MCP401: Design Report of Piezeo-electric charger

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Abstract

This is the mid-semester design report on our **MCP401** course project in the semester-1 of the 2023-2024 session. We report the complete design and manufacturing techniques for the proposed design for our piezo-electric charger.

Aim:

To conceptualize, design and fabricate the piezo-electric charger that could harness energy from the sources of variable loading conditions such as gym training, children's playgrounds, or instances where we know that loads are oscillating with respect to time.

Theoretical background on Piezo-electrics

The piezoelectric phenomenon is characterized by converting electrical energy into mechanical energy and vice versa. It is observed in numerous crystalline materials, with certain substances like quartz, Rochelle salt, and lead titanate zirconate ceramics exhibiting a powerful effect that finds practical applications. In the case of the direct piezoelectric effect, a fixed electric polarization emerges when a piezoelectric crystal is subjected to deformation. This polarization is directly proportional to the extent of the deformation, resulting in the development of an electric potential difference across the crystal. Conversely, the inverse piezoelectric effect represents the reverse of the direct phenomenon. This signifies that applying an electric potential difference leads to a deformation of the crystal.

Proposed Design

We are proposing a cylindrical frame with 3 slots for piezo-cell sets, where cells in those slots will sit. Followed by an extrusion on the top which is responsible for pressing the piezo cells, followed by a spring which ensures the position of the top platform returns to the original state. The output wires from the piezo-cells are then transferred to the storage section in the setup for later use. We also incorporate a diode bridge at the output of the piezo-cells to ensure that flow of charge is one way only and no losses possible due to back-flows.

Loading conditions

We would be modelling our device under cyclic loading conditions. Here we see that our model would be experiencing a load varying from 0 to max load. The Figure 1, gives a visual description of the same. Please not the figure is just for visualization purposes only. It's not necessary that it follows a cosine nature as depicted. Load would be applied on the platform, which pressing the piezo-cells siting beneath it. The load on the platform is applied on the flat surface (figures shown in the CAD section) whereas for the main body that load would be loaded at the base of the piezo-cells. We have grounded (keeping the platform of the main body stationary).

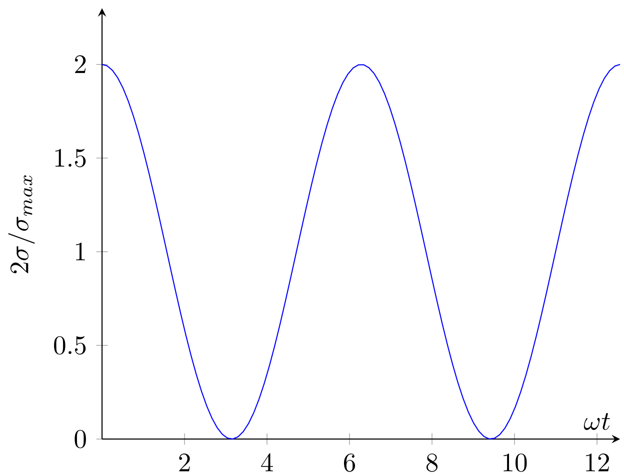

Figure 1: Cyclic loading visualization

Factor of safety

Designing based on Goodman's criteria: We try to map the transient load then we estimate the static load corresponding to the same using the most conservative design approach known to us. In this way we can run static simulations on AutoDesk-Inventor with static loads. Further we ran dynamic simulations on SolidWorks. The section **Simulations** will cover those analysis. The advantage of these simulations is we get the distribution of the parameter factor of safety on the geometry volume, which helps us analyse our problem better. We can locate the prospective faliure point with such analysis.

Calculations

Design based

Due to the constraints on the size of material and size of the piezo-cells we need to come up with constraint estimates on the dimensions of the structure of the proposed model. Thus we went with design making it 10 times the diameter of piezo-cells. Later we will discuss about these dimension estimates come to working good, when we observed a good factor of safety as per the simulations. Corresponding we estimated the depth with putting the piezo-cells into the wholes made in the main body. Then we estimated to make a good charger at least it should be capable of holding 2Ahr, which is least required by any decent smart phones these days. Thus our aim is to able to generate that much charge in feasible time frames. Also for our analysis we found the equivalent static load corresponding to the applied dynamic loading using the Goodman's criteria.

Update it

Experimentation based

First we tried to charge a capacitor in order to determine the charging rate of the piezo-cell system. We took 3 cells in series and combined 3 sets in parallel, using 9 cells. Then we applied a oscillating load (L) of 10N, 110 times at regular interval, with total time of 5 minutes = 300 seconds. The data recorded from experiment as follows:

$$\text{Capacitance (C)} = 47\,\mu F$$

The load frequency assuming regular interval loading,

$$\text{load-frequency (f)} = \frac{110}{300}$$

Reading of the potentiometer attached to the Capacitor

$$\text{Potential difference } (V_0) = 3V$$

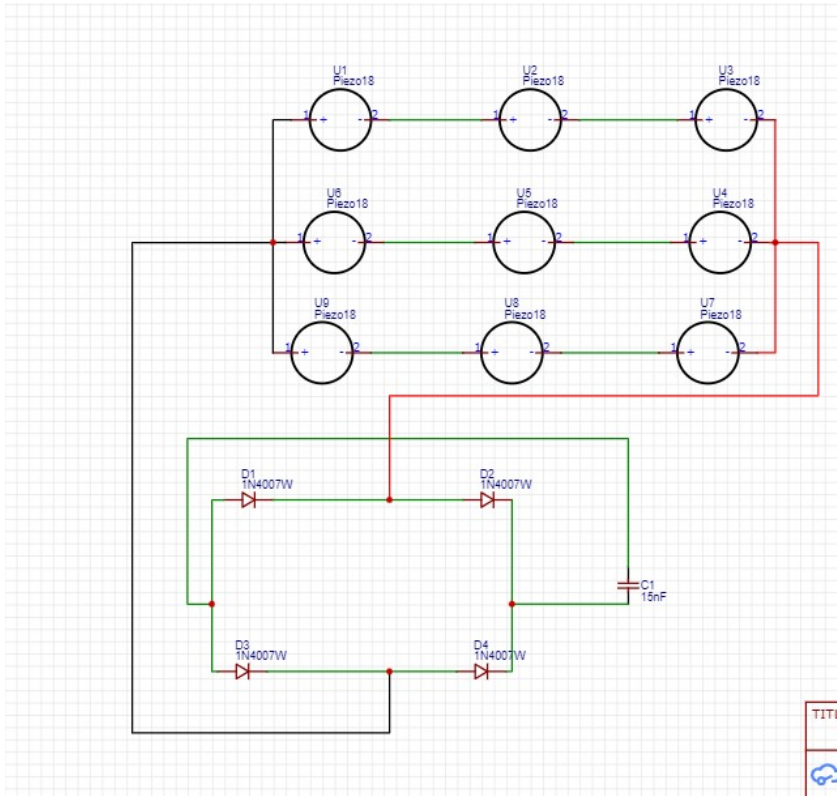

Figure 2: The Circuit layout for our experiment

Thus charge stored is

$$\text{Charge Q} = CV_0 = 141\mu C$$

Imperial results suggest that charges are function of stress in one direction, thus we need to look into small currents generated and take time integrals of the same. Then summing all of them would be giving us total charge.

Thus we can relate the charge, with load-frequency(f) and operating instances(n) with the load as,

$$Q \propto f \ n \ L \tag{1}$$

Later in the project we intend to harness more charging capacity using the above expression.

CAD

There are majorly 2 components in our design, the top section is the platform where we apply the load. The below section is the part where the piezo cells sits and connections are made to store energy harness from the pizeo cells. The main housing ensures the piezo sits in required space. This has to endure the stresses and retain the geometry without deforming much, otherwise it might take away the stress shares from the piezeo cells. The top ensures piezeo cells are pressed uniformly with almost in-phase. This ensures we have piezeo cell's output in phase, and not cancel each other out while they are connected.

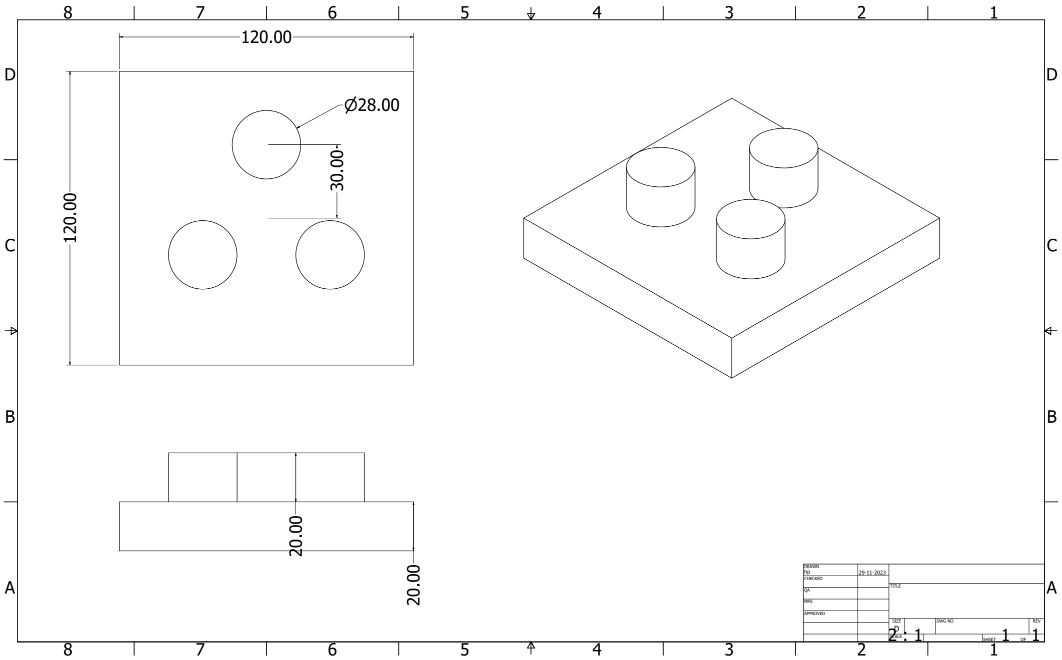

Figure 3: Drawing of the body

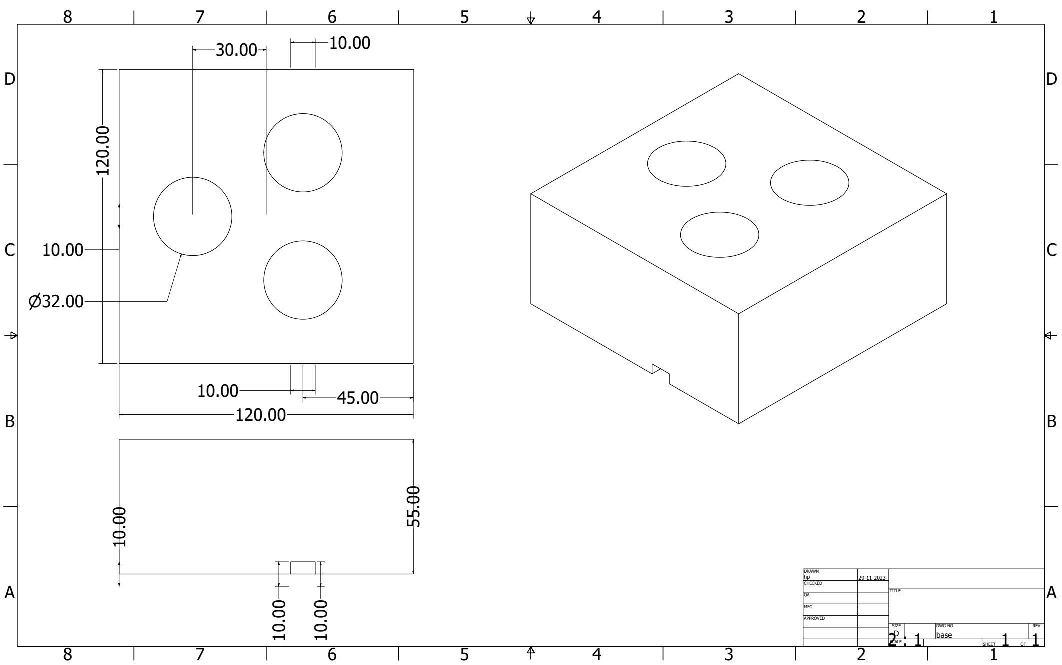

Figure 4: Drawing of the top platform

Fits & tolerances

Diameter of hole: 30 mm

IT grade (Tolerance grade) can be between IT10 to IT13 for the Milling manufacturing process
Fit as per the application : **Loose running fit**
So, the tolerance as per application and process is IT11
Magnitude for IT11 as shown in Figure 5 = 100i
Formula for i to calculate tolerance is:

IT grades of various manufacturing processes

Machine operation	*Obtainable IT grades*
Boring	IT8 to IT13
Boring — diamond	IT5 to IT7
Broaching	IT5 to IT8
Casting — sand	IT16
Die casting	IT15
Drilling	IT10 to IT13
Extrusion	IT10
Flame cutting	IT16
Grinding — surface	IT5 to IT8
Grinding — cylindrical	IT5 to IT7
Honing	IT4 to IT5
Lapping	IT4 to IT5
Milling	IT10 to IT13
Press — metal forming	IT12, IT13, IT14
Planing	IT10 to IT13

Figure 5: IT grades of various manufacturing processes

Application of different FITS

Hole basis	*Shaft basis*	*Name of fit*	*Application*
			Clearance Fits
H11-c11	C11-h11	Loose running fit	Commercial rough applications

Figure 6: Fit as per application

Relative magnitude of tolerance grades

Tolerance grade	IT 5	IT 6	IT 7	IT 8	IT 9	IT 10	IT 11	IT 12	IT 13	IT 14	IT 15	IT 16
Magnitude	7 *i*	10 *i*	16 *i*	25 *i*	40 *i*	64 *i*	100 *i*	160 *i*	250 *i*	400 *i*	640 *i*	1000 *i*

Figure 7: Magnitude as per tolerance grade

Basic size (Diameter steps) in mm	
Over	1
To and inc.	3
Over	3
To and inc.	6
Over	6
To and inc.	10
Over	10
To and inc.	18
Over	18
To and inc.	30
Over	30
To and inc.	50
Over	50
To and inc.	80

Figure 8: Range in which our radius lies

$$\text{i} = 0.45\sqrt[3]{D} + 0.001D$$

Here, D is the geometric mean diameter in mm
For D, as our diameter 30 mm lies in the range (30-50). So, D would be:

$$\text{D} = (\sqrt[2]{30 * 50})mm = 38.73\,mm$$

So, by using the value of D we found :

$$\text{i} = 0.00156\,mm$$

$$\text{Tolerance} = 100i = 0.156\,mm$$

Now for hole, H stands for a dimension whose lower deviation refers to the basic size. The hole H for which the lower deviation is zero is called a basic hole. So,

$$\text{Lower limit} = \mathbf{15 + 0.000}\,mm = 15.000\,mm$$

$$\text{Upper limit} = \mathbf{15 + 0.156}\,mm = 15.156\,mm$$

Surface roughness

By using the Centre Line Average method (briefly known as CLA method), the relationship between surface roughness and tolerance is:

$$\text{CLA roughness} = 0.25 * IT(Tolerance) = 0.25 * 0.156$$

$$\text{CLA roughness} = 0.38\,mm$$

Simulations

Simulations are the essential part of any design problem. It provides us a check on our design proposal and help us improve if it fails in the simulations. We simulated our proposed model in SolidWorks at CAGIL facility, Mechanical Eng. department. SolidWorks had the required package for solving the dynamic problem as well the visco-elastic materials library, thus we could model wood as the building material for the proposed model. The elasto-plasticity theory suggest the main cause of the failure are the principal stresses and thus we are using the Mohr-Coulomb theory to determine the factor of safety of our system.

Material

We used the inbuilt library of the SolidWorks simulation software to model the wood material. Specifically we modeled the Oak wood, due to its availability. Also the reason we choose wood was ease with using the same. In the MakerSpace facility IIT Delhi, we have wood cutting equipment's like laser cutting. The below chart shows the material properties we have.

Property	Value	Units
Shear Modulus	5000000000	N/m^2
Mass Density	700	kg/m^3
Tensile Strength	70000000	N/m^2
Compressive Strength	60000000	N/m^2
Yield Strength		N/m^2
Thermal Expansion Coefficient		/K
Thermal Conductivity		W/(m·K)
Specific Heat		J/(kg·K)
Material Damping Ratio	0.01	N/A

Figure 9: The material properties

Results of simulations

Here, we discuss the outcomes of the simulations we ran. We mainly looked into theories of elasto-plastic as it has been used to describe the properties of wood. We would be looking into the components one by one, that is first we look into the simulation results of the main body and then into the results from the platform. Figure (10)-(13) shows the visualization of the simulation results fro the body. After this we have analysis for the platform, Figure (14) -(16).

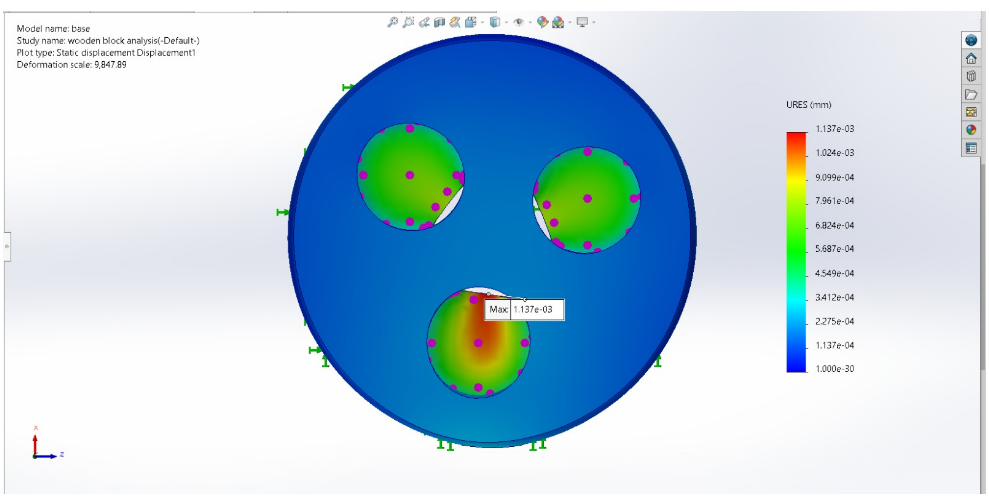

Figure 10: Body: Loading site and extension predicted

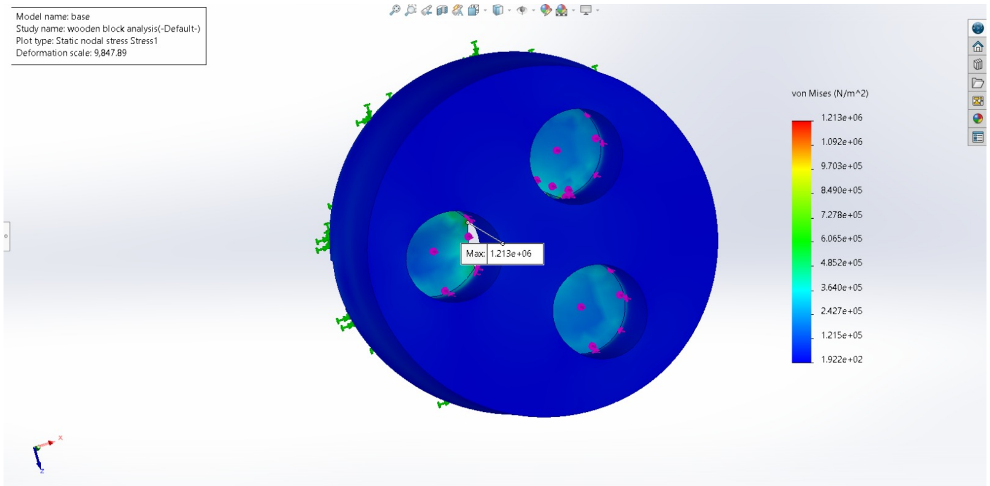

Figure 11: Body: Von-Mises stress predicted

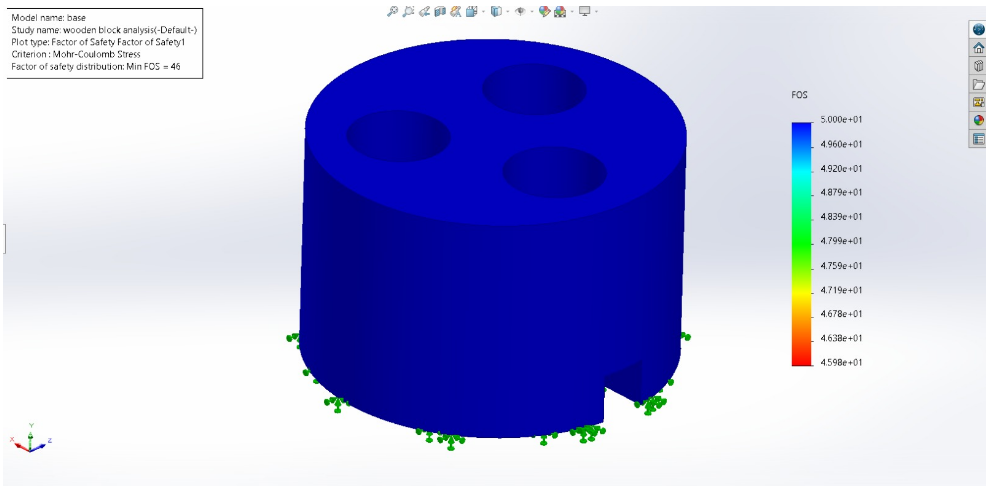

Figure 12: Body: Factor of safety

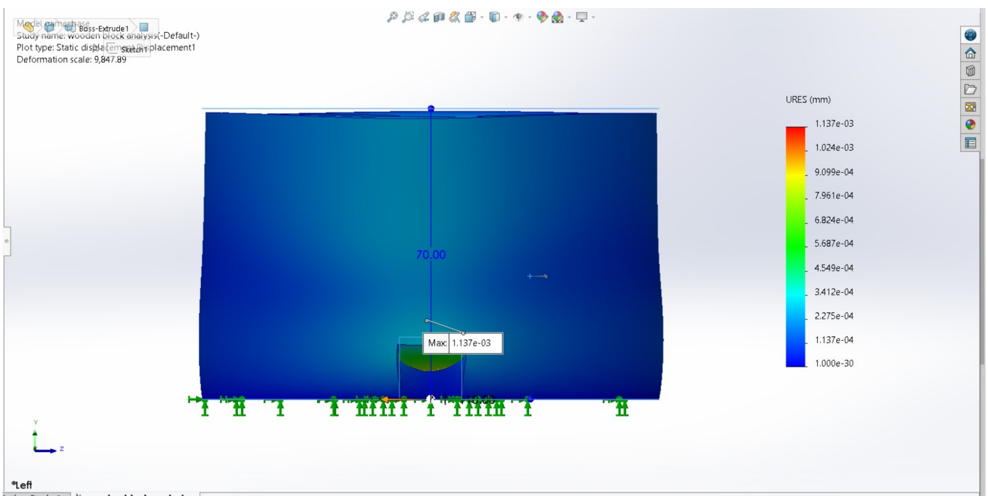

Figure 13: Body: Extensions and boundary conditions

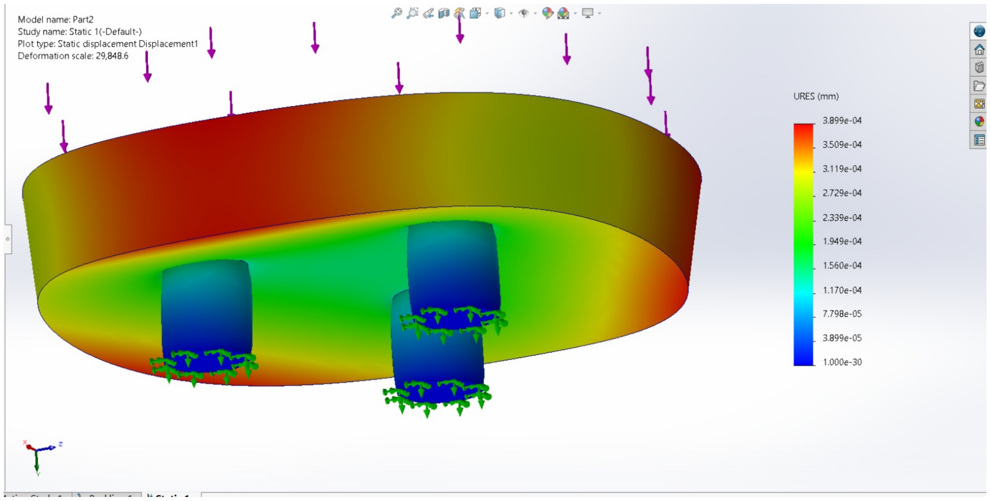

Figure 14: Top: Loading site and extension predicted

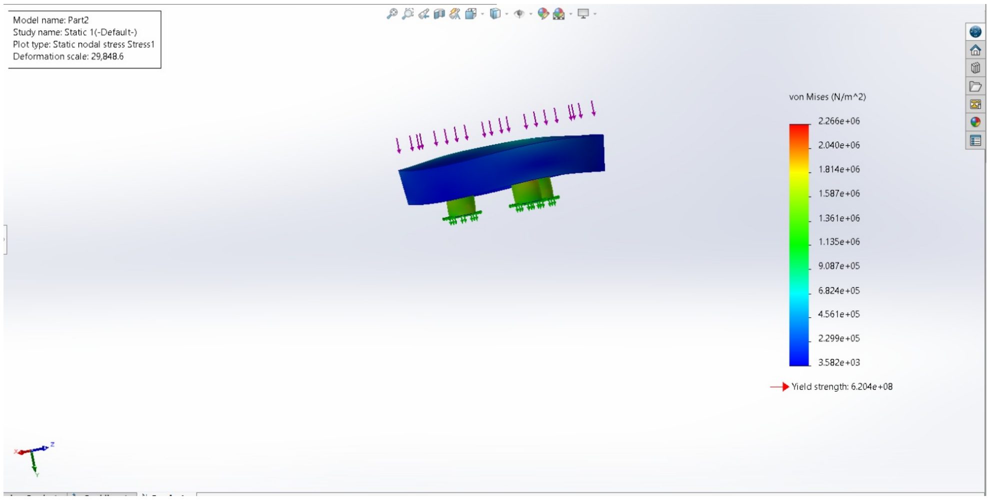

Figure 15: Top: Von-Mises stress predicted

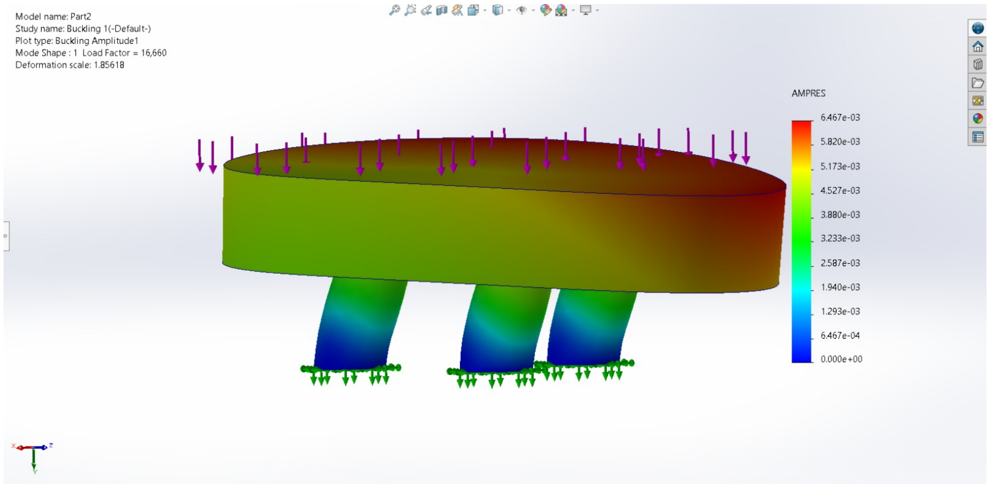

Figure 16: Top: Buckling analysis

Specifications

The followings were specifications of the materials we used:

Frame

The conceptualized model is enclosed within a framework made of plywood. This plywood structure, with a thickness of 3.5 cm, serves as a housing for the model. Additionally, there's a wooden block, 2 cm thick and with an area of $12 \times 12\text{cm}^2$, likely providing support or acting as a base for the model. To cover the entire setup, an acrylic frame is used. It contains all components within a defined zone, ensuring protection and to cover up the whole frames, wiring etc into one zone. The piezoelectric cells' output is subsequently channeled from the container to the storage module. Storage module is containing the main rechargeable lithium ion battery with charing and discharging state with switch cases.

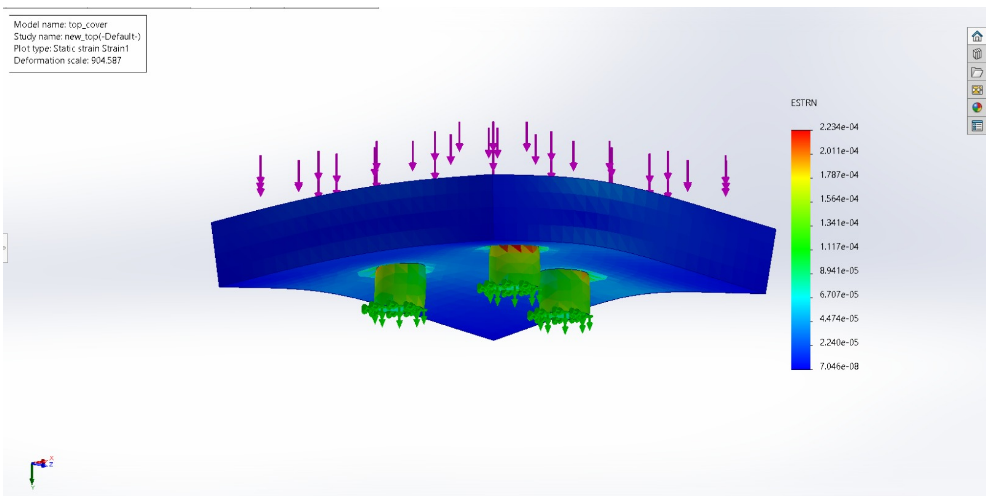

Figure 17: Top sections deformations

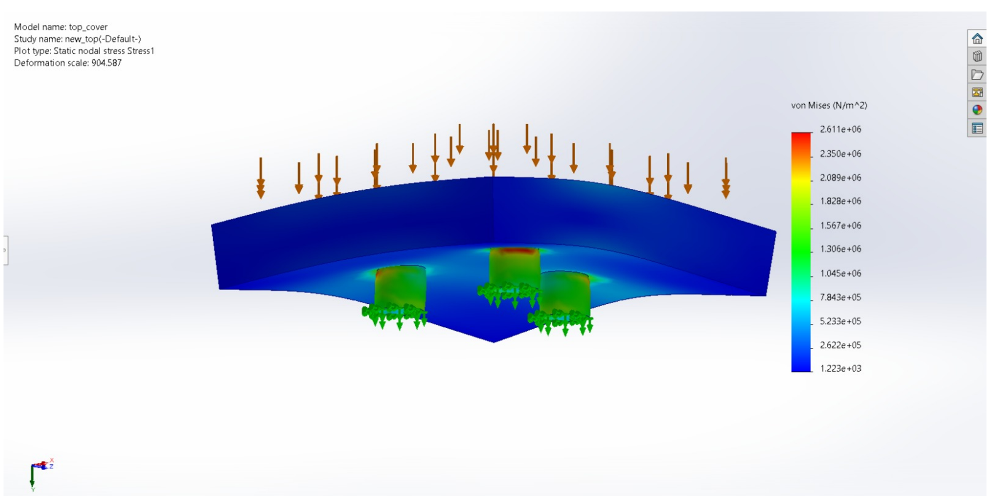

Figure 18: Top section von-mises

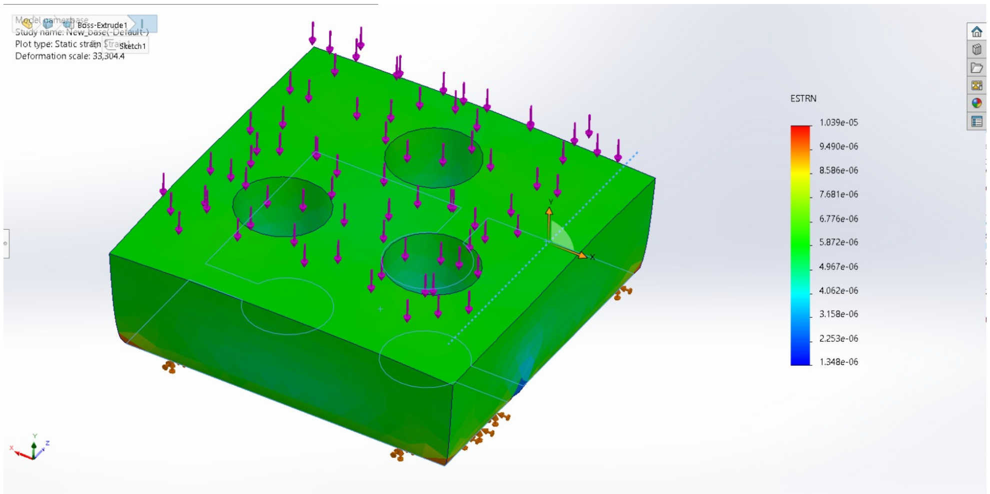

Figure 19: bottom section deformations

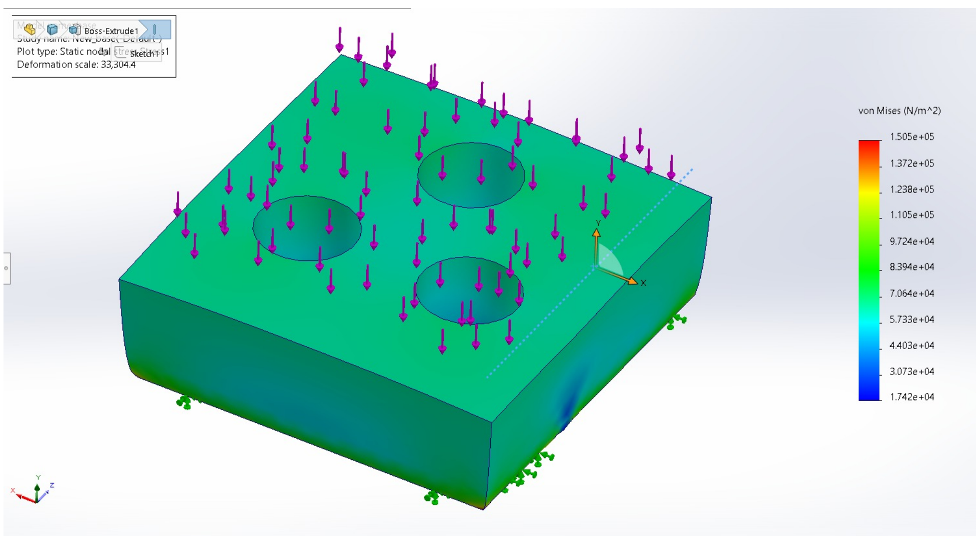

Figure 20: Top section von-mises

Piezeo cells

The measurement of the geometric diameter stands at 30 mm, accompanied by each crystal's diameter at 25 mm. Each cell possesses the capability to produce a peak voltage of 10V when operating under no load conditions. Our development process involved the creation of three stacks of piezoelectric cells. Within each stack, we arranged 5 independent cells in a series. Subsequently, this arrangement was repeated in parallel twice, culminating in a total of 10 cells within each stack. To achieve an amplified overall current output, we interconnected 3 of these stacked configurations in parallel within the ultimate setup.

Litium-ion battery

We implemented a rechargeable lithium-ion battery within our system, precisely rated at 12V DC, featuring a commendable charge storage capacity of 2 Ahr. The primary objective of this battery integration was to efficiently store the output derived from the piezoelectric cell container. It's pivotal to note that the piezoelectric cells yield an output characterized by irregularities in its potential, rendering it unsuitable for direct storage. Hence, our strategic approach involved channeling this non-uniform output into the Li-ion battery for storage. This intricate process ensures that the erratic energy generated by the piezoelectric cells finds a stabilized abode within the battery, enabling subsequent discharge in alignment with specific usage requirements or applications within the system.

Diodes

Simple diode

1. current rating : Can range from around 1 mA to several amps, depending on the size and type of diode. For instance, a small signal diode might have a current rating around 100 mA, while a power diode could handle currents of 10 A or more.

2. breakdown potential : Typically ranges from around 50 volts to several hundred volts for standard diodes. This voltage determines the maximum reverse voltage that the diode can withstand before breakdown occurs.

Zener

1. current rating : Can vary widely based on the size and type of Zener diode. Common ratings range from a few milliamps (e.g., 5 mA) to higher values such as 1 or 2 amps for larger Zener diodes.

2. breakdown potential : Zener diodes are specifically designed to operate in the breakdown region. The breakdown voltage or Zener voltage is a fixed value specified for each diode and can range from as low as a few volts (e.g., 2.4V) up to several hundred volts (e.g., 200V)

Performance metric and measurables

For our proposed project we are mainly interested in the rate of charging. Thus we are focusing to construct a metric which is capable of capture that property.

Measurable

1. Load vs Potential difference: Analysed with load cells on what load at given loading frequency the potential developed across the piezeo-cells was observed.

2. No. of presses vs charge stored: To determine this, we run simple experiment of running mallet on the housing top and tracking the rate of charge growth. We will demonstrate that live for the whole setup. Frequency was 1 hit per second. The weight of the piezeo box was 8.428 kg-wt (N), and from image processing we concluded the mallet force to be 1.9639 kg-wt (N).

3. Energy discharge time: We estimated that to be around 24 VAhr, This was estimated through theory, practical we ran a series of motors (4 in parallel) for nearly 170 min to completely discharge the cell

4. With the experiments we came to know that to generate 0.235 mC of charge we need 50 mallet presses. Implying we need 30,638,298 (3 million presses on an average) mallet presses for completely charging the Li-ion battery.

Fabrication

From conceptualization we now moved to the

1. Holes in Wood Casing: Utilizing a drilling machine, we created 3 holes, each having a diameter of 32 mm, within the casing. These openings are made for accommodating individual piezo stacks, ensuring a good fit for optimal placement.

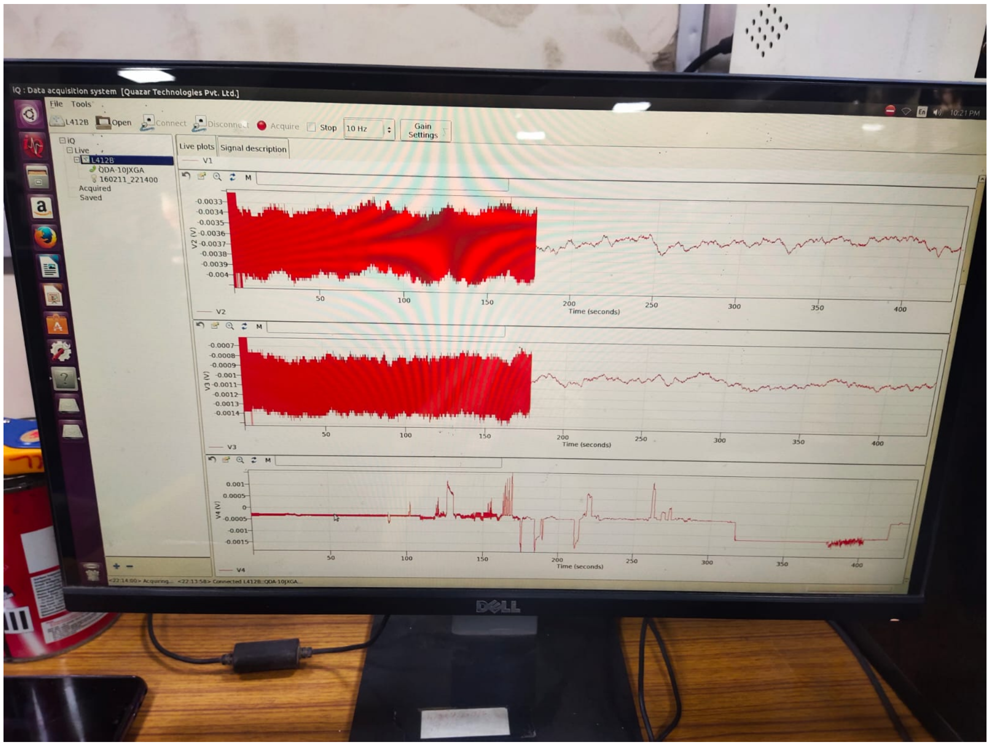

Figure 21: Load vs Potential difference on a load cell

2. Housing, Base, and Lid Construction: A jigsaw machine was used for cutting the wood into custom dimensions required for the housing, base, and lid. The dimensions were precisely followed to the specifications outlined in the frame section, ensuring precision and alignment.

3. Assembly of Housing to Base: Using the drilling machine, we carefully generated 3 holes with identical diameters in both the base and housing components. These holes were made to securely fasten the housing to the base using bolt and nut mechanisms. Furthermore, we crafted slightly larger diameter holes in the lid, strategically designed to facilitate the smooth application of dynamic loads, ensuring operational stability.

4. Diode Bridges + Zener Diode Integration: Incorporating diode bridges played a crucial role in managing the bidirectional flow of charge generated by the piezoelectric source. By utilizing diode bridges, we ensured that regardless of the charge's polarity, the storage in the battery occurred in the same direction. Additionally, the inclusion of a Zener diode set to a specific 5-volt threshold served as a protective measure, regulating and stabilizing the voltage, thus safeguarding the battery from potential overvoltage situations.

5. Discharging Port Setup: To facilitate convenient utilization of the stored charge, a female USB port was thoughtfully integrated into the charger. This port configuration allowed for seamless access to the stored energy, enabling effortless discharging for various applications through standard USB-compatible devices.

Challenges faced

Inability to create a circular profile of the model

The absence of specialized cutting tools or machinery specifically designed for this purpose presented a significant obstacle in crafting the model to exact circular specifications. As a result, we encountered difficulty in realizing the intended circular profile, leading to a deviation from the desired shape or form outlined for the model (circular). So, we had to shift from circular to square geometry of the model.

Fusing of battery charging module

While working with the charging module, we encountered overloading of the charging module due to the high output voltages of the

How we tackled

Redesigning the CAD model as per known processes

We moved into simple geometry of the setup to ease while manufacturing with makerspace capabilities. The designs shown in the figures (17)-(20).

Developing custom charging module

After fusing of the charging module, we developed our known DC discharge through zener diode and resistors, zener diode in reverse bias ensured nealry constant breakdown voltage is been output for the safety of the charging entity. The other port is connected similarly.

Final model design

Our current estimates suggest that we need to make 3 million (on an average) instance for charging 2Ahr. The product is capable of charging a mobile phone rated 5V & 2A. We have provided 2 discharge ports for the product we designed, based on what requirements does the user have.

References

1. COMSOL documentation of Piezeo electric physics

2. ICMM TCZilenlinski Piezeo electrics

3. Roland MDX 540CNC manual

4. SoliWorks manual cum Documentation

5. Tippner, Jan, Milch, Jaromír, Sebera, Václav and Brabec, Martin. "Elasto-plastic material model of oak at two moisture content levels" Holzforschung, vol. 76, no. 10, 2022, pp. 886-896.