Design Considerations For A Non-contact, Inductively Coupled Lamb Wave Transducer

D.W. Greve
Department of Electrical and Computer Engineering
Carnegie Mellon University, Pittsburgh, PA, USA

I.J. Oppenheim and H. Sohn
Department of Civil and Environmental Engineering,
Carnegie Mellon University, Pittsburgh, PA, USA

Abstract—**The wafer-type transducer is attractive for Lamb wave generation because it offers a degree of mode selectivity and is potentially compact and inexpensive. However, mounting and in particular the provision of electrical connections has been problematic, especially when permanent installation on exposed structures is contemplated. We have recently demonstrated inductive coupling that achieves excellent transducer performance while obviating the need for electrical connectors. In this paper, we report on detailed electrical analysis and modeling of our inductively coupled transducer. We will report detailed analysis of an inductively coupled transducer consisting of a PZT wafer, a ferrite sheet, and a two-layer printed circuit board.**

Keywords-piezoelectric, ultrasonic, transducer, inductive, Lamb

I. INTRODUCTION

Lamb waves generated by wafer-type piezoelectric transducers have been widely studied for the detection of flaws in critical structures. These transducers can be designed to emit primarily a single mode [1,2], and have been studied in structures as diverse as composite wings [3,4] and steel plate girders [5]. While these applications are highly promising, the wafer transducer itself is not practical in its present form. Robust packaging is required if transducers are to be permanently attached, while at the same time cost must be acceptably low. A scheme for packaging of Lamb wave transducers has recently been proposed by Kessler et al. [6]. However the electrical connections are a weak point of this design, as corrosion of connectors will be a problem, especially when transducers are permanently installed in locations exposed to weather and other types of contamination. In addition, some applications contemplate embedding transducers inside composite materials, making the provision of electrical connections even more problematic.

We have previously proposed an inductively coupled Lamb wave transducer that overcomes many of these problems [7,8]. By using inductive coupling we eliminate the need for exposed electrical connectors or wiring. The transducer itself is entirely passive and consequently will have an indefinite lifetime when suitably encapsulated. In addition, the components are inexpensive and easily fabricated. Good results are obtained for gaps between the probe and the transducer of several millimeters. Consequently signals can be recorded from shallowly embedded transducers or by using coarse manual or automatic positioning of a probe above surface-mounted transducers.

In the following sections we first briefly describe the transducer design. We will then examine the coupling of signals into and out of such a transducer with particular emphasis on the effect of the gap between a probe coil and the transducer. We will show that the experimental behavior is in reasonable agreement with predictions. Finally, we comment on the design of transducers for operation in a particular frequency range.

II. TRANSDUCER DESIGN

Figure 1 shows the transducer concept. The piezoelectric wafer is wired to winding #1. Winding #2 is excited by an external source (usually providing a windowed sinusoidal excitation), exciting an ultrasonic pulse in the structure. The return pulses from reflections in the structure cause a voltage on the same piezoelectric wafer. That voltage produces a signal in winding #2 and #3. Only the piezoelectric wafer and winding #1 remain permanently attached to the structure under study; the other coils and the electronics for pulse generation and detection form a removable probe. If desired the additional winding #3 can be used for receiving only (also shown in the figure). Ferrite cores are used to increase the mutual inductance of the two coils and also to reduce the magnetic flux through the structure, which will induce circulating currents if the material is a conductor.

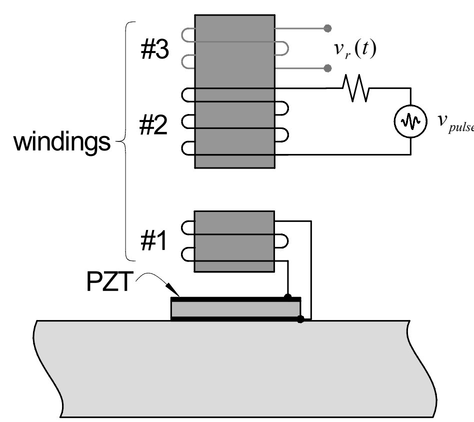

Figure 1. Inductively coupled transducer concept.

Figure 2 shows the equivalent circuit for excitation. We are interested in determining the transfer function v_2/v_s that relates the PZT voltage v_2 to the excitation signal v_s. In order to predict this transfer function, we need to determine the transformer parameters L_1, L_2 and M, especially their dependence on gap between the probe coil and the transducer coil.

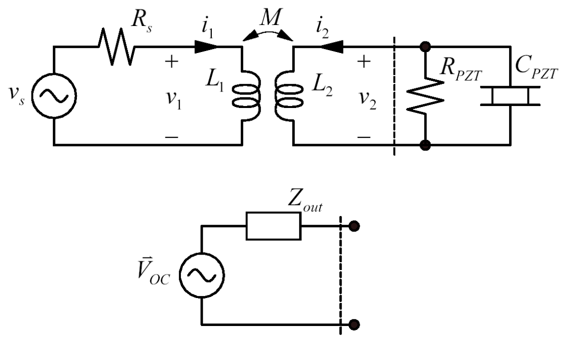

Figure 2. Transducer equivalent circuit during excitation (top) and Thévenin equivalent circuit at the PZT terminals (bottom).

TRANSDUCER FABRICATION AND PREDICTED PERFORMANCE

The transducer design used in this study is shown in Fig. 3. The PZT wafer, ferrite sheet, and printed circuit board are approximately 26 mm square. The double-sided board printed circuit board has a coil consisting of 32 turns. The ferrite sheet has a thickness of 1 mm and the PZT is 5A4 material from Piezo Systems, Inc. 1 mm in thickness. The PZT is nickel-metallized on both surfaces and the metallization is patterned as shown in Fig. 3. The probe coil used with this transducer is made from a ferrite pot core approximately 30 mm in diameter with two 20-turn windings.

The transformer parameters were calculated as a function of the gap between the probe and transducer coils using the finite element package COMSOL 3.2 in the magnetic quasi-static mode (emqa). Calculations were performed in 2-D cylindrical symmetry using as the inner and outer coil radii the radii of the largest circles that fit inside the eight-sided turns (14 mm and 29 mm diameter respectively). A relative permeability of 200 was used for the flat ferrite sheet and a relative permeability of 2000 for the ferrite pot core.

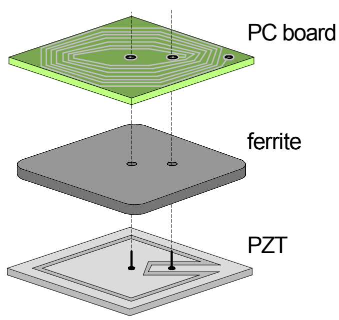

Figure 3. Design of the inductively coupled transducer.

Figure 3 shows the simulation results for two values of the gap when the transducer coil is excited by a DC current of 1 A. Note that the magnetic flux is guided through the ferrite sheet despite its small thickness. As expected the magnetic energy density decreases as the gap is increased.

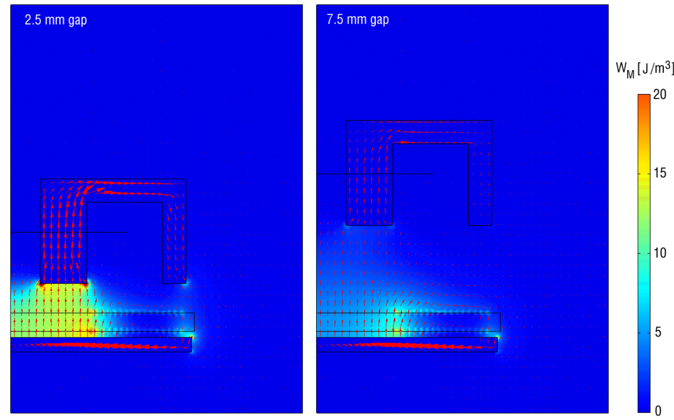

Figure 4. Finite element calculations for transducer- probe coil gaps of 2.5 mm (left) and 7.5 mm (right). Color indicates the magnetic energy density and arrows the magnetic flux density.

The self-inductance L_2 and the mutual inductance M can be determined from the integrated magnetic energy density and the magnetic flux density linking the primary coil, respectively [9]. A separate simulation with the primary coil excited by a 1 A current then permits calculation of the remaining parameter L_1. The resulting inductances as a function of gap are plotted in Fig. 4. These inductances are in reasonable agreement with measurements at 300 kHz and 0.32 cm gap (L_1 = 34 μH, L_2 = 50 μH, and M = 20 μH).

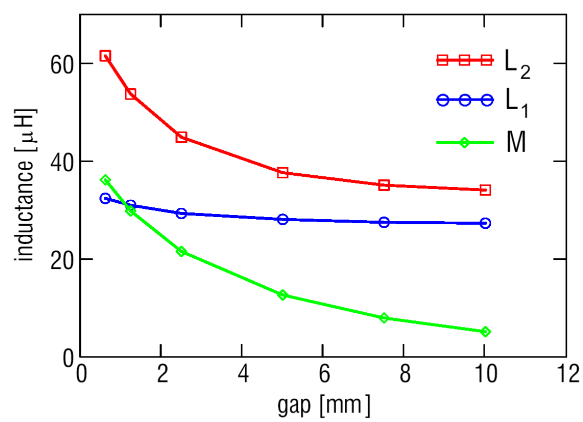

Fig. 4. Finite element simulations of the inductances L_1, L_2 , and M as a function of the gap between the probe coils and the transducer coil.

We can now calculate the transfer function v_{PZT}/v_s. For a lossless transformer with less than perfect coupling, we have the two-port equations

$$v_1(t) = L_1 \frac{di_1(t)}{dt} + M \frac{di_2(t)}{dt}$$

$$v_2(t) = M \frac{di_1(t)}{dt} + L_2 \frac{di_2(t)}{dt}$$

resulting in the Thévenin equivalent circuit at the PZT terminals with open circuit voltage given by

$$\vec{V}_{OC} = \frac{k\sqrt{L_2 / L_1}}{1 + R_s / j\omega L_1} \cdot \vec{V}_s$$

and with Thévenin impedance

$$Z_{out} = \frac{j\omega L_2[R_s^{\ 2} + (1-k^2)\omega^2 L_1^{\ 2}] + \omega^2 k^2 L_1 L_2 R_s}{R_s^{\ 2} + \omega^2 L_1^{\ 2}}$$

In order to plot the transfer function we also need the PZT transducer impedance $Y_{PZT} = j\omega C_{PZT} + 1/R_{PZT}$. The impedance of coupled wafer type PZT transducers has been explored experimentally and theoretically by Giurgiutiu [10]. The transducer impedance is predominantly capacitive with a parallel resistive component that models the radiation of ultrasonic energy. In addition sharp resonances modeled by RLC networks are associated with vibrational modes of the transducer or structural dimensions. Here we will neglect the sharp resonances and we model the PZT by a capacitor $C_{PZT} = 2$ nF (calculated using the transducer dimensions and dielectric permittivity) and a resistor R_{PZT} which models the radiation losses. The resistor value of 400 Ω is estimated from impedance measurements between 200 and 400 kHz (not shown). Figure 5 shows the predicted dependence of transfer function magnitude as a function of frequency with these assumptions.

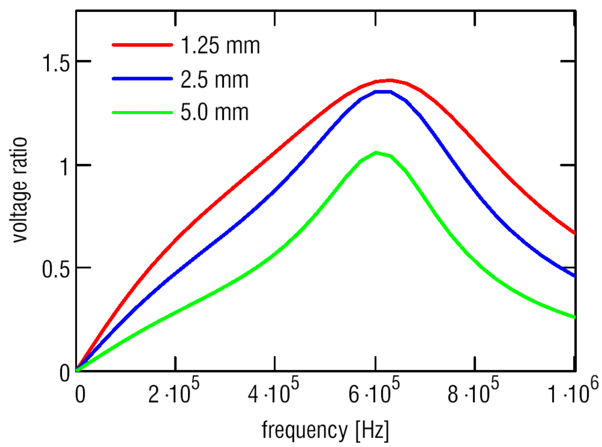

Figure 5. Ratio of source voltage and PZT voltage magnitudes as a function of frequency, predicted using inductance and *k* values from Fig. 4.

The frequency dependence in Fig. 5 can be understood as follows. In the limit of large gap (small *M*) the output impedance $Z_{out} \sim 1/j\omega L_2$ and consequently the output circuit has a resonance at $\omega = 1/\sqrt{L_2 C_{PZT}}$. In the large gap limit the *Q* would be determined entirely by the PZT losses, that is, $Q = R_{PZT}\sqrt{C_{PZT}/L_2}$. As the gap is decreased, there is additional loss from the source resistance reflected into the output circuit. So the increase in coupled signal is accompanied by a decrease in *Q* and an increase in bandwidth. As the losses of the PZT wafer are relatively high the bandwidth is fairly large even for poor coupling.

In operation, it is important that the overall system bandwidth be large enough to permit the use of short pulses and the bandwidth must remain large as the gap is varied. The system bandwidth is not easily calculated, however, because the PZT transducer itself has some frequency dependence [1,2]. Consequently we will examine the overall system behavior experimentally.

The discussion above has only addressed the transfer function from the source to the PZT. The transfer function in the receive mode can be calculated similarly [9] and exhibits the same resonant behavior.

Transducer performance- experimental

A fabricated transducer was attached to a steel specimen using cyanoacrylate glue. The steel specimen was fabricated from a plate 6.4 mm in thickness additional welded plates 6.4 and 12.8 in thickness, yielding a scaled model of a plate girder [11]. The additional welded plates provided discontinuities which produced several ultrasonic reflections. In structural health monitoring the objective is to detect the appearance of additional reflections associated with cracks or other defects. In this paper we illustrate the observation of reflections caused by the discontinuities in the undamaged structure.

Ultrasonic pulses were excited using a 5-cycle waveform

$$\boldsymbol{v}_s(\boldsymbol{t}) = \begin{cases} \boldsymbol{v}_{s0}\sin(\omega \boldsymbol{t})\cdot\left(\sin(\frac{\omega \boldsymbol{t}}{10})\right)^2 & \boldsymbol{t} < \frac{10\pi}{\omega} \\ 0 & \boldsymbol{t} > \frac{10\pi}{\omega} \end{cases}$$

where the exciting pulse amplitude v_{s0} was typically 5- 10 volts. The pulses were excited and the return signal was detected using a National Instruments PCI-6110 DAQ board. Winding #2 was used to excite the transducer and winding #3 was used to measure the return signal. As the receiver coil is loaded only by the 1 MΩ input impedance of the data acquisition board it does not change the transfer function calculated above. However there is a recovery period of approximately 40 μsec after the end of the exciting pulse.

Figure 6 shows typical data obtained for a pulse center frequency of 351 kHz. Several of the prominent reflections can be attributed to reflections from particular discontinuities based on comparison of the arrival times and the known propagation velocities of S0 and A0 mode. Similar measurements taken at a range of pulse center frequencies are consistent with the behavior in Fig. 5 in that the pulse amplitudes decrease with decreasing frequency. However a detailed comparison is not possible because the reflections and the transducer itself have significant frequency dependence [1,2].

The dependence of pulse shape on the gap between the probe and transducer coils is of particular importance. As the probe coil may be repositioned between measurements it is important that any variations in pulse shape be small compared to the changes caused by cracks. Changes in amplitude not important as they can be compensated by scaling the acquired waveforms.

Figure 8 also compares the observed waveforms as a function of gap between the probe and transducer coils. In this figure the bottom trace is for zero gap and the upper traces have been scaled by factors of 2.6 and 6.5 respectively. The detail overlays the two waveforms and shows that there are negligible changes in the pulse shape even when the gap is changed from zero to 6 mm.

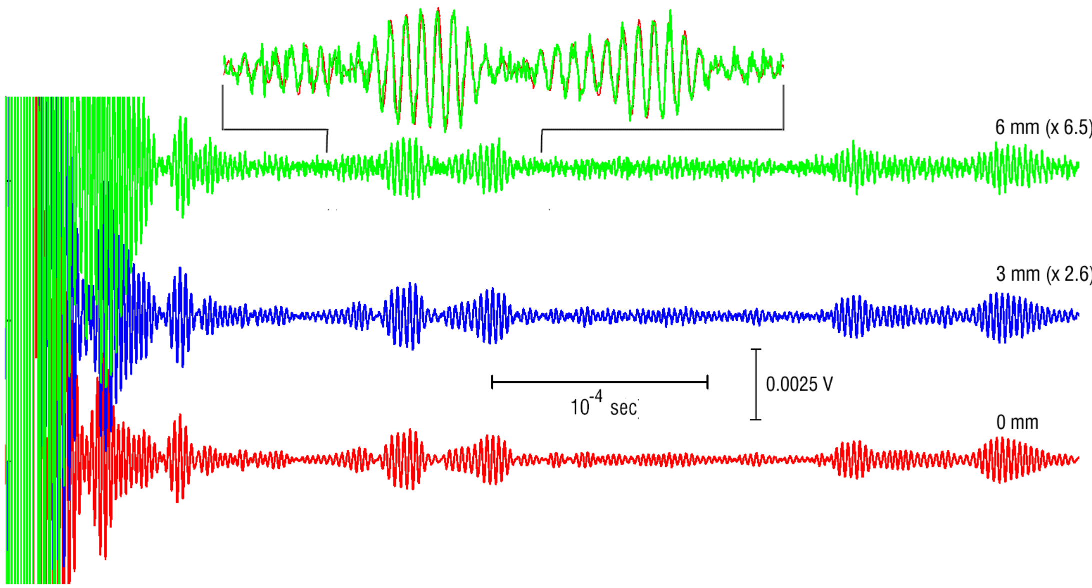

Figure 6. Effect of varying the gap between probe and transducer coil with a pulse center frequency of 351 kHz. Data at 3 mm was scaled by 2.6 and data at 6 mm by 6.6. Inset: detail of data for 6 mm gap superimposed on data from 0 mm gap.

These results show that acceptable signals are obtained in this transducer and that variations in probe coil- transducer gap change the amplitude but not the shape of the transient signal. in this particular transducer.

Finally, we briefly consider the effect of changing the PZT type or size. This can result in changes in either the transfer function peak frequency, quality factor Q, or both. Within limits the resonant frequency can be adjusted by changing the coil inductance. With respect to Q, problems may be encountered when the Q is too high, especially with weak coupling or large gap. In such a case it may be necessary to introduce additional damping which may have the additional undesirable effect of reducing the overall signal levels.

ACKNOWLEDGMENT

We thank the Pennsylvania Infrastructure Technology Alliance and the National Science Foundation for support. This material is based upon work supported by the National Science Foundation under Grants Nos. CMS-0529208 and CMS-0329880. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

[1] V. Giurgiutiu, “Lamb Wave Generation with Piezoelectric Wafer Active Sensors for Structural Health Monitoring,” in *Smart Structures and Materials 2003: Smart Structures and Integrated Systems* San Diego, vol. 5056, pp. 111-122.

[2] J. Nieuwenhuis, J. Neumann, D.W. Greve, and I.J. Oppenheim, “Generation and detection of guided waves using PZT wafer Transducers,” *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control,* vol. 52, pp. 2103-2111, 2005.

[3] S.S. Kessler, S.M. Spearing, and C. Soutis, “Damage detection in composite materials using Lamb wave methods,” in *Smart Materials and Structures*, vol. 11, 2002, pp. 269-78.

[4] H. Sohn, G. Park, J.R. Wait, N.P. Limback, and C.R. Farrar, “Wavelet-based active sensing for delamination detection in composite structures,” *Smart Materials and Structures*, vol. 13, 2004, pp. 153-60.

[5] D.W. Greve, I.J. Oppenheim, and N.L. Tyson, “Interaction of defects with Lamb waves in complex geometries,” in *IEEE Ultrasonics Conference Proceedings*, Rotterdam 2005, pp. 297-300.

[6] S.S. Kessler, S.M. Spearing, S.Young, and C.T. Dunn, “Packaging of structural health monitoring components,” *Proceedings of the SPIE - The International Society for Optical Engineering* San Diego, vol. 5391, 2004, pp. 219-29.

[7] D.W. Greve, I.J. Oppenheim, H. Sohn, C.P. Yue, and A.K. Boscha, “Active sensing with an inductively coupled (wireless) Lamb wave transducer,” Fourth World Conference on Structural Control and Monitoring, San Diego, July 2006.

[8] D.W. Greve, I.J. Oppenheim, H. Sohn, and C.P. Yue, “An inductively coupled (wireless) Lamb wave transducer,” Third International Workshop on Advanced Smart Materials and Smart Structures, Lake Tahoe, May 2006.

[9] D. W. Greve, H. Sohn, C. P. Yue, and I. J. Oppenheim, “An inductively-coupled Lamb wave transducer,” IEEE Transactions on Sensor, accepted for publication.

[10] V. Giurgiutiu and A.N. Zagrai, “Characterization of Piezoelectric Wafer Active Sensors,” *J. Intelligent Material Systems and Structures*, Vol. 11, pp. 959-975 (2000).

Do not remove this page reference numbers will disappear

[1] V. Giurgiutiu, "Lamb Wave Generation with Piezoelectric Wafer Active Sensors for Structural Health Monitoring," in *Smart Structures and Materials 2003: Smart Structures and Integrated Systems* San Diego, vol. 5056, pp. 111-122.

[2] J. Nieuwenhuis, J. Neumann, D.W. Greve, and I.J. Oppenheim, "Generation and detection of guided waves using PZT wafer Transducers," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control,* vol. 52, pp. 2103-2111, 2005.

[3] S.S. Kessler, S.M. Spearing, and C. Soutis, "Damage detection in composite materials using Lamb wave methods," in *Smart Materials and Structures*, vol. 11, 2002, pp. 269-78.

[4] H. Sohn, G. Park, J.R. Wait, N.P. Limback, and C.R. Farrar, "Wavelet-based active sensing for delamination detection in composite structures," *Smart Materials and Structures*, vol. 13, 2004, pp. 153-60.

[5] D.W. Greve, I.J. Oppenheim, and N.L. Tyson, "Interaction of defects with Lamb waves in complex geometries," in *IEEE Ultrasonics Conference Proceedings*, Rotterdam 2005, pp. 297-300.

[6] S.S. Kessler, S.M. Spearing, S.Young, and C.T. Dunn, "Packaging of structural health monitoring components," *Proceedings of the SPIE - The International Society for Optical Engineering* San Diego, vol. 5391, 2004, pp. 219-29.

[7]D.W. Greve, I.J. Oppenheim, H. Sohn, C.P. Yue, and A.K. Boscha, "Active sensing with an inductively coupled (wireless) Lamb wave transducer," Fourth World Conference on Structural Control and Monitoring, San Diego, July 2006.

[8]D.W. Greve, I.J. Oppenheim, H. Sohn, and C.P. Yue, "An inductively coupled (wireless) Lamb wave transducer," Third International Workshop on Advanced Smart Materials and Smart Structures, Lake Tahoe, May 2006.

[9] D. W. Greve, H. Sohn, C. P. Yue, and I. J. Oppenheim, "An inductively-coupled Lamb wave transducer," IEEE Transactions on Sensor, accepted for publication.

[10] V. Giurgiutiu and A.N. Zagrai, "Characterization of Piezoelectric Wafer Active Sensors," J. Intelligent Material Systems and Structures, Vol. 11, pp. 959-975 (2000).