# Guided Wave in Engineering Structures Using Non-Contact Electromagnetic Acoustic Transducers – A Numerical Approach for the Technique Optimisation.

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**Abstract:** There are over 10 million kilometres of pipes and pipelines around the world that carry hazardous fluids and gases. Fluids include oil, oil products, chemicals such as solvents, caustics, acids, corrosives and combustibles often at high pressure and temperature. These pipes are susceptible to corrosion if they are not protected properly by the environment or the contents. Inspection of pipes is usually mandatory to ascertain their structural integrity as corrosion can lead to failure or rupture of the pipe leading to leakage of hazardous material into the environment or even explosion. Guided wave inspection such as Teletest is a screening technique that is utilised to locate corrosion on pipelines. These commonly use piezoelectric transducers in contact with the pipe surface to induce the ultrasonic wave into the pipe.

This paper looks into an alternative approach for generating guided ultrasonic wave in pipes using non-contact electromagnetic transduction (NCET) technique to overcome limitations of using surface contact sensors. Numerical modelling was carried out, using COMSOL, to determine the axisymmetric modes of guided wave with minimal radial displacement and maximum axial displacement. The work focuses on the selection of guided ultrasonics wave (GUW) in the frequency * thickness range of [2.4-3.25] mm.MHz. For standard pipe dimensions, [2.4-3.25] mm.MHz represents short range inspection at relatively high frequency whereas long range inspection of pipes is usually applied at [0.1-1] mm.MHz at frequencies lower then 100kHz.

**Keywords: Electromagnetic transduction,** EMAT, Guided ultrasonic wave, Long range ultrasonics, NDT inspection, Modelling, COMSOL, Tubular structures.

## 1. Introduction

Guided Ultrasonic Wave (GUW) techniques are widely used in the industry for the inspection of pipelines. The standard technique offers rapid screening of long lengths of pipe for the detection of corrosion and other defects under insulation. The existing piezoelectric techniques require mechanical coupling between the transducer and surface of the solid whose properties or structure are to be studied in order to propagate the ultrasonic wave. Coupling is usually achieved using either (i) immersing method (transfer of the ultrasonic signals between the transducer and test sample by placing both objects in liquids) or (ii) contact (the transducer is pressed directly against the test sample with or without coupling gel). For some applications; e.g. inspection of very high temperature pipelines and tubes above 500$^o$C, both coupling methods are extremely problematic.

An alternative approach is to use the contactless and coupling-free NCET technique. The technique is based on the generation of transitory Lorentz forces using an enhanced magnetic field. The aim of this work was to simulate the generation of the GUW in pipes using axisymmetrical NCET and optimise the performance of the NCET technique. In this paper, the longitudinal L(0,3) mode has been selected because it has significant particle displacement at both the inner and outer surfaces which is good for the detection of surface breaking flaws [1].

## 2. Model description

### 2.1 General

Modelling of the wave propagation in pipes is an efficient way to predict the performance of the GUW generation using NCET and establish theoretical parameters that can be subsequently used to optimise the sensor configuration and characteristics needed in the Long Range Ultrasonic Testing (LRUT).

Guided waves can be represented in the form of displacement vector at an arbitrary point and this can be written in the frequency domain as:

$$U(x,y,z,t)= A(x,y) \exp(j\xi z) \exp(j\omega t) \tag{1}$$

where $\xi$ is the wave number and $\omega$ is the pulsation. The wave propagation is in the z direction and its amplitude is a function of the x and y coordinates [2, 3].

At a fixed $\omega$, the dispersion curve gives fundamental solutions ($\xi$) of the guided waves that could appear in the pipe when excited using a transitory tone burst signal.

When solving the wave equation using (1) as a solution form, an infinite number of $\xi$ are generated; in which the solution is also known as the dispersion curves.

In order to determine the dispersion curves of a pipe, the Eigen-frequency analysis was used to study a 40mm length pipe where the edges were clamped in the axial direction. This analysis provided the Eigen-frequencies and the mode shape of the pipe. The wavelength was then calculated based on the mode shape, and finally the velocity of the guided wave was obtained using the relationship (2) between the frequency and the wavelength:

$$c= f.\lambda \tag{2}$$

For the transient analysis, three formulations were used in the development of the models. The first formulation dealt with the static field induced by a permanent magnet, the second formulation dealt with the induced magnetic field pulsed from the coils, and the third formulation dealt with the elastodynamic wave travelling in the pipe induced by the Lorentz forces.

One of the advantages of having two magnetic formulations was to avoid numerical problems in the transient solver when solving a very small oscillation superposed to large static fields (tolerance issues, cancellation effects, etc).

The models were first solved using the stationary solver in order to determine the magneto-static solutions. Then, the transient magnetic and structural problems were solved taking into account the magnetic field derived from the stationery solver.

### 2.2 Case study

The electromagnetic transducers have been assessed with the aim to excite an axisymmetrical wave in the cross section of the pipe at high frequencies. A pipe diameter where the longitudinal mode L(0,3) has a cut-off frequency at 269kHz will be used.

The excitation profile of the function used to excite the coil was a N cycles modulated tone burst (3):

$$I= I0 \sin(\omega t)\ (1-\cos(\omega t/n))\ (t<N/f) \tag{3}$$

The dimension of the pipe, coil and magnet modelled in this paper are summarised in Table 1 below.

**Table 1:** Dimensions used for the models (in mm)

| | |
|---|---:|
| Pipe length | 1941 |
| Pipe diameter (internal) | 120 |
| Pipe thickness | 6.575 |
| Coil diameter | 133.6 |
| Magnet diameter | 134 |
| Magnet thickness | 8 |

### 2.3 Configuration of NCET

The efficiency and performance of different types of EMATs have been reported in [4, 5]. These EMATs were used to excite in-plane and out of plane waves in half space configuration. The configuration in Figure 1 shows an example of an axisymmetric NCET coil setup to excite L waves, Rayleigh waves, or guided modes. This configuration was chosen for the modelling work conducted in this paper.

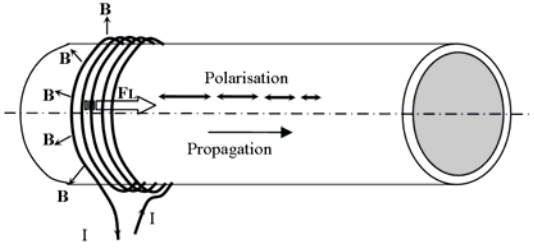


**Figure 1**. Schematic of the current, magnetic field and the Lorentz force, generated in tubular structure.

With this configuration, the magnetic field is present in the radial direction with the current tangent to the pipe and the resulting Lorentz force in the axial direction (Figure 1).

The structure (i.e. coil, magnet and pipe) was represented as a 2D axisymmetric model in COMSOL. Indeed, the geometry, loadings, boundary conditions and materials were symmetric with respect to the axis.

In the transitory analysis, the discretisation in the pipe region used mesh criteria that respects the condition $le=\lambda_{L03}/6$, where $le$ is the element length in the z direction.

## 3. Technique optimisation

In order to investigate the propagation of the GUW in pipe using NCET, advanced post processing techniques had to be introduced.

The two dimensional Fast Fourier Transform (2D FFT) was used in order to dissociate the mode content of the resulting displacement wave along the pipe. This technique transforms the displacement extrusion plot (Time, Distance) into dispersion curve plot (Frequency, Wave-number) in the frequency bandwidth excited by the tone burst signal.

In this model, a 5-cycle 441 kHz tone burst signal was applied to the NCET technique. Figure 2 shows frequency spectrum of the signal.

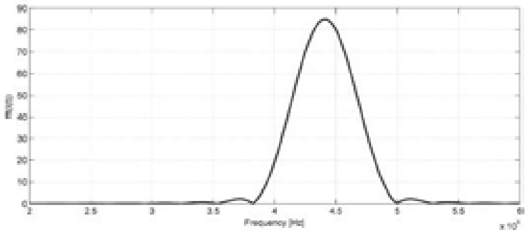


**Figure 2**. Frequency spectrum of the 5 cycles tone burst excitation.

The purpose of the optimisation was to assess the mode contents and amplitudes of L(0,1), L(0,2), L(0,3), L(0,4) and L(0,5) modes excited using the NCET technique. By optimising the NCET parameters the authors aimed to select the L(0,3) mode in order to enhance its amplitude and make it more efficient for complex inspection.

## 4. Results

### 4.1 Eigen-frequency analysis:

The results of the stationary analysis are presented in the Appendix. The table shows a list of wave mode frequencies and wave-number determined using COMSOL. Figure 3 shows the correlation between the results from the stationary analysis and the analytical calculations based on potential decomposition [5].

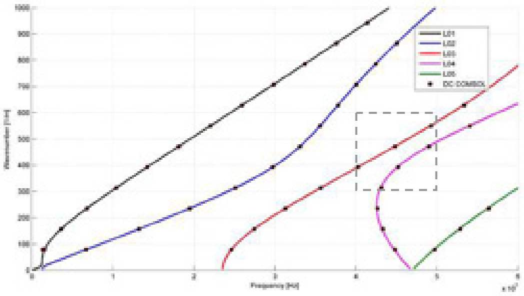
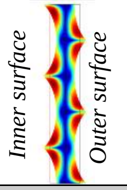
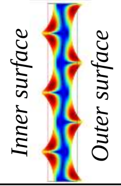
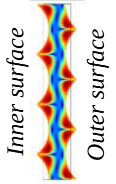
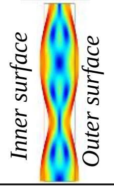
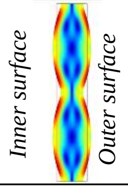
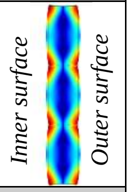


**Figure 3**. Correlation of the COMSOL dispersion curves results with analytical solution.

The design of the NCET technique focused on exciting the L(0,3) mode at maximum group velocity to simplify experimental verification. This mode has significant particle displacement at both the inner and outer surfaces, demonstrating potential for surface defect detection. In addition, (441 kHz, 459m$^{-1}$) is the point of minimum dispersion of the L(0,3) which is advantageous for applications requiring propagation of GUW over long distances [1].

Table 2 shows L(0,3) and L(0,4) mode shapes of the guided waves in the frequency range from 400 kHz to 500 kHz (wave-number from300 m-1 to 600 m$^{-1}$) at both the inner and outer surface of the pipe.

**Table 2:** Mode shape of the L(0,3) and L(0,4) GUW

| | | | |
|---|---|---|---|
| L(0,3) |  |  |  |
| *f (Hz)* | 402,476 | 448,270 | 492,446 |
| L(0,4) |  |  |  |
| *f (Hz)* | 426,475 | 431,332 | 490,140 |

The study showed that L(0,1) and L(0,2) modes had concentrated energy near the outer surface of the pipe and did converge to Rayleigh waves at high frequencies. For this reason, these modes proved to be unsuitable for the inspection of pipes with internal corrosion or erosion. The L(0,4) mode may be used but remained relatively dispersive at high frequencies.

Consequently, the L(0,3) mode remained the best mode for the application under study, because of its less dispersiveness at high frequencies and the possibility to cancel any other wave modes. As a result of these advantages, L(0,3) was expected to increase the resolution of the inspection leading to less complicated data analysis.

## 4.2 Transient analysis:

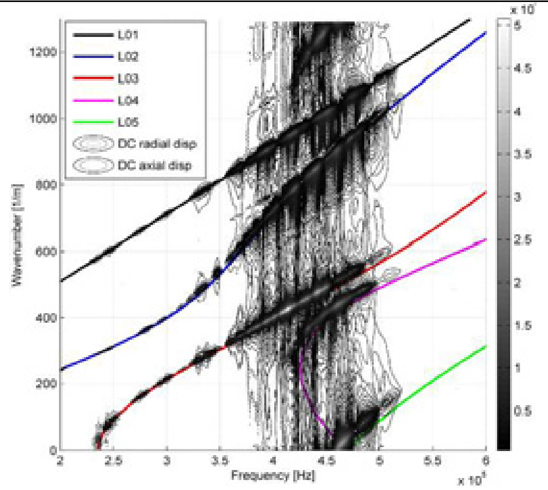
In order to select the L(0,3) mode, the following part of the study presents a comparison between three NCET configurations where one used a full magnet covering the entire coil and the two others used a series of magnets (7 and 14 respectively for configurations 2 and 3) separated by a spacing equal to the mode's wavelength, "$\lambda_{L03}$". The spacing was selected as such, to improve the amplitude of the mode, however the number of elements (i.e. magnets) chosen was arbitrary.

The 2D FFT results for those configurations are shown in the Figures 4, and 5. The parameters used in the 2D FFT analysis are summarised below:

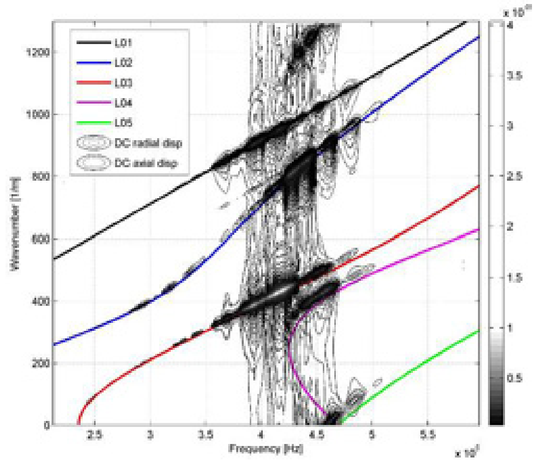
- The time stepping was $2e^{-7}$s. The resulting maximum frequency range was 5 MHz and the resulting resolution was 2 kHz.
- The distance stepping was $5e^{-3}$ m. The resulting maximum wave-number covered by the analysis was $1291m^{-1}$ and the resulting resolution was $3.23m^{-1}$.

The content of the generated field was dissociated and appeared to be in agreement with the dispersion curves obtained using the Eigen-frequency analysis of COMSOL (Figures 4).

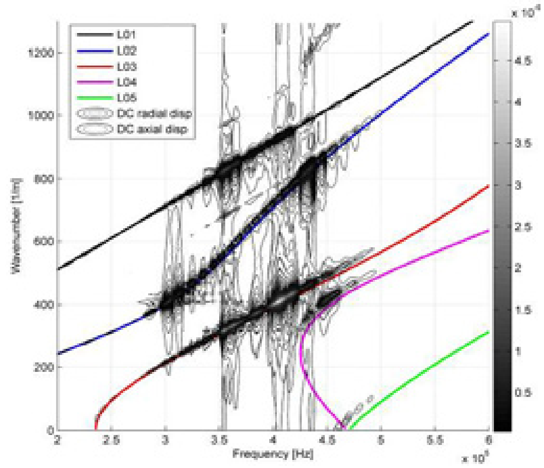
Figures 5 clearly shows an improvement of the L(0,3) mode spectra amplitude in the case of the selective NCET. In fact the amplitude of this mode increased compared with the case of the standard NCET, and the amplitude of the L(0,4) and L(0,5) decreased.



a) Conf. 1: Full magnet without spacing

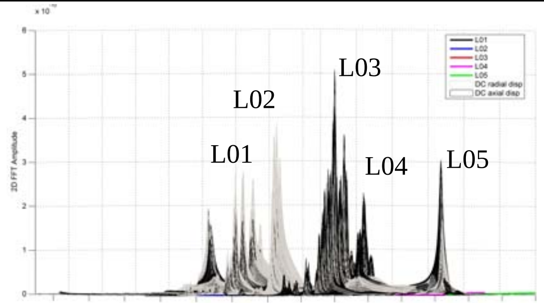


b) Conf. 2: Series of 7 magnets with $\lambda_{L03}$ spacing

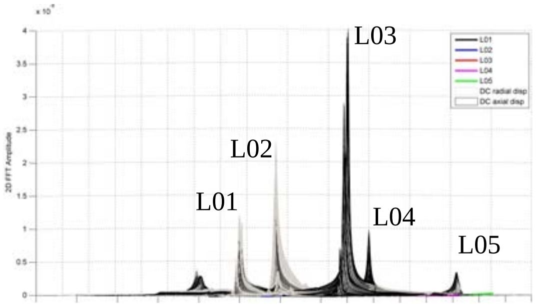


c) Conf. 3: Series of 14 magnets with $\lambda_{L03}$ spacing

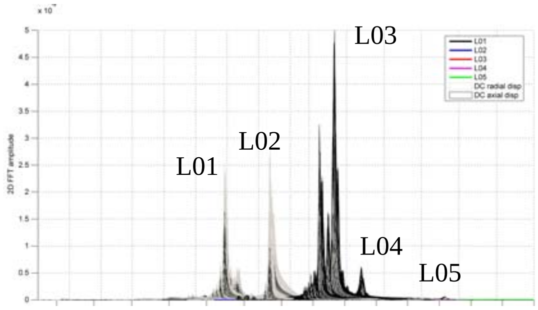
**Figure 4.** 2D FFT analysis of the mode content for various NCET configurations.



a) Configuration 1: Full magnet without spacing



b) Conf. 2: Series of 7 magnets with λL03 spacing



c) Conf. 3: Series of 14 magnets with λL03 spacing

**Figure 5**. 2DFFT amplitude of the modes for various NCET configurations.

Table 3 summarises the maximum amplitude obtained for the various modes, after 2D FFT post-processing for the three configurations previously studied (Figure 5). It can be noted that the amplitudes obtained with the use of multi-element magnets were improved from the original configuration.

Moreover, the increase of elements enabled to increase the amplitude of L(0,3) and decrease the one of unwanted modes, such as L(0,4) and L(0,5).

Notice that most of the L(0,3) and L(0,4) mode content appears in the axial DC, the L(0,1) and the L(0,2) mode content appears in the radial DC (figures 5). The axial component of the mode is more likely to be detected using NCET as a receiver transducer.

**Table3:** Summary of modes maximum amplitude obtained after 2D FFT for various configurations

| | **Maximum Amplitude ($10^{-9}$)** | | | | |
|---|---|---|---|---|---|
| **Conf.** | **1** | **2** | | **3** | |
| **L(0,1)** | 0.2 | 1.1 | **+0.9** | 2.5 | **+2.3** |
| **L(0,2)** | 0.4 | 2.3 | **+1.9** | 2.7 | **+2.3** |
| **L(0,3)** | 0.5 | 4 | **+3.5** | 5 | **+4.5** |
| **L(0,4)** | 0.3 | 1 | **+0.7** | 0.6 | **-0.3** |
| **L(0,5)** | 0.23 | 0.3 | **+0.07** | 0.1 | **+0.13** |

## 5. Conclusions

The work carried out in this paper showed that COMSOL can be used to develop the modelling and the optimisation of guided wave generation and properties in order to inspect tubular structures such as pipes. The results were well correlated with the Eigen-frequency approach. In this paper, using multiphysics interaction, a new concept for generating GUW using non-contact transducers has been established. A high frequency range was selected in the order of 3mm.MHz. This range corresponds to a wavelength of 15mm ($\lambda_{L03}$) which allow the short range inspection using high resolution. The optimisation of the NCET transducer using multi-magnets with constant spacing proved to be very efficient to select one mode and reduce the amplitude of undesired modes, such as L(0,4) and L(0,5).

## 6. Further work

Further work will be carried out experimentally to validate the NCET approach. Experiments will be conducted to prove the performance of the L(0,3) mode when testing fluid loaded pipes.

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## 8. Acknowledgements

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## 9. Appendix

The table below presents the numerical values of the wave modes calculated using the Eigen-frequency analysis of COMSOL. The number $n$ was deduced based on the post processing of the displacement shape; it represents the number of the resulting of wavelength of the pipe deformation. $\lambda$ was then deduced from the following formula (4):

$$\lambda = L/n. \tag{4}$$

where $L$ is the length of the pipe ($L$=40mm).

| *f(Hz)* | *n* | *λ(mm)* | *c(m/s)* | *k(1/m)* |
|---|---|---|---|---|
| 13465 | 0.5 | 80.00 | 1077 | 79 |
| 15641 | 0.5 | 80.00 | 1251 | 79 |
| 36070 | 1 | 40.00 | 1443 | 157 |
| 66818 | 0.5 | 80.00 | 5345 | 79 |
| 67827 | 1.5 | 26.67 | 1809 | 236 |
| 104124 | 2 | 20.00 | 2082 | 314 |
| 132206 | 1 | 40.00 | 5288 | 157 |
| 142295 | 2.5 | 16.00 | 2277 | 393 |
| 181192 | 3 | 13.33 | 2416 | 471 |
| 194712 | 1.5 | 26.67 | 5192 | 236 |
| 220295 | 3.5 | 11.43 | 2518 | 550 |
| 246307 | 0.5 | 80.00 | 19705 | 79 |
| 251258 | 2 | 20.00 | 5025 | 314 |
| 259371 | 4 | 10.00 | 2594 | 628 |
| 274540 | 1 | 40.00 | 10982 | 157 |
| 297347 | 2.5 | 16.00 | 4758 | 393 |
| 298322 | 4.5 | 8.89 | 2652 | 707 |
| 313028 | 1.5 | 26.67 | 8347 | 236 |
| 330777 | 3 | 13.33 | 4410 | 471 |
| 337112 | 5 | 8.00 | 2697 | 785 |
| 355723 | 3.5 | 11.43 | 4065 | 550 |
| 356698 | 2 | 20.00 | 7134 | 314 |
| 375741 | 5.5 | 7.27 | 2733 | 864 |
| 377883 | 4 | 10.00 | 3779 | 628 |
| 400395 | 4.5 | 8.89 | 3559 | 707 |
| 402476 | 2.5 | 16.00 | 6440 | 393 |
| 414221 | 6 | 6.67 | 2761 | 942 |
| 424432 | 5 | 8.00 | 3395 | 785 |
| 426475 | 1.5 | 26.67 | 11373 | 236 |
| 431333 | 2 | 20.00 | 8627 | 314 |
| 433116 | 1 | 40.00 | 17325 | 157 |
| 448173 | 0.5 | 80.00 | 35854 | 79 |
| 448270 | 3 | 13.33 | 5977 | 471 |
| 450275 | 5.5 | 7.27 | 3275 | 864 |
| 451987 | 2.5 | 16.00 | 7232 | 393 |
| 452573 | 6.5 | 6.15 | 2785 | 1021 |
| 477856 | 5.5 | 7.27 | 3475 | 864 |
| 490140 | 3 | 13.33 | 6535 | 471 |
| 490818 | 7 | 5.71 | 2805 | 1100 |
| 492447 | 3.5 | 11.43 | 5628 | 550 |
| 497254 | 0.5 | 80.00 | 39780 | 79 |
| 506985 | 6.5 | 6.15 | 3120 | 1021 |
| 528723 | 1 | 40.00 | 21149 | 157 |
| 528978 | 7.5 | 5.33 | 2821 | 1178 |
| 533696 | 4 | 10.00 | 5337 | 628 |
| 537448 | 7 | 5.71 | 3071 | 1100 |
| 540765 | 3.5 | 11.43 | 6180 | 550 |
| 563909 | 1.5 | 26.67 | 15038 | 236 |
| 567074 | 8 | 5.00 | 2835 | 1257 |