussianity. The central frequency of the optimal scale wavelet is equal to that of the ultrasonic pulse, and the frequency band of the ultrasonic pulse is within the support of the optimal scale wavelet, hence majority of the interest frequency components of the ultrasonic signal can pass through after processing by the optimal scale wavelet.

Experimental results have been presented to evaluate the effect of the optimal scale wavelet transform filtering on ultrasonic flaw detection. In particular it has been possible to detect ultrasonic signals buried in heavy noises, without any loss of accuracy in the time measurement.

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