Design of Regenerative Damper for Energy Harvester in Playground Seesaw

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***Abstract*—Increasing demand for electricity, coupled with a greater understanding of the environmental impact of conventional power generation, has led to growing research interest on alternative energy sources. Energy harvesters based on playground equipment, such as the seesaw, has been proposed as an alternative method to generate electrical power. In this study, a new harvesting mechanism based on the electromagnetic regenerative damper is proposed as an alternative method to harness energy from a playground seesaw. The proposed design is intended for higher power output and efficiency, smaller dimensions, and ease of installation on a seesaw. Lab tests have been carried out to characterize the proposed design experimentally. The energy harvesting (stroke velocity-to-voltage) coefficient for the proposed seesaw-based energy harvester is obtained as 73.18 V/(ms^{-1}). The regenerative damper is capable of producing up to 110 mW of power at 9.34% efficiency.**

Keywords—playground seesaw, alternative energy, energy harvesting, regenerative damper

I. INTRODUCTION

Energy, in particular electrical energy, is the driving force of growth and development of modern society. Demand for electricity increases along with the technological, economic, and societal development of a country. Thus, it is imperative to develop alternative sources and methods of electrical power generation.

Harnessing waste energy from playground equipment has recently been proposed, either on laboratory and practical scales. Playground activities produce a large amount of wasted energy due to the energetic nature of their activities. Pandian [1] notes that playground activities potentially produce a significant amount of energy that can be stored and utilized as a power source for simple electrical equipment. Various playground equipment, such as the seesaw, swing ride, and merry-go-round, have been used to harness energy, both on a laboratory and commercial scale [1]–[9]. The energy-generating playground can also be used as a way to educate children about renewable energy, which has the potential to improve student engagement by providing a physical medium to interact with and observe [10].

This study focuses on the seesaw, playground equipment commonly found in schools and public parks. The seesaw play activities provide significant potential for energy harvesting as it involves active movements. It also combines the energy of two people, increasing the potential energy of the system [5].

Proposed designs for harvesting energy from a playground seesaw have overwhelmingly use pneumatic mechanisms; these include designs by Pandian [1], Abad et al. [3], and Banlawe and Acosta [4], among others. Pneumatic seesaw energy harvester uses an air pump below the seesaw beam to dissipate the seesaw's excess energy and power a pneumatic motor, which is used to generate electricity by coupling it with an electric generator [1], [3]. Khan and Saeed proposed a gear transmission mechanism to harvest energy from a playground seesaw. In this design, the rotation of the seesaw's pivot as the seesaw oscillates also rotates an electric generator through a sprocket and chain or gear train, producing electricity [5]. The design was realized in [6], using a ratchet mechanism to constrain the rotation of the shaft in one direction only.

While these designs were viable, there are still several issues that warrant attention. Researchers have consistently found that pneumatic seesaw energy harvesters suffer from leakage and fluid friction, expensive components, and dirty air. Pandian also notes that power conversion is hindered by unregulated pressure [1], [3]. Pneumatic systems also require large components, resulting in unwieldy systems that awkwardly integrate with a typical seesaw. The system proposed in [3], for example, require the entire contraption to be raised from the ground on a platform, while designs used in [1], [4] utilize large tanks put to the side of the seesaw. Gear transmission-based seesaw energy harvester would require large transmission ratio, and thus large gears or sprockets, to effectively run the motor, as a seesaw produce only minimal angular displacement. The ratio resulted in low and irregular angular velocity, reducing efficiency and component lifespan. These problems highlight the opportunity to improve the seesaw energy harvester, particularly by exploring alternative mechanisms to harvest energy from a seesaw.

This study proposes an alternative harvesting mechanism based on the electromagnetic regenerative damper. The regenerative damper is a type of energy harvester used to harness energy dissipated during the damping of vibrating or oscillating structures by converting linear oscillatory motion into rotational motion of a generator shaft, and subsequently into electricity. The electromagnetic regenerative damper has been successfully utilized to harness energy from various sources, such as vehicles [11]–[14], bridge structure [15],

[16], wave-energy converter [17], [18], and many others. This mechanism has several potential advantages, most notably high energy yield, relatively high efficiency, and compact size. Regenerative dampers are typically used in structures with a high-frequency-low-amplitude oscillation profile. In contrast, this study proposes the research and testing on its use with a low-frequency-high-amplitude oscillation profile typical of a seesaw play activity.

This study presents the design, implementation, and testing of the regenerative damper for energy harvester in playground seesaw. These include the mathematical model characterizing the dynamics of the system, the prototyping, and the test of performance in the laboratory setting. These yield in the feasibility of a regenerative damper-based seesaw energy harvester and the identification for the opportunity for improvement.

The presentation is organized as follows. Section II introduces a conceptual model describing the processes involved in seesaw energy harvesting. These are followed by the proposed design and working principles of the regenerative damper-based energy harvester in Section III. These principles are represented in a mathematical model in Section IV. Section V follows by reporting prototyping and laboratory testing. Finally, Section VI concludes the findings in this study.

II. PRINCIPLES OF SEESAW ENERGY HARVESTING

When two people play a playground seesaw, the beam undergoes oscillatory motion. Seesaw energy harvesters utilize this oscillatory motion to obtain useful energy from this activity. To understand how energy can be harnessed from a seesaw, this Section describes the conceptual model of seesaw operation.

The oscillatory motion of seesaw play activity is started when the first player pushes on the ground, exerting an input force on the seesaw beam. Assuming players' masses are equal, the motion rotates the beam away from the first player. Different masses would create a resultant force acting on the beam, accelerating or decelerating the rotation. As the other end of the beam reaches the ground, the movement stops. Typically, a spring or cushion installed below the beam or the player's legs would dampen the movement by absorbing excess energy until the seesaw stops moving. The second player would then push the ground and exert a force on the beam, starting the process all over again. The net effect of this process is an oscillatory motion of the seesaw beam.

The above process infers that energy is wasted during play activity. The players expend energy as they start the movement, but then energy is dissipated into the environment during the damping process. A playground equipment-based energy harvester seeks to convert this excess energy into usable forms of energy instead. The harvester is installed in points where damping or friction happens, usually below the beam, replacing the spring or cushion. In energy harvesters that convert waste energy into electrical energy, the damping or friction element is shifted to an electromagnetic actuator (e.g., generator), producing electrical current.

Harnessing energy from playground activities shows promise as an alternative energy source due to the high energy involved in children's play activities. As outlined in [19], playground activities expend on average 336 W (5.4 child metabolic equivalents/METs) of power. If even just a fraction of this available energy is harnessed, a significant amount of energy can be gained. This concept has been used to supply electrical loads for a variety of environments, such as lighting loads in schools, parks, or remote locations [2], [3], [9].

III. PROPOSED DESIGN OF SEESAW ENERGY HARVESTER

A. *Regenerative damper*

Since the current seesaw energy harvester designs pose several shortcomings that reduce their performance, this study seeks to utilize electromagnetic regenerative damper design to alleviate some of those problems.

An electromagnetic regenerative damper utilizes relative linear motion between a piston and a cylinder frame to obtain useful energy from oscillatory motion by converting it to rotational motion [11], [20]. The regenerative damper is installed underneath the seesaw beam, similar to pneumatic mechanisms. It moves up and down along with the beam as the seesaw is played. The linear motion is amplified and converted to rotary motion via a series of transmission mechanism to rotate an electric generator. Thus, the system directly converts linear motion to electricity as it operates.

In contrast to pneumatic systems which absorb energy via viscous (fluid) damping and stores energy in the form of compressed air, electromagnetic regenerative damper presents an electric damping element, through the effect of an electromagnetic actuator, as the energy absorber. The regenerative damper can store energy temporarily through two means: mechanically via inertia (such as through a flywheel mechanism), or electrically via a battery. The flywheel and battery combination benefits over compressed air storage, namely that they are generally more compact (have higher energy density), do not pose leakage issues, and do not require complex control mechanisms (e.g., valves).

B. *Design of Regenerative Damper-based Seesaw Energy Harvester*

Fig. 1 shows the proposed design for the seesaw energy harvester. The proposed design consists of a set of rack-pinion, a transmission shaft, and three sets of bevel gear operating in a “freewheel” configuration. The rack-pinion and bevel gear mechanism is chosen for its simplicity, component availability and cost, and compatibility with long piston stroke (as opposed to vehicle shock absorbers, which generally have shorter stroke amplitude.)

Installation is done by securing the moving part (the piston) to the beam and the stationary part (the cylinder frame) to the ground. The working principles of the regenerative damper are as follows. When the seesaw beam oscillates, the piston and rack move up and down, rotating the pinion gear in the process. Two sets of bevel gear are attached to the transmission shaft using a one-way clutch. The clutch allows the gears to engage and rotate only in one direction and disengages when the shaft rotates the other way. This study installs the two gears in opposite directions, resulting in constant engagement of just one gear with the shaft. Both gears interlock with the third bevel gear. The latter connects to the generator shaft and rotates the shaft unidirectionally. Hence, the oscillatory motion converts unidirectional motion. Fig. 2 illustrates the working principle described above.

The freewheeling and motion rectification effect of the transmission poses several advantages. Motion rectification has been shown to reduce impact force and, thus, component

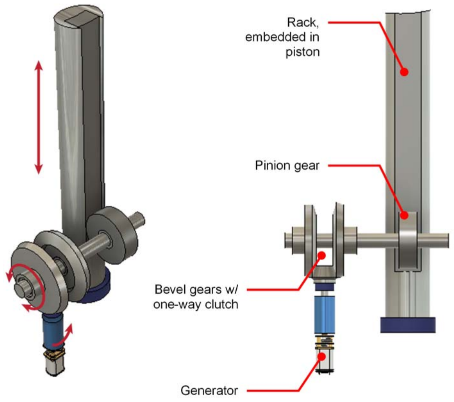
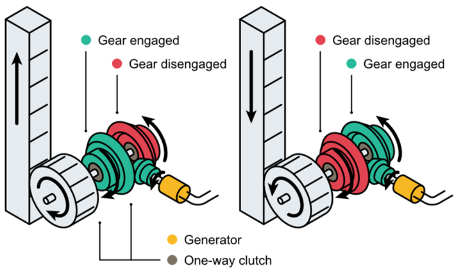


Fig. 1 General structure of the proposed seesaw energy harvester design. The rack and piston are housed inside a cylinder frame, while the transmission components (gears and generator) are housed outside the frame and inside a gearbox.



(a) (b)

Fig. 2 Working principle of the proposed design.

fatigue [13]. Motion rectification also means the generator will always produce positive voltage, eliminating the need for an electric rectifier. The freewheel mechanism enables gears and generator to coast instead of slowing down and stopping every time the seesaw beam and piston changes direction. This approach improves generator efficiency and power output, reduces energy loss from transmission slowdown, as well as enables the use of flywheel.

Fig. 3 shows a prototype built according to the design principles and objectives described above. In general, the prototype consists of four main parts: (1) cylinder frame, (2) cylinder piston, which contains the rack, (3) transmission module, and (4) generator. A pinion and three bevel gears are used in the transmission module; the pinion interlocking with the rack, while the bevel gears move the generator shaft. Unlike most regenerative damper design used in vehicles, the transmission components are located outside the cylinder frame, as the seesaw does not pose size and location constraint on the damper, allowing for a more compact frame. This design also enables the rack to be centered on the piston, as opposed to offset from the center as commonly found in vehicle regenerative dampers, so force moment on the piston and rack and excessive rack bending can be reduced.

TABLE I. MAJOR COMPONENTS OF THE HARVESTER SYSTEM

Rack	M2, face width 18 mm
Pinion	M2, ⌀38 mm (pitch), width 12 mm
Driver bevel gear	35 teeth
Pinion bevel gear	13 teeth
Clutch	HF1012 one-way needle clutch
Generator	N20 micro motor, DC 6 V/100 rpm

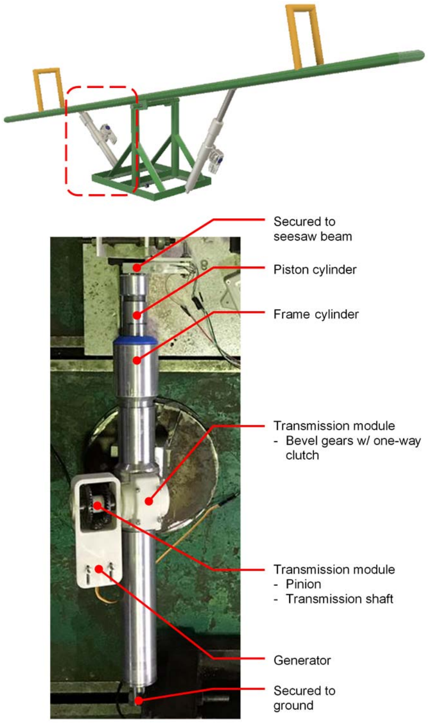


Fig. 3 Built prototype and installation illustration of the seesaw energy harvester.

Table I provides the major parts used in the prototype and its specifications. The components are chosen based on the expected operating conditions and desired parameters as outlined above, ease of use, availability, and affordability in the market, and design compatibility, particularly with regards to dimensions.

IV. MODELING AND ANALYSIS

This Section provides a derivation of the mathematical model and the analysis of characteristics of the proposed energy harvester system. Fig. 4 presents the model diagram of the system. The system is represented by transmission mechanisms consisting of a rack-pinion transmission, a bevel gear set operating in a freewheel configuration, and an electric generator. The freewheel mechanism is represented by a gear transmission whose transmission ratio is defined by a nonlinear equation,

$$N_B'(\omega_S) = \begin{cases} N_B \operatorname{sgn}\omega_S\,, & \omega_S \geq \omega_{Th} \\ 0, & \omega_S < \omega_{Th} \end{cases} \qquad (1)$$

Here, N_B is the gear ratio of the driver (large) gear, and the pinion (smaller) gear and ω_S and ω_{Th} each represent the shaft and threshold angular velocity. This behavior is caused by the one-way clutch, which locks and rotates when the shaft velocity is above a threshold velocity. The signum represents the fact that the gear configuration will always cause the pinion gear to rotate in one direction. This threshold value is determined by the mechanical design of the transmission, particularly the clutch's fitting, where the clutch fits well with the gear and shaft, and the threshold is minimal, the transmission ratio becomes $N_B \operatorname{sgn}\omega_S$.

A. Energy Harvesting Characteristics

The relationship between the generated current i and piston displacement ds/dt can be described by the ordinary differential equation (2),

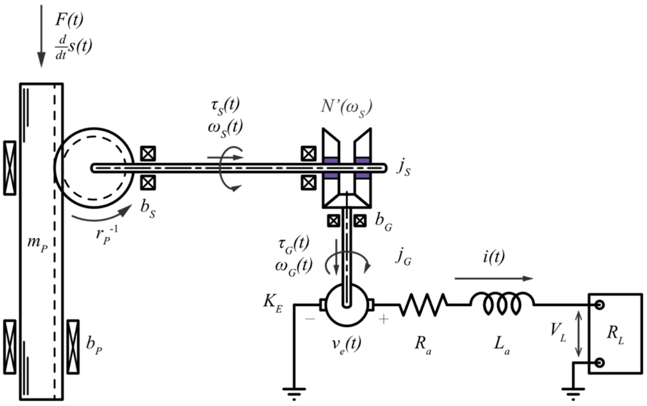


Fig. 4 Model diagram of the harvester system.

$$\frac{di}{dt} = -\frac{R_a+R_L}{L_a}i + \frac{1}{L_a}\frac{K_E N_B'(\omega_S)}{r_P}\frac{ds}{dt} \tag{2}$$

It is predicted that the dynamics of the seesaw energy harvester (2-3 s oscillation period for a typical seesaw play) is several orders of magnitude slower compared to the circuit (less than 0.1 s for a typical generator). Using this assumption, the transient response caused by the inductance is negligible. Thus, (2) can be simplified into

$$i = \frac{1}{R_a+R_L}\frac{K_E N_B'(\omega_S)}{r_P}\frac{ds}{dt} \tag{3}$$

Expressing (3) in terms of voltage, which are easier to measure during experiments,

$$V = \frac{R_L}{R_a+R_L}\frac{K_E N_B'(\omega_S)}{r_P}\frac{ds}{dt} \tag{4}$$

The term $\frac{R_L}{R_a+R_L}\frac{K_E N_B}{r_P}$ is defined as the energy harvesting coefficient (EHC). This coefficient is measured in V/(ms^{-1}) and represents the voltage generated for a certain input velocity.

The model described above shows that the stroke velocity of the piston directly determines the generated voltage. Hence, designing the proper value of the mechanical parameters of the system can increase the generated voltage. These include the design of the gear transmission ratios r_P and N_B, and the characteristics of the generator, the EMF constant K_E and internal resistance R_a.

B. Dynamic Characteristics of the System

This study model the energy harvester as a force equation, involving the equivalent inertia (mass), damper, and transmission mechanisms as follows

$$F_D = M_{eq}\frac{d^2x}{dt^2} + B_{eq}\frac{dx}{dt} + \frac{1}{\eta_{123}}\frac{K_E N_B'(\omega_S)}{r_P}i \tag{5}$$

$$M_{eq} = m + \frac{1}{\eta_1}\left(\frac{1}{r_p}\right)^2 j_s + \frac{1}{\eta_{12}}\left(\frac{N_B'(\omega_S)}{r_p}\right)^2 j_g$$

$$B_{eq} = b_p + \frac{1}{\eta_1}\left(\frac{1}{r_p}\right)^2 b_s + \frac{1}{\eta_{12}}\left(\frac{N_B'(\omega_S)}{r_p}\right)^2 b_g$$

M_{eq} and B_{eq} are the equivalent mass and damping of the system, respectively. These parameters are determined by the inertia (mass/moment of inertia) and damping of the piston (m, b_P), the transmission shaft (j_S, b_S), and the generator shaft (j_g, b_g). Assuming the generator circuit has negligible transient characteristics, (5) can be simplified as follows:

$$F_D = M_{eq}\frac{d^2s}{dt^2} + \left[B_{eq} + \frac{1}{R_a+R_L}\left(\frac{K_E N_B'(\omega_S)}{r_P}\right)^2\right]\frac{ds}{dt} \tag{6}$$

Equation (6) shows that electrical damping (the $1/(R_a+R_L)$ term) and the generator mass and damper determine the dynamic characteristics of the energy harvester system. A factor of $(K_E N_B / r_P)^2$ amplifies the generator mass and damper if the bevel gear and generator gearbox have high transmission ratios. The mass and damping of other components have less significance in determining the dynamic characteristics unless the rack-pinion and other transmission components are significantly larger than the generator.

The source of input force F_D is the mass of the players and the force they exerted. Hence, the electrical damping represents harvestable energy for a given force. Therefore, mechanical inertia and damping (friction) should be minimum to increase the efficiency of the system.

V. LAB TEST AND ANALYSIS

Fig. 5 shows the experimental setup to test the performance of the seesaw energy harvester. A customizable-frequency displacement tester is used to mimic a measured oscillatory stroke to the seesaw beam. Measurements were done using a force sensor (load cell), linear variable differential transformer (LVDT), an external load (a power resistor) connected to the generator, and an oscilloscope. During the experiment, the characteristics of the energy harvester were tested for a range of excitation periods and load resistance. The energy harvesting characteristics of the prototype are presented next.

A. Qualitative Observation

Fig. 6 shows a sample of the test result with test parameters T = 3.11 s, A = ±45 mm, and R_L = 216 Ω. Several characteristics of the proposed design can be observed from this result. First, the freewheel mechanism converts the seesaw's oscillatory motion to the generator's unidirectional rotation. The conversion is shown by the output voltage, which remains positive throughout the test. As explained in Section III, this mechanism reduces impact force and component fatigue, as well as eliminating the need for electrical rectification.

Second, the result suggests that the dominant element of the system's dynamic characteristic is the electrical and mechanical damping, with inertial (mass) element relatively insignificant. The latter is indicated by no observable phase shift (i.e., delay) on the force and voltage output relative to the stroke velocity, meaning that no first-order response appears. Since the equivalent mass governs the first-order response (see (6), noting that the input is stroke velocity ds / dt), this means that the mass is negligible compared to the damping elements. The latter is due to the small size and high transmission ratio of the generator and transmission components, reducing mass/moment of inertia while increasing friction.

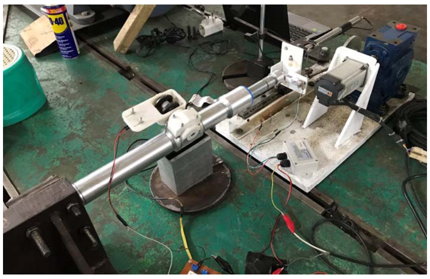


Fig. 5 Experiment setup.

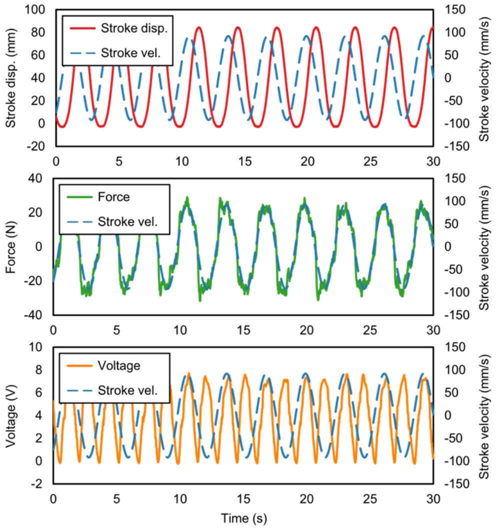
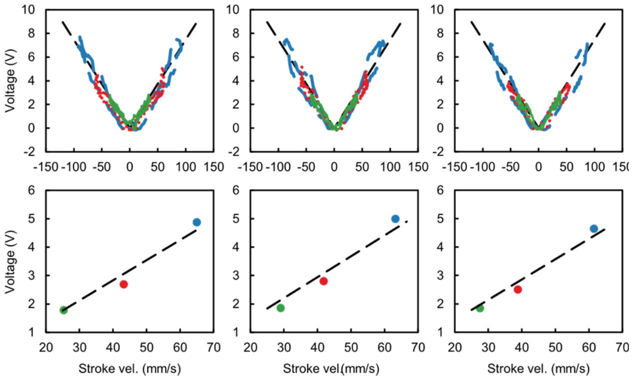


Fig. 6 Sample of experiment result. $T = 3.11$ s and $R_L = 216$ Ω.

Third, no delay is observed between the force and voltage outputs, and the stroke velocity also shows that the threshold velocity, as defined in (1), is also negligible. The existence of the threshold represents a significant leveling off of force and voltage around zero stroke velocity. It indicates that all transmission elements are disengaged (and hence no voltage would be produced) until the stroke velocity is high enough to engage the clutch again. The previous prototype of the design shown this problem, where the clutch is not adequately secured to the gear. The current prototype thus shows significant improvement and that the transmission ratio of the bevel gears can be approximated as $N_B \operatorname{sgn} \omega_S$.

B. Energy Harvesting Characteristics

The energy harvesting characteristics of the prototype and the respective performance are represented by the energy harvesting coefficient described in Section IV. The relationship between the output voltage and stroke velocity for various load resistance is given in the top charts of Fig. 7. The results show that the generated voltage closely follows the (absolute value) of the stroke velocity, with little hysteresis, indicating that the system best approximates a zero-order system, and transient characteristics are negligible (i.e., the inertia/mass of the system is negligible relative to the force and resistance/friction involved and thus does not produce a higher-order system). This observation is consistent with the analysis given in Section IV and reinforces the results of Section V-A.



216 Ω 648 Ω 1080 Ω

Fig. 7 A sample of the voltage–stroke velocity relationship for various input period and load resistance, instantaneous (top) and rms (bottom) values.

TABLE II. ENERGY HARVESTING COEFFICIENT AT VARIOUS LOAD

Load (Ω)	Energy harvesting coefficient. (V/ms^{-1})
216	70.84
432	73.11
648	73.55
864	76.98
1080	71.44
Average	***73.18***

From these data, a coefficient is obtained through linear regression on the data points where the load resistance is the same, for a total of five obtained coefficient values. Averaging these results yield the final energy harvesting coefficient value for the prototype. Table II shows the computed energy harvesting coefficient. The average value is 73.18 V/(ms^{-1}). This would produce 5–10 V of electricity for a typical seesaw play activity. This value is affected by the load resistance (see (4)). However, for a higher ratio of load resistance to the generator's internal resistance (as is the case in this study), the value does not differ significantly.

C. Harvester Performance and Efficiency

The generated power and overall efficiency for all test parameters are shown in Fig. 8. The input and output (generated) power are calculated from the force-displacement data and the voltage-resistance data, respectively. The efficiency is measured by taking the ratio of generated power to input power. The result shows that the prototype benefits from higher stroke velocity, with a maximum efficiency of 9.34% when T = ~3 s. Efficiency drops by 4.56 p.p. when the oscillation period is dropped to ~5 s. It stays around the same value when the period is dropped further to ~7 s. These drops are possibly due to significant friction in the gears, preventing smooth movement of the transmission components at low velocity. The variable load test results show that the efficiency drops by 3.56 p.p. from 216 Ω loads to 432 Ω loads. This condition is consistent with (6), which suggests that electrical damping (that corresponds to the power output of the generator) is inversely proportional to the load resistance R_L.

This observation shows that the damper performs better for faster excitation periods and lower load resistance. The period $T = {\sim}3$ s and load resistance $R_L = 216$ Ω yield the best performance, in which 110.00 mW of power is generated at 9.34% efficiency. While this represents an improvement over previous research, the efficiency is still relatively low. Qualitative and quantitative analysis suggests that mechanical damping element, e.g., friction on bearing and transmission elements, remains the dominant source of loss in the system. Other factors relating to design, such as misalignment on the transmission components, also contribute to the inefficiency.

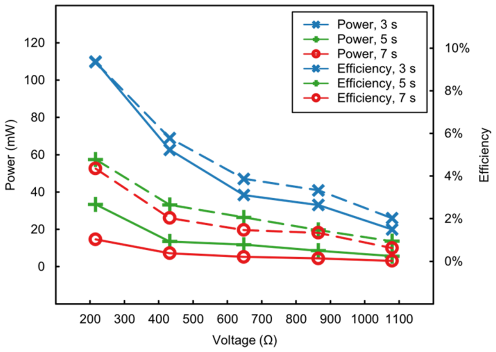


Fig. 8 Power and efficiency values obtained for the prototype.

D. Analysis

The prototype shows the capability of harvesting energy from a simulated seesaw play input. It produces up to 110 mW of power at 9.34% efficiency. The design represents an improvement over pneumatic harvesters at around 1.6% efficiency [1], as well as the gear transmission mechanism, producing 14 mW of power at 9.35% efficiency [6]. It should be noted that the power output reported for pneumatic designs usually indicates instantaneous power, as opposed to the average power reported in this study, and does not take into account the time taken to fill the air tanks.

The prototype works best at higher stroke velocity ($T \leq 3$s). Higher performance can be achieved at lower load resistance. As per (6), increasing stroke velocity and lowering load resistance increases the damping force, and thus the prototype needs strengthening to increase the force. Considering that typical seesaw play activities produce an oscillation period of 2.5–3 s, an improved prototype coupled with a power management circuit that has a low input impedance can yield much higher power.

This study reports the power output for only one damper. In an actual seesaw, two dampers would be used (one under each side), and so even higher power would be produced. The electromagnetic regenerative damper design thus shows promising potential for harnessing energy from seesaw play, especially when the electrical energy is accumulated over long periods of seesaw play.

VI. CONCLUSION

A prototype of the seesaw energy harvester system based on a regenerative damper has been developed, and its performance has been tested. The system consists of a transmission system based on a rack-pinion, gear sets, and a generator. The regenerative damper with a freewheel mechanism manages to convert the oscillatory motion of a seesaw beam to electrical power. Lab tests have shown that the system manages to produce consistently positive voltage.

The design is characterized by an energy harvesting coefficient, the ratio between the stroke velocity of the piston and the generated voltage, which is 73.18 V/(ms^{-1}). The prototype manages to produce up to 110 mW of power at 9.34% efficiency, an improvement over previous seesaw energy harvester designs, having smaller dimensions, and ease of installation on a seesaw.

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