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419

Guided Wave Flexural Mode Tuning and Focusing for Pipe Testing

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ABSTRACT

Beam focusing potential for ultrasonic guided wave testing of pipes is discussed. Natural focusing with nonaxisymmetric wave impingement is studied along with circumferential phased array focusing. A frequency tuning exercise with a new signal display is presented, as are a few sample experiments.
Keywords: *guided waves, flexural modes, beam focusing, pipe testing.*

INTRODUCTION

Ultrasonic guided wave techniques have been developed for the rapid survey of pipes for the detection of both internal and external corrosion. The primary advantage is that long lengths, 30 m (98 ft) or more in each direction, may be examined from a single test point. Other benefits are:

- a reduction in the costs of gaining access to the pipes for testing as well as avoidance of removal and reinstallation of insulation (where present), except for the area on which the transducers are mounted
- the ability to test inaccessible areas, such as sleeved or buried pipes and areas under clamps
- that the entirety of the pipe wall is tested.

Long range ultrasonic testing was introduced in 1998 for the in service monitoring of pipes and pipelines (Mudge and Lank, 1997). It is predominantly used by the oil and gas industry for the detection of corrosion and other metal loss discontinuities and is becoming widely accepted as a valid means of assessing the condition of pipes and pipelines.

The principle of the technique is that guided waves may propagate over long distances in metals with minimal attenuation and are reflected from discontinuities. Thus, it is feasible to examine many tens of meters of pipe from a single test point by detecting the reflections from features and discontinuities in the pipe wall.

An example of the effectiveness of this approach is shown in Figure 1a. This was a 0.3 m (10 in.) diameter buried line, examined from a bell hole excavation. The trace shows a discontinuity, characterized by the mode converted signals at 25.6 m (84 ft) from the transducer location. Subsequent excavation revealed severe corrosion at a field butt weld where the protective coating had failed.

Performance Demonstration

For any novel testing technique, it is vital that the capabilities and limitations for detection and testing of discontinuities are known, so that users are able to use the results with confidence. The smallest area of metal loss which long range ultrasonic testing can detect is approximately 3% of the pipe wall cross section. The probability of detection increases as the area of the discontinuity becomes larger. This performance was demonstrated by tests within a joint European project managed by University College London (1999). A major part of this was the gathering of NDT data from controlled corroded pipe specimens using eight different methods in order to determine their detection and testing performance. The blind trials were conducted without prior knowledge of the discontinuities present and the results were tested by an independent team from Bureau Veritas, Paris. Figure 1b shows the results on 36 individual discontinuities. The plot is in terms of depth and circumferential extent of the discontinuities and indicates whether each was detected or not. The lines representing 3% and 9% of the discontinuity area for the 0.2 m (8 in.) diameter pipes tested are also included.

From the figure it is clear that the limit of detection is clearly at the 3% level, with virtually no successful detections below this size. The data show the classic probability of detection characteristics,

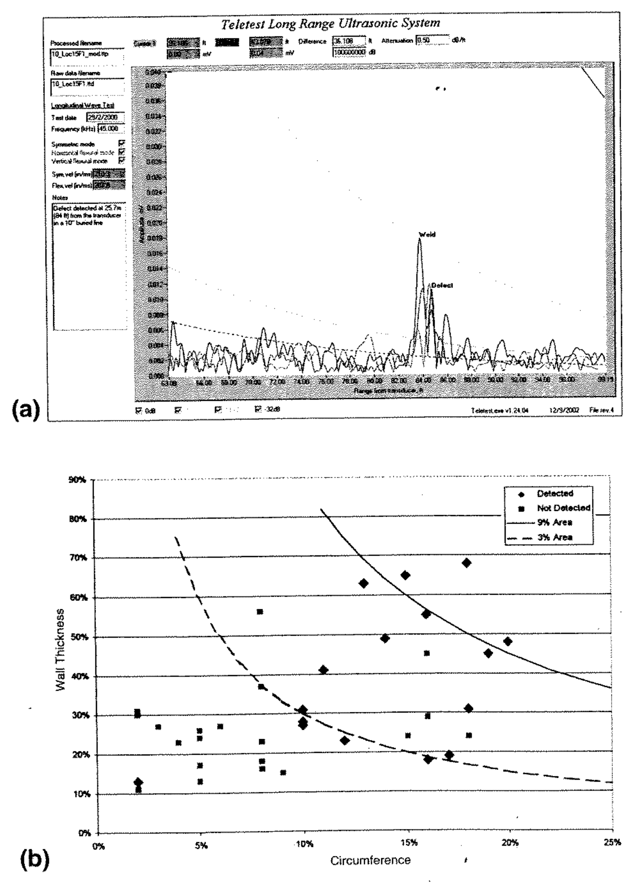

Figure 1 — Results from pipe testing with guided waves on: (a) 0.3 m (10 in.) buried pipeline; (b) 0.2 m (0.7 ft) diameter pipes from the reliability assessment for containment of hazardous materials project.

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with an increasing likelihood of detection within the area above the 3% level. All discontinuities examined which were around or greater than the 9% reporting level were detected. These results demonstrate that the performance of the technique, determined from open tests on known specimens, could be reproduced when testing real corroded pipes with unknown (internal) discontinuities. Thus these tests provide valuable evidence of the performance level which may be expected in the field.

However, the long range guided wave techniques as they stand today provide only a basic screening facility. Once a discontinuity has been detected, further tests are required to identify the nature of the degradation and its severity. There is now a considerable need for the capability to be enhanced so that more quantitative information may be obtained about degradation in inaccessible pipes.

A new guided wave test instrument for pipe testing that goes beyond the equipment that is being used today is being developed to add a focusing capability. Traditional C-scan tests that provide a planar cross sectional view of a structure were revolutionized by the introduction of focused ultrasonic transducers in image generation with extraordinary resolution over 30 years ago. Over twenty years ago, linear phased arrays for the medical field were developed to improve B-scan imaging of cross sectional views of the human body. It led to a breakthrough in medical imaging and diagnostic capability. It is now proposed to focus ultrasonic energy inside a pipe that moves the focal point both circumferentially and axially along an entire section of pipe. Focusing in a pipe is much more difficult to do compared to C-scan tests and phased array applications inside the human body because of the pipe wall boundaries. Waves constantly superimpose on each other as a result of boundary reflections and mode conversion.

Focusing can improve discontinuity detection sensitivity by finding smaller discontinuities since focused beams have larger amplitudes and improved signal to noise ratios. Additionally, the maximum range of testing from a single access point can be increased.

Reference material on guided waves in pipe testing can be found in Rose (2002). A few references directly related to focusing and phased arrays can be found in Zhu and Rose (1999), Li and Rose (2001a), Li and Rose (2001b), Wooh and Shi (2001), Li and Rose (2002) and Hayashi et al. (in press).

The next generation of guided wave units will have the capability of generating both lamb type and torsional wave modes, axisymmetric and nonaxisymmetric wave modes, a frequency tuning ability, an improved and efficient signal display, natural focusing via circumferential segment loading and forced focusing via time delay profiling of the elements around the circumference. This leads to all sorts of flexibility in data acquisition and overall test capabilities with improved sensitivities and penetration power. A few sample laboratory experiments are included to illustrate some capabilities of the new instrument. Some topics are taken from Rose (2002) and Lebsack and Rose (2002).

Let's now consider three topics: a natural focusing problem, a phased array situation and a frequency tuning new signal presentation technique to get some ideas of future sensor and instrumentation capability.

GUIDED WAVES FOR AXIAL 180 DEGREE TESTING

Quite often, access to the far side of a pipe structure is not possible. As an example, consider a boiler tube when the boiler is in service. Newly developed guided wave techniques make it possible to find discontinuities on the far side at various axial distances via nonaxisymmetric waves (flexural waves) impingement onto a discontinuity. With partial loading around a circumference, flexural modes are introduced. The tubular structure, via wave superposition as it travels down the pipe, leads to unusual circumferential profiles where energy on the far side is possible via the correct phase velocity, frequency and degree of partial loading. This leads to a natural focusing phenomenon. Figures 2a and 2b provide an example (Li and Rose, 2001a). A sample experiment illustrates this phenomenon. Figures 3a and 3b show typical waveforms. In this case, by frequency tuning alone, the discontinuity can be found on

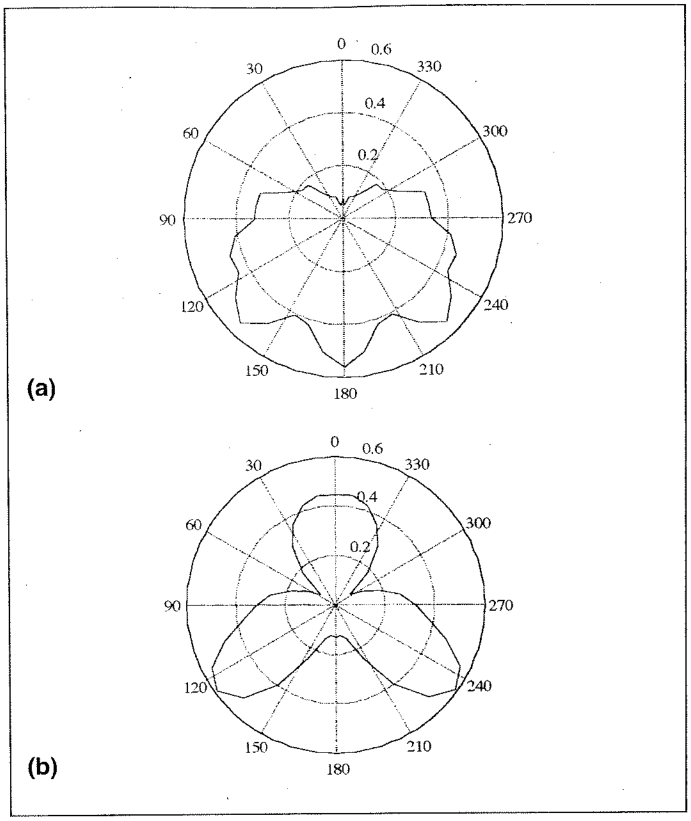

Figure 2 — Possible circumferential displacement distribution in a steel pipe — note that in this case a discontinuity on the bottom of the pipe at an axial distance Z = 4 m (13 ft) can be found if using 250 kHz but will be missed if using 350 kHz: (a) Z = 4 m (13 ft), f = 250 kHz (maximum point); (b) Z = 4 m (13 ft), f = 350 kHz (minimum point).

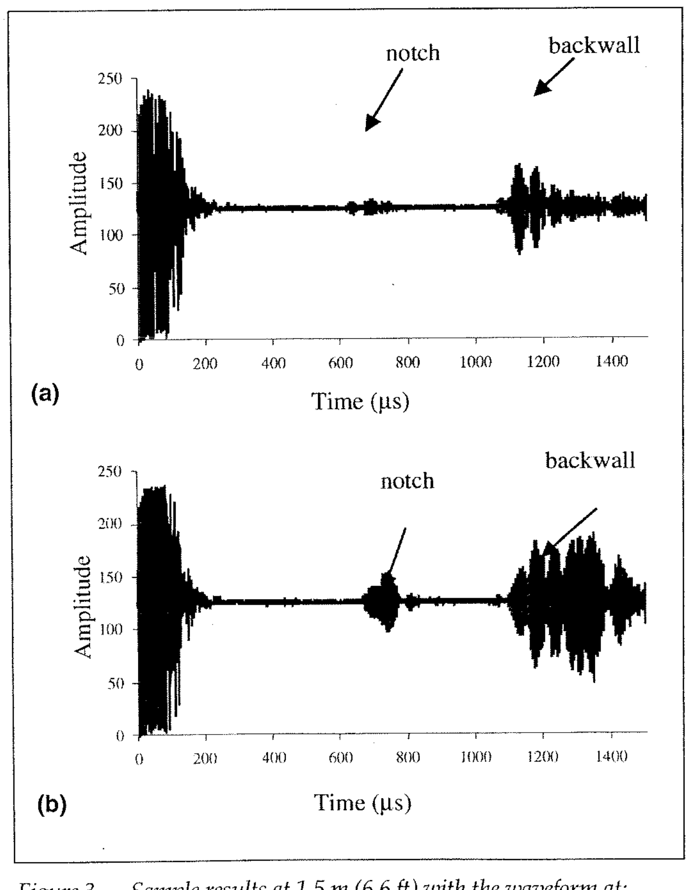

Figure 3 — Sample results at 1.5 m (6.6 ft) with the waveform at: (a) 290 kHz; (b) a tuned frequency of 340 kHz.

the far side. Tuned frequency results versus axial distance away from the discontinuity is shown in Figure 4a followed by the actual reflected amplitudes versus axial distance in Figure 4b. Note that the amplitude at the tuned frequency is always larger than the amplitude results for a prescribed frequency.

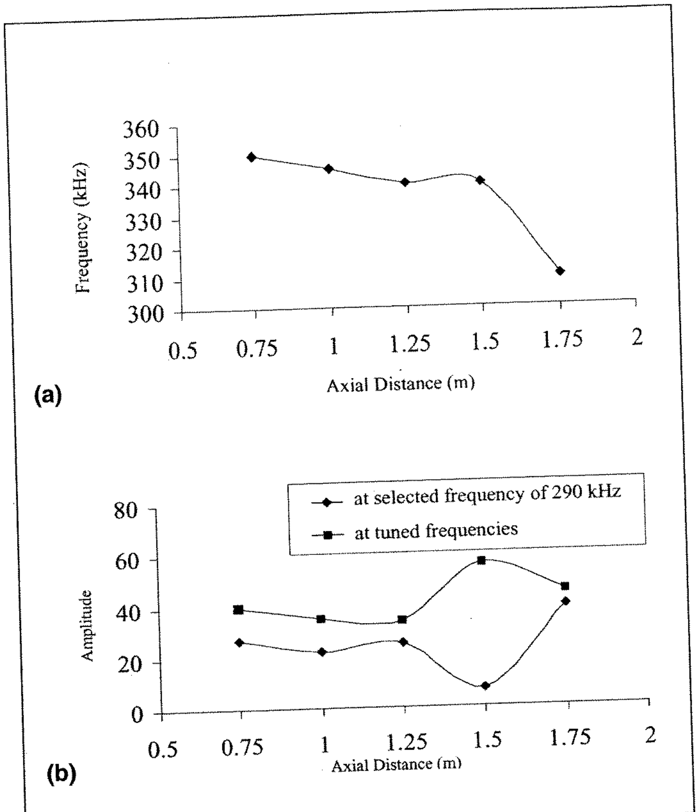

Figure 4 — Results for: (a) best tuned frequency values versus axial distance; (b) discontinuity echo amplitude versus axial distance for tuned and untuned initial frequency choice.

STRAIGHT PIPE FOCUSING WITH A CIRCUMFERENTIAL PHASED ARRAY

Guided wave pipe testing to date relies on axisymmetric lamb type or torsional mode generation from a series of sensors mounted circumferentially 360 degrees around a pipe. With the use of nonaxisymmetric or flexural mode impingement it becomes possible to naturally focus ultrasonic energy in a pipe. The natural focusing technique can be significantly improved by using a phased array concept (Li and Rose, 2001b; Li and Rose, 2002). The sensitivity can increase significantly, hence some modes can find smaller discontinuities; we could say that the effective range from a single access point can be increased when considering the same size discontinuity (telescoping). A few sample experiments are presented to illustrate this focusing effect.

Figure 5 shows the experimental configuration with a steel pipe of 91 mm (3.6 in.) outer diameter, 76 mm (3 in.) inner diameter and a wall size of 7.9 mm (0.3 in.). The theoretical profile at 1.75 m (68.9 in.) when using only a single transducer at 0 degrees has maximum values located at the 0 degree and 180 degree positions (top and bottom, respectively). Since we have eight transmitting transducers, we can examine eight experimental profiles. Figures 6a through 6h show these. The agreement with theory is excellent. The 4 degree rotations from one transducer to its counterclockwise neighbor are quite apparent and as expected. Sample waveforms are illustrated in Figures 7a through 7h. Again, note the excellent results at the 0 degree and 180 degree locations, which coincide with theoretical

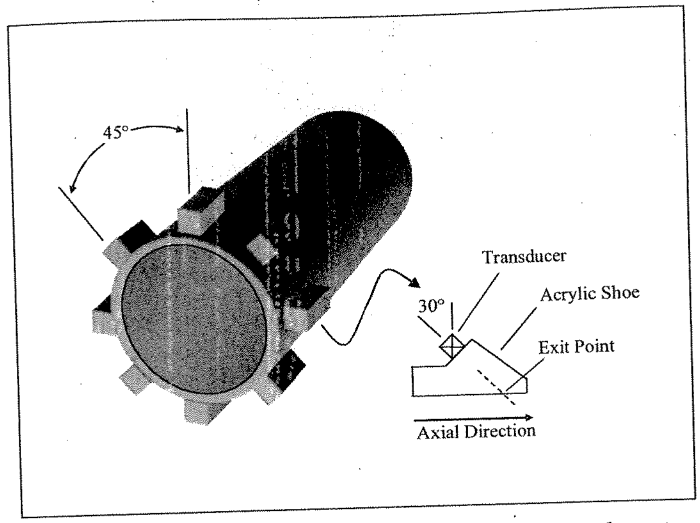

Figure 5 — Circumferential locations of the eight transducer elements. The inset shows the configuration of each element. The excitation frequency was 290 kHz.

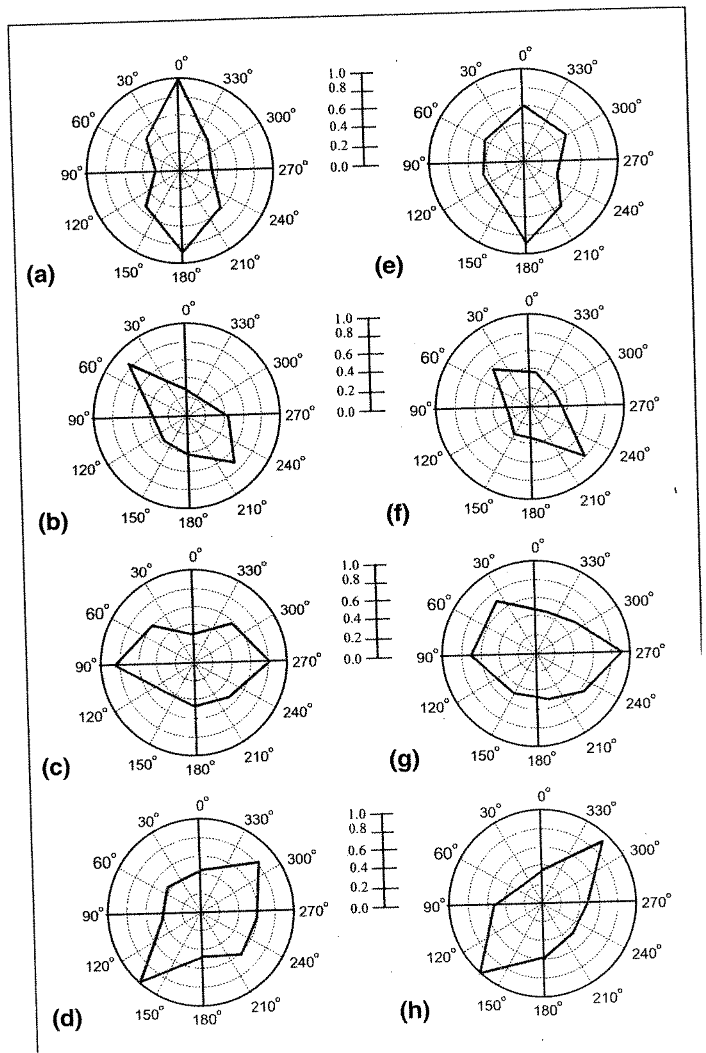

Figure 6 — Profiles of experimental data obtained from eight separate individually pulsed transducers distributed at 45 degree intervals around a 76 mm (3 in.) pipe — a receiver, located 2 m (69 in.) away from each transducer, was used to gather the data: (a) channel one; (b) channel two; (c) channel three; (d) channel four; (e) channel five; (f) channel six; (g) channel seven; (h) channel eight.

predictions. A similar result can be obtained by using axisymmetric impingement but with individual receiving channels. The result is not quite as good as that shown in Figures 7a through 7h, however, with respect to notch amplitude. The summed response of all eight elements is shown in Figure 8a. The resulting response when using calculated time delays (a delay per transducer) is shown in Figure 8b. The notch echo amplitude increased by 2.3 and the backwall echo was reduced to 0.4 of its amplitude when time delay profiling was used. Additionally, when comparing these results against a single element transducer, a tenfold increase in amplitude was realized.

The summed response, when using time delay profiling, shows a significant improvement in the amplitude of the notch echo and the overall signal to noise ratio. The specific time delay and amplitude adjustments to achieve this are shown in Table 1. The computational details for obtaining such a set of values can be found in Li and Rose (2001b) and Li and Rose (2002).

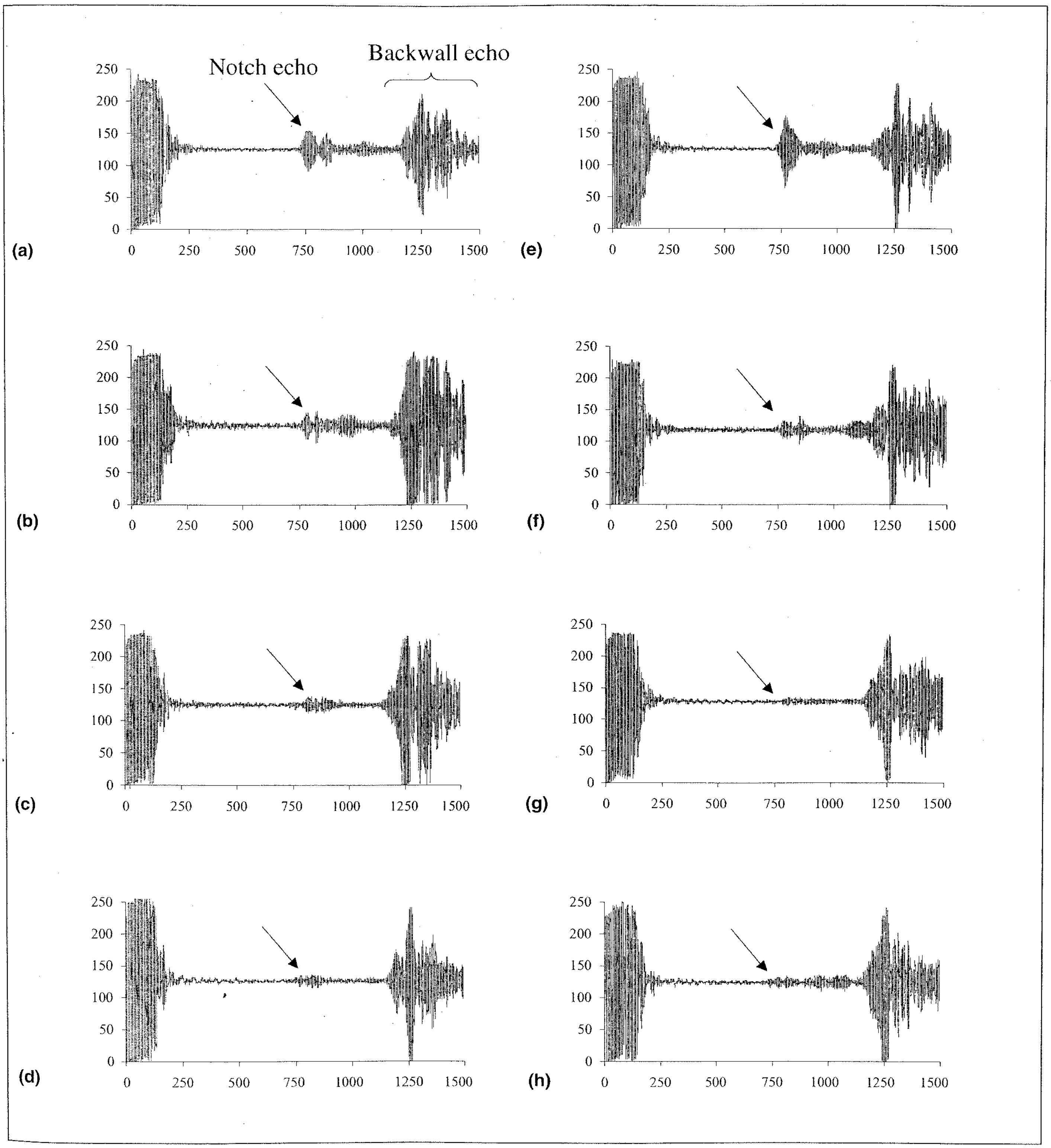

Figure 7 — Pulse echo results from a 34% through wall notch (saw cut) in the 180 degree position when each of the eight transducer elements were individually excited and also used as receivers (the small arrows designate the notch echo in each case): (a) channel one at 0 degrees; (b) channel two at 45 degrees; (c) channel three at 90 degrees; (d) channel four at 135 degrees; (e) channel five at 180 degrees; (f) channel six at 225 degrees; (g) channel seven at 270 degrees; (h) channel eight at 315 degrees.

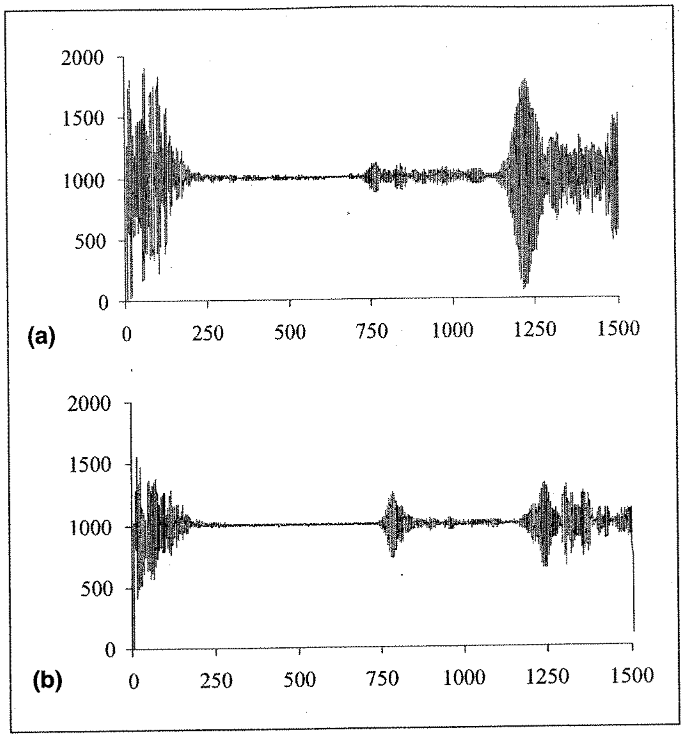

Figure 8 — Summed pulse echo responses of all eight transducer elements: (a) without time delay profiling — the notch echo amplitude was 219 and the backwall echo amplitude was 1707; (b) with time delay profiling — the notch echo amplitude was 512 and the backwall echo amplitude was 696.

Table 1 Time delay schedule for focusing at 0 degrees and 1.75 m (5.7 ft)

Channel	Amplitude	Time Delay
1	1.000	0.000 μs
2	0.346	0.956 μs
3	0.132	1.606 μs
4	0.398	0.044 μs
5	0.965	2.573 μs
6	0.398	0.044 μs
7	0.132	1.606 μs
8	0.346	0.956 μs

RESONANCE TUNING FOR IMPROVED DISCONTINUITY DETECTION

Frequency tuning for 360 degree axisymmetric loading can enhance discontinuity detection analysis to the point of making positive calls with great confidence. At a fixed frequency, large discontinuities can usually be seen, but smaller discontinuities could be missed as they could be buried in a noisy signal display. Even making a call on larger discontinuities is simplified. Two examples demonstrate this tuning phenomenon. The experiment is conducted on two discontinuity types. See Barshinger et al. (2002) for details. A frequency scan from 100 to 675 kHz was carried out with a 500 kHz piezocomposite broad band circumferential array of angle beam transducers pulsed to produce an axisymmetric waveform. The single round bottom hole is best seen at 275 kHz and the cluster at several frequencies, best from 300 kHz to 350 kHz. The amplitudes over the complete frequency range is illustrated in Figures 9a and 9b. Obviously, many frequency values work well, but some are better than others. Frequency tuning helps us determine which ones work best.

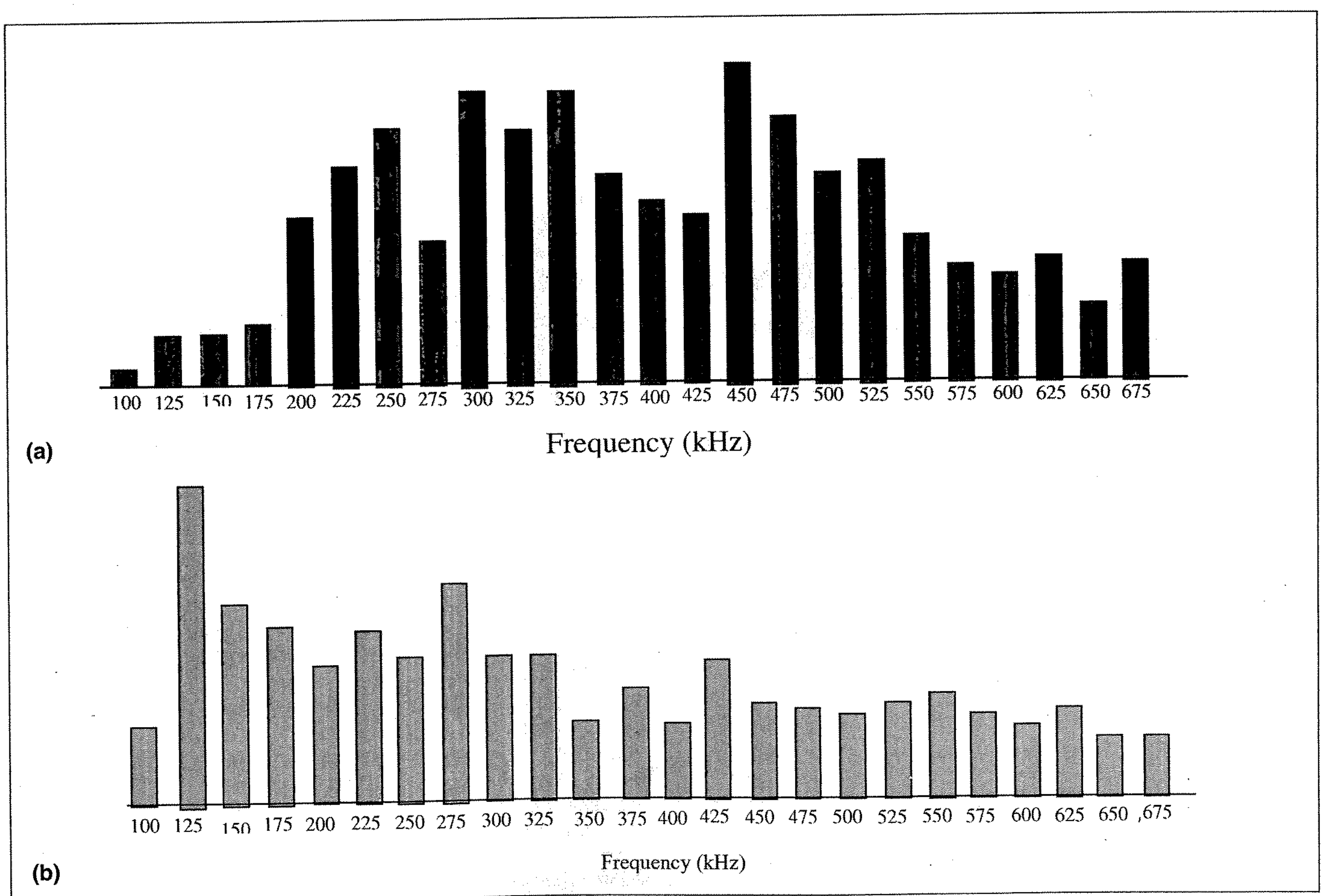

Figure 9 — Amplitude versus frequency distribution of discontinuity echoes over the range of 100 to 675 kHz: (a) seven hole cluster; (b) single round bottomed hole.

An interesting signal display enhancement procedure is being studied to simplify the analysis by preparing a single display that incorporates the information from all of the frequencies studied.

The goal of the study was to present a single signal display from frequency tuning rather than study tens or hundreds of signals acquired at different frequencies. Many signal processing routines will be considered but one very encouraging sample result is presented here.

To illustrate the concept of display enhancement, an algorithm was constructed and applied to an ensemble of 100 waveforms. Varying the excitation frequency to a circumferential array transducer from 205 kHz to 700 kHz in 5 kHz increments and recording the responses generated the waveform ensemble.

Each waveform spanned 8192 points. For processing, the main bang and the back wall echo were removed. The amplitude of each time coordinate of the remaining portion of each waveform was examined and the maximum amplitude used as the amplitude at the selected time coordinate. Finally, the array of maximum amplitudes was squared. Figures 10a and 10b show the results.

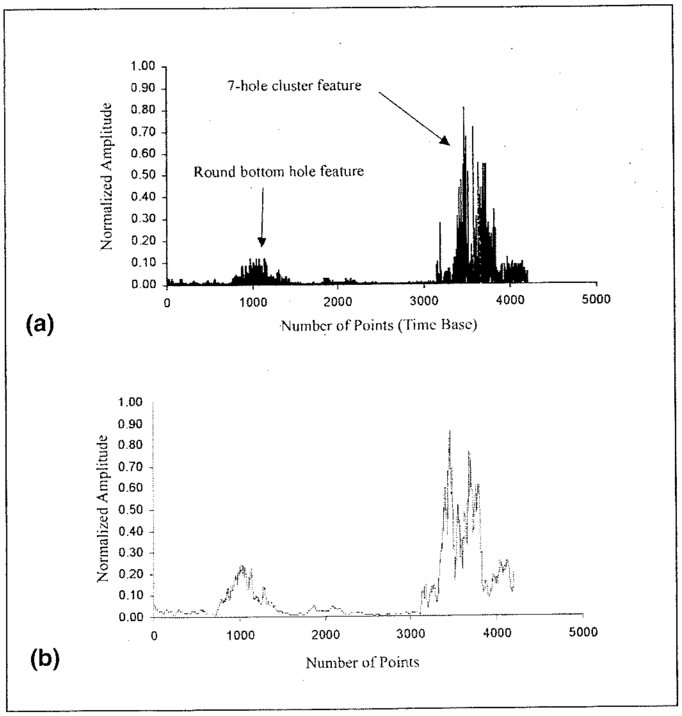

Figure 10 — A single signal display obtained as a result of superimposing 100 waveforms, each at a different frequency from 205 to 700 kHz, saving the maximum value at each time increment and then squaring them: (a) normal version; (b) low-pass filtered version.

CONCLUDING REMARKS

Guided waves via a four dimensional tuning process of adjusting circumferential loading length, circumferential position, phase and frequency, can create a natural focusing effect almost anywhere inside a pipe. It gives us the ability to find discontinuities all over the pipe from a fixed transducer excitation position. Further improvements in focusing can be made by applying phased array technology around the circumference of a pipe. Only a few examples were presented to illustrate the influence of a countless number of testing possibilities. In addition, the value of frequency tuning is clearly demonstrated along with a new single display presentation as a consequence of frequency tuning.

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