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Finite element simulation of guided waves in pipelines for long range monitoring against third party attacks

Salisu El-Hussein, John J. Harrigan and Andrew Starkey

Lloyd's Register Foundation Centre for Safety and Reliability Engineering, School of Engineering, University of Aberdeen, Aberdeen AB24 3UE, United Kingdom

Email:r02se13@abdn.ac.uk

Abstract. Guided waves (GW) are finding more applications for structural health monitoring (SHM) of pipelines and other long, slender structures, particularly in the areas of corrosion and crack detection. Third party impact, both accidental and intentional, is also a major cause of pipeline failure. The use of low frequency (below 10 kHz) GW to detect damage caused by a third-party is investigated. Field test data on a 1 km long pipeline are compared with finite element (FE) predictions to illustrate the potential of low frequency GW to travel long distances along a pipeline. An FE study indicates the type and frequency of GW that can propagate long distances (low attenuation) without significant change in shape (low dispersion). The FE analysis is conducted on a typical 10 in (255 mm) diameter steel pipe with 7.8 mm wall thickness. The effects of pipe diameter and thickness on the GW propagation characteristics are illustrated. It is shown that certain frequencies for certain pipe geometries produce a very dispersive signal and should be avoided for GW SHM and the reasons for this are discussed.

1. Introduction and Background

Vandalism and stealing from petroleum product pipeline has been a major problem in the Niger-Delta area of Nigeria. The consequence of this is huge in terms of repair cost, environmental damage and fatalities. It was reported that a total of 15,796 cases of pipeline vandalism was recorded in Nigeria between 2000-2010 with 2,800 fatalities, about $1.2bn cost of repairs and daily revenue loss to the government of about $10.4million [1]. This research is investigating the potential use of GW for pipeline monitoring to detect third party interference such as act of vandalism and theft. GW propagates in a thin material thickness of the waveguide in similar fashion to Rayleigh and Lamb waves. Plates, rods and hollow cylinders are the common example of natural waveguides. Unlike the longitudinal and shear waves their velocity is not only dependent on the material properties but also on the thickness of the material and propagation frequency. Its propagation is in one dimension which allows the retention of energy thereby ensuring long distance propagation with potentially low energy loss. GWs are also natural properties of the waveguide similar to a natural vibration; hence, changes in the waveguide in the form of damage can be used to detect and locate the damage. The major challenges of GW application are the energy dissipation (material attenuation), dispersion (phase velocity dependence frequency) and attenuation due to reflections from features such as welds and supports.

The interest in the use of GW in SHM is stimulated by its ability to propagate long distances along slender structures allowing 100 percent circumferential monitoring [2]. Other advantages of GW over the conventional methods include: cost effectiveness (of about 5%) and inspection speed [3]. GW can also propagate over curved and straight surfaces and is applicable for both ferromagnetic and non-ferromagnetic materials [4]. These advantages provide the incentive for the choice of GW in this research work. The behaviour of GW in the ultrasonic frequency regime is well researched and documented [5-8] and has been successfully employed as a pipe inspection tool [9, 10] over short distances. This is evidenced by their use in through-thickness Non-destructive testing (NDT) and short range in-plane Non-destructive Evaluation (NDE) of structures. The current research is focussed on low frequency GW (below 10 kHz). Numerical analysis of GW propagation at low frequencies was carried out using Abaqus/Explicit Commercial FE analysis software. It is shown that the use of selected low frequency-mean diameter product can achieve long distance monitoring. To verify the FE result a field test data on 1 km pipeline was analysed. This paper reports the potential of GW for long distance propagation along a pipeline. A brief introduction and background of the research is given in section one followed by a short discussion on GW in cylindrical structures in section 2. Current GW long range application is discussed in section 3. The potential of low frequency GW for long range monitoring is discussed in section 4; followed by long range propagation potential from field test in section 5. Discussion and conclusion are contained in section 6.

2. Guided Waves in Cylindrical Structures

Cylindrical waveguides support 3 modes of GW vibrations: longitudinal, torsional and flexural while for plate like structures only longitudinal and shear horizontal modes are supported. The governing equation for bulk wave and GW are the same; only that a traction free boundary condition needs to be satisfied for GW. The main difference is that GWs are multi-modal and more of these modes are produced in cylindrical waveguides. Fig.1 shows the schematic of a traction-free hollow cylinder with inner and outer radius ‘a’ and ‘b’ respectively. Under each of the 3 modes, several other modes are produced depending on the frequency-thickness product. According to the convention by Silk and Bainton [11] these modes are labelled as *L(0,m), T(0,m)* and *F(n,m)* for longitudinal, torsional and flexural modes respectively. The letter ‘*m*’ represents the GW vibration within the pipe wall thickness while ‘*n*’ describes the number of spiral vibrations of the pipe as a whole. Each of the 3 modes is distinguished by its particles displacement fields in the radial, circumferential and axial directions, as described by the following equations:

$$\begin{aligned} u_r &= U_r(r)\cos n\theta \cos(\omega t + kz) \\ u_\theta &= U_\theta(r)\sin n\theta \cos(\omega t + kz) \\ u_z &= U_z(r)\cos n\theta \sin(\omega t + kz) \end{aligned} \tag{1}$$

where ω is the angular frequency, kz is the component of wave vector in the axial direction and n = 0,1,2,3,… which describes the spiral propagation of GW around the circumference. The axisymmetric modes correspond to the situation where the displacement field has no angular component (i.e. $n = 0$). Non-axisymmetric modes have ‘*n*’ sinusoidal variation along the circumference (i.e. $n \neq 0$). The quantities U_r, U_θ and U_z are the displacement amplitudes composed of Bessel functions. The displacement fields in the material are obtained by the summation of partial bulk waves in the form of matrix, called ‘characteristics function’.

$$\left|c_{ij}\right| = 0, \qquad (i, j = 1 \ \ to \ \ 6) \tag{2}$$

Eq. (2) is the dispersion equation for GW propagating along a pipe as a function of inner '*a*' and outer diameter '*b*' of the pipe, Lame's constants λ and μ, angular frequency ω and wavenumber [3]. When the wave number *n = 0*, the determinant matrix in eq. (2) can be expressed as product of sub determinant $D_1 D_2 = 0$.

$$D_1 = \begin{vmatrix} c_{11} & c_{12} & c_{14} & c_{15} \\ c_{31} & c_{32} & c_{34} & c_{35} \\ c_{41} & c_{42} & c_{44} & c_{45} \\ c_{61} & c_{62} & c_{64} & c_{65} \end{vmatrix} \text{ and } D_2 = \begin{vmatrix} c_{23} & c_{26} \\ c_{53} & c_{56} \end{vmatrix} \qquad (3)$$

Where $D_1 = 0$, corresponds to the longitudinal wave propagation in which the particle's displacement is independent of angular coordinate while $D_2 = 0$, refers to the torsional wave propagation in which the particle's displacement is dependent on angular coordinate only. The detailed derivation of this equation can be found in [4].

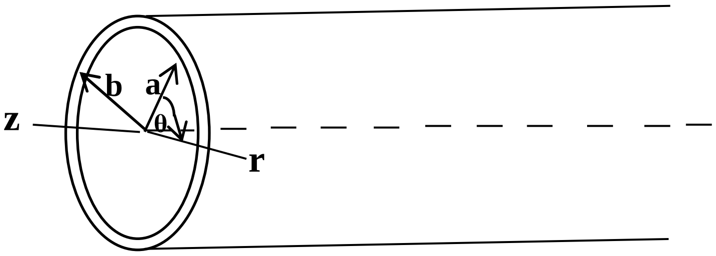

Figure 1. Schematic of hollow cylinder with inner radius 'a' and outer radius 'b' and cylindrical coordinate

An important aspect in the use of GW in SHM is the excitation of the required mode (selective excitation). Multiple modes excitation generates signals which are difficult to interpret. Single mode excitation within its non-dispersive region is therefore a prerequisite for a successful long range GW application.

3. Long range guided wave application

GW has potential to achieve the objective of SHM of providing real-time data on the state of a structure to be monitored. Its application involves sending a wave pulse through a probe attached to a structure to be examined and recording the reflected signals from defects and features along the structure as shown in fig. 2. However, there is a trade-off between the potential propagation distance and the sensitivity to detect defects. The sensitivity of GW is frequency dependent and as the frequency reduces, the sensitivity to defect also reduces. Hence, GW is currently being applied in short (< 5 m), medium (up to 5m) and long (< 10m) range depending on the frequency used [6]. The predominant application areas have been on elongated structures such as pipeline and rail line networks. A GW rail inspection system with the potential to inspect 100 m of rail from a single position was jointly developed by Imperial College and Guided Ultrasonics Ltd [12]. A 1 km GW monitoring range has been reported for the detection of breaks in the railway line [13]. A portable GW rail inspection system was also developed at Pennsylvania State University using electromagnetic acoustics transducer (EMATs) [14]. GW has also being used for defect detection in bones [15], plate [16] and rock bolt testing [17] for mine roof support. In the area of pipeline inspections there are many commercial vendors such as Plant integrity Ltd, Wavesinsolids LLC (WINS), MISTRAS Asset Property Solution, etc., with varying reported inspection distance ranging from 35 m to 300 m. All these operate at higher frequencies above 200 kHz. To date GW application in the low frequency region is yet to be fully exploited. As human ingenuity in the area of inspection and monitoring continues to grow, understanding the behaviour of GW at low frequency will further expand its application boundary especially in elongated structures. FE analysis of GW propagation in pipes can provide the understanding that is required to extend the inspection distance.

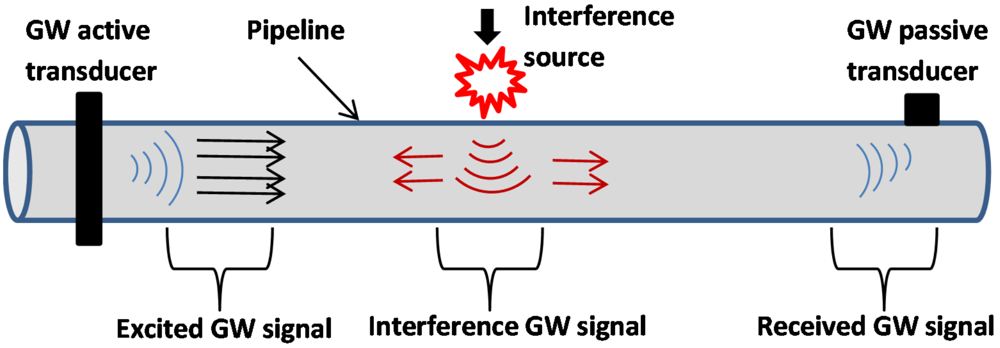

Figure 2. Illustration of guided wave inspection/monitoring techniques

4. Long range guided wave finite element simulation

GW propagation along 10 in pipe 1000 m long, with 7.8 mm wall thickness was simulated in Abaqus/Explicit on a High Performance computer Cluster (HPC). A L(0,1) GW mode was excited by applying a uniform pulse load from one end of the pipe as shown in fig. 3. The pulse load was excited with 5 cycles tone burst modified by Hanning window with a centre frequency of 2.5 kHz. Stresses, displacements and acceleration signals were recorded at 3 nodal positions, 125 m, 250 m and 500 m away from excited end. The nodes positions were chosen so that they correspond to the same nodes positions used in a field test discussed in section 5. Each of these (stress, displacement and acceleration) signals can be used to determine the characteristics of the propagated wave. Here displacement signals were used. Fig. 4 (a) and (b) show the time domain displacements at the 3 nodal positions and their corresponding frequency spectrum respectively. The dispersion and attenuation of the signals were low at this centre frequency as observed from the fig.4 (a) and (b). The propagation characteristics (wavenumber, attenuation and phase velocity) were determined using the transfer function between the nodes 1 and 2 signals and shown in fig.5. Up to 5 kHz (where the magnitude of the signal spectrum is significant), the attenuation is low and dependence of phase velocity on frequency is nearly constant. This shows the potential of GW long range propagation at this region.

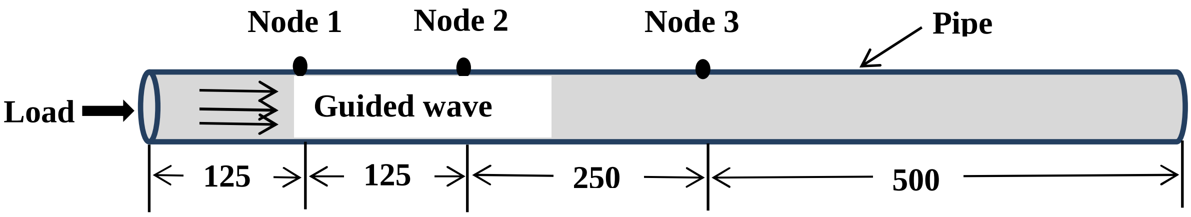

Figure 3. Schematic of the pipe used in FE model and the nodes positions

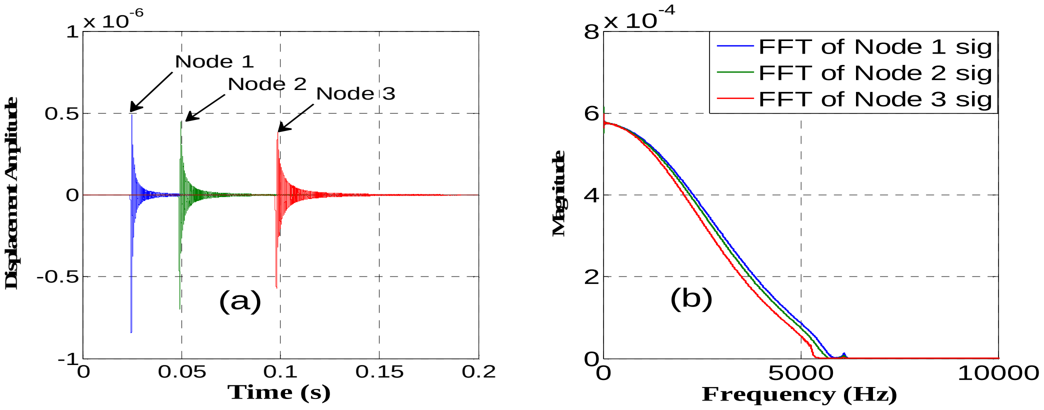

Figure 4. Displacements signals recorded at the nodal positions (a) time domain and (b) its corresponding frequency spectrum

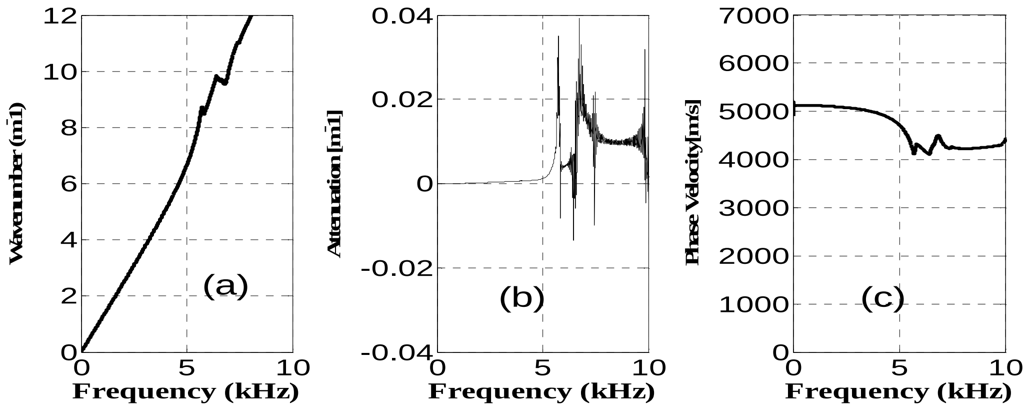

Figure 5. propagation characteristics between nodes 1 and 2 signals

4.1. Effect of frequency-diameter on guided wave propagation

A frequency sweep of 1 – 10 kHz was carried out to investigate the relationship between the centre frequency of the input signal and external diameter of the pipe. It was discovered that at certain frequencies the generated GW was excessively dispersive and does not decay to zero. The reason for this is that GW in pipe has wavenumber in both axial and circumferential direction. Along the length of the circumference, there are 0,1,2…n wavelength λ. Where the λ of the input signal is comparable to the circumferential dimension of the pipe, this type of dispersion is observed. At this region, other frequencies were excited which make the signal processing difficult. For a 12 in diameter pipe, this happens when the centre frequency of the input signal was 5 kHz. Fig.7 (a – f) illustrates the effect of the external diameter and the wavelength of the input signal. At centre frequency of 2.5 kHz, the λ is about 2.064 m which is not comparable to the pipe circumference of 0.958 m and hence, a good signal was recorded as shown fig.7 (a) and (b). When the frequency of the input signal was changed to 5 kHz (λ now 1.032 m), the signal becomes dispersive as shown fig. 7 (c) and (d). The external diameter was then increase to 25 in (635mm) and 2.5 kHz centre frequency was used, the signal was again dispersive as was the case with 5 kHz centre frequency as shown in fig.7 (e) and (f). Therefore, the selection of the right input signal frequency would enhance signal purity, reduce dispersion and ensure long propagation with retention of sufficient signal energy. The results show the need for frequency selection for different pipe dimension in order to achieve long range potential of GW propagation along a pipeline.

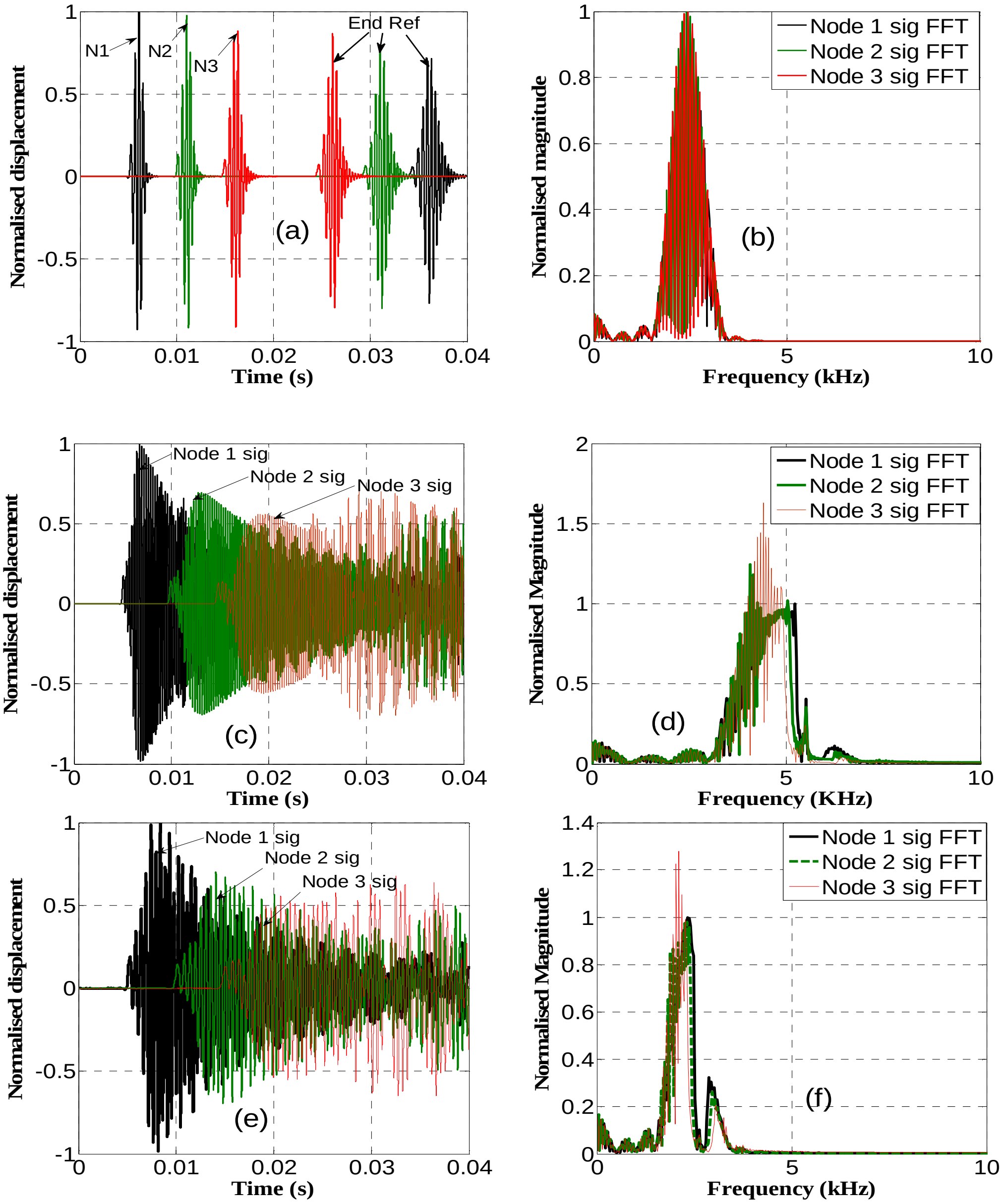

Figure 6. Time domain and frequency spectrum (a, b) 12 in pipe with 2.5 kHz Centre frequency (c, d) 12 in pipe with 5 kHz Centre frequency and (e, f) 25 in pipe with Centre frequency of 2.5 kHz

5. Potential guided wave long distance monitoring from field tests

A field test data conducted on a 1 km long pipeline looped with a 5D bends (i.e. bend radius of 5 times the nominal diameter) was analysed for long range propagation of GWs. The test was carried out by TBG Solution Ltd, a specialist control and automation company which is developing technology for automatic detection of pipeline theft (ADEPT). The test pipe is coated with 5 mm bitumen and has flange connections at approximately every 20 m. PCB Piezotronics 3-wire TO-8 accelerometer (1000mV/g, range 0.13 -800 Hz), PCB Piezotronics 2-wireT0-8 accelerometers (1000mV/g, 0.32 – 8000 Hz) and Hansford HS-100 series accelerometers (100mV/g, 2- 10000 Hz) were used to record the vibration signals. Fig.7 shows the test pipeline loop and position of the sensors. The pipeline has 10 in (254 mm) outer diameter and 7.8 mm wall thickness coated with about 5 mm thick bitumen. Drop tests with a 534 g ball bearing were conducted at heights 2 cm – 50 cm above the pipeline. An

FE model of a similar pipe (but without the bitumen coating) was also created with a simulated ball bearing drop similar to the field trials, and Fig.8 shows the frequency domain analysis comparison of the field tests with the FE results. The field signals were recorded at about 500 m away from the initial impact point where the ball bearing was dropped onto the pipeline while FE signals were taken at a nodal point 25 m away from the ball bearing drop point due to memory and processing constraints on the FE model. The field test result confirms the low attenuation of GW discussed in section 4, with the figure showing the presence in the signal of low frequencies that match the profile of the simulated ball bearing drop (particularly centred on 1.5 kHz). It can be observed that the energy of the propagated frequency in the field tests shows no signal above approximately 2.5 kHz, whereas the FE results do exhibit a frequency response in these higher frequency regions. These results show how the frequency profile over longer distances has changed and that the higher frequencies have higher attenuation and effectively disappear from the analysis, whereas the lower frequencies particularly in the main dominant frequency range produced by the ball bearing drop continue to propagate through the pipeline. This result confirms the potential for long distance propagation of GW through pipelines, at defined frequency ranges which will be determined by the physical attributes of the pipeline as explained in section 4.

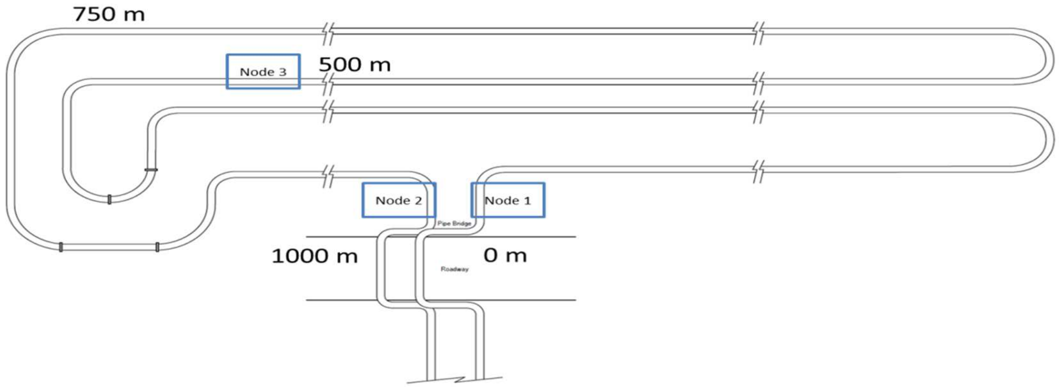

Figure 7. Pipeline loop Layout used for the field test (Source: TBG SOLUTION LTD)

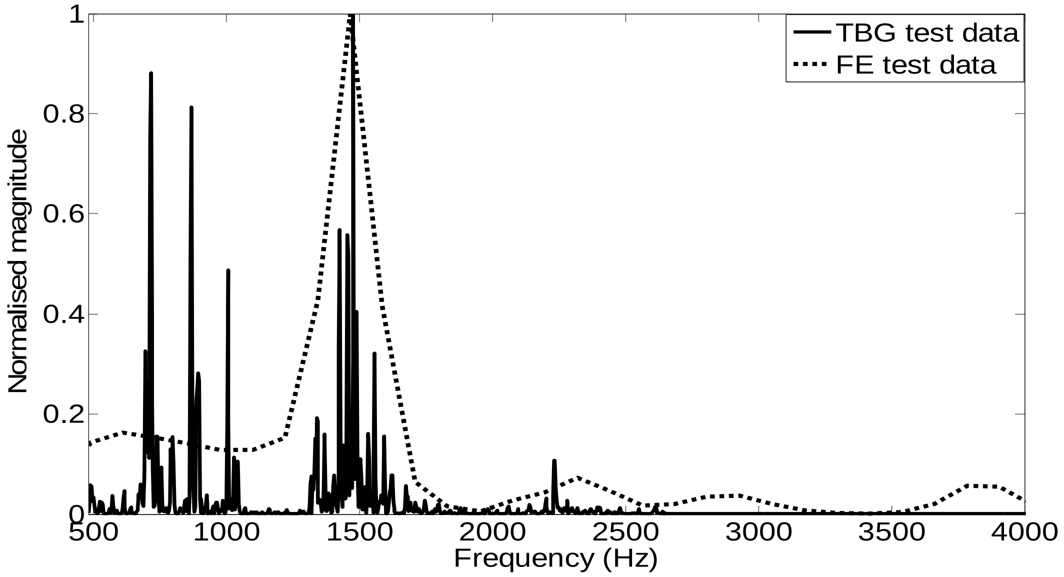

Figure 8. Comparison of frequency content of TBG field test and FE results

6. Discussion and Conclusion

Conventional ultrasonic waves propagate with constant velocity whereas GW velocity varies with waveguide geometry and frequency. Low frequency GW has been shown to have potential to propagate long distance and still retain sufficient energy for detection. In GW propagation, the waveguide plays a more significant role in determining the characteristics of the transmitted signal than the input signal. This is evident in the input frequency and external diameter relationship. However, the input signal has significant effect on the quality of the GW propagation along a pipeline when its wavelength (which has inverse relationship with frequency) is comparable in dimension to the length of the pipe circumference. This region should be avoided for long range GW monitoring and inspection. The good news is that, at low frequency, the wavelength is large; hence, a wide range of pipelines can be excited without approaching the unwanted frequency-diameter region. For example at 2.5 kHz, the wavelength is about 2 m and corresponding unwanted external diameter with about 2 m circumferential length is for about 25 in diameter pipe. The frequency spectrum of the generated GW from ball bearing drop field tests on a 1 km pipeline shows that the energy of the signal concentrated below 3 kHz and can propagate through long distances, and the results at these lower frequencies agree with a scaled FE ball bearing drop simulation results. The results from FE and field tests indicate the potential of low frequency GW for long range monitoring applications. The multimodal nature of GW in particular poses difficulty in exciting, reception and processing of the required signals. Despite these shortcomings, GW application has advantages over the conventional methods such as cost effectiveness, inspection speed and ability to propagate over curved and straight surfaces. Further work and field trials is required to prove the effectiveness of GW for SHM purposes.

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