Non-Contact Energy Harvesting for Rural Grade Crossings - Year 1

Joseph A. Turner
Robert W. Brightfelt Professor of MME
Mechanical and Materials Engineering
University of Nebraska-Lincoln

Mohsen Amjadian
Assistant Professor
Civil Engineering
University of Texas Rio Grande Valley

Carl Nelson
Professor
Mechanical and Materials Engineering
University of Nebraska-Lincoln

Prince Mensah
Graduate Research Assistant
Mechanical and Materials Engineering
University of Nebraska-Lincoln

A Report on Research Sponsored by

University Transportation Center for Railway Safety (UTCRS)

University of Nebraska-Lincoln

November 2024

Technical Report Documentation Page

<table>
<tr><td colspan="2">1. Report No.
UTCRS-UNL-M1CY23</td><td colspan="2">2. Government Accession No.</td><td colspan="2">3. Recipient's Catalog No.</td></tr>
<tr><td colspan="4" rowspan="2">4. Title and Subtitle

Non-Contact Energy Harvesting for Rural Grade Crossings – Year 1</td><td colspan="2">5. Report Date
November 30, 2024</td></tr>
<tr><td colspan="2">6. Performing Organization Code</td></tr>
<tr><td colspan="4">7. Author(s):
Joseph A. Turner, Mohsen Amjadian, Carl Nelson, Prince Mensah</td><td colspan="2">8. Performing Organization Report No.
UTCRS-UNL-M1CY23</td></tr>
<tr><td colspan="4" rowspan="2">9. Performing Organization Name and Address
University Transportation Center for Railway Safety (UTCRS)
Mechanical and Materials Engineering
University of Nebraska-Lincoln (UNL)
W342 Nebraska Hall
Lincoln, NE 68588</td><td colspan="2">10. Work Unit No. (TRAIS)</td></tr>
<tr><td colspan="2">11. Contract or Grant No.
69A3552348340</td></tr>
<tr><td colspan="4" rowspan="2">12. Sponsoring Agency Name and Address
U.S. Department of Transportation (USDOT)
University Transportation Centers Program
1200 New Jersey Ave. SE
Washington, DC, 20590</td><td colspan="2">13. Type of Report and Period Covered
Project Report
June 1, 2023 – August 31, 2024</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code
USDOT UTC Program</td></tr>
<tr><td colspan="6">15. Supplementary Notes
This project is a collaboration between UNL and UTRGV</td></tr>
<tr><td colspan="6">16. Abstract

The network of US railroads often spans remote parts of the country that are sparsely populated. In these areas, rail grade crossings are much less likely to have warning lights or crossing gates primarily due to the lack of electricity. Such unprotected or passive crossings have the majority of the grade crossing fatalities and accidents. In order to reduce rail accidents, enhanced warning systems are needed at as many passive crossings as possible. We propose to create a new energy harvesting approach based on the motion of the wheels to generate sufficient power for an LED-based grade crossing warning system. Recent advances to create small and powerful magnets allow for the design of a non-contact power generation approach that is activated with each passing wheel. The feasibility of this approach has been shown in the first year of this project and an initial prototype will be designed and tested during the second year.</td></tr>
<tr><td colspan="3">17. Key Words
Electric power generation, passive grade crossings, highway railroad grade crossings, railroad safety</td><td colspan="3">18. Distribution Statement
This report is available for download from https://www.utrgv.edu/railwaysafety/research/mechanical/index.htm</td></tr>
<tr><td>19. Security Classification (of this report)
None</td><td colspan="2">20. Security Classification (of this page)
None</td><td colspan="2">21. No. of Pages
12</td><td>22. Price</td></tr>
</table>

Table of Contents

List of Figures

List of Abbreviations

AREMA	American Railway Engineering and Maintenance-of-Way Association
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
HRGC	Highway-Rail Grade Crossings
UTCRS	University Transportation Center for Railway Safety

Disclaimer

Acknowledgements

The authors wish to acknowledge the University Transportation Center for Railway Safety (UTCRS) for funding this project under the USDOT UTC Program Grant No 69A3552348340. The authors also wish to acknowledge the assistance received through partnership with faculty and students from the University of Texas Rio Grande Valley.

1. Introduction

A major goal of the UTCRS is devoted to a reduction in fatalities and overall accidents associated with rail transport. Rural rail crossings are often uncontrolled or "passive" which means that no signal lights or barriers are activated by an on-coming train. These types of crossings represent a large percentage of the total accidents that occur at roadway-rail intersections. The purpose of this project is to create an energy harvesting system that is located near the rail and is driven by the interaction with passing railcar wheels. Crossings with lighted signals require ~40 W of power [1], so the goal for this project is very clear. The large number of passive crossings is primarily due to a lack of power in such remote locations. The proposed research is focused on a new approach to power generation that would provide sufficient energy for one or more signaling modalities in order to have cost-effective solutions for such an important safety need. During this first year of the project, a computational model was created, and a laboratory experiment was designed. The goal was to show that sufficient power could be generated with this approach, and this objective was achieved. Now, this basic concept must be optimized and a prototype created in order to generate experimental data from field tests.

2. Summary

There is a high need for signal lights at passive rail crossings throughout the United States. Many prior designs required complex changes to the rail bed or were based on contact with components of the train. Our goal is to create a noncontact power harvesting system that can be easily integrated with most rail crossings. In the first year of the project, the feasibility of this approach was studied computationally and experimentally with a positive outcome.

3. Computational Model

In the first year of this project, the initial computation model was created with COMSOL to quantify the power that could be generated from a single magnet moving through a coil. First, the force generated by the interaction of a magnet with a steel plate was studied with a COMSOL model that was verified through a comparison with an analytical model as shown in Figure 1A. Then, the COMSOL model was used to create a model of a magnet moving within a coil (Figure 1B). That profile was then used to quantify the power that could be created for a given parameter set for a single railcar by a single magnet. The COMSOL model was used to estimate the shape of the input excitation in terms of a Gaussian pulse based on the force on the magnet for different positions of the plate (Figure 2A). This feasibility study suggests that the proposed approach could generate ~820 mW per railcar per magnet-coil device (Figure 2B).

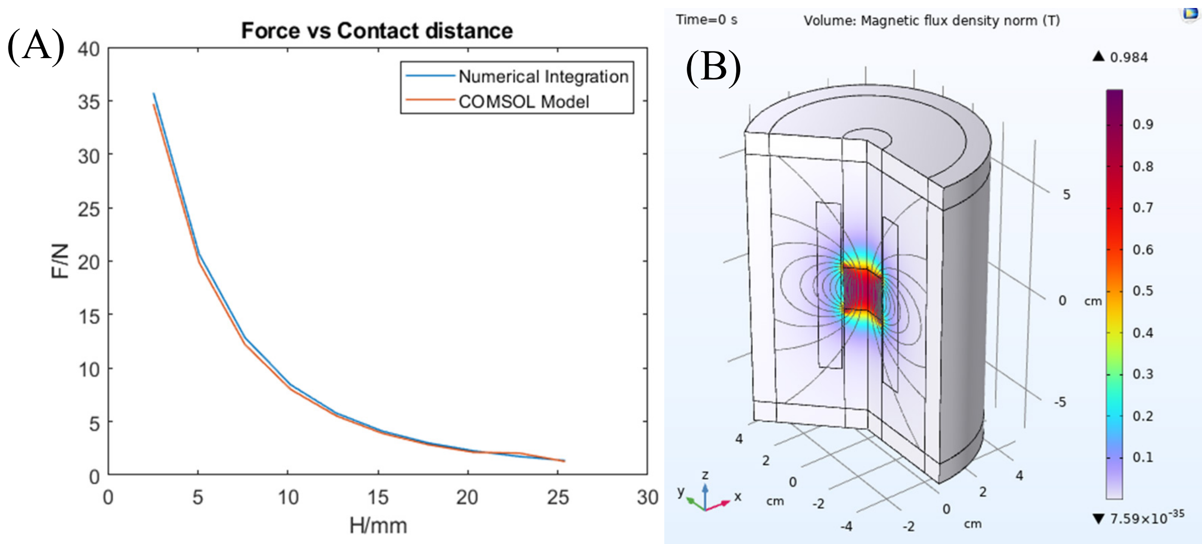

Figure 1. The initial COMSOL computational model.
This model was first verified relative to an analytical model [2] to show the force of a magnet as a function of the gap between the magnet and a large steel plate. The comparison shown in (A) allowed the COMSOL model to be expanded to include a magnet moving through a copper coil (B).

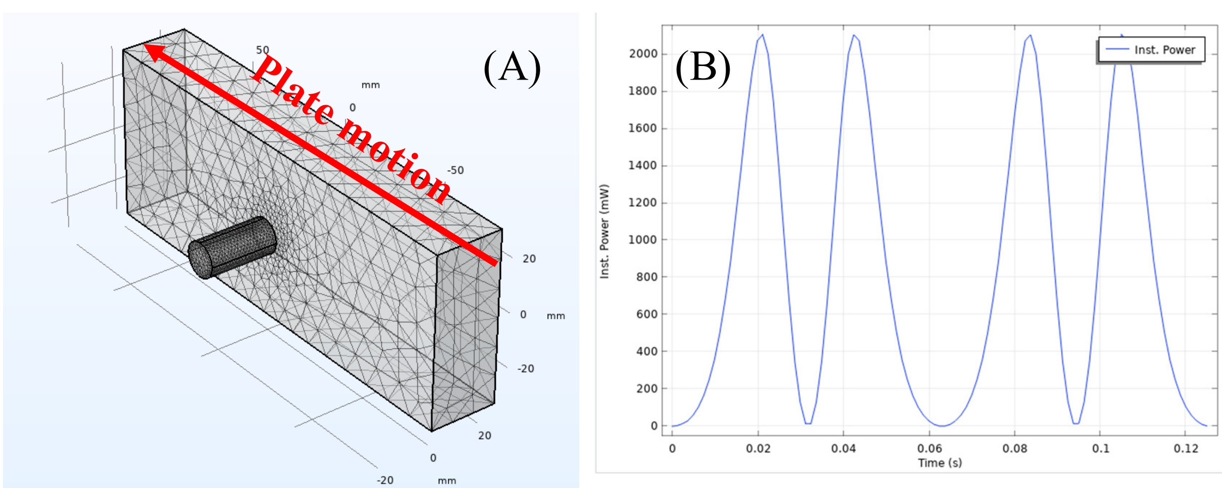

Figure 2. COMSOL model of a magnet with a moving steel plate.
This model was used to study the magnet response with respect to different plate speeds (A). The interaction between the plate and the magnet turned out to be nearly impulsive for typical railroad speeds. In this way, the motion of the magnet as excited by 4 wheels of a railcar could be estimated. Our results indicate average power of ~820 mW which is sufficient with respect to the feasibility test.

The COMSOL results also suggested that typical train speeds would result in force inputs on the magnet that were close to impulsive. This information was used to create an analytical model to study potential power generation based on design parameters and train speed. The impulse amplitude was defined in terms of the magnet-plate gap, and the power generation was defined relative to some selected coil parameters [3,4,5]. Some example results are shown in Figure 3. For these calculations, the mass-spring-damper was assumed to have a natural frequency of 15 Hz. Two different train speeds were assumed, 25 and 35 mph. The magnet velocity, induced voltage in the coil, and instantaneous power generated are shown as a function of time in Figure 3A, B, and C, respectively. As expected, the response characteristics are a function of the train velocity and the oscillator natural frequency.

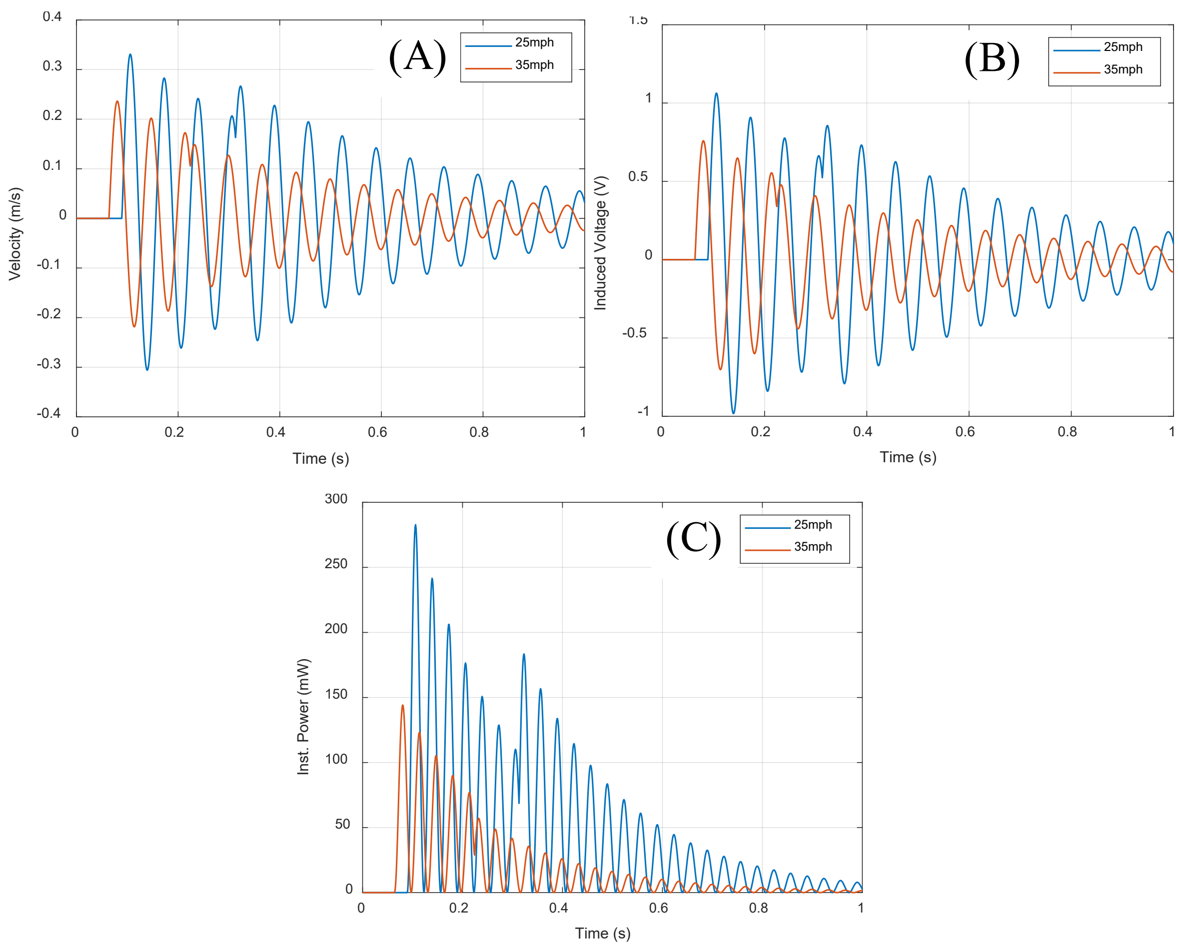

Figure 3. Example model calculations for an oscillator with a 15 Hz natural frequency. Assuming two different train speeds (25 and 35 mph), (A) shows the magnet velocity as a function of time and (B) shows the corresponding induced voltage in the coil. Finally, (C) shows the instantaneous power as a function of time. Clearly, the response is a function of the train velocity and the oscillator frequency.

To study these effects further, the average power generated was calculated for 4 different natural frequencies as a function of train speed, as shown in Figure 4. In this case, four different natural frequencies were used including 1, 5, 10, and 15 Hz. The average power generated has a strong dependence on the combination of natural frequency and train speed as expected. However, for a given rail crossing, the range of speeds will be known so that specific designs can be developed. Ultimately, a device that can adjust the natural frequency for incoming speed can be imagined.

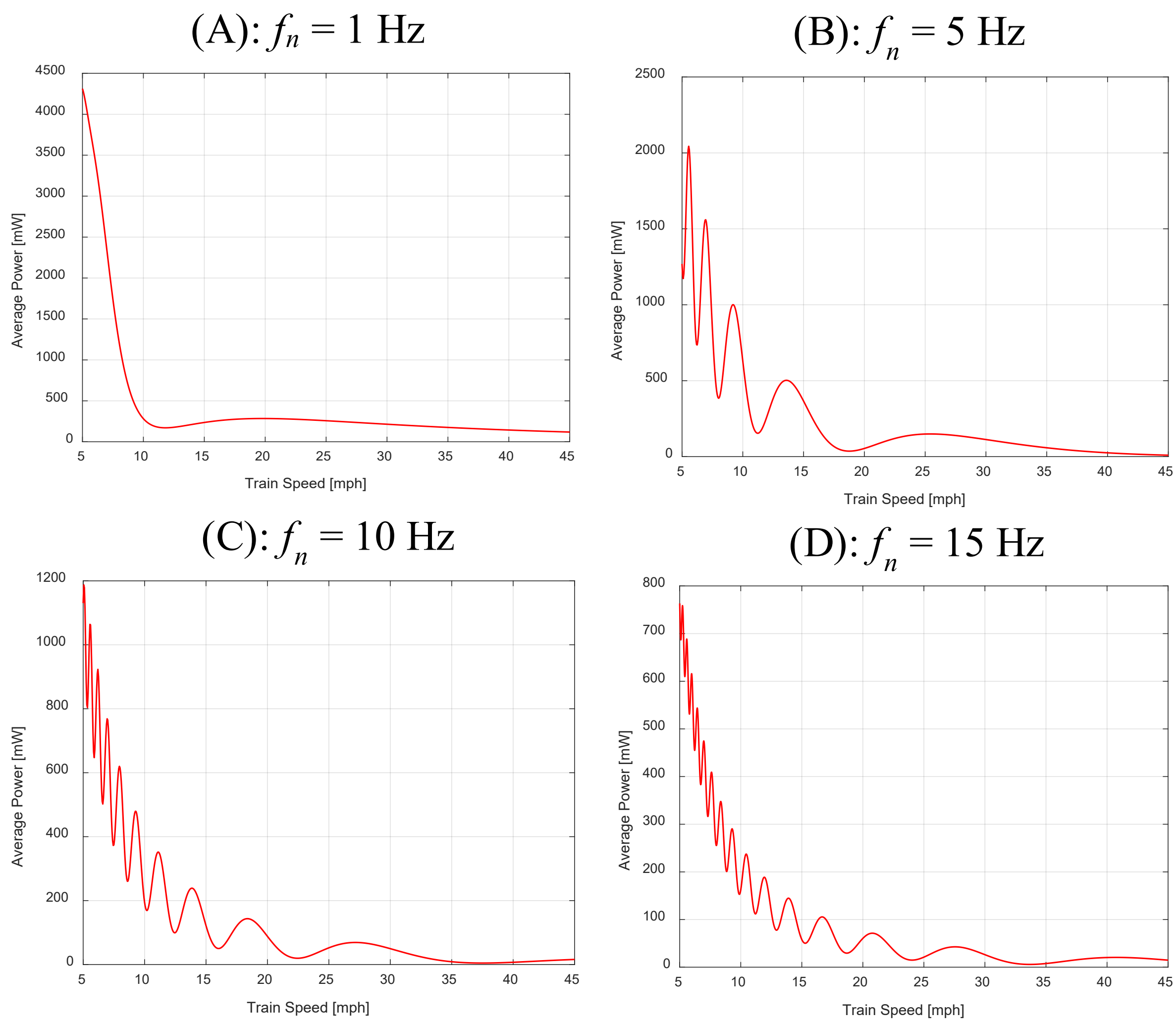

Figure 4. Average power generated as a function of train speed for 4 oscillator frequencies. Note that the y-axis values are different for each graph. The lowest natural frequency of 1 Hz in (A) shows a very steep drop in power but reaches a much higher value for slower speeds. The higher frequencies of 5, 10, and 15 Hz in (B), (C), and (D), respectively, show a similar drop as train speed increases. This model can be used to optimize the device design for optimal power generation. It may be possible to alter the oscillator characteristics dynamically for each train crossing.

Although the specifics of a given design still must be determined and optimized, these initial results suggest that this approach has merit. With the prospects for sufficient positive energy, an initial laboratory experiment was created to show experimental viability.

Experiments

An initial experiment was designed and created as shown in Figures 5 and 6. A magnet was mounted on a thin beam made of spring steel. In this mass-spring oscillator, the beam plays the role of the spring and the magnet is the mass. As the magnet moves within the coil, a voltage is generated. A LabVIEW code was written to integrate with a National Instruments data acquisition system to collect data from the coil voltage. Example time-domain responses are shown in Figure 6. These responses were excited by hand to demonstrate that the data collection system was working correctly. The experiment was designed to be flexible so that different beams can be used to change the natural frequency of the system. The bending stiffness is controlled by the length, width, and thickness of the beam. The next step is to install a rail system above the magnet. A steel plate will be mounted on the rail. In this way, the vibrations can be excited from the plate motion. This laboratory experiment will be modeled with COMSOL to establish a strong connection between the model and experiments.

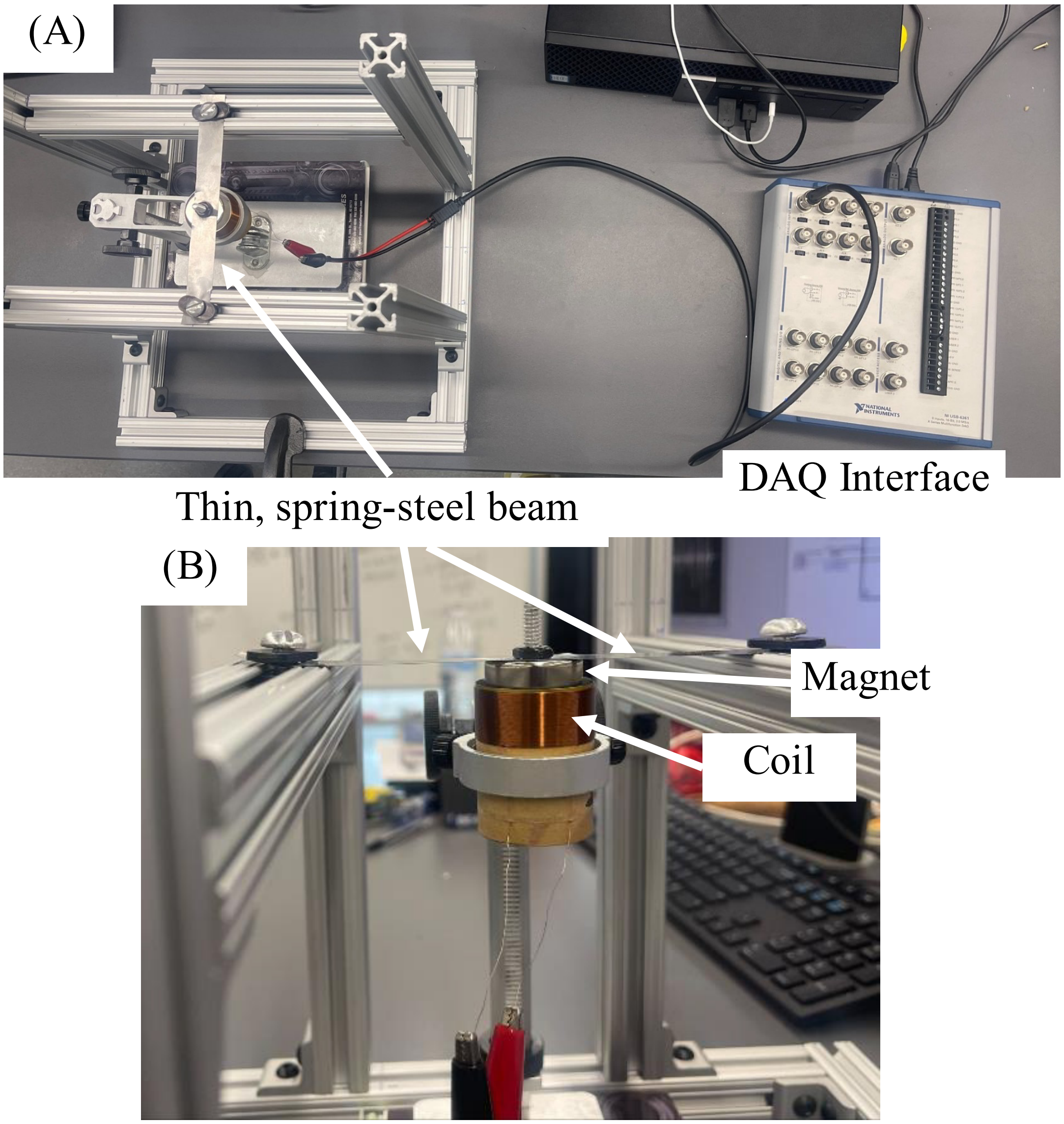

Figure 5. Initial experimental setup to explore feasibility.
The top view in (A) shows the thin beam that is used as the spring for the oscillator. The data acquisition (DAQ) interface is connected to the coil to measure voltage as a function of time. The side view in (B) shows the magnet which oscillates within the coil to generate power.

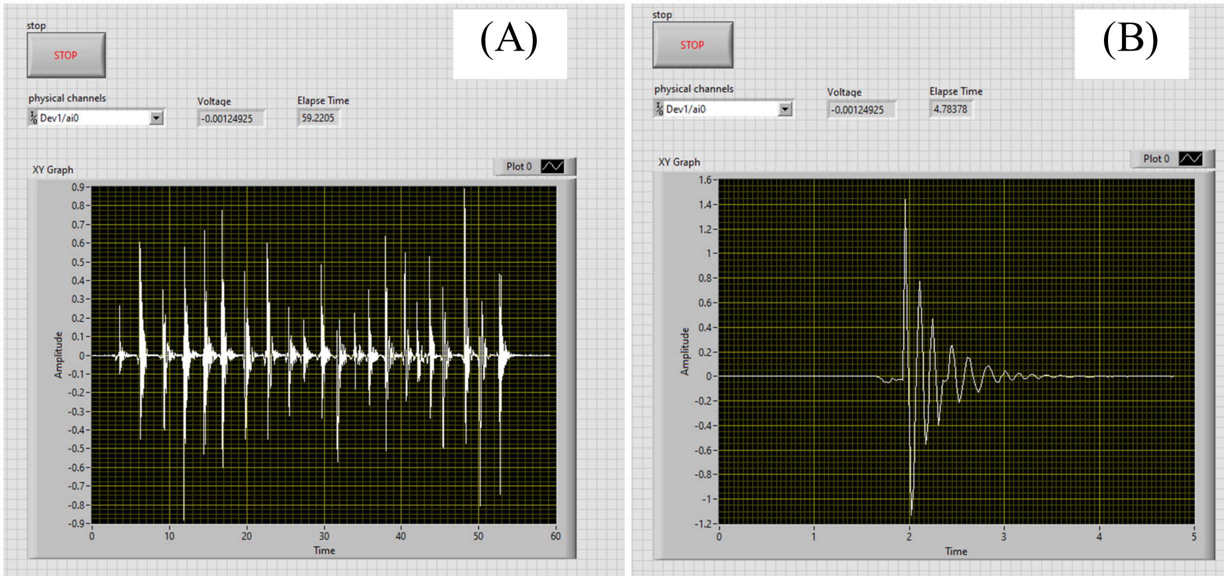

Figure 6. Example coil voltage responses from the experiment shown in Fig. **5**. The result in (A) is several consecutive excitations of the magnet within the coil. The result shown in (B) is a single oscillation of the coil response to the vibrating magnet.

4. Conclusions and Future Work

The computational model and preliminary experimental data have proven the viability of this approach for power generation. The non-contact approach has great value for field implementation but there is much more research to accomplish. In the second year of this project, the experiments will be expanded to include a moving plate so that the corresponding power generation data can be collected. Then, the specific experiments will be modeled with COMSOL. In this way, the model can be validated and several of the unknown parameters for the model can be defined in order to match the model with the experiments. Finally, our main objective for Year 2 is to design and manufacture an experimental unit for field testing. Our goal is to collect field test data before the end of the second year. A patent disclosure will be submitted soon.

5. References

[1] Institute of Transportation Engineers. (n.d.). Grade crossing safety: Section 4B. Retrieved September 29, 2024, from https://toolkits.ite.org/gradecrossing/sec04b.htm.

[2] González, M. I. (2016). Forces between permanent magnets: experiments and model. European Journal of Physics, 38(2), 025202.

[3] Amjadian, M., Agrawal, A. K., & Nassif, H. H. (2022). Development of an analytical method for design of electromagnetic energy harvesters with planar magnetic arrays. Energies, 15(10), 3540.

[4] Halim, M. A., Cho, H., Salauddin, M., & Park, J. Y. (2016). A miniaturized electromagnetic vibration energy harvester using flux-guided magnet stacks for human-body-induced motion. Sensors and Actuators A: Physical, 249, 23-31.

[5] Bijak, J., Trawiński, T., & Szczygieł, M. (2022). Simulation and investigation of the change of geometric parameters on voltage induced in the energy harvesting system with magnetic spring. Electronics, 11(10), 1639.