Wireless power transmission using ultrasonic guided waves

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Abstract. The unavailability of suitable power supply at desired locations is currently an important obstacle in the development of distributed, wireless sensor networks for applications such as structural health monitoring of aircraft. Proposed solutions range from improved batteries to energy harvesting from vibration, temperature gradients and other sources. A novel approach is being investigated at Cardiff University School of Engineering in cooperation with Airbus. It aims to utilise ultrasonic guided Lamb waves to transmit energy through the aircraft skin. A vibration generator is to be placed in a location where electricity supply is readily available. Ultrasonic waves generated by this device will travel through the aircraft structure to a receiver in a remote wireless sensor node. The receiver will convert the mechanical vibration of the ultrasonic waves back to electricity, which will be used to power the sensor node. This paper describes the measurement and modelling of the interference pattern which emerges when Lamb waves are transmitted continuously as in this power transmission application. The discovered features of the pattern, such as a large signal amplitude variation and a relatively high frequency, are presented and their importance for the development of a power transmission system is discussed.

1. Introduction

Distributed sensor networks, particularly for aviation structural health monitoring applications, have recently been receiving increasing interest and are being developed by several institutions [1], [2].

Such networks are expected to be wireless, as the added weight and routing difficulties of a suitable wiring harness would be prohibitive. The aforementioned research programmes have identified as a significant obstacle the need for a wireless power source for the sensing network nodes. Such power sources are required to work through the entire lifetime of the aircraft without being accessed. The latter requirement rules out the use of batteries, at least at the current sensors’ power consumption levels (single to tens of mW). Ambient energy harvesting devices have been proposed as an alternative. Such devices are currently available from a multitude of manufacturers, albeit a successful integration with a wireless sensing network has not, to the author’s knowledge, yet been reported.

Lightweight Structural Health Monitoring System (SHeMS) is a wireless sensing network project carried out by a consortium including, among others, Airbus UK and Cardiff University [3]. Within this project the idea was proposed to provide a wireless power source by the means of power transmission through the aircraft skin via ultrasonic Lamb waves.

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The concept of power transmission through a structure using any type of ultrasonic waves is relatively new. Previous work focused on the ultrasonic power transmission through the thickness of metal sheets, such as the skin of pressure vessels or ships. In this configuration ultrasonic bulk waves must be used as the transmission medium. The main driver for the development of these wireless solutions is the need to avoid drilling holes in the material, which could decrease its strength. The power transmission capability is usually combined with a data transmission function by the means of modulating the power-transmitting carrier signals.

Shaudy et. al [4] developed a system capable of transmitting 250 mW of power through a 57 mm thick steel wall. The system operated at 1 Mhz carrier frequency and in addition to power transmission offered a communication rate of 55 kb/s. The authors did not provide information about the power transmission efficiency. The system utilized piezoelectric transducers for transmission (Tx) and reception (Rx). The transmitting transducer was operated at the voltage of 40 V peak-to-peak (Vpp) maximum. The intended use of the system was to provide wireless sensing inside a pressure vessel.

Kluge et al. [6], [7] developed and tested a similar system working across a ~5 mm thick aluminium wall of an aviation hydraulic accumulator. The system utilized cylindrical piezoelectric transducers vibrating in the thickness mode at 741 kHz and, in a subsequent version, at 3 MHz. Its Tx transducer was supplied with a 20 Vpp electric signal. It was capable of transmitting 30 mW of power with an 80 % efficiency and 1 kb/s of data.

More recently Neasham et al. [7], [8], [9] developed a system for power and data transmission through up to 80 mm thick steel marine vessel walls. In order to overcome the problem of the bonding of piezoelectric transducers to corroded and contaminated surfaces, they used electro-magnetic acoustic transducers (EMATs). Such transducers are coil electromagnets which induce eddy currents in the metal structure and in turn generate acoustic vibration. The authors showed that with these transducers data communications can be achieved at wall-transducer standoff distances of up to 10 mm. Of the many tested configurations, the authors quote the performance of a 400 mW Tx system operating across a 25 mm steel wall. This system achieved a 10 mW power transmission (0.25 % efficiency) and a 1 Mb/s data transmission rate. The authors expect that the power transmission efficiency can be increased to 1 %.

While ultrasonic power transmission using Lamb waves has not been attempted before, these type of waves have been used for damage detection since at least the 1960s. A large amount of literature on this topic has been published since that time. In this project the authors aim to expand the available, damage detection-related knowledge of Lamb waves to the power transmission application. The appearance of a static interference pattern when Lamb waves are transmitted continuously, as in the power transmission application, has been identified as an important difference between the two applications. This article presents the results of a theoretical and experimental investigation of this phenomenon and its consequences for the ultrasonic power transmission system design.

2. Interference pattern measurement

2.1. Background
An experiment was designed to investigate if the expected Lamb wave interference pattern was indeed present and to measure its magnitude. The experimental setup comprised an aluminium plate mimicking an aircraft skin panel and a set of piezoelectric transmitting (Tx) transducers. The receiving (Rx) transducer could be moved across the plate surface in order to map the magnitude of the acoustic signal at a given location.

2.2. Experimental setup
The test specimen was a 1.025 x 0.9 m, 1.5 mm thick 6082 aluminium plate. The plate was placed horizontally on a number of foam blocks in order to minimise the damping of the vibration by the support structure (Figure 1).
The Tx transducers: 150 kHz McWade, 5 mm long Macro Fiber Composite (MFC) and a 23 mm long MFC were placed along a line parallel to the shorter edge of the plate, 0.2 m from that edge. The McWade and P15 transducers were bonded to the plate with silicone rubber; the MFCs were bonded with cyanoacrylate glue (Figure 2).

Electrical measurements previously carried out by the author had indicated that the crystal-type McWade transducers had sharp resonance peaks at around 117.06 kHz (Figure 3). This frequency was an average taken from several samples of the same transducer model. Individual transducers’ resonance frequencies differed from these by up to 1 kHz. The interference experiment was to be
carried out at these frequencies. The same electrical measurement had indicated that MFCs did not
demonstrate a resonance peak in the range of frequencies between 50 and 250 kHz. Thus, they were to
be operated at the frequencies chosen for the McWade transducer, allowing for a performance
comparison.

![Electric power consumed by piezoelectric transducers](image)

Figure 3. Measurement of electric power consumed by different types of piezoelectric transducers.
Peak-to-peak driving voltages quoted in the legend. Resonance peaks visible for P15 and McWade.
MFC power consumption is close to zero at all frequencies, as it was measured in a free state.

The lengths of the MFCs were chosen to match the wavelengths of the Lamb waves expected to be
generated during the experiment. The 5 mm transducer was to be roughly half the wavelength of the
$A_0$ mode wave at $\sim$120 kHz (near McWade transducer’s resonance frequency of 117.06 kHz) and the
23 mm transducer was to be half the wavelength of the $S_0$ mode wave at the same frequency. This
choice of lengths was to facilitate a comparison of the effectiveness of the generation of the two Lamb
wave modes by transducers tuned to their wavelengths.

The Rx sensor was a National Physical Laboratory’s “point contact” transducer (Figure 4). This
transducer is built of a conical piezoelectric sensing element enclosed in a metal case and pressed
against the specimen surface by a spring. Such a design facilitates a flat frequency characteristic, a
small area of contact with the measured surface ($\sim$ 2 mm diameter) and a constant force with which
the sensing element is pressed against the surface. The Rx sensor was connected to a translation
mechanism utilizing a Vernier screw in order to permit sufficiently small translation steps. No
couplant was used. This was dictated by firstly the need to maintain the sensor’s small contact area (a
meniscus of a couplant could significantly expand the area from which the vibration was collected)
and secondly the need to slide the sensor from one measurement location to the next during the
experiment. During the sensor’s movement the coupling gel, if used, could flow in an unpredictable
manner and change the sensor sensitivity. It was decided that the aforementioned problems associated
with the use of a couplant would outweigh the possible decrease and variation of sensitivity that could
be expected in operation without a couplant.
Figure 4. NPL “point contact” transducer. The white foil covering the conical sensing element is visible. The sensing contact area is in the centre of the foil.

The signal generation and recording electronics consisted of an Agilent signal generator and oscilloscope. No preamplifier was used between the Rx sensor and the oscilloscope.

2.3. Experimental procedure
The measured value was the peak-to-peak amplitude of the electric signal output by the NPL Rx transducer. The measurements were taken in 0.5 mm translation steps over a distance range of 340 to 360 mm from the Tx transducers. This roughly corresponded to half the distance between the Tx transducers and the far edge of the plate. The Rx sensor was translated along a line parallel to the plate’s centreline, facing the tested Tx transducer. Each measurement was repeated three times.

2.4. Experimental results
For the frequency of 117.03 kHz, regardless of the Tx transducer type, the measurement revealed near-sinusoidal signal amplitude patterns with a period of 5.5 mm. The peak and dip magnitudes of the patterns differed between Tx transducers. The results are plotted in Figure 5.

2.5. Additional observations
During the experiment it was visually observed that a strong sensitivity of the received signal to pressure applied to various locations on the plate was evident. By holding the edge of the plate between two fingers a decrease in as much as 50% of the measured signal amplitude could be observed.

3. Time of flight measurement
3.1. Background
In order to provide sufficient input data for the theoretical modelling work (described in the next section of this paper), the amplitudes of individual signals contributing to the interference pattern were measured. These signals were expected to be: Lamb wave $S_0$ and $A_0$ modes travelling directly from the Tx to the Rx sensor; and these modes’ signals reflected from the far edge of the plate. The measurement was carried out using pulsed, instead of continuous, signals. Combined with the knowledge of time of flight (TOF) of the respective signals this enabled the received pulses to be identified and their amplitudes measured.

As the previously used Agilent electronics were not capable of recording pulsed signals, Physical Acoustics Corporation (PAC) data acquisition equipment was used instead.
3.2. Results
The signal pulses corresponding to the two Lamb wave modes, both direct and reflected, were easily identifiable however, the sensitivity of the PAC equipment was significantly different from the sensitivity of the Agilent electronics. Thus, the measured signal amplitudes could not be compared. The only reliable pieces of information that could be derived from the TOF experiment were the proportion between the amplitudes of $S_0$ and $A_0$ modes and the reflection coefficients (from the edge of the plate) of the two modes, results of which are presented in Table 1.

![Graph 1](image1.png)

![Graph 2](image2.png)

![Graph 3](image3.png)

Figure 5. Interference pattern – experimental and modelling results
Table 1. $A_0/S_0$ mode amplitude proportions and reflection coefficients derived from time of flight measurement. Reflection coefficients are transducer-independent

| Tx transducer type | McWade | 5 mm MFC | 23 mm MFC |
|--------------------|--------|----------|-----------|
| $A_0 / S_0$ amplitude proportion | 84.65  | 21.8  | 5.75 |
| Reflection coefficient for $S_0$ mode | 0.64 |          |           |
| Reflection coefficient for $A_0$ mode | 0.49 |          |           |

4. Interference pattern modelling

4.1. Physical and mathematical model

A simplified physical model of Lamb wave propagation and interference was used as a basis for the subsequent computer-based simulation. The model assumed that the Tx transducer emitted two continuous, sinusoidal signals, corresponding to the $A_0$ and $S_0$ Lamb wave modes. Upon reaching the far edge of the plate, the signals were reflected. During reflection, the signals amplitude was reduced by being multiplied by a fractional reflection coefficient (Figure 6).

![Figure 6. Schematic of assumed physical model of Lamb wave interference](image)

The model omitted reflections from side walls and all other, more complex paths of propagation. The attenuation of the signal as well as the magnitude loss during reflection were represented by the reflection coefficient measured in the TOF experiment. These assumptions were considered reasonable as the geometry of the experimental setup was straightforward and the signal paths chosen to be modelled were expected to be dominant. Such an approach greatly simplified the computer modelling task.

Mathematically, the interference pattern was calculated in the distance domain by evaluating sums (or resultant amplitudes) of the four aforementioned Lamb wave signals over one oscillation period:

$$\text{Resultant amplitude (dist) = maximum } [S_0 \text{ direct (dist, } t) + A_0 \text{ direct (dist, } t) + S_0 \text{ reflected (dist_refl, } t) + A_0 \text{ reflected (dist_refl, } t)]$$

evaluated over time $t = 0$ to one full oscillation cycle

(1)

where:

- $dist$ is the distance between the Tx and the Rx transducer
- $dist$ _refl_ is the distance covered by the signal reflected from the far edge of the plate before arriving at the Rx transducer.

The Lamb waves $A_0 \text{ direct, } S_0 \text{ direct, } A_0 \text{ reflected, } S_0 \text{ reflected}$ were modelled as sinusoidal signals at the given distance and time, calculated as in the following example:

$$A_0 \text{ direct} = A_0 \text{direct} \cdot \sin[2 \pi \cdot (distance/\lambda - t/T) + \phi]$$

(2)
where $A_{d\text{irect}}$ is the amplitude of the wave, $\lambda$ is the wavelength, $T$ is the period and $\phi$ is the initial phase shift. (The remaining three signals are calculated analogously.)

4.2. Input data

The wavelengths of the $A_0$ and $S_0$ modes were calculated from the phase velocities obtained from the commercial software Disperse. Proportions between amplitudes of the two modes as well as reflection coefficients where known from the time-of-flight experiment.

The absolute amplitudes of the modes were adjusted in order to achieve the best fit between the simulated and experimental results. This step was necessary in the absence of reliable experimental data regarding mode amplitudes. The adjusted values are listed in Table 2.

Table 2. Signal amplitudes used in the model, adjusted to achieve a good fit with experimental data

| McWade         | MFC 5 mm | MFC 23 mm |
|----------------|----------|-----------|
| $A_{A0}$ = 55 mV | $A_{A0}$ = 6.4 mV | $A_{A0}$ = 6.8 mV |
| $A_{S0}$ = 0.65 mV | $A_{S0}$ = 0.29 mV | $A_{S0}$ = 1.18 mV |

4.3. Modelling results

In the case of all three Tx transducer types a satisfactory model-experiment fit was achieved (Figure 5). In the case of the McWade transducer, the pattern frequency match was very good, but the magnitude variation was not fully reflected by the model. For the 5 mm MFC the fit was very good both in the frequency and magnitude. In the case of the 23 mm MFC the magnitude match was good (even repeating the secondary variation of the peak magnitude), but the frequency did match exactly.

5. Discussion

5.1. Model – experiment differences

The authors consider several sources of the imperfect fit between the experiment and the model.

1) The omission of signal paths other than direct and straight-line reflected. An analysis of the TOF experiment data showed that the signal reflected diagonally from the side edges of the plate could be equal in magnitude to the signal reflected from the far edge. This signal (and possibly others, not identified) must have also played a significant role in the emergence of the measured interference pattern. The model did not take this influence into account.

2) Measurement error. For each measurement point the Rx transducer was moved to a different position on the plate. While the condition of the plate surface appeared uniform, it may have, in fact, differed from location to location. This might have affected the vibration transmission from the plate to the sensor. The match between the three subsequent measurement repetitions was good. This suggests that, if there was a measurement-related variation, it can be associated with the plate surface condition rather than with the movement of the sensor itself.

Despite these sources of error, the theoretically predicted pattern shows a reasonably good match with the experimental data. This strongly suggests that the assumed theoretical explanation of the measured phenomenon is correct and can be used in further work.

The good match also confirms that the signals paths chosen for the model (direct and straight line reflected) were indeed dominant. It has to be noted that the geometry of the experiment was very simple: the plate was square and the main signal propagation path was parallel / perpendicular to the plate’s edges. In the case of more complex geometries using more complex 2- or 3-dimensional modelling software may be necessary to obtain correct predictions.
5.2. Characteristics of the observed interference pattern and their consequences for the power transmission application

The measured signal magnitude proportion between the dips and the peaks of the interference pattern fell in the range between 0.5 and 0.3. This means that, should the Rx transducer be positioned in a pattern dip instead of a peak, the power transmission efficiency can drop by up to 70 % of the achievable maximum.

The period of the observed pattern – 5.5 mm – is small in relation to the size of commonly used piezoelectric transducers (a 20 mm diameter is typical) and very small in relation to the distances over which the power transmission system is expected to work (several metres). In real-life applications this feature will make it extremely difficult to position the receiving transducer optimally, over a signal peak. In addition, the observed sensitivity of the experimental setup to touch suggests that the real-life system will also be very sensitive to environmental factors such as icing of the aircraft. This will make an optimum positioning of the Rx transducer even more difficult, if not impossible.

5.3. Efficiency of \( S_0 \) and \( A_0 \) Lamb wave mode generation by different transducer types

As shown in Table 2, the proportion between \( S_0 \) and \( A_0 \) out-of-plane vibration amplitude was roughly an order of magnitude in higher in the signal generated by a 23 mm MFC than in the signal generated by a McWade transducer. The \( S_0/A_0 \) magnitude proportion of the 5 mm MFC was roughly four times higher than McWade’s. These results lead to two conclusions. Firstly, MFCs of any length generate stronger \( S_0 \) mode than the crystal-type McWade. This can be caused by the fact that MFCs vibrate in-plane, coupling to the dominant vibration direction of the \( S_0 \) mode, while the McWade transducer in this experiment was operated at its out-of-plate resonance. Secondly, tuning the MFC length to \( S_0 \) mode wavelength significantly increases its \( S_0 \) mode generation efficiency.

6. Conclusions and recommendations

An important feature of the continuous Lamb wave transmission – the emergence of a distinct, relatively high frequency, static interference pattern – was observed experimentally and explained theoretically. This feature has little importance for the damage detection application of Lamb waves and therefore its investigation is not available in previously published literature. The continuous signal interference seems, however, to be of importance for the power transmission application of Lamb waves. An examination of the interference pattern characteristics, in particular its high frequency and sensitivity to environmental influence indicates that any future ultrasonic Lamb wave power transmission system will have to be specifically designed to overcome the problems caused by the existence of this pattern. Possible solutions may include a receiving sensor designed to be insensitive to the pattern (e.g. encompassing an area of several signal peaks), or a system which will tune automatically in order to match the signal peak position with the location of the receiving sensor.

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