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A New Electromagnetic Acoustic Transducer Design for Generating Torsional Guided Wave Modes for Pipe Inspections

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Abstract. Guided waves inspection is a well-established method for the long-range ultrasonic inspection of pipes. Guided waves, used in a pulse-echo arrangement, can inspect a large range of the pipe from a single point as the pipe structure carries the waves over a large distance due to the relatively low attenuation of the wave modes. However, the complexity of the dispersion characteristics of these pipe guided wave modes are well known, and can lead to difficulty interpreting the obtained results. The torsional family of guided wave modes are generally considered to have much simpler dispersion characteristics; especially the fundamental T(0,1) mode, which is nominally non-dispersive, making it particularly useful for guided wave inspection. Torsional waves have been generated by a circumferential ring of transducers to approximate an axi-symmetric load to excite this T(0, 1) mode. Presented here is a new design of Electromagnetic Acoustic Transducer (EMAT) that can generate a T(0, 1) as a single transducer, rather than a circumferential array of transducers that all need to be excited in order to generate an axisymmetric force. The EMAT consists of a periodic permanent magnet array and a single meander coil, meaning that the excitation of the torsional mode is greatly simplified. The design parameters of this new EMAT are explored, and the ability to detect notch defects on a pipe is demonstrated.

INTRODUCTION

The generation of torsional guided wave modes is of great interest for the inspection of pipes. This is primarily due to the favourable qualities of the torsional family of wave modes, which makes them ideal for guided wave inspections of pipes. In particular, the fundamental torsional wave mode, like the plate wave equivalent shear horizontal wave (SH) mode, is completely non-dispersive [1, 2]. Consequently, the energy contained within a wavepacket does not disperse out as it propagates, meaning that the wave can travel further before the energy is lost. As the fundamental torsional wave is non-dispersive for all frequency-thickness products, higher frequency waves can be used, whereas lower frequencies are used for inspections using other wave modes due to the region of minimal dispersion at low frequency-thickness products. The non-dispersive nature of the fundamental torsional wave, T(0,1), also significantly simplifies the post-processing of the ultrasonic signals. In addition, as liquids cannot support shear waves, the torsional wave modes are not affected by the presence of fluids in the pipe and the wave energy does not leak into any surrounding fluid medium [3, 4].

Generating Torsional Waves

Due to the beneficial characteristics of torsional wave modes, attention has been given to investigating numerous ways to generate these ultrasonic waves. As with SH waves, torsional waves can be difficult to generate using piezoelectric transducers due to the requirement to produce shear horizontally polarised stresses [5]. However, they have been generated using an axisymmetric array of dry-coupled piezoelectric transducers [6, 7].

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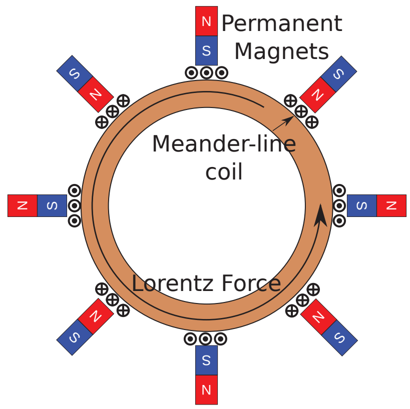

FIGURE 1. The arrangement of meander line coil and PPM array, which gives rise to a in-phase torsional force

Circumferential arrays of electromagnetic acoustic transducers (EMATs) have also been used to successfully generate torsional wave modes. Specifically, an array of periodic permanent magnet (PPM) EMATs have been used. These transducer have been regularly deployed to generate shear horizontal waves in plates [5, 8, 9], and so the principle is applied to torsional waves in pipes by placing a number of these PPM transducers around the circumference of the pipe to generate the required circumferential twisting motion to launch these waves [10, 11]. As the transducers are coupled to the sample via the Lorentz force,these arrays are non-contact and can be use to axially scan along the pipe.

As both of these methods generate an axisymmetric force using ultrasonic arrays, there is a compromise with regards to the amount of transducers. A greater number of transducers leads to a more axisymmetric force applied to the pipe, but it comes at the expense of greater complexity of the torsional transducer.

Magnetostrictive transducers have also been used to generate torsional wave modes. Usually, these transducers require a patch of highly magnetostrictive material to be bonded to the sample surface in order to enhance the strength of the magnetostrictive force. This, of course, means that the transducers are no longer non-contact [12–14].

Consequently, reflecting upon these issues with generating torsional wave modes, a new design of EMAT is presented that generate a series of circumferential forces around the pipe using a single coil, negating the requirement for electronics to individually excite a number of transducers. This greatly simplifies the operation of the transducer, and means that there is no longer the compromise between the complexity of the transducer and its ability to produce a circumferential uniform force to launch a torsional wave. As this proposed EMAT couples to the sample using the Lorentz force mechanism, it means that it is non-contact and does not require either dry couplant or the application of a magnetostrictive patch. This is advantageous if the transducer needs to be scanned or if the sample to be inspected is at an elevated temperature.

In the following section, the arrangement of the new torsional wave EMAT is described, showing how a combination of two basic EMAT design principles - periodic permanent magnet arrays and meander line coils - can be combined to produced a coherent torsional force to an electrically conductive pipe sample. The layout of this new design is then examined, specifically investigating the geometry of the coil and what effects this will have on the spatial impulse response of the transducer. This design is further developed to include a double row of periodic permanent magnet arrays, which can increase the effective frequency range in which these transducers can be used, thereby improving the resolution of such measurements. The ultrasonic waves generated by this transducer are then examined and analysed by looking at the dispersion characteristics of the waves.

EMAT Design

The proposed EMAT utilises the Lorentz force mechanism to generate the desired torsional waves, and it ensures that the generated forces are torsional in nature by using a combination of a periodic permanent magnet array and a meander line coil. These two fundamental constituents of EMAT design have been extensively used separately to generate a range of different ultrasonic waves, including SH, SV and Lamb waves [5, 8, 15–17]. However, they have never been used together in this way to generate torsional waves. In this design, both the meander line coil and

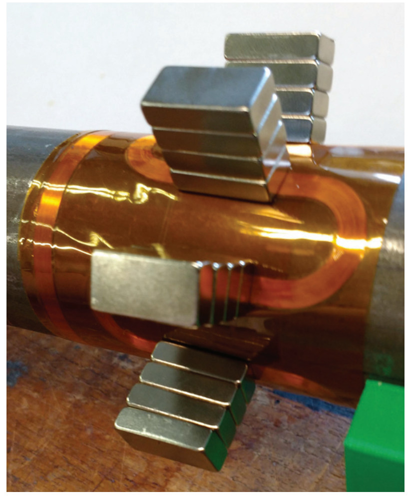

FIGURE 2. A photograph of the transducer showing the meander line coil and PPM array set up on a pipe sample

the PPM array are placed circumferential around the pipe. The PPM array leads to an alternating pattern of radial magnetic fields, whilst the meander line coil creates a circumferential arrangement of currents travelling in the axial direction, also with a different polarisation to its nearest neighbour, as shown in Fig 1. As the polarisation of both the magnetic field and current is alternating around the circumference of the pipe, the force generated by each 'element' in the circumferential array is polarised in the same direction. The result of the current polarised in the axial direction and the radial magnetic fields mean that the Lorentz force is directed in the circumferential direction. This series of coherent, in-phase torsional, twisting forces initial the torsional wave.

As only a single coil is used, as can be seen in Fig 2, only a single current source is required to drive the EMAT. This means it is possible to create any number of 'elements' in the transducer, without the need for complex electronics, which results in a more axisymmetric force distribution around the pipe. However, it should be noted that there are still other technical considerations which limit the amount of elements in the transducers, such as the strength of the magnetic field as permanent magnets are made smaller and the impedance of the coil it is made longer. As a consequence of these considerations, the transducer was designed with eight elements as this was found to be a good compromise between generating a wave with a good amplitude and being axisymmetric.

Spacial Impulse Response

In addition to the number of circumferential elements, the axial length of the active area of transducer was also considered. In particular, its effect on the spatial impulse response, with regards to the bandwidth of the transducer, is investigated. If it is assumed that only torsional wave modes are generated, then the spatial impulse response of the transducer with a length, L, can be written as

$$h(L,\omega) = \operatorname{sinc}\left(\frac{\pi \mathrm{L}}{\lambda(\omega)}\right). \tag{1}$$

Where $\lambda(\omega)$ is the wavelength of the ultrasonic wave at a particular angular frequency, ω. This equation captures the well-known relationship between the physical size of the transducer and its bandwidth; namely that as the transducer length grows, the range of frequencies that the transducer can efficient produce reduces. Equation 1 is plotted graphically in Fig 3 for a non-dispersive wave with a phase velocity of 3277 m s^{-1} and shows this key tendency. For this wave, once the transducer is over 20 mm in length, the efficiency bandwidth is less than 100 kHz.

However, of more interest than the efficiency of generating a wave of a particular frequency is the signal amplitude of such a wave using a transducer of a particular length. This can be calculated multiplying equation 1 by the transducer length, L. Whilst this approach only considers the geometric features, and neglects other factors such as changes in electromagnetic coupling efficiencies, it does give a good indication of the expected signal amplitudes. Figure 4 shows the expected characteristics, namely that a larger transducer will signal amplitude, due to the larger active area, although at the expense of a smaller bandwidth. From Fig 4, it is clear that using this transducer, it would

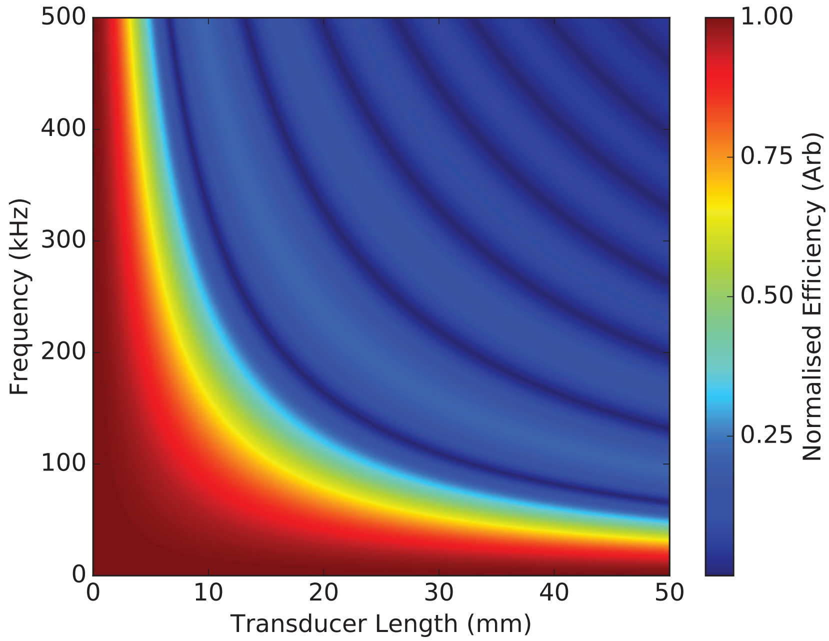

FIGURE 3. The generation eciency of a wave with a phase velocity of 3277 $\mathrm{m\,s^{-1}}$ calculated from the spatial impulse response.

be difficult to generate a torsional wave mode of an appreciable amplitude with a frequency above 60 kHz. Whilst pipeline inspections can be carried out at frequencies this low [18], it would be beneficial to be able to generate waves of a higher frequency.

Double PPM Array

A nominal wavelength of the torsional wave can be defined by using a second PPM array shifted axially along the pipe. This is a result of phase matching, and works in the same way as for conventional PPM and meander line transducers [19]. If this second PPM array is in anti-phase with the original one, an ultrasonic wave is most efficiently generated when the wavelength is equal to twice the distance between the centres of the two PPM arrays, as demonstrated in Fig 5. Now, the frequency of the most efficiently generated wave can be tuned by adjusting the separation of the two PPM arrays, or by varying the axial length of the magnets used to form the PPM arrays. If it is assumed that these two PPM arrays are not separated in the axial direction, then the total axial length of transducer is equal to twice the axial length of the magnet. With this assumption, the signal amplitude as a function of the total axial length of the transducer and the generation frequency is shown in Fig 6.

It is immediately apparent that the frequency at which the peak amplitude occurs has been shifted to a higher value when compared to Fig 4. Now, even the 50 mm transducer has peak amplitudes at at 50 kHz with the peak frequencies being inversely proportional to the transducer length, so that when the transducer size is 20 mm, the peak frequency is around 150 kHz. This is a vast improvement when compared to the single PPM torsional EMAT, and means the inspections can be carried out with a much improved resolution as a consequence of this increase frequency.

These analytic results show how the introduction of a second PPM array can be introduced to improve the frequency response of the torsional wave EMAT. It should also be remembered that this improvement does not result in added transducer complexity; the transducer still consists of a single coil. The utilisation of the phase matching principle is also expected to improve the signal to noise ratio of the generated ultrasonic wave. This is because the axial periodicity of the transducer, when used as a detector, also inherently filters out any wavelengths that do not match the wavelength of the generated torsional wave.

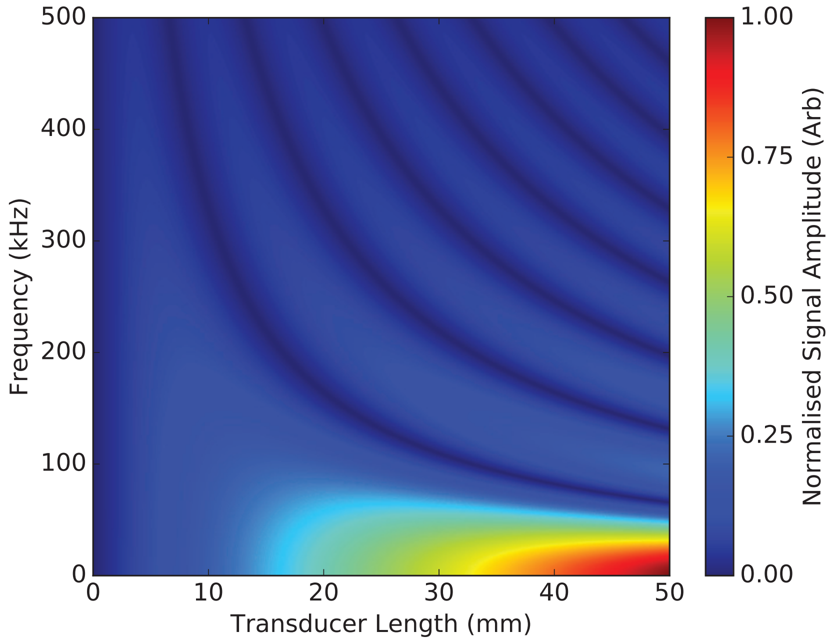

FIGURE 4. The normalized wave amplitude with a phase velocity of 3277 $\mathrm{m\,s^{-1}}$ calculated from the spatial impulse response.

Experimental Verification

With the theoretical basis of the design of the double PPM torsional EMAT now well understood, it is possible to construct such a transducer and experimentally verify the results. The coil was hand wound using 40 turns of insulated wire with a diameter of 0.2 mm. Neodymium-Iron-Boron magnets with dimensions of 20 x 10 x 5 mm were used to provide a static biasing magnetic field. As the magnets had an axial length of 10 mm, and there was no spacing between the two PPM arrays, this meant that the total active length of the array was 20 mm. The transducer had eight circumferential 'elements' that formed the array to provide an axisymmetric force to the pipe.

The sample itself was a steel pipe with an outer diameter of 50.8 mm and a wall thickness of 6.35 mm, and an axial length of 1 m. In order to assess what wave modes that the transducer is generating, a second transducer was used to scan along the axial direction of the pipe to determine what waves were generated. This scan was performed with the transmitter position fixed, so that the resultant scan results show how the wave propagates along the pipe. Initially, the transducers were separated by 300 mm, and the detector was moved axially in 5 mm increments until the

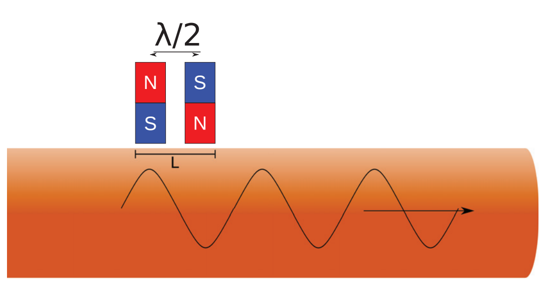

FIGURE 5. The layout of a double PPM torsional EMAT, showing the location of the second PPM array. Note that the PPM arrays still continue circumferentially around the pipe, but this was omitted to make the figure more clear.

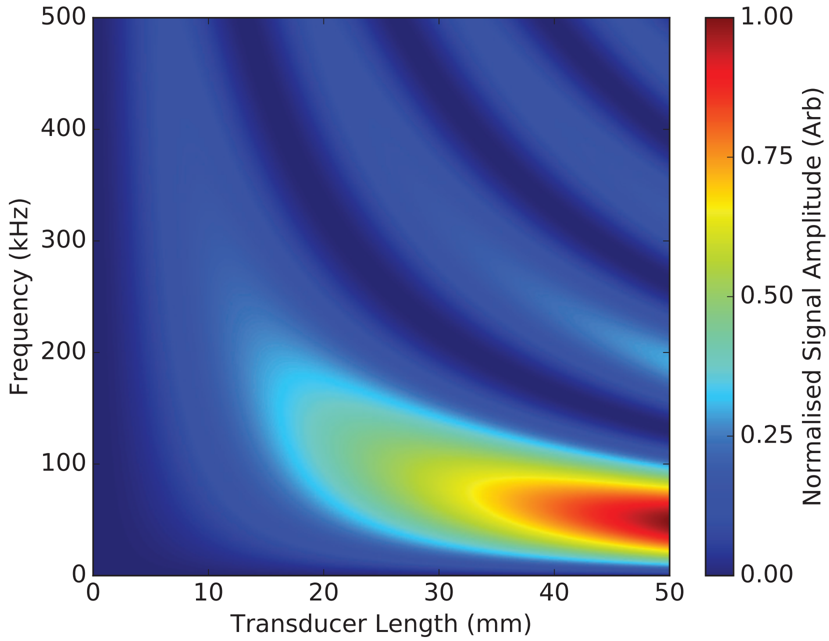

FIGURE 6. The normalized wave amplitude for with a phase velocity of 3277 m s^{-1} calculated from the spatial impulse response of a double PPM torsional EMAT.

separation was 400 mm.

A Ritec RPR-4000 pulser receiver unit was used to excite the generation EMAT, as well as amplify and filter the received signal from the receiver transducer. A three cycle tone burst signal with a central frequency of 150 kHz was used to excite the transducer. The signal recorded by the detection EMAT was amplified and bandpass filtered (50 - 800 kHz) by the Ritec. The signal to noise ratio was further improved by taking 64 coherent averages of the signal before saving the signal.

This scan result is shown in Fig 7, and shows a number of features. The first signal, which is visible between 100 and 150 μs is the direct incident wave. It appears to be generally non-dispersive with the wavepacket retaining its shape. The slope of this envelope represents the velocity of the wave. There are also two other apparent signals, which appear after 250 μs, with two different gradients to the wavepacket as the transducer separation is changed. The arrival times of these signals are consistent with reflections from either end of the pipe (as the transducer will generate two waves travelling in opposite axial directions).

The signals associated with the incident wave can be analysed using Fourier methods to reveal the dispersion characteristics of the wave. By performing a two-dimensional Fourier transform on the scan results shown in Fig 7, it can transform data from the distance-time domain into the wavenumber-frequency domain. This will highlight the dispersion characteristics of whatever modes are present in the signal. These modes can then be identified by comparing the results to known solutions of the dispersion curves calculated analytically.

The dispersion relationship for the scan results are shown in Fig 8. The highest amplitude feature in this dispersion curve is the straight horizontal line marked in Fig 8 as a T(0,1) feature, with the peak amplitude occurring at around 150 kHz. This feature was identified as corresponding to the T(0,1) as it conforms to the expected profile. As the gradient of this line is constant, it confirms that this mode is non-dispersive with a constant phase speed. This feature is quite clearly the dominant feature in this 2D spectrum, which demonstrates that the double PPM torsional EMAT is predominantly generating the expected T(0,1) mode.

There are, however, some lower amplitude features that are indicated in the figure, which correspond to the higher order torsional wave modes. This is to be expected from the design of the transducer and the way it was operated. The transducer consists of only two PPM arrays in the axial direction, meaning that the spatial frequency bandwidth of the EMAT is very large. Likewise, as the transducer is excited with a three cycle, 150 kHz tone burst signal, the

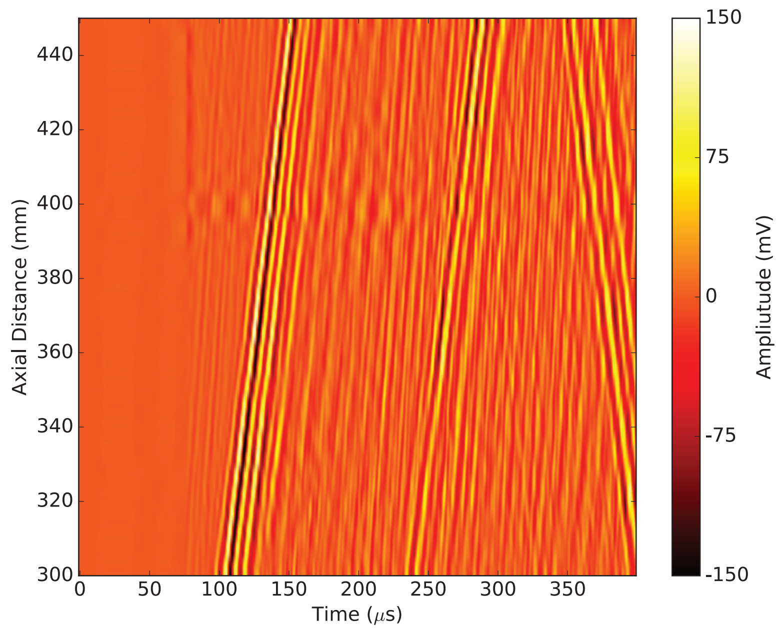

FIGURE 7. Axial propagation of the generated wave showing the incident T(0,1) and the two reflected signals from both ends of the pipe.

bandwidth of the excitation signal is quite large. As a consequence of these large bandwidth, in both the wavenumber and frequency domain, a large area in the wavenumber-frequency domain is excited, meaning some of the energy can leak into the higher order modes. The generation area can be made more selective by increasing the number of axial PPM arrays used to construct the transducer or the number of cycles used in the tone burst signal, but this will result in a longer wavepacket and a reduction in the axial resolution [20, 21]. However, it should be noted that even with the current design, the higher order modes have an amplitude around an order of magnitude lower than the fundamental mode, so most of the energy is contained within the non-dispersive T(0,1) mode.

CONCLUSION

A new EMAT design for generating torsional wave modes in pipes has been presented, which possesses a number of benefits over existing methods of generating these wave modes. The design of this new EMAT is based upon combining two elements of EMAT design - meander line coils and periodic permanent magnet arrays - to generate an axisymmetric, in-phase twisting Lorentz force around the circumference of a pipe. This twisting force can then give rise to torsional ultrasonic guided waves.

As the new EMAT relies on the Lorentz force mechanism to couple of the sample, it will work on a range of electrically conductive samples and does not require contact with the sample, unlike piezoelectric arrays or magnetostrictive transducers, which require a coupling medium and a magnetostrictive patch, respectively. Consequently, this transducer can easily be adapted to scan along the surface of a pipe or be used if the pipe is at elevated temperatures.

The design of the transducer is also extremely simple when compared to other ways of generating torsional waves that require an array of transducers to be placed circumferentially around the pipe. This is because the transducer consists of a single meander line coil, which is placed circumferentially around the pipe, meaning that the transducer requires only one pulser circuit to generate an axisymmetric force distribution.

Basic physical principles, such as the spacial impulse response, were used to inform the design process of the transducer in order to optimize certain characteristics, such as the amplitude and frequency content of the generated

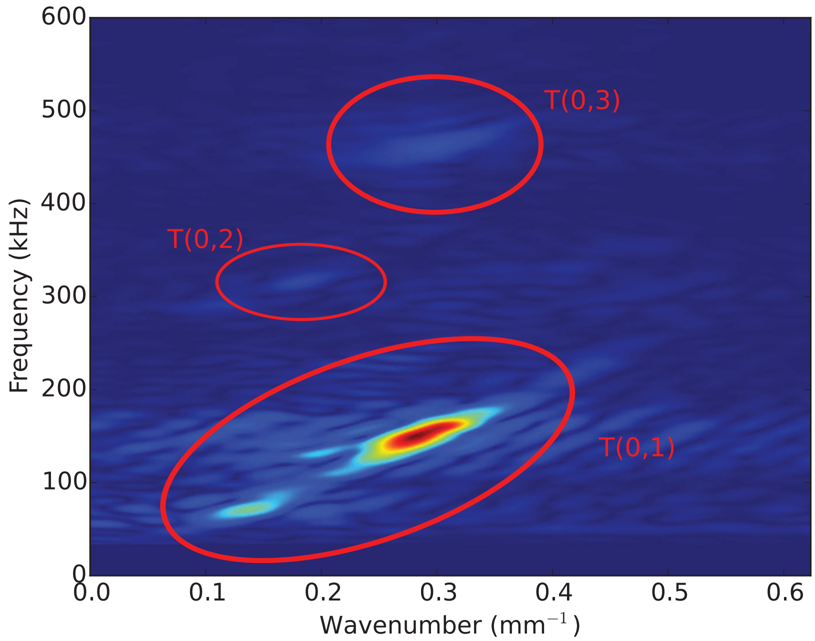

FIGURE 8. The wavenumber-frequency representation of the incident signal, showing the dispersion relationship of the wave. The different torsional wave modes are indicated on the figure

waves. Whilst it was found that a single circumferential PPM array could be used in conjunction with a meander line coil to generate torsional waves, it was found that spacial bandwidth of such transducers were rather limited. Consequently, another circumferential PPM array was added to create an alternating, periodic force dispersive in the axial direction of the pipe. This was found to raise the frequency content of the transducer from below 50 kHz to being able to generate waves with a maximum amplitude at 150 kHz.

The double PPM array design was experimentally verified and was found to be able to generate the fundamental T(0,1) wave mode at 150 kHz. The propagation characteristics of the generated ultrasonic waves were investigated using a two-dimensional Fourier transform. This allowed the dispersion attributes to be examined and compared to analytic torsional wave dispersion curves. Using this method, it was confirmed that the transducer was indeed generating the non-dispersive T(0,1) wave. Energy was found to be leaking into higher order torsional wave modes, although the fundamental mode was the dominant wave generated. The reason for this leakage was because of the large bandwidth - both in the frequency and wavenumber domain - of the generation event. The bandwidth can be constrained by increasing the number of elements in the axial PPM array or the number of cycles in the current tone burst signal. However, both of these alterations will lead to a longer wavepacket, and a reduction in the axial resolution. Consequently, a compromise must be found between mode selectivity and axial resolution.

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