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Development of a magetnetostrictive transducer for nondestructive testing of concrete structures

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A magnetostrictive transducer operating at 100 kHz using rare earth transition metal giant magnetostrictive material for nondestructive testing (NDT) applications was designed and fabricated. The giant magnetostrictive $Tb_{0.3}Dy_{0.7}Fe_2$ material was chosen as the active element for the present purpose. From the impedance measurements, the resonant frequency of the transducer is found to be 100 kHz. The performance of the transducer was validated by carrying out NDT on a test concrete block with delaminated regions, using the ultrasonic through-transmission technique and the pitch-catch method. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2834368]

Giant magnetostriction has been observed in several RFe_2 compounds and several applications have been reported[1–9] and one such application is ultrasonic nondestructive testing (NDT). RFe_2 intermetallics have larger strain capabilities compared to the piezoelectric ceramic material that make the RFe_2 materials more suitable as active elements in high power electroacoustic transducers than the latter.[10] Current ultrasonic NDT methodologies for evaluation of thick concrete structures are limited by the high attenuation (caused by scattering from particulates) of the output power of the (piezoelectric) transducers. Attenuation coefficients of −0.7 dB/mm (−17.8 dB/in.) at 200 kHz and −2.7 dB/mm (−68.6 dB/in.) at 800 kHz have been measured in concrete. Moreover, signal-to-noise ratio is generally low in concrete due to the scatterings from grains, reinforcements, etc., and this could hide meaningful signal information; this cannot be improved by time averaging because in most cases, the noise is coherent. In the pulse echo ultrasonic testing methods, as the wave has to travel twice the depth due to reflection, the attenuation is enhanced.

Impact echo has been the preferred method of nondestructive inspection of concrete. Impact echo is a common point test method employed to determine the integrity of concrete structures.[11–13] However, in this method, extremely low frequencies (1–20 kHz), where attenuation is less pronounced, are employed and these make this method more acceptable for testing concrete structures for gross defects such as delaminations and wall thinning. The resolution of flaws in a material depends on the frequency of the ultrasonic wave used for inspection. At higher frequencies, the resolution of defects is better. However, as the frequency increases, the penetration capability of the ultrasonic waves decreases due to higher attenuation. This is particularly true during the preferred one-side-access pulse-echo mode of inspection since the wave has to travel to the flaw and back. Also, materials such as concrete attenuate the high frequency sound waves significantly, leading to severe limitation in the resolution of damage detection, particularly when they are thick. Therefore, it was of interest to develop a 100 kHz magnetostrictive transducer that generates high strain excitation into the structure and to characterize its performance for the inspection of defects in concrete structures. Giant magnetostrictive $Tb_{0.3}Dy_{0.7}Fe_2$ material was chosen as the active element for the present purpose. Nondestructive testing measurements were carried out on a test concrete block using both the ultrasonic through transmission technique and the pitch-catch method.

$Tb_{0.3}Dy_{0.7}Fe_2$ was prepared by arc melting the stoichiometric amounts of high-purity elements (Tb, Dy: 99.9% and Fe: 99.95%) in high purity argon atmosphere. The ingot was melted several times to ensure homogeneity and the total weight loss was found to be less than 0.5%. Subsequently, the ingot was zone melted in vacuum in an induction furnace (Pillar Induction, Chennai, India), in order to obtain the grain oriented sample, employing a pulling (the coil, upward) rate of 0.05 mm/s. The zoned rods were wrapped in tantalum foils and were annealed at 900 °C in evacuated quartz tubes for one week. Powder x-ray diffraction (XRD) patterns were taken for the compound using Fe $K\alpha$ radiation. Magnetostriction measurements on the grain oriented rods were carried out using the strain gauge method. The impedance measurements on the developed magnetostrictive transducer were carried out to determine the resonance frequency of the transducer. Both the ultrasonic through transmission technique and pitch-catch method were used in order to test the transducer.

From the powder XRD patterns, it was confirmed that $Tb_{0.3}Dy_{0.7}Fe_2$ formed in the cubic Laves phase structure. The lattice parameter was determined using powder XRD patterns and was found to be 7.321 Å, which is in agreement with the literature value.[14] Figure 1 shows the magnetostriction (λ-H) graph for $Tb_{0.3}Dy_{0.7}Fe_2$. The magnetostriction at 10 kOe is found to be 1279×10^{-6}. For the design of the transducer, the following characteristics of the active element (rod) were used:[10]

(a) magnetomechanical coupling coefficient as 0.62,
(b) Young's modulus as $4.5\times10^{10}\ \mathrm{N/m^2}$,

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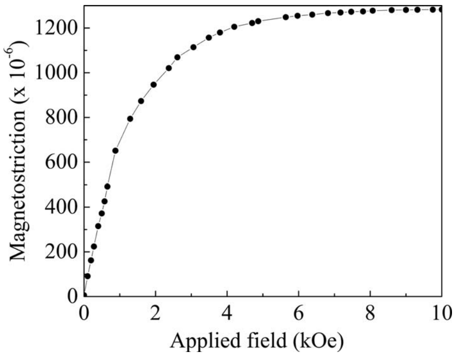

FIG. 1. Magnetostriction graph of $Tb_{0.3}Dy_{0.7}Fe_2$.

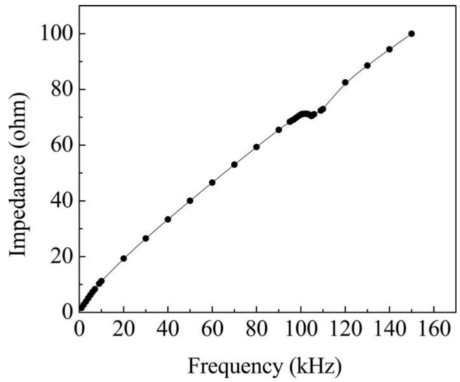

FIG. 3. Frequency vs impedance graph of the magnetostrictive transducer.

(c) speed of sound in the rod as 2125 m/s, and
(d) Density of the rod as 9.15×10^3 kg/m^3.

A frequency of 100 kHz was chosen in order to identify the defects in concrete with high resolution. As the mechanical frequency of the rod is inversely proportional to its length, a rod of 11 mm length was chosen in order to obtain a resonant frequency of 100 kHz. The linear region in the magnetostriction curve was used for fixing the bias field to be 1500 Oe. Figure 2 shows the cross sectional view of the developed transducer. A permanent magnet was used to generate the bias field. A solenoid through which an alternating current was passed produced the excitation field. The number of turns in the solenoid was calculated to be 150. A screw mechanism was employed to prestress the active element to prevent it from a possible fracture under high dynamic drive. Figure 3 shows the frequency versus impedance graph of the developed magnetostrictive transducer. From the frequency dependence of the impedance, the resonance frequency is seen to be 100 kHz.

In order to test the transducer, the ultrasonic through-transmission technique and the pitch-catch method were used. A high strength concrete bridge deck sample that had earlier been subjected to three point bending loading leading to the development of visible cracks at some locations was used as the test sample. The sample was 3000 mm long, 750 mm wide, and 900 mm thick. Along with the magnetostrictive transducer, a commercially available 100 kHz piezoelectric transducer (referred to as PZT, subsequently) (Panametrics Inc., USA) was employed, as a detector.

The ultrasonic through transmission measurements were carried out by a PC based measurement system and the schematic diagram of the setup is shown in Fig. 4. The system consists of RITEC Inc., SNAP (RAM 5000). A commercially available couplant *D*-type gel was used to ensure good coupling of the ultrasonic waves between the transducers and the test sample. The results were displayed in the conventional rf *A*-scan mode, which represents the received ultrasonic signal in the form of the plot of the signal voltage versus time for a given transducer position. Figure 5(a) shows the signal obtained from the 3 m concrete block when the magnetostrictive transducer was used as transmitter and the PZT was used as receiver in the through transmission mode. The velocity of the ultrasonic wave in concrete block of a given thickness can be determined by the equation $v = D/T$, where D is thickness of the concrete block and T is time taken for the signal to travel through the concrete block. The velocity was obtained to be 4341 m/s, which is comparable with the reported value in the literature.[15] Figure 5(b) shows the signal obtained from the 3 m concrete block when both the transmitter and receiver were two similar PZTs, again in the through transmission mode. It is seen that the signal received was significantly weak when the PZT was used as the transmitter compared to the case when the magnetostrictive transducer was the transmitter.

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In order to evaluate the utility of this transducer for inspection of concrete structures that are accessible from only

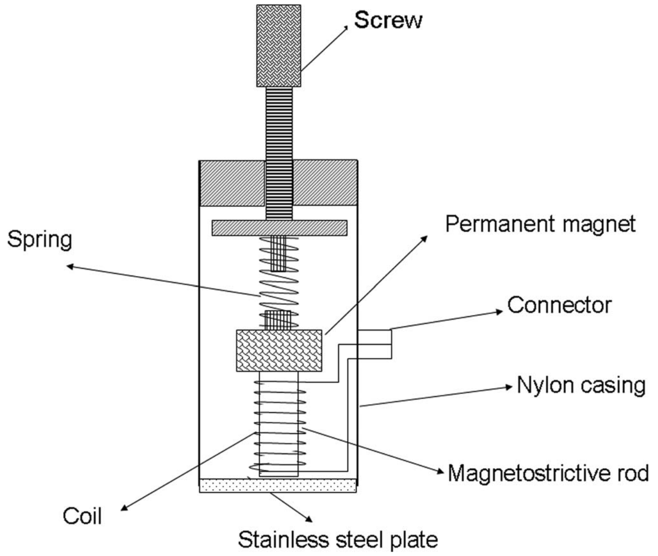

FIG. 2. Cross sectional view of the magnetostrictive transducer.

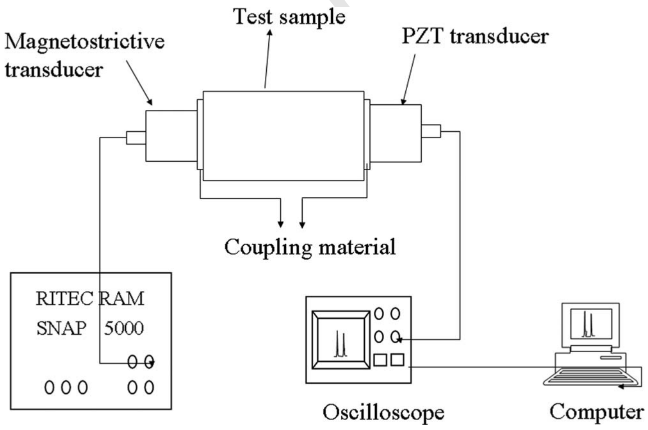

FIG. 4. Schematic diagram of experimental setup for through transmission technique.

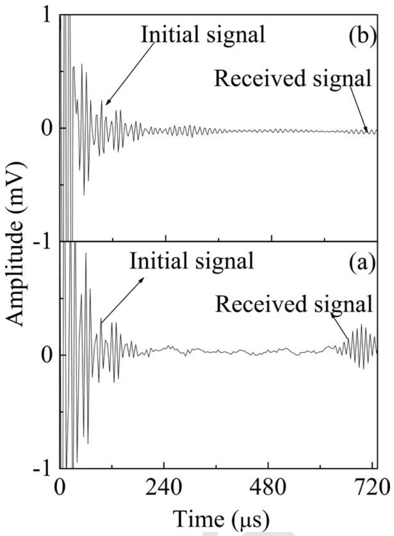

FIG. 5. Signal from the 3 m concrete block with the magnetostrictive transducer as the transmitter and PZT as the receiver. (b) Signal from the 3 m concrete block with the PZT as the transmitter and another PZT as the receiver.

one side, the magnetostrictive transducer (transmitter) and the PZT (receiver) were configured in a pitch-catch mode (Fig. 6). The same 3 m concrete block was employed for the experimental investigation, but the waves were transmitted and received from its top surface. The concrete block structure consisted of two blocks; the interface between the top block and the bottom block is prone to delaminations and these were treated as the defects. The transmitter (pitch) and the receiver (catch) pair were placed at different locations on top of the concrete block and the signals received by the PZT were recorded. It can be observed that the weak reflection from the interface between the two slabs could be observed in the regions of no delamination [Fig. 7(a)], while in several locations, particularly near the edges, the defective region led to high amplitude signals reflected from the interface [Fig. 7(b)]. This is due to the higher acoustic impedance mismatch between the concrete and the air at the delaminated regions. The increase in the signal strength was of the order of 20 dB, which demonstrates that this technique can be used for locating and mapping defects such as delaminations in concrete at much higher frequencies compared to the impact echo technique thereby, with increased sensitivities.

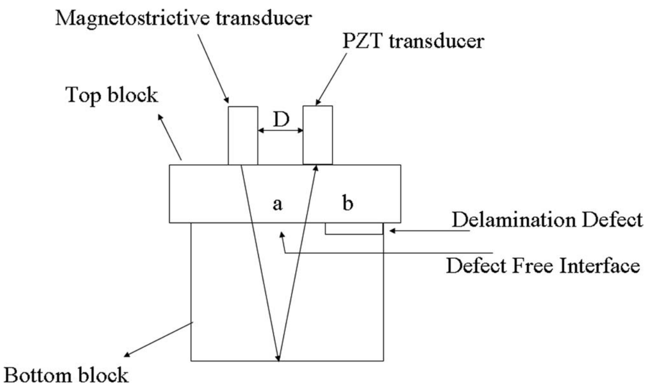

FIG. 6. Schematic diagram showing the ultrasonic pitch-catch technique.

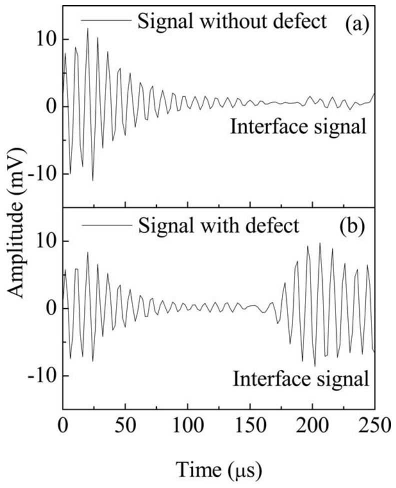

FIG. 7. Signals obtained in pitch-catch mode. (a) Without defect (b) with defect.

In conclusion, a 100 kHz giant magnetostrictive transducer was developed and tested using both the ultrasonic through transmission technique as well as the pitch-catch method for the investigation of defects in a concrete structure. It is observed that signal was able to pass through a 3 m concrete block and that the signal strength at the receiver end was large enough not to require further amplification. In the pitch-catch mode, the defective interface region could be detected.

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