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Practical guided wave inspection and applications to structural health monitoring

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Abstract: The application of ultrasonic guided waves for the long range inspection of large structures is reviewed. The technique is in routine commercial use on pipes and this technology is described. However, the method is much more difficult to apply on complex structures where the reflections from multiple features are not resolved in time. Here it is necessary to look for changes relative to a baseline condition as part of a structural health monitoring strategy; this requires a method to compensate for benign changes such as temperature variations, and possible methods for achieving this are discussed.

Keywords: pipe inspection, SHM, temperature compensation, ultrasonic guided waves.

1 Introduction

Ultrasonic guided waves of different types can propagate in any bounded medium and include the well-known Rayleigh (surface) waves on a half-space and Lamb waves in plates. Similar types of wave can propagate in rods, cylinders and elongated structures which are not axially symmetric such as railway rails and I-beams. The use of guided waves in NDE has been discussed for over 40 years, Worlton [1] being one of the first to recognise their potential. The textbook by Rose [2] gives an introduction to the theory and application of guided waves and the same author has discussed the history and potential of this type of inspection [3].

Guided wave inspection can be used over propagation distances ranging from a few mm to many tens of metres; this paper focuses on long range inspection over ranges upwards of 1m, this being carried out at frequencies below around 200 kHz and frequently below 50 kHz. The main attraction of long range guided wave inspection is that it enables a large area of structure to be tested from a single transducer position, so avoiding the time-consuming scanning required by conventional ultrasonic or eddy current methods. The technique becomes even more attractive if part of the structure to be tested is inaccessible, for example a pipe passing under a road.

Unfortunately the ratio of the number of practical applications of guided waves to the number of research papers in the area is rather small. This paper discusses the reasons for this and describes how the difficulties may be overcome so that the potential of the technique can be realised. This is followed by practical examples of pipe inspection and a discussion of the application of guided waves to the structural health monitoring of complex structures such as airframes.

2 The practical problems - coherent noise and dispersion

The main difficulty with medium and long range guided wave inspection is that it is very easy to obtain signals like that shown in Fig 1a. This shows the pulse-echo signal produced on a length of plain pipe by a group of transducers covering a quarter of the pipe circumference and connected in parallel so that they effectively act as a single transducer. Ideally the signal should contain two distinct echoes from the two ends of the pipe rather than the very complicated trace seen in the figure. The complication arises from the excitation of multiple modes which travel at different velocities in both directions, these velocities being in general a function of frequency (i.e. the modes are dispersive). Fig 2a shows the dispersion curves for a 6 inch diameter, schedule 40 steel pipe. There are about 50 modes present at frequencies below 100 kHz and many of them are strongly dispersive. Fig 2b shows the corresponding diagram for a plate. Here the group velocity is plotted as a function of frequency-thickness product and below about 1.6 MHz-mm only three modes are present (a_0 , s_0 and SH_0). Therefore in a 10 mm thick plate there are only 3 modes present below 160 kHz. Mode control is therefore easier in a plate than a pipe but other problems are more difficult, as will be discussed later.

Fig 1b shows a clearer signal obtained at an early stage in the development of the pipe screening system discussed later. Reflections from two welds approximately 15m apart in a long pipe can clearly

be distinguished. However, there are many smaller signals between the two weld echoes which should not be present since this was a new pipe. Averaging did not improve the signal, indicating that the problem is coherent, rather than random, noise. The welds are approximately -14 dB reflectors and the coherent noise level is about 10 dB below the weld echoes indicating that the signal to coherent noise ratio is between 20 and 25 dB. However, the target reflection size in this application was -26 dB so the system needed further refinement to reduce the noise. The coherent noise has two main sources:

- the excitation and reception of unwanted modes;
- the transmission of waves in the opposite direction along the pipe and the reception of echoes from that direction.

The key to controlling coherent noise is therefore to control the modes excited and received, and their propagation direction. The choice of mode will be influenced by the ease of exciting it while minimising the excitation of other modes, and by its sensitivity to the defect type(s) of interest. In addition to controlling coherent noise, it is also necessary to control dispersion. If the chosen mode is dispersive, the different frequency components in the signal travel at different velocities so the signal duration increases which compromises the spatial resolution (the ability to distinguish echoes from closely spaced reflectors). Dispersion is not very evident in Fig 1b since it was controlled by applying narrow band excitation centred on a region where the mode of interest is non-dispersive. This strategy to overcome dispersion problems is often sufficient, though dispersion compensation [4] can also be valuable.

3 Controlling coherent noise

It is important to use a transducer which forces the structure in the most appropriate direction. For example, at low frequency the s_0 mode in a plate involves predominantly in-plane motion, while the a_0 mode is predominantly out-of-plane. It is therefore very difficult to obtain a satisfactory ratio of s_0 to a_0 signal by using a transducer such as a piezoelectric transducer on an angle wedge because it applies an out-of-plane force to the structure surface; if the s_0 mode is to be used in this regime, an EMAT designed to apply an in-plane force is preferable. The issue of mode excitability is discussed further in [5].

The degree of modal selectivity obtained is governed by the size of the transducer and the excitation signal. The transducer size controls the effective wavenumber bandwidth, while the excitation signal governs the frequency bandwidth. This is discussed further in [6-9]. In order to obtain satisfactory mode control, the transducer generally has to be a round 3-5 wavelengths long. For a mode with a phase velocity of 3 mm/ μ s, the wavelength is 6 mm at a frequency of 500 kHz so the required transducer size is modest. However, if the frequency is reduced to 50 kHz, the wavelength increases to 60 mm and the required transducer size becomes impractical. Therefore in long range testing an alternative to single, monolithic transducers must be sought and it has been found that an array of point sources is very attractive in several applications, as discussed below.

If an array is used, satisfactory mode control requires that the direction of the force applied by the individual elements is appropriate for the desired mode, and that the individual array elements have good gain and phase consistency. Signal processing makes an important contribution to extracting the desired input mode - received mode combination from the array and rejecting other combinations, so improving the signal to coherent noise ratio. It is also potentially possible to subtract a baseline signal obtained at an earlier stage in the life of a structure from the current signal in order to track changes. This is particularly applicable in health monitoring applications where the transducers are permanently attached, but the operation is not straightforward since, for example, temperature changes or small, unimportant changes in material properties with age will affect the received signals; this is discussed further below.

4 Pipe testing

The safe operation of petrochemical plant requires screening of the pipework to ensure that there are no unacceptable levels of corrosion. Since a significant proportion of industrial pipelines are insulated, this means that even external corrosion cannot readily be detected without the removal of the insulation, which can be prohibitively expensive. A quick, reliable method for the detection of corrosion under insulation (CUI) which does not involve removal of all the insulation is therefore required. The

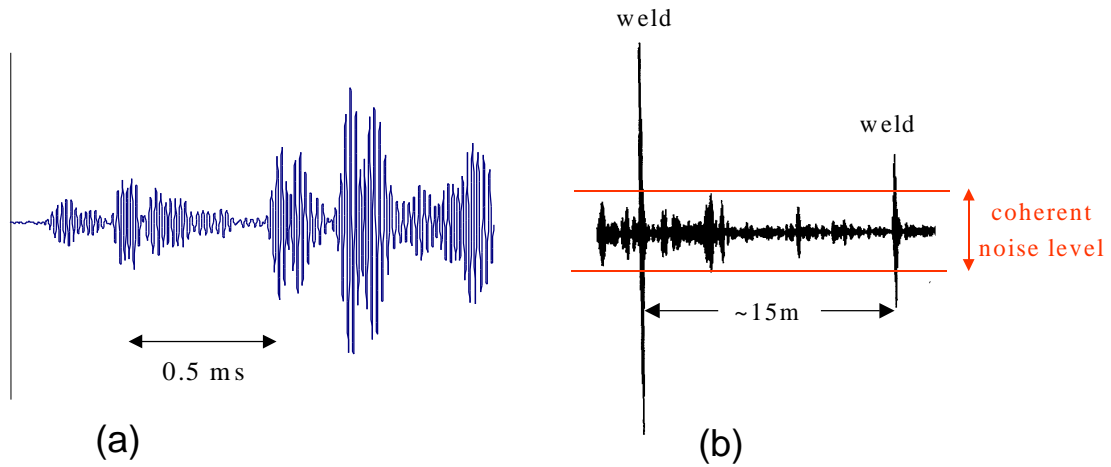


FIGURE 1. (a) Signal received on length of plain pipe using transducers over quarter of circumference; (b) signal received on welded pipe in early site test.

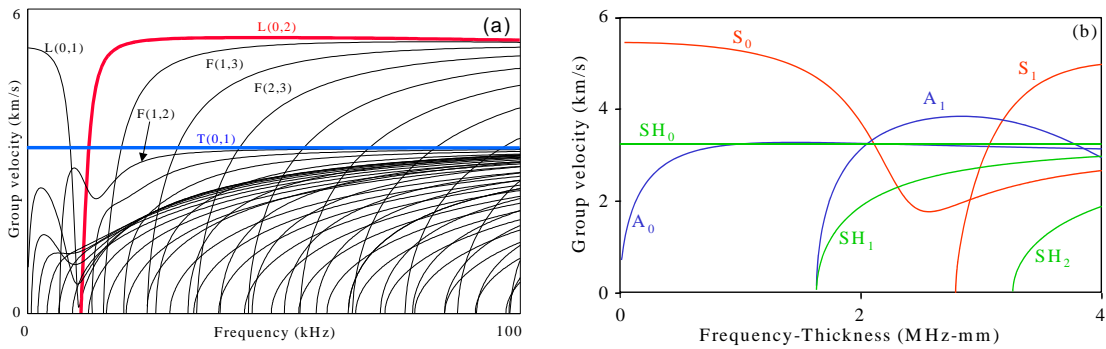


FIGURE 2. Dispersion curves for (a) 6 inch, schedule 40 steel pipe; (b) steel plate.



FIGURE 3. Solid transducer assembly for 8 inch pipe showing array of dry coupled piezoelectric transducers.

problem is even more severe in cases such as road crossings where the pipe is underground (often in a sleeve) for a limited distance; excavation of the pipe for visual or conventional ultrasonic inspection is extremely expensive so a technique to address this problem is particularly beneficial.

The Imperial College NDT group, and latterly the spin-out company Guided Ultrasonics Ltd, have developed a guided wave technique designed for the screening of long lengths (>10m) of pipes for corrosion. It seeks to detect corrosion defects removing of the order of 5-10% of the cross sectional area of the pipe at any axial location. It was originally developed for use on pipes in the 2-24 inch diameter range, though it is also used on both smaller and larger pipes.

The most attractive modes to use are those which have a mode shape which has uniform stress over the whole cross section of the pipe. This means that there will be equal sensitivity to cross section loss at any location through the wall thickness or round the circumference. Modes with a simple mode shape are also easier to excite in a pure form which is important in controlling coherent noise. The two modes which meet these criteria are the $L(0,2)$ and $T(0,1)$ modes shown in Fig 2a. These are essentially extensional and torsional modes respectively. Both modes have the additional advantage of being non-dispersive over a wide frequency band.

Initial site trials of the technique carried out in the research phase in the mid 1990s used the $L(0,2)$ mode at frequencies around 70 kHz [10, 11]. However, there is a second, unwanted, axially symmetric mode with particle displacements primarily in the axial and radial directions, $L(0,1)$. This mode, which has a much lower velocity than $L(0,2)$ in the operating frequency range above 35 kHz as shown in Fig 2a, makes it more difficult to obtain pure mode signals. In contrast, $T(0,1)$ is the only axially symmetric torsional mode in the frequency range of interest, so axially symmetric torsional excitation will only excite the $T(0,1)$ mode. The torsional mode also has the advantage that, in contrast to the $L(0,2)$ mode, it does not involve radial displacement of the pipe wall. Therefore its propagation characteristics are not affected by the presence of liquid in the pipe so in-service inspection of lines carrying a liquid is straightforward.

The Guided Ultrasonics Ltd Wavemaker Pipe Screening System transducer array for an 8 inch pipe is shown in Fig 4. The array comprises two rings of dry-coupled, piezoelectric transducers which apply a tangential force to the pipe surface, so exciting the torsional mode; the two rings of transducers positioned roughly a quarter wavelength apart along the pipe (the precise fraction of the wavelength depends on the test frequency used) enable direction control. The transducer array is connected to the battery-operated testing instrument by a flexible cable; the test is controlled by a portable PC that is connected to the instrument by an umbilical cable. In some cases it is convenient for the operator of the PC to be adjacent to the test location, but on other occasions it is better for the computer and operator to be in a van that can be up to 50m from the test location. Solid rings of the type shown in Fig 3 are manufactured for pipe diameters up to 8 inch, but above this they become bulky so a flexible, pneumatic clamping arrangement is used; the flexible system can also be used on 6 and 8 inch pipes.

The initial site trials [10, 11] showed that corrosion defects of the target size (half wall thickness deep and half pipe diameter (16% circumference) in circumferential extent) could reliably be identified. However, echoes were also seen from butt welds since the weld caps are not generally removed so the weld presents a change in cross sectional area, and hence in effective acoustic impedance. The presence of the echo from a good weld makes it difficult to identify defects at welds, and also introduces the possibility of a weld being incorrectly identified as a defect in cases where the pipe is insulated or buried so the weld cannot be seen. This problem can be overcome by measuring the extent of mode conversion produced by a reflector.

If an axially symmetric mode is incident on an axially symmetric feature in the pipe such as a flange, square end or uniform weld, then only axially symmetric modes are reflected. However, if the feature is non axially symmetric such as a corrosion patch, some non axially symmetric waves will be generated. These propagate back to the transducer rings and can be detected. If the $T(0,1)$ mode is incident, the most important mode conversion is to the $F(1,2)$ and $F(2,2)$ modes. The amount of mode conversion obtained depends on the degree of asymmetry, and hence on the circumferential extent of the defect. The use of an array of transducers facilitates detection of the mode converted signals; if a monolithic transducer (equivalent to wiring all the elements of one ring of the array together) were to be used, the mode converted signals would not be detected since their displacements vary harmonically around the pipe so that the mean displacement is zero. In order to measure the mode conversion it is therefore necessary to access the signals received by individual transducers (or

groups of adjacent transducers around the pipe) separately and to add them together in software with the appropriate phase shifts; the principles of this procedure are given in [12].

Fig 4 shows typical reflections from symmetric and asymmetric features; the increase in the mode converted signal can clearly be seen in the asymmetric case and this is a key element of the defect identification scheme. Fig 5 shows an example report generated by the Wavemaker WavePro software for an epoxy painted, 4 inch pipe at a test position adjacent to a road crossing. The test range extends over more than 20m on either side of the rings which are located in the middle of the plot. The software identifies welds and computes a distance-amplitude correction (DAC) curve for the welds. It then calculates the defect call level by comparison with the weld echo level and the calculated output amplitude, knowing that an average site weld is a -14 dB reflector. The received axisymmetric signals are shown as a black curve while the non-axisymmetric, mode converted signals are shown as a red curve. The echo identified as +F2 is the only one where the red (mode converted) signal is significant compared to the black (reflection of incident mode) signal and this indicates possible corrosion at the entry point to a road crossing.

Further practical examples of the use of the Guided Ultrasonics Ltd Wavemaker Pipe Screening System can be found in [13-15]; another commercial system based on the earlier work [11] is described in [16]. The technique offers the possibility of rapid screening of long lengths of pipework for corrosion and other defects. A test range of 50m (25m in each direction) is commonly obtained from a single transducer position. No surface preparation is usually required and the transducers can be attached in less than 1 minute so long lengths of pipe can be screened in a day. Typical applications are the rapid, full coverage screening of long lengths of pipe. The method is also commonly used for the inspection of difficult-to-access locations such as sleeved road crossings, insulated pipe, wall penetrations and areas where rope access is required. In addition to the technology generated by the Imperial College group, the South West Research Institute has also developed a pipe testing system [17].

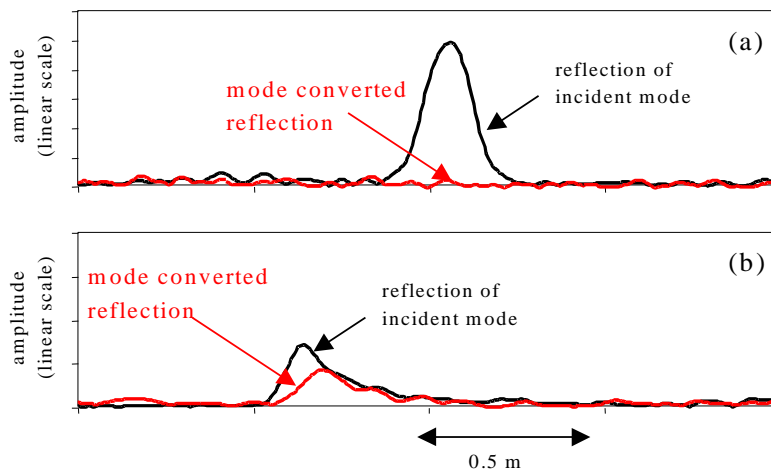


FIGURE 4. Typical signals from (a) axisymmetric feature e.g. weld; (b) corrosion.

5 Health monitoring of complex structures

The current industrial applications of long range guided wave inspection are on one dimensional structures with low feature density such as pipes and rail [18] where the echoes from individual features can readily be separated. Defects are then identified from changes in the nature of these reflections or from the appearance of reflectors at positions between the known features. A similar approach is also possible with simple plate-like structures [19]. However, this strategy breaks down if complex structures such as airframes are to be tested. Here, the ribs and stiffeners are too close together for the reflections from the different features to be separated so it is not possible to identify changes in the characteristics of a single reflector. An obvious strategy to overcome this would be to use a higher frequency and so to shorten the wave packet, but this drastically shortens the propagation range in structures of this type [20]. Another approach is to look for changes in the signal

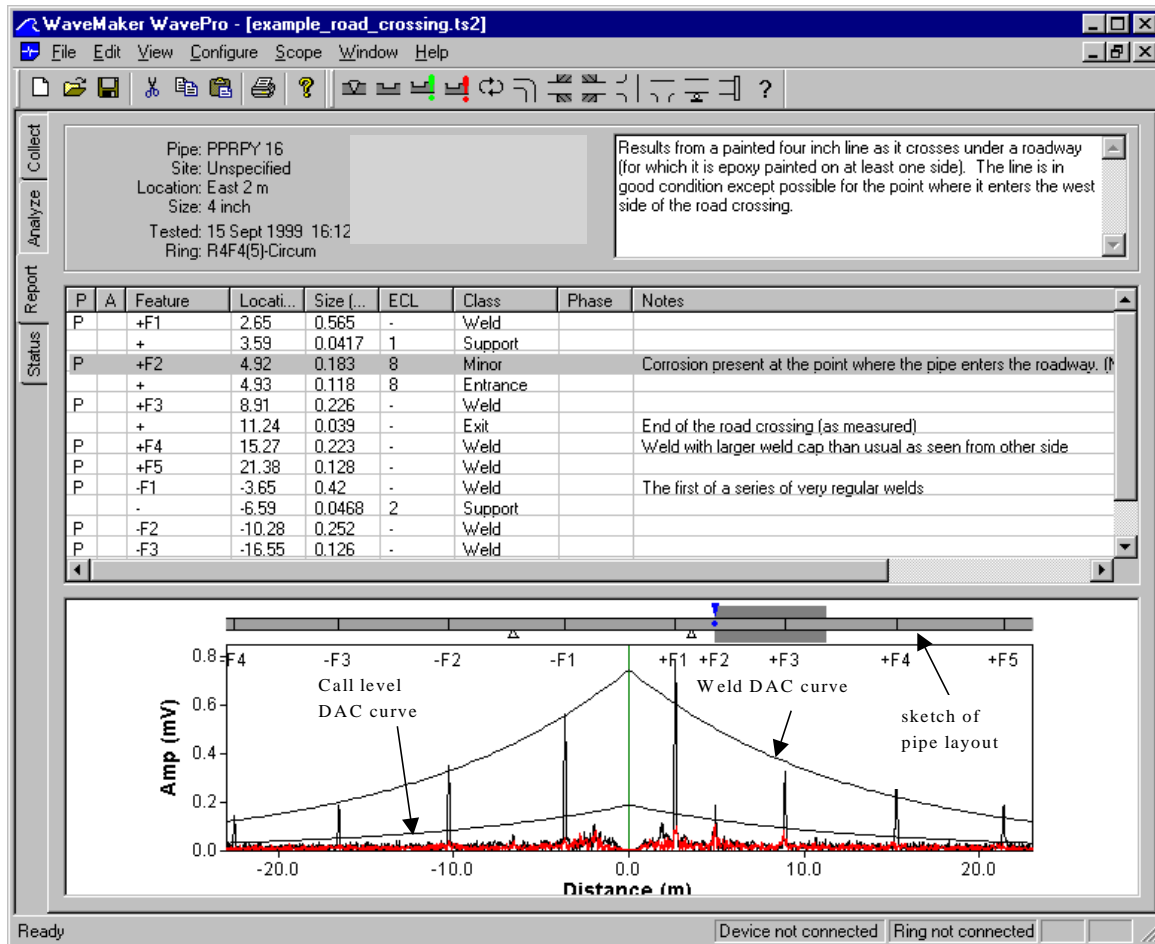


FIGURE 5. Guided Ultrasonics Ltd Wavemaker Pipe Screening System report from test adjacent to road crossing.

from a baseline taken when the structure is new or the monitoring system is installed; this strategy relies on the received signal being stable in the absence of damage. Unfortunately the signal is strongly affected by temperature which affects the dimensions and, more importantly, the velocity of the propagating waves; it can also affect the transducer properties, and those of the bond between the transducer and the structure. The problem is that a typical small defect might be a -25 dB reflector so, once beam spreading is accounted for, a signal to noise ratio of around 40 dB is needed for defects to be reliably detectable over a reasonable distance. This sets a very challenging target for temperature compensation systems.

Considerable progress has recently been made in this field, notably by Wilcox et al at University of Bristol [21] and Michaels et al at Georgia Tech [22-24]. They have developed several alternative approaches to the problem; the results presented here use the 'baseline stretch' technique described in [21]. Due to cumulative effects the shift in time between two signals taken at different temperatures increases with propagation time (and hence distance) [23, 25]. Frequency also has a direct influence on the residual level of the signal obtained by subtracting the current signal from the baseline [21]:

$$u = 2.u_0.\pi.f.\delta t \quad (1)$$

where u is the amplitude of the residual (subtracted) signal, u_0 is the amplitude of the signal, f is the frequency and δt is the time shift between the two signals. One should note that in [22-25] an impulse excitation was used while in [21] the input signal was a toneburst with a centre frequency which would result in a 1MHz-mm frequency-thickness product. In all cases, higher frequency-thickness products were used for excitation in comparison to those of this paper and little attention was paid to mode purity.

Recent work at Imperial College has led to the development of a low frequency a_0 mode transducer which enables a very pure a_0 mode signal ($a_0:s_0$ energy ratio better than 30 dB) to be generated at frequencies around 30 kHz giving frequency-thickness products well below 200 kHz-mm in typical structures [26]. We hope that this will reduce the baseline changes due to variations in s_0 mode generation with temperature that are likely to be caused by changes in the bond between the transducer and the structure. In an initial evaluation of the system, two transducers were attached to a 5mm thick, 1m square aluminum plate. The plate was positioned in an enclosed room and the transducers were operated in a pitch-catch configuration. The room was heated by more than 10°C and signals were recorded every 1°C. The signal recorded at the initial room temperature was used as the baseline. Figure 6a shows the signals obtained at different temperatures and the subtracted signal obtained if no temperature compensation technique is applied. Figure 6b shows the amplitude of the subtracted signal of Figure 6a as a function of time relative to the amplitude of the first arrival. From these figures it is clear that, without temperature compensation techniques, baseline subtraction methods would be ineffective in defect detection.

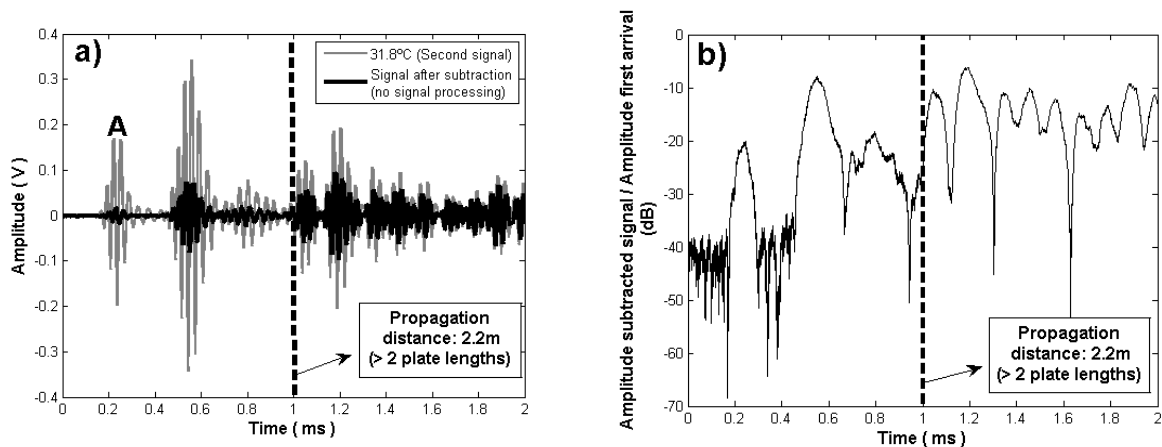


FIGURE 6. a) Second signal (31.8°C) and subtracted signal with no temperature compensation. Reference signal taken at 21.6°C; b) Amplitude of subtracted signal relative to amplitude of first arrival (A in Figure 6a).

5.1 Signal matching and subtraction

To improve the subtraction of the signal obtained from the temperature variation experiment a temperature compensation technique reported in literature was applied [21, 25]. The technique consists of stretching the second signal in the time [25] or frequency domain [21]. This is done simply by increasing the size of the time or frequency step. For each step size the difference between the stretched signal and the reference signal is taken and minimizing the rms error of the subtracted signal or maximizing the coherence between the two signals before subtraction finds the optimal stretch; frequency domain processing was used in this work. This allowed the power normalization of both spectra and consequent correction of some amplitude changes seen in the time domain. Figure 7a shows the results of the subtraction of both signals and Figure 7b shows the amplitude of the subtracted signal relative to the amplitude of the first arrival. The same set of data presented in Figure 6 was used to obtain the results on Figure 7.

5.2 Filtering of noise in the subtracted signal

By analysing the results obtained with the baseline stretch method it was found that the largest amplitudes in the subtracted signal were at frequencies significantly above or below the centre frequency of the input signal. If the subtracted signal is analyzed in the frequency domain, as shown by the grey line in Figure 8, it is clear that large energy values are present especially in the low frequency region. If a simple narrow band filter as shown in Figure 8 is applied most of the low frequency noise is removed. This leads to an improvement of 5-10dB when the amplitude of the subtracted noise signal is compared to the amplitude of the first arrival, as shown in Figures 9a and 9b. The highest residual amplitude after two plate transits for the worst case tested (10°C temperature change)

was around -38dB. Some sudden increases in values of amplitude in later parts of the recorded time period are still to be studied.

5.3 Response of system to simulated defect

To verify the sensitivity of the system, a brass cylinder (6mm length, 5mm diameter) was attached to the same plate used for previous experiments with a viscous couplant. This simulated defect could be shifted in position and signals could be captured and processed on site. Figure 10a shows the signals obtained before the reflector was attached to the plate. Two time-traces of the undamaged structure were recorded over a period of two days and with a slight temperature variation. The signal obtained by subtracting the two time-traces after temperature compensation was used as a reference (Figure 10b). This helped to identify changes both in the area where the reflection from the mass was expected to be and in the subsequent time-trace. Figure 11 shows the signals obtained when the reflector was attached to the plate. An increase in amplitude can be seen in the region where the reflection is expected along with an overall increase in the amplitude in the region of the time-trace beyond the reflection. This is probably due to interactions between the reflection from the “defect” and reflections from the edges. These interactions modify the phase and amplitude of the signal in this region and lead to high amplitudes in the subtracted signal. This effect helped to identify the presence of a “defect” even when the mass was positioned very close to the edges of the plate.

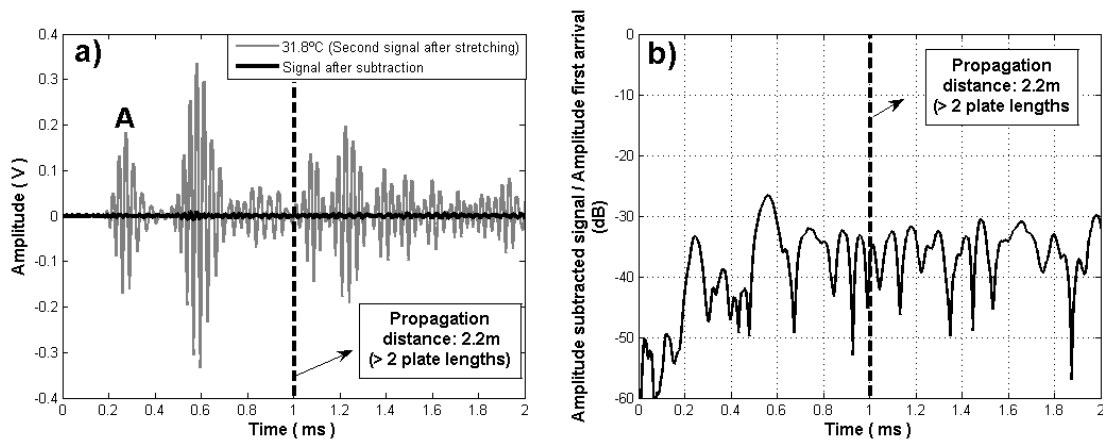


FIGURE 7. a) Same set of data presented in Figure 6 after temperature compensation (optimal stretch); b) Amplitude of subtracted signal relative to amplitude of first arrival (A in Figure 7a).

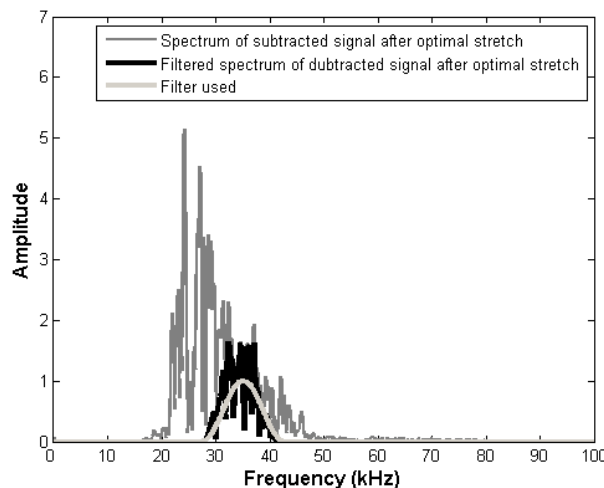


FIGURE 8. Spectrum of subtracted signal before and after filtering. Filter used was a Hanning window with a shorter bandwidth in comparison to the spectra of the input signal.

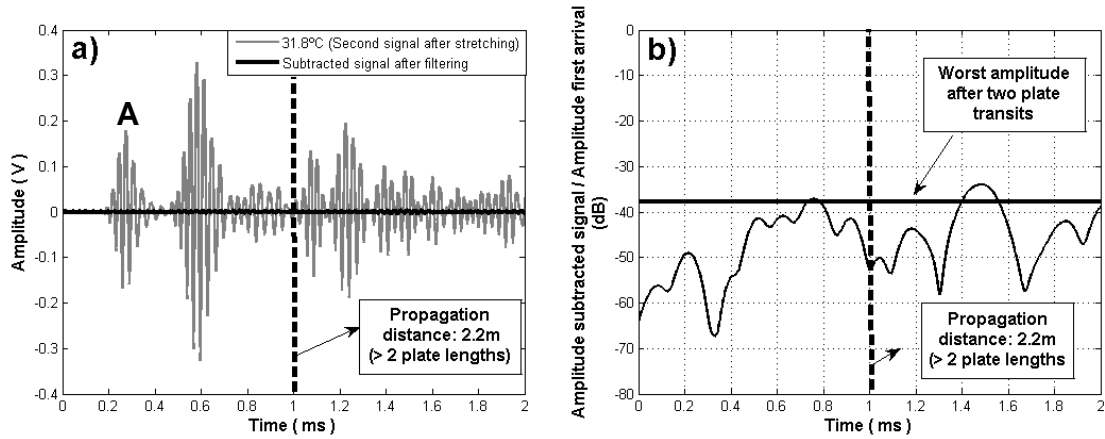


FIGURE 9. a) Same set of data presented in Figure 7 after noise filtering; b) Amplitude of subtracted signal relative to amplitude of first arrival (A in Figure 9a).

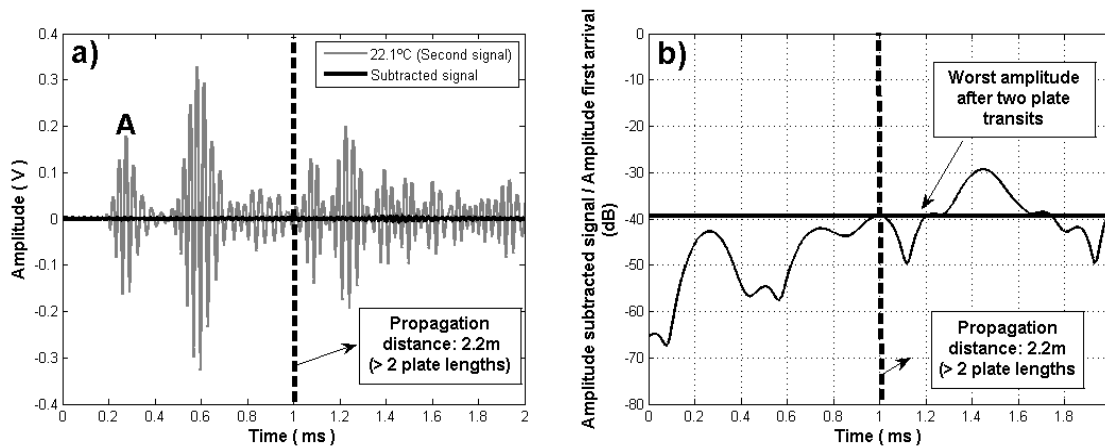


FIGURE 10. Signals for undamaged structure: a) Second signal (22.1°C) and subtracted signal after temperature compensation. Reference signal taken at 21.6°C; b) Amplitude of subtracted signal relative to amplitude of first arrival (A in Figure 10a).

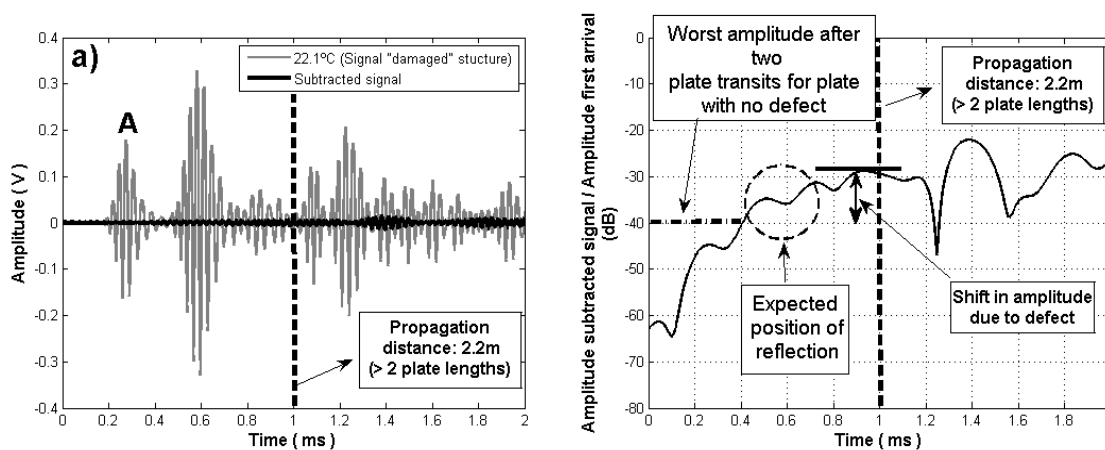


FIGURE 11. Signals for “damaged” structure: a) Second signal (22.1°C) and subtracted signal after temperature compensation. Reference signal (21.6°C); b) Amplitude of subtracted signal relative to amplitude of first arrival (A in Figure 11a).

6 Conclusions

Long range guided wave inspection of pipes is now a well established technique that is in routine worldwide use, and commercial systems are also available for rail. These structures are essentially one dimensional and typically have very low feature density so it is easy to separate reflections from individual features and to study their characteristics. The problem becomes much more complicated in structures such as airframes. The problem is not the move from one dimensional to two dimensional structures, but the increase in feature density which means that the reflections from different features overlap, making it impossible to analyse an individual reflection or to identify an extra reflection from a defect. In principle it is possible to monitor changes in the response of the structure by subtracting the current response from a baseline measurement taken when the state of the structure was known. However, this requires a very high degree of signal stability with time in the absence of damage, or a means to correct for benign changes such as differences in temperature. A temperature compensation scheme has been tested which shows considerable promise and further research is continuing to optimise its performance. However, there are still concerns about temperature gradients in the structure and also about other benign changes such as ageing or moisture uptake in adhesives; these would be localised to bondlines rather than uniformly distributed. There is therefore a great deal of research to be done before a reliable health monitoring system for complex structures can be realised.

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