Structural health monitoring with an inductively coupled (wireless) Lamb wave transducer

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ABSTRACT

Wafer-type PZT transducers are very effective as active sensors for Lamb wave studies in elastic plates and in steel bridge girders. It has been demonstrated that a single transducer can be used in pulse-echo mode, transmitting a transient waveform and then detecting return signals echoing from boundaries, irregularities, and flaws such as cracks. We describe here an inductively-coupled system consisting of a permanently attached transducer and a probe attached to the control electronics. When the probe is brought in proximity to the transducer an exciting pulse is coupled into the transducer and received reflections are coupled out of the transducer and recorded by the control electronics. We present experimental results establishing the effectiveness and practicality of the approach. Ample signal strength is obtained with excitation at less than 10 V.

INTRODUCTION

Ultrasonic Lamb waves offer several important advantages for structural health monitoring. Lamb waves propagate for considerable distances in plate-like structures

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and are reflected at defects such as cracks [1,2]. In addition recent work on wafer-type transducers has shown that Lamb waves can be efficiently generated and detected by a single compact transducer [3,4]. A further advantage of wafer-type transducers is that they offer selective generation of a single wave mode. As a result Lamb waves are currently being explored for monitoring applications as diverse as composite wing structures [5] and bridge girders [1].

Despite the desirable characteristics of Lamb waves, the wafer-type transducer in its present form is not practical for long-term, exposed installations. Even if the transducer is carefully packaged and sealed, corrosion of exposed electrical connectors will be a serious problem. Consequently we have been exploring an inductively coupled Lamb wave transducer that eliminates the need for wired contact. A major advantage of this transducer is the absence of any exposed electrical connections, which eliminates a major point of failure. In addition the transducer is compact and constructed with a small number of inexpensive parts.

In this paper we first outline the transducer concept. We then present the results of experimental demonstrations using two different transducer designs. Finally, we will outline the directions for future transducer development and testing.

TRANSDUCER CONCEPT

Figure 1 illustrates the transducer concept. 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. Alternatively the received signal $v_r(t)$ can measured using a separate winding, possibly with a different turns ratio.

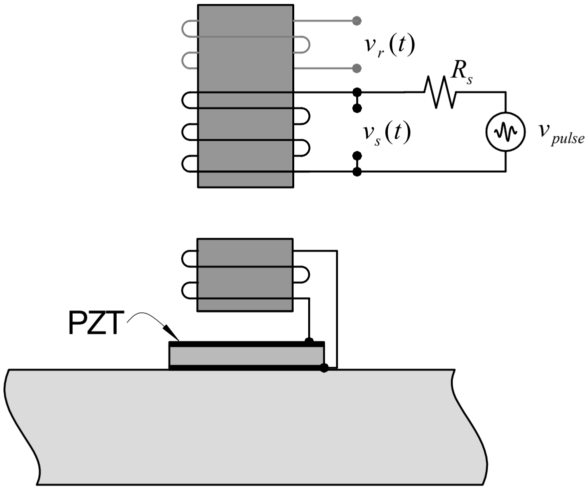

Figure 1. Concept of inductively coupled transducer.

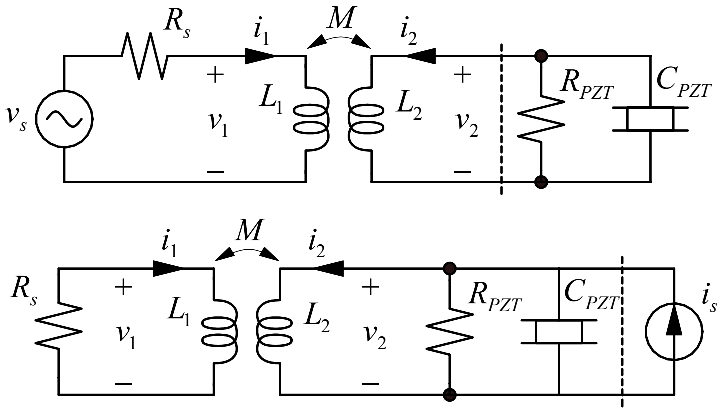

Figure 2. Equivalent circuits for pulse excitation (top) and reception (bottom).

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.

There are several important aspects of this design that need to be explored. Pulses are inductively coupled both into and out of the transducer and as a result the coupling needs to be good enough to obtain adequate signal strength. In practice the probe coil would be positioned manually or with coarse mechanical alignment. Consequently variation of the gap between probe and transducer coils is to be expected and the effect of this gap on signal strength needs to be explored. Finally, isolation of the exciting and received pulses needs to be adequate. We will report experiments addressing these various issues in the following sections.

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 receive, 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 37 cm × 67 cm in size using cyanoacrylate glue.

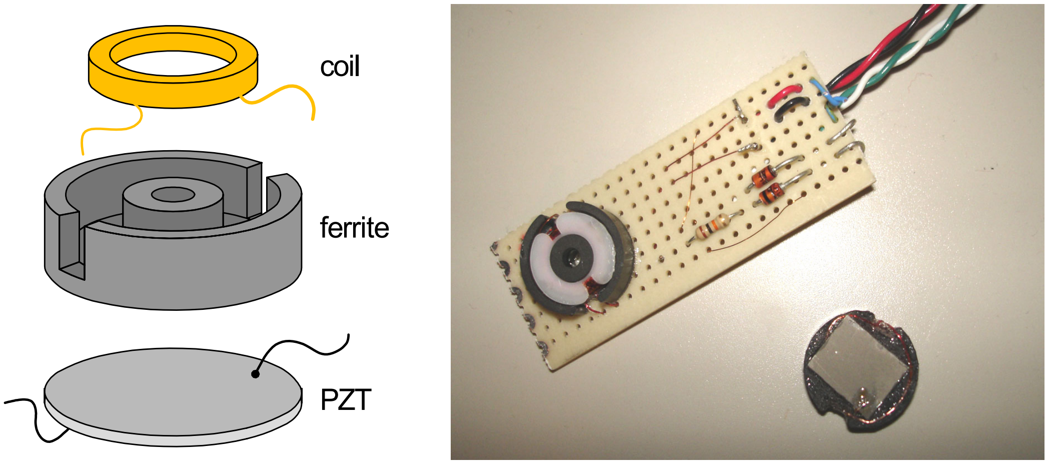

Figure 3. Transducer design using ferrite pot cores: (left) PZT with transducer coil; and (right) photograph of completed transducer and probe coil.

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 and 10 V peak-to-peak in amplitude. The received pulse waveform was monitored using the 72 turn receive coil in series with a 10 kΩ 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 adn 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 [4]. 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 window. Several additional pulses are visible corresponding to longer travel distances. Similar signal levels were observed over the frequency range from about 150 kHz to 333 kHz and for a range of gaps between the cores (not shown).

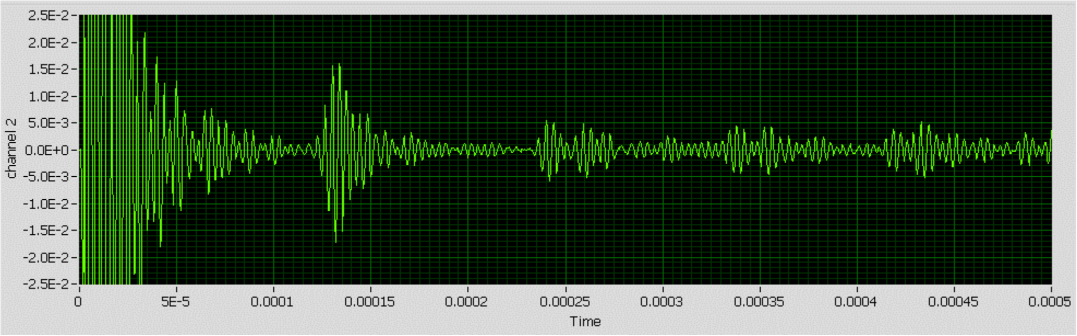

Figure 4. Observed transients for pot core transducer. The pulse center frequency was 286 kHz and there was a 1 mm gap between the two cores.

Results from 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. The alternative design discussed in the next section does not require this contact, and in addition has other advantages.

PLANAR COIL TRANSDUCER

In this section we consider an alternate transducer design that has a smaller protrusion from the structure. This design also offers simpler assembly and possibly lower cost.

The planar coil transducer is shown in Fig. 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 as 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.

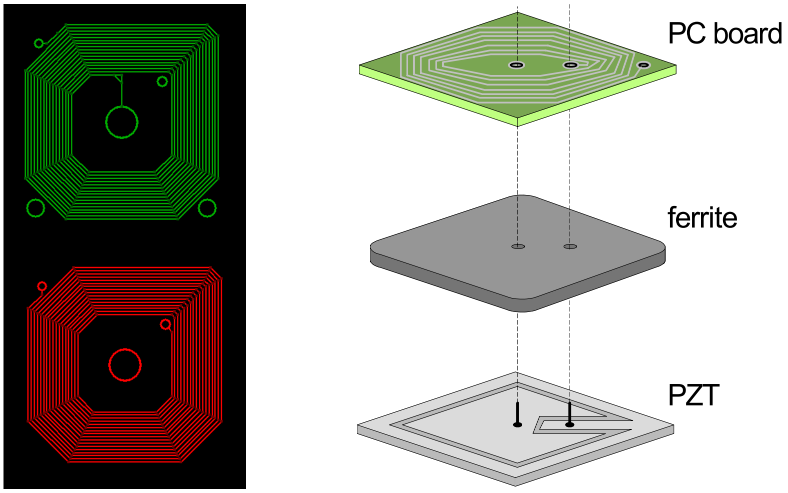

Figure 5. Planar coil transducer: (left) top and bottom metal layers of the printed circuit board; and (right) assembly of the three components.

Testing of this transducer was performed using the scale model steel plate girder shown in Fig. 6. The plate girder is fabricated from steel 3.2 mm thick (web and stiffener) or 6.4 mm thick (flanges). This specimen is approximately 1/3 the size of plate girders commonly used in bridge construction. Often the stiffener does not run the full depth of the girder leading to a potential crack location as indicated [6]. The transducer was attached near this potential crack location using cyanoacrylate adhesive. Figure 6 also shows a photograph of the mounted transducer.

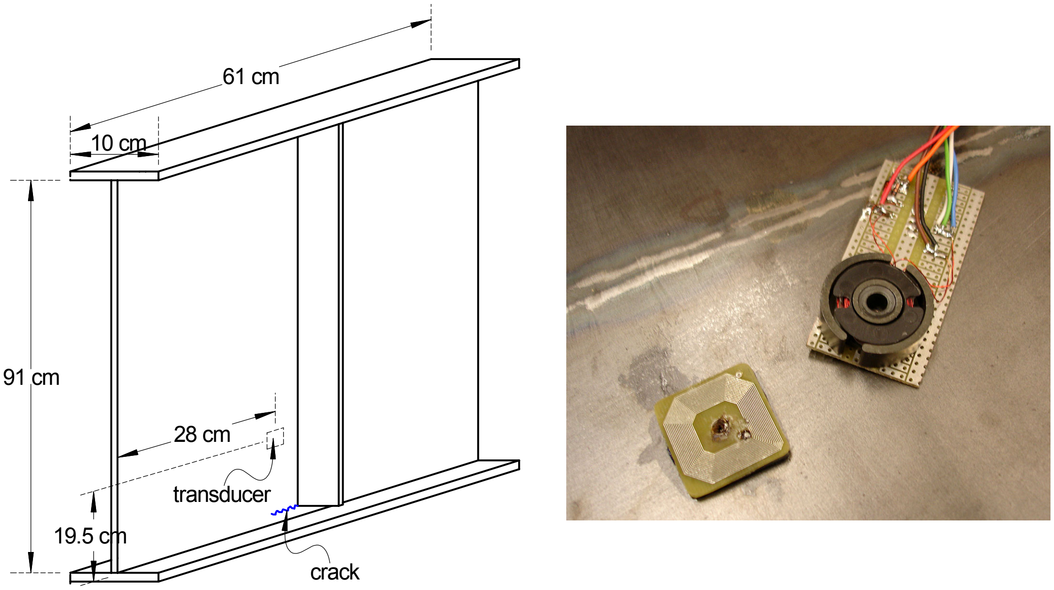

Figure 6. (Left) scale model steel plate girder showing transducer location and potential crack location; and (right) photograph of planar coil transducer mounted on model plate girder and probe coil.

We will report here on signals obtained from the undamaged specimen; testing to induce fatigue cracks is still in progress. Finite element simulations show that the reflections observed are complex even in the undamaged specimen [1,2]. 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 is strongly reflected at the flange edges. At the web-stiffener joint there is significant propagation of energy past the stiffener together with excitation of multiple modes in the stiffener.

Experimental results obtained using the inductively coupled transducer are shown in Fig. 7. These results were obtained using the data acquisition system described previously. The coils for excitation and receiving consisted of 20 turns on a ferrite pot core (dimensions 30 mm diameter × 9.5 mm thick). In this case no protection diodes were used and consequently there is a dead time during which the input stage recovers from the overload caused by the exciting pulse. For best results a switching circuit should be included to minimize this recovery time. In these initial experiments a switching circuit has not been used. The main consequence of omitting this switching circuit is the loss of data during the recovery time which contains information about reflections from nearby surfaces. In these experiments the recovery time was approximately 25 μsec which corresponds to 12 cm of travel time for the S0 mode.

Figure 8 shows the measured reflections for pulses with four different center frequencies. The first strong reflection after the recovery time is attributable to reflection of the S0 mode from the end of the stiffener. An earlier reflection from the web- stiffener weld should be present although that reflection is expected to be weaker and is apparently within the recovery time. Other strong reflections that can be clearly identified include reflections from the end of the flange and the near edge of the plate girder (S0 modes) and the reflection of an A0 mode from the near edge of the girder. At the three highest frequencies the reflections are strong and occur approximately at the same time, which is consistent with the predicted group velocities for steel at these frequencies. However at 250 kHz some reflections are not clearly visible and other reflections have different relative amplitudes. This is partly due to the frequency dependence of reflections from joints [1]. An additional factor is frequency dependence associated with the transducer itself.

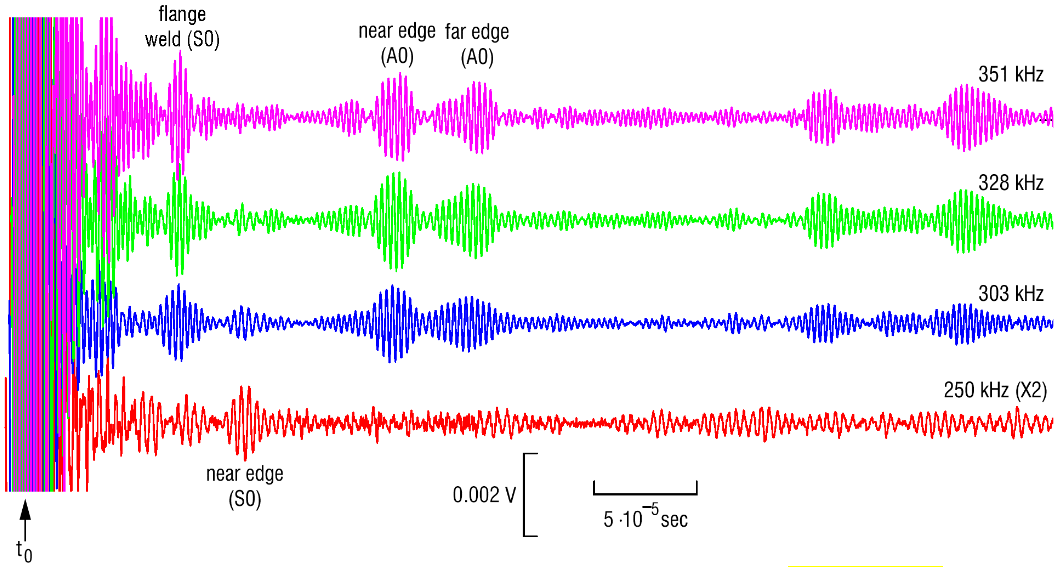

Figure 7. Reflections observed in the model plate girder specimen CORRECTED.

It is well known that the relative strength of A0 and S0 modes varies with frequency and is dependent on the transducer geometry [3,4]. An additional factor with the inductively coupled transducer is frequency dependence caused by the combined effects of the PZT wafer, the transformer, and the generator source impedance (Fig. 2). This is presently being studied analytically and this analysis will be reported elsewhere [7].

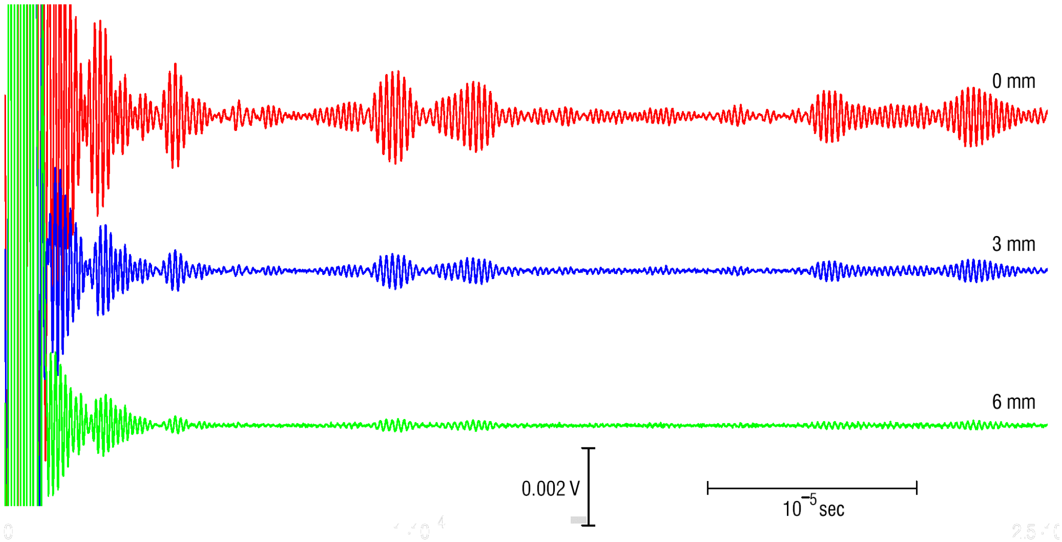

Fig. 8. Effect of varying gap between the probe and transducer coils (center frequency of 328 kHz) CORRECTED.

A major concern is possible distortion of pulse shape due to variations in the circuit component values with the gap between the probe coil and the transducer. We have investigated this issue experimentally and results are shown in Fig. 8. This figure shows the reflections for a center frequency of 328 kHz where the gap between probe and transducer coils is varied from 0 to 6 mm. There is a substantial decline in signal strength as expected when the gap is increased. While the signal strength decreases the location and relative strength of reflections is unchanged.

Acceptable signal strength is obtained for a 3 mm gap and possibly greater if noise is reduced by careful shielding and pulse averaging. This range should be very acceptable for many structural health monitoring applications in which transducers are probed manually or using coarse automatic positioning.

SUMMARY

This work has demonstrated a self-contained, inductively coupled transducer for the generation and detection of ultrasonic Lamb waves. Construction of the transducer is simple and inexpensive and the absence of active components will make this type of transducer very robust and long-lived. Inductively coupled transducers are highly suited for structural health monitoring applications in which many transducers will be permanently installed in exposed locations. Of the two transducer designs, the pot core design is superior with respect to magnetic coupling efficiency. However the planar design is very attractive because of its low profile and fabrication simplicity.

Finally, there are remaining issues concerning inductively coupled transducers. The PZT wafer response and the electrical components of the transducer are both frequency dependent. Consequently careful design will be required to match the PZT wafer and the coupling coils. Finally, the successful application of this type of transducer to flaw detection must be demonstrated in laboratory and/ or field testing.

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