Ultrasonic Waveguide Sensor Design using Various Reflectors for Elastic Moduli and Temperature Measurement

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1. INTRODUCTION AND OBJECTIVE

In this research work, we developed an ultrasonic strip waveguide sensor by utilizing various reflector embodiments, including bend, symmetric rectangular notches (along width and thickness), and symmetric V-notches. This ultrasonic sensor concept can measure temperature-dependent elastic moduli using the symmetric wave (**S_0**) mode. Initially, FEM simulations were conducted using Abaqus software to analyze the signal behavior of strip waveguide sensors using various reflector configurations. We used an SS304 strip waveguide with a thickness of 0.5 mm, a width of 3 mm, and a length of 1000 mm. In the Finite Element Method (FEM) study, we used **S_0** wave mode by exciting a Hanning pulse tone burst signal at one end of the waveguide. Based on the FEM study, we have designed the sensor for experimental purposes. We conducted the experiments using S_0 mode based on the pulse-echo approach to monitor the Young's modulus (E) of the waveguide material while varying the temperature. The ultrasonic parameter, difference in time of flight (δToF), was used to determine temperature-dependent elastic moduli. Later, the sensor was calibrated based on δToF using the Hilbert transform (HT) due to a change in moduli. Finally, we used the calibrated sensors to measure the temperature of the hot surface/chamber. The study helped us identify better ultrasonic reflectors that can enhance wave propagation in the long waveguide and effectively measure the sensors surrounding medium temperatures. Also, V-notch may be a better reflector for sustaining and propagating ultrasonic waves in a long-strip waveguide. This sensor is a simple concept, robust, and can effectively work in hostile environments.

Keywords: Ultrasonic strip waveguide, Temperature, Elastic moduli, Sensors.

2. RESULTS AND HIGHLIGHTS OF IMPORTANT POINTS

This study carried out FEM simulations of different strip waveguides with various reflector embodiments such as bend, symmetric rectangular notches (along thickness and width), and symmetric V-notches on Abaqus software. We found that **S_0** wave mode at 250 kHz in SS304 strip waveguides (at 1mx 3mm x 0.5 mm) shows non-dispersive behavior, which was ensured and verified by a 2D FFT plot through FEM simulations. We obtained the A-scan plots of the waveguides with the different reflector embodiments (refer to Fig. 1) from the FEM simulation studies. On comparing those A-scans, we found that waveguides with bend and rectangular notch reflector embodiments gave better results while using a single reflector in the strip waveguide. However, we studied the distributed reflectors' configurations in a strip waveguide to find the better reflector configuration. Hence, we experimented using strip waveguides with bend and rectangular notches with **S_0** wave mode using excitation frequency 250 kHz at one end of the waveguide. Using the Hilbert transform, we estimated the difference in time of flight of the S0 wave between the reflector embodiment and the end of the waveguide at room temperature and instantaneous temperature. Then, we were able to estimate the temperature-dependent elastic moduli. Furthermore, we calibrated the waveguide sensor (using δToF) with a co-located K-type thermocouple near the reflector embodiment. The obtained calibration equation can be used for multiple/distributed sensors for measuring the temperature of a solid surface/hot chamber.

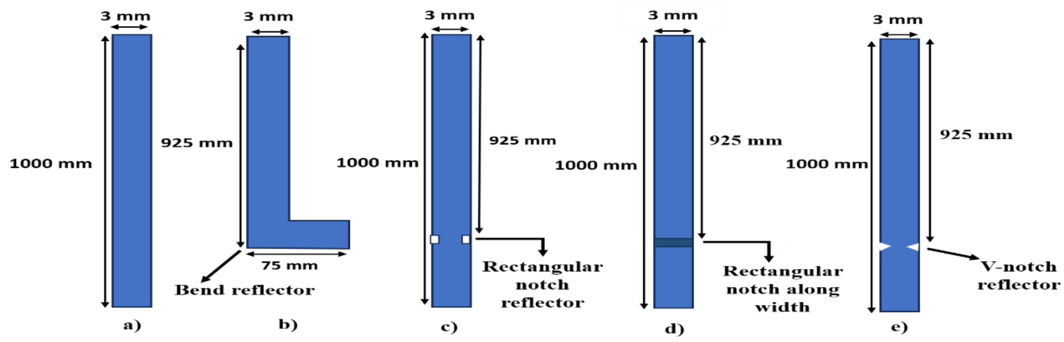

Fig. 1 Waveguides with a) no reflector, b) bend reflector, c) and d). Symmetric rectangular reflectors along width and thickness respectively, e) V-notch reflector

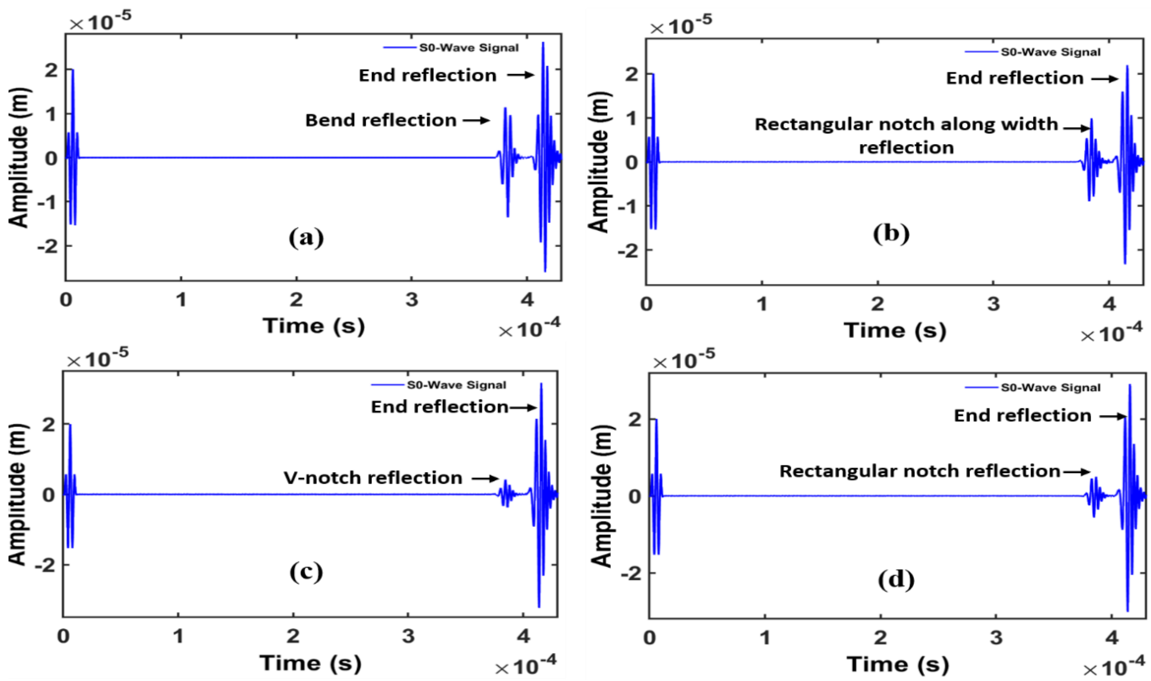

Fig. 2 A-scan signals (S_0 mode) of waveguides obtained from FEM model with (a) bend reflector, (b) rectangular notch along width, (c) V-notch reflector, and (d) rectangular notch/reflector along thickness.

REFERENCES

1. K. Balasubramaniam, and S. Periyannan, “Ultrasonic waveguide technique for distribute sensing and measurements of physical and chemical properties of surrounding media”, US Patent 11,022,502, 2021.
2. K. Balasubramaniam, S. Periyannan, “Waveguide technique for the simultaneous measurement of temperature-dependent properties of materials,” US Patent 10,794,870 B2, 2020.
3. S. Periyannan., P. Rajagopal, & K. Balasubramaniam, “Ultrasonic bent waveguides approach for distributed temperature measurement.” Ultrasonics, 74, 211-220, 2017
4. Y. Bao, H. Zhang, M. Ahmadi, MA Karim, Wu H Felix, “Measurements of Young's and shear moduli of rail steel at elevated temperatures,”, Ultrasonics, 54(3):867-73, 2014 Mar, doi: 10.1016/j.ultras.2013.10.015.
5. A. Kumar, S. Periyannan, “Enhancing the ultrasonic waveguide sensor’s fluid level sensitivity using through-transmission and pulse-echo techniques simultaneously.” Review of Scientific Instruments, 94(6), 2023
6. A. Kumar, S. Periyannan, “Helical waveguide sensor for fluid level sensing using L(0,1), T(0,1) and F(1,1) wave modes simultaneously,” IEEE Sensors Journal, Manuscript Number: Sensors-61676-2023, Article DOI: 10.1109/JSEN.2023.3296931.
7. J.L. Rose, Ultrasonic Waves in Solid Media. Cambridge, U.K.: Cambridge Univ. Press 1999, PP. 143-152.
8. S. Periyannan, P. Rajagopal, and K. Balasubramaniam. "Re-configurable multi-level temperature sensing by ultrasonic “spring-like” helical waveguide." *Journal of Applied Physics* 119, no. 14, 2016.
9. S. Periyannan, and K. Balasubramaniam. "Simultaneous moduli measurement of elastic materials at elevated temperatures using an ultrasonic waveguide method." *Review of Scientific Instruments* 86.11, 2015.