Studies of Acoustic-Electric Feed-throughs for Power Transmission Through Structures.

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ABSTRACT

There are numerous engineering design problems where the use of wires to transfer power and communicate data through the walls of a structure is prohibitive or significantly difficult that it may require a complex design. Using physical feedthroughs in such systems may make them susceptible to leakage of chemicals or gasses, loss of pressure or vacuum, as well as difficulties in providing adequate thermal or electrical insulation. Moreover, feeding wires thru a wall of a structure reduces the strength of the structure and makes the structure prone to cracking due to fatigue that can result from cyclic loading and stress concentrations. One area that has already been identified to require a wireless alternative to electrical feedthroughs is the container of the Mars Sample Return Mission, which will need wireless sensors to sense a pressure leak and to avoid potential contamination. The idea of using elastic or acoustic waves to transfer power was suggested recently by [Y. Hu, et al., July 2003]. This system allows for the avoidance of cabling or wiring. The technology is applicable to the transfer of power for actuation, sensing and other tasks inside any sealed container or vacuum/pressure vessel. An alternative approach to the modeling presented previously [Sherrit et al., 2005] used network analysis to solve the same problem in a clear and expandable manner. Experimental tests on three different designs of these devices were performed. The three designs used different methods of coupling the piezoelectric element to the wall. In the first test the piezoelectric material was bolted using a backing structure. In the second test the piezoelectric was clamped after the application of grease and finally the piezoelectric element was attached using a conductive epoxy. The mechanical clamp with grease produced the highest measured efficiency of 53% however this design was the least practical from a fabrication viewpoint. The power transfer efficiency of conductive epoxy joint was 40% and the stress bolts (12%). The experimental results on a variety of designs will be presented and the thermal and non-linear issues will be discussed.

Keywords: Ultrasonic, Bulk Acoustic Waves, power conversion, isolation, pressure vessels

1. INTRODUCTION-THEORY

A variety of situations exist where power or information is required to be transmitted across a physical barrier without perforating the barrier. If the barrier material is thin or transparent to electromagnetic waves in the frequency of interest this can be accomplished optically or with magnetic coupling. If this is not the case then other means are required to accomplish this task. The idea of using elastic or acoustic waves as to transfer power was suggested recently by Y. Hu, et al.\footnote{1} In the system they investigated a transmit and receive piezoelectric transducer were separated by a sealed armor (wall). A sinusoidal voltage was applied across the transmitting piezoelectric at a known frequency generating an acoustic wave that travel through the armor into the receiving piezoelectric where the stress wave generated a sinusoidal voltage. Useful work was done on a load impedance connected electrically in parallel with the receiving piezoelectric. A similar configuration to the one they described is shown schematically in Figure 1. In the configuration shown a front and tail mass have been added to the system in an effort to increase the design variables. In the work of Hu et. al\footnote{1} the piezoelectric/elastic layer/piezoelectric was solved using the wave equation and linear equations of piezoelectricity and constant stress boundary condition between the layers and traction free surfaces. An alternative approach based on network equivalent circuits\footnote{2,3} that can easily be modified to account for additional acoustic elements and connected directly to other networks or circuits. All the possible loss mechanisms of the solution can be accounted for and introduced into the model. The circuit model allows for both power and data transmission in the forward and reverse directions through acoustic signals at the harmonic and higher order resonances. This system allows for the avoidance of cabling or wiring. The technology is applicable to the transfer of power for actuation, sensing data or other tasks inside sealed containers and vacuum/pressure vessels. One possible application for this technology is in the measurement of seal integrity of the sample container of the Mars Sample Return (MSR) mission, which is critical to
mission success. If the Mars environment is not entirely contained within the sample container, it could contaminate Earth’s environment upon reentry into the Earth atmosphere. Even a very small risk of this contamination would be enough to require the mission to be aborted. A reliable system to verify the seal integrity of the container and monitor any leakage is therefore a necessity. Integral to any seal/leak detection system for MSR is the ability to pass electrical power and data through the container wall without compromising the integrity of the wall. To this end a Wireless Acoustic Electric Feed-Through (WAEF) transducer is being developed.

**Figure 1.** Schematic of the physical acoustic-electric system with a piezoelectric generator and receiver. The tail and front mass are optional. The delivered power is consumed in the impedance $Z$.

**Figure 2.** Schematic of the network equivalent circuit for the physical system shown in Figure 1. The delivered power is consumed in the impedance $Z$. ZTL and ZTR are the terminating mechanical impedances associated with the front and tail mass.

Before it can be applied to MSR, Hu, et. al.’s initial theoretical model requires much more development to understand high power behavior such as piezoelectric nonlinearity and thermal effects. Practical issues such as bonding must also
be understood. Investigation of these issues must be completed to ultimately allow for the WAEF to be optimized and implemented for use in the MSR mission. Progress to date includes the development of computer aided solutions of the analytical model, experimental prototype development, bonding method investigation, power transfer demonstration, and power transfer efficiency measurements. A schematic diagram of the model for the system shown in Figure 1 is shown in Figure 2. The model parameters for the network circuit shown in Figure 2 are in the previous paper by Sherrit et. al. These models have been widely used for backed/matched and mass loaded resonators, transient response, material constant determination, and a host of other applications.

Using typical representations of piezoelectric elements and acoustic/elastic layers, an equivalent circuit model (Figure 2) of the WAEF transducer was developed. Two computer aided methods were developed to solve this circuit. The first method solves the circuit with an iterative network solution using MathCad. Results match the wave equation solution found in. In order to allow for iterative manipulation of the computer solution, a second solution of the equivalent circuit model using a MatLab script was developed. This model takes advantage of the matrix equation representation of the equivalent circuit to allow for an expandable model. Results of the MatLab solution are identical to those in the MathCad solution. Figure 2 shows the input electrical impedance of the WAEF transducer for piezoelectric and elastic layer properties used in the example used in reference. Power transfer efficiency of the same WAEF with a 20 ohm resistive load is also shown.

Further development of the matrix model will facilitate modification of the theoretical solution for the WAEF as the design changes. These changes may include additional piezoelectric layers, a stress bolt, and the explicit inclusion of bonding layers. This iteratively modifiable computer solution will be invaluable to the optimization process.

2. EXPERIMENTAL

Bond Investigation

One important practical difficulty involved in the implementation of the WAEF transducer is finding a method to mechanically couple the piezoelectric elements to the elastic element(s). The current theoretical model assumes that elastic layers are ideally coupled at their interface surface. However, in reality some sort of bond layer or compressive force must exist to hold each coupling surface in mechanical contact. Furthermore, there must be an electrical flow path to and from each piezoelectric electrode. Several coupling methods were investigated to determine their ability to meet the practical requirements above. To evaluate the effectiveness of each coupling method, the measured input electrical impedance of a prototype WAEF was examined. For a well coupled system, clean resonance peaks for each layer’s thickness mode and for the overall system thickness mode should be visible in the input impedance curve.

The first coupling method investigated was the use of low temperature alloys to ‘solder’ the interface surfaces together. The effectiveness of two alloys, whose properties are shown in Table 1, was examined. Measurements of the input electrical impedance showed poor mechanical coupling between the piezoelectric and elastic layers. This poor performance can be attributed to ineffective tinning of the metal elastic layer material with the alloys (see Figure 4).
None of the elastic materials used (copper, titanium, stainless steel) were able to be effectively tinned with the alloy metal.

### Table 1: Low Temperature Alloy Properties

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Melting Temp (°F)</th>
<th>Material Composition</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Bismuth</td>
</tr>
<tr>
<td>CerroLow</td>
<td>136</td>
<td>49 %</td>
</tr>
<tr>
<td>CerroShield</td>
<td>203</td>
<td>52.5 %</td>
</tr>
</tbody>
</table>

**Figure 4:** Tinned Elastic Wall Plates (left and center) and Assembled WAEF (right) Using Low Temperature Alloy ‘Solder’ Bond

Coupling was also attempted using a compressive force via a stress bolt (Figure 5). To achieve correct electrical connections, this method requires a two-piezo elements on either side connected electrically in parallel and mechanically in series on either side of the elastic wall. These stacks were stressed to 20 MPa by an electrically insulated bolt, but poor coupling was observed in the input electrical impedance measurements.

**Figure 5:** Stress Bolt WAEF Prototype

One method, which showed a relatively good coupling, used grease between each piezoelectric element and the elastic wall with a clamp applying a light compressive load to the transducer (Figure 6). However, this coupling method is impractical for the MSR application since a compression clamp spanning the entire transducer could not span the wall of a sealed container.
The final coupling method, which is the most practical for the eventual flight application, used an epoxy bond (Figure 7). The epoxy (TRA-DUCT 2907 Room Temperature Medium Viscosity Electrically Conductive Epoxy) was chosen to be electrically conductive to facilitate an electrical connection between the piezoelectrics ground electrodes and the metal elastic layer. Effective mechanical coupling was seen in the impedance curve and power transfer was demonstrated (see following section).

For flight applications, the epoxy bond would need to be flight qualified. The use of existing flight-qualified epoxies would be preferred. If the bond layer is thin enough, electrical connection between the piezoelectric ground electrode and the metal elastic layer may be achieved using a non-conductive epoxy. This bonding method is common in current medical applications of piezoelectric transducers, and would allow for the use of an existing non-conductive flight-qualified epoxy.

**Power Transfer Experiment**

An experimental test bench (Figure 8) was set up to allow for power transfer efficiency measurements. An electrical voltage signal from a signal generator/power amplifier source is applied across the input electrical ports of the WAEF.
On the receive side, a load resistance is connected across the output electrical ports. The input and output voltages are easily measured using oscilloscope probes. To measure the input current without affecting the input voltage, an inductive current meter is used. The input power can be calculated using the input current and voltage. If the load is entirely resistive and known a priori, the power delivered to the load can be calculated using the output voltage. The ratio of these two power measurements (power delivered / input power) is the power transfer efficiency.

![Source](Scope CH 1)
![Scope](Scope CH 2)
![Scope](Scope CH 3)

**Figure 8:** Power Transfer Experiment Test Schematic

In order to calculate the input power, the time average product of input current and input voltage must be found. The power delivered to an entirely resistive load is simply calculated using the magnitude of the output voltage. A MatLab script was written to perform these calculations from the exported oscilloscope waveform data and to calculate power transfer efficiency. Efficiency measurements were made at very low power levels (input power on the order of 0.050 W).

Table 2 shows the power transfer performance of the different coupling methods. The grease coupling model demonstrates that very efficiency power transfer is possible. The more practical epoxy bond model shows lower efficiency power transfer but is promising for these initial measurements. Continued optimization is needed to maximize efficiency in a configuration that is applicable to MSR.

<table>
<thead>
<tr>
<th>Piezo-to-wall coupling method</th>
<th>Measured Efficiency</th>
</tr>
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<tbody>
<tr>
<td>Stress bolt</td>
<td>12 %</td>
</tr>
<tr>
<td>Mechanical clamp with grease</td>
<td>53 %</td>
</tr>
<tr>
<td>Conductive epoxy bond</td>
<td>40 %</td>
</tr>
</tbody>
</table>

By replacing the load resistance in the above configuration with a 1 W flashlight bulb, power transfer at a level capable of powering a small electrical device was demonstrated (see Figure 8). Since the impedance properties of the light bulb were not entirely known over the frequency range of interest, the power transfer efficiency measurement method detailed above could not be used. In this application with more significant power levels, both nonlinear and thermal effects were evident. Nonlinear effects were clearly visible in the input current waveform, and the elastic wall became hot to touch.
Thermal and Non Linear effects

The driving of piezoelectric materials at high power is accompanied by both non linear and thermal effects which can become coupled if the power dissipation in the material is high. In general the loss components increase as the field levels increase causing an increase in the local temperature rise which in turn increases the dielectric and elastic losses and cause further increase in the temperature rise. This temperature increase is limited by the thermal coupling of the material to the local environment. Consider the plate shown in Figure 9. with a vacuum on both sides (worst case- no convection) with the edges of the plate connected to a heat sink.

\[
\Delta T = \frac{Q}{k \pi t \ln \left( \frac{R_1}{R_o} \right)}, \tag{1}
\]

where \( k \) is the thermal conductivity and \( \Delta T \) is the temperature difference between \( R_1 \) and \( R_o \). If we consider a 2.5 mm thick plate of titanium with a \( k \) of 21.9 W/mK and allow for a practical design which suggests \( R_1 = 2^{0.5} R_o \) (Plate area is twice piezoelectric area). Now let \( R_o = 0.05m \) and the power transferred to be 125 W at 80% efficiency. In the worst-

**Figure 8:** 1 Watt Power Transmission Demonstration a) figure on left - no power to piezoelectric transmitter. b) figure on right - piezoelectric transmitter excited

**Figure 9.** Schematic of a plate and the thermal geometry to calculate the heat rise at the piezoelectric edge.
case design we assume that radiative heat transfer is small compared to the conductive path. The temperature rise using equation 1 is found to be about 25 degrees Celsius for 25 Watts dissipated through the plate. Other calculations suggest that if the transfer efficiency can be increased to 80% then thermal problems can be accomodated.

Future Development

Although some important milestones were reached during this initial development effort, much work remains to be done before the WAEF transducer can be integrated for use in a practical design. The computer model must be developed further to allow for functionality capable of easy addition and modification of elements. A continued iterative validation process must be carried out. This process should validate the theoretical computer model with experimental results. The computer model should be updated as necessary to account for nonlinearity and thermal losses. Based on preliminary qualitative analysis of the light bulb experiment heat appears to be generated primarily in the elastic wall. Since this elastic layer has a very low quality factor (i.e. a much higher damping loss factor) compared with the piezoelectric layers, vibration energy will be converted to heat at a much higher rate. This excessive heat generation in the elastic wall needs to be understood and possibly mitigated. Work to date has focused only on the power transfer function of the WAEF transducer. The ability to transfer data is also a necessary function of the transducer. Although it is self evident that information can be transmitted (ex. Turning a light on and off) the bandwidth of the information transfer has yet to be determined. This capability needs to be demonstrated in a practical manner, and data transfer methods (ex. AM, FM modulation) needs to be developed.

3. CONCLUSIONS

A wireless acoustic electric feed-through network model was investigated by building and testing laboratory prototypes. The three designs used different methods of coupling the piezoelectric element to the wall. In the first test the piezoelectric material was bolted using a backing structure. In the second test the piezoelectric was clamped after the application of grease and finally the piezoelectric element was attached using a conductive epoxy. Initial results using a low melting point solder to bond the piezoelectrics to the plate were not successful. The mechanical clamp with grease produced the highest measured efficiency of 53% however this design was the least practical from a fabrication viewpoint. The power transfer efficiency of conductive epoxy joint was 40% and the stress bolts (12%). The importance of thermal and non-linear issues were discussed and simple models of the thermal limits suggest 100 Watt transmission is feasible in 0.2 m diameter plates.

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REFERENCES


