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Bulk Ultrasonic NDE of Metallic Components at High Temperature using Magnetostrictive Transducers

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Abstract. Online ultrasonic NDE at high-temperature is of much interest to the power, process and automotive industries in view of possible savings in downtime. This paper describes a novel approach to developing ultrasonic transducers capable of high-temperature in-situ operation using the principle of magnetostriction. Preliminary design from previous research by the authors [1] is extended for operation at 1 MHz, and at elevated temperatures by amorphous metallic strips as the magnetostrictive core. Ultrasonic signals in pulse-echo mode are experimentally obtained from the ultrasonic transducer thus developed, in a simulated high-temperature environment of 350 °C for 10 hours. Advantages and challenges for practical deployment of this approach are discussed.

INTRODUCTION

Nondestructive Evaluation (NDE) of nuclear reactor components operating at high temperature is conventionally performed during shutdown. In view of reducing downtime and improving standards of safety, online methods of performing NDE are of great interest. Quantitative ultrasonic NDE has been widely accepted as a tool to characterize defects, study microstructural degradation, detects leaks [2] and to perform under-sodium viewing [3] in different nuclear reactor assemblies. Conventionally, transduction of ultrasonic waves in the medium of interest is achieved by piezoelectric or eddy current transducers [2]. This paper describes a methodology for developing an in-situ magnetostrictive ultrasonic transducer based on amorphous metallic strips for operation at elevated temperatures. Amorphous metallic strips form the magnetostrictive core of the developed transducer. Recently, the authors' research group has reported the use of these magnetostrictive strips for stable operation at 350°C for extended durations [4]. We use this magnetostrictive material as the core to develop an ultrasonic transducer to perform in-situ bulk ultrasonic NDE at the frequency range of 1 MHz at elevated temperatures.

BACKGROUND

The principle of magnetostriction, the Joule [5] and Villari [6] effects has been used for various applications, including torque sensors, motion and position sensors, material characterization sensors and magnetic field sensors [7]. Conventionally, magnetostrictive transducers for NDE applications have been developed to generate guided ultrasonic waves in the non-dispersive, low-frequency regimes for defect characterization in pipelines, plates [8] and cables [9]. However, operation in the low-frequency regime restricts the minimum size of defects that can be detected in the specimen under inspection. Such a limitation is disadvantageous for applications such as safety critical industries. The waveguide, on which the magnetostrictive transducer is fabricated, is permanently bonded to the bulk test specimen. In this paper, the authors report generation of guided ultrasonic waves in the high-frequency regimes

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using magnetostrictive transducers to be converted as bulk longitudinal modes for bulk NDE of metallic structures. This paper is organized as follows: firstly, the problem of study is introduced, following which, the description of the fabrication of the test specimen, elements of the developed transducer, and the experimental arrangement are detailed. Results are then presented and discussed, after which the paper concludes with directions for further work.

THE PROBLEM STUDIED

The problem of interest is the online inspection of the reactor vessel in a Sodium cooled Prototype Fast Breeder Reactor (PFBR). In a typical PFBR, the reactor vessel is 25-40 mm thick, with an annular gap. The annular gap, approximately 300 mm, provides space for inspection techniques applicable. The temperature in this region ranges from 250 - 350°C. The defect characterization studies require the developed transducer to operate at a center frequency of 1 - 2 MHz.

METHODS

This section describes the fabrication of the test specimen and the elements of the magnetostrictive transducer. A brief description of experimental arrangement follows after that.

Procedure for Fabrication

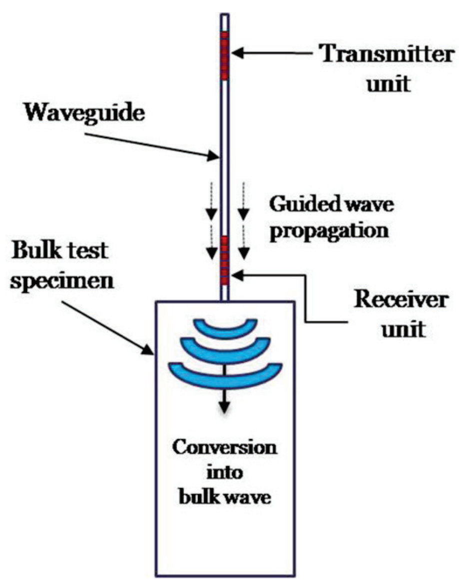
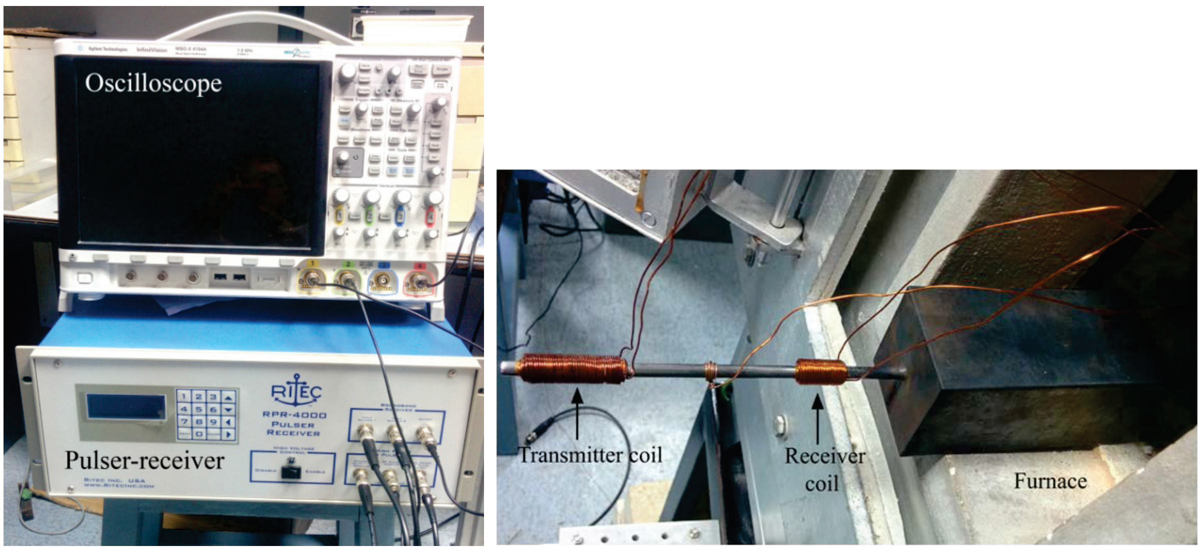


FIGURE 1. A schematic of the fabricated test specimen.

The magnetostrictive transducer is fabricated on a cylindrical waveguide. The waveguide is then permanently bonded to a rectangular block. The rectangular block represents the thickness of the reactor vessel which is subjected to bulk ultrasonic NDE. A schematic representation of the fabricated test specimen is shown in Fig. 1. The waveguide has an outer diameter of 5 mm and a length of 140 mm. The rectangular block has the following dimensions, 105 mm x 50 mm x 50 mm. The waveguide and the test block are made of Mild Steel. The magnetostrictive transducer consists of two independent windings and magnetostrictive cores, which act as the transmitter and receiver unit, also shown in Fig. 1. The amorphous metallic strips which form the magnetostrictive cores are adhesively bonded to the surface of the cylindrical waveguide. Over the magnetostrictive core strips, standard Copper wires are wound. The transmitter and receiver unit are placed a certain distance away from each other to avoid magnetic field interferences influencing the receiver unit. These wires enable generation of the alternating magnetic field when connected to the pulser-receiver. The magnetostrictive strips enable transduction of ultrasonic waves into the waveguide. Thus, when longitudinal guided waves are generated in the waveguide, they transmit into the bulk test specimen as longitudinal bulk ultrasonic waves. Suitable grounding mechanisms are also provided.

Experimental Arrangement

A photograph of the experimental arrangement and the transducer elements are shown in Figs. 2 (a) and (b). The Copper wire wound over the magnetostrictive cores is connected to an RITEC RPR-4000 (RITEC Inc., Warwick, RI). The output from the Pulser-receiver is connected to an InfiniiVision-3000 oscilloscope (Agilent Technologies, Inc., CO, USA).



(a) (b)

FIGURE 2. A photograph of the (a) experimental arrangement, (b) transducer in the furnace.

A photograph of the transmitter and receiver unit on the waveguide are shown in Fig. 2 (b). The test specimen with the transducer on the waveguide is placed inside the furnace. Amplitude vs. time plots are recorded at regular intervals, as the temperature is increased. A choke time is also provided to make the temperature inside the furnace approximately uniform. After 350°C is reached, the temperature is held for 10 hours to study the variation of amplitude of recorded ultrasonic measurements. We study the performance of the transducer while measuring the thickness of the test specimen ultrasonically, using the magnetostrictive core as a patch.

RESULTS AND DISCUSSION

Operation at Elevated Temperature

In the study, the amorphous metallic strip is cut into patches and is used as the magnetostrictive core. One patch for the transmitter unit and another one of similar dimensions for the receiver unit. The A-scan, shown in Fig. 3 is recorded by the transducer at 350°C after a period of approximately 3 hours. It has three parts marked in rectangular boxes as *I, II* and *III*. After the ultrasonic wave is generated by the transmitter unit, the first arriving ultrasonic wave recorded by the receiver unit is indicated as *I.* Further we observe another set of reflections. The first from the interface of the waveguide and the bulk rectangular block, and the second from the welded joint; this is indicated as *II*. Finally, we also observe a reflection the rear end of the bulk test block, indicated as *III*.

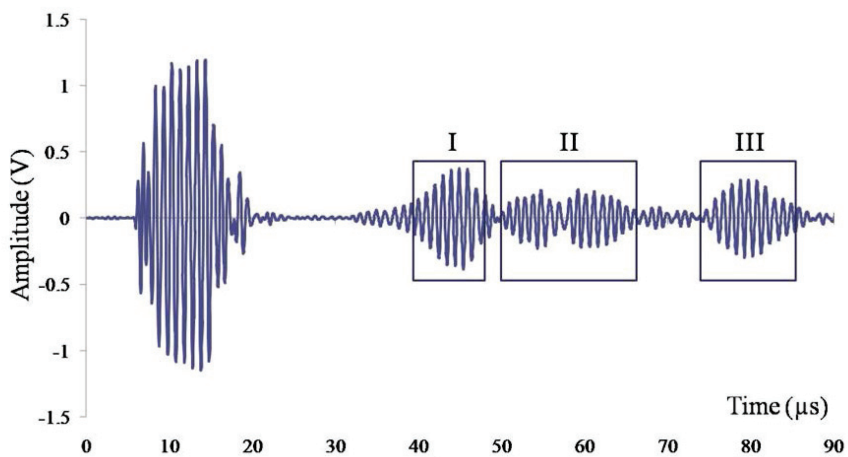


FIGURE 3. A-scan recorded from the developed transducer at 350°C.

We observe a peak-to-peak voltage amplitude of 0.557 V from the reflected signal obtained from the rear end of the test block, shown in the rectangular box *III*. The amplitudes recorded are comparable to that obtained from piezoelectric transducers. These results indicate the developed ultrasonic transducer can operate at elevated temperatures up to 350°C. The A-scan also indicates that the signal fidelity is excellent with no additional post-processing tools. These preliminary results are very attractive as an high-temperature bulk NDE methodology.

Operation during Extended Duration

The A-scans shown in Fig. 3, are recorded for ten hours continuously. The operation of the developed ultrasonic transducer is studied during the online operation at high temperature. The peak-to-peak amplitude of the reflected signals from the rear-end of the test block is studied as a function of time, and the results are shown in Fig. 4.

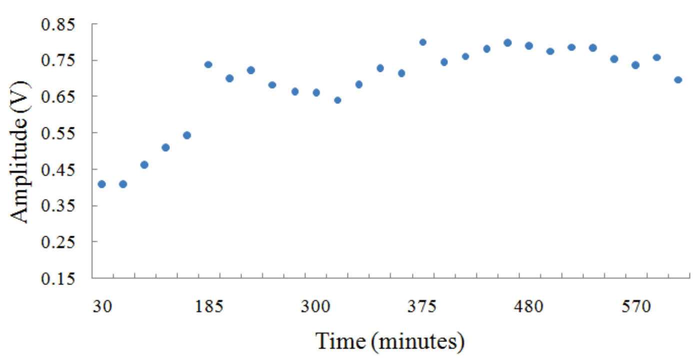


FIGURE 4. Variation of peak-to-peak amplitude of reflected signal from rear-end of test block, as a function of time.

The variation of amplitude is relatively stable during continuous operation of 10 hours. The average peak-to-peak amplitude is estimated to be 0.687 V. These results show that the operation at elevated temperatures for extended durations of the prototype ultrasonic transducer is very encouraging from the standpoint of reducing downtime.

Operating Center Frequency

The center frequency is estimated from a Fast Fourier Transform of the amplitude vs. time plot recorded during operation at high temperature. The frequency response of the output is shown in Fig. 5. The frequency response can give an understanding of the minimum size of defects that can be detected.

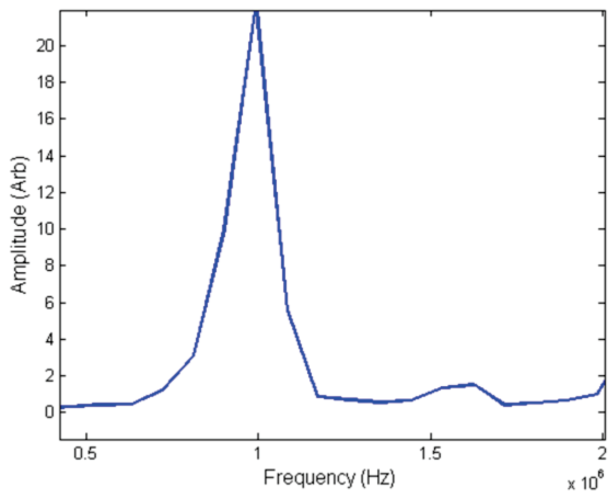


FIGURE 5. Frequency response of the output recorded from the developed ultrasonic transducer.

The center frequency is calculated to be around 1 MHz, indicating that the developed transducer is capable of operation in the higher frequency regime. The transmitter unit generates a certain guided wave mode in the waveguide which transmits into the metallic block. We understand that this guided wave mode has a center frequency of 1 MHz, from the frequency response shown in Fig. 5. We can now infer that by selecting a specific guided wave mode, the center frequency can be either increased or decreased depending on the application. Guided wave modes can also be selected on the basis of certain special features exhibited by them. Optimizing the developed transducer implementing mode selection will be a topic for future work.

LIMITATIONS

The primary limitation for practical deployment is that developed magnetostrictive transducer needs to be permanently bonded to the test specimen, which is highly undesirable for many applications. Additionally, the direction of the transmitted wave is normal to the surface of the test specimen making defect characterization difficult when the defects are parallel or nearly parallel to the propagation direction of the transmitted wave. Conventionally, defect characterization is performing with angle beam transducers or wedge transducers.

CONCLUSION AND FUTURE WORK

This paper describes the development of a magnetostrictive transducer capable of in-situ bulk inspection at high-temperatures. Further, the variation of performance as a function of time is studied experimentally. The center frequency of the developed transducer is estimated to be around 1 MHz. Overcoming the mentioned limitations by developing methodologies which do not require permanent bonding of the transducer to the surface of the test specimen will be a topic of future work. The final stage of the transducer will consist of a stand-alone ultrasonic transducer, enclosed and ruggedized for in-situ bulk ultrasonic NDE.

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