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Prototype Development of a Piezo-heating array for deicing application on bridges

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16. Abstract

A novel piezoelectric transducer was designed and fabricated to demonstrate energy harvesting from traffic-induced loading on pavement. The piezoelectric transducer is based on the "cymbal transducer" design used for underwater acoustic and sonar. A novel surface electrode pattern increases energy density and steel end caps enable mechanical coupling through matched stiffness to the pavement. Multi-physics simulation with finite element modeling was used to optimize the geometric design of transducer considering failure stress criteria and maximum energy output. Sixty-four lead zirconate titanate (PZT) Type 5X (Sinocera, PA) square plates with 32-mm width and 2-mm thickness were fabricated into transducers with alloy steel end caps. Sixty-four piezoelectric transducers were assembled in 4 layers of 16 transducers each, inside of an energy-harvesting array. The prototype energy-harvesting array was tested using a pneumatic system to simulate vehicle loading. The output energy of the prototype module was 0.8 mJ at 60V from a 600 lb load. Under continuous loading of 500 lb at 5Hz, the power output was 2.1 mW. Using a DC-DC step down converter, the output power was used to illuminate a string of LEDs.

17. Key Words	18. Distribution Statement
Energy Harvesting, Piezo, deicing, bridges	

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Introduction and Description of the Problem

The Research goal and objective is to develop and construct a model prototype that demonstrates how piezo-heating arrays can be embedded in bridge approach slabs, generating sufficient heat for deicing operations.

The proof-of-concept prototype will be a scaled model of a bridge and its approach slab. The model will have a scaled version of an axle tandem loading the approach slab. On the approach slab, the team will install the prototype technology - a piezo-electric array linked ~~(in series?)~~ and tied to a battery. As the axle tandem rolls on the model bridge approach, electricity will be generated and stored. The prototype will serve as an example of how modern bridge approach slabs could be constructed to harness the energy produced by truck traffic to mitigate winter conditions.

The team envisions triggering a heat element to raise the temperature of the mock road-surface up to sufficient temperature to surpass the needed energy to melt an inch of snow or moderate amount of ice. ~~The prototype will be constructed to conform to a technical memorandum documenting performance metrics for a successful competitor to deicing chemicals.~~

Approach and Methodology

Traditional cymbal transducers utilize the lateral piezoelectric coefficient, d_{31}, where stress is applied perpendicular to the direction of polarization. In this project, a unique electrode pattern was designed to change the direction of polarization to utilize the longitudinal piezoelectric coefficient d_{33}, where the stress is applied in the direction of polarization. The longitudinal coefficient is more than double the lateral coefficient. The result is greater energy conversion from input mechanical to output electrical energy. The electrode pattern (Figure 1) separates the single ceramic into 7 sections or capacitive/piezoelectric cells with each cell connected in parallel. In addition to increasing the effective piezoelectric coefficient, the electrode pattern increases capacitance by a factor of 60 compared to the single ceramic. A high capacitance is necessary for the generation of charge in an energy harvesting piezoelectric transducer.

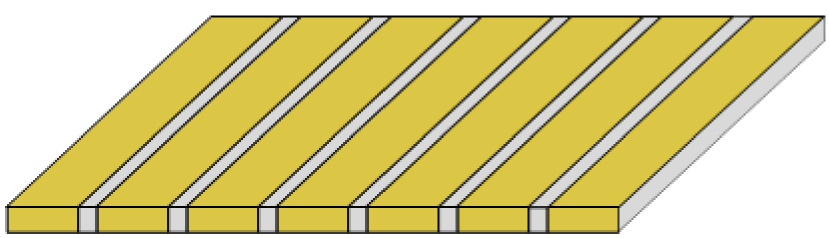


Figure 1 - Electrode pattern for piezoelectric ceramic

The electrode pattern is applied to the ceramics using DuPont 7095 air-fired silver paste. First the opposing sides are completely electroded and fired to prevent damage in later steps. Once fired, the electrode is permanently bonded to the surface of the ceramic.

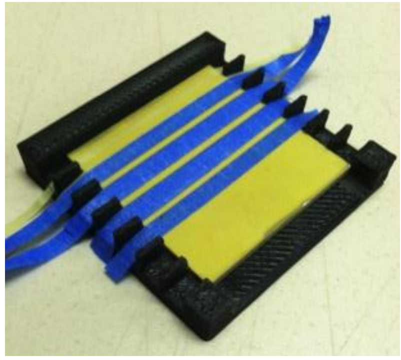


Figure 2 - Tape applied to ceramic using 3D printed fixture as guide

A brass mask was used as a guide to paint the 6 line electrodes to the top and bottom faces of the ceramic. Another method was developed using a 3D printed holder and painter's tape (Figure 2) to guide the application of the electrodes. This method produced straighter electrodes but is tedious and time consuming. The electroded ceramics, with 40 out of 100 samples been completely electroded with repeating line electrodes, is shown in Figure 3. Three ceramics have top and bottom faces completely electroded and are used measuring the properties of this type of PZT and to optimize poling conditions in order to maximize piezoelectric properties. These three ceramics were built into the traditional type of cymbal transducer that utilizes the lateral piezoelectric coefficient d_{31} and used for comparison to the new design.

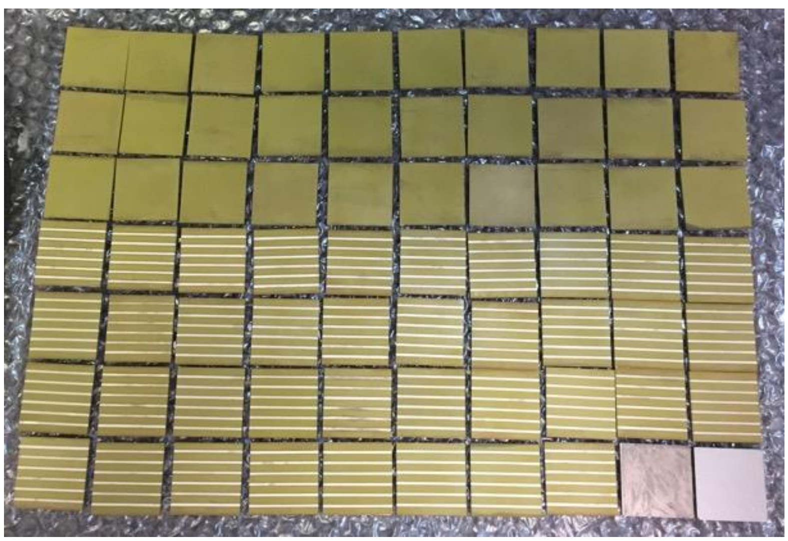


Figure 3 - Representation of the ceramics with and without electrodes

The ceramics need to be polarized to have piezoelectric properties. The poling conditions needed for maximum piezoelectric properties are 3000-4500V per millimeter at 80-90ºC for 10 minutes. Based on the geometry of the electrode configuration this requires a supply of 17kV. The electrodes must be connected in the correct configuration so that each section of the ceramic is connected in parallel. A Teflon fixture was designed that can hold 5x ceramics at a time (Figure 4). Alternate poling fixtures were used to attempt to polarize the ceramics while the Teflon fixture was being machined. Two different holders were designed and 3D printed to hold the ceramics and connect the electrodes using copper tape or wire (Figure 5). Poling at 10kV and 90-100ºC was not sufficient to completely polarize the ceramics. Increasing the temperature to 120ºC caused the ABS plastic to soften and deform. Poling at higher temperature and higher electric field using Teflon fixture was resulted in failure of approximately 20 ceramics. It is common for a few piezoelectric ceramics to fail (burn, chip, or fracture) during poling due to the stress induced by the applied electric field and flaws inside of the ceramic. Flaws may exist as result of non-uniformity during processing that can leave residual porosity or voids that mechanical weaken the ceramic. Although some ceramics failed due to mechanical flaws, it was found that the ceramics were failing during poling because the Teflon was mechanically constraining them. The ceramic must have room to expand as the electric field is applied or the stress developed may cause a fracture. The Teflon fixture was modified to provide the ceramic more space; however, pressure was needed to allow wires to make electrical contact with all of the electrodes. Future designs for poling should not clamp or constrain ceramics with a surface electrode configuration.

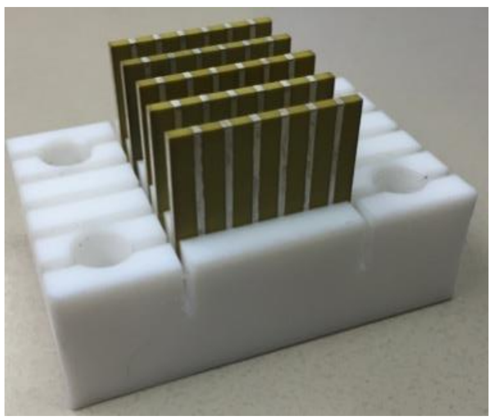


Figure 4 - Teflon holder for poling 5 ceramics at a time

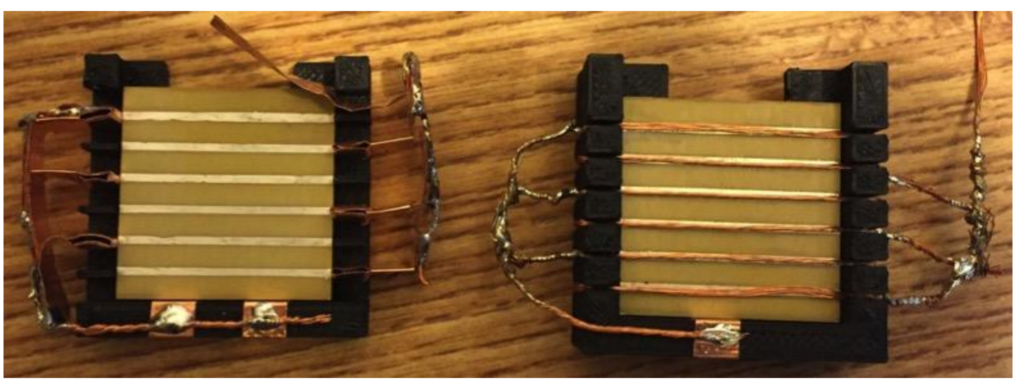


Figure 5 - 3D printed fixtures with wire connections for poling

Once the ceramics are polarized, the electrical connections to connect all of the segments in parallel are applied (Figure 6). A layer of insulating epoxy is applied the side of the ceramic while leaving alternating electrodes exposed. After the insulating layer cures, a conductive silver epoxy connects the exposed electrodes. The conductive epoxy is coated with silver paint to ensure a reliable electrical connection to the electrodes.

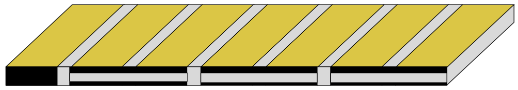


Figure 6 - Conductor on the side of the ceramic connects the electrodes in parallel.

The ceramics are fabricated into cymbal transducers by bonding steel end caps to the top and bottom faces. The precise shaping of the steel end caps is difficult due to the tendency of the steel to spring back when formed and to warp during heat treatment. A metal fabricator with expertise in stamping sheet steel was contracted to fabricate the end caps to the high precision required. The end caps were stamped from 4130 alloy steel sheets and heat-treated to a hardness of Rc36. The end caps were bonded to the ceramics using epoxy and were held in custom fixture that applied pressure as the epoxy hardened (Figure 7).

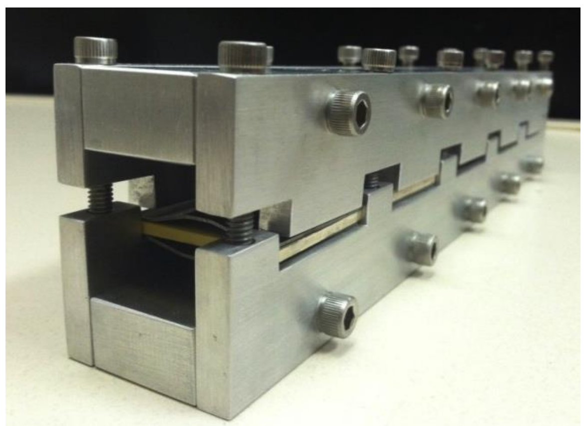


Figure 7 - This fixture was used to hold the end caps to the ceramic as the epoxy cured.

The fabricated transducers were assembled into an energy-harvesting module (Figure 8). The module is built from 0.5” thick aluminum and has 4 layers. Each layer has 16 transducers arranged in a 4x4 configuration. The module has 64 transducers connected in parallel with the copper plates acting as current collectors. There is a gap between the top plate and the sidewalls of the module casing that can be adjusted to percent over-loading the transducers, which would result in failure.

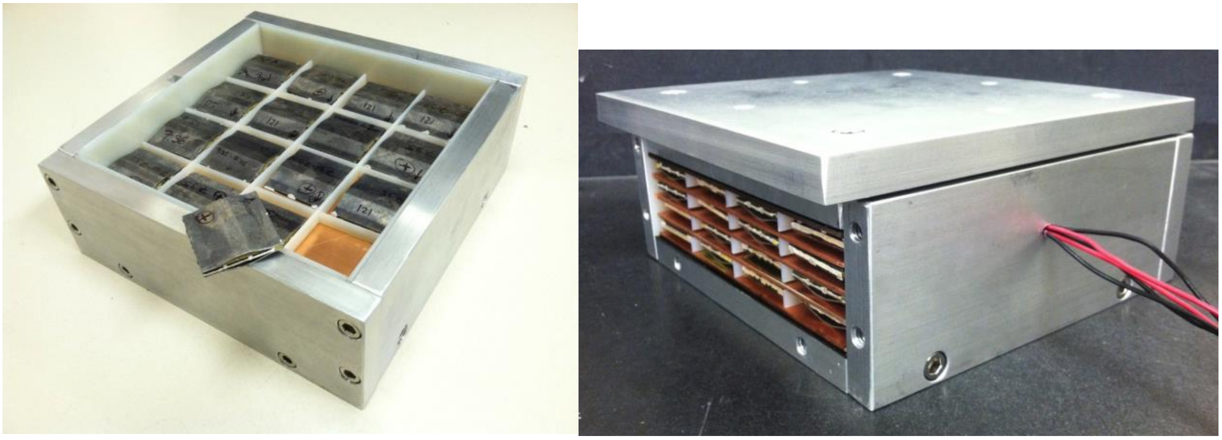


Figure 8 - The transducers are arranged inside of an energy harvesting module.

The energy-harvesting module was tested using a pneumatic loading system that can repeatedly apply a load of up to 800lb at a frequency up to 5Hz (Figure 9). The energy generated was measured at different loads, frequency, and electrical load (Figure 10). The energy produced is proportional to the applied load. A load of 600lb produces 90V and 0.4mJ of energy. Energy is generated when the piston applies the load to the module, and energy is generated when the load is removed. Power is measured by loading the module repeatedly at 5Hz and is measured at different electrical resistance values to determine the maximum output. At a resistive load of 330kΩ, the output power was 2.1mW.

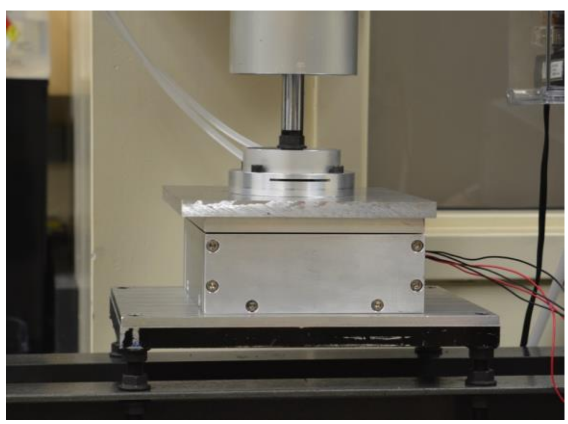
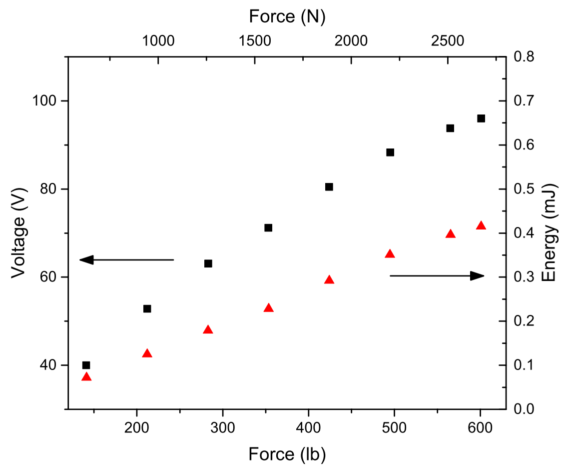


Figure 9 - Energy-harvesting module inside of the pneumatic loading system



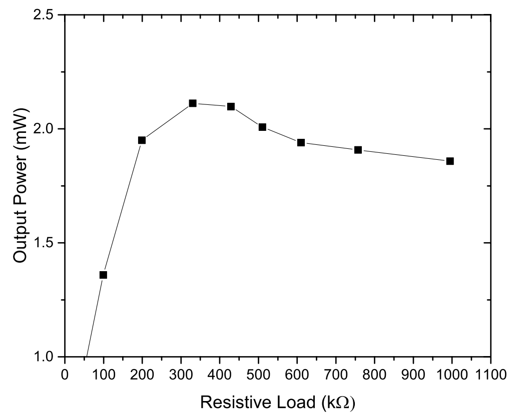


Figure 10 - Energy generated (mJ) from each loading and power generated (mW) at 5Hz and 500lb.

A circuit was designed to convert the high voltage, low impedance output generated by the transducer and convert it into usable, constant low voltage DC (Figure 11). The circuit lowers the resistive load where the maximum power output occurs in order to efficiently power LEDs, charge a battery, or provide current for a heating element. The energy generated by the transducers was used to power a series of LEDs. The circuit was tested using a simulated transducer output produced by a function generator in conjunction with an amplifier (Figure 12). AC pulses were amplified up to 200V to simulate the transducer output under typical loading cycles and were modulated by the circuit while monitored with an oscilloscope. In this demonstration, the energy was used to power LEDs. The circuit, shown in the picture, is enclosed in an acrylic box for safety.

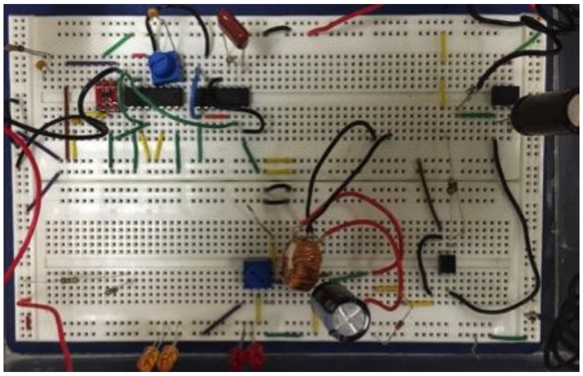


Figure 11 - Energy harvesting circuit design

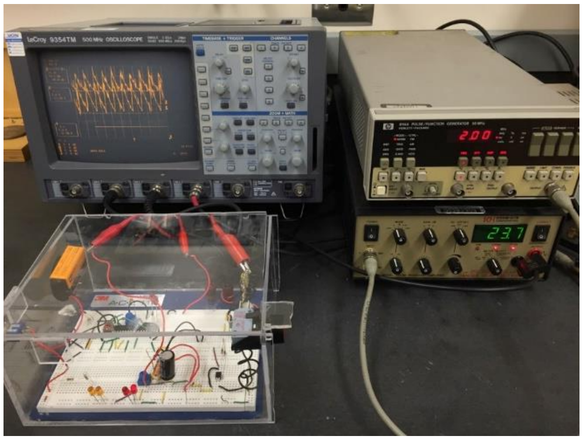


Figure 12 - Energy harvesting circuit converting the simulated transducer output from the amplifier

Optimization sensor design

Two different shapes are used in FEA to get the performance of Cymbal and Bridge transducer. For Cymbal transducer as shown in (Figure 13) (which is circular shape), the diameter of the transducer is 32 mm; the diameter of the cavity base is 22 mm; the height of the cavity is 2 mm; the thickness of the PZT is 2 mm. Also, the thickness of the metal cap is 0.6 mm and the diameter of the end cap is 10 mm. At the same time, a Bridge transducer is also analyzed, whose shape is rectangular (Figure 14) and is modified from the Cymbal. Almost all the dimensions of the Bridge are same with the Cymbal except the length and width is 32 mm, and the thickness of metal end cap is 0.6 mm.

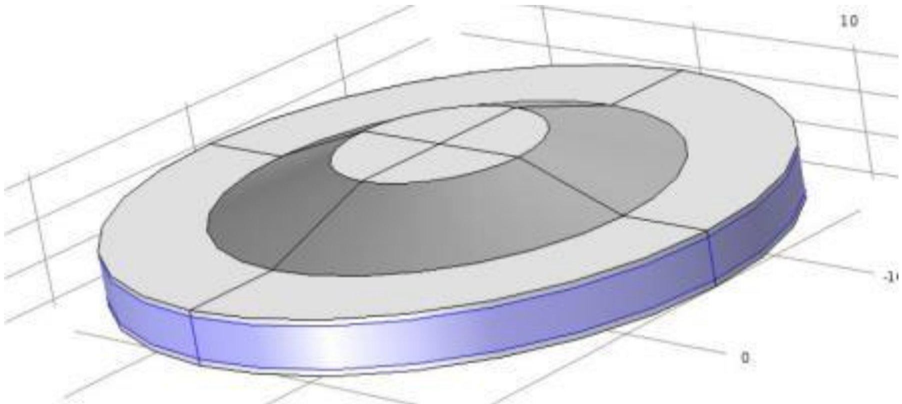


Figure 13 - Circular cymbal transducer

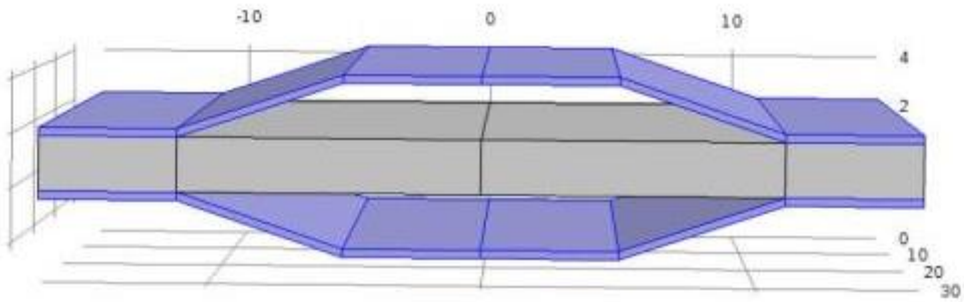


Figure 14 - Rectangular bridge transducer

As a first step, stresses are obtained via FEA using Bridge transducer only, as well as the electric potential under open circuit for both transducers. There are two stress criteria due to limitations of material properties, namely stretching stress and shear stresses. The stretching stresses on PZT element must be less than 40 MPa to avoid material crack. This stress concentration is to cause the cracking of PZT disk. Shear stress must be less than 12 MPa to avoid connection failure.

The team ran the simulation to optimize transducer geometry by changing the end cap dimensions (Li – see Figure 15) based on material on-hand to optimize for the following specifications: PZT dimensions = 32 mm (square shape), PZT thickness =2mm, and steel end cap =0.6 mm. The only way to meet the criteria (stretching stress less than 40 MPa and shear stress less than 16 MPa) is to optimize the end cap dimensions. But due to this modification, the team anticipates some loss in electric potential based on an empirical correlation between electric potential decrease, increasing thickness and modulus of metal cap. Also, with the increasing thickness and modulus of the metal cap, the maximum tensile stress, and shear stress are gradually moved to the inner corner of the contact area between cap and PZT disk. Thus, the stress concentration could manifest itself in the inner corner when the metal cap thickness and modulus are higher than an absolute value.

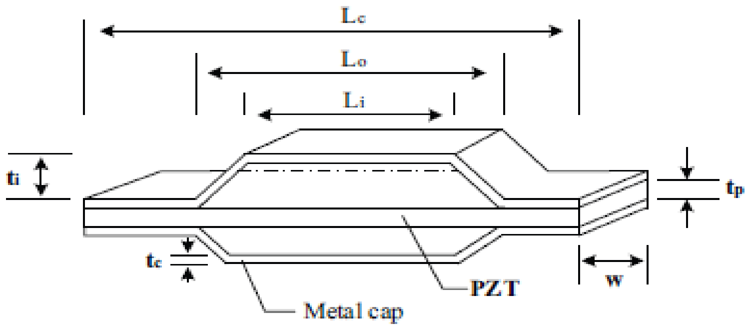


Figure 15 – Bridge transducer schematic including dimensions

FEA was used for simulation and optimization with 0.7 MPa stress distributed at the top of the sensor. Also, 2D model was used to evaluate mesh sensitivity of the transducer using different mesh sizes. Singularities are usually seen at points, edges, or reentrant corners. So it happens at the connection corner between PZT and steel end cap. Base on this issue, curved shape at the connection corner between the steel end cap and PZT are used to avoid singularities, whose function diverges to infinity. In addition, adaptive mesh refinement can be used to avoid singularity as shown below.

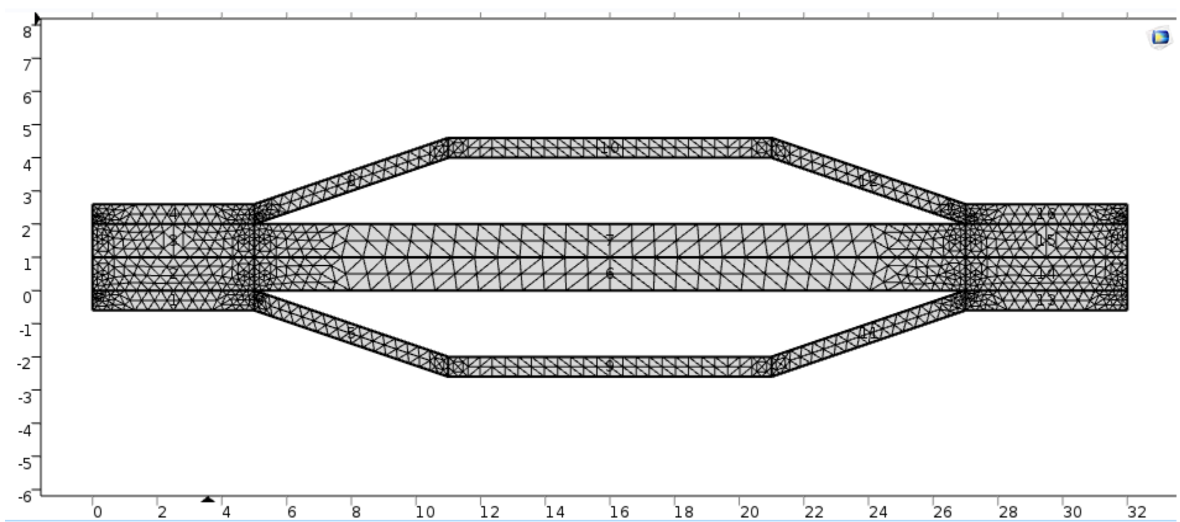


Figure 16 - Bridge transducer FEA mesh

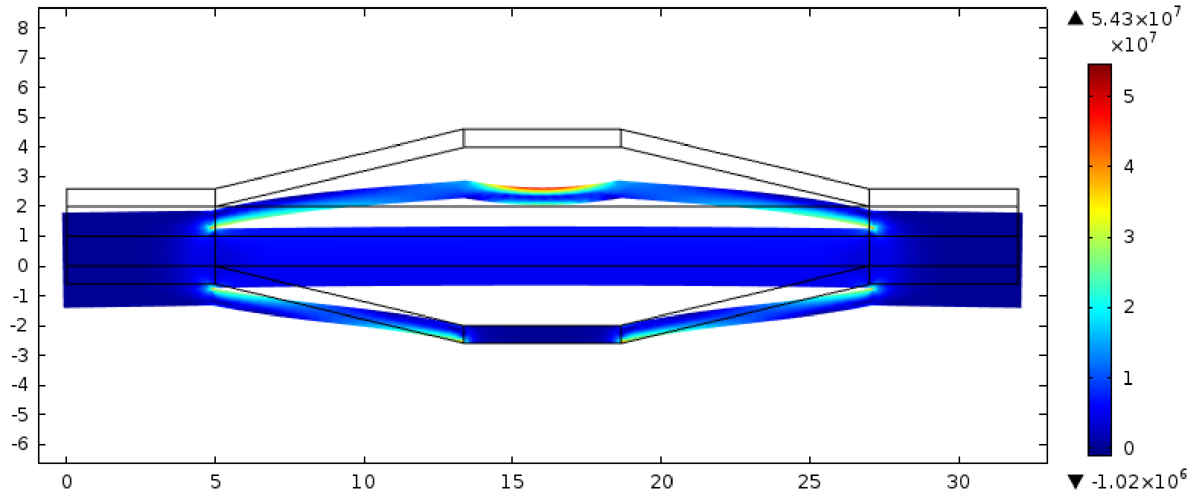


Figure 17 - Surface: Von Mises stress, Gauss-point evaluation (N/m^2)

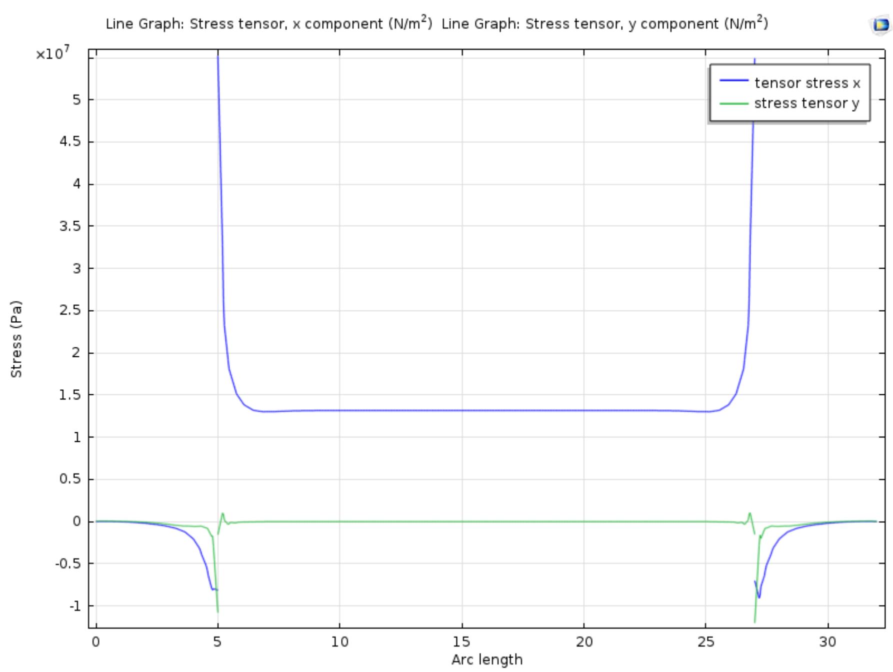


Figure 18 - Stress at the Top of PZT (Li=10 mm before optimization)

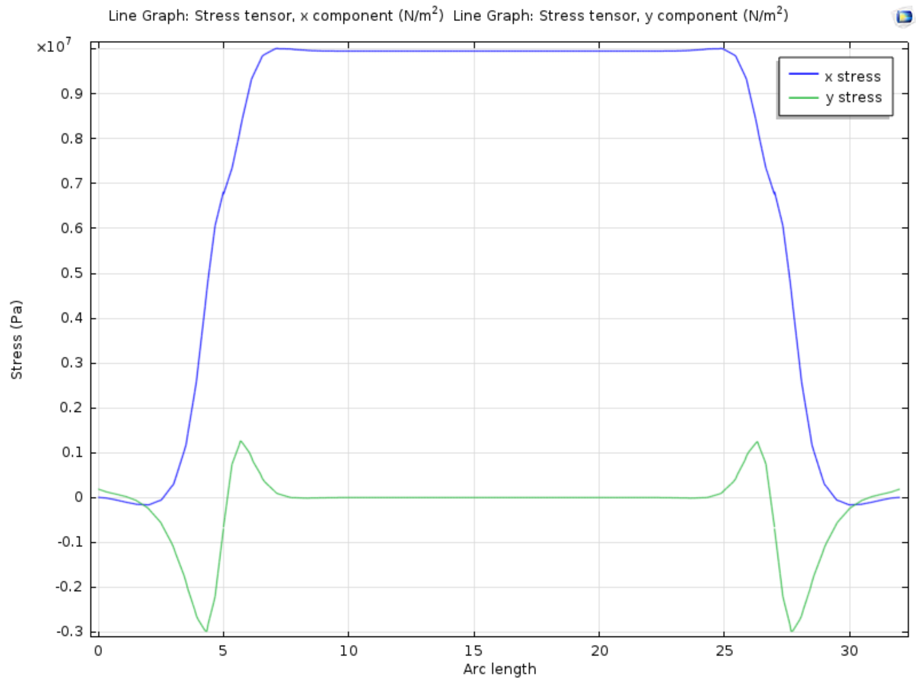


Figure 19 - Stress at the middle of PZT (Li=10 mm before optimization)

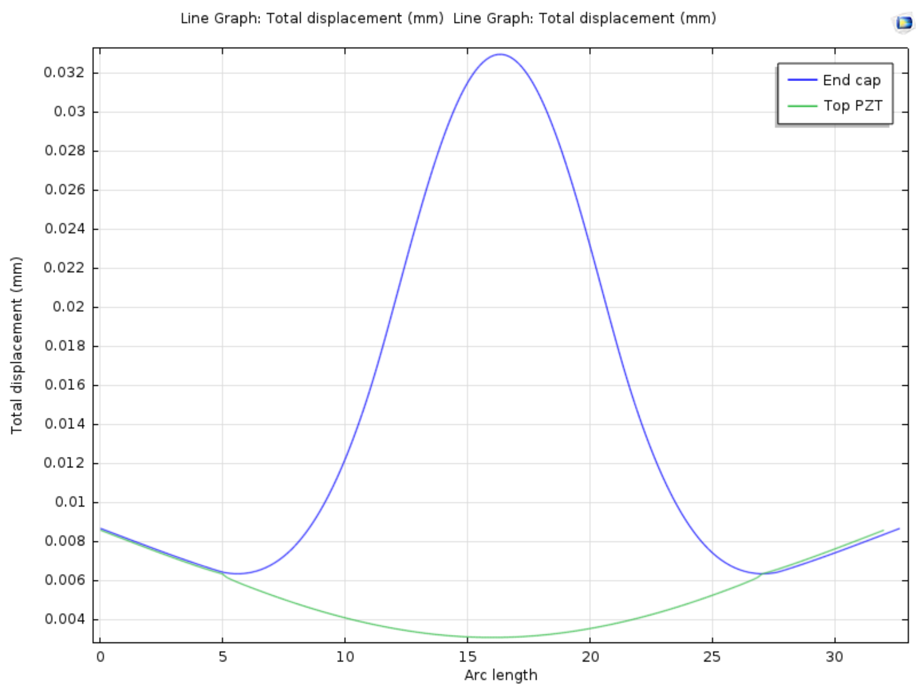


Figure 20 - Displacement at the top of the steel shell (Li=10 mm before optimization)

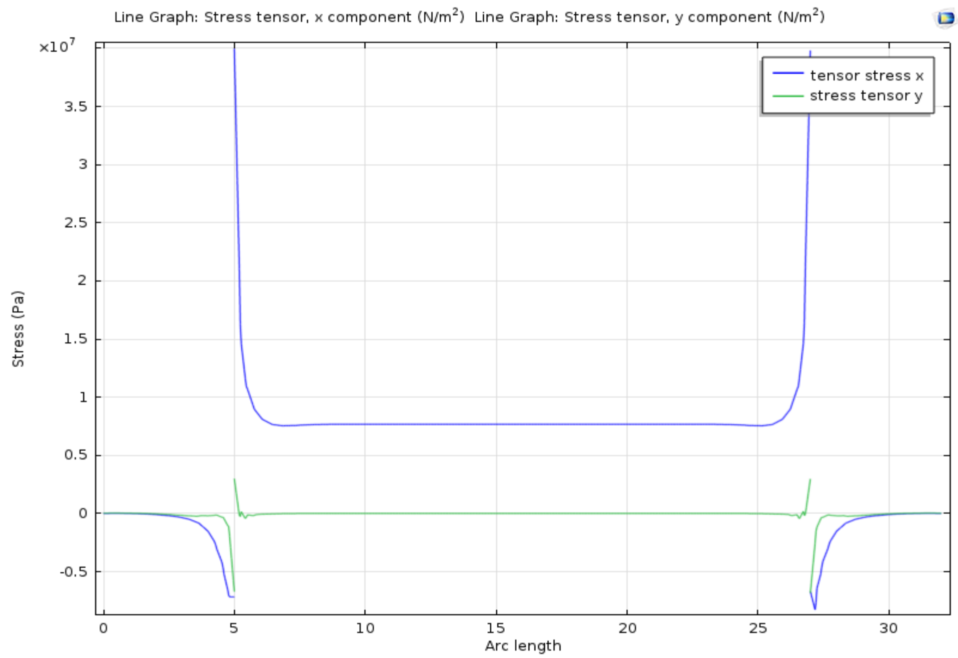


Figure 21 - Stress at the Top of PZT (Li=5 mm after optimization)

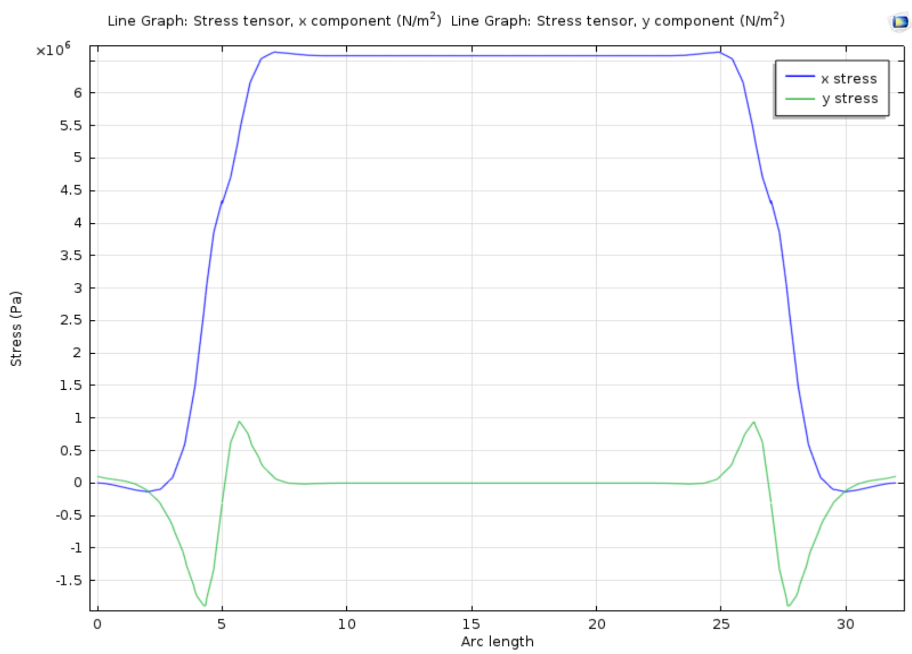


Figure 22 - Stress at the center of PZT (Li=5 mm after optimization)

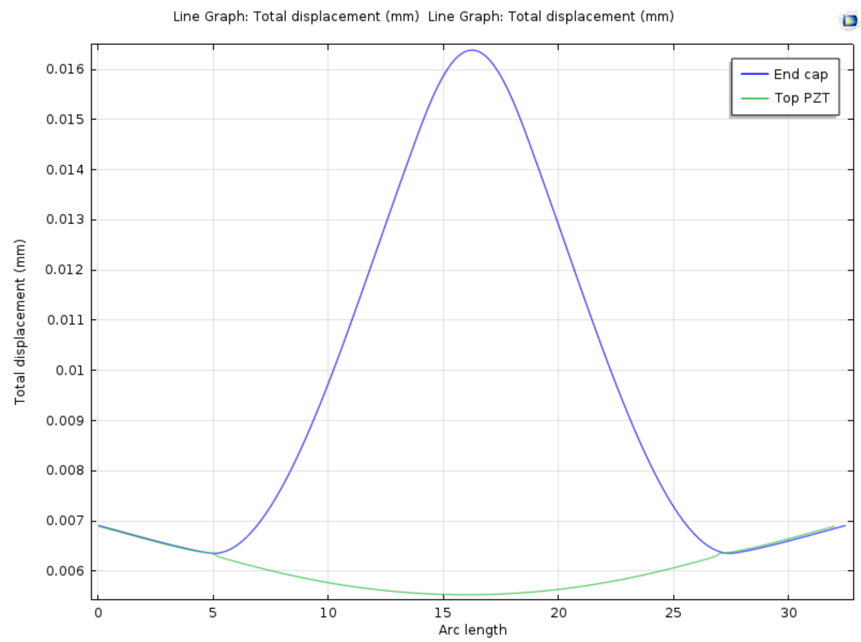


Figure 23 - Displacement at the top of the steel shell (Li=5 mm after optimization)

Based on the latest discussion with the electronic materials team, the next step is to simulate the new transducer design using wrap electrodes as shown in Figure 24.

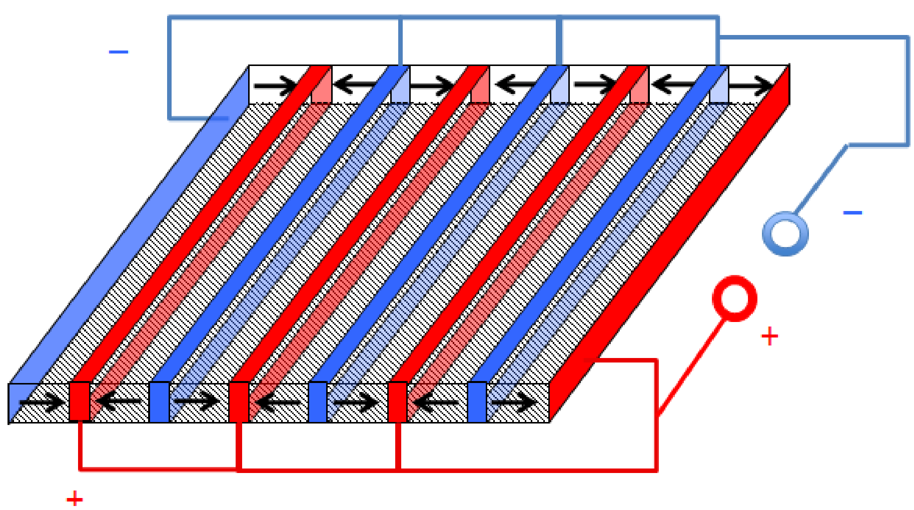


Figure 24 Layered transducer design

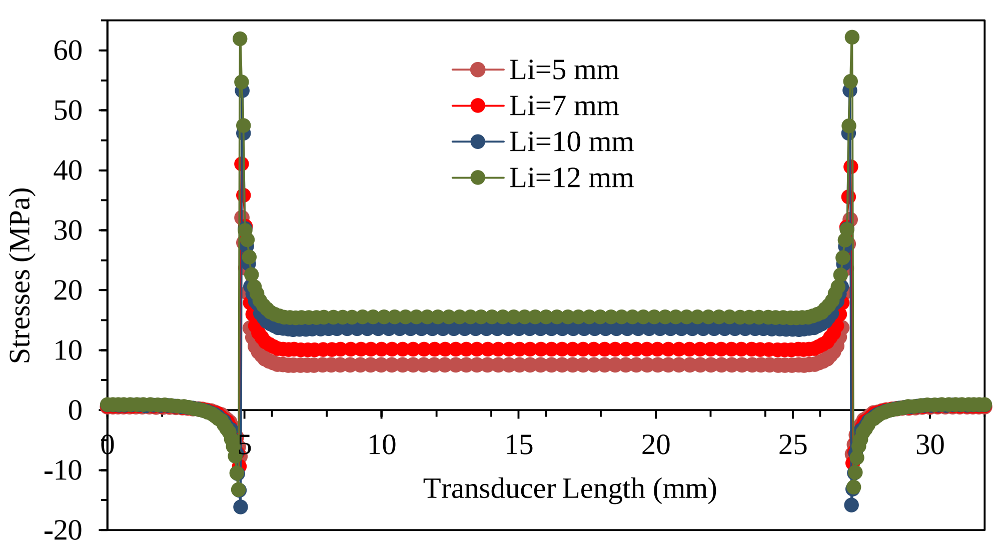
Then cymbal transducer design, utilizing a unique poling and electrode configuration of a square ceramic plate, was optimized based on available material in the laboratory. FEA was used to evaluate the inner length of the steel end cap that was only attached to the ceramic plates. Only one parameter was used for the evaluation because the available material had the following characteristics: PZT dimension = 32 mm (square shape), PZT thickness = 2 mm, and steel end cap = 0.6 mm. In this case, the PZT thickness

(t_p), the total length of the transducer (L_c), outer length of the transducer (L_o), and the steel end-cap thickness (t_c) parameters were ignored in the evaluation process.

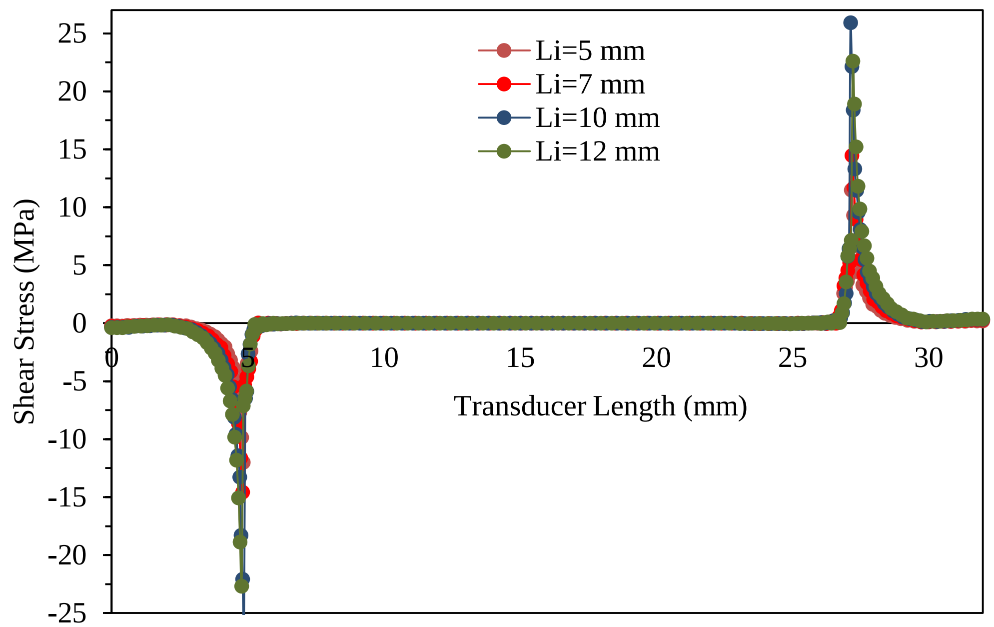
A classic evaluation must meet certain maximization/minimization goals, as well as one or more constraints. In addition to the objectives and limitations, the available material is an essential factor in optimization. For example, in terms of the goals and constraints of using FEA, the objective of this study was to increase the maximum generated energy with two stress limitations that affect the transducer. Two different limitations needed to be considered in relation to the PZT material properties and epoxy material, namely, stretching stress and shear stress. The tensile stresses on the PZT element had to be less than 40 MPa to prevent the material from cracking. A higher stress concentration would be responsible for the cracking of the PZT disk. In addition, the shear stress needed to be less than 16 MPa to prevent connection failure. Based on the goals and constraints mentioned above, a two-dimensional (2D) model using finite element analysis was employed to evaluate the mesh sensitivity of the transducer. The model used different mesh gradations, with 0.7 MPa of stress distributed at the top of the transducer.

The only way to satisfy the material strength requirement (tensile stress of less than 40 MPa and shear stress of less than 16 MPa) was to optimize the inner end cap dimensions. A range between 4-12 mm of inner length value (L_i) was selected to maximize the output energy and confirm the tensile and shear stresses. The evaluation results are shown in Figure 4.1. Figure 4.2 shows the tensile and shear stresses for the selected inner steel cap length, using L_i = 5 mm.

However, due to this modification, some electric potential was lost. This loss was due to the discovery of a decreased electric potential with a decrease in the inner steel end cap length, as shown in Figure 4.3. Figure 4.4 shows the generated voltage (V) using a 32 mm square-shaped PZT ceramic (L_c), PZT thickness (t_p) = 2 mm, steel end cap thickness (t_c) = 0.6 mm, and inner length of steel end cap of 5 mm.



(a)



(b)

Figure 25 - Effect of inner steel end cap length on (a) Tensile stress and (b) Shear stress

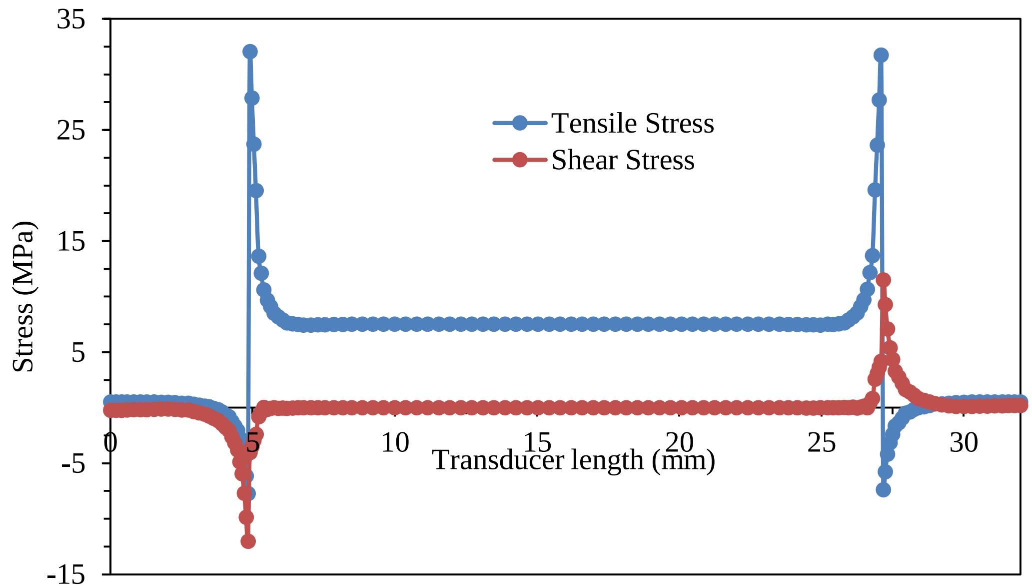


Figure 26 - Tensile stress and shear stress for selected inner steel cap length (Li=5mm)

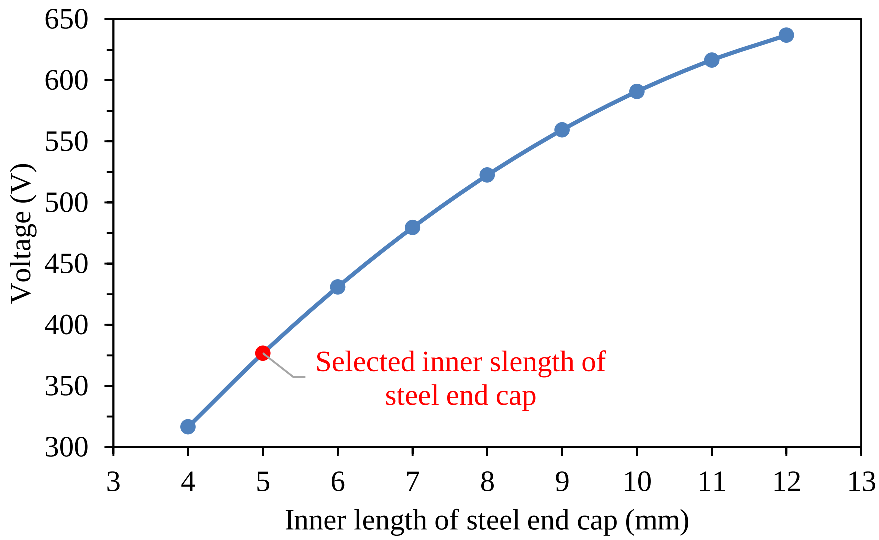
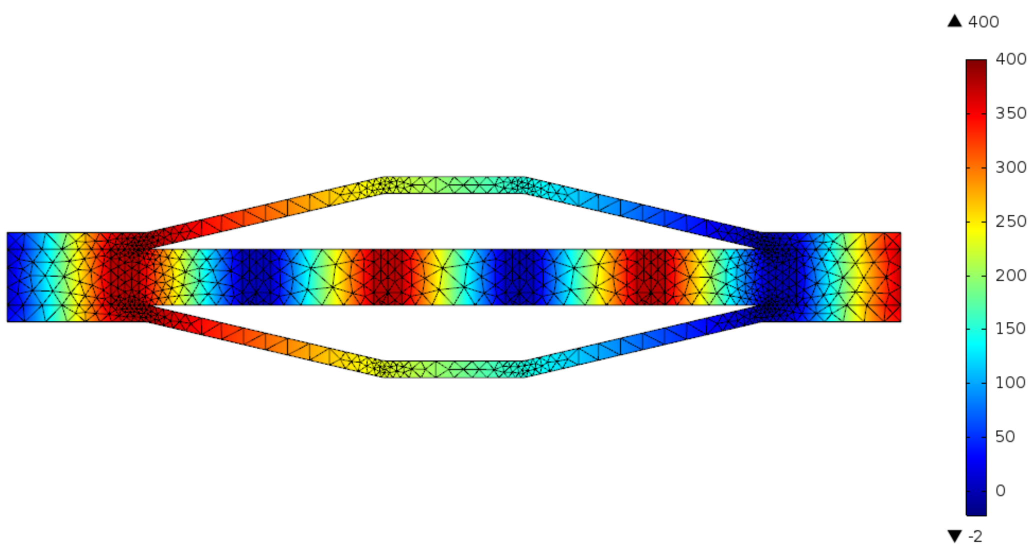
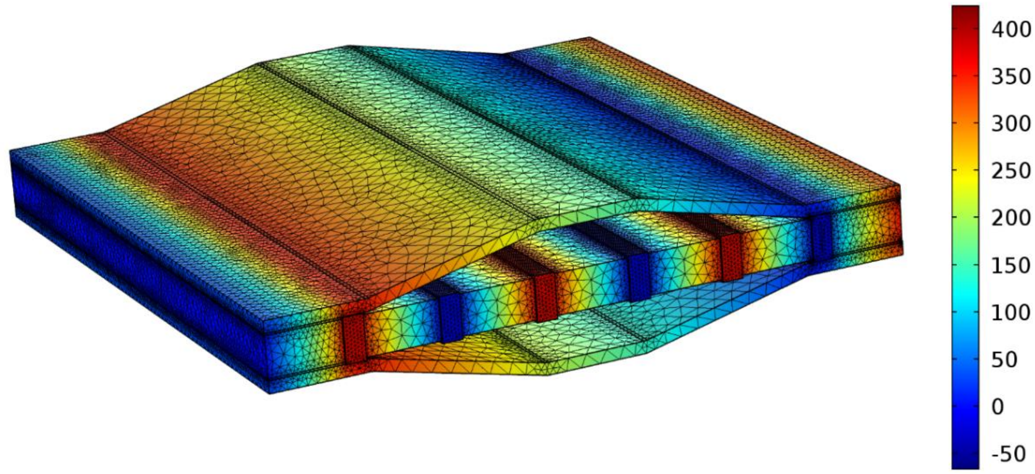


Figure 27 - Voltage versus inner length of steel end cap



(a)



(b)

Figure 28 - Generated voltage of Li= 5mm using (a) 2-D analysis results (b) 3-D analysis results

Scaled bridge model design and fabrication

The schematics of the proposed prototype, Figure 29, which simulates the dynamics of stress loading of these piezo arrays, consists of a scaled-version of a typical truck axle carrying double tires, which oscillates on an array of piezo cells operating under a predetermined load. The loading is applied pneumatically by air cylinders and the oscillating motion is achieved by a crank-connecting rod mechanism.

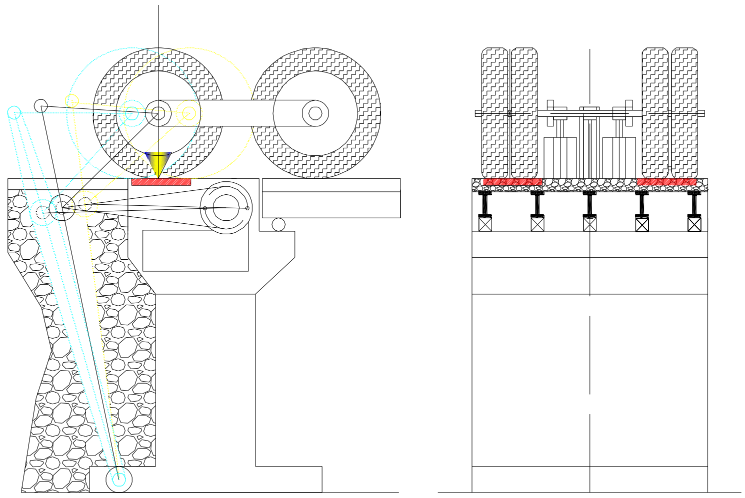


Figure 29 - Schematic of the proposed prototype

Applied force is controlled by a pressure regulator and the operating velocity is controlled by a variable-speed gear-motor. The frame that carries the reaction forces emulates an approach slab on a bridge.

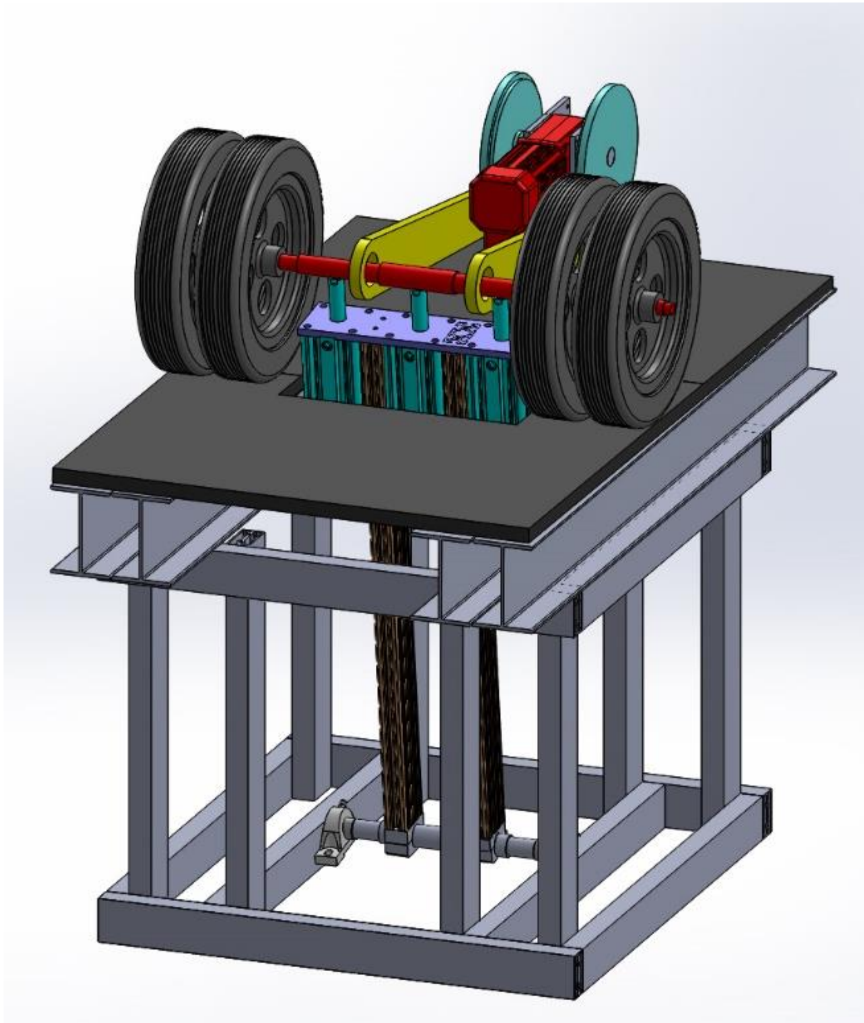


Figure 30 - 3D rendering of prototype

Design of load applicator prototype

The design of the prototype for load applicator which simulate actual loading with a scaling factor based on loading conditions that is proportional to expected bridge live loading, and to maximize prototype functionality while minimizing footprint, only the approach slab, containing the piezo energy generating pads are considered. However, the abutment and a portion of the superstructure are also proposed for easy visualization. Live loading of a single axle with double tires was simulated. However, the double-axle concept is implemented with a dummy second axle for enhanced visualization.

Proof of concept of load applicator

To accelerate experimental setup and minimize construction cost, a proof of concept load applicator has been constructed that provides the anticipated loading levels, and frequency of load application, under predetermined values of controllable input/ output parameters.

This proof of concept load applicator, which were constructed to fulfill severe time and cost constrains, were successfully build using a 20 ton press steel frame fitted with innovative pneumatic load actuators system. This loading system consists of two pancake air cylinders placed in tandem,

The top cylinder acts as a load placing actuator which insures proper contact of the load applicator cylinder with the piezo arrays. it also acts as an overloading safety device to prevent crushing of piezo array if applied load exceeds predetermined levels set by a precision pressure regulator.

The lower cylinder has a very short stroke, and are used for applying the energizing loads set by the second pressure regulator and frequencies, set by the signal control unit, thus simulating actual live loads of the bridge under consideration, Figure 31

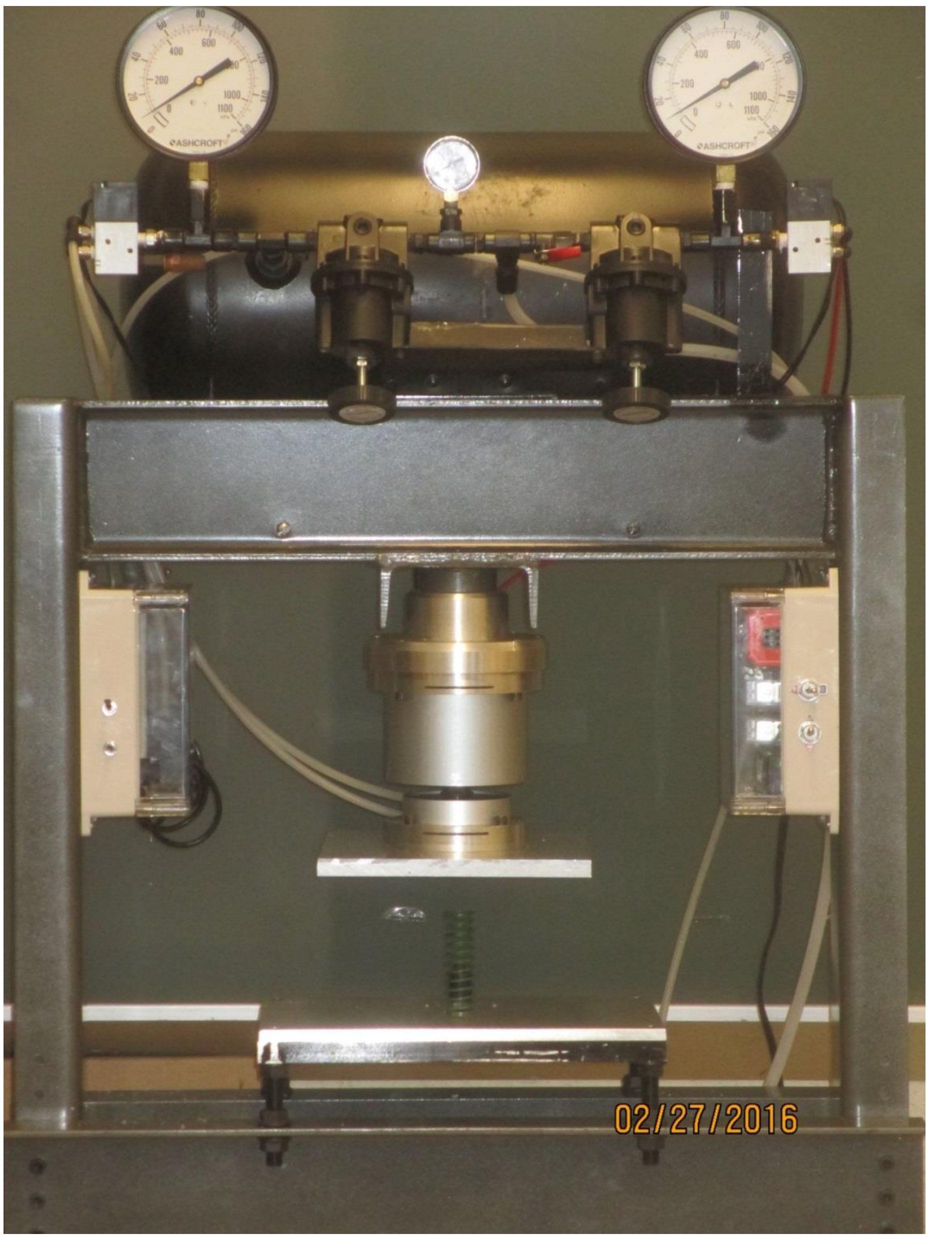


Figure 31 - The load applicator arrangement of the press unit

The double contoured closed frame steel body provided the needed high rigidity requirements for this application, The adjustable mid bream load bearing beam enabled testing of piezo modules of   different height of configurations. The press frame was also used to fit the control unit and the air tanks, in as compact configuration Figure 32.

Figure 32 - Pneumatically operated press frame load applicator press unit

The pneumatic circuit designed for that purpose, Figure 33. It consists of a high pressure air compressor feeding large capacity air tanks, connected to precession high air flow regulators that are actuated by controllable timing signals that correspond to the required frequencies and loading levels.

The unit was very successful in generating the desired loading conditions, and the publications below investigated the performance of these piezo arrays using the above proof of concept press unit load applicator.

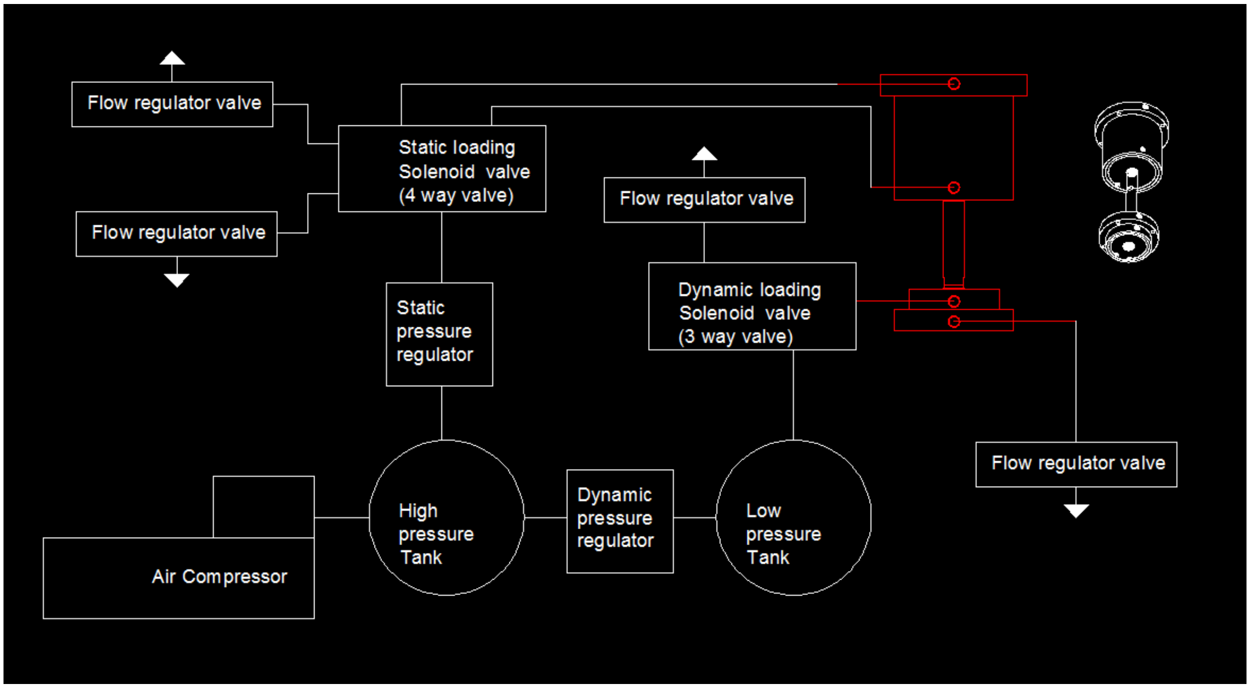


Figure 33 - The pneumatic circuit diagram of the load applicator press unit

Load applicator specifications:

A- Impacting loads

Maximum impacting load	1100 lb
Maximum holding load	2000lb
Maximum operating pressure	160 psi
Impact load control	0→1000
Holding load	0→2000
Loading platen dimensions	8x8 inches
Daylight	8 inches

B- Impact Loading frequency

Low impacting frequency	6→60 Impact/minute
Medium impacting frequency	60→600 Impact/minute
High impacting frequency	600→3000 Impact/minute

C- Data Transition

Force/time signal	Solid state pressure transducer
Data acquisition card	Measurement and computing (USB-108LS)

Conclusions and Recommendations

This successful prototype provides the opportunity for researchers to develop a field-deployable concept. The prototype has demonstrated measurable and quantifiable energy generation for myriad applications. The design of the novel transducer and the prototype array can be optimized to increase the amount of energy generated. The novel electrode pattern allows the piezoelectric to be poled horizontally, utilizing the larger lateral piezoelectric coefficient d_{33}, which can be further increased by reducing the inter-electrode spacing and adding additional electroded segments. This will also increase the capacitance of the transducer and increase the output current.

The materials used for the prototype and methods of fabrication can be optimized to improve the design. The poling fixture that does not clamp or constrain the ceramics should be used in order to avoid failure during poling. The end caps were stamped from alloy steel because it is easier to shape than stainless steel and can be hardened by heat treatment. However it was only available with a thickness of 0.025”. Compared to a thinner steel end cap, this reduces efficiency because more mechanical energy absorbed by the metal rather than converted to electrical energy by the piezoelectric.

Further work is needed to develop materials that will encase and protect the piezo-heating array, while serving in any selected application. The research team acknowledges there are challenges ahead and recommends continued investigations on suitable interface for future application in transportation infrastructure.

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