MODE CONVERSION OF GUIDED WAVES BY DEFECTS IN PIPES

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INTRODUCTION

The corrosion of pipework is a major problem for the oil and gas and petro-chemical industries. Large facilities operate hundreds of kilometres of pipes which may carry corrosive substances. General wall-thinning and localised pitting corrosion can occur both from the inside and the outside of pipe walls. A high proportion of these pipes are insulated, so that even the external defects cannot be detected by conventional NDE techniques without the expense of removing of the insulation.

The authors are working on a project whose aim is to develop a guided wave testing technique for the inspection of such industrial pipework. The testing scheme employs a pulse-echo arrangement from a single location on a pipe, using cylindrical Lamb waves which are guided along the pipe wall. The presence and axial location of defects in the pipe wall are determined by any reflections and their arrival times. Since the energy in the waves is carried by the whole of the wall thickness, signals are reflected from defects at either the inside or the outside surface of the pipe. Clearly the technique requires the insulation to be removed only at the location where the transducers are attached. The original objective of the project was to detect any areas of corrosion larger than 3T x 3T in area and T/2 deep where T is the pipe wall thickness. The scope is for insulated pipe in the 2 -12 inch (51 - 305 mm) nominal bore diameter range and an inspection range of at least 15 m from the transducer position.

Previous work relating to the use of guided waves in pipes has been reported by other authors, for example in [1-4]. Substantial progress relating to the present project has also been made and reported [5-10]. This has included fundamental studies of wave interaction with defects, mode selection and the development of the test methodology, and the development of transducer technology. The success of the technique in site trials is reported elsewhere in these proceedings [10] and a commercial instrument is under development.

The technique uses a ring transducer [6] made up of mechanically-independent dry-coupled piezo-electric elements distributed around the circumference. By exciting all of the elements equally and concurrently, an axially symmetric mode is launched. The careful selection of a single mode is extremely important in order to have received signals which are interpretable. The complicated nature of the modal properties of pipes is clear from the example of group velocity dispersion curves for a 3 inch diameter, 5.5 mm wall thickness

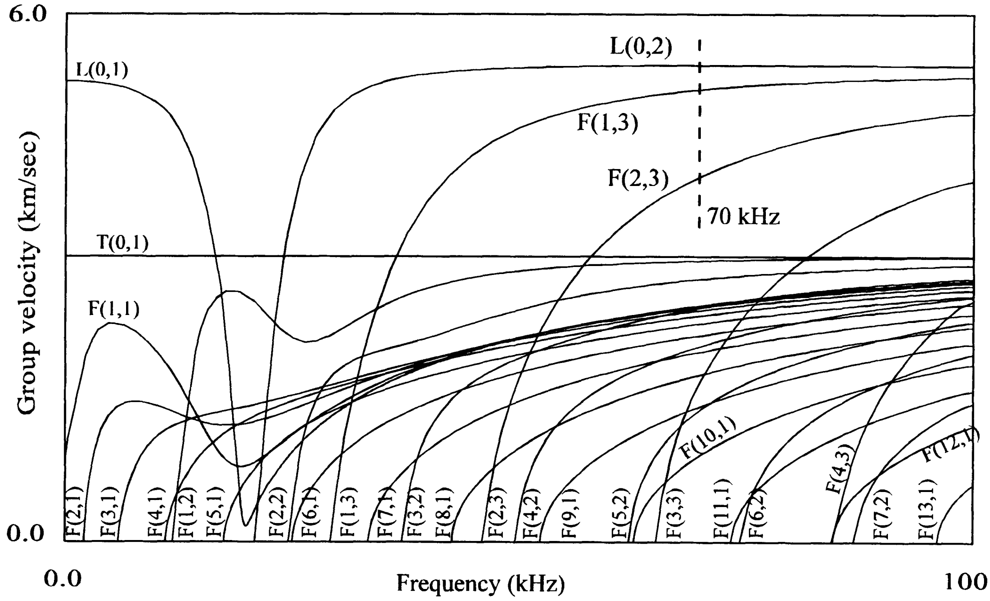

Figure 1. Group velocity dispersion curves for 3 inch diameter schedule 40 steel pipe.

pipe, in Fig 1. The modes are labelled after the convention of Silk and Bainton [1]; they include modes of longitudinal, flexural and torsional motion of the pipe wall, with axial symmetry or integer harmonics of variation around the circumference. Without giving a detailed description of the modes, it is sufficient here to note that the first integer of the integer pair in each mode label gives the harmonic order of circumferential variation; thus all modes whose first integer is zero are axially symmetric. The inspection technique uses a narrow-band excitation of the L(0,2) mode at a centre frequency of about 70 kHz, as indicated on the figure. This mode has the advantages of being non-dispersive and fast. Its deformation shape is extremely simple, consisting of axial membrane elongation of the pipe wall, with axial symmetry. For the 3 inch diameter pipe with 16 transducers around the circumference, no higher order modes can be excited. Excitation of the remaining unwanted mode, the L(0,1) mode (whose deformation shape consists of wall bending), is minimised by transducer design.

The aim of the work presented in this paper is to investigate the feasibility of utilising a mode which is not axially symmetric in order to improve the detection capabilities of the technique for some specific occurrences of defects. The problem arises when attempting to detect defects at locations where there are circumferential welds: the small changes in geometry at a circumferential weld are sufficient to reflect part of the test signal which thereby masks any reflection from a defect. The idea is to exploit the fact that the weld is approximately axially symmetric but a defect is invariably located at one side of the pipe and so is not axially symmetric. Therefore, for an incident L(0,2) mode, the weld will reflect only L(0,2), but at the same time, because a defect is not axially symmetric, it will reflect energy in higher order mode-converted modes in addition to L(0,2). Thus a measurement of reflected higher order modes could be used to indicate the presence of a defect without influence by the weld. This paper describes a fundamental study using both a laboratory experiment and a Finite Element simulation. The study examined the mode conversion behaviour from incident L(0,2) to reflected F(1,3) and F(2,3) modes (indicated on Fig 1) due to a part-circumference defect. Following this study, the discrimination capability of the technique was demonstrated using a second laboratory experiment with a welded pipe.

EXPERIMENTAL ARRANGEMENTS

The initial laboratory experiments were performed on a 2.6 m length of 3 inch, Schedule 40, steel pipe (internal diameter 76 mm, wall thickness 5.5 mm), illustrated in Fig 2. The aim was to measure the reflected wave modes from a through-thickness circumferentially-oriented notch for a range of lengths of the notch. Three rings of 16 transducers each were clamped to the pipe near end 'A' as shown, the use of multiple rings allowing the excitation of backward-travelling waves to be avoided [9]. An arbitrary function generator and power amplifier were used to generate a 5-cycle, 70 kHz toneburst modulated by a Hanning window, as input, and all of the elements on each transmitting ring were excited equally. The transducer elements on the receiver ring were wired separately so that the signal from each could be amplified and recorded independently. The signals were captured on a digital oscilloscope and 200 averages were taken for each measurement.

In order to obtain a reference measurement, reflections from end 'B' were recorded before introducing any defect to the pipe. A through-thickness circumferential notch was then machined 0.85 m from end 'B', using a 3.2 mm diameter slot drill cutter. For practical interest, such a notch could reasonably represent a circumferential crack because the precise nature of the crack tip is unimportant when the wavelength is long compared to the axial dimension of the notch [6,8]. Similarly, a region of wall loss due to corrosion whose axial extent is significantly less than the 80 mm wavelength would be represented. Furthermore, it may be possible to infer the behaviour due to part-through corrosion, by using the relationships which were established for reflection of the L(0,2) mode from part-through notches [8]. Measurements of the reflections from the notch were recorded for a range of different lengths of the notch, up to a maximum length of 50 % of the circumference.

Following these experiments and the analysis of the recorded signals, a second set of laboratory experiments was conducted using a welded pipe. The experimental procedure was essentially identical, except that the specimen consisted of two pipes joined end-to-end by a (typical) circumferential butt-weld. The average height of the weld profile above the pipe surface was 3 mm and the weld cap width was about 12 mm. The notch was machined at the axial location of the centre of the weld. The specimen length and the axial distances between transducers and notch were approximately the same as those in the initial experiments.

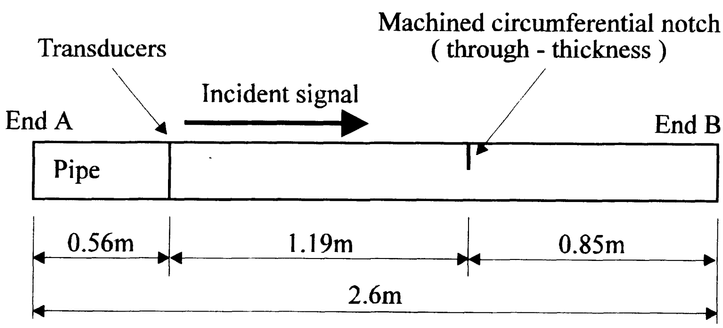

Figure 2. Experimental arrangement.

FINITE ELEMENT MODEL

A full Finite Element analysis of the interaction of guided waves in a pipe with discrete defects requires a three dimensional solid model which, though possible, is computationally intensive. However, it is often possible to perform meaningful analyses of three dimensional problems using reduced spatial domains. In this case it was possible to model the pipe accurately using a three dimensional membrane Finite Element model. The basis for such a simplification is the simple nature of the mode shapes of the incident L(0,2) mode and the reflected F(1,3) and F(2,3) modes at 70 kHz. All three modes are described accurately by membrane stresses and strains of the pipe wall. The justification is reasoned in detail in [8].

The model is illustrated in Fig 3. Half of the circumferential extent of a length of pipe was modelled, assuming one plane of symmetry. A mesh of identically-sized linear quadrilateral membrane elements was used, with 16 elements around the 180 degree circumference of the model. Explicit marching was employed in the time domain, assuming a diagonal mass matrix. Material damping is minimal in practice and was ignored in the model. A 5 cycle, 70 kHz toneburst in a Hanning window was chosen for the input, thus matching the experimental signal. The toneburst was applied as a sequence of prescribed displacements in the axial direction of the pipe, the same sequence being applied concurrently at all of the nodes around the circumference at one end of the pipe. The detection of the reflected waves was achieved simply by monitoring the axial displacements at a ring of nodes around the circumference, as indicated.

A series of analyses incorporating through-thickness notches of various circumferential lengths was conducted. In order to satisfy the symmetry which was implied by modelling only half of the pipe, half of the circumferential extent of each notch was defined, starting from the plane of symmetry. The notches were introduced very simply by disconnecting adjacent elements in the model. Such an approach yields accurate behaviour of the model in a global sense; there is inaccuracy only in the variation of the stress field very close to the notch roots [8].

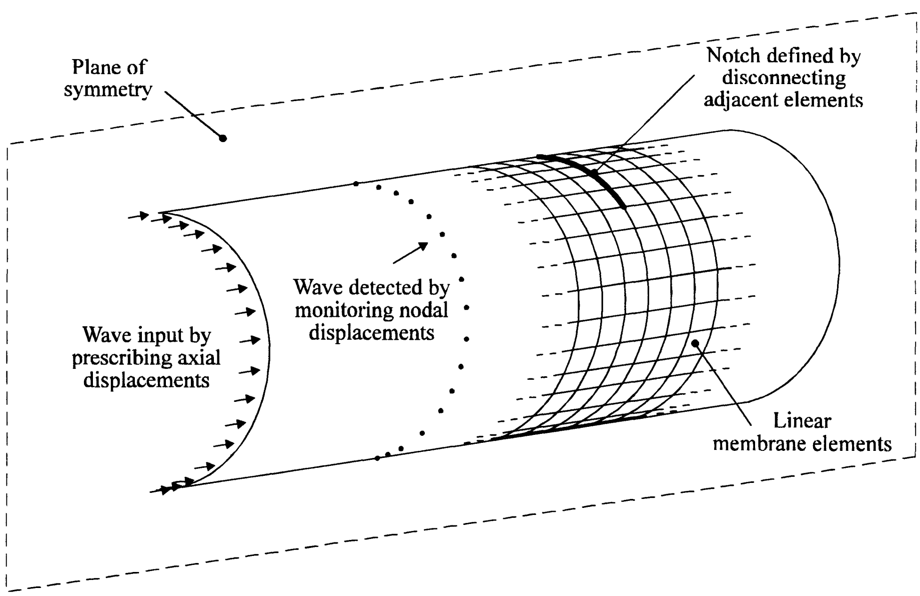

Figure 3. Finite Element model.

SIGNAL PROCESSING METHODOLOGY

The purpose of the signal processing was to determine the amplitudes of the mode-converted reflections from the notch. Considering the nature of the incident L(0,2) mode, and that the notch was through-thickness, it must be expected that only modes involving axial membrane motion should be excited. Thus the modes of interest for the mode conversion study were the F(1,3) mode and the F(2,3) mode. The displacements of the F(1,3) mode vary with one sinusoid around the circumference. This is the same distribution which would be found in the axial displacements if the pipe was subjected to gross bending. The displacements of the F(2,3) mode vary with two sinusoids around the circumference. At 70 kHz, the F(1,3) mode is slightly slower than the L(0,2) mode but reasonably non-dispersive; the F(2,3) mode is significantly slower and fairly dispersive.

An identical methodology was applied to both the experimental and the Finite Element results. For the reflection of the axially symmetric L(0,2) mode, the 16 individual signals from the transducers (or nodes) were simply added. The resulting signal was thus exactly as if the transducers were wired together, as reported in all previous studies of L(0,2) reflection. For the other two modes, a phase delay of $N\theta/2\pi$ was added to each signal before summing them. N is the circumferential order number and θ is the angular distance from the centre of the notch. Thus a separate processing calculation was performed in order to extract the amplitude of each of the three modes from the 16 transducer records. Since the signals were rather narrow-band, the processing could reasonably have been performed directly on the raw time records. However, for better accuracy, the calculations were performed in the frequency domain.

To present the results, the reflection coefficient was defined simply as the ratio of the amplitude of the reflected signal to the amplitude of the L(0,2) reference signal taken from the end of the pipe before introducing the notch.

RESULTS

A typical time record is plotted in Fig 4. This shows the received signal for the experiment when the notch extended around one eighth of the circumference of the pipe. The 16 channels of information have been processed to give the order 0 signal (i.e. they have simply been added without phase delay). The reflections from the notch and from end 'B' of the pipe are clearly present, and the non-dispersive nature of the L(0,2) mode is demonstrated by the consistent shape of the two reflections. The signal after the end reflection is due to multiple reflections and is not of interest.

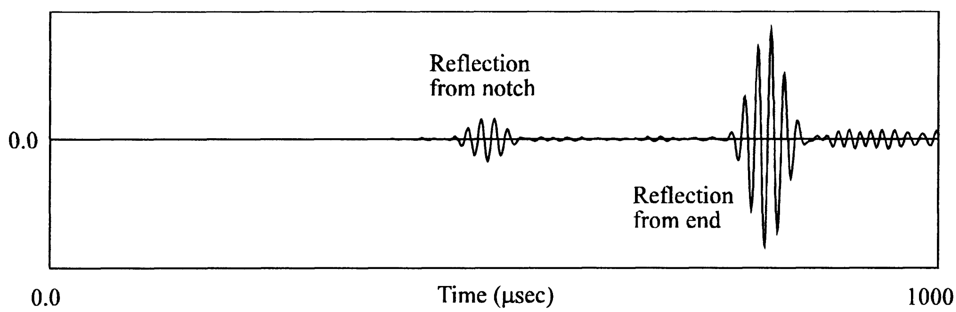

Figure 4. Typical time record: L(0,2) reflection (order 0) from a notch extending around one eighth of the circumference.

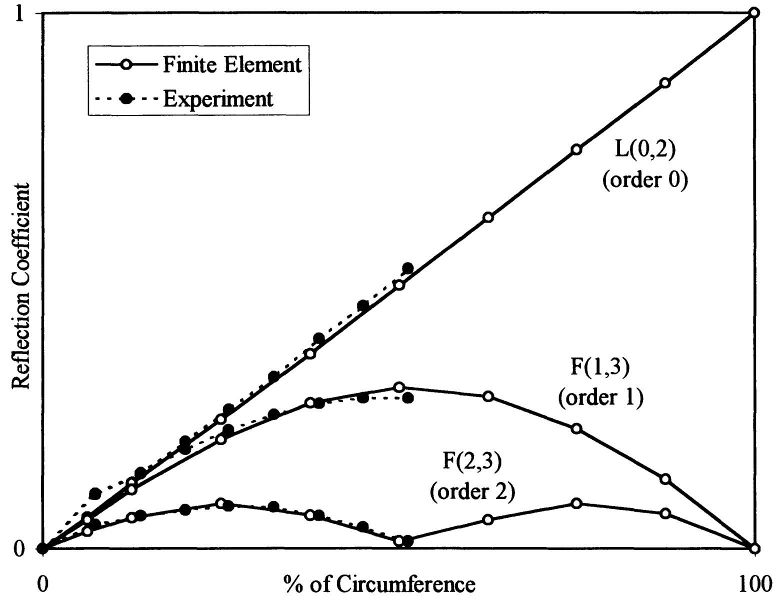

Figure 5. Measured and predicted reflection coefficients for a through-thickness notch in a 3 inch diameter pipe at 70 kHz as a function of the percentage circumferential extent.

The full results of the reflection study are shown in Fig 5. Good agreement is seen between the experimental measurements and the Finite Element predictions for all three modes. The reflection coefficient for the L(0,2) mode is seen to be rather linear with respect to the circumferential extent of the notch, exactly as reported previously [6-8]. The reflection coefficients for the F(1,3) and F(2,3) modes approximate to the shapes of rectified half-sine and sine waves respectively. The limiting values are intuitive: zero reflections of F(1,3) and F(2,3) should be expected for no notch or for a full-circumference notch; maximum reflection of F(1,3) should be expected for a 50 % notch. It is interesting, and encouraging, to observe that the reflections of F(1,3) are comparable to those of L(0,2) for short notches. This is the most important part of the diagram to wish for sensitivity for practical testing, and it appears that there is no loss in sensitivity here in using F(1,3) as an alternative to L(0,2).

Finally, the discrimination capability of exploiting the mode conversion is illustrated in Figs 6 and 7. These results are measurements from the second experiment, conducted on the pipe with the circumferential weld. All of the results are plotted on the same linear amplitude scale, for ease of comparison.

Fig 6 shows the reflections which were measured before introducing the notch. Part (a) shows the signal after processing for order 0; it therefore shows the axially symmetric component of the reflections. A strong reflection from the weld is evident, as should be expected because of its axial symmetry. Part (b) shows the signal after processing for order 1. Here it can be seen that there is almost no reflection from the weld, indicating as expected that there is very little mode conversion to the F(1,3) mode. However, some signal arrives later, suggesting that some order 1 energy is reflected from the end of the pipe. It is believed that this signal is due to differences between the strengths of coupling of the different transducer elements, introducing errors in the processing. Thus in this case there is 'leakage' from order 0 to order 1. This leakage is only pronounced when (as here) the axially symmetric signal is strong.

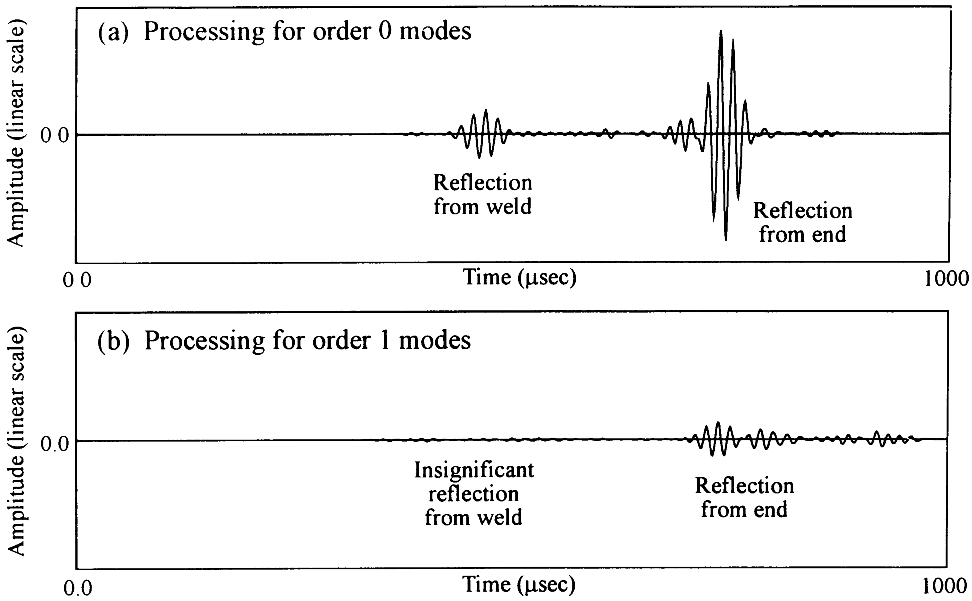

Figure 6. Reflections from weld, before introducing notch: (a) order 0, (b) order 1 processing

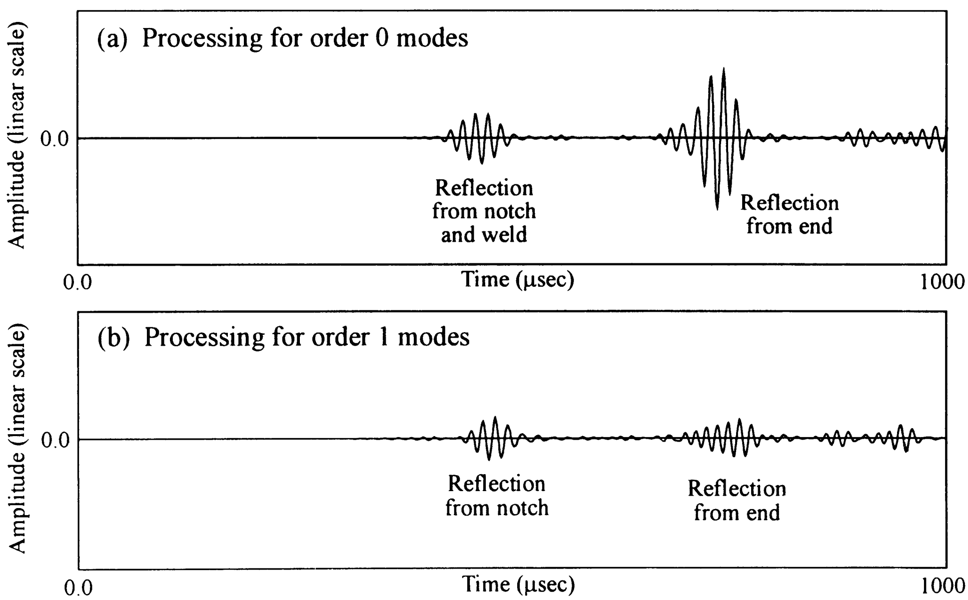

Figure 7. Reflections from weld with 1/8 circumference notch: (a) order 0, (b) order 1 processing

Fig 7 shows the reflections which were measured when a notch extending around one eighth of the circumference of the pipe was cut into the weld. Again part (a) shows the signal after processing for order 0 and part (b) shows the signal after processing for order 1. The reflection from the notch and weld in part (a) is similar in magnitude to that from the weld alone, in Fig 6(a), illustrating clearly that the order 0 mode cannot be used to discriminate between the two features. However, a clear reflection from the notch can now be seen, in part (b), when the order 1 processing is performed.

CONCLUSIONS

A series of experiments was conducted in which an axially symmetric mode was incident on a saw-cut which extended over part of the circumference of a pipe. The reflections of the axially symmetric mode and of mode-converted non-axially-symmetric modes were measured as the circumferential extent of the cut was increased. In parallel, Finite Element simulations of all of the experiments were performed. Excellent agreement was found between the experimental and the predicted results.

The implications of the study are that mode-conversion in reflection from the axially symmetric L(0,2) mode to the harmonic order 1 mode F(1,3) could be used in order to discriminate between axially symmetric reflectors such as circumferential welds and any non-axially-symmetric defects. As a demonstration, it was shown that the presence or absence of a notch at the same axial location as a circumferential weld could be determined from the mode converted signal.

Future work will address the optimisation of the technique for practical applications. This will include the feasibility of reducing the number of channels of information and the processing of mode-converted signals without prior knowledge of the angular orientation of defects.

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