Inductive coupling for wireless Lamb wave and longitudinal wave transducers

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ABSTRACT

Piezoelectric transducers have been widely used for the generation and detection of ultrasonic waves for structural health monitoring. Recently, we proposed the use of inductive coupling in order to implement wireless coupling to a Lamb wave transducer. In that transducer the ultrasonic waves were generated by a piezoelectric wafer attached to the surface of a plate. These transducers are effective for generation and detection of low-order Lamb waves. In this paper we report the extension of the inductively coupled technique to higher-frequency longitudinal waves near 2 MHz . In this report longitudinal waves were generated by a piezoelectric wafer edge-mounted to a plate and provided with inertial backing.

INTRODUCTION

In many structural health monitoring applications it is advantageous to permanently mount piezoelectric ultrasonic transducers to the structure. Permanent mounting gives reliable ultrasonic coupling and therefore makes it practical to detect damage by comparison with recorded reference waveforms. While robust transducer designs have been developed [1], connectors remain a point of failure vulnerable to corrosion and damage. Recently we reported an inductively coupled transducer that makes electrical connections unnecessary [2]. Figure 1 shows the transducer concept. A piezoelectric transducer is permanently mounted to the structure and wired to a coupling coil. A probe coil with one or two windings is used to couple an exciting pulse (Fig. 1a) or a received reflected pulse (Fig. 1b) to the measurement electronics. The transducer unit mounted on the structure is inexpensive, passive, and can be completely encapsulated.

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In this paper, we first discuss the design and modeling of inductively coupled transducers operating at frequencies near 2 MHz. This extends the range of application of the inductively coupled transducer we previously reported [2]. We will then report on experimental characterization of the inductively coupled transducers and in particular on the generation of nearly longitudinal waves.

INDUCTIVELY COUPLED TRANSDUCERS

Previously we reported inductively coupled Lamb wave transducers operating in the 100-400 kHz region. These transducers are suitable for mounting on the flat surfaces of plate girders and similar plate-like structures. In this frequency range only the lowest-order Lamb modes are generated for typical plate thicknesses ($f{\cdot}d$ < 1.8 mm·MHz). Many authors have noted that it is advantageous to have only low-order Lamb modes present, as this simplifies the interpretation of measurements. However operating at low $f{\cdot}d$ means that the wavelength is long (typically of the order of cm) and this leads to reduced scattering by small defects and poor defect localization. As a result in this paper we explore higher frequencies and higher $f{\cdot}d$ products.

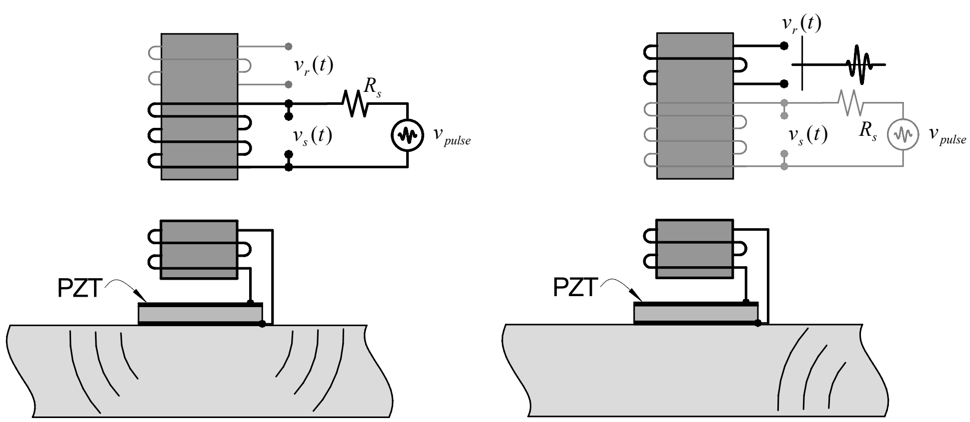

Fig. 1. Inductively coupled transducer concept.

Figure 2 shows the design of an inductively coupled high-frequency transducer. This transducer is designed to be edge-mounted on a plate-like member, in contrast to the transducer of Fig. 1 which is intended to be surface mounted. The piezoelectric element is Piezo Systems type 5A4E material 15 mm × 15 mm in size and 1 mm thick and is bonded to the plate with cyanoacrylate adhesive. A lead backing 3 mm thick is also bonded to the piezoelectric element. Contact is made to the front surface using copper foil. The coupling coil consists of 3 turns wound on a ferrite E-core (FR42216EC from Magnetics, Pittsburgh, PA).

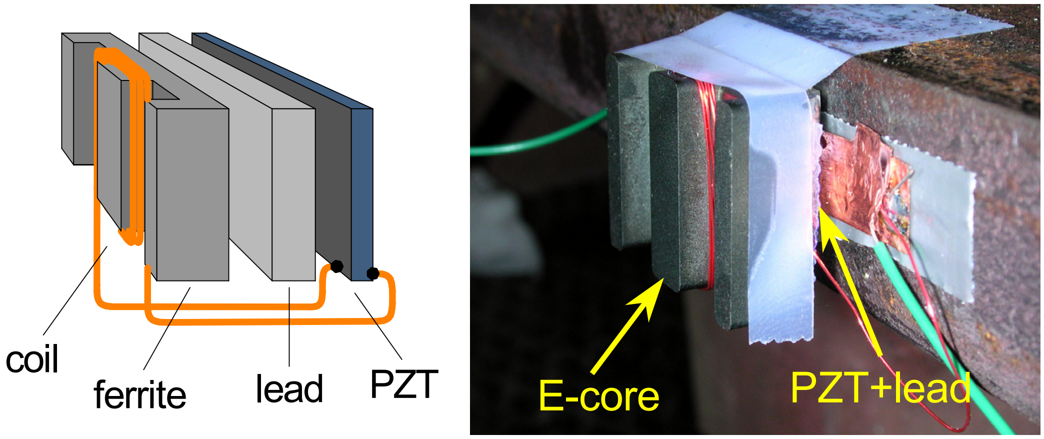

Fig. 2. A single inductively coupled transducer designed for edge mounting to a plate: (left) drawing showing components of the transducer and (right) photograph showing a transducer mounted to a steel plate.

Design of such an inductively-coupled transducer is complicated by the frequency dependence associated with the coupling coils and the piezoelectric wafer itself. Accordingly, we have developed a circuit model that can predict the performance of the inductively coupled transducer. Of particular interest are the overall frequency dependence of the transducer and the effect of varying gap between the probe coil and the transducer coil. In the following, we report the results of such modeling on a transducer design for operation at a nominal frequency of 2 MHz.

Figure 3 shows the electrical equivalent circuit that models two inductively coupled transducers operated in pitch-catch mode. From left to right, we have the following elements:

- Vi and Ri model the pulse generator. The pulse generator has an output resistance Ri = 50 Ω and generates a 5-cycle windowed sinusoid. Simulations are performed as a function of the center frequency *f*.
- Mutual inductor K1 represents the transformer consisting of the probe coil and the transducer coupling coil. The transformer parameters used in the simulation were measured as a function of gap using a HP 4192A impedance analyzer.
- The mutual inductor K2 models the electrical to mechanical transformation of the piezoelectric transducer. C1, L1, and C2 are extracted from impedance measurements on a piezoelectric element bonded to a steel plate.
- T1 is a lossless delay line. The characteristic impedance of this delay line was chosen to model the radiation resistance and other losses of the bonded piezoelectric element.
- L2, C3, K3, and C4 model a second piezoelectric element that receives the ultrasonic pulse and converts it back into an electrical signal.
- K4 is a mutual inductor that models the coupling transformer for the second (receiving) transducer.
- Ro and Co model the input impedance of the receiver electronics.

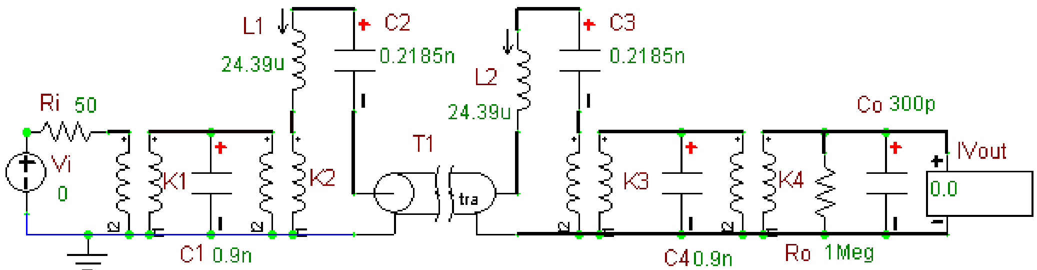

Fig. 3. Equivalent circuit for modeling a pair of inductively coupled transducers operated in pitch-catch mode.

Results from simulations with an input signal of amplitude 19.2 V peak-to-peak are shown in Fig. 4. Note that this simulation does not account for acoustic losses so only the relative values are significant. We see that for close coupling the peak transmission occurs near 2.3 MHz. As the one of the gaps is increased the transmitted amplitude is modestly reduced. The peak shifts slightly to lower frequencies and the peak becomes broader, consistent with our previous results on inductively coupled transducers operating at lower frequencies [2].

These simulations have been compared with experiments on inductively coupled transducers edge-mounted on a steel plate with a thickness of 19 mm and a transmission length of 30.3 cm. The exciting pulse was generated by an Agilent 33120A signal generator and the received transient was recorded using a National Instruments PXI-6115 data acquisition card. The peak-to-peak amplitude of the received pulse was recorded as a function of pulse center frequency and transducer gap.

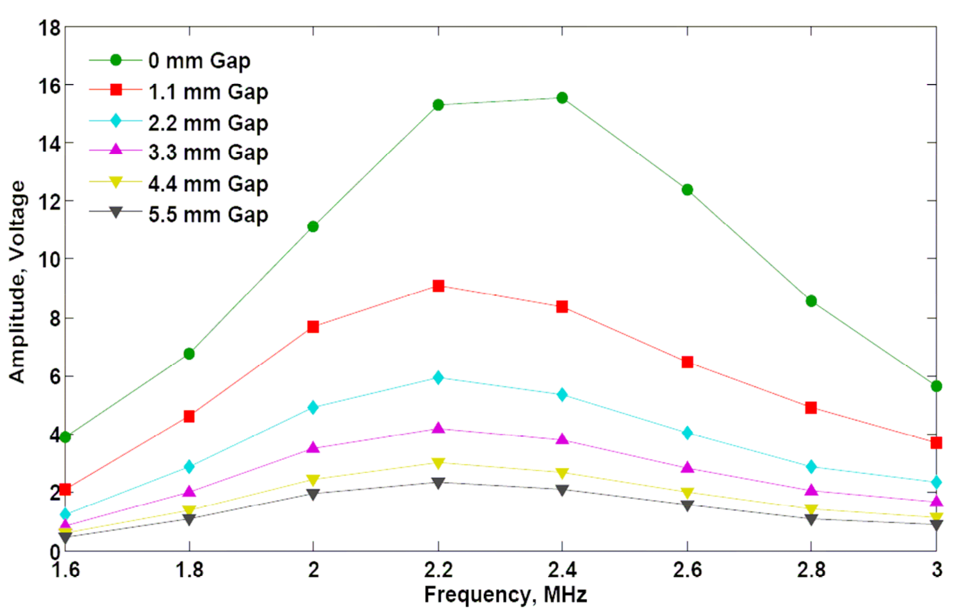

Figure 4. Simulated peak-to-peak amplitude at receiver for two inductively coupled transducers operated in pitch-catch mode.

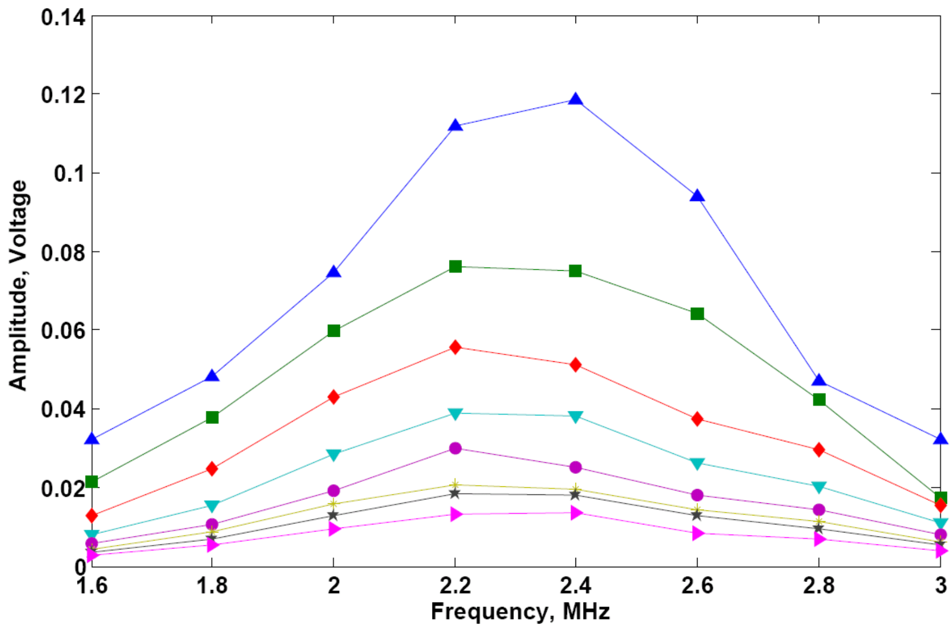

Fig. 5. Measured peak-to-peak amplitude as a function of frequency as one of the gaps is varied: (▲ 0 mm gap, ■ 1 mm gap, ◆ 2 mm gap, ▼ 3 mm gap, ● 4 mm gap, + 5 mm gap, ★ 6 mm gap, and ▶ 7 mm gap).

These experimental results are presented in Fig. 5. The received peak amplitude is approximately two orders of magnitude lower than the excitation signal amplitude, mostly as a result of geometric spreading in the plate. The peak frequency and the dependence of peak height on gap are in excellent agreement with simulations. This shows the value of circuit simulations for predicting the performance of a particular transducer design.

PLATES WITH HIGHER *f·d* PRODUCTS

The experiments reported above were performed in a plate with $f{\cdot}d$ = 38 mm·MHz. At this $f{\cdot}d$ product there are a considerable number of different Lamb wave modes possible with varying group velocity. As a result one might expect the received pulse to be considerably broadened. However the experimental result is quite different as shown in Fig. 6; we see instead a train of sharp pulses with uniform spacing. The first pulse arrival corresponds to a group velocity of 5.8×10^5 cm/sec, in excellent agreement with the longitudinal wave velocity in steel.

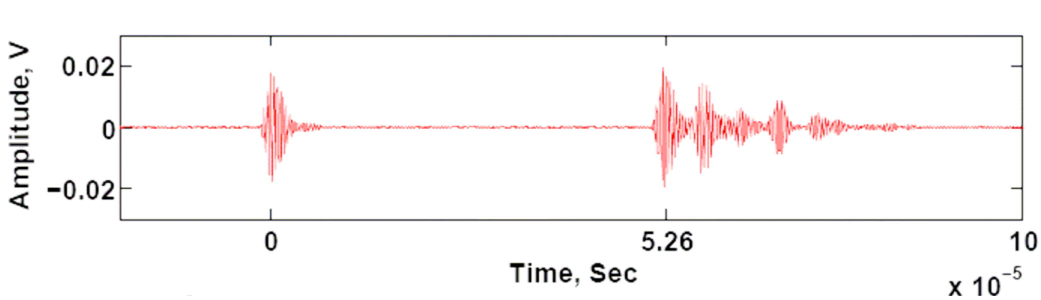

Fig. 6. Received signal after a propagation distance of 30.3 cm. The pulse center frequency was 2.2 MHz. The signal at t = 0 is due to electrical stray coupling.

This "trailing pulse" phenomenon, termed [3] "secondary echoes produced by split-off transverse waves," is well-known and has a straightforward explanation. Assume that a longitudinal wave is launched in the plate. A longitudinal wave incident on a surface of a plate at grazing incidence will reflect as a longitudinal wave traveling parallel to the plate surface and a transverse wave at an angle θ (in steel) of about 33 degrees, where θ is measured between the propagation direction of the transverse wave and the normal to the plate surface. This transverse wave will then strike the opposite face and produce another pair of longitudinal and transverse waves. This reflected longitudinal wave will be delayed by time $\Delta t = [d/(c_t \cos\theta) - d \cdot \tan\theta / c_l]$ where c_t and c_l are the transverse and longitudinal wave velocities, respectively. This process repeats, producing a train of trailing pulses.

While the phenomenon is a familiar one, we are not aware of any investigation of the transition from the emission of Lamb waves to these nearly longitudinal waves. Accordingly we have performed finite element simulations of the emission of ultrasonic waves resulting from edge excitation of a plate. The simulations below were performed using Comsol Multiphysics for a plate 2 cm in thickness. A five-cycle windowed sinusoid force excitation was applied normal to the edge of a steel plate. Simulations were performed in the time-dependent plane strain structural mechanics mode.

Figure 7 shows the *x* displacement (displacement in the direction normal to the plate edge) observed after 50 μs as a function of the pulse center frequency. At low $f \cdot d$ ($f \cdot d$ < 9 mm·MHz) the pulses have complex character and the leading edge of the pulse travels more slowly than the longitudinal velocity. This is consistent with generation of a mixture of the Lamb modes with the different group velocities that are allowed at this frequency. Beginning approximately at 750 kHz ($f \cdot d$ ~ 15 mm·MHz), the leading edge propagates at the longitudinal velocity and the *x* displacement is nearly uniform across the plate.

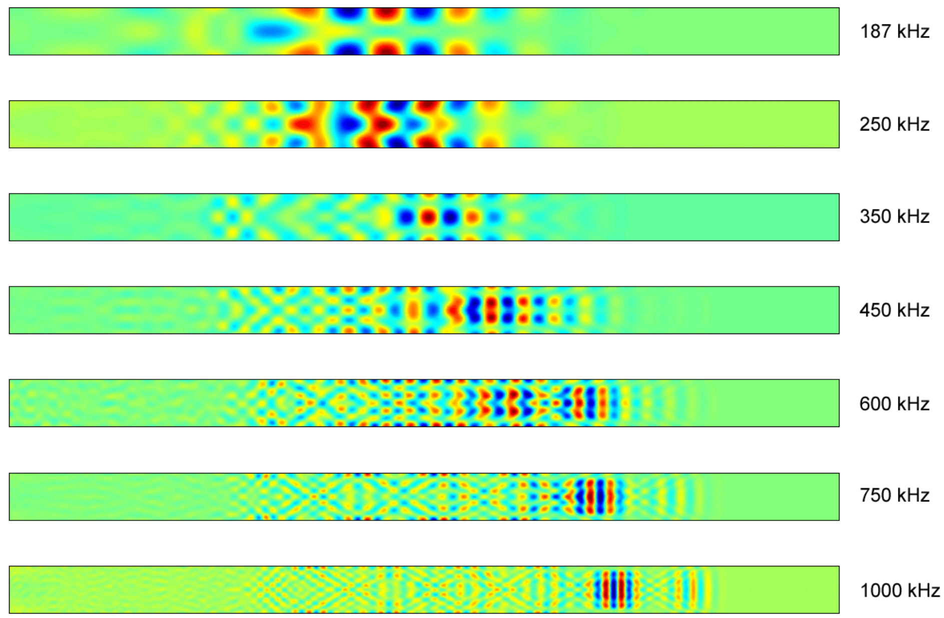

Fig. 7. Particle displacement in the *x* direction 50 μs after a pulse is launched from the left edge. This illustrates the transition from a mixture of Lamb modes (f < 600 kHz) to a nearly-longitudinal wave front (f > 600 kHz)

Figure 8 shows the decay of the leading pulse and growth of trailing pulses at 1 MHz ($f{\cdot}d$ = 20 mm·MHz). The simulations show the formation of a near-planar wavefront within the first 5-10 μs of propagation. This wavefront propagates at the longitudinal velocity and gradually loses energy while a second trailing pulse forms and gains energy. The beginnings of a third trailing pulse behind the second can also be seen.

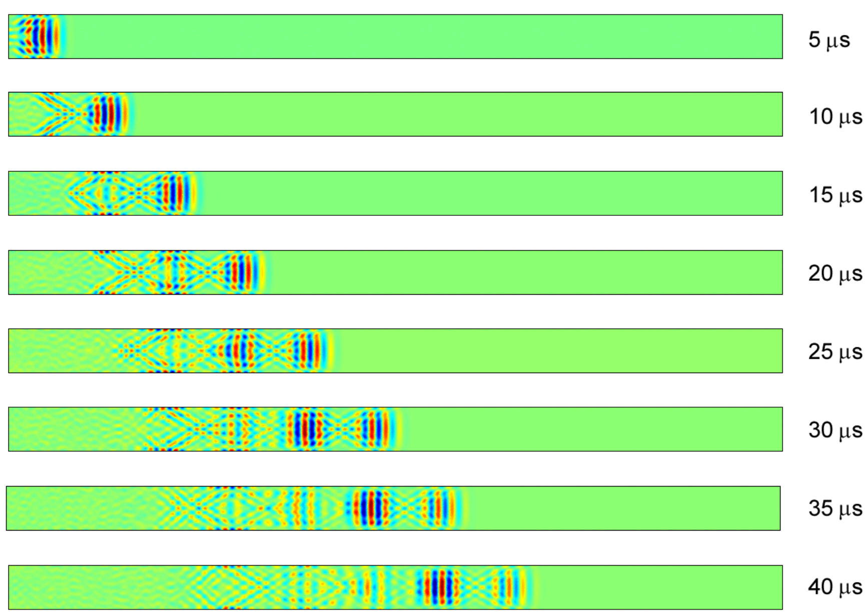

Figure 8. Simulated *x* displacement at various times after a 1 MHz pulse is launched from the left edge.

Both simulations and experiment show that nearly longitudinal pulses can be formed for moderate values of the $f \cdot d$ product. A single excited pulse forms a train of trailing pulses as it propagates. The individual pulses within remain sharp even after propagation for relatively long distances.

We suggest that these nearly-longitudinal waves offer some advantages over Lamb waves for flaw detection. By using a higher frequency the wavelength is reduced and the detection of small flaws will be enhanced. The formation of a pulse train will complicate interpretation somewhat; however, it is likely that the advantage of improved reflections from small flaws will outweigh the disadvantage of more complex interpretation.

SUMMARY

We have extended our previously reported inductively coupled ultrasonic transducer to higher pulse center frequencies near 2 MHz. Inductive coupling works well in this frequency range and the performance of the transducer can be accurately modeled using the equivalent circuit described earlier. Operation at higher frequencies is potentially advantageous because of stronger scattering from small flaws. However operation in this frequency range results in the formation of a train of pulses. We suggest however that the advantage of shorter wavelength will make it desirable to operate in this frequency range.

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