DECREASING THE INFLUENCE OF DISPERSIVE WAVE MODES IN LONG-RANGE ULTRASONIC RAIL TESTING USING WAVELETS

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Abstract

The sensitivity and the resolution of long-range ultrasonic testing (LRUT) are significantly limited by the presence of dispersive wave modes, commonly inherent to the acquired ultrasonic signals. This paper presents a signal processing technique based on the discrete wavelet transform (DWT) for reducing the effect of dispersive wave modes in LRUT of rails. A comparative study of different type of wavelet, thresholding procedures and threshold selection rules is presented. The proposed concept has been evaluated in the presence of high level of additive dispersive waveform at signal to noise ratio (SNR) from -20dB to 20dB. The results show that the effect of dispersion can be reduced in great extent even in the case of extremely high SNR level.

1 Introduction

Rail failure may result in very serious derailments of trains, such as in Hatfield in 2000 [1], causing loss of life, costs, significant damages and loss of confidence in rail transport by the public. The catastrophic rail failure due to growth of structural defects can be avoided by careful inspection and appropriately scheduled maintenance. There are several non-destructive testing (NDT) techniques such as visual inspection, magnetic induction, eddy current, Photo-thermal, and conventional ultrasonic testing, used for maintenance and inspection of the rail network [2, 3]. These current NDT techniques are not able to effectively detect all the defects that may cause catastrophic failure of the rails [4].
LRUT is a relatively recent technology being developed for rail inspection. The LRUT employs low frequency ultrasonic waves to detect defects and imperfections some distance away from the ultrasonic source. These waves are naturally propagated in several dispersive and non-dispersive wave modes. Dispersion of a wave causes the energy of a signal to spread out in space and time as it propagates. Practically, this is manifested as an increase in received signal duration compared to the duration of the transmitted signal. This phenomenon deteriorates resolution quality and makes experimental data hard to interpret because of signal overlap [5].
The dispersive signal is mainly coherent (non-random) and occupies the same bandwidth as the signal of interest. This is the reason that most conventional signal processing techniques such as filters cannot be used to reduce the effects of the dispersion signal. A technique for removing the effect of dispersion from LRUT signal has been presented [6]. This technique used knowledge of the dispersion characteristics of wave mode to map signals from the time to the distance domain, removing dispersion for one particular wave mode only. Another study used cross-correlation and wavelet de-noising techniques for reduction of coherent noise in received LRUT signals [7]. The results show that neither technique appears to effectively differentiate between dispersive and non-dispersive wave modes.
This paper presents a wavelet signal processor for efficient reduction of the influence of high level dispersive wave modes of LRUT of rails. A comparison of several processing parameters has been made, including the type of wavelet, thresholding method and the threshold selection rules.

2 Signal processing techniques

To decrease the influence of dispersive wave mode, it is necessary to apply some advanced signal processing techniques. In the following paragraphs, the main points of these techniques are described.

2.1 Empirical mode decomposition

Empirical mode decomposition (EMD) is a method of breaking down a signal in the time domain [8]. The EMD is based on direct extraction of the signal energy associated with various intrinsic time scales. A typical ultrasonic time series $X(t)$ using EMD, can be defined as,

$$X(t) = \sum_{i=1}^{N} IMF_i(t) + r_N(t) \qquad (1)$$

where $r_N(t)$ stands for a residue and $IMF_i,\ i = 1,2,\dots N$ are intrinsic mode functions (IMFs) that should satisfy the following two conditions:

(1) The number of extrema and the number of zero-crossings in the whole data series must be equal or differ at most by one.
(2) At any time, the mean value of the envelope defined by the local maxima and the envelope of the local minima is zero.

The first condition is similar to the narrow-band requirement for a stationary Gaussian process which ensures that the local maxima of the data series are always positive and the local minima are negative. The second condition is a new idea which modifies a global requirement to a local one.

The algorithm of empirical modes can be summarized as follows:

(1) Identify all extrema of $X(t)$.
(2) Interpolate (here we use spline interpolation) between minima (respectively, maxima), ending up with an "envelope" $e_{min}(n)$ [respectively, $e_{max}(n)$].
(3)Compute average $m(n) = (e_{min}(n) + e_{max}(n))/2$.
(4) Extract the detail $d(n) = x(n) - m(n)$.
(5) Iterate on the residue $r(n)$.

2.2 Wavelet de-noising

The wavelet transform is a signal processing technique that can represent the ultrasonic signal in the time and frequency domains simultaneously [9]. The DWT analyzes the signal by decomposing it into its coarse and detailed information, which is achieved with the use of successive high-pass and low-pass filtering and sub-sampling operations, on the basis of the following equations:

$$y_{high}(k) = \sum_n x(n) \cdot g(2k - n) \qquad (2),$$

$$y_{low}(k) = \sum_n x(n) \cdot h(2k - n) \qquad (3),$$

where $y_{high}(k)$ and $y_{low}(k)$ are the outputs of high-pass and low-pass filters with impulse responses 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 (low-pass filters) and detailed (high-pass filters) coefficients, the inverse discrete wavelet reconstructs the signal, inverting the decomposition step by inserting zeros and convolving the results with the reconstruction filters.

The wavelet transform is based on the correlation between the original signal and the wavelet function. Wavelet de-noising is a thresholding procedure that reduces the smaller amplitudes of the decomposed signals and this could further reduce parts of the signal that have a low level of correlation with the wavelet. In the case that the wavelet function is similar to the transmitted signal, wavelet de-noising could preserve signals where the pulse shape has been maintained and reduce those where the pulse shape has been distorted (i.e. dispersive wave modes). However, the DWT uses several template signals, different thresholding procedures and threshold selection rules.

2.3 Dynamic time warping

Dynamic time warping (DTW) is an algorithm for measuring similarity between two time series [10]. The series are "warped" non-linearly in the time dimension to determine a measure of their similarity independent of certain non-linear variations in the time dimension. As $X(x_1, x_2, \dots, x_n)$ and $Y(y_1, y_2, \dots, y_m)$ are two time series with lengths n and m, respectively. The goal of DTW is to find a mapping path $w = \{(p_1, q_1), (p_2, q_2), \dots, (p_k, q_k)\}$ such that the distance on this mapping path is minimized

$$DTW(X, Y) = \min_{w} \sum_{i=1}^{k} |X(p_i) - Y(q_i)| \qquad (4).$$

3 Signal database creation

3.1 Simulated signals

To achieve detailed analysis and comparative performing of the method, it is necessary to obtain a LRUT received signal which results from the minimum transmitted non-dispersive wave modes. These wave modes have been chosen based on their sole existence in one part of the rail sample with little expected leakage into the other parts. The displacement of each mode exists in the entire section of the rail, suggesting that 100% coverage of the rail cross-section may be achieved. Also, they have displacement pattern similar to each other, hence similar transducer arrangements can be used for the generation and reception of each wave mode. Finally, these selected wave modes are relatively non-dispersive in the 20-80kHz range, therefore, their propagation characteristics are favourable for defect detection in this frequency range. They also have relatively similar phase velocities at 70kHz [11]. Therefore, a tone burst signal at centre frequency of 70kHz is used to excite these identified wave modes.

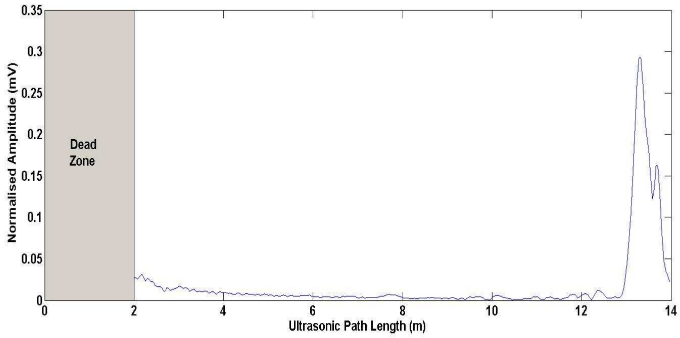


Figure 1: Simulated reflection from the foot part of rail for centre frequency of 70kHz.

3.2 Experimental signals

To contain the LRUT received signal dispersive and non-dispersive wave modes, an experimental investigation was carried out in a 6.64m steel long rail (CEN 56). The Teletest commercial guided wave ultrasonic system by Plant Integrity Ltd [12] was used to excite and to collect the wave mode responses. The piezo-electric elements were mounted

(bonded) at one end of the rail sample (figure 2). A tone burst signal at a centre frequency of 70kHz is used to excite these identified wave modes [11].

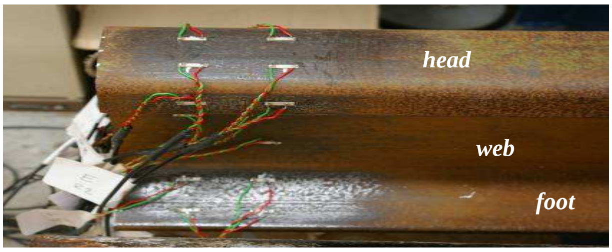


Figure 2: Mounted piezo-electric elements at the one end of the rail sample.

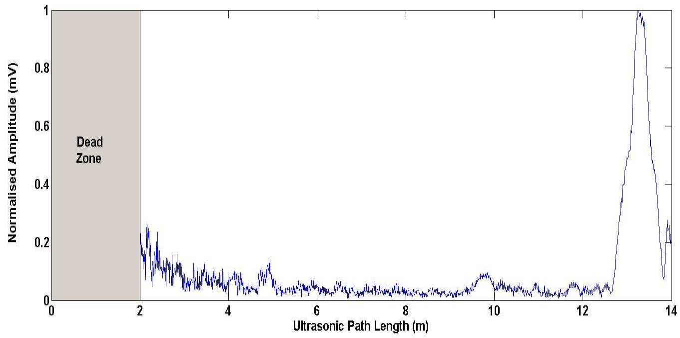


Figure 3: Experimental signal from the foot part of rail at centre frequency of 70kHz.

4 Dispersion reduction procedure, results and discussion

The dispersion reduction procedure has been carried out on the three sections of a rail i.e. head, web and foot. Among these three main rail sections of the rail, the foot has been identified as priority for inspection [4], since the existing methods cannot suitably inspect the foot. In this study, results are presented mainly for the foot section of rail.

The EMD technique was used to decompose the normalised experimental signals. The following figure show the twelve decomposed modes for the foot section of rail.

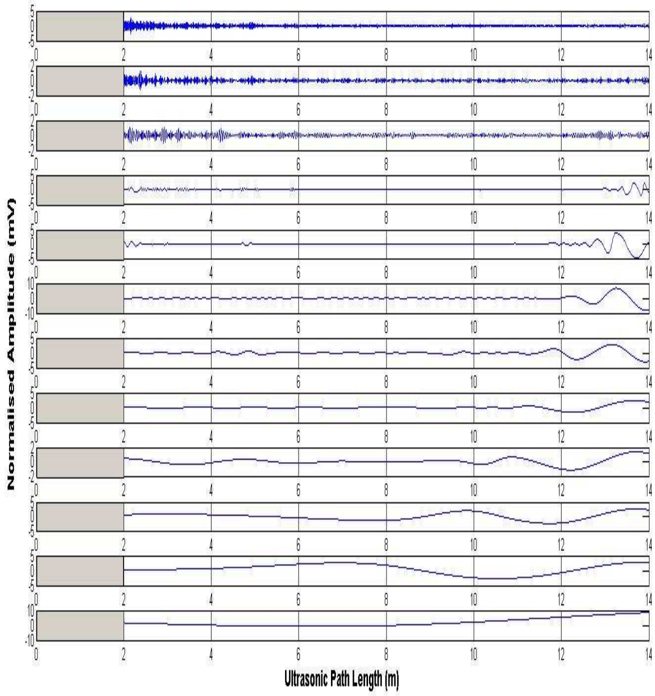
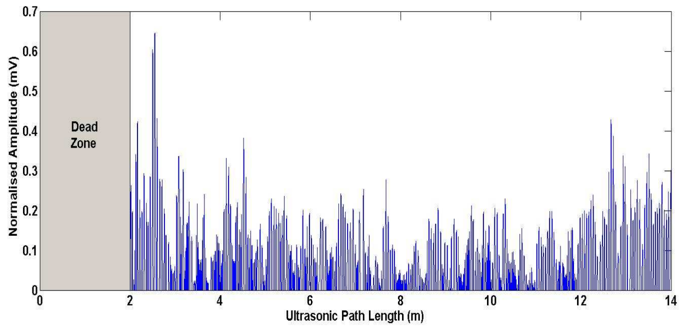
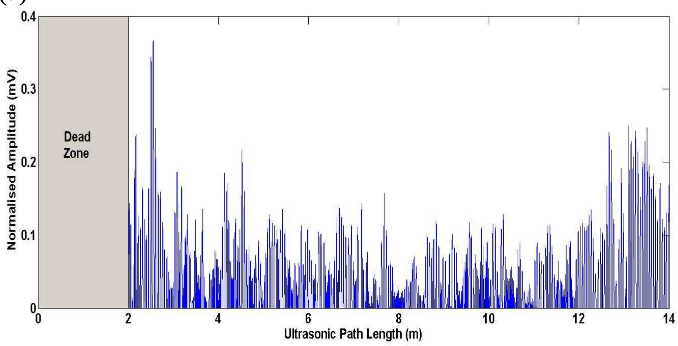


Figure 4: The decomposed twelve modes using EMD for the experimental signal from foot section of the rail sample

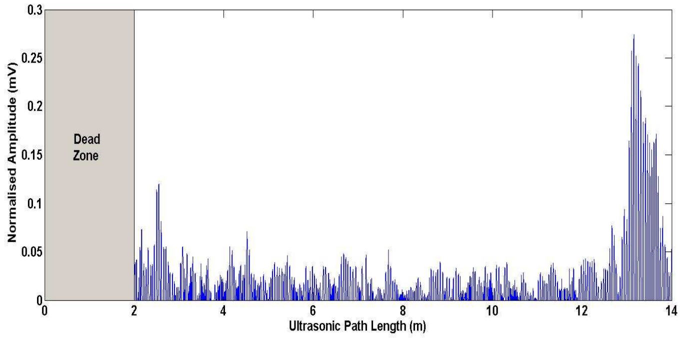
Dispersive waveforms were visually selected and were added to the simulated reflection. For the foot section of the rail, the third mode was added to the "ideal" reflection (containing the minimum transmitted non-dispersive wave modes), simulating the dispersive waveform. High levels of additive dispersive waveform, at SNR -20dB, -10dB, -5dB, 0dB, 5dB, 10dB, 15dB, 20dB, were added to the “ideal” reflection. Figure 5 show simulated signal from the foot section with added dispersive waveform at different SNR level.



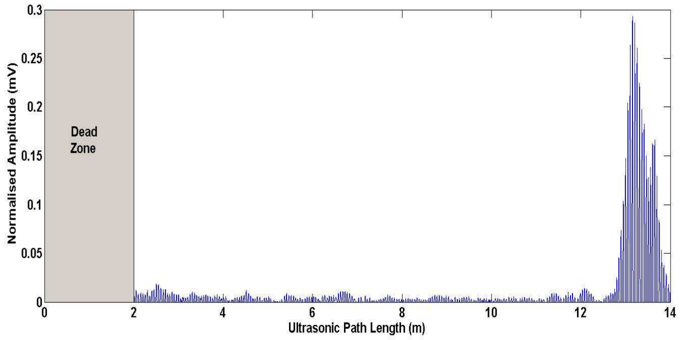
(a)



(b)



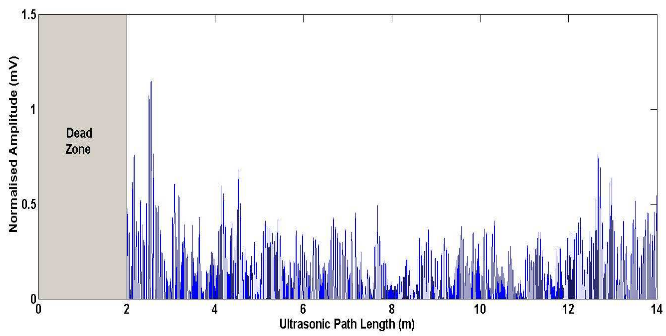
(c)



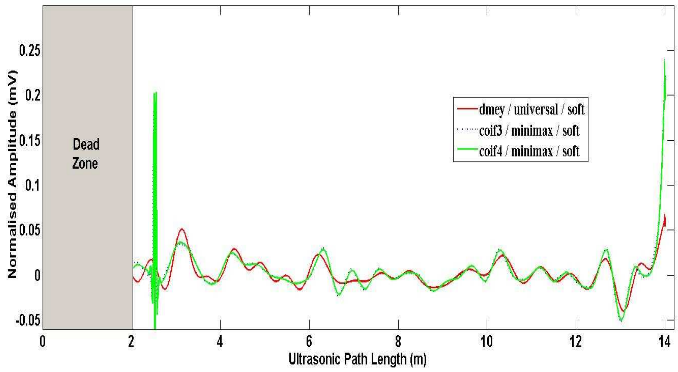
(d)

Figure 5: Simulated signal from the foot section of the rail with added dispersive waveform at different SNR of -15dB (a), -10dB (b), 0dB (c), 20dB (d).

In this work, wavelets were considered for reduction of the effect of dispersive wave mode. The type of the "mother" wavelet, the number of decomposed levels, the thresholding technique and the threshold selection rules are of great importance for the performance of the wavelet processor [13]. The wavelets included in this analysis belong to the families of Haar, Daubechies, Symlets, Coiflets and the discrete version of the Meyer wavelets. For each of these, hard and soft thresholding was applied with either universal, minimax or SURE threshold estimator. As an example, figure 6b shows the trace obtained by processing the original trace from the foot section of figure 6a, using different wavelet families and different thresholding technique.



(a)



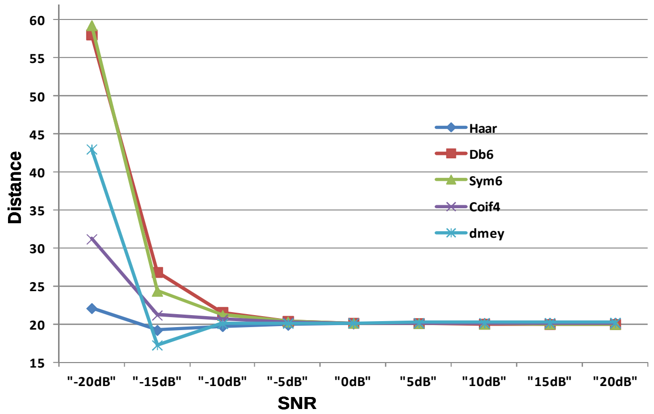
(b)

Figure 6: Simulated signal from the foot section of the rail with added dispersive waveform at different SNR of -20dB (a) and waveform after DWT processing (b).

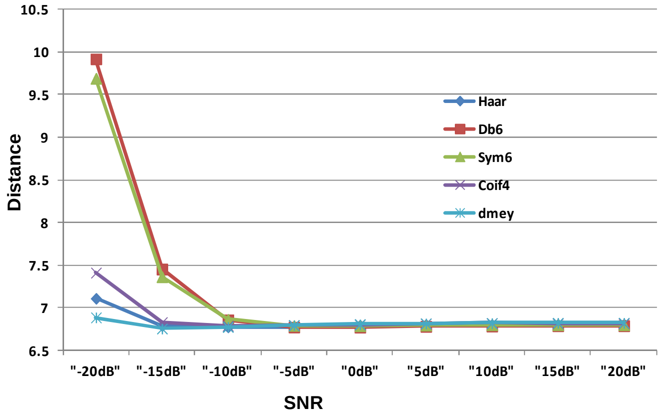
Finally, the DTW was used for measuring similarity between the simulated (including the minimum transmitted non-dispersive wave mode) and the "de-noised" signals. The quantity of results obtained by varying all processing parameters is extremely large. Table 1 for the foot section of rail and figure 7 for the all sections of rail sample summarize some significant results, presented the "distance" between the simulated and the "de-noised" signals for different/ -type of wavelet, -thresholding method, -threshold selection rule, -SNR level of additive dispersive waveforms.

Wavelet type	Universal		Minimax		SURE	
	Soft	Hard	Soft	Hard	Soft	Hard
-20dB						
Haar	7.61	7.61	6.69	48.93	12.95	73.48
Db4	6.63	30.26	6.30	64.62	22.54	116.12
Coif4	6.39	35.69	5.18	59.46	31.76	146.14
dmey	4.17	33.76	6.52	89.50	18.48	120.28
-10dB						
Haar	7.11	7.11	7.11	7.11	7.11	7.11
Db4	7.26	7.26	7.26	7.26	7.26	7.26
Coif4	7.22	7.22	7.22	7.22	7.22	7.22
dmey	7.20	7.17	7.17	7.17	7.17	7.17
10dB						
Haar	7.21	7.21	7.21	7.21	7.21	7.21
Db4	7.23	7.23	7.23	7.23	7.23	7.23
Coif4	7.23	7.23	7.23	7.23	7.23	7.23
dmey	7.23	7.23	7.23	7.23	7.23	7.23
20dB						
Haar	7.21	7.11	7.21	7.21	7.21	7.21
Db4	7.23	7.23	7.23	7.23	7.23	7.23
Coif4	7.23	7.23	7.23	7.23	7.23	7.23
dmey	7.23	7.23	7.23	7.23	7.23	7.23

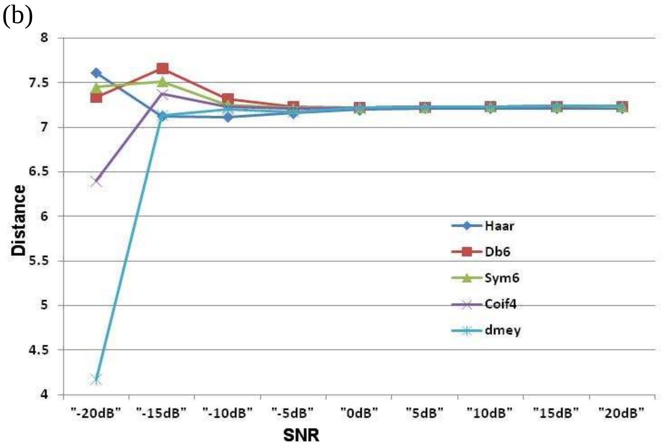
Table 1: The "distance" using different/ -type of wavelet, -thresholding method, -threshold selection rule in the presence of different SNR level of additive dispersive waveforms (from -20dB to 20dB) for the foot section of rail.



(a)



(b)



(c)

Figure 7: The "distance" using different type of wavelet families, soft threshold and universal estimator in the presence of different SNR level of additive dispersive waveforms (from -20dB to 20dB) for head (a), for web (b) and for foot (c) section of rail.

Higher value of "distance" means lower similarity between the simulated (minimum transmitted non-dispersive wave mode) and the "de-noised" signals. In the case of head section, the most effective of the set of available "mother" wavelet functions is haar, while for the web and the foot is dmey, since probably these wavelet functions are more similar to the transmitted signal than the other wavelet functions. In almost all combinations between rail sections and different SNR levels, the "best" results in terms of the value of "distance", were obtained with universal or minimax threshold. The table 1 show that for low levels of additive dispersive waveform, the "distance" doesn't affect by the choice of the type of "mother" wavelet, thresholding technique and threshold selection rules. According to the figure 7, soft threshold and universal estimator give very constant results of dispersive wave form with level less than -10dB. The effect of the dispersive wave modes can be reduced at higher degree to web and foot sections than head section.

4 Conclusions

Different DWT signal processing techniques have been examined in terms of their ability to reduce the effect of dispersion in LRUT signals from each part of rail. These techniques have been evaluated in the presence of high level of additive dispersive waveform (from -20dB to 20dB SNR). In the extreme level of additive dispersive waveform (-20dB) the most effective results were observed mainly using haar and dmey as "mother" wavelet function with the universal threshold. In almost all cases, hard thresholding give great "distance" value, as the reconstructed signal being affect by a big distortion.

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