1KW Power Transmission using Wireless Acoustic-Electric Feed-through (WAEF)

S. Sherrit, X. Bao, M. Badescu, J. Aldrich, Y. Bar-Cohen, W. Biederman,
and Z. Chang

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove
Drive, Pasadena, CA 91109, USA

ABSTRACT

A variety of space applications require the delivery of power into sealed structures. Since the structural integrity can be degraded by holes for cabling we present an alternative method of delivering power and information using stress waves to the internal space of a sealed structure. One particular application of this technology is in sample return missions where it is critical to preserve the sample integrity and to prevent earth contamination. Therefore, the container has to be hermetically sealed and the integrity of the seal must be monitored in order to insure to a high degree of reliability the integrity of the sample return vessel. In this study we investigated the use of piezoelectric acoustic-electric power feed-through devices to transfer electric power wirelessly through a solid wall by using elastic or acoustic waves. The technology is applicable to a range of space and terrestrial applications where power is required by electronic equipment inside sealed containers, vacuum or pressure vessels, etc., where holes in the wall are prohibitive or may result in significant structural performance degradation or unnecessarily complex designs. To meet requirements of higher power applications, the feasibility to transfer kilowatts level power was investigated. Pre-stressed longitudinal piezoelectric feed-through devices were analyzed by finite element models and an equivalent circuit model was developed to predict the power transfer characteristics to different electric loads. Based on the results of the analysis a prototype device was designed, fabricated and a demonstration of the transmission of electric power up to 1.068-kW was successfully conducted. Efficiencies in the 80-90% range were also demonstrated and methods to increase the efficiency further are currently being considered.

KEYWORD: piezoelectric devices, acoustic wave, electric power supply, wireless power feed, pressure vessels

1. INTRODUCTION

There are numerous engineering applications where the use of wires to transfer power and communicate data thru the walls of a structure is prohibitive or involves a significantly complex design. The use of feed-through wires in such systems may make them prone to leakage of chemicals or gasses, loss of pressure or vacuum, as well may hamper the ability to perform adequate thermal or electrical insulation. Various future NASA missions are expected to require transmission of power into sealed solid metallic structures. Such structures may include a sample container providing planetary protection that requires internal power for monitoring, power a spacecraft or the Space Station in rendezvous and docking, as well as support autonomous operations. To address this need the method of wireless acoustic-electric transmission using acoustic waves to transmit power [Hu et al, 2003] was investigated. This transmission device uses the indirect piezoelectric effect as means of generating stress waves that are transmitted through walls where the received wave is converted to an electric power using a direct piezoelectric effect and is delivered to an electric load. Potentially, this enabling technology will allow for both power and/or data transfer from either direction. The details of the test devices and the results of the tests are presented in this paper. A 1068 Watt feed-though capability with 50.8 mm diameter device and 88% efficiency was achieved.

2. BACKGROUND

The idea of using elastic or acoustic waves to transfer power was suggested by [Hu et al, 2003]. In the system that these researchers investigated, they used transmit and receive piezoelectric layers that 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 travels through the armor into the receiving piezoelectric where the stress wave generated a sinusoidal voltage. In parallel, useful work was done on load impedance connected electrically with the piezoelectric receiver. A similar configuration to the one they described is shown schematically in Figure 1, where the backing masses were added to the system in an effort to increase the design variables. In this work [Hu et al, 2003], the theoretical problem of a piezoelectric/elastic layer/piezoelectric was solved using the wave equation and the linear equations of piezoelectricity, using a constant stress boundary condition between the layers, and traction free surfaces. An alternative approach based on network equivalent circuits (Figure 2) was suggested by [Sherrit et al. 1999, and Sherrit et al. 2005] that can be easily modified to account for additional acoustic elements that are 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.

Figure 3 shows an example of the input electrical admittance of the piezoelectric transmitter with load z = 20 Ω and power transfer efficiency with various resistive load calculated by the network equivalent circuit model for a certain design. There are numerous peaks in the admittance curve that indicate the resonance frequencies of the system and the peaks of the power transmission efficiency are corresponding to the resonance. The power transmission efficiency is also dependent on the load. The model provides a useful tool for searching best operating frequency and matching load impedance and optimization of the device design.

One important practical difficulty involved in the implementation of the power transmission between the transducers 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 surface in mechanical contact. In a previous study, various coupling methods were investigated [Sherrit et al. 2005]. Several test samples using epoxy as the coupling layers were fabricated. The experimental test results are presented in the following sections.

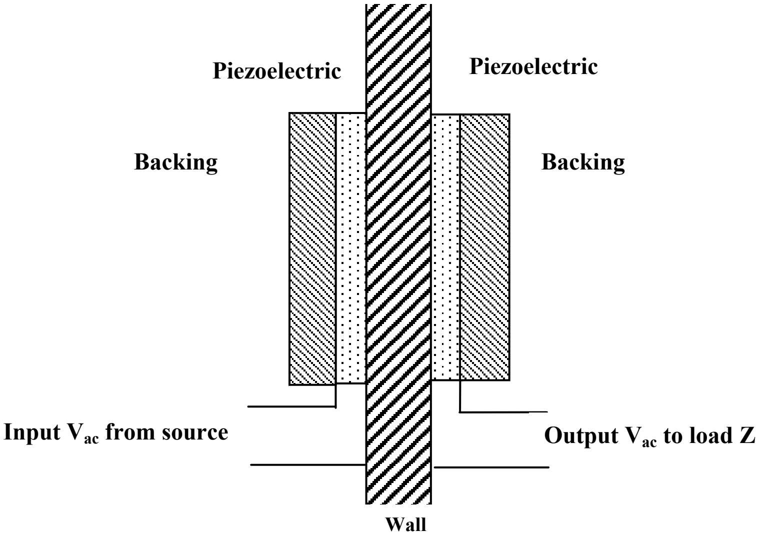


FIGURE 1: Schematic view of the physical acoustic-electric device with a piezoelectric generator and receiver. The backing masses are optional. The delivered power is fed to the load impedance Z.

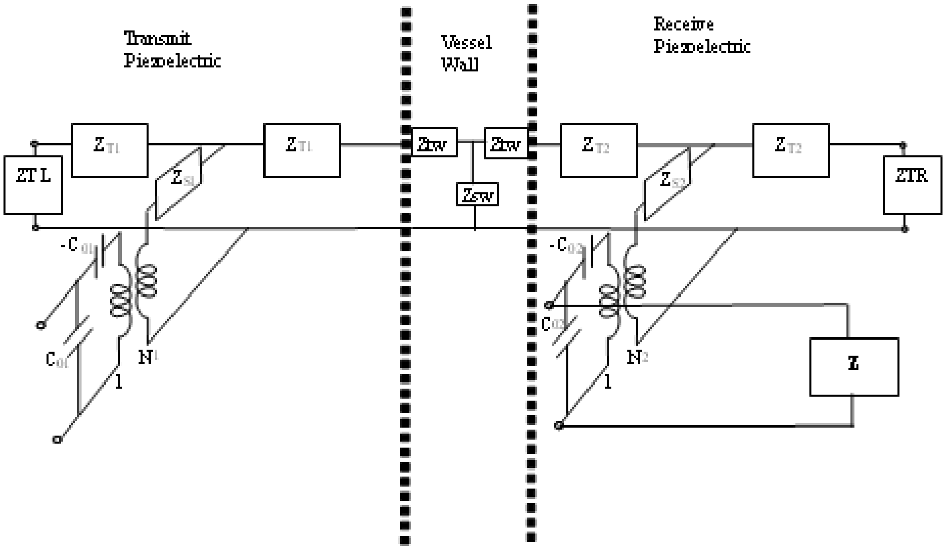


FIGURE 2: Schematic diagram of the network equivalent circuit for the physical system shown in Figure 1. The delivered power is consumed in the load impedance Z. Z_{TL} and Z_{TR} are the terminating mechanical impedances associated with the optional backing masses.

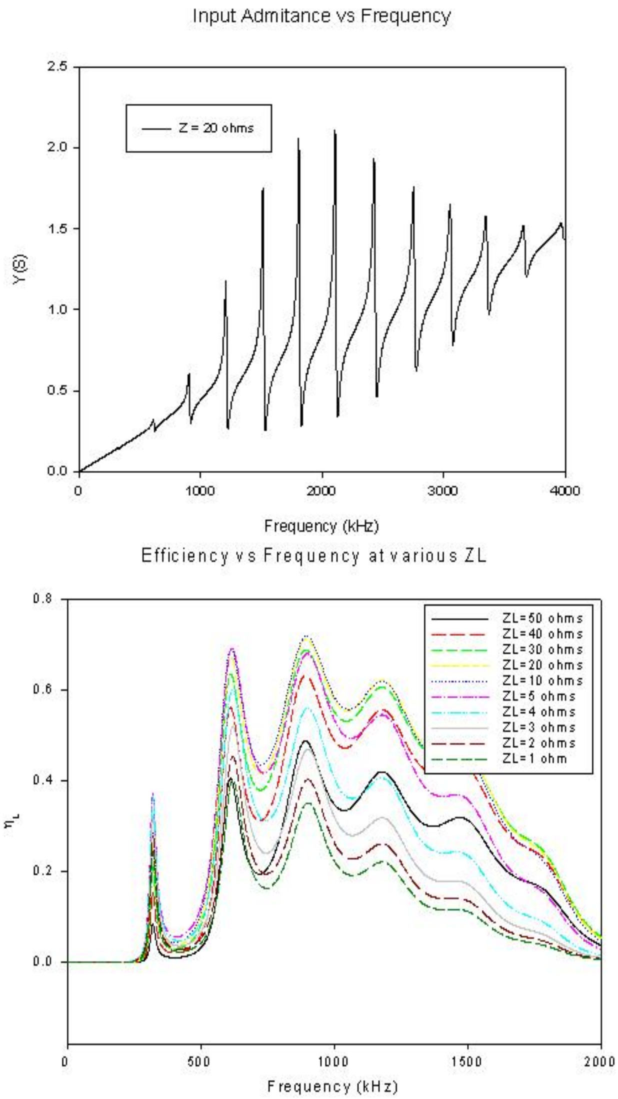


FIGURE 3: Power transmission solution using computer models of equivalent circuit model

3. TEST SETUP AND POWER MEASUREMENT

In previous work we demonstrated the transmission of 100 W, at 87-88% efficiency through a 3.4 mm thick titanium plate [Bao et al. 2006] using two ceramic disk piezoelectric transducers with oil couplant. In order to increase the power transmission to 1000 W and remove coupling agents from the design it was necessary to enhance and optimize the original device. For a single element the level of stress necessary to produce power levels at the 1 kW level in piezoelectric ceramics may exceed the strength of the material, or the maximum amount of stress that can be applied to the material before it fractures. In order to counter this effect, the number of ceramic elements was increased thereby increasing the current for the same stress or resultant voltage level. Since the compressive strength of ceramics is much larger than the tensile strength the elements were pre-stressed under compression using a concentric bolt to insure minimal tensile stress in the piezoelectric during expansion.

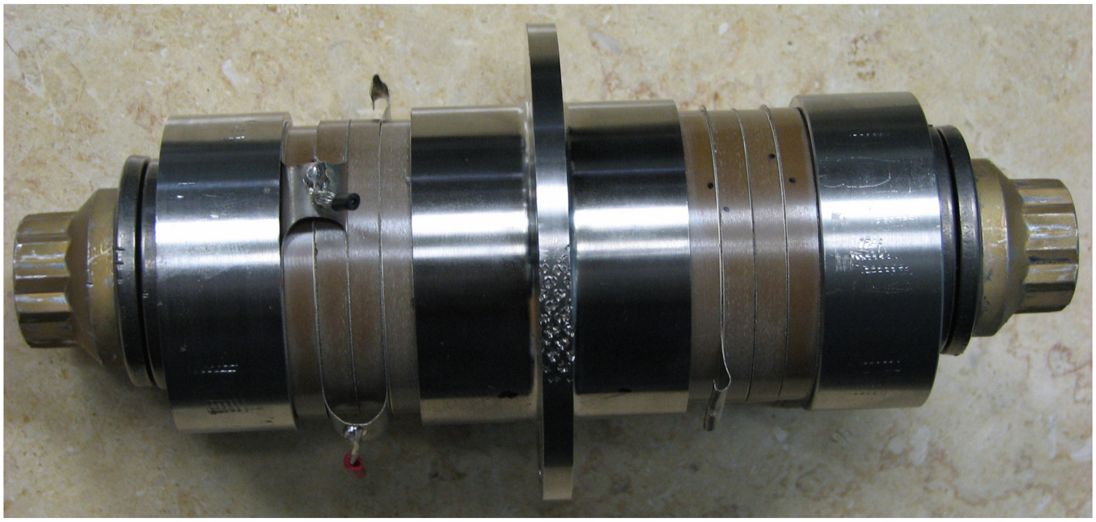
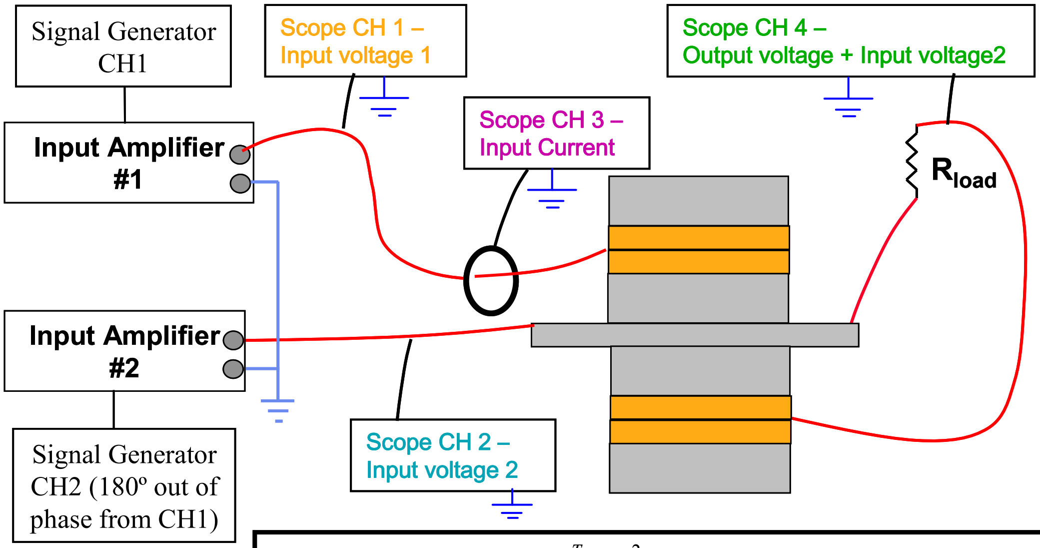


Figure 4. Breadboard device for acoustic power transmission with a pair of piezoelectric stacks. Each stack is comprised of 4 rings.

A prototype WAEF device consisting of two piezoelectric stacks is shown in Figure 4. Each stack consisted of four piezoelectric ceramic disks that are 50.8 mm in diameter and were bonded together by epoxy. As the device is symmetric about its center, either stack may serve as the power transmitter or the receiver. The simulated wall consists of a 5 mm thick titanium plate 85 mm in diameter with a 20 mm thick 55 mm diameter sections on either side of the plate to thread the stress bolts and mechanically attach the piezoelectric ceramic rings. In order to reduce the fabrication costs for this prototype, the diameter of the titanium plate was kept to a diameter of 85 mm. This small diameter also means that the radial surface waves in the plate generated from the vibrations are not dissipated and are instead reflected when they reach the edge of the plate. Therefore, this prototype we will not suffer from significant acoustic loss, which we will discuss later. In addition, the small surface area of the plate leads to heat buildup and limits the time we can operate the device. Plates with larger surface areas can dissipate heat more efficiently, but they do not perform as well due to acoustic leakage in the form of Lamb waves in the plate.

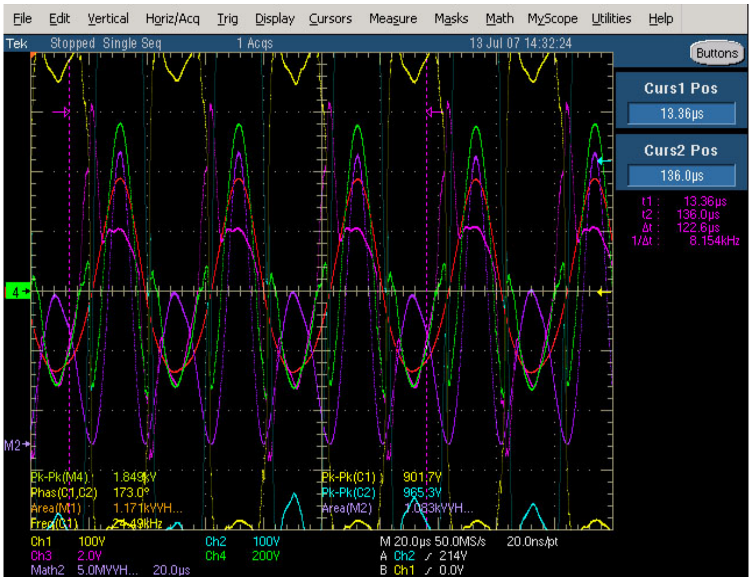
In order to prove the feasibility of transmitting 1 kW with this method for transmitting power acoustically an experimental set up (shown in Figure 5) was designed and built to measure the power transmissions and the power transfer efficiency. The power transfer efficiency is the power delivered to a load divided by the input power. The input power waveform was generated from signal generators feeding an ENI 1140L amplifier and applied across the input electrodes of the device. In order to generate enough input power, two amplifiers were connected in a series configuration with their signals 180° out of phase. On the receiving end, a load resistance is connected across the output electrodes which simulate the resistance of the device we are tying to transmit power to (conditioning circuitry, batteries, etc.). To measure the input and output power, a multi channel digital oscilloscope is used. The input and output voltages are measured using high voltage probes, and the input current is measured using a current probe. Using these measurements, we can calculate the average input power to the device, as well as the output power. The formulas used to calculate the input power, output power, and transfer efficiency are also presented in Figure 5.



$$Efficiency = \frac{P_{out}}{P_{in}} = \frac{\int_0^T \frac{V_{out}^2}{R_{load}} dt / T}{\int_0^T (V_{CH1} - V_{CH2}) * I_{in} dt / T} = \frac{Area[\frac{(CH4-CH2)^2}{R_{load}}]/T}{Area[(CH1-CH2)*I_{in}]/T}$$

Figure 5. Test bench setup and power calculations

In order to automate these measurements a LabView program was written to control the instruments. The two function generators were swept through a broad frequency range and analysis of the data revealed multiple resonance frequencies for the device where the input impedance was a minimum and the current peaked. The most efficiency resonance frequency was found at 24.5 kHz as determined by applying the formula shown in Figure 5. The preliminary tests found that our measurement setup was yielding overestimates in the efficiency calculation since the method we used to calculate efficiency is highly dependent on the phase of the waveforms. It was determined that the current probe and wire round resistors were causing phase errors in our output power calculations and a MatLab script was written to perform a truncation and manual phase shift of the waveform data gathered from the oscilloscope. Power calculations were done in MatLab using this corrected data. In latter tests we used a set of new high power metal film resistors with extremely low inductance which was found to reduce the correction. An example of the data generated for this device is shown in Figure 6.



```
Tek   Stopped  Single Seq          1 Acqs                    13 Jul 07 14:32:24
Curs1 Pos  13.36µs
Curs2 Pos  136.0µs
t1 :     13.36µs
t2 :    136.0µs
Δt :    122.6µs
1/Δt :     8.154kHz
Pk-Pk(M4)     1.849kV        Pk-Pk(C1)    901.7V
Phas(C1,C2)   173.0°         Pk-Pk(C2)    965.3V
Area(M1)      1.171kVVH...   Area(M2)     1.083kVVH...
Freq(C1)      24.49kHz
Ch1     100V            Ch2     100V       M 20.0µs 50.0MS/s     20.0ns/pt
Ch3     2.0V            Ch4     200V       A  Ch2  ⁄  214V
Math2   5.0MVVH...   20.0µs                B  Ch1  ⁄  0.0V
```

Figure 6. The various waveforms for a 24.5 kHz signal, 1083 Watts at 84% efficiency.

To demonstrate visually the device's ability to supply power to a realistic load, ten 100 W light bulbs were lit using 1 kW power transferred through a 5 mm titanium plate. This demonstration was executed by applying a continuous signal to the transmission device at 24.5 kHz for approximately five seconds. After using the MatLab code designed to compensate for phase errors from the current probe, it was found that the overall transmission efficiency was 84%. A photograph of the activated light bulbs is shown in Figure 7.

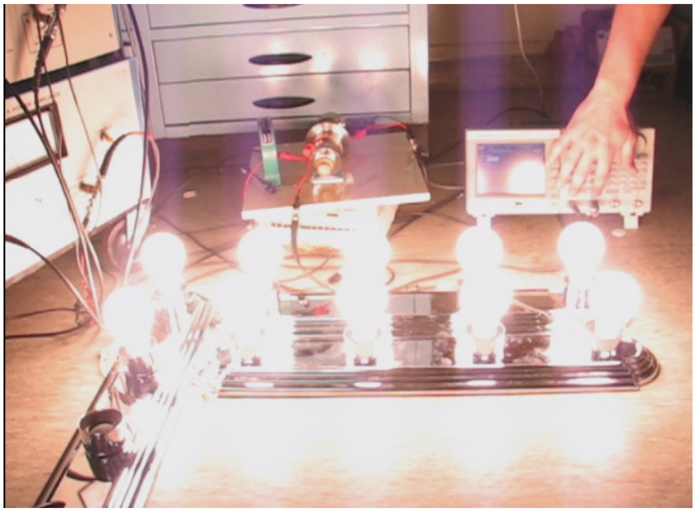


Figure 7. Ten 100W light bulbs powered by the wireless transmission device for ~5 seconds.

4. THERMAL ANALYSIS

A finite element model was initiated to estimate the temperature rise in the wireless transmission device. The assumption is that in a final device the wall will be very large compared to the diameter of the PZT transducer and the data was determined for an area that is 200 mm in diameter. The heat dispersion by radiation and convection was neglected. This assumption is valid for operation in vacuum and when the temperature rise is not very large. A typical temperature distribution pattern is shown in Figure 8. The thickness of the wall is 3.4 mm. The PZT transducers are 38 mm in diameter and 3.4 mm in thickness. The feed-thru power is 100 W and, based on the test results, the efficiency was set at 88% which is the same as the efficiency achieved by the test previous tests on similar structures. The case for various wall materials with different thermal conductivities are calculated and listed in Table 1. Based on our analysis it was determined that the maximum temperature rise is strongly dependent on the thermal conductivity of the wall material. Further, for a wall that is made of Al 6061 or steel 1020, with the current breadboard configuration it can continuously transfer 100-W power through the wall without overheating under ambient conditions. However, for the Ti Grade 1 or stainless steel 316 wall additional means are needed to disperse the generated heat.

TABLE 1: Temperature rise for different wall materials

Wall material	Thermal conductivity (W/m°C)	Max ΔT (°C)
Al 6061	155	15
Steel 1020	64.5	28
Stainless steel 316	13.3	113
Ti (Grade 1)	21	74

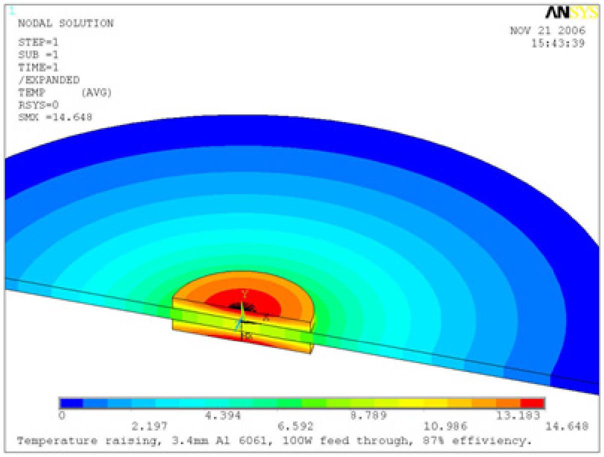


FIGURE 8: Calculated by the FE model the distribution in temperature rise given for a 200 mm diameter area with 3.4-mm wall made of Al 6061, 100W feed-thru power and 88% efficiency.

5. ACOUSTIC LOSS COMPENSATION

In actual structures acoustic radiation in the wall may cause loss of energy and a decrease in efficiency of the device. In an effort to reduce these losses to reasonable levels we modeled larger structures and looked at the effect of using a step ring reflector in the plate. The FEM model is shown in Figure 9. In the FE model, the transmitted wall was assumed to be very large compared to the diameter of the PZT transducer and the wall was modeled as a circular plate with a diameter 30 times larger than the diameter of the PZT transducer. The material of the wall was made of titanium and the PZT transducer was located at the center of the circular plate. Further, the plate was divided into 9 rings with different damping coefficients which increase as the radius increases. This way the elastic wave energy will be absorbed and there is no reflection from the edge. A harmonic analysis was performed for the case of the feed thru device on 4.76-mm (3/16”) thick titanium wall. A pair of steel rings was included in the model. A parametric study was performed with various ring thicknesses. As presented in Figure 10 the results show the rings can effectively reduce the loss caused the plate waves. The energy loss was 25% with no ring reflector and reduced to 0.2 with 18-mm thick rings.

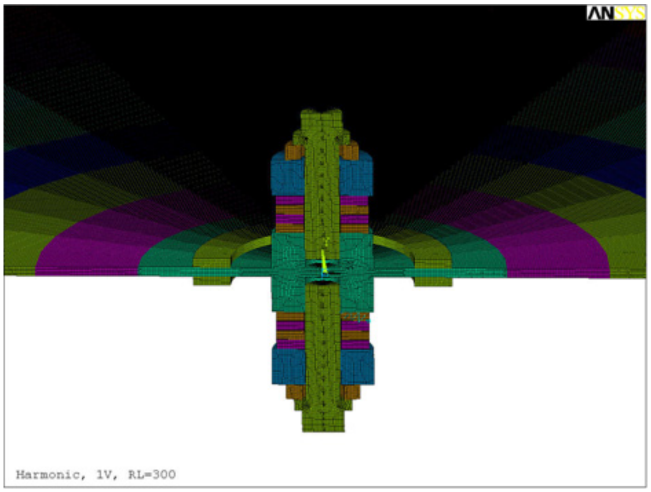


Figure 9. The FE model including the prototype piezoelectric device, 4.76-mm Titanium wall, reflector rings and a load resistor of 300 Ω.

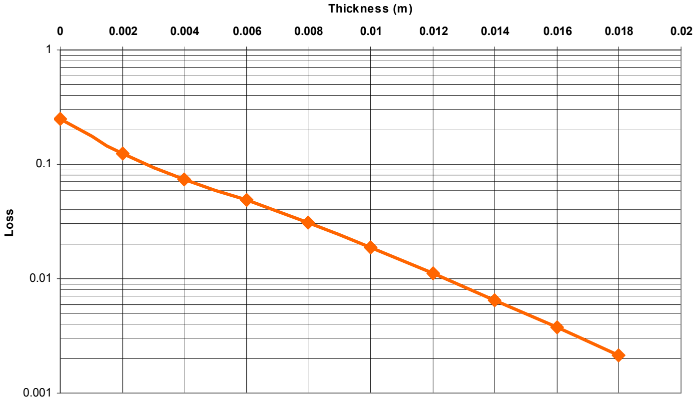


Figure 10. Percent energy loss due to plate waves vs. thickness of steel rings with 100mm inner diameter and 20mm wide on 3/16” titanium wall

6. SUMMARY

This study focused on developing the capability to transmit 1 KW of electric power through metal walls using acoustic stress waves. Our results show that transmitting such power levels is feasible using a device that consists of four 50.8 mm diameter piezoelectric transducer disks on each side of the structure. While the overall goal of the effort was met successfully, further modeling needs to be conducted to determine the requirements that allow for longer transmission periods with minimal power loss and for operation on larger areas. In a final design the energy loss due to the lamb waves can be reduced with radial reflectors in the wall and concentric about the stacks. In addition, an update of the finite element thermal analysis is necessary to determine temperatures on the device for extended transmission periods since the properties of piezoelectric ceramic rings are temperature dependent and the potential exists for the device to thermally detune. Finally, other modes (shear radial) and geometries (concentric tubes) need to be investigated to potentially maximize the transmission efficiency, which in turn reduces the amount of generated heat and parasitic plate waves.

ACKNOWLEDGMENT

Research reported in this manuscript was conducted at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under a contract with National Aeronautics Space Agency (NASA). The authors would like to express their appreciation of Neville Marzwell, Program Manager, Advanced Concepts-Innovative Technology Programs (ESMD) for supporting this reported task

REFERENCES

Bao X., Doty B. J., Sherrit S., Badescu M. , Bar-Cohen Y., Aldrich J., and Chang Z. “Wireless piezoelectric acoustic-electric power feedthru “ Proc. SPIE 6529, 6529-40, 2007

Chang Z., Bao X., Doty B. J., Sherrit S., Bar-Cohen Y., Badescu M., and Aldrich J., “Power loss considerations in wireless piezoelectric acoustic-electric power feedthru,” SPIE Smart Structures and Materials & Nondestructive Evaluation and Health Monitoring 14th International Symposium, Proceedings of SPIE - The International Society for Optical Engineering, v 6529-136, 2007

Hu Y., Zhang X., Yang J., Jiang Q., “ Transmitting Electric Energy Through a Metal Wall by Acoustic Waves Using Piezoelectric Transducers, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 50, 7, pp. 773-781, 2003.

Sherrit S., S. P. Leary, B. P. Dolgin and Y. Bar-Cohen, “Comparison of the Mason and KLM Equivalent Circuits for Piezoelectric Resonators in the Thickness Mode”, Proceedings of the IEEE Ultrasonics Symposium, Lake Tahoe, 1999, pp. 921-926.

Sherrit S., Badescu M., Bao X., Bar-Cohen Y., Chang Z., “Efficient electromechanical network model for wireless acoustic-electric feed-throughs,” Proceedings of the SPIE - The International Society for Optical Engineering, v 5758, n 1, 2005, p 362-372

Sherrit S., Doty B.J., Badescu M., Bao X., Bar-Cohen Y., Aldrich J., and Chang Z., “Studies of acoustic-electric feed-throughs for power transmission through structures,” Proceedings of SPIE - The International Society for Optical Engineering, v 6171, 2006,