ENHANCEMENT OF ULTRASONIC GUIDED WAVE SIGNALS USING SPLIT-SPECTRUM PROCESSING TECHNIQUE

S.K Pedram*, M Deere, P Mudge

TWI, Ltd, Granta Park, Great Abington, Cambridge CB21 6AL, UK

*Corresponding Author: kamran.pedram@twi.co.uk

ABSTRACT

Ultrasonic guided wave testing (GWT) systems are broadly used in several industry sectors where structural integrity is of concern and has become an established method for testing long lengths of pipes from a limited number of test locations. In such systems, signal interpretation can often be challenging due to the multi-modal and dispersive propagation of the signal. This degradation of signals reduces the sensitivity to small defects and inspection range, which is a particular issue for coated and buried pipelines. This paper employs split-spectrum processing (SSP) application to enhance the GWT signal response in terms of spatial resolution and signal-to-noise ratio (SNR) in real time scenario for coated pipe inspection. An investigation is provided to clarify the sensitivity of SSP performance to the filter bank parameter values for GWT. As a result, the optimum values are estimated to significantly improve the spatial resolution and SNR of the signal response. The proposed technique is experimentally compared with conventional methods and the result shows that the proposed technique has been successful in increasing the sensitivity to small defects and the test range.

KEYWORDS: Signal Processing, SNR, Split Spectrum Processing, Ultrasonic Guided Wave Testing,

1. INTRODUCTION

Long range ultrasonic testing also known as “Guided wave testing” (GWT) is an advanced nondestructive testing (NDT) method that utilizes ultrasonic guided wave (UGW) to inspect large complex structures such as pipes, rods, bars, etc. GWT is widely employed for the inspection of oil and gas pipelines and is able to screen long lengths of pipes rapidly and identify defects (e.g., corrosion) from a single test location. It is normally based on a pulse-echo principle, and the testing frequency range is between 20-100 kHz. Dry-coupled transducers are positioned around the pipe’s circumference that propagates waves within the pipe wall and along the pipe’s main axis, scattering of the waves occur when the waves encounter discontinuities in wall thickness [1-2].

In general, GWT has inherently low attenuation characteristics compared with shear and compression ‘bulk’ wave modes used for conventional ultrasonic testing (UT), so that in a bare pipe test ranges in excess of 50m each direction are possible. However, many pipelines are buried in the ground for safety or aesthetic reasons and in such cases, non-metallic coatings are widely used as the primary means of corrosion protection for the pipe. The propagation characteristics of the guided wave are significantly influenced by the presence of such coatings, which are often viscoelastic in nature. When a pipe is coated and buried, the coating will isolate sound energy inside the pipe. This will reduce the attenuation ratio of axisymmetric wave modes compared to a buried pipe (uncoated). The attenuation is dependent on several factors such as test frequency, material properties of the pipe and coating, as well as the thickness of the coating and how well the coating is bonded to the pipe. Overall, coating significantly reduces the test range, as the viscoelastic coating absorbs the sound energy.

In GWT, short pulses are employed to reduce the effect of dispersion and obtain a reasonable resolution between features. The received signal is often averaged over the repeated test to minimize the effects of random noise [2]. Fig 1 shows typical 50 kHz 5-cycles Hann windowed signals comprising of excited (Fig 1. a, b) and received (Fig 1. c, d) time domain and frequency domain signals respectively. The aim is to generate a pure axisymmetric wave mode to promote non-dispersive propagation; however, the interaction of the signal with the non-axisymmetric features can cause mode conversion that results in the generation of dispersive wave modes (DWM). Since the different frequency components travel at different velocities for dispersive modes, the energy spreads over time/space during propagation, which makes the interpretation more difficult. In addition, as is illustrated in Fig 1 c) the scattering and dispersion of multiple wave modes lead to coherent noise that reduces the sensitivity of GWT [3].
To maintain sensitivity, it is necessary to identify small signals that may be within the noise floor and this makes signal interpretation very challenging, due to the complexity of the noise signature. In particular, the issue of detection of corrosion in coated and buried lines has been identified as a major factor affecting plant availability in the oil and gas industry. Hence, in order to enhance the sensitivity to small defects and increase the inspection range, it is vital to minimize the presence of coherent noise. It is known that dispersion is one of the main sources of coherent noise that is required to be minimized in the received signal. Therefore, the aim is to investigate the enhancement that could be made to the inspection and sensitivity to defects on coated and buried pipe by means of determining the effect of coating on guided wave propagation. This is achieved by employing split-spectrum processing (SSP) technique as a post-processing method to remove/reduce the effect of DWM in the received signal. The optimum parameters for the use of SSP in GWT are developed, proposed and evaluated for ordinary bar pipes in a limited trial in the previous paper [3] whereas in this work the more challenging scenarios include coated pipelines where the attenuation is much higher compared with the bare pipes are investigated.

Many researchers over the last decades investigated the effect of dispersion in GWT to compensate the dispersive behaviour of the signal by reversing the effect of dispersion [4, 5]. This has been achieved by utilizing the prior knowledge of dispersion characteristic of the signal to map it from time to frequency domain and then reverse/restore it as an undispersed pulse. In addition, some other methods such as dispersion compensation (DC), pulse compression (PuC), and a combination of these two techniques were studied to analysis the propagation behaviours of the signal [6-8]. However, these methods were only successful for highly dispersive wave modes and not that effective for non-dispersive wave modes (axisymmetric signals). Reduction of the effect of dispersion is also investigated using post-processing techniques such as cross-correlation and wavelet de-noising [9]. The results illustrated that neither of these methods was suitable for GWT as both methods removed the smaller amplitudes regardless of whether or not they were signal or noise.

Furthermore, other researchers considered the use of split-spectrum processing (SSP) method in NDT applications for SNR enhancement, in particular for conventional ultrasonic testing (UT) [10-12]. It has been claimed that this method could reduce the grain scatter in the UT signal as long as the signal’s response divides into a set of sub-band signals with different centre frequencies. These papers described that SNR enhancement was sensitive to the selection of filter bank parameters. However, the result of the theoretical basis of parameters indicated that some parameters obtained larger values than expected ones. This was mainly due to the use of a Gaussian function for filtering (because of its simplicity) while the calculation was based on Sinc function.

Rubbers [13] reviewed the SSP application and stated that the use of SSP is limited due to the non-linearity of the amplitude of the signal as it does not allow for the sizing of flaws. A new filter bank design of SSP proposed by Rodriguez et al. [14] based on the use of variable bandwidth filters, where filters were equally spaced in frequency and their energy gain equalized. It has been stated that the frequency multiplication (FM) algorithm gave the greatest resolution and SNR
enhancement when combined with the new filter bank design. This paper described that this method reduced the number of filter bands compared to other algorithms; hence, it reduced the system complexity. However, this technique was not evaluated for non-stationary models, highly dispersive material, or a model with multiple defects. Therefore, further investigation into this more challenging scenario is required.

The mentioned literature expose that the successful implementation of SSP is highly sensitive to the selection of filter bank parameters. In addition, most of the literature investigated the use of SSP in conventional UT applications and although some of them managed to obtain a reasonable enhancement in terms of SNR, their optimum values were not suitable for guided wave testing that contains a combination of axisymmetric and non-axisymmetric wave modes with different velocities that operate in kHz range. Hence, a parametric study carried out in the previous papers [3, 15] to find the optimum parameters in terms of its capacity to provide such enhancement in GWT. As a result, optimum parameters identified that was able to improve the SNR and spatial resolution of signal response for bare pipes without any coating in a limited trial. Hence, the potential of using this method for more challenging scenarios such as coated and/or buried pipelines where the attenuation and noise level is quite high is still unclear. In this work, the main concept is to investigate the use of SSP for coated and buried pipes in order to enhance the sensitivity of defect detection and increase the inspection range.

In order to evaluate the proposed technique, a laboratory experiment was carried out where the pipe was partly coated with widely-used Denso tape (Winn & Coales International Ltd), as it was easily applied in a spiral wrap. In addition, a Teletest unit [16] was utilized for data collection to excite and receive the signal using the pulse-echo method. The result illustrated that the proposed algorithm was able to enhance the SNR of the received signal up to 40 dB compared to the conventional method. The proposed method showed that it has a great potential to increase the inspection range and enhance the sensitivity of defect detection in GWT.

The paper is organized as follows: Section 2 describes the concept of split-spectrum processing (SSP) with its implementation. The method defined in Section 3. Section 4 provides details of SSP application for an experimental GWT signal and its discussion and finally, Section 5 concludes the paper.

2. SPLIT-SPECTRUM PROCESSING (SSP)

SSP divides the spectrum of a signal using a bank of band-pass filters to create a set of sub-band signals at different centre frequencies. These sub-band signals are subjected to a number of non-linear processing algorithms to generate an output signal in the time domain. The block diagram of SSP is displayed in Fig 2 that defines the systematic operation of SSP where the input signal $x(t)$, is transformed into the frequency domain $X(f)$, using the fast Fourier transform (FFT). A bank of band-pass filters are employed next to filter the signal, $X_k(f)$ ($k = 1, 2, ..., n$), and is converted it into the time domain using the inverse FFT. Then, the weighting factor $w_k$ is applied and finally, one of the SSP recombination algorithms is utilized to add these non-linear signals together to generate the output response, $y(t)$. It is notable that the velocity of dispersive wave modes varies with frequency, hence their components will vary through the sub-bands whereas the components of non-dispersive wave modes stay constant. The main advantage of this technique is that it is able to suppress regions of the signal that vary across the bandwidth, reducing the effect of wave modes that are dispersive.
SSP RECOMBINATION ALGORITHMS

Many recombination algorithms exist that could be utilized to combine the filter bank parameters together to generate an output signal [13]. It is shown in [3] that Polarity Thresholding (PT) achieved the greatest SNR enhancement and spatial resolution of signal respond without distorting it. Therefore, the PT algorithm is selected in the work that is calculated as follows:

\[
y_{PT}[m] = \begin{cases} 
  x[m] & \text{if all } x[i][m] > 0, \quad i = 1, ..., n \\
  x[m] & \text{if all } x[i][m] < 0, \quad i = 1, ..., n \\
  0 & \text{Otherwise}
\end{cases}
\]

Fig 2. SSP block diagram

2.2 IMPLEMENTATION OF SSP

As mentioned earlier the filter bank parameters play an important role in the SSP process in order to enhance SNR. The parameters display in Fig 3 are i) total bandwidth for processing (B), ii) filter separation (F), iii) filter crossover point (x), iv) number of filters (N), v) sub-band filter bandwidth (Bfilt). These parameters are explained in the previous paper [3], where the optimum values have been investigated, developed and proposed for the use of SSP in GWT that achieved a promising enhancement in terms of SNR and spatial resolution for ordinary pipeline inspection.

In this paper, the aim is to investigate the proposed technique for more challenging scenarios where the pipe is partially coated. Hence, in order to obtain optimum parameters a new brute force search algorithm is applied to the collected data.

In order to implement the SSP technique, a program is written in Matlab environment that takes the unprocessed time domain signal as an input, then transfers it to the frequency domain and filters it with Gaussian band-pass filters by multiplying its Fourier transform by a Gaussian window to produce a set of sub-bands signal. Then in order to generate the output signal, PT algorithm is applied to these sub-bands signal. The lower, \(f_l\), and higher, \(f_h\), cut-off frequencies that applied for each sub-bands can be calculated as follow:
\[
\begin{align*}
    f_{in} &= \begin{cases} 
    f_{\text{min}} - F & n = 1 \ 
    f_{in-1} + F & n = 2, 3, \ldots, N
    \end{cases} \\
    f_{hn} &= f_{in} + B_{filt} & n = 1, 2, \ldots, N
\end{align*}
\]

where \( f_{\text{min}} \) is the lower cut off frequency of the whole bandwidth, \( F \) is the filter separation, \( N \) is the number of filters, and \( B_{filt} \) is the sub-band filters. The lower cut off frequency for the first sub-band \( f_{1} \) needs to cover the start point of the signal, thus it is selected as the difference between \( f_{\text{min}} \) and \( F \).

3. METHOD

Modelling algorithms have been studied and developed to identify the attenuation rate for buried and coated pipes [17, 18]. One facet of the work was to obtain realistic values for the relevant acoustic properties of the coating to be studied. Denso tape (Winn & Coales International Ltd). Two axisymmetric wave modes, \( L(0,2) \) and \( T(0,1) \), were used as the incident modes and their attenuation was measured. To extract the material properties, a trial and error procedure was used by gradually modifying the material properties in the SAFE model, until a good fit was found between the theoretical model and the measurements for all the frequencies. The attenuation rate of 3dB/m, is obtained for Denso coated pipe that is fully explained in [18]. However, it should be noted that this behaviour is heavily dependent on the coating acoustic properties and on the coating thickness. The importance of this information about coating properties is that it may be used to select optimised testing conditions, such as frequency, if the coating shows high-frequency dependence on attenuation. It is also found out that the \( L(0,2) \) mode has an intrinsically lower attenuation characteristic for the coating studied, so is likely to achieve a longer test range. However, this mode also scatters more easily, thereby increasing baseline noise, so that the overall effect on test performance will have to be evaluated.

Furthermore, the rate of attenuation gives rise to a very wide range of amplitudes in the received signals along the test length, which is potentially many meters. For example, on bare pipe with an attenuation rate of 0.2dB/m, an ultrasonic signal with an initial value of unity will have an amplitude of 0.8 after 10m propagation. For 3dB/m (the value obtained for \( T(0,1) \) for Denso coated pipe, the amplitude will be 0.03 and for 6dB/m the amplitude will be 0.001, i.e. 1/1000 of the initial amplitude.

4. EXPERIMENTS

Fig 4 illustrates a pipe under investigation, which was an 8” schedule 40 steel pipe (219mm diameter, 8.18mm wall), 18 meters long, partly coated with Denso tape (Winn & Coales International Ltd) to simulate the transition from an unburied to a buried section that was used to illustrate this effect. The TeleTest unit was employed for this experiment using the pulse-echo method. SSP is then applied as a post-processing technique to the received signal in order to increase the SNR and enhance the spatial resolution. The set-up in Fig 4 shows the TeleTest collar located at 62cm away from the near pipe end. The signal is excited/received using a ‘3 Ring Torsional’ to transmit a 10-cycles, Hann window modulated tone burst of \( T(0,1) \) wave mode. The ring spacing between transducers was 30mm and the sampling frequency sets to 1MHz.

A brute force search algorithm is applied to find the optimum parameters of SSP in GWT for this experiment. The ranges of these values that nominated to be employed in the brute force search are inspired by the values that was proposed in [3]. These values as shown in Fig 3 are independent, which means changing one value will require other values to change. Therefore, it is
required to search for the optimum parameters in parallel and select them appropriately. In order to achieve that, a portion of the frequency spectrum of the unprocessed signal is selected as the total bandwidth \((B)\), and fed into the brute-force search algorithm as listed below:

- **Step 1:** The range for the total bandwidth \((B)\) is altered from the signal bandwidth containing 86% to 100% of the frequency spectrum in steps of 3%.
- **Step 2:** The sub-band filter bandwidth \((B_{fil})\) is varied from the total bandwidth value \((B)\) divided by 3 to the total bandwidth divided by 15 in steps of 2. Note that the selection of sub-band filter bandwidth range is a tradeoff between loss of temporal resolution and the number of filters.
- **Step 3:** The filter separation \((F)\) is varied from the value of sub-band filter bandwidth \((B_{fil})\) divided by 1 to 6.5 in steps of 1.
- **Step 4:** The filter crossover point \((x)\) is varied from 1 \(dB\) down from the filter peak to 6 \(dB\) down.

![Fig 4. Experimental setup for an 8” steel pipe with 219mm diameter and 8.18mm wall thickness.](image)

The performance is quantified by measuring SNR of the received signals. The aim was to preserve all the axisymmetric features and remove coherent noise (mainly flexural wave modes) as much as possible. The best result was achieved with the following parameters:

- 99\% of the total operation frequency,
- A sub-band filter bandwidth that is equal to the total operating bandwidth divided by 11,
- A filter separation that is equal to sub-band filter bandwidth divided by 1.5,
- A filter crossover of 1 \(dB\).

Thus, the above values are selected as the optimum SSP parameters for axisymmetric \(T(0,1)\) wave mode, 10-cycles Hann windowed with the centre frequency of 35 kHz. The aforementioned parameters are subsequently used in the processing of the experimental data used in this work. The result is presented in Fig 5 where the Teletest axisymmetric wave mode (blue trace) and the output of SSP-PT (red trace) are displayed. It is clearly demonstrated that the proposed method with optimum parameters has removed all the coherent noise in the whole trace and preserved all the reflection echoes of the axisymmetric signal. It must be noted that the optimum values have been identified using the brute force search algorithm as mentioned before by measuring the SNR of the signal response using the following calculation:

\[
SNR = 20 \times \log_{10} \left( \frac{S}{N} \right)
\]  

(4)

where \(S\) is the peak value of the weld 3 reflections (Fig 5) and \(N\) is the RMS value of the coherent noise region around the weld 3 that is under the wrap region. The results show that the SSP with optimum parameters enhanced the SNR up to 40 \(dB\) without distortion in the signal. Note, the responses at 8m and 14m are multiple reflections from welds 1 and 2 respectively.

**4.1 CREATING A DEFECT**

In the next step in order to validate the optimum parameters of SSP, an 8\% cross-sectional area (CSA) defect was cut (saw cut) in the pipe mid-way between weld 3 and pipe end B. Then signals post-processed with the proposed SSP optimum parameters were compared with the conventional Teletest system result using the Matlab software. Fig 6 illustrates the result after the introduction of the defect for the unprocessed Teletest data (blue trace) and SSP (red trace). Fig 6 (a) displays the whole length of the trace, and Fig 6 (b) shows the zoom-in result. This figure indicates that the result of Teletest system contains a continuum of background signals and the defect was hidden below noise level whereas the SSP
technique has successfully removed background noise entirely and preserved all the features from real reflectors, including those which are multiple reflections from the high amplitude welds. Therefore, by using the proposed method an inspector can call the defect with a good confidence.

Furthermore, in order to quantify the improvement given by the SSP technique, the SNR is calculated using equation (4) where S is the peak value of the defect’s reflection and N is the RMS value of the coherent noise region around the defect. The results illustrate that the SSP has increased the SNR approximately by 40 dB without distortion the signal.

**Fig 5.** Unprocessed signal (blue trace) and SSP – PT (red trace) signal with optimum SSP filter bank parameters.
The result presented in this paper illustrated that the SSP application has a great potential to reduce the level of coherent noise that is mainly due to the presence of dispersive wave modes in guided wave testing. One of the main primary limitation factors for defect detection is coherent noise and if it can be reduced successfully it can substantially enhance the spatial resolution and SNR of the signals. It was highlighted that the outcome of SSP is sensitive to the selection of filter bank parameters, hence, a brute force search algorithms was utilised to find the optimum filter bank parameters by checking the SNR and spatial resolution of the signal response using the Polarity Thresholding (PT) recombination algorithm.

In order to achieve that, an experimental test was carried out on an 8” pipe that was partially coated with Denso tape. The excitation signal was the Torsional T(0,1) wave mode, 10-cycles modulated Hann windowed with the centre frequency of 35 kHz. Using the brute force search algorithm, the optimum values were identified that considerably enhance the SNR of the received signal. The proposed algorithm is compared experimentally with the conventional technique that is currently utilised in Teletest unit and the result illustrated that the proposed method enhanced the SNR around weld 3 approximately by 40dB without distorting the signal.

Enhancement in GWT sensitivity and spatial resolution can lead to detecting smaller defects and increase the inspection range. This was validated by identifying an 8% CSA saw cut defect that has been created after the weld 3 that was surrounded by the noise level. The result demonstrated that the proposed method identified the defect and removed the coherent noise around the defect entirely whereas the conventional method was unsuccessful to do that.

5. CONCLUSION

The attenuation rates for guided wave testing in pipelines where the pipes are buried in the ground and/or viscoelastic coating exist are quite high that cause a major reduction in GWT capability, which is a major problem for oil and gas industry. In order to tackle this issue, a post-processing technique “SSP” has been developed that showed it has a great potential to reduce the attenuation effects for coated pipes by reducing the effect of coherent noise. The technique is applied to data gathered in the
laboratory where the pipe was partially coated with Denso tape for the restoration of signals suffering from attenuation with the aim to increase the sensitivity, SNR, and inspection range. It is demonstrated throughout this work that the SSP method with optimum parameters has the capability to enhance the SNR and the spatial resolution of the received signal. It must be noted that the SNR enhancement in GWT can improve the ability of detecting small defects and increase the inspection range, as the technique is able to remove the coherent noise entirely for the whole length of the signal. Whereas the commercial Teletest software was not able to reduce the noise level at all.

The conclusion reached in this work pave the way for guided wave testing through more reliable signal interpretation and defect detection for coated and buried pipelines. However, this approach has been shown to be effective in limited trials and in order to make it automated, further field data analysis is required. Hence, further work on this topic will focus on testing more field data with different centre frequencies, creating a different type of defects on coated pipes where the attenuation is high and investigate the optimum parameters for these scenarios.

ACKNOWLEDGMENT

This work was partly funded by Innovate UK under the ‘UNION’ project within the ‘Developing the Civil Nuclear Supply Chain’ initiative.

REFERENCES