An Embedded SHM System for Monitoring of Pipelines Using Torsional Guided Wave Ultrasonics

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***Summary*—Ultrasonic guided wave (GW)-based structural health monitoring (SHM) is highly effective for real-time monitoring of emerging defects in infrastructure, including pipelines. Torsional GW modes are of great interest in pipeline monitoring, being non-dispersive and not attenuated by presence of fluids inside pressurized pipes. In this work, we leverage torsional GW modes for monitoring of a metallic pipe using in-plane poled thickness-shear d_{15} PZT transducers and a custom-designed FPGA-based embedded system for transduction and signal processing. The sensor configuration used in this work is suitable for transduction of the axisymmetric torsional mode, confirmed through finite element (FE) simulations and experiments. We also study the interaction of the axisymmetric torsional mode with circumferential defects (crack and notch).**

***Keywords*—Guided wave ultrasonics, torsional mode, pipeline, structural health monitoring**

I. Introduction

Non-destructive guided wave (GW) testing is an attractive method for long-range monitoring and inspection of pipelines. GWs are highly sensitive to incipient defects, and could be used for screening the pipeline for emerging defects and avoid failures [1]. The curved geometry of a pipe leads to complicated mode profiles and therefore poses a highly multimodal and dispersive GW scenario composed of axisymmetric (longitudinal and torsional) and non-axisymmetric (flexural) modes. This makes it difficult to selectively interrogate the desired mode shape and examine changes in the corresponding signal parameters (e.g. amplitude and phase) due to defects. The torsional mode T(0,1) is non-dispersive and less affected by the presence of fluid in a pipe as compared to other modes [2]–[4] (see Fig. 1(a) for dispersion curve of various modes for the steel pipe studied in this work). These modes are also highly sensitive to notch and cracks of varying axial and circumferential extent [5], [6]. Experiments with bidirectional SH wave transducer based on antiparallel in-plane poled d_{15} mode piezoelectric strips have been reported to satisfactorily suppress undesired Lamb wave modes [7]. Most such reports utilize lab-grade GW transducer instruments and are not suitable for permanent deployment on remote, buried pipelines. In such applications, it is therefore imperative to design a low-cost and low-power embedded system for GW transduction of pipelines to realize the true potential of this newly developed SHM technology.

In this work, we report preliminary results to highlight the suitability of an FPGA-based embedded system for transduction of fundamental torsional wave mode T(0,1) in a metallic pipe using d_{15} thickness shear transducers. Finite element (FE) simulations were carried out on a steel pipe with one receiver PZT and varying numbers of transmitter PZTs uniformly placed along the circumference of the pipe. The torsional mode was examined at different actuation frequencies and distance between transducers. The sensitivity of this mode to crack and notch defects was evaluated through FE simulations, and supported with preliminary experimental results.

II. Methods and Results

FE simulations (COMSOL Multiphysics 5.5) and experimental investigation were carried out on a $1\,\mathrm{m}$ long steel pipe of $114.6\,\mathrm{mm}$ outer diameter and $4\,\mathrm{mm}$ thickness, instrumented with shear mode piezoelectric transducers (material properties corresponding to APC International Ltd., 850 WFB) of dimensions $15\,\mathrm{mm} \times 15\,\mathrm{mm} \times 1\,\mathrm{mm}$. The orientation of the PZT transducers, and direction of polarization and electric field were chosen such that torsional modes are excited along the length (axis) of the pipe. The arrangement of transmitters (multiple, 16) and receiver (single) PZTs around the pipe is shown in Fig. 1(b). Simulations were carried out by varying the number of actuators (transmitters). A five-cycle Hanning-windowed sinusoidal pulse with peak-to-peak amplitude of $10\,\mathrm{V}$ and center frequency of $85\,\mathrm{kHz}$ was used for actuation. The choice of excitation frequency was based on the requirement to obtain sufficient separation between group velocity (and hence arrival time) of various modes relative to the desired T(0,1) mode. Defects (circumferential through-thickness notch and crack) were introduced between the transmitters and receiver, and the impact on wave propagation was studied. The simulated signals were compared to experiments carried out on a steel pipe of same dimensions. The transmitters and receiver (APC International Ltd., 850 WFB) were placed at a distance of $300\,\mathrm{mm}$ from each end of the pipe, resulting in transmitter-receiver separation of $400\,\mathrm{mm}$. Fig. 1(c) shows a comparison of the simulation and experimental signal. The PZTs are oriented such that the shear waves are generated in the axial direction of the pipe. Fig. 1(d) shows the transducers connected to an FPGA-based embedded system (Xilinx Artix®-7 XC7A15T-1CPG236C, Digilent Cmod A7-15T module) for transduction and signal acquisition and processing. Details of the embedded system are reported in our prior work [8].

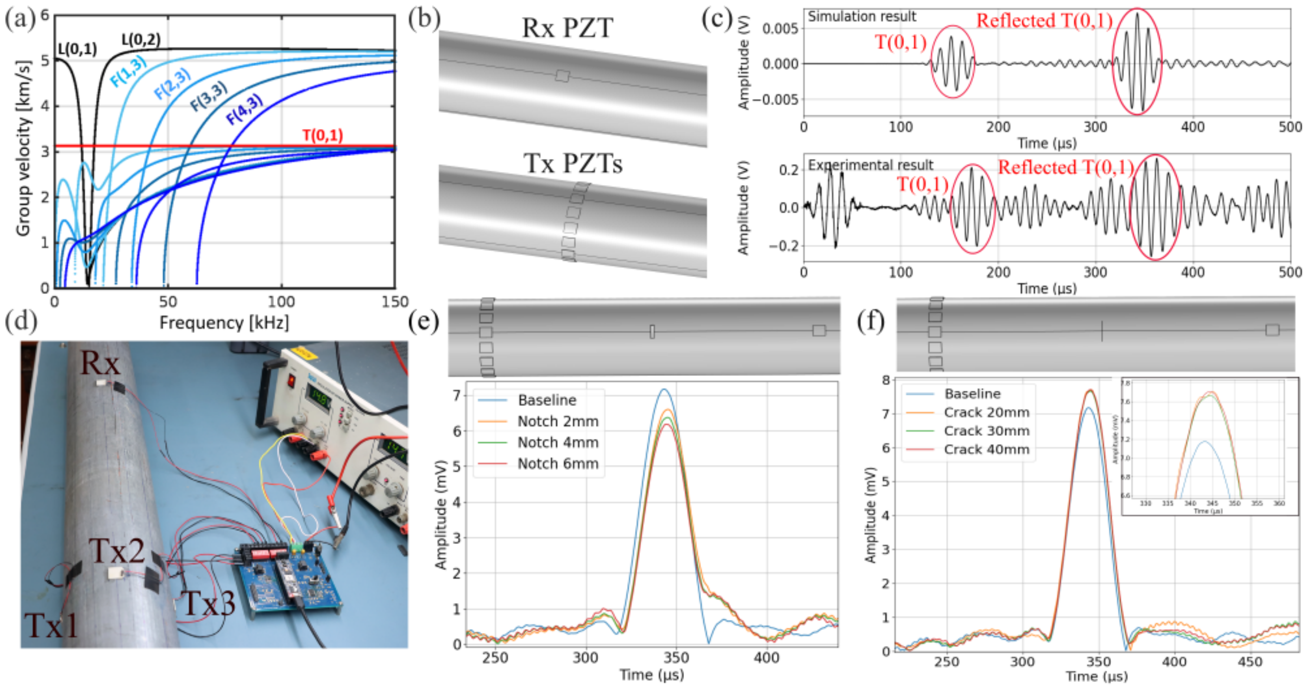

Fig. 1. (a) Dispersion curves of group velocity for GW modes in 4 mm thick steel pipe obtained using GUIGUW software. (b) Placement of transmitter and receiver PZTs on steel pipe for FE simulations. (c) Simulated and experimental result for signal recorded at receiver PZT, showing T(0,1) mode and reflected T(0,1) mode. (d) Photograph of experimental setup showing a steel pipe with PZT transducers attached and an FPGA based embedded system for data logging. (e) Schematic view of defect and Hilbert transform of GW signals for baseline (no defect) and through-thickness notch of varying widths. (f) Schematic view of defect and Hilbert transform of GW signals for baseline (no defect) and with through hole crack of varying lengths (inset: zoom-in).

III. Discussion

Using higher number of transmitters shows greater suppression of non-axisymmetric flexural modes, as seen in simulation results in Fig. 1(c). The experimental results were obtained with only 4 transmitters, and therefore several modes other than the T(0,1) mode are seen, some with arrival time close to that of the T(0,1) mode. Based on the group velocity of T(0,1) mode, the arrival time for the mode is expected to be approximately 150 μs, as seen in both simulation and experimental results. The wave mode at 350 μs is the reflected T(0,1) mode, which has the highest amplitude when excited using 16 PZTs. The introduction of defects in FE simulation show significant change in the torsional mode amplitude. The impact of varying the width of the notch on the T(0,1) mode amplitude is shown in Fig. 1(e) (signal amplitude shown via Hilbert transform), and the impact of crack on signal amplitude is shown in Fig. 1(f). The impact due to crack is significantly lesser than that due to notch.

In further experiments, the number of transmitter PZTs were increased in the circumferential direction to 8 as shown in Fig. 2(a). The signal captured on the receiver PZT for this configuration is compared with the result of 4 transmitter PZTs as shown in Fig. 2(b). These measurements verify the suppression of non-axisymmetric flexural modes with increasing number of PZTs in the circumferential direction. With 8 transmitter PZTs, data were collected at different frequencies and the torsional mode observed is shown in Fig. 2(c). The arrival time for the torsional mode wave packet is independent of the frequency of actuation due to its non-dispersive nature observed in the dispersion curve.

In simulation setup, the number of receiver PZTs were increased to 16 to observe the effect of defect on signal propagation along the circumference. Initially, baseline signal was recorded at each receiver PZT when all the transmitter PZTs are excited at once. The length of the through-thickness notch was varied and signals were recorded for each receiver. In order to observe the effect of notch on the signal, signal difference coefficient (SDC) value was calculated for each receiver PZT, defined as follows:

$$SDC = 1 - \rho \tag{1}$$

where ρ is the correlation coefficient of the received signal for each receiver PZT to the corresponding baseline signal. The SDC values for all PZTs are plotted using radar plot as shown in Fig. 2(d). The angular positions indicate the locations of the receiver PZTs on the pipe. The notch is located at 90° and at the centre of the pipe. The plot shows increase in SDC values with increase in the length of notch.

IV. Conclusion

In this study, we have explored the feasibility of using torsional GW modes with an embedded SHM system for damage assessment in pipelines. Preliminary simulation and experimental results indicate that the use of shear mode d_{15} PZTs for generating torsional modes is suitable for identifying

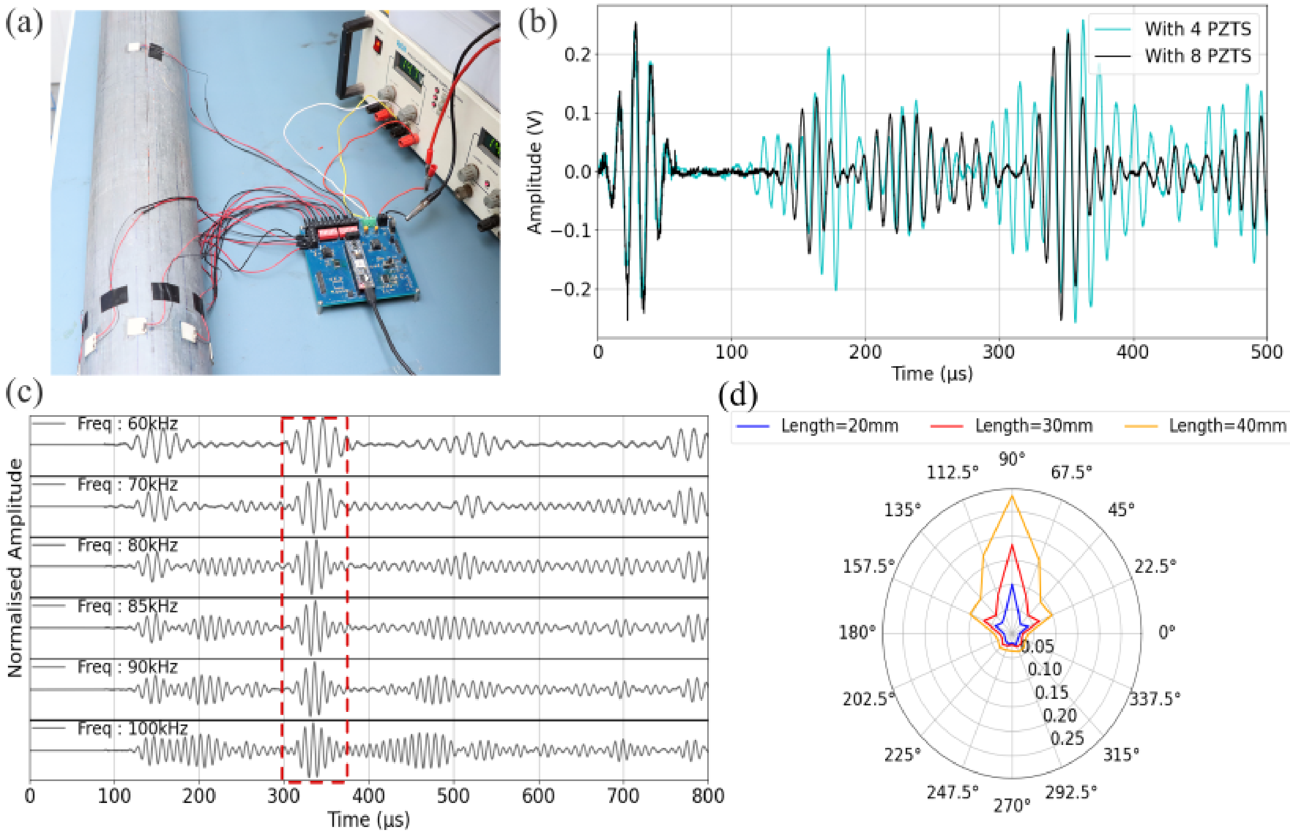

Fig. 2. (a) Photograph of experimental setup with 8 transmitter PZTs. (b) Experimental result for signal recorded at receiver PZT with 4 and 8 transmitter PZTs. (c) Signals recorded at different frequencies with 8 transmitter PZTs. (d) Radar plot of SDC values for 16 receiver PZTs, for through-thickness notch of varying lengths.

small circumferential defects. Our future work will focus on additional experiments for extending the range of the SHM system, and exploring optimal signal processing techniques for robust damage assessment in presence of time-varying environmental, ambient and operating conditions.

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