

Optimization of Low-Frequency Shear Wave Transducers for Guided Wave Applications

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Abstract: Development of ultrasonic transducers for the excitation of a torsional mode $T(0,1)$ mode in a large pipe of the material typical of actual oil/gas pipelines is discussed. Towards this, 16 ultrasonic transducers are designed and fabricated using shear plates of PIC 255 material, backing mass of tungsten-epoxy composite and brass shims as wear plates. The transducers are qualified using Laser Doppler Vibrometry. Then, the transducers are embedded in a spring-loaded ring and tested on a pipe using a multi-channel ultrasonic system. The results show the successful excitation of $T(0,1)$ mode and it is seen to propagate for distance of 60 m with a good SNR.

Keywords: Ultrasonic guided waves, torsional mode, shear PZT plates, ring array transducer design, pipe testing

Background, Motivation and Objective

The structural integrity of pipelines is critical in oil/gas and chemical industries. A large percentage of world's primary fuels namely, gas and oil are transported by pipelines. Although, the pipes are manufactured and operated in accordance with established standards, they can pose a high risk to human life and environment, in the case of failures, due to the products they carry. Adhering to established standards, good design and construction might mitigate the problems. However, the structural integrity of the pipelines is also threatened by defects (corrosion, erosion, cracks, mechanical damage etc.) that can occur in-service. These service-induced defects are the main cause of failures. This translates to routine non-destructive testing (NDT) and structural health monitoring (SHM) to identify potential defects for safe operation. Traditional ultrasonic bulk-wave methods are reliable due to limited in-sonification and point-by-point screening but are not suitable for inspecting long pipelines, whereas ultrasonic guided-wave (UGW) methods can inspect longer distances but encounter challenges like dispersion and multiple wave modes [1]. Exciting a single, non-dispersive wave mode is essential. Excitation of a non-dispersive mode in a pipe can allow examination of the entire volume of the pipe for many tens of meters (~ 100 m) from a single point of excitation, thus paving the way for rapid screening and reducing maintenance costs and inspection time [1]. Usually, UGWs for pipe testing are operated at much lower frequencies (\sim kHz) to support propagation over long distances with minimal attenuation [1].

The solutions of Navier's equation dictate that three types of guided waves propagate along a pipe's axial

direction: longitudinal $L(0,n)$, torsional $T(0,n)$, and flexural $F(m,n)$ modes [2]. The integer variables, m and n refer to the circumferential variation of the displacement fields and the mode number, respectively. Zeros in L and T indicate no variation of fields around the circumference and hence, $L(0,n)$ and $T(0,n)$ are axisymmetric. $F(m,n)$ modes are non-axi-symmetric in nature. Axisymmetric modes L and T are preferred for long-range inspection and defect detection. The fundamental torsional wave mode, $T(0,1)$, is advantageous due to its completely non-dispersive nature and minimal interaction with low-viscosity fluids due to its shearing nature. There are various transducer solutions to generate $T(0,1)$ mode, which include electromagnetic acoustic transducers (EMATs), magnetostrictive devices, and piezoelectric transduction [3]. EMATs and magnetostrictive devices require a large biasing for good electromechanical coupling and efficiency and are prone to high levels of noise, while piezo-based transduction involves high efficiency, high SNR, high sensitivity, compact size, and ease of fabrication. There are a few commercial portable PZT based guided wave inspection systems available that involve dry coupling by distribution of transducers around a pipe either by clamping mechanism or pneumatics. The technical know-how in the public domain for making one is limited or patented and furthermore, they are prohibitively expensive. PZTs used for $T(0,1)$ mode are usually $d15$ thickness shear plates with the variation of shear displacements along the thickness of the PZT. Bonding thickness shear PZTs to a pipe can excite $T(0,1)$ mode, but suffers from an inefficient transfer of shear strains to the pipe and in addition, retrieval of PZTs without damage after examination is

also difficult. The generation of T-mode based on d24 and d36 face shear PZTs with d24 generating almost pure T(0,1) mode is reported [3]. However, this study focuses on the development of piezo-based transduction with the use of d15 thickness shear plates of PIC 255, a soft ceramic from PI Ceramic to excite and receive T(0,1) mode. First, individual transducer elements were designed and fabricated in-house, and were embedded in a ring. Secondly, the transducers were spring loaded for dry coupling onto the pipe. Finally, experiments were conducted to check the performance of the proposed transducer ring. The technique employed was the pulse-echo method. The study shows very promising results for SHM of pipelines and the technique is simple to employ at site for operation.

Mode Selection from Dispersion Curves

As mentioned above, T(0,1) mode is the targeted mode for this study. The pipe used was a carbon steel pipe (S235JRH) of outer diameter 88.9 mm and the wall thickness of 3.2 mm. This material is commonly found in oil/gas pipelines with minor variations in alloying elements. To select the range of frequencies, dispersion curves were traced using an in-house developed Scaled Boundary Finite Element Method (SBFEM) code [4]. Figure 1 shows the group velocity dispersion curves. The T(0,1) mode is totally non-dispersive in the frequency range of 0-200 kHz. It can be seen in the figure that T(0,1) mode is surrounded by F(n,1), F(n,2) and F(n,3) modes. The mode shape of F(n,1) mode is similar to that of L(0,1) mode with a small circumferential component. F(n,2) modes are similar to T(0,1) modes and have a large circumferential component with the axial component becoming significant at higher frequencies [3]. F(n,3) modes have significant circumferential and axial displacements at lower frequencies. In the frequency range of 90-150 kHz, the circumferential displacement is significantly lower. Assuming similar excitation efficiencies of F modes and with the aim to suppress their excitation, the number of exciters was chosen to be 16 as a trial.

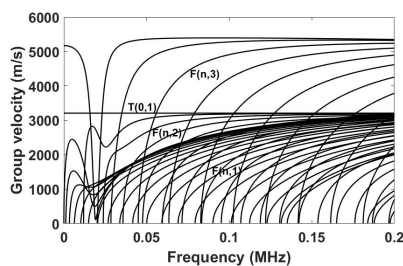


Fig. 1: Group velocity dispersion curves for a carbon steel pipe of outer diameter 88.9 mm and the wall thickness 3.2 mm.

Fabrication of Transducers and a Ring and Experimental setup

PIC 255 shear plates of dimensions 8 mm × 8 mm × 1 mm were used. Each plate has a wrap-around electrode with an electrode-free gap of 0.5 mm. The resonant frequency of the PZT is 890 kHz and the present study involves non-resonant regions of the frequency response of the PZT. Non-resonant regions have relatively flat frequency response leading to uniform excitation. CAD models of enclosures were designed and 3D printed using PLA (polylactide) material. The thickness and height of the enclosure were 1 mm and 20 mm, respectively. The PZT was mounted to the front of the enclosure and glued. A backing mass made of tungsten-epoxy was prepared and cured on the back of the PZT. Towards this, a mixture of tungsten powder of particle size $\sim 10 \mu\text{m}$ size and epoxy resin (Epotek 301-2) was prepared. The volume fraction of the tungsten powder was approximately 50% in epoxy, which was seen to reduce the ringing significantly. This volume fraction was obtained based on a finite element model developed by us incorporating tungsten-epoxy mixture as inhomogeneous random medium. The results of this are not presented here. The height of the backing was 6 mm, and the remainder of the enclosure was filled with epoxy through which wires from the PZT pass. The enclosure was sealed, and brass sheet of 0.1 mm was glued to the front of the PZT to avoid wear and provide rigidity to the PZT. The performance of the transducers was assessed using a Laser Doppler Vibrometer (LDV) from Polytec. Finally, a ring was prepared using PLA material by 3D printing. The spacing between transducer units was kept at 45° . Each 45° location is flanked by two transducers separated by 5 mm, which makes 16 transducers in total. The transducers were spring loaded, and a screw mechanism was provided to compress the springs onto the transducers. Each spring was calculated to provide 100-150 N force to the transducer. Figure 2 shows the transducer loaded ring mounted close to one end of a 3.0 m long pipe of outer diameter 88.9 mm and 3.2 mm wall thickness. The transducers in the ring were connected to the low-frequency version of Versonics Vantage system, which has the capability of exciting and receiving on 128 channels simultaneously. The system was controlled by a MATLAB loaded computer. The 16 channels were excited in phase and in parallel by 10-cycled windowed tonebursts of frequency 90-150 kHz in the step of 10 kHz and the data were collected in parallel and summed to obtain T(0,1) mode.

Results and Discussion

Figure 3 shows the shear deformation of the PZT plate captured by LDV. Figure 4 shows the average

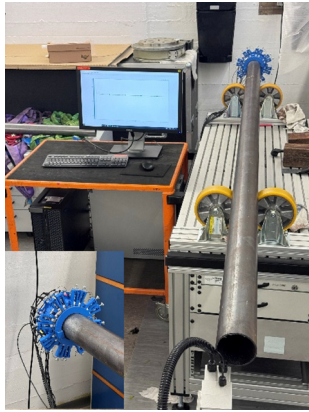


Fig. 2: Experimental setup.

shear displacement (U_x) obtained on the face of the transducer. The transducer was excited with a 50 V Gaussian windowed toneburst of 6 cycles at the center frequency of 110 kHz. The displacement components (U_x , U_y and U_z) were collected from 49 scan points on the face of PZT, as shown in Fig. 3. The signal looks very clean with a good SNR. A minor ringing of 4-5 cycles is also seen to be present in the signal due to minor acoustic impedance mismatch between the PZT and the backing mass. The acoustic impedance of the shear plate PZT is approximately 17 MRayl while that of the backing mass may be close to that causing small energy retention within the PZT after the duration of excitation. This could have resulted from a minor deviation in the volume fraction of the tungsten powder in epoxy during its preparation or a minor discrepancy in the modelling of tungsten-epoxy composite as having smoothly distributed properties. However, for practical purposes, the signal appears clean and can be used for conducting experiments. The out-of-plane component (U_z) and the other in-plane component (U_y) have magnitudes of one order lower than that of U_x . Much lower U_y and U_z are desirable as they might suppress the excitation of longitudinal and flexural modes. It was also discovered that these values are tightly tied to the dimensions of the PZT. And this implies the need for finding the optimized size, which is beyond the scope of the paper. Figure 5a shows the experimental time signal generated by the ring transducer, excited by a 40 V peak Hanning windowed toneburst of 10 cycles at the center frequency of 90 kHz in the 3.0 m long pipe of 88.9 mm diameter and 3.2 mm wall thickness. The 40 dB down point bandwidth of the excitation signal is 240 kHz. The signal appears clean with a good SNR of 20 dB. Furthermore, the signal shows 10 end reflections amounting to the propagation distance of 60 m. Each of the end reflected signals maintains almost

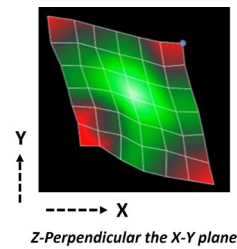


Fig. 3: LDV captured vibration of PZT showing shear deformation.

the same duration indicating that the wavepacket is non-dispersive. There is a gradual fall of the amplitudes due to unavoidable propagation losses. The attenuation of amplitudes turns out to be 0.14 dB/m. The group velocity calculated from the end reflections turns out to be 3200 m/s, which agrees well with the theoretical group velocity of T(0,1) mode of 3206 m/s. This indicates that the mode generated is indeed T(0,1) mode and the ring developed performs well. Furthermore, there are also flexural modes in the signal. However, it is not of serious concern because their amplitudes are extremely small. It can be noticed in the figure that there is a large low frequency portion of the signal at the beginning, which is probably a noise from the receiver amplifier of the system. It can be removed to improve the readability of the signal. Figure 5b is the bandpass filtered version of the signal in Fig. 5a in the range of 40-160 kHz, and it can be seen that the filtering has removed the low-frequency portion of the signal, and the initial zone can now be used for defect detection. However, there is a deadzone of nearly 700 mm, which cannot be avoided. Furthermore, it was also observed that the responses for other frequencies in the range 90-150 kHz were found almost similar. Figure 6 shows the excited amplitudes for various frequencies in the range of 90-150 kHz. The amplitudes are nearly flat indicating similar excitation efficiency of T(0,1) mode in this range validating our assumption. Besides, the signals for higher frequencies in this range also show gradually increasing excitation of flexural modes probably due to the similarity of mode shapes. The SNRs of the signals in the frequency range considered vary from 20-11 dB with higher SNRs for the lower frequencies.

Conclusions

In this paper, the design and development of a ring with ultrasonic transducers embedded for the excitation of T(0,1) mode in large pipes have been presented. First, ultrasonic transducers with shear plates were fabricated in-house, and the performance was assessed by a Laser Doppler Vibrometer. The transducers were

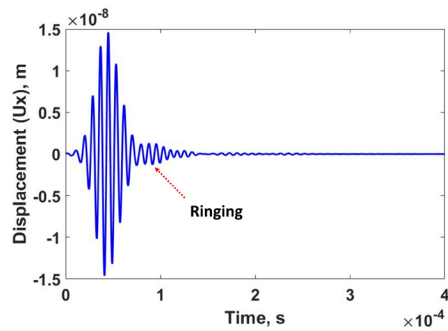


Fig. 4: Average shear displacement (U_x) on the face of the PZT obtained using LDV.

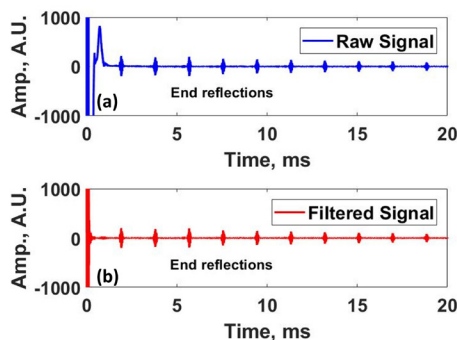


Fig. 5: Experimental signal obtained in a pipe of 88.9 mm OD using a ring of ultrasonic transducers, (a) raw signal and (b) bandpass filtered signal.

found to perform well with a minor ringing. Secondly, a ring was fabricated by 3D printing, and 16 transducers were spring-loaded in the ring, and tested on a pipe. The ring was found to excite the torsional mode $T(0,1)$ successfully, and the mode was found to propagate for a distance of 60 m with reasonable amplitudes. The group velocity obtained experimentally was found to be in good agreement with the theoretical velocity. The mode excited was also found to be very clean. In light of the above promising results, it seems to have a good potential for deployment in actual NDT and SHM for defect detection. Additionally, the use of PIC 255 shear plates and tungsten-epoxy backing demonstrates a cost-effective and efficient approach, offering high SNR for long-range pipeline inspection. The non-dispersive nature of the $T(0,1)$ mode, validated over 60 m, highlights its potential for rapid screening, reducing maintenance costs and inspection time. Future work could focus on optimizing PZT dimensions to further suppress unwanted modes like $F(n,1)$ and $F(n,2)$, enhancing the system's robustness. The spring-loaded ring design proves adaptable for dry coupling, simplifying field deployment. Moreover, the

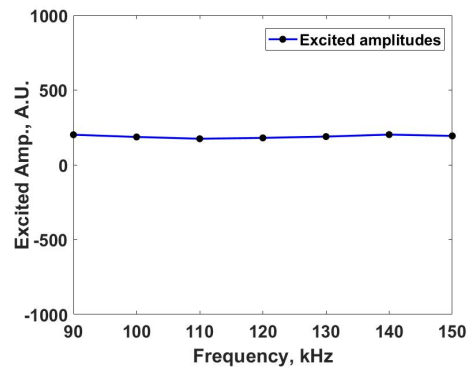


Fig. 6: Excited amplitudes of $T(0,1)$ mode in the frequency range of 90-150 kHz.

minor ringing observed suggests potential improvements in acoustic impedance matching, which could be explored to refine signal quality. This technique's simplicity and scalability make it a viable solution for the oil/gas industry's structural health monitoring needs

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