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Temperature Compensation for Ultrasonic Guided Wave Measurements

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Abstract

Guided wave ultrasound is an increasingly popular non-destructive testing method for inspecting and monitoring elongated elastic waveguides, such as pipes and rail. Monitoring systems using a pulse-echo mode of operation typically excite guided waves using permanently installed piezoelectric transducers, and reflections from defects are often detected using the same transducer. Many propagating modes are usually excited by the transducer, and the propagation speed and dispersion characteristics of each mode are different. The propagation speed is temperature dependent, and therefore reflections from discontinuities in the waveguide have different arrival times depending on the environmental temperature. In order to differentiate between reflections from benign structural features such as welds and growing defects such as cracks, measured signals are compared to a baseline signal, which is assumed to be damage free. However, since measured signals are temperature dependent, potentially masking damage signatures, a method to compensate for temperature is required.

In this paper various temperature compensation methods will be applied to measured guided wave signals, collected from an operational train railway line. The measured results were sampled at various times of the day under different environmental conditions. The primary purpose of this paper is to analyse various signals which have similar signal characteristics, however due to environmental conditions (such as temperature differences) the signals are not identical.

This paper compares three temperature compensation methods, namely scale-invariant correlation (SIC), a combined scale-invariant correlation with iterative scaled transform (SIC/IST) and a method developed by the authors, called envelope stretching (ES). Simple baseline subtraction is used as a basis to evaluate and compare the various methods. Applying these methods to measured results and using the baseline subtraction as the basis, SIC, SIC/IST and ES are shown to on average reduce the error to 48.5 %, 48.4 % and 20%, respectively. A comparison between SIC and SIC/IST indicates that SIC offers a marginal (0.4%) improvement when compared to SIC/IST. The developed ES method is shown to offer between 80 % - 51.5% error percentage reduction when compared to BS, SIC and SIC/IST. The ES method still maintains the modal information of the signal, which is important in non-destructive testing to detect faults.

Keywords : Baseline subtraction; iterative scaled transform; scale-invariant correlation; temperature compensation

1. Introduction

Guided wave ultrasound is a non-destructive testing (NDT) method, which is increasingly being used to monitor the health of stretches of train railway lines and pipes. With guided wave ultrasound, piezoelectric transducers are attached to specific mediums, such as a railway line or pipe. These transducers are typically used as a transceiver, when excited these transducers produce many travelling waves (modes of propagation) which propagate along the waveguide. When these traveling waves encounter defects such as cracks, reflection of the various modes occur back to the same piezoelectric transducers. As a crack grows the amplitude of the reflection would typically increase. After studying the reflected signals, the health of specific structures can be observed by comparing the measured signal to a baseline signal, which was initially assumed to have no damage. This provides an operator with sufficient knowledge to schedule the necessary preventative maintenance measures. Guided ultrasound waves are popular as they can travel long distances with little attenuation [1]. This allows permanently installed piezoelectric transducers to interrogate large areas.

The propagating modes produced by the transducer usually travel at different speeds. The speed of mode propagation and mode reflections are temperature dependent [2]. As the temperature changes, the guided wave behaviour also changes [3]. Temperature compensation is required for effective baseline comparisons in order to ensure that damage signatures are not masked. In this paper, specific temperature compensation methods will be applied to guided wave signals taken from an operational train railway line. These guided wave signals were sampled at various times in the day, this allowed for the influence of temperature variation to be studied.

Several temperature compensation techniques have already been developed. These techniques can be divided into two categories: data driven methods and model driven methods [4]. With the data driven approach a collection of ultrasonic signals are measured over a range of temperatures, with the first measurement taken as a baseline signal. Specific criteria, such as maximum residual amplitude after subtraction from a baseline signal, are applied for damage detection. This technique requires a large baseline signal sample set with sufficient temperature resolution. For practical applications this might not be readily available [5].

This paper will focus on a model driven approach, which attempts to build a model of the effects of temperature. The advantage of this method being that a small baseline signal sample space is required (one baseline signal). In this paper time stretching models are examined. Various time stretching models have been developed [3, 6-9]. Two approaches named [4]: scale-invariant correlation and a combined scale-invariant correlation with iterative scaled transform, were chosen as these were suggested to offer minimal error and are claimed to be more computational efficient than currently available techniques. The authors also propose a method called envelope stretching (ES) for temperature compensation.

The outline of this paper is as follows: in Section 2, the temperature compensation problem is formulated. Possible solutions for temperature compensation are developed in Section 3. In Section 4, the methodology used to test these solutions are presented. In Section 5, the results from the proposed solutions are provided and conclusion are presented in Section 6.

2. Problem Formulation

This problem formulation presented, is graphically depicted in Figure 1 and follows closely to that presented in [4]. A change in temperature, $T_{\propto}\{\cdot\}$, on an ultrasonic signal, $x(t)$ is approximated by a time-stretch, $x(\propto t)$ signal where, $\propto$, is the stretch factor as in Eq (1) .

$$T_{\propto}\{x(t)\} \approx x(\propto t). \tag{1}$$

This time-stretch model indicates, as the temperature within a medium increases, a wave traveling in such a medium stretches. To compensate for temperature stretching the ultrasonic signal can be re-stretched by a factor of $1/\propto$. As $\propto$, the stretching factor is unknown, an estimate of this needs to be obtained. An estimate of the optimal re-stretching factor can be described as

$$\hat{\propto} \approx 1/\propto. \tag{2}$$

Here, the $\hat{}$ notation indicates re-stretching (stretching an already stretched signal).

This temperature compensation, $T_{1/\propto}\{\cdot\}$, process can be written as

$$\mathrm{s}(\hat{\propto}\, t) = T_{1/\propto}\{x(\propto t)\}\,. \tag{3}$$

In Eq (3), s $(\hat{\propto}\, t)$, refers to a re-stretched or temperature compensated signal. By minimizing the normalized square error between the original signal, $x(t)$, and the temperature compensated re-stretched signal, s $(\hat{\propto}\, t)$, the optimal re-stretching factor between can be obtained and written as

$$\varepsilon = argmin_{\hat{\propto}} \int_0^\infty \left|\frac{x(t)}{\sigma_x} - \frac{s(\hat{\propto}\, t)}{\sigma_s/\sqrt{\hat{\propto}}}\right|^2 dt. \tag{4}$$

In Eq (4), σ_x and $\sigma_s/\propto$ are normalization factors, given by

$$\sigma_x{}^2 = \int_0^\infty |x(t)|^2 dt\,, \qquad \sigma_s{}^2/\propto = \int_0^\infty |s(\hat{\propto}\, t)|^2 dt. \tag{5}$$

This normalization process ensures the energy of the original signal, $x(t)/\sigma_x$, and re-stretched temperature compensated signal, $s(\hat{\propto}\, t)\sqrt{\hat{\propto}}/\sigma_s$, are unity. This process mitigates possible attenuation effects which might hamper the determination of the optimal re-stretching factor, $\hat{\propto}$. Expanding Eq (4), results in

$$\begin{aligned}\varepsilon &= argmin_{\hat{\propto}} \int_0^\infty \frac{|x(t)|^2}{\sigma_x{}^2} + \frac{|s(\hat{\propto}\, t)|^2}{\sigma_s{}^2/\hat{\propto}} - 2\frac{x(t)s(\hat{\propto}\, t)}{\sigma_x(\sigma_s/\sqrt{\hat{\propto}})}dt \\ &= argmin_{\hat{\propto}}\ \ 2 - \int_0^\infty 2\frac{x(t)s(\hat{\propto}\, t)}{\sigma_x(\sigma_s/\sqrt{\hat{\propto}})}dt \\ &= argmin_{\hat{\propto}}\ \ 1 - \frac{\sqrt{\hat{\propto}}\,\Phi_{xs}(\hat{\propto})}{\sigma_x\,\sigma_s}\end{aligned} \tag{6}$$

where,

$$\Phi_{xs}(\hat{\propto}) = \int_0^\infty x(t)s(\hat{\propto}\, t)\,dt. \tag{7}$$

From Eq (6) the re-stretch factors $\hat{\propto}$, which maximizes the cross correlation between the original signal, $x(t)$, and the re-stretched signal, $s(\hat{\propto}\, t)$ provides an optimal solutions. In [4], to solve Eq (6), two optimization methods are recommended. These are: scale-invariant correlation and a combined scale-invariant correlation with iterative scaled transform. These methods perform domain transformations in order to determine optimal re-stretched, $\hat{\propto}$, values (the

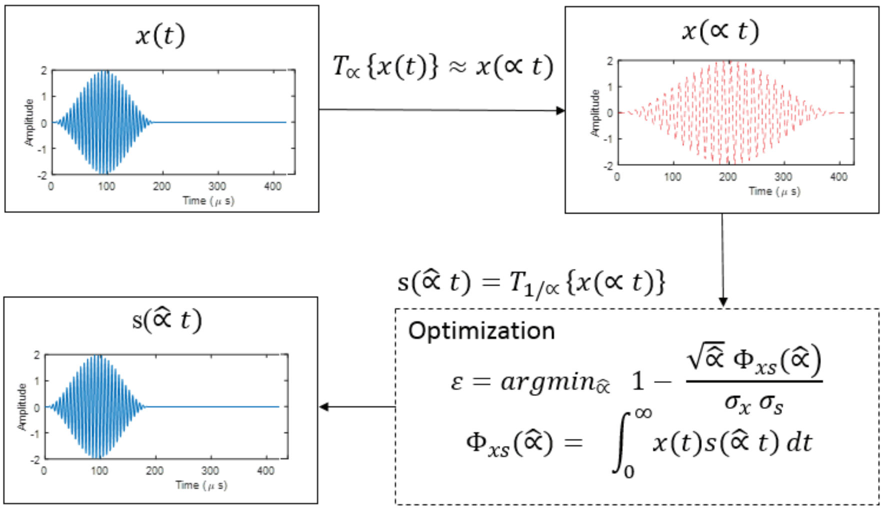

Figure 1: Temperature compensation, problem formulation.

stretch factor might not be consistent) which maximize the cross correlation. Interested readers can refer to [4], for the exact details of the method.

3. Proposed Solutions

To demonstrate the scale-invariant correlation (SIC) and a combined scale-invariant correlation with iterative scaled transform (SIC/IST) process. To simulate the stretching effects of temperature on a signal, a theoretical Hanning windowed 40 kHz baseline signal is obtained, as indicated in Figure 2a. As in Figure 2b, an arbitrary stretching factor is applied to this baseline signal to produce a stretched baseline signal. When applying both the SIC and SIC/IST methods to re-stretch the signal in Figure 2b, the original signal seen in Figure 2a is reconstructed.

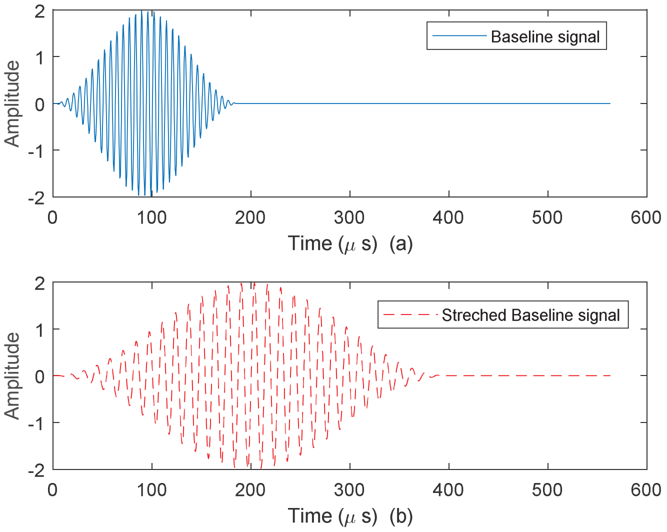

Figure 2: Baseline and a simulated temperature stretched signal.

The SIC and SIC/IST methods work for theoretically stretched signals as demonstrated. Guided waves are inherently multimodal [10], contain noise and change due to environmental and operating conditions (passing trains). During the non-destructive testing, after applying temperature compensation the multimodal signals are analyzed to detect defects. When attempting to find the maximum correlation between the baseline and re-stretched signal with methods such as SIC and SIC/IST, inherently the phase of the re-stretched signal is changed. This re-stretching process changes the multimodal nature of the signal. This change in the multimodal signal could possible mask defects and emphasis benign features. In order to maintain multimodal information an alternate method called envelope stretching is proposed by the authors. Envelope stretching, uses the signals envelope for signal correlation to determine the optimum stretch factor, while still maintaining the phase of the baseline signal. The methodology behind this method is as follows.

The envelopes of both the baseline and stretched baseline signals, as shown in Figure 2, can be extracted by using a Hilbert transform ($H[\cdot]$), the result of this extraction are depicted in Figure 3.

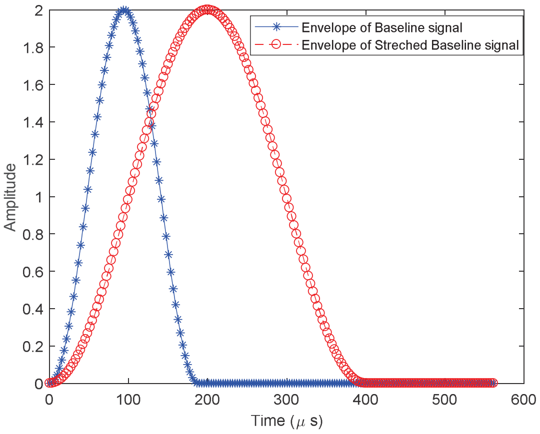

Figure 3 : Comparison of signals before envelope stretching.

After which, the envelope of the stretched baseline signal, is re-stretched ,$\overline{s(\hat{\propto}\ t)}$, to maximize the correlation, $\Phi_{xs}(\bar{\bar{\propto}})$, with the envelope of the baseline signal, $\overline{x(t)}$, to achieve a minimal error (ε). With this notation, $\bar{\cdot}$, denotes the envelope of the signal. Applying the same methodology as that of Eq (6), results in Eq (8) and Eq (9).

$$\varepsilon = argmin_{\bar{\bar{\propto}}}\ \ 1 - \frac{\sqrt{\bar{\bar{\propto}}}\ \Phi_{xs}(\bar{\bar{\propto}})}{\overline{\sigma_x}\ \overline{\sigma_s}} \tag{8}$$

$$\Phi_{xs}(\bar{\bar{\propto}}) = \int_0^\infty \overline{x(t)}\overline{s(\hat{\propto}\ t)}\, dt \tag{9}$$

In Eq (8), $\overline{\sigma_x}$, $\overline{\sigma_s}$ are the normalization factors and $\bar{\bar{\propto}}$, is the re-stretching envelope factor. In this particular case the SIC method can be used to determine the optimal $\bar{\bar{\propto}}$, envelope re-stretching factor. This re-stretched signals envelope is superimposed onto the envelope of baseline signal, as indicated in Figure 4, to produce perfect alignment between the signal envelopes.

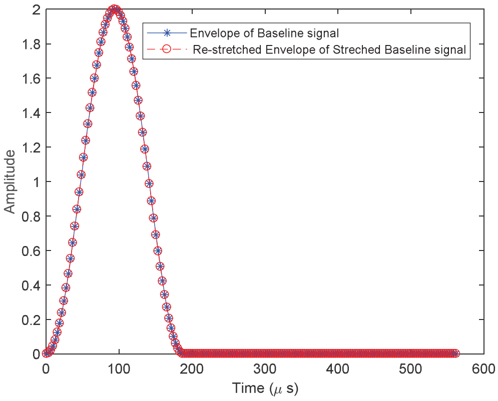

Figure 4: Comparison of signals after envelope stretching.

Traditional temperature compensation methods such as SIC and SIC/IST, re-stretch the stretched baseline signal (RSBS) such that maximum signal correlation with the baseline signal is achieved. In essence an attempt is made to match the phase of the baseline signal ($x(t)$) to that of the RSBS ($s(\hat{\propto}\ t)$). This can be accomplished in a simpler manner by using the current phase of the baseline signal (to which an attempt will traditionally be made to match) and multiplying this by the RSBS envelope $(x(t)\overline{s(\hat{\propto}\ t)})$ as indicated in Figure 5.

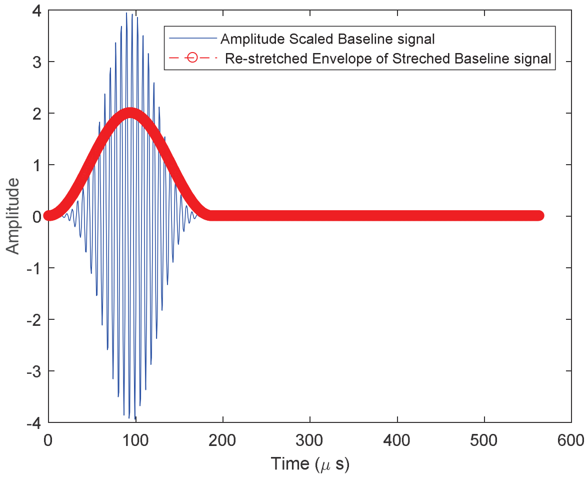

Figure 5 : Envelope Stretched signal construction.

This output can be written as

$$y(t) = \frac{\overline{s(\hat{\propto}\ t)}}{|H[x(t)]|}x(t)\,. \tag{10}$$

In Eq (10),$|H[x(t)]|$, the envelope of the baseline signal, provides the necessary scaling required. The output $(y(t))$ of termed envelope stretching is also depicted in Figure 6.

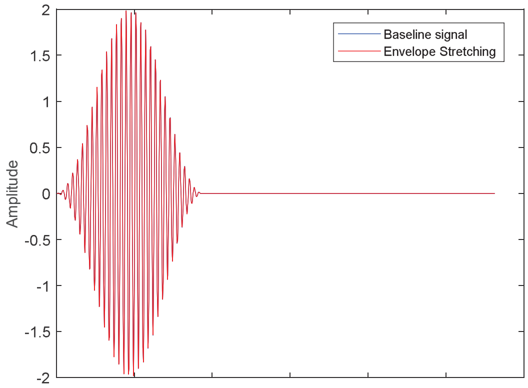

Figure 6: A comparison between a baseline signal and a temperature compensated envelope stretched signal.

In Figure 6, the initial baseline signal and the stretched baseline signal to which the envelope stretching method has been applied are undistinguishable from each other. This suggests that envelope stretching is a viable alternative stretching methodology which can be adopted.

4. Experimental Methodology

In this section, the methods previously discussed namely scale-invariant correlation, a combined scale-invariant correlation with iterative scaled transform and the developed method called envelope stretching will be compared. The methods will be compared using measurements taken on an operational train railway line, taken at various times of the day under various conditions. A series of measurements were taken, using pulse-echo (transmit and receive) at various frequencies, a summary of this can be seen in Table 1, together with the abbreviations used to describe specific measurements that will be used in this paper.

Table 1: Measurements used.

Centre Frequencies (kHz)	Number of Cycles	Abbreviation used
39	17.5	39175
39	35	3935
39	70	3970
41	30	4130
40	30	4030
43	30	4330
43	70	4370

These measured results are a series of averaged received echo results obtained at various times of the day for each centre frequency indicated in Table 1. For instance, the signal at 43 kHz, containing 30 cycles is abbreviated by 4330.
To simplify the explanation of the methodology followed, consider the 4330 case from Table 1. Measurements were collected under similar conditions at various times during the day, as indicated in Table 2. Signal 1 (Table 2), refers to a 4330, pulse-echo measurement taken at 11:38:30 and similar signal 5, refers to a 4330, pulse-echo measurement taken at 14:12:31.

Table 2: 43 kHz, 30 cycle (4330) measurement times.

Measurement Signal	Time measurement was taken (hour:minute:second)
1.	11:38:30
2.	12:23:16
3.	13:27:33
4.	13:59:03
5.	14:12:31

In Figure 7, a portion of all five pulse-echo results, from Table 2 are plotted. For NDT, the received wave packets with significant energy in the signal are of interest. In Figure 7, one such packet is identified (encapsulated between dashed lines). A snippet of all five signals are taken within the same time frame. Temperature compensation is performed on these five signal snippets, by using the methods discussed (SIC/IST and ES). Under ideal conditions, damage can be detected by performing baseline subtraction [8]. Baseline subtraction is a method by which the stretched signal is subtracted from the baseline signal and the residual is studied to detect defects. This method is also applied to the five signal snippets.

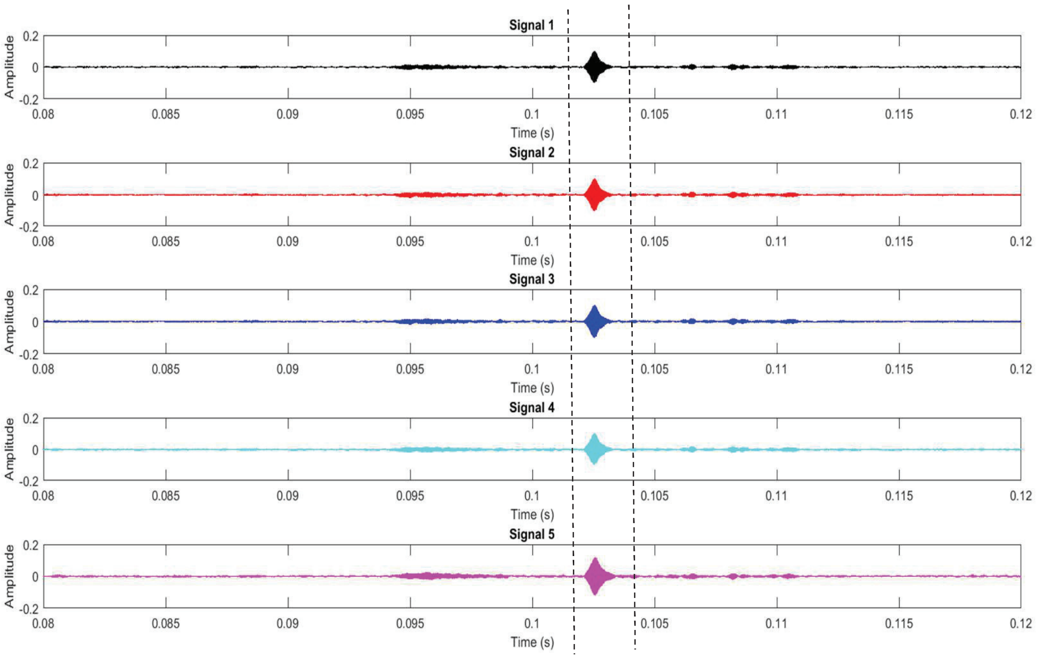

Figure 7 : Signal measurements taken at various times (Table 2) of the day for the 43 kHz 30 cycle case (4330)

The measured signals are arranged in ascending order, this paper assumes that the temperature increases as the day progresses and the rail remained damage free. For temperature compensation a baseline signal is required, the measurement taken earlier in the day are used as a baseline and the measurement taken later in the day, are re-stretched to perform temperature compensation. In Figure 8, a set of all possible signal (not temperature compensated) comparisons are presented. The purpose of Figure 8, is to indicate the various sets of signal comparisons that this process undertakes, this also indicates which signal is used as the basis of the stretching.

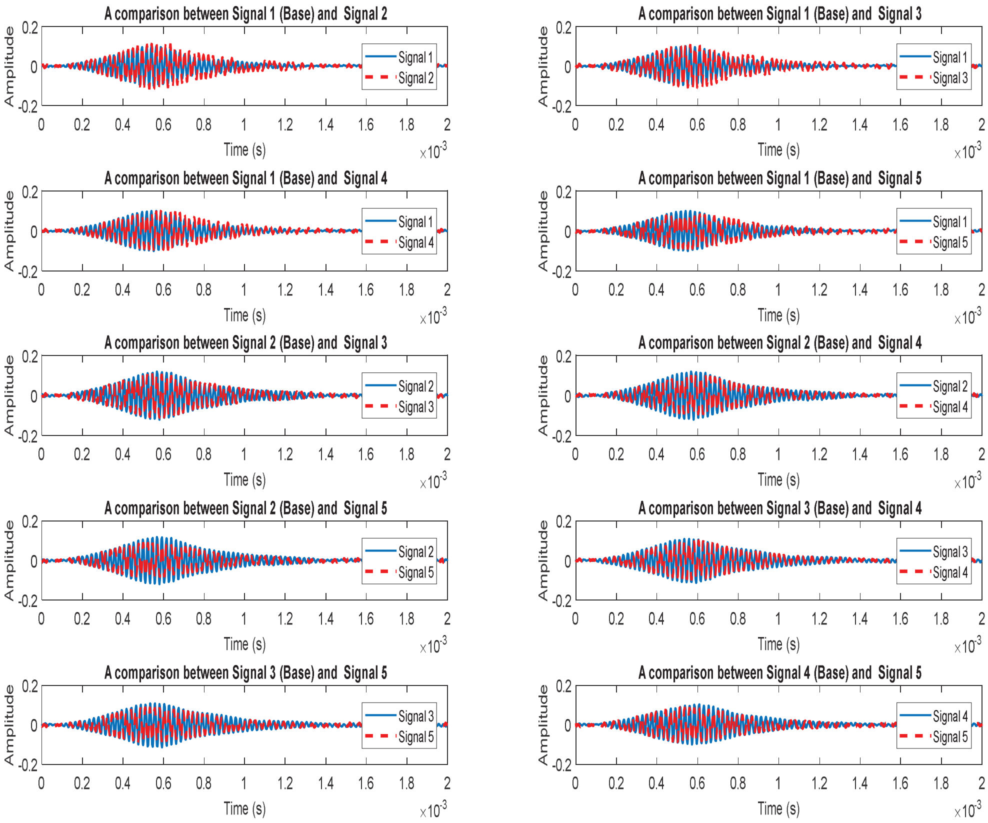

Figure 8: Various average signal comparisons for the 43 kHz 30 cycle case (4330).

For each signal comparison in order to facilitate temperature compensation, scale-invariant correlation (SIC), a combined scale-invariant correlation with iterative scaled transform (SIC/IST) and the envelope stretching (ES) are applied. These approaches were applied by using Matlab. The re-stretched signal obtained from these various methods (SIC, SIC/IST and ES) are subtracted from the baseline signal and the error calculated. A small error indicated effective temperature compensation. The error for each of the 10 cases above (Figure 8), after temperature compensation, are obtained and averaged to produce a final error result, which will be presented in Figure 9. In the same manner, as discussed for the 4330 case, this approach was applied to all remaining entries in Table 1 (39175 – 4370).

5. Results and Discussion

The averaged error result from each measurement indicated in Table 1, are summarized in Figure 9.

Figure 9: Average errors obtained from various temperature compensation strategies when applied to ultrasonic measurements from an operational railway line.

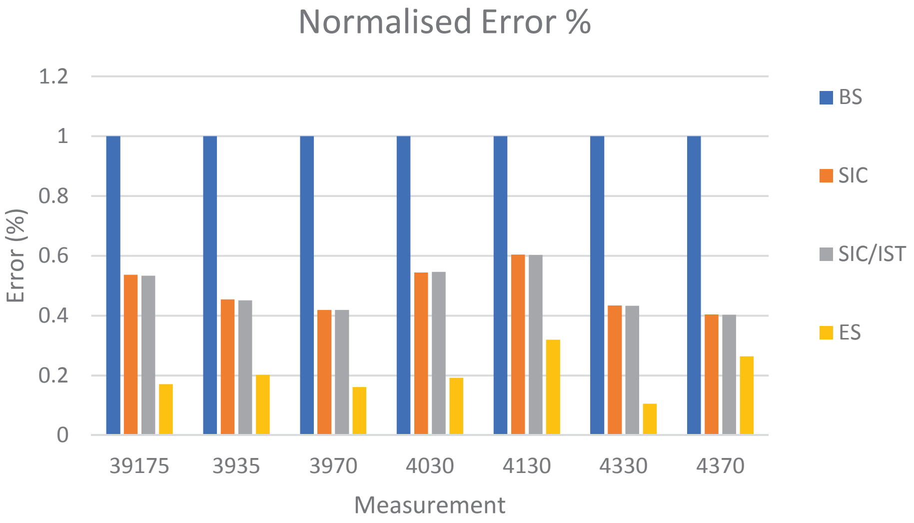

Figure 10: Average normalized errors obtained from various temperature compensation strategies when applied to ultrasonic measurements from an operational railway line.

In Figure 10, the normalized output error results are presented, each signal is normalized with respect to the BS error. In Figure 10, it can be seen that both SIC, SIC/IST and ES on average reduce the error to 48.5 %, 48.4% and 20% when compared to the BS method. SIC is shown to offer a marginal (0.4%) improvement when compared to SIC/IST. The proposed ES is shown to offer a significant (80%-51.5%) reduction in the error rate when compared to both BS, IST and SIC/IST. This can be primary attributed to the phase alignment which this method adopts. In addition, when the ES approach is adopted, multi-mode information is retained, whereas the IST and SIC/IST methods have a tendency of distorting multi-mode information during its stretching process. This multi-mode information is typically used for NDT.

The performance of the SIC and SIC/IST methods can be explained by, these methods were developed for lamb waves for small plate inspection. This experimental data was obtained from a functional railway line where distances are much greater, making dispersion and temperature induced changes much larger. In this particular environment the entire wave packet may shift, rather than a small phase shift seen during plate inspection. Additional on this rail, there are changes in the signal amplitude. Apart from temperature changes, operational changes also occur due to passing trains. These conditions suggests, there will not be a zero baseline residual. The proposed ES method has a reasonable non-zero low residual (20%) and can be considered more versatile, being able to cater for both small changes (plate inspection) and large changers (railway line), caused by environmental conditions.

6. Conclusion

Three temperature compensation methods have been compared, namely scale-invariant correlation, a combined scale-invariant correlation with iterative scaled transform and a method developed called envelope stretching. When using the baseline subtraction as a basis SIC, SIC/IST and ES are shown on average to reduce the error to 48.5 %, 48.4 % and 20%, respectively. A comparison between SIC and SIC/IST indicates that SIC offers a marginal (0.4%) improvement when compared to SIC/IST. The proposed ES is further shown to offer between 80%-51.5% reduction in the error rate when compared to both BS, IST and SIC/IST. This significant reduction in error rate is primarily attributed to phase alignment used by the ES method. The ES method also retains multimode information, which might be hampered when using either the IST and SIC/IST methods. These aspects make envelope stretching a good method for temperature compensation.

7. References

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