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The scattering of torsional guided waves from Gaussian rough surfaces in pipework

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In older sections of industrial pipework there are often regions of general corrosion that typically have a Gaussian thickness distribution. During guided wave inspection this corrosion causes an increase in the background noise and a significant attenuation of the inspection wave. These effects are investigated in this paper through finite element modelling of the interaction of torsional guided waves with rough surfaces in pipes. Pipes of different diameter and rough surface profile are modelled and it is found that the attenuation of waves is explained by significant mode conversion and scattering within the rough surface. This mode conversion is greatest when the non-axisymmetric modes to which energy is scattered are close to the cutoff frequency or when the ratio of surface correlation length to wavelength is around 0.2–0.25. Mode conversion increases with increasing surface roughness and is a strong function of frequency–diameter product, with larger pipes causing more mode conversion. When this mode conversion occurs the energy is lost mostly to those waves with a displacement profile closest to the original torsional inspection wave. Resulting attenuation of the inspection signal can be severe; for example a mean wall thickness loss of 28% can cause 2.7 dB/m attenuation in a pulse-echo configuration. © 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

I. INTRODUCTION

Long range guided wave testing is a low frequency (<100 kHz) ultrasonic technique for non-destructive evaluation. Although used in a number of industries the technique has found particular application in the oil and gas industry for inspecting pipework. Using the walls of the pipe as a waveguide, a guided wave will travel along the pipe axis with very low attenuation and full volumetric coverage. This makes it especially suited to long range screening applications where a small number of sensors can be used to monitor a long length of pipe; a single sensor can routinely inspect more than 50 m of pipe from a single location. This coverage does, however, come at the expense of lower sensitivity and this type of sensor is, therefore, typically used alongside a localised, high accuracy technique such as ultrasonic thickness gauging to follow up on the areas guided wave inspection has highlighted as suspect.

Considerable research effort has gone into improving the range and sensitivity of guided wave inspections. In pipelines, much of this research has focused on understanding the interaction of guided waves with different types of pipe feature such as supports, notches, holes and complex defect profiles. However, little research effort has gone into understanding the interaction of guided waves with general corrosion. General corrosion is important because evidence from the field suggests that this type of defect causes significant scattering of incident waves, leading to increases in the background noise in the reflected signal and increased attenuation of the inspection wave. These two effects are clearly shown in Fig. 1, an example guided wave signal from a laboratory test on a clean section of 3 in. pipe with a 30 yr old generally corroded section welded to one end. An increase in the background noise is an issue because it may mask the reflection from more severe localised defects within the generally corroded area, thereby reducing sensitivity. Attenuation is an issue because it reduces the energy reaching features beyond the corrosion and hence reduces the effective inspection range (note for example how in Fig. 1 the reflection from the weld beyond the corroded section is greatly reduced). Another interesting phenomenon from industrial signals is that the attenuation of the T(0,1) inspection wave is greater than would be expected from the energy in the scattered T(0,1) background noise. The weld reflection after the corrosion is a factor of four smaller than the weld reflection before the corrosion, with a maximum reflection within the corrosion patch around 10% of the initial weld reflection. Given that energy is related to the square of amplitude, there is clearly energy being lost between the two welds which is not presenting as reflected T(0,1) energy from the corrosion patch. This effect has never been satisfactorily explained.

The ubiquity of this wave–rough surface interaction problem has led to studies in a number of fields, including radar, astrophysics, and ultrasonics. In ultrasonics, solution procedures are usually split into analytical solutions with several simplifications or full solutions based on numerical methods. Studies have looked at a range of different
surface types but are largely confined to bulk ultrasonic waves. The problem of guided wave interaction with rough surfaces has received much less attention. Important work in this area was performed by Chimenti and Lobkis, who looked at guided wave interaction with rough surfaces in plates. Their analytical approach is based on a phase screen approximation first introduced by Eckart and ignores amplitude effects of the scattering and considers all influence to be felt in the signal phase. Their work achieved generally good agreement between model and experiment but was, due to the approximations used, a partial treatment.

Recent advances in computing power mean that full three dimensional (3D) simulations of guided wave propagation in long lengths of pipe are now feasible. This paper makes use of these recent advances to carry out a full 3D parametric study of the effect of roughness on guided wave propagation. The approach used in this paper does not rely on the simplifications of the earlier analytical treatments and allows new physical insights into the mode conversion caused by rough surfaces. The effect of several parameters is investigated, including the correlation length of the surface, the surface roughness, the inspection wave frequency and the pipe diameter. This requires multiple large finite element models to be constructed; a typical model used in this study contains $\sim 6 \times 10^6$ degrees of freedom. Section II introduces the finite element modelling procedure which allows multiple models of this size to be constructed and solved and also considers the morphology of the rough surfaces, starting with an analysis of a corrosion patch from industry. Section III shows how the energy in a $T(0,1)$ guided wave scatters when it interacts with a rough surface and how this scattering is a function of several parameters. Section IV then describes validation of the simulations and conclusions are drawn in Sec. V.

II. METHOD

A. Model

Most of the work in this study was on a 6 in. schedule 40 pipe (a common size in the oil and gas industry), 168 mm outer diameter with a wall thickness of 7 mm and a length of 4.0 m. Initially, all regions of the pipe were given the properties of a non-attenuative mild steel. Youngs Modulus of 207 GPa, Poisson’s ratio of 0.27 and density of 7900 kg/m$^3$. The pipe was then grouped into five sections along the length as shown in Fig. 1, with two sections of absorbing region, two monitoring regions and a region of general corrosion. The absorbing regions were 0.3 m long and were set up following Pettit et al.; the stiffness and damping properties of the model were varied to attenuate any waves passing into these regions, in this way providing a convenient approximation for an infinitely long section of pipe.

The corroded region was modelled as a change in geometry of the inner surface so that it followed a given rough surface profile. Although the inner surface was chosen for convenience, the torsional wave used in this study has a similar stress profile through the thickness, and hence results will be very similar for corrosion on the outside surface. This rough surface was based on the parameters of corrosion surfaces seen in industry, with an example industrial corrosion patch shown in Fig. 3. This surface comes from a length of steel pipe with general corrosion around the full circumference of the pipe and along a 1 m axial length, caused by intermittent wetting of the surface. A thickness loss map for the corrosion patch is shown in Fig. 3(a), where the profile has been measured using a bulk wave ultrasonic thickness probe on a 1 mm grid. To obtain the distribution of this surface the corrosion depths were ordered into the histogram shown in Fig. 3(c). Different distributions were fitted to the data and it was found that a normal distribution with a mean of 1.5 mm and a standard deviation of 0.75 mm gave the best fit. The probability density function for such a distribution is shown in Fig. 3(e) for comparison. The use of a Gaussian distribution to model general corrosion is supported in the literature, where several industrial corrosion patches have been found to follow this type of distribution (although it is noted that experimentally it is possible to misinterpret exponential distributions as Gaussian). The correlation length of the corrosion surface was then calculated, defined as the offset distance at which the autocorrelation drops to $1/e$ of the autocorrelation at zero offset. The autocorrelation for the industrial corrosion surface is shown in Fig. 3(b), where the correlation length around the circumference is approximately 10 mm while the correlation length along the axis is approximately 30 mm. From this analysis it was concluded that the rough surface should be modelled as a Gaussian random surface, with a mean depth of the order 1.5 mm and correlation lengths of the order 30 mm.

Simulated rough surfaces were then generated based on an initial random grid drawn from a Gaussian distribution supported in the literature, where several industrial corrosion patches have been found to follow this type of distribution (although it is noted that experimentally it is possible to misinterpret exponential distributions as Gaussian). The correlation length of the corrosion surface was then calculated, defined as the offset distance at which the autocorrelation drops to $1/e$ of the autocorrelation at zero offset. The autocorrelation for the industrial corrosion surface is shown in Fig. 3(b), where the correlation length around the circumference is approximately 10 mm while the correlation length along the axis is approximately 30 mm. From this analysis it was concluded that the rough surface should be modelled as a Gaussian random surface, with a mean depth of the order 1.5 mm and correlation lengths of the order 30 mm.
with a mean $e$ and a standard deviation one third of the mean $\sigma = (1/3)e$, which means that surface roughness and surface mean depth are directly linked. To give this surface a specified correlation length the grid was then convolved with a 3D Gaussian distribution with a characteristic length which is defined as the distance from the peak at which the amplitude of the distribution drops to $1/e$ of the maximum. This gave rough surfaces such as that shown in Fig. 4(a), an example surface with a mean depth of 1.25 mm and correlation length of 20 mm. As shown in Fig. 4(c) the surface has a Gaussian distribution, although the left tail is distorted due to the fact that all depths less than zero have been set to zero. This was done because corrosion has been modelled here as a thickness loss only. The autocorrelation of the surface is shown in Fig. 4(b), with a correlation length of 20 mm around the circumference and along the axis.

The pipe model was then discretised into tetrahedral elements with a characteristic length of 2 mm using an implementation of the Netgen algorithm in the Gmsh software. This element characteristic length was chosen from a convergence study which showed that 2 mm elements were sufficient for the frequencies and corrosion geometries used in this study. The minimum wavelength in the model was 60 mm, calculated as the minimum wavelength for all modes which can exist in the pipe over the frequency range used in this study. This is well within the criteria usually used for finite element modelling of guided waves, which in general states there should be 10–30 elements per wavelength depending on the type of wave modelled. The minimum rough surface correlation length was 7 mm, meaning in the worst case there were four elements per correlation length. Therefore, in our model the key parameter that determined element size was the resolution with which the rough surface was modelled, rather than a limit on the element size for correct simulation of guided wave propagation. Note that at this element size a typical pipe model will have $\sim 6 \times 10^6$ degrees of freedom. The rough surface could then be applied to the pipe model by adjusting mesh node position, with the mesh smoothing algorithm in Gmsh used to minimise mesh distortion. Some example cross sections along the length of the pipe are shown in Fig. 5. This figure clearly shows the distortion introduced on the pipe inner surface by the simulated general corrosion.

The final stage in setting up the model was to select nodes to excite and measure guided waves. A ring of 50 nodes were selected 0.31 m from one end and these nodes designated as the source nodes. Each source node was then excited using a force tangential to the pipe surface, with the magnitude of the force...
behaviour and so at each condition 10 models were run multiple models at each condition to determine mean. However, since the rough surfaces are random it is necessary.

depths, each under 15 different correlation lengths. This then gave a total of 45 model conditions to solve; three corrosion thickness loss) and 15 different correlation lengths, from 1.25 mm (18% wall thickness loss), and 2.00 mm (28% wall depths and correlation lengths, with the study looking at mean depth 1.5 mm. The pipe shown has a smaller diameter than most

of the pipes used in this study so wall thickness variations can be seen more clearly. Cross sections are shown at the following distances into the rough surface region of the model (a) 0.1 m, (b) 0.2 m, (c) 0.3 m, (d) 0.4 m, (e) 0.5 m, and (f) 0.6 m.

the same at all nodes. The magnitude of this force varied in time according to a six cycle Hanning window toneburst, centre frequency 28 kHz. At these frequencies, this force pattern excites the T(0,1) mode whilst suppressing the generation of other higher order modes. Rings of nodes were then selected either side of the corrosion patch and designated monitoring nodes. Each ring consisted of a selection of nodes on the pipe outer surface, all at the same axial location along the pipe. These nodes were set up to measure the radial, circumferential and axial displacement of each node throughout the time advancement of the model. A total of 50 rings were set up either side of the corrosion patch, with these rings axially spaced 0.02 m along the pipe length. Nodes before the corrosion patch, closest to the excitation point, measure the inspection wave and the reflection from the corrosion patch. Nodes beyond the corrosion patch measure the transmitted waves.

Models were built with rough surfaces of different depths and correlation lengths, with the study looking at three mean depths: 0.75 mm (11% wall thickness loss), 1.25 mm (18% wall thickness loss), and 2.00 mm (28% wall thickness loss) and 15 different correlation lengths, from 7 mm in 7 mm steps to 105 mm. These correlation lengths were chosen based on their relationship to the wavelengths of the inspection wave; since the T(0,1) mode is non-dispersive it has a frequency-invariant velocity of 3200 m/s and the centre frequency of the wave used in this model is 28 kHz, giving significant energy in wavelengths ranging from 100 to 140 mm. The 15 correlation lengths, therefore, correspond to correlation length over wavelength in the range 0.05 to 1.05, depending on the frequency. This then gave a total of 45 model conditions to solve; three corrosion depths, each under 15 different correlation lengths. However, since the rough surfaces are random it is necessary to run multiple models at each condition to determine mean behaviour and so at each condition 10 models were generated and then their average behaviour calculated, giving a total of 450 cases to solve. Simulations were also performed for a smaller 3 in. pipe and a larger 12 in. pipe, in both cases with the same wall thickness as for a 6 in. schedule 40 pipe. These models were solved at only one correlation length and depth and their purpose was to investigate diameter effects.

These models were then solved using POGO, a finite element solver based on a Graphics Processing Unit (GPU) which is two orders of magnitude faster than similar commercial solvers. This speed improvement enables the current work, making it possible to simulate wave propagation over 4 m with models of ~6 × 10⁶ degrees of freedom in around 10 min. An example time history from a monitoring node 0.2 m from the source is shown in Fig. 6.

**B. Signal post-processing**

Solving the model in POGO gave the time history of the radial, tangential, and axial displacement at each of the monitor nodes. However, this information is difficult to interpret since it is the total displacement due to a number of overlapping and interfering guided wave modes. A better representation of the data is one in which the contribution from different modes has been separated, since the relative magnitudes of different modes often reveals useful information about the system. In a simple system the modes can be separated using a time of flight analysis, where differences in group velocity between guided wave modes means different modes can be time separated. However, it was not possible to use that method in this study as the different modes are being generated at unknown locations within the corrosion patch and the model is short. These displacements can, however, be separated using a phased summation around the circumference and a 2D fast Fourier transform (FFT), a technique that makes use of the fact that different modes have different wavenumbers. The monitoring nodes are selected in rings around the full circumference, with 50 of these rings equally spaced along the axis. For each ring, an artificially imposed phase lag followed by a summation around the circumference can be used to separate modes with different circumferential orders, for example separating F(2,3) from F(1,2) but not separating F(1,2) from F(1,3). This is a common technique for separating guided wave modes in simple pipe systems (see, for example, Ref. 1). The displacement history associated with each circumferential

![FIG. 6. Raw circumferential displacement history for a monitoring node 0.2 m from the source. The initial large wave is the passing inspection signal while smaller subsequent signals are due to backscatter from the rough region.](image)
order is then calculated at 50 axial locations along the length of the monitoring region. For each circumferential order, the 50 time histories are converted from the time–space domain into the frequency–space domain using the Fourier transform. The Fourier transform is then used again to convert to the frequency–wavenumber domain where differences in wavenumber between individual modes means that each mode appears as a separate peak. A schematic of this processing and example peaks in the frequency–wavenumber domain are shown in Fig. 7. Note that an equivalent result is obtained when applying a 3D-FFT to the node data, but the phased summation approach could be used here because of the relatively small number of modes which can exist at the frequencies used in this study. These peaks can then be separated whilst in the frequency–wavenumber domain and the inverse Fourier transform applied twice to recover the time histories for each mode (as shown for example in Fig. 8). Note that the width of the peaks in the frequency–wavenumber domain is given by the time step used in the model and the overall axial length covered by the sampling nodes. Since the monitoring region necessarily has a finite extent, the peaks will have a non-zero width and some overlap will occur which introduces small errors in the attribution of displacements to different modes. For example, in Fig. 8 there is a small reflected T(0,1) wave at 0.1 ms. This wave is spurious and arises because at this point in time there is a very large amplitude (100%) transmitted T(0,1) wave. Due to the wave spreading in the frequency–wavenumber domain part of the transmitted wave (with positive wavenumber) is attributed to reflected waves (with negative wavenumber).

FIG. 7. (Color online) A schematic diagram showing how the three dimensional transform technique can be used to separate guided wave modes by transforming from the time–space domain into the frequency–wavenumber domain. Monitoring nodes distributed in space measure displacement as a function of time. This information distributed in space–time is then converted to a frequency–wavenumber representation using repeat application of the Fourier transform. In this representation different modes are shown as separate peaks and can, therefore, be isolated.

FIG. 8. Example transmitted and reflected components from a surface with a correlation length of 28 mm and mean depth of 0.75 mm showing (a) transmitted T(0,1), (b) reflected T(0,1), (c) transmitted F(1,2), (d) reflected F(1,2), (e) transmitted F(2,2), (f) reflected F(2,2), (g) transmitted F(3,2), and (h) reflected F(3,2).
The error in this case is small and this is the only mode for which this spreading is a significant problem.

From the time histories for each mode the displacement as a function of frequency was then calculated and this displacement was converted to an energy by normalising the frequency–displacement curves by power normalised mode shapes taken from DISPERSE. These normalised spectra are then squared (since energy is related to displacement squared) and divided by the energy spectrum of the input toneburst. This gave the energy in each mode as a fraction of the input energy, both for modes reflected and transmitted from the corrosion patch. The frequency range was constrained to look only at those frequencies where the energy input is 10% or greater than the energy input at the centre frequency of 28 kHz.

III. RESULTS AND DISCUSSION

A. Effect of inspection wave frequency

We first look at the interaction of guided waves with rough surfaces as a function of the frequency of the inspection wave. Figure 9 shows the distribution of energies for a rough surface with a correlation length of 28 mm and mean depth of 1.25 mm, where the average across 10 random surfaces is plotted. This figure shows two behaviours that are observed across a range of correlation lengths and mean depths: significant decreases in transmitted T(0,1) energy at frequencies of 24, 30, and 32 kHz and a gradual decrease in transmitted T(0,1) energy with increasing frequency. At the frequencies where there is a significant dip in transmitted T(0,1) there is a corresponding increase in energy in the F(3,2), F(2,3) and F(4,2) modes. This suggests that the energy which is being lost from the T(0,1) inspection wave is being scattered into the higher order flexural waves. Analysis of the dispersion curves shows that these increases occur at the cutoff frequencies of the higher order modes. A large mode conversion to a mode at its cutoff frequency has been reported in the literature for other types of guided wave interaction and is usually attributed to wall-thickness resonance effects. The study of Ref. 24 was at higher frequencies than are considered here so at the cutoff frequencies of higher order modes the resonance condition is through the thickness of the waveguide. In the low frequency propagation along a pipe considered here, the cutoffs correspond to standing waves around the circumference of the pipe; however, the physics is analogous. This resonance condition encourages mode conversion and successive cycles pump more energy into this cutoff mode, giving the peaks in the scattered modes close to their cutoff frequencies as seen in Fig. 9. The other significant feature of this graph is that there is an overall decrease in transmitted T(0,1) energy as the frequency increases. Although there are local variations due to the cutoff frequencies, the overall trend when considering the frequency range as a whole is for decreasing transmitted T(0,1) energy. It is thought the reason for this decrease is that more modes can exist at higher frequencies and so it is more likely that energy will find a suitable mode to scatter into at higher frequencies. This point is revisited in the discussion of the effect of pipe diameter (Fig. 13) below.

B. Effect of corrosion correlation length

The energy in different modes as a function of correlation length is given in Fig. 10. Note that in this figure the energy has been calculated at a frequency of 32 kHz with this frequency chosen to be well away from the cutoff frequencies of any modes. The behaviour is shown at one particular frequency rather than on a normalised frequency scale because different modes can exist at different frequencies and so the energy scattering will be different in each case. Results at other frequencies are very similar, with the difference that the energy is scattered into different modes. Also note that the correlation length has been converted to a non-dimensional parameter through division by the wavelength of the T(0,1) mode at the respective frequency. The results have been plotted here as the average over 10 random surfaces for each correlation length, with the mean indicated as a solid symbol and the error bars showing one standard deviation.

The main feature of these graphs is that the minimum transmission of T(0,1) occurs when the correlation length over wavelength is in the region 0.2–0.25. At this correlation length to wavelength ratio the T(0,1) inspection wave is...
being strongly scattered into the higher order flexural waves, as shown by the corresponding increase in energy in these modes. This is consistent with scattering from many other pipe features which have their maximum interaction with guided waves at length scales of around one quarter wavelength, for example axi-symmetric notches. In the case of notches this maximum scattering is due to constructive interference effects and it is thought a similar mechanism is responsible for the behaviour in rough surfaces. Away from frequencies close to cutoff, the scattered energy is transferred mainly to the higher order \([F(*,2)]\) modes in transmission. This preference for higher order flexural modes is due to the similarity in displacement profile between the fundamental torsional mode and these flexural modes, as shown in Fig. 11. Since these modes have the greatest circumferential displacement for a given power flow they will couple most easily to the torsional mode. It is interesting that the \(F(*,3)\) modes have relatively high circumferential motion close to cutoff which together with the resonance phenomenon discussed above gives peaks in the conversion to these modes. The proportions in which the energy scatters to these higher order flexural modes is also a function of frequency since these modes cannot exist below a threshold frequency, a threshold which is different for each mode. It is also interesting to note that most of the scattered energy is transmitted through the corrosion patch rather than being reflected towards the source. This observation is a direct validation of the phase phase-screen approximation, which assumes that the transmitted energy is not affected significantly by roughness. Surface roughness attenuates the transmitted coherent wave by scrambling the phase of the transmitted wave.

**C. Effect of rough surface mean depth**

The energy in the transmitted \(T(0,1)\) mode as a function of correlation length and rough surface mean depth is shown in Fig. 12. Note that in this paper surface mean depth and surface roughness are linked, such that an increase in mean depth is also an increase in surface roughness. Average results have been plotted here, with the typical standard deviation 10% of the mean. This shows that the amount of scattering from the corrosion surface increases as the depth of corrosion and surface roughness increase. This is in agreement with previous studies, which in general find that the interaction of guided waves with pipe features is roughly proportional to the cross sectional loss represented by that feature.

**D. Effect of pipe diameter**

A comparison of the transmitted \(T(0,1)\) energy for 12, 6, and 3 in. diameter pipes is shown in Fig. 13, where all pipes...
have been modelled with a wall thickness of 7 mm and all rough surfaces have a correlation length of 50 mm and a mean depth of 18% of wall thickness. The results have been plotted as a function of frequency $/C_0 d$ to highlight the influence of pipe diameter on the transmitted T(0,1) energy. It is clear that the attenuation of T(0,1) waves is a strong function of pipe size. As in Fig. 9, significant, localised reductions in transmitted T(0,1) which are due to cutoff frequencies of higher order modes occur at different frequencies since these cutoff frequencies will be a function of pipe diameter. Away from these frequencies the transmission reduces with pipe diameter. This diameter dependence is due to the existence of higher order flexural modes at a given frequency for the energy to scatter into. In commercial pipework wall thickness for a given pipe schedule increases with pipe diameter but not in proportion to it. The analysis was, therefore, repeated for schedule 40 pipes of the three diameters and the results were very similar to those of Fig. 13 (maximum difference 5%), showing that the effect of frequency—thickness product is much smaller than that of frequency—diameter. This figure also shows that for a given pipe diameter there is a gradual decrease in transmitted torsional energy with increasing frequency. This is consistent with the arguments made in Sec. III A.

IV. VALIDATION

A. Validation through energy balance

All the results presented so far come from finite element simulations of guided wave propagation. To ensure that these simulations are accurate, two kinds of validation were performed: an energy balance across the simulations and laboratory experiments on a pipe machined with a rough surface. The energy balance is based on the displacement of the waves generated and measured within the model. Knowing the amplitude of the T(0,1) wave excited at the end of the model it is possible to calculate the energy put into the system. Since the simulations have been done with no material damping, this energy should be the same as the energy measured in all the waves scattered and transmitted from the patch. A ratio is defined, termed in this paper the energy balance, which gives the ratio of the input and output energies:

$$\text{energy balance} = \frac{\text{energy input}}{\text{transmitted energy} + \text{reflected energy}}.$$  

An energy balance of unity indicates that the input energy and the measured reflected and transmitted energy is the same. A value greater than unity indicates more energy in the transmitted and reflected components, while a value less than unity indicates some energy has been lost in the model.

Figure 14 shows this energy balance sampled across a range of correlation lengths and a range of frequencies. Overall the energy balance is very good, with a maximum discrepancy of 3% from the ideal. The energy balance is worst at lower correlation lengths, the conditions under which the greatest scattering occurs.

B. Validation through experiment

A 3.5 m length of 3 in. diameter, schedule 40 pipe was machined with a rough surface which had an overall length of 0.75 m, a correlation length of 50 mm and a mean depth of 2.0 mm (36% wall thickness), generated using the same procedure as for the simulations. This patch started 1.1 m from the end of the pipe end and extended over half of the circumference, with half circumference machining chosen in preference to full circumference so that the pipe did not have to be moved during the machining operation which was done on a numerically controlled flat bed milling machine. This patch also had a linear ramp at its edges to provide a smooth transition to the surrounding plain pipe. A thickness map for the patch is shown in Fig. 15, which shows the distribution of peaks and troughs. A commercial transducer ring from Guided Ultrasonics Ltd. was then clamped to the pipe at one end. The ring comprises 32 dry coupled transducers that apply a circumferential traction to the pipe wall, which when excited simultaneously generate a pure T(0,1) mode and when linked in reception receive this mode preferentially. Measurements were made with this sensor at five different centre frequencies: 23, 28, 34, 41, and 50 kHz. This inspection setup, shown in Fig. 16, was then modelled using finite element simulations based on the same procedure as used for the rest of the results presented in this paper. For accurate comparison with experiments the finite element results were corrected for the slight attenuation which occurs.
as the waves pass under the ring itself. This was done by applying an attenuation to the time histories from the model; the correct attenuation was calculated by performing a guided wave test on an undamaged length of 3 in. schedule 40 pipe and measuring the attenuation of the inspection wave with successive passes under the sensor.

Example time histories at a centre frequency of 28 kHz are shown in Fig. 17 for both the experiment and the simulations. These time histories show a series of large reflections which are due to successive end reverberations from the pipe, the amplitude of which is reducing due to mode conversion within the corrosion patch. The signals between end reverberations are due to scattering of $T(0,1)$ waves from the patch. Note that in Fig. 17 the measured time history has been set to zero for the first 5 m, which explains the discrepancy between predicted and measured time histories in this region. This zeroing was done because the guided wave sensors do not give accurate measurements immediately after transmission due to ring-down of the transducers.

By then comparing the amplitudes of successive reverberations for both the experiment and simulations it is possible to compare the mode conversion in both. The amplitudes of the end reflections for both the simulations and experiments are shown in Fig. 18 at a range of centre frequencies. This figure shows that there is excellent agreement between experiments and simulations at all frequencies. It is worth noting that the attenuations seen in the experiment and corresponding simulations are larger than the attenuations predicted in the earlier simulations. The reason for this is that multiple patches with similar statistics were modelled and one with a large attenuation was chosen for the experiment in order to make the measurements easier. The patch also has a mean depth greater than was used in the earlier simulations and since the sensor is configured in pulse–echo mode, the transit distance of the wave through the corrosion patch is 1.5 m compared with the 1.0 m used in the 6 in. pipe simulations. It is also possible that machining the random surface over part of the pipe circumference rather than the whole circumference increases asymmetry and so promotes mode conversion. Further investigation of this possibility is beyond the scope of this paper.

V. CONCLUSIONS

This paper has used finite element simulations to investigate the mode conversion of torsional guided waves passing through rough surfaces in pipes. These rough surfaces, modelled as a Gaussian, random wall thickness loss were designed to investigate the reason for the greatly increased attenuation seen in the inspection of generally corroded pipe. It was found that these rough surfaces cause mode conversion from the torsional wave to non-axisymmetric higher order flexural modes, which explains the significant attenuation seen during commercial inspections.

This mode conversion was found to be a function of several variables: the frequency of the inspection wave, the characteristics of the rough surface and the diameter of the pipe.
pipe. In general it was found that the mode conversion increases as the inspection frequency increases, since at higher frequencies more modes can exist and hence there are more modes for the energy to scatter into. However, this trend breaks down close to the cutoff frequencies of the higher order flexural modes where the mode conversion is particularly strong; at their cutoff frequency flexural modes form standing waves around the pipe circumference and this resonance condition encourages mode conversion. The mean depth and correlation length of the surface also has an influence on mode conversion, with attenuation greatest for surfaces where the correlation length over wavelength is in the region 0.2—0.25; the attenuation approaches zero at low and high values of correlation length relative to the wavelength. The deeper the rough surface the more severe the mode conversion, with rough surface depth related to surface roughness in this study. It was also found that mode conversion is a strong function of pipe diameter; for pipes with the same wall thickness and rough surface statistics the attenuation increases significantly with frequency—diameter product. This is because larger diameter pipes can support more modes at a given frequency, so there are more possible modes for the energy to scatter into. Away from cutoff frequencies the mode conversion is mostly to the F(*,2) modes since these modes have the greatest circumferential displacement for unit power flow; the T(0,1) mode, therefore, couples most easily into these modes.

The finite element simulations on which these results are based have been validated using an energy balance and experimental validation. The energy balance was performed across the inputs and outputs from the finite element model and gave a worst-case discrepancy of 3%. Experimental validation in the time histories from the finite element model across the inputs and outputs from the finite element model and gave a worst-case discrepancy of 3%. Experimental validation of the energy to scatter into. Away from cutoff frequencies the mode conversion is mostly to the F(*,2) modes since these modes have the greatest circumferential displacement for unit power flow; the T(0,1) mode, therefore, couples most easily into these modes.

This mode conversion can cause severe attenuation of the inspection signal; for example a mean wall thickness loss of 28% can cause 1.35 dB per m attenuation of the torsional wave, corresponding to 2.7 dB loss per metre in a pulse-echo configuration. This is for a frequency range typical of commercial deployment. This does not include the effect of any adhered corrosion product which could further increase attenuation, an effect which has not been modelled in the simulations. To minimise this attenuation the inspection should be performed at the lowest possible frequency while avoiding cutoff frequencies and the region where the correlation length is around a quarter wavelength.

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