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

Lamb waves propagate for considerable distances in plate-like structures and are reflected at defects such as cracks (Cho et al. 1997, Lowe and Diligent 2002, Greve *et al.* 2005, Greve et al. 2006). Consequently Lamb waves are attractive for defect detection in structures such as airplane wings (Sohn et al., 2006) and bridge girders (Greve *et al.* 2005, Greve et al. 2006). Recent work on wafer-type transducers has shown that Lamb waves can be efficiently generated and detected by a single compact transducer (Giurgiutiu, 2003, Nieuwenhuis et al., 2005). A further advantage of wafer-type transducers is that they offer selective generation of a single wave mode.

Despite its desirable characteristics, 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. An important

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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, leading to potentially long lifetime and high reliability.

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. In operation a probe with one or two coils is 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.

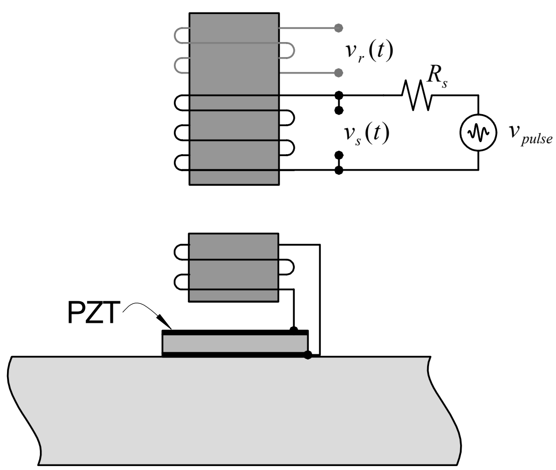

Fig. 1. Concept of inductively coupled transducer.

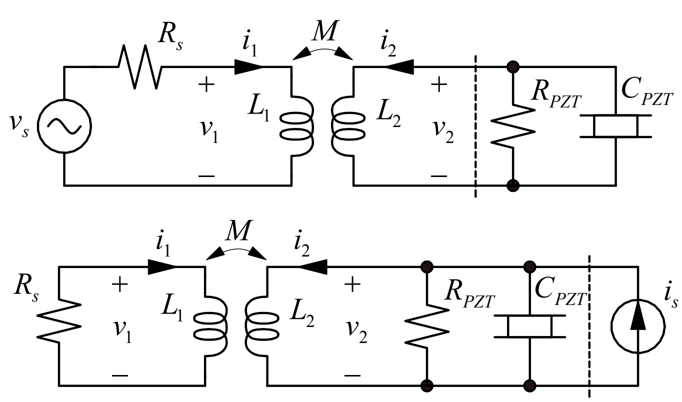

Figure 2. Equivalent circuits for pulse excitation (top) and reception (bottom).

Figure 2 shows the equivalent circuits for exciting and receiving a pulse. For simplicity we show the use of the same winding for excitation and reception. An exciting pulse is coupled through a transformer and drives the PZT transducer. 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 some 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 examined. We will report experiments addressing these various issues in the following sections.

FERRITE POT CORE TRANSDUCER: TESTING OF RECEIVER PERFORMANCE

In this section we compare the performance of the inductively coupled transducer and the conventional wired transducer, when acting as a receiver. Figure 3a 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 55 turns and the probe end had two coils of 55 turns (excitation and receive). The transmit coil was terminated with a 50 ohm resistor to simulate the loading effect of a pulse voltage source. This particular ferrite composition is typically used at frequencies in the range 1 kHz- 2 MHz. The PZT wafer was about 1 cm × 1 cm in size and 0.5 mm thick with nickel electrodes on both sides (type 5A4E from Piezosystems Inc.). The completed transducer was bonded to a 3.2 mm steel sheet using cyanoacrylate adhesive. An ultrasonic pulse was created by an identical PZT wafer located at a distance of 28 cm, by a windowed sinusoidal pulse 5 V in amplitude. A second identical PZT wafer, equidistant from the source, was configured as a conventional wired receiving transducer.

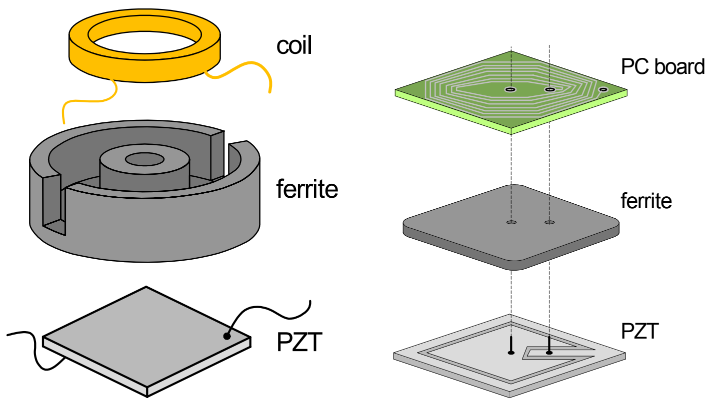

Figure 3. Transducer design using ferrite pot cores: (left) PZT with transducer coil; and (right) photograph of completed transducer and probe coil. Planar coil transducer: (left) top and bottom metal layers of the printed circuit board; and (right) assembly of the three components.

Testing was performed using a National Instruments PCI-6110 DAQ board controlled by LabVIEW. In order to reduce the noise level, 10 transients were averaged to obtain the final signal. Figure 4 compares the received transients using wired and inductive coupling for a pulse with a center frequency of 286 kHz. For the inductive coupling transients are shown for probe to transducer coil gaps of zero and 1 mm. The pulse near $t = 0$ results from stray electrical coupling of the exciting pulse. Clearly visible are the first arrivals of the S0 and A0 pulses at 64 μsec and 97 μsec, respectively. The signal amplitudes are in the 5- 15 mV range with somewhat larger pulse amplitudes observed for the wired transducer. The pulse amplitudes in all cases are sufficiently large to obtain nearly noise- free transients.

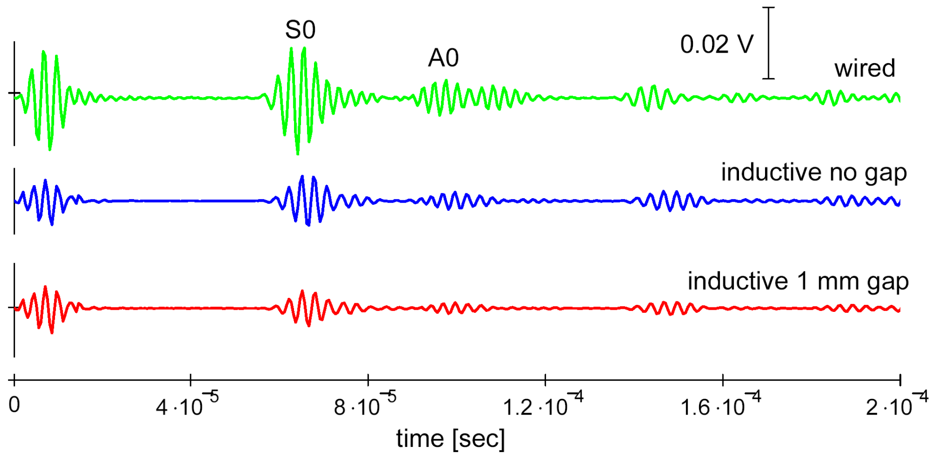

Figure 4. Observed transients for pot core transducer. The pulse center frequency was 286 kHz and there was a 1 mm gap between the two cores.

We have performed similar measurements over a range of pulse center frequencies from 100 to 400 kHz. Figure 5 plots the maximum amplitude of the first arrivals of S0 and A0 pulses as a function of the center frequency. The wired transducer data shows the expected behavior for a wafer-type transducer. The A0 mode has a minimum amplitude near 220 kHz which corresponds to the first minimum $f_{min} = v_{phase}(\mathrm{A0})/2a$ where $2a$ = 1 cm is the length of the PZT transducer. The S0 amplitude shows a maximum near 350 kHz. Data was not collected above 400 kHz because of limitations of the measurement system. The inductively coupled transducer shows similar behavior above 200 kHz, but there is nearly zero response below 200 kHz.

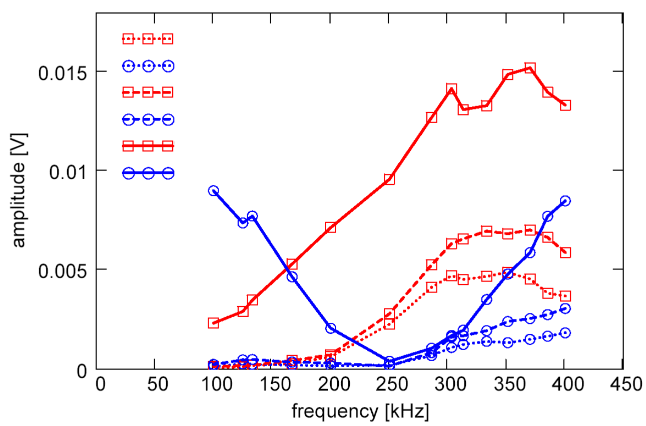

Fig. 5. Frequency dependence of received signal as a function of frequency.

Figure 5 illustrates the important difference between an inductively coupled transducer and a wired transducer. The response of an inductively coupled transducer goes to zero at low frequencies. This can be understood based on circuit analysis of the complete equivalent circuit which will be reported elsewhere (Greve et al., submitted 2006). In addition, the leakage inductance of the transformer leads to additional frequency dependence when the transformer coupling is not perfect. This frequency dependence is not a significant problem; indeed, it has the advantage of suppressing low frequency components associated with structural vibrations, etc.

The experiments so far show that the inductively coupled transducer is suitable as a receiver. In the following section we show that a single transducer can be used to both excite and detect ultrasonic signals.

PLANAR COIL TRANSDUCER: TESTING OF TRANSMIT/RECEIVE PERFORMANCE

In this section we consider a planar transducer design that has a smaller protrusion from the structure. This design also offers simpler assembly and possibly lower cost. The planar transducer design is shown in Fig. 3b. 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 the 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.

Testing of this transducer was performed using the scale model steel plate girder shown in Fig. 5. 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 "web-gap" crack location as indicated (Fisher, 1981). The transducer was attached near this potential crack location using cyanoacrylate adhesive. Figure 5 also shows a photograph of the mounted transducer.

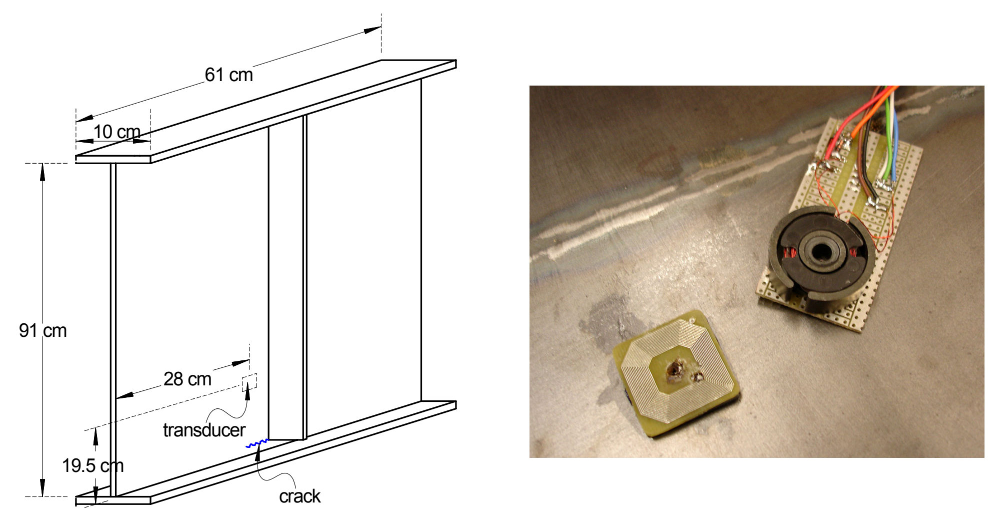

Figure 5. (Left) scale model steel plate girder showing transducer location and potential crack location; and (right) photo of planar coil transducer mounted on model plate girder and probe coil.

We will report here on signals obtained from the undamaged specimen. Finite element simulations show that the reflections observed are complex even in the undamaged specimen (Greve *et al.* 2005, Greve *et al.* 2006). 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 subsequently 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. 6. 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 the transient record 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, however 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 35 μsec which corresponds to 18 cm of travel time for the S0 mode.

Figure 6 shows the measured reflections of pulses with four different center frequencies. The first strong reflection after the recovery time is attributable to reflection of the S0 mode from the flange weld. An earlier reflection from the stiffener weld should be present although that reflection is possibly obscured by the recovery time. Other strong reflections that can be clearly identified include reflections from the free edges of the plate (A0 modes). 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 (Greve *et al.* 2005). An additional factor is frequency dependence associated with the transducer itself.

The reflections are relatively strong over a range of frequencies near 325 kHz and distinct reflections are observed for a considerable time after the exciting pulse. For example, reflections toward the end of the record in Fig. 6 correspond to round-trip travel distances of 250 cm (S0) or 140 cm (A0). As a result it should be possible to detect defects using a relatively sparse array of transducers.

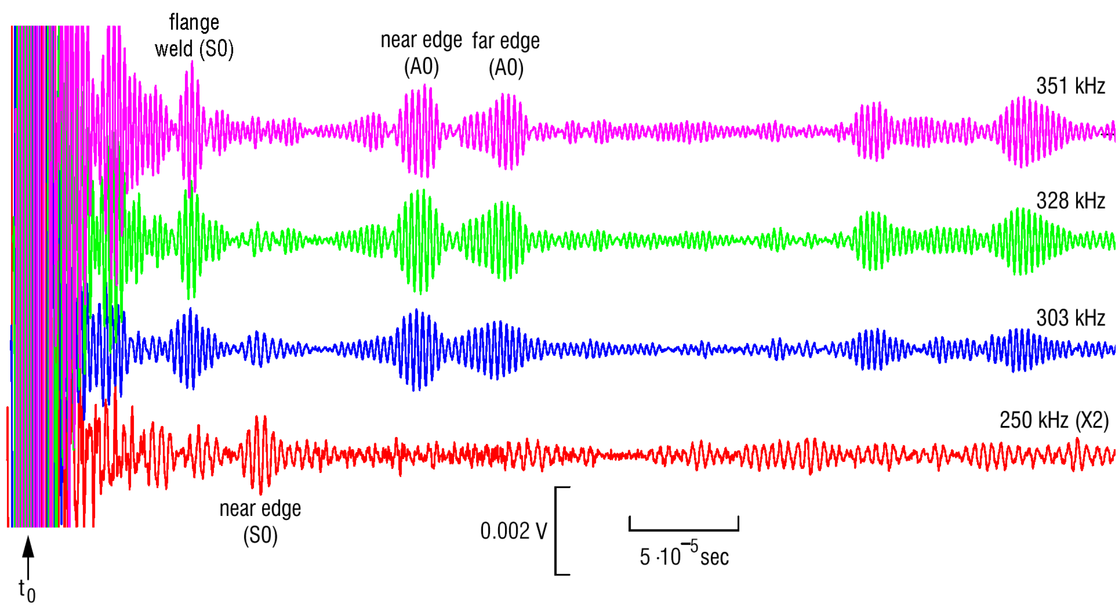

Figure 6. Reflections observed in the model plate girder specimen.

A remaining challenge is the reliable detection of flaw- induced changes in complex geometries where there are many reflections in the undamaged state. Our current work is directed at monitoring the changes to the reflections resulting from the introduction of cracks in girder specimens. Both referenced and non-referenced signal processing approaches need to be evaluated for this task.

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. Two transducer designs have been demonstrated, one with very low profile (~ 3 mm protrusion).

It is important to recognize that both the PZT wafer response and the electrical behavior of the coupled coils contribute to the overall frequency response. 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.

ACKNOWLEDGEMENTS

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