Non-Contact Generation and Reception of Guided Waves Using Near-Field Inductive Coupling*

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Abstract: Wafer-type PZT transducers are widely used for generation and detection of elastic guided waves. In this study, an inductively-coupled transformer system, which consists of primary and secondary ferrite-core coils, is developed for near-field transmission of excitation waveform and guided wave response signals. The primary coil is connected to power source for generation of an input waveform, and the excitation signal is coupled with the secondary coil when the coils are brought into proximity. The secondary coil is affixed to the PZT wafer and consequently to the test specimen where the PZT wafer is attached to. Then, the guided waves generated at the PZT wafer and reflected from the boundaries of the test specimen are transmitted back to the primary coil. Three progressive versions of the transform systems are presented. The feasibility of the proposed inductively coupled transformer systems is demonstrated by comparing the performance of the proposed contactless system with a conventional wired system.

Key words: elastic guided waves, inductive coupling, contactless power supply, PZT transducer

INTRODUCTION

Structural Health Monitoring (SHM) and Non-Destructive Testing (NDT) is an integrated process of sensing, information technology and statistical inference used to ensure the safety and performance of a structure and to provide early detection of critical damage. Within our society, there are increasing demands to adopt this technology for monitoring and maintenance of aerospace, civil infrastructure and mechanical systems.

While there has been a large volume of literature in SHM and NDE (Sohn et al. 2004 and Chang et al. 2003), there has been little crossover between the local NDE and global SHM techniques: The conventional NDE techniques often require structures to be at least partially disassembled and a skilled technician to interpret data, which increases labor costs and adds to the time needed to complete the inspection. They are "local" methods in a sense that they can only find flaws in a small area in each test. On the other hand, vibration-based approaches mainly rely on low-frequency responses of the structure, and they can rapidly cover larger inspection areas. However, they are often insensitive to local damage because the size of local damage is often much smaller than the wavelength of the global vibration response.

Guided waves have been widely used for damage detection because they have a sensing range, which is in-between of those conventional NDT techniques and global SHM techniques. Guided waves offer the large sensing range similar to the coverage of the global SHM methods while achieving the detection sensitivity of the local NDT techniques. Wafer-type piezoelectric materials such as Lead Zirconate Titanate (PZT) are often used for exciting and measuring guided waves in SHM and NDT applications (Sohn et al. 2004, Greve et al. 2005, Cho et al. 1997, Giurgiutui 2003, Kessler et al. 2003). One of the important characteristics of the PZT materials is that it can be used for both sensing and actuation.

Despite their desirable characteristics, the PZT wafer-type transducer in its present form may not be practical for long-term exposed instrumentation mainly due to wiring issues. In this study, a near-field magnetic coupling effect is introduced to the PZT wafer transducer to eliminate the need for wired contact.

THEORETICAL CONCEPT

The transducer concept is pictured schematically in Figure 1. A PZT wafer transducer is wired to a coil with a ferrite core. The transducer, coil, and core can be encapsulated and permanently mounted to the structure being monitored. A probe with one or two coils is then brought in proximity to the transducer. The figure shows the coil excited by a pulse generator with internal resistance R_s. The pulse is coupled to the PZT wafer and consequently an ultrasonic wave is excited in the structure. Return pulses reflected from boundaries or flaws will then be coupled back into the probe coil resulting in a signal $v_s(t)$ appearing across the generator resistance R_s. Alternately, the received signal $v_r(t)$ can measured using a separate winding, possibly with a different turns ratio.

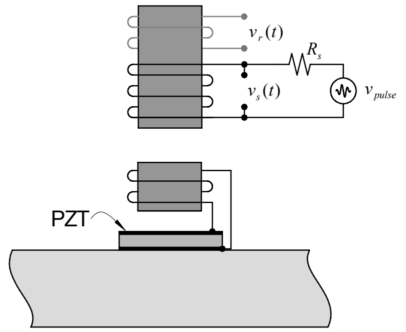

Fig. 1. Schematic concept of inductively coupled transducer

Figure 2 shows the equivalent circuits for exciting and receiving a pulse. For simplicity we consider the use of the same winding for excitation and reception. An exciting pulse is coupled through a transformer and drives the PZT transducer, which can be approximately modeled by the parallel combination of capacitor and a resistor. Because of the nonideal transformer coupling and the loading effect of the PZT wafer, the PZT voltage may be less than predicted from the transformer turns ratio. In the receive condition the PZT is loaded by the transformed source resistance, again possibly leading to reduced signal levels.

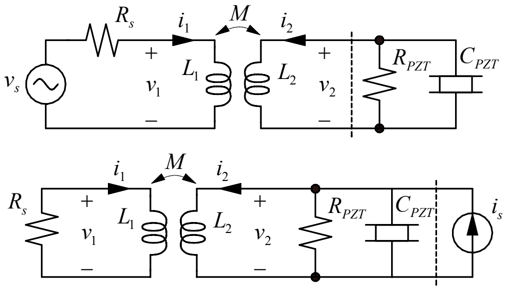

Fig. 2. Equivalent circuits for pulse excitation (top) and reception (bottom).

Several important aspects of the design demand further study. Pulses are inductively coupled into and out of the transducer, and therefore the coupling must be sufficient to obtain adequate signal strength. In practice, the probe coil would be coarsely positioned;

therefore, variation of the gap between probe and transducer coils will occur and the effect on signal strength needs to be explored. Finally, adequate isolation of the exciting and received pulses must be achieved. A comprehensive study (Greve, *et al*., 2006b) addresses the equivalent circuits and transducer measurements, while this paper summarizes the results and the potential for SHM.

FIRST GENERATION FERRITE POT CORE TRANSDUCER

Figure 3 shows a transducer design using ferrite pot cores, commonly used for power supply inductors. Ferrite cores (18 mm in diameter, 5 mm deep, initial relative permeability 2000) were obtained from CWS Bytemark. The PZT coil was wound with 54 turns and the probe end had two coils of 36 and 72 turns (excitation and reception, respectively). This particular ferrite composition is typically used at frequencies in the range 1 kHz- 2 MHz. The PZT wafer was about 1 cm^2 in area and 0.5 mm thick with nickel electrodes on both sides (type 5A4E from Piezosystems Inc.). The completed transducer was bonded 7 cm from the corner of a glass window panel 37 cm × 67 cm in size using cyanoacrylate glue.

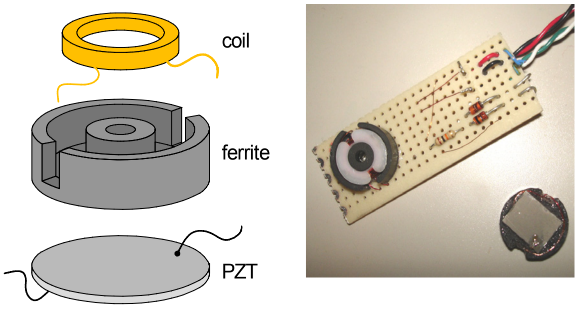

Fig. 3. Transducer design using ferrite pot cores

Testing was performed using a National Instruments PCI-6110 DAQ board controlled by Labview. The exciting pulse waveform was a smoothly windowed sinusoid 5 cycles in length with 10 V peak-to-peak amplitude. The received pulse waveform was monitored using the 72 turn receive coil in series with a 10 k-ohm resistor and with two diodes connected in parallel with the input terminals. This arrangement was intended to reduce the voltage applied to the input circuitry during excitation and thus to decrease the recovery time. In order to reduce the noise level, signal averaging of the transients was used (20 to 100×).

Figure 4 shows the received transient for a pulse with a center frequency of 286 kHz. For this measurement the gap between probe and transducer cores was 1 mm. Several return pulses are clearly visible with amplitudes in the 5- 15 mV range. Return signals of this amplitude are typical for conventional (wired) PZT transducers. The first and second pulses at approximately 130 and 240 μs are consistent with reflections of an S0 mode ultrasonic pulse from the two distant edges of the glass panel. Additional pulses are visible which correspond to greater travel distances. Similar signal levels (not shown) were observed for center from about 150 kHz to 333 kHz, and for a range of gaps between the cores.

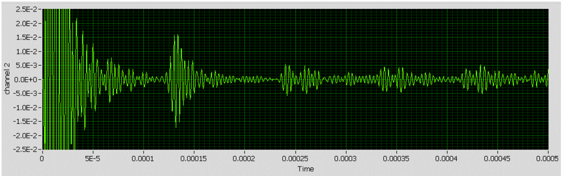

Fig. 4. Observed transients for pot core transducer; 286 kHz center frequency, 1 mm gap.

Test results with this transducer design validate the basic concept. However, one problem with this design is the need for a contact to the front surface of the PZT wafer.

An alternate design discussed in the next section avoids the contact requirement, and also has fabrication advantages.

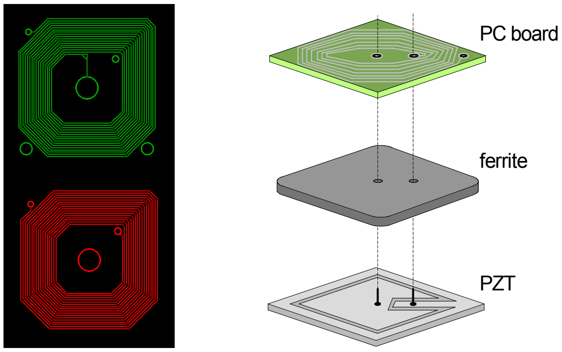

Fig. 5. Planar coil transducer: (left) top and bottom metal layers of the printed circuit board; and (right) assembly of the three components.

SECOND GENERATION PLANAR COIL TRANSDUCER

Here we consider an alternate transducer design well suited for surface mounting, with little protrusion from the structure. This design also offers simpler assembly and possibly lower cost. The planar coil transducer is shown in Figure 5. There are three parts: a double-sided printed circuit board forming a flat coil of 32 turns total; a ferrite sheet; and a PZT wafer with a patterned top surface. By patterning the top surface it becomes possible to excite the transducer using only contacts on one surface. Contacts between the printer circuit board and the PZT wafer were made using short soldered wires. No insulation is necessary between these wires and the ferrite as the ferrite conductivity is low compared to the impedance of the PZT and generator source resistance. The ferrite sheet was Steward model MP1040-100, 1 mm in thickness and 26 mm × 26 mm in size. The manufacturer does not report the magnetic properties of this material because these sheets are intended to suppress electromagnetic radiation from electronic components like microprocessors. The PZT wafer was the same type 5A4E used above but was 1 mm in thickness.

THIRD GENERATION MACRO FIBER COMPOSITE TRANSDUCER

To further decrease the thickness of the wafer-type transducer system, an alternative piezoelectric material is being investigated for inductive coupling. Figure 6 shows the third generation of the inductively coupled transducer system that consists of a Macro Fiber Composite (MFC) device, a rubber ferrite layer, and a flexible printed circuit board with a printed coil.

Recently, NASA has developed a piezocomposite device called Macro Fiber Composite (MFC) that couples the electro-mechanical efficient of piezoelectric materials with high flexibility (Williams et al. 2002). The MFC device consists of rectangular piezo ceramic rods sandwiched between layers of adhesive and electroded polyimide film. This film contains interdigitated electrodes that transfer the applied voltage directly to and from the ribbon shaped rods. The typical thickness of the MFC is 0.3 mm. Because of its flexibility, durability and non-intrusive natures, the MFC has potential uses in a broad range of applications including curved surfaces and pipelines. This device is commercially available from www.smart-material.com.

In order to fabricate the ferrite layer of inductively coupled transducer, we employed a spin coating method. The goal is to produce a rubber ferrite layer that is as thin as possible but has high magnetic permeability. First, 40 vol% of Magneto-Rheological Fluid (MRF)-312AD (Lord Corporation, NC, USA) and 60 vol% of Room Temperature Vulcanizing (RTV)-500 silicone casting rubber (Hastings Plastic Company, CA, USA) were hand-mixed Then, a 1 part (weight) of associated catalyst was poured into a 10 part of MR/silicone rubber composite and mixed repeatedly. About 3 g of the mixture was dropped into the center point of the MFC and coated the ferrite layer by using a spin coater with 1000 rpm of speed rate for 40 sec. The samples were cured at room temperature for 24 hours. The final thickness was measured to be 0.7mm.

There are ample companies where costume-designed flexible printed circuits can be fabricated. For our project, we intend to fabricate a single-sided flexible circuit with printed coils that consists of a single copper conductor layer on a flexible dielectric film. The typical thickness of the flexible printed circuit is 0.1 to 0.2 mm. Therefore, we expect that the total thickness of the transducer system will be less than 2 mm, making it attractive for embedment and surface mounting. The results using the third generation transducer will be reported in near future.

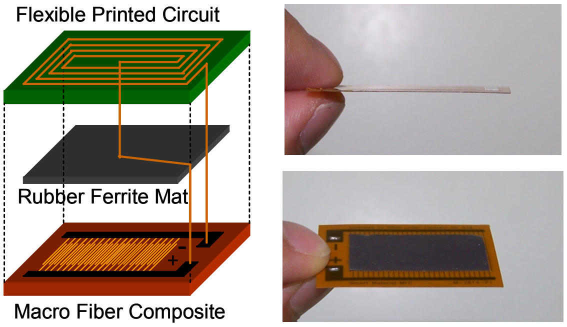

Fig. 6. A macro fiber composite device with a rubber ferrite and a flexible printed circuit board.

EXPERIMENTAL TESTING

Transducer testing was performed on model steel plate girders such as shown in Figure 7, with proportions representative of plate girders but at approximately 1/3 the size of girders used in bridges. The web height of the girder specimen in Figure 7 is 900 mm with a thickness of 3.2 mm, for an h/t_w ratio near 280, and the flange width is 100 mm with a thickness of 6.4 mm, for a b/t ratio near 16. The specimen shown is 2400 mm long with vertical stiffeners (one side only) creating panels with an aspect ratio of 1.25; the stiffeners are detailed with a web gap at the bottom flange. Transducers were attached at various locations using cyanoacrylate adhesive. Tests were performed both with ferrite pot core and with planar coil transducers; Figure 7 shows a ferrite pot core transducer mounted on the web.

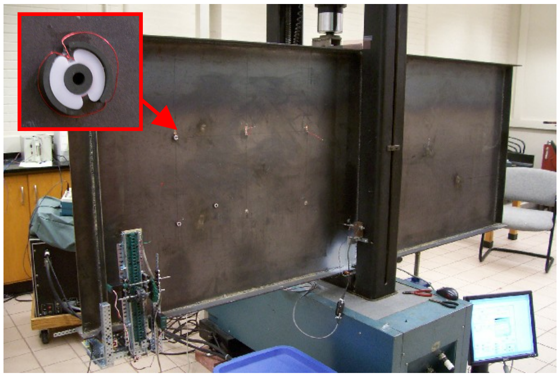

Fig. 7. Plate girder specimen; flange-crawling i at lower left

In an attempt to demonstrate the broad issues raised by the technology, a flange-crawling inspection robot was assembled from hobbyist (Vex system) components and used to bring the probe coil into proximity with the transducer. Figure 8 shows the flange-crawling inspection unit, which performed successfully. The crawler base is underslung and travels longitudinally on the bottom flange through the action of two drive wheels. The arm mounting the scanner coil has two actuated degrees of freedom with respect to the base, arm extension and arm rotation.

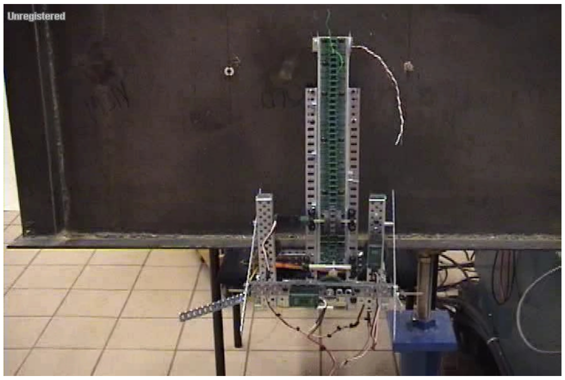

Fig. 8. Flange-crawling inspection robot

The inductively-coupled transducer requires only coarse positioning of the probe, making it a good candidate for such robotic deployment. Because the robot was human-operated, visual contact was needed at all times for positioning purposes. Because of the aforementioned two degrees of freedom associated with the arm, the operator could reposition the arm to avoid protruding obstacles during longitudinal translation, and then return the arm to proximity with the web when conducting an inductively coupled measurement.

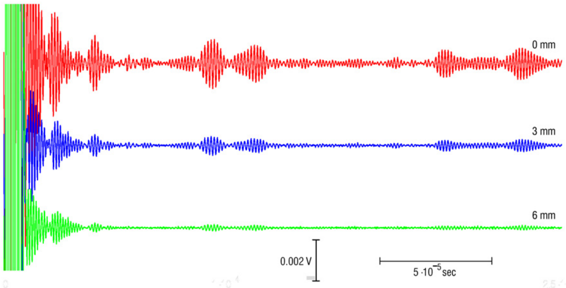

Fig. 9. Effect of gap between probe and transducer coils; plate girder specimen, 328 kHz center freq.

Distortion of pulse shape with the gap between the probe coil and the transducer, because of variations in the circuit component values, was initially a serious concern. We investigated this issue experimentally (for a different steel plate girder specimen, not shown) and the results are shown in Figure 9. This figure shows the reflections for a center frequency of 328 kHz when the gap between probe and transducer coils was varied from 0 to 6 mm. There was a substantial decline in signal strength when the gap was increased, as expected. However, the location and relative strength of reflections is unchanged. Acceptable signal strength is observed with a 3 mm gap, and better signal strength can be achieved if noise is reduced by careful shielding and pulse averaging. This range for the gap should be acceptable for SHM applications in which transducers are probed manually or using coarse automatic positioning.

We report here on signals obtained from undamaged plate girder specimens. Finite element simulation studies of Lamb waves in plate girder geometries (Greve, *et al*., 2006a) show that the reflections are complex. For example, an incident wave is weakly reflected at the web-stiffener or web-flange joints. At the web-flange joint a considerable amount of the incident energy is coupled into the flange, where it propagates transversely and then reflects strongly from the free edges of the flange. At the web-stiffener joint there is significant propagation of energy past the stiffener together with excitation of multiple modes in the stiffener.

Representative experimental results obtained using the ferrite pot core transducer (Figure 7) are shown in Fig. 10; these results were obtained using the data acquisition system described previously, positioned by the flange-crawling inspection robot as shown in Figures 7 and 8. The transducer was mounted on the web, approximately 250 mm above the bottom flange and approximately 30 mm from the vertical stiffener. Tests are shown at four center frequencies; the f-d product for a web thickness of 3.2 mm ranges from 0.8 to 1.28 MHz-mm, within which range only S0 and A0 modes are expected. Reflections detected near 100 µs suggest that the web-flange joint has been illuminated and returned a reflection, corresponding to a path length of roughly 500 mm with an S0 group velocity of 5 mm/µs. The somewhat complex earlier arrivals are associated with reflections from the stiffener.

In earlier simulation studies (Greve, *et al.*, 2006a) we observed that a wave transmitted into a flange from a web will propagate transversely in the flange, reflect from the free edge, and then be refracted back into the web. In this instance the stiffener can be expected to show a similar behavior. The stiffener, which is 3.2 mm thick, projects 50 mm from the web and thereby creates an additional path segment with a length of 100 mm. Therefore, additional reflections at a spacing in time of roughly 20 µs for an S0 wave may be expected. In related experiments reported elsewhere (Greve *et al.*, 2006c) stronger signal levels have been achieved, and further interpretation of Lamb wave modes and reflection paths have been discussed. Moreover, it is well known that the relative strength of A0 and S0 modes varies with frequency and is dependent on the transducer geometry. For an inductively coupled transducer, a major additional factor is frequency dependence caused by the combined effects of the PZT wafer, the transformer, and generator source impedance (Greve, *et al.*, 2006b).

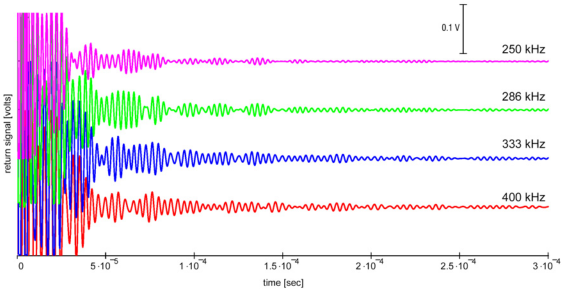

Fig. 10. Reflections observed in the plate girder specimen

SUMMARY

This study has demonstrated a self-contained, inductively coupled piezoelectric transducer for the generation and measurement of guided waves. Three progressive versions of such transducer systems have been developed with the main goal of reducing the thickness of the transducer system with little compromise of mutual inductivity. It is expected that the final thickness of the transducer system be less than 2 mm, making this type of transducer attractive for embedded sensing and surface mounting. In addition, the construction of the transducer is simple and inexpensive. Because of its robustness, simplicity and non-intrusive nature, the inductively coupled transducer can be highly suited for long-term continuous monitoring of in-site structures. Transducer function has been demonstrated preliminarily on a laboratory specimen of a plate girder, and a flange-crawling inspection robot has been developed to demonstrate coarse positioning of the probe coil. Additional laboratory and/or filed testing will be conducted to investigate the applicability of this type of transducer to flaw detection.

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