High-power piezoelectric acoustic-electric power feedthru for metal walls

Xiaoqi Bao[1], Will Biederman, Stewart Sherrit, Mircea Badescu, Yoseph Bar-Cohen, Christopher Jones, Jack Aldrich and Zensheu Chang

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

ABSTRACT

Piezoelectric acoustic-electric power feed-through devices transfer electric power wirelessly through a solid wall by using acoustic waves. This approach allows for the removal of holes through structures. The technology is applicable to power supply for electric equipment inside sealed containers, vacuum or pressure vessels, etc where the holes on the wall are prohibitive or result in significant performance degrade or complex designs. In the author's previous work, 100-W electric power was transferred through a metal wall by a small, simple-structure piezoelectric device. To meet requirements of higher power applications, the feasibility to transfer kilowatts level power was investigated. Pre-stressed longitudinal piezoelectric feedthru devices were analyzed by finite element model. An equivalent circuit model was developed to predict the power transfer characteristics to different electric loads. Based on the analysis results, a prototype device was designed, fabricated and a demonstration of the transmission of electric power up to 1-kW was successfully conducted. The methods to minimize the plate wave excitation on the wall were also analyzed. Both model analysis and experimental results are presented in detail in this presentation.

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 as 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 acoustic-electric transmission using acoustic waves to transmit power [Hu et al, 2003] was investigated. This transmission device uses the direct and indirect piezoelectric effects as means of generating stress waves that are transmitted through walls where the received wave is converted to an electric power using a piezoelectric and is delivered to an electric load. Potentially, the enabled technology will allow for both power and/or data transfer from either direction. In previous work we demonstrated the transmission of 100 W, at 87-88% efficiency through a 3.4 mm thick titanium plate using two ceramic disk piezoelectric transducers [Bao et. Al. 2007]. In this paper, a 1kW feed though by pre-stressed PZT transducer with 88% efficiency is reported.

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

[1] Correspondence: xbao@jpl.nasa.gov

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 was suggested by Sherrit et al 2005] that can be easily 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.

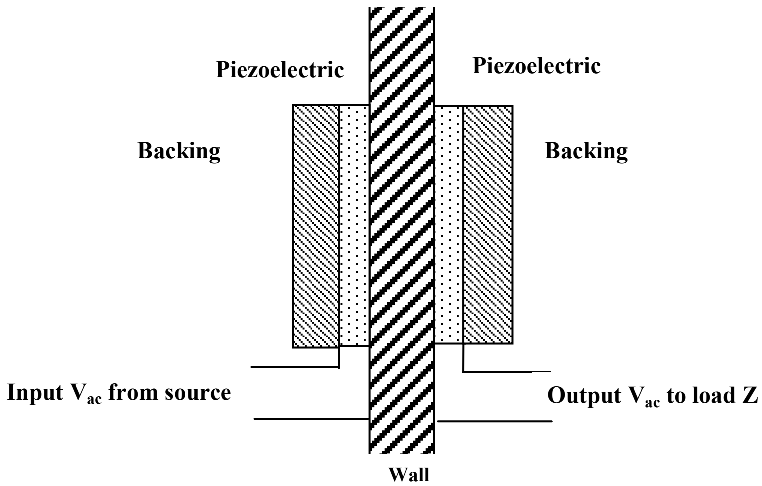
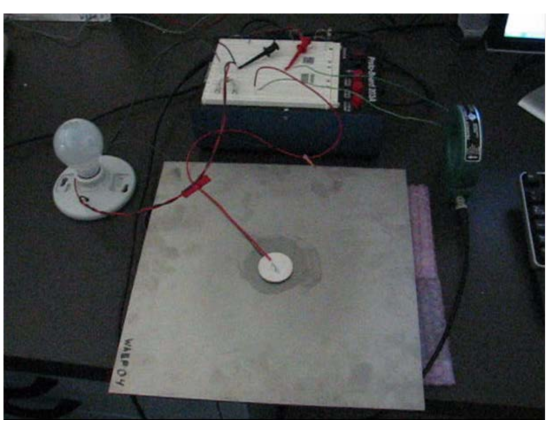
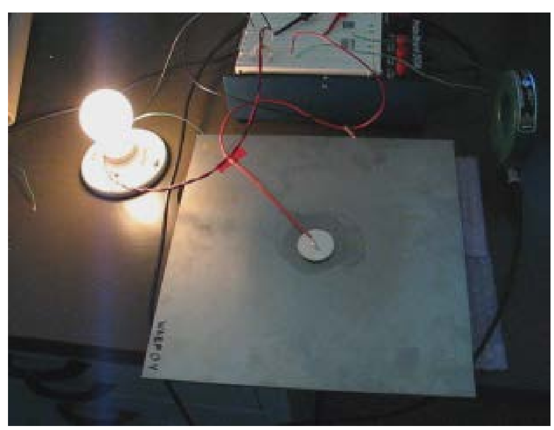


Figure 1. Schematic view of the physical acoustic-electric device with a piezoelectric generator and receiver. The backing masses are optional. The delivered power is fed to the load impedance Z.

In previous work we demonstrated the transmission of 100 W, at 87-88% efficiency through a 3.4 mm thick titanium plate using two ceramic disk piezoelectric transducers [Bao et. Al. 2007]. Several wireless piezoelectric acoustic-electric power feedthru devices were fabricated and tested. Test results show that 100-W power feed-though is feasible for the device using two 38-mm diameter PZT disks. To demonstrate the feasibility of powering a realistic load, a 100W light bulb was lit using the power transferred by the unit (see Figure 2). This demonstration was executed by applying a continuous signal to the unit at 747 kHz.



No power to piezoelectric transmitter.



Piezoelectric transmitter excited

Figure 2. 100-Watt light bulb demonstration.

3. ANALYSIS OF HIGH POWER FEEDTHRU DEVICE

In order to increase the high-power transmission to the level of 1000 W, it is 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.

The vibration characteristics of the design were analyzed by finite element. An equivalent circuit model was developed to predict the energy transfer performance (Figure 3). The circuit represents the characteristics of the feedthru device at the frequency near its resonance. The parameters of the circuit were determined by the finite element analysis or the parameter fitting function of Agilent Impedance Analyzer 4294A.

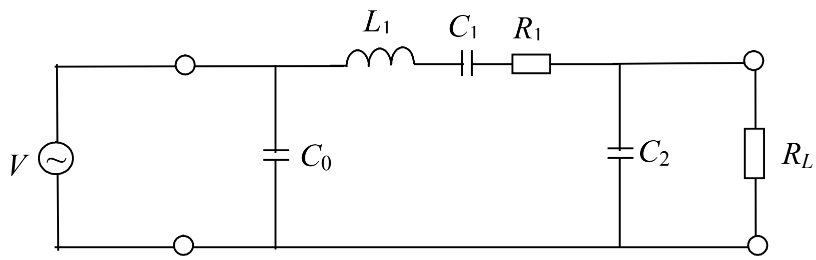
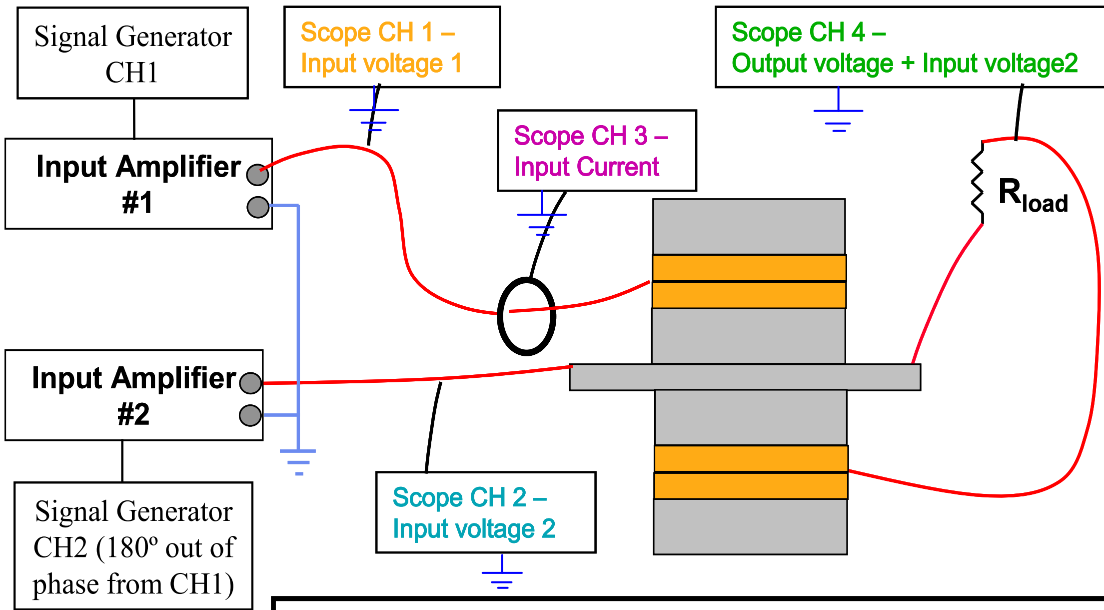


Figure 3. Equivalent circuit for the feedthru device near resonance frequency

4. TEST SAMPLES AND EXPERIEMENTAL RESULTS

An experimental setup of wireless feedthru was made consisting of two sets of piezoelectric stacks that are 50 mm in diameter. 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 plate (lamb) waves in the plate. This issue will be closely investigated in section 5.

In order to prove the feasibility of transmitting 1 kW with this method for transmitting power acoustically an experimental set up (shown in Figure 4) 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 4.



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

Figure 4: Test bench setup and power calculations

In order to automate these measurements a LabView program was written to control the instruments. The 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 4. 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 5.

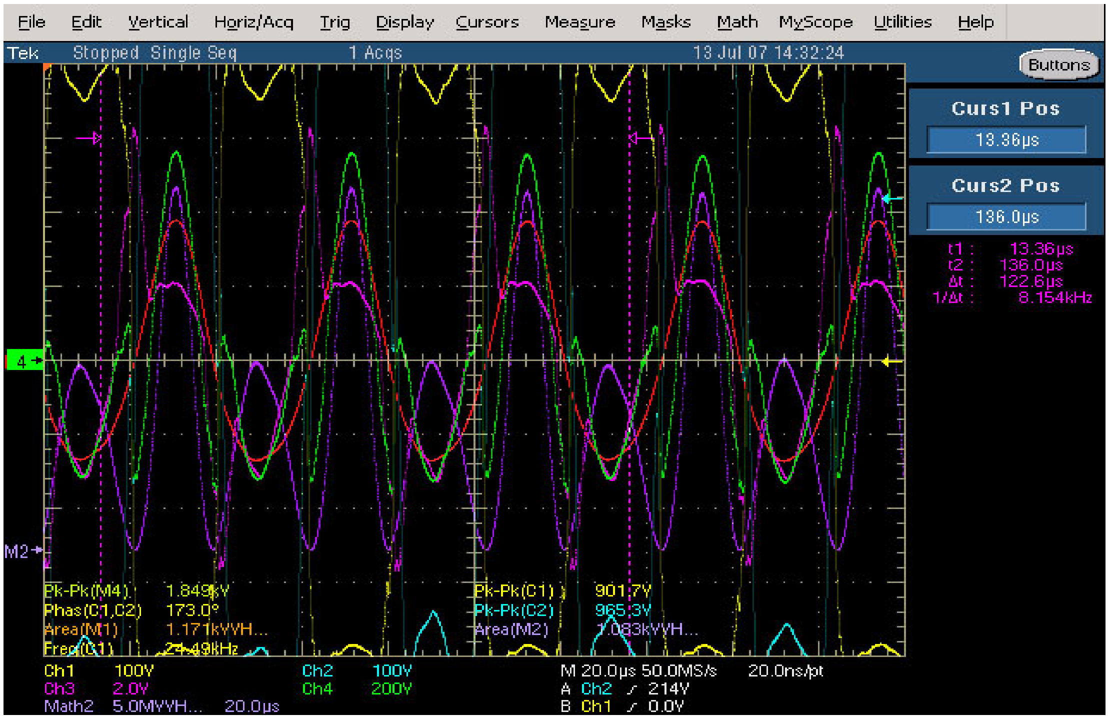


Figure 5: The various waveforms for a 24.5 kHz signal, 1083 Watts at 84% efficiency.

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 6.

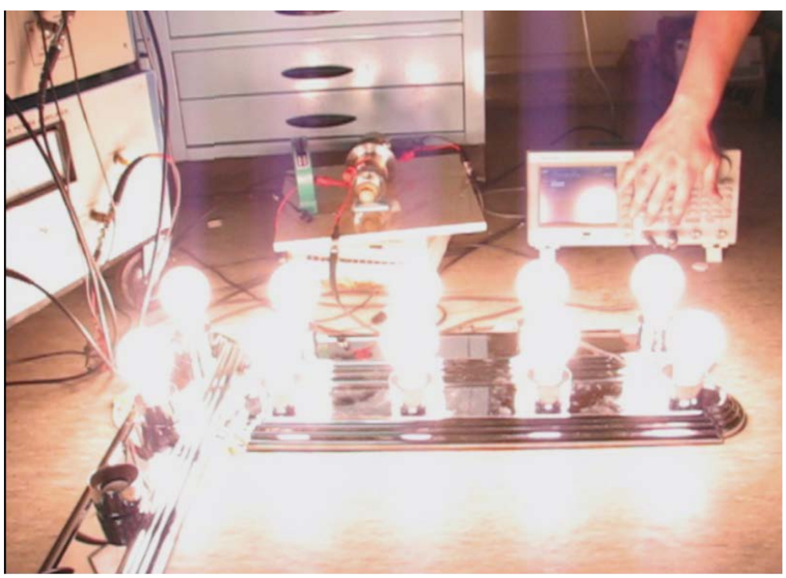


Figure 6. Ten 100W light bulbs powered by the wireless transmission device for ~5 seconds.

5. PLATE WAVE LOSS AND COMPENSATION

In realizable 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 7. 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. Figure 8 shows the plate wave propagates on the wall with no reflector rings. A parametric study was performed with various ring thicknesses. As presented in Figure 9 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.

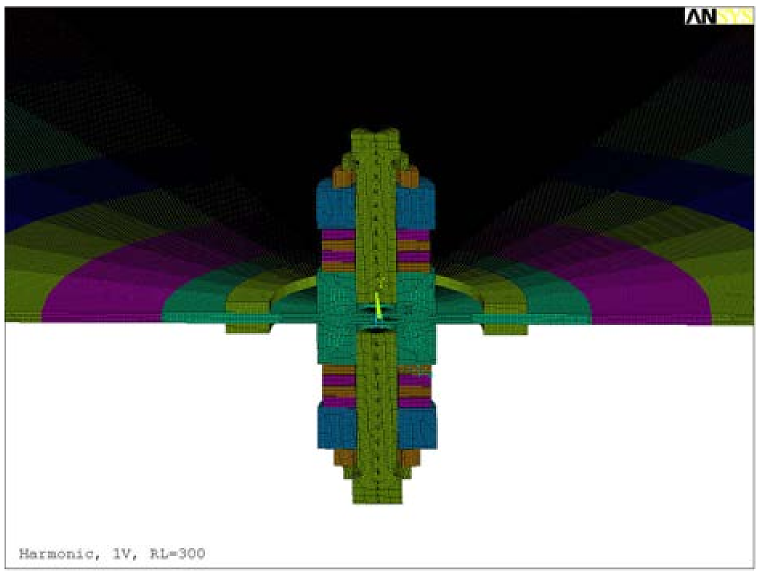


Figure 7. The FE model including the prototype piezoelectric device, 4.76-mm Titanium wall, reflector rings and a load resistor of 300 Ω.

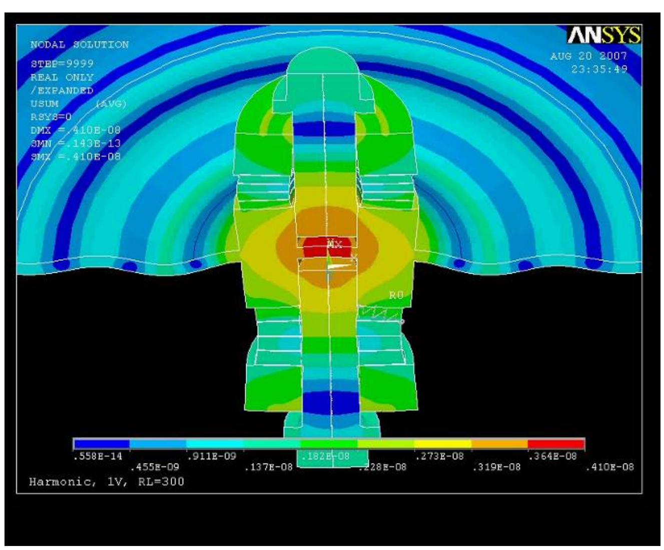


Figure 8. The plate wave propagates from the device area and takes part of the transmitted energy into the structure.

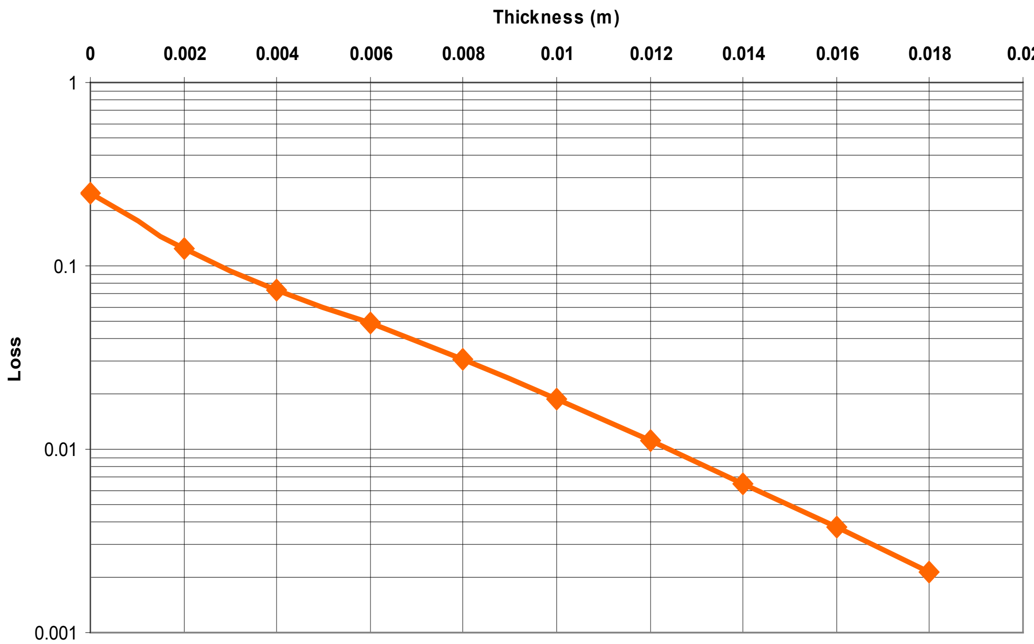


Figure 9. Loss due to plate waves vs. thickness of steel rings with 100mm inner diameter and 20mm wide on 3/16" titanium wall

5. 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 power at levels of more than 1kW is feasible using a device that consists of two sets of 50 mm diameter piezoelectric transducer disks. While the overall goal of the project 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. In addition the function of reflector to minimize loss of the plate waves needs to be demonstrated experimentally.

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