Design and Modelling of a Piezoelectric Road Energy Harvester

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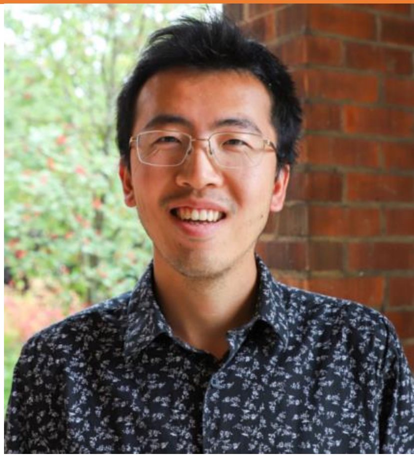

Presenter’s bio:

Dr. Bin Wei is an Assistant Professor at Algoma University, Canada. He received PhD in mechanical engineering in 2016 from Ontario Tech University, Canada. His research interests include robotics, control theory, and complex dynamical systems.

Overview

- The physical model of a piezoelectric road energy harvester is successfully illustrated in this work.
- The design of the piezoelectric elements has been determined by various simulations in Matlab, and the plots of which have been represented thoroughly.
- Based on the Matlab results, a physical model of the piezoelectric energy harvester has been successfully designed using SolidWorks.
- The dynamic analysis of the harvester is used to elucidate the operation of the design.
- Finally, the stress and displacements plots are used to validate the proposed design of the piezoelectric road energy harvester.

Introduction

- In this paper, the aim is to evaluate the performance of an impact based piezoelectric energy harvester consisting of cylindrical piezoelectric elements that are embedded into a robust steel structure that can endure the forces exerted by various vehicles passing on the road.

- The actuation of the harvester is done through a separate hydraulic mechanism with minor changes, which transmits the forces exerted by the vehicles into a hydraulic piston, which then stresses the piezoelectric block to cause electricity generation.

THE PRINCIPLE

- The piezoelectric material has been used in the form of a transformer model as shown below:

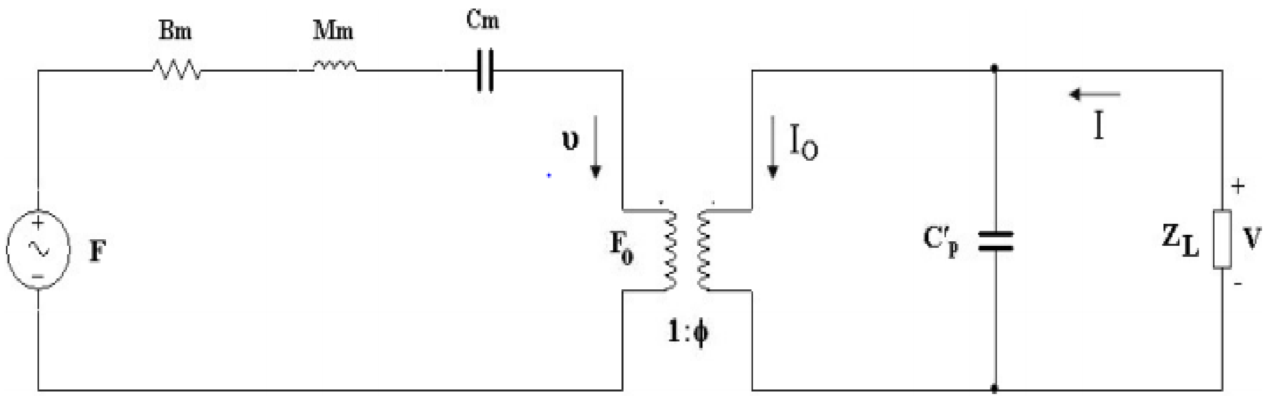

Figure 1. The piezoelectric generator transformer model

- The transformer model illustrates two sides: the primary side and the secondary side. The primary side of the transformer uses the mechanical and dynamic properties of the piezoelectric material to model an analogous electrical representation.

THE PRINCIPLE

- On the secondary side, Z_L represents the load connected to the piezoelectric model. C_P' is the blocked capacitance while V is the potential difference across the load Z_L. I is the resultant current generated while I_O is the current corresponding to the internal force Fo of the piezoelectric material. The mechanical realization of this model is shown below.

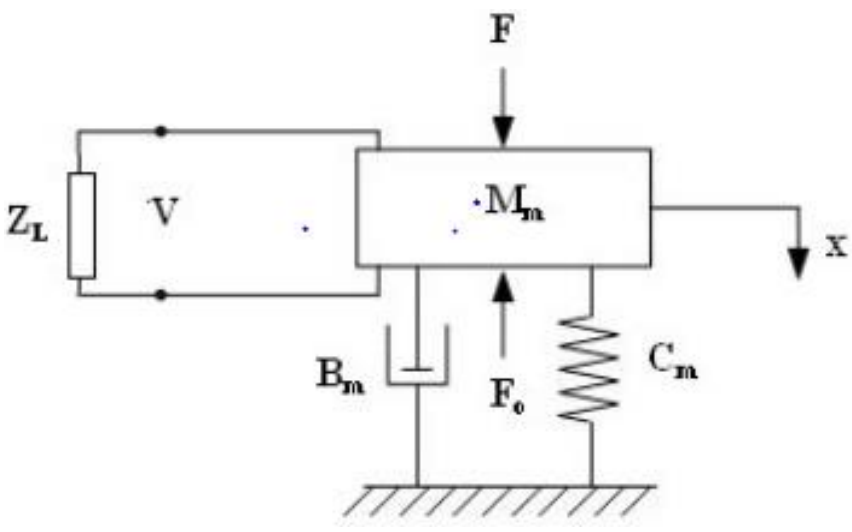

Figure 2. Mechanical realization of piezoelectric generator model

ANALYSIS

- A circular cross section for the piezoelectric material is deemed most appropriate for the piezoelectric energy harvester. This is because a cylindrical structure is much easier to manufacture for future mass production without incurring excessive production costs.

- The initial iterations take into consideration different diameters and thicknesses based on which power and voltage are calculated. For thickness ranging from 1 to 10 cm, the power plot is discontinuous as the curve would go back to zero soon after the first impact.

- Moreover, the plot for power generated for diameters ranging from 1 to 10 cm also shows tremendous variations.

- Hence, the thickness to area ratio is a critical factor in determining the optimum power generated, which is helpful in determining the dimensions of the piezoelectric cylinder.

ANALYSIS

TABLE 1. DIMENSIONS OF THE PIEZOELECTRIC CYLINDER

Diameter	6.5 cm
Thickness	18 cm

- The goal is to achieve sustained oscillations for the piezoelectric cylinder after impact in order to generate continuous power and thus facilitate continuous energy generation, which can later be used in various applications.
- Hence, further iterations are conducted by varying the thickness of the piezoelectric cylinder to up to 20 cm. The diameter of the cylinder is restricted to a value below 10 cm.
- The most suitable results are obtained when the piezoelectric material is designed according to dimensions mentioned in Table 1, the result of which will be used to determine the resultant mean power over the time interval [0, 200] seconds.

ANALYSIS

The resultant plots for input force, voltage and power generated versus time are shown below.

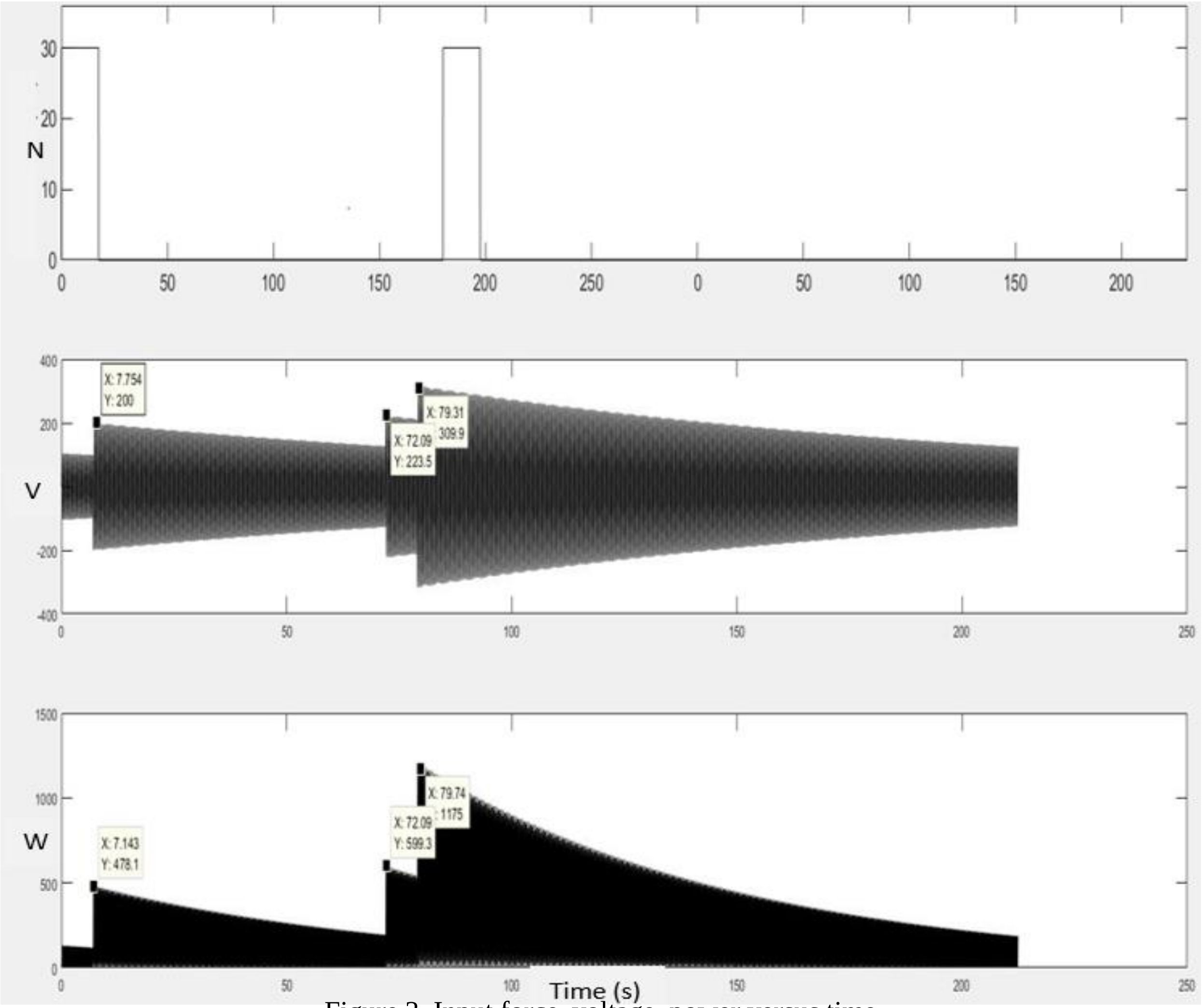

Figure 3. Input force, voltage, power versus time

ANALYSIS

According to the Table 1, the resultant mean power over the time interval [0, 200] seconds is also calculated as shown in Figure below.

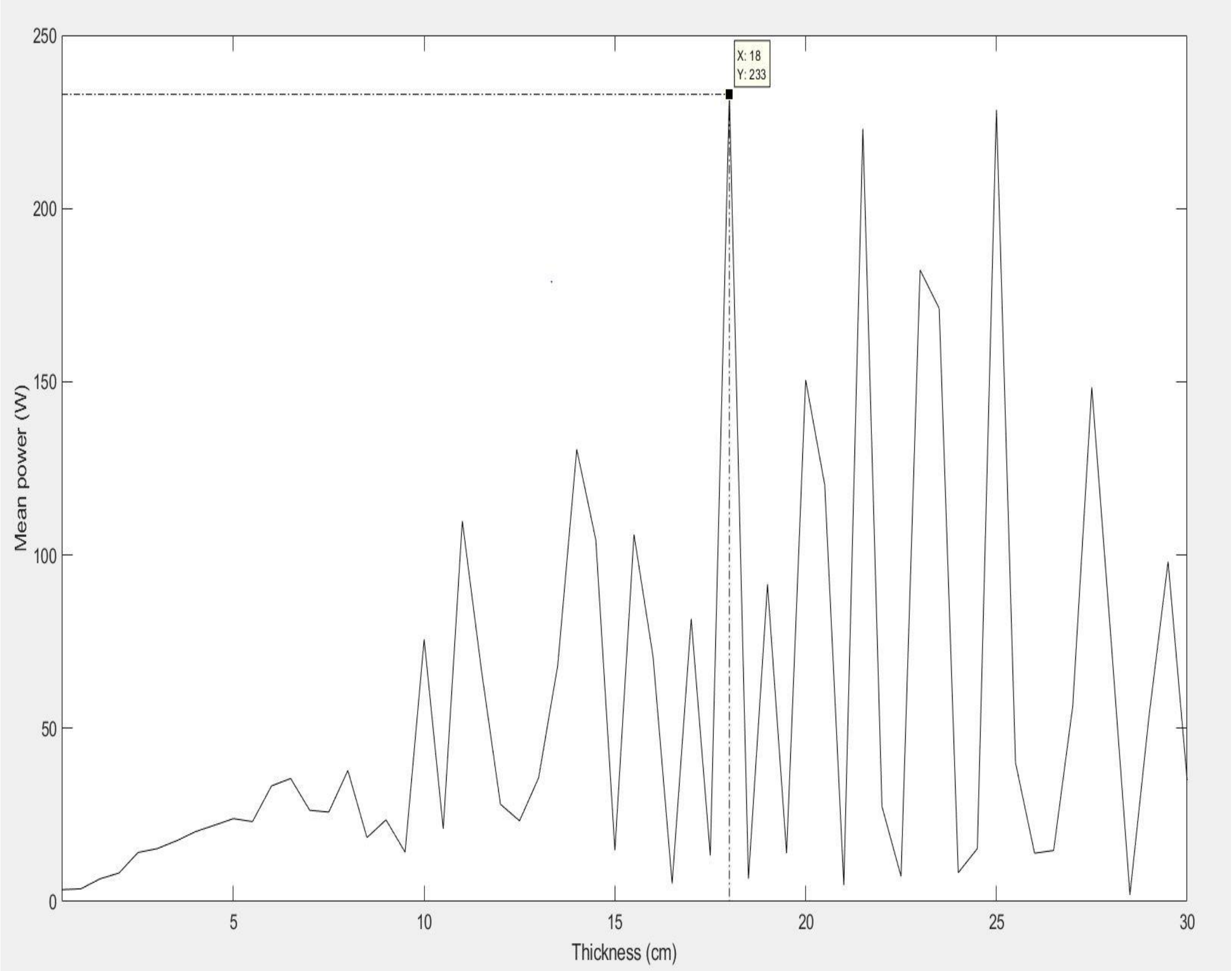

Figure 4. Calculation of mean power

ANALYSIS

- The optimized values of voltage and power after the first impact is obtained. For a value of maximum possible input force (weight of the vehicle), the corresponding power and voltage outputs are successfully calculated using Matlab.

- The average power over the time interval [0, 200] seconds, as a result of this design is theoretically obtained to be close to 233W, which is larger than that of the previous attempts.

DESIGN OF THE PIEZOELECTRIC MODULE

- The power generation potential of the piezoelectric cylinders is predicated mainly on the impact-based approach of the pressuring plate caused by the movement of vehicles on the road.

- The inclusion of dampers causes the movement of the pressuring plate to slow down with the entire scenario liable to be analysed in a quasi-static state rather than an impulsive impact based state. This affects the power generation capacity of the piezoelectric cylinders.

- The best solution to combat this problem is to make use of an embedded system of thick steel block and piezoelectric cylinders. The elasticity modulus of steel could be used favourably to perform the spring and damping action simultaneously.

DESIGN OF THE PIEZOELECTRIC MODULE

- The material used for the piezoelectric cylinders is PZT-5H. The material properties for PZT-5H is shown in Table below.

TABLE V. MATERIAL PROPERTIES OF PZT-5H

1.	Density	7.4 g/cc
2.	D33	585e-12
3.	K33	0.59
4.	K(eff)	0.53
5.	Modulus of Rupture	61.5 MPa
6.	Damping Constant	5e-8

- The selection of the PZT-5H material is based on the comparatively higher values of D33 (piezoelectric coefficient), K33 (piezoelectric coupling coefficient) and K(eff) (effective piezoelectric coupling coefficient) against the other grades of commercially available piezoelectric material.

DESIGN OF THE PIEZOELECTRIC MODULE

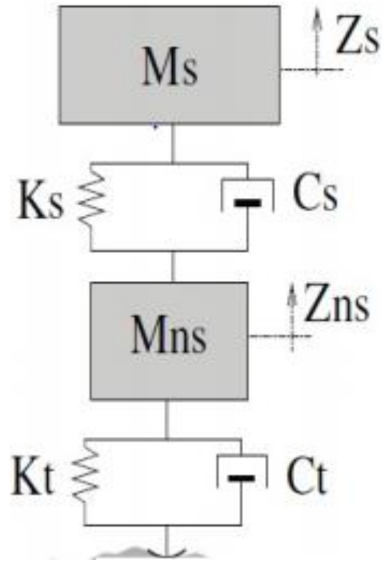

Figure 6. 2 DOF mass-spring-damper system

- In Figure 6, Ms represents the mass of the vehicle while K_s and C_s resemble the spring constant and damping constant for its suspension system, respectively. Similarly, M_{ns} represents the combined mass of the piezoelectric cylinders within the module while K_t and C_t resemble its spring constant and damping constant, respectively.

DESIGN OF THE PIEZOELECTRIC MODULE

- The force exerted due to the vertical acceleration of the vehicle suspension system is the same force responsible for stressing the piezoelectric material within the module. The free body diagram of the two masses in the system yields the following two equations:

$$M_s \ddot{Z}_s = K_s(Z_{ns} - Z_s) + C_s(\dot{Z}_{ns} - \dot{Z}_s)$$

$$M_{ns} \ddot{Z}_{ns} = -K_t Z_{ns} - C_t \dot{Z}_{ns} - M_s \ddot{Z}_s$$

- Thus, the acting force on the piezoelectric module depends on the vertical acceleration of the vehicle during motion.

DESIGN OF THE PIEZOELECTRIC MODULE

The module design is shown in Figure below.

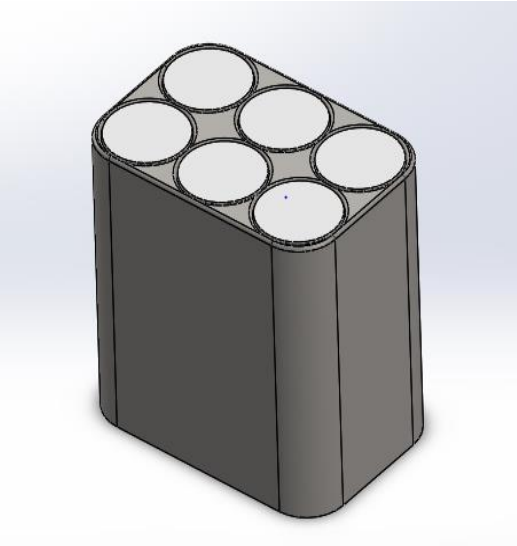

Figure 7. Piezoelectric energy harvester module

- Stress analysis of the module was essential in determining the mechanical feasibility of the proposed design. The acting force on the upper plate of the module was fixed as per the value discussed in the previous section.

STRESS ANALYSIS OF HARVESTER

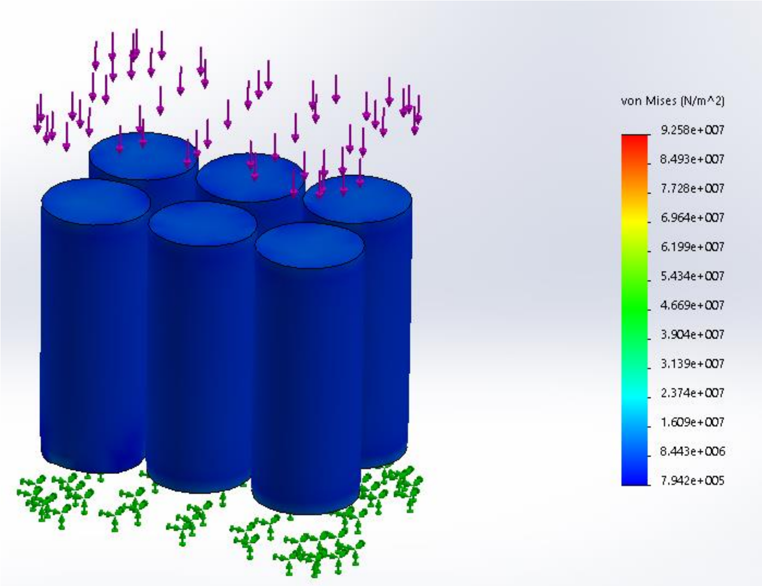

Figure 8. Stress analysis for piezoelectric cylinders

- The stress analysis of the piezoelectric cylinders is as shown in Figure above. From this dynamic analysis, it is shown that the stress exerted on the piezoelectric cylinder is approximately 0.8 MPa, which is less than the modulus of rupture for the PZT-5H material. Hence, the piezoelectric cylinders can be expected to operate as expected according to the calculations presented in the previous section.

STRESS ANALYSIS OF HARVESTER

- Figure 9 represents the displacement plot for the piezoelectric cylinders under applied stress. Hence, the maximum displacement occurs at the upper layer of the piezoelectric cylinder with a value of approximately 2.4e-2 mm (as expected).
- The stress analysis of the steel block with the upper pressuring plate is as shown in Figure 10. The maximum stress experienced by the steel block is within the elastic limit of the material. Thus, the validity of the design is verified.

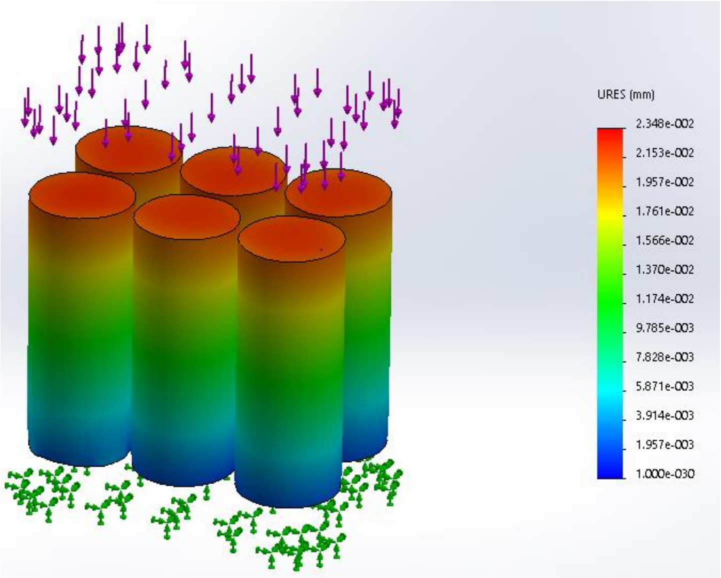

Figure 9. Displacement plot for piezoelectric cylinders

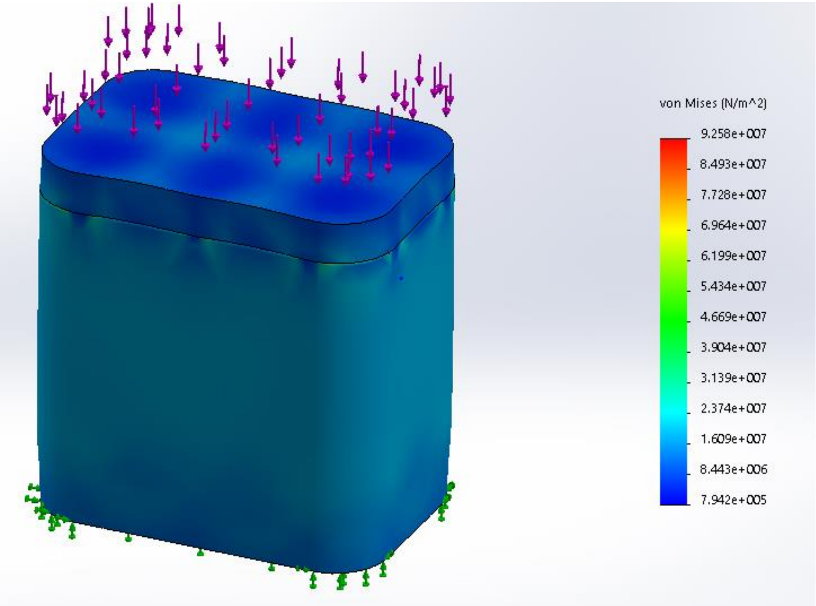

Figure 10. Stress plot for steel block with upper plate

CONCLUSION & FUTURE WORK

- The material selections for the steel block and the piezoelectric cylinders are justified according to the method of application desired. The piezoelectric cylinders are designed according to the value of the input force (weight of the vehicle).

- The average power over the time interval [0, 200] seconds, as a result of this design is theoretically obtained to be close to 233W, which is larger than that of the previous attempts.

- The design of the energy harvester is successfully validated via stress analysis in SolidWorks. The actual calculation for input force is successfully illustrated in Section 4 of this study.

- Future work will focus on a proposition of installation method of converter in real situation, which can hold much more load.

Thank you! Questions?

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