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Energy-Harvesting Shock Absorber with a Mechanical Motion Rectifier

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Abstract. Energy-harvesting shock absorber is able to recover the energy otherwise dissipated in the suspension vibration while simultaneously suppress the vibration induced by road roughness. It can work as a controllable damper as well as an energy generator. An innovative design of regenerative shock absorbers is proposed in this paper, with the advantage of significantly improving energy harvesting efficiency and reducing the impact forces caused by oscillation. The key component is a unique motion mechanism, which we called "mechanical motion rectifier", to convert the suspension's oscillatory vibration into unidirectional rotation of the generator. An implementation of motion rectifier based harvester with high compactness is introduced and prototyped. A dynamic model is created to analyze the general properties of the motion rectifier by making analogy between mechanical systems and electrical circuits. The model is capable of analyzing electrical and mechanical components at the same time. Both simulation and experiments are carried out to verify the modeling and the advantages. The prototype achieved over 60% efficiency at high frequency, much better than the conventional regenerative shock absorbers in oscillatory motion. The motion rectifier based design can also be used for other applications of electromagnetic vibration energy harvesting.

1. Introduction

Vehicles consume over 40% of petroleum in US and the exhaust causes more air pollution than anything else [1]. The improvement of the fuel efficiency is always an important issue. Considering only 10-16% of fuel energy is used to actually drive vehicles - to overcome the resistance from road friction and air drag [2], the energy dissipated by shock absorbers is a source worthy of attention for energy recovery. Recently research also indicates that vehicle suspensions have substantial influence on the fuel efficiency [3].

Regenerative shock absorbers have been developed for more than two decades to recover the kinetic energy dissipated by the traditional oil shock absorbers. Many researchers explored different principles and designs of regenerative vehicle shock absorbers, which can be classified in two main categories. The first category is based on the specialized design of linear generator, which generates power from the relative linear motion between magnets and coils. Karnopp[4] first proposed an idea of designing mechanical dampers with controllable damping coefficients using permanent magnet linear motors for the application of vehicle suspensions. Suda et al[5] used a linear DC generator to harvest vibration energy for a active control system and developed a hybrid suspension system. Goldner et al[6] designed an electromagnetic shock absorber and analyzed its effectiveness with lab experiments. Ebrahimi et al[7] explored the feasibility of an electromagnetic shock absorber for the application of a sensor/actuator. Zuo et al[8] designed and prototyped a linear electromagnetic energy harvester capable of generating more than 16-64 watts of energy from all four shock absorbers with 0.25-0.50 m/s RMS suspension velocity. These designs are mainly used for energy harvesting, and they can also be used as actuators for active control or semi-active control. Martins et al[9] validated the feasibility of electromagnetic active suspensions, in which he made some improvement in power electronics, permanent magnetic materials and microelectronic systems. Chen and Liao[10], and Sapinski[12] developed linear electromagnetic energy harvesters to power MR dampers for the purpose of active/semi-active control.

Besides the linear regenerative shock absorbers, the second category is to convert the linear suspension vibration into oscillatory rotation and use rotational permanent magnetic DC or AC generators to harvest energy. Those mechanical mechanisms include ball screw, rack and pinion, and hydraulic transmission. Gupta et al[13] did a comparative study between a linear and a rotary shock absorbers and found that the rotary shock absorber could have larger energy density. Zhang et al[14] developed and prototyped a regenerative shock absorber based on ball-screw mechanism and validated it with full-vehicle experiments in lab. Avadhany et al[15] patented one type of rotary regenerative shock absorber based on hydraulic transmission. And Choi et al[16] combined the controllable electrorheological (ER) damper with a rack-pinion based regenerative shock absorber to set up a self-powered controllable suspension. Zhang and Zuo[17,18] designed a retrofittable regenerative shock absorber based on rack and pinion mechanism and tested it in lab. Li et al[19] proposed a new design and characterized it with both lab tests and road tests.

The rotary energy harvesting absorbers translate the up-and-down suspension vibration into the bi-directional oscillation of the electrical generation and produce electricity. Since low-cost and off-shelf rotary generator can be used, they are more compact and cost effective. However, the irregular oscillation of the motion mechanism causes numerous problems such as low mechanical reliability and bad vibration performance. For example, the ball screw mechanisms investigated in [19-22] have a good power density, but the absorber is too stiff to control at high frequency due to large motion inertia, resulting worse ride comfort at high frequency above 7-10 Hz even with active control [23,24]. More important, the bidirectional oscillation will cause large impact force, backlash, and friction in the transmission system, causing the fatigue or even failure. The rack teeth were worn out and broken quickly due to large impact force in our early prototype of regenerative shock absorber based on oscillatory rotation generator. In addition, the bidirectional oscillating motion will produce an irregular AC voltage. In order to charge batteries or power vehicle electronics, the voltage needs to be commutated with electrical rectifier, in which the forward voltage of diodes unavoidably reduces the circuit's efficiency.

The main contribution of this paper is an innovative concept of "mechanical motion rectifier", which can convert bidirectional motion into unidirectional motion. It is not a substitute of electrical voltage rectifier. It can significantly improve the reliability by reducing impact forces and increase efficiency by decreasing the influences of friction. It also enables the electrical generator to rotate unidirectionally at relative steady speed with higher energy efficiency. The second contribution is a circuit based modeling to analyze the system's dynamic properties both in electrical domain and mechanical domains. The third contribution of this paper is simulation and lab experiments to verify the concept and advantages of mechanical motion rectifier based vibration energy harvester.

2. Principle of Motion Rectifier

Shock absorbers are installed between chassis and wheels to suppress the vibration, mainly induced by road roughness, to ensure ride comfort and road handling. Conventional rotational regenerative shock absorbers translate the suspension oscillatory vibration into bidirectional rotation, using a mechanism like ball screw or rack pinion gears. Figure 1 shows one such an implementation [25], where the rotary motion is changed by 90 degree with a pair of bevel gears for retrofit.

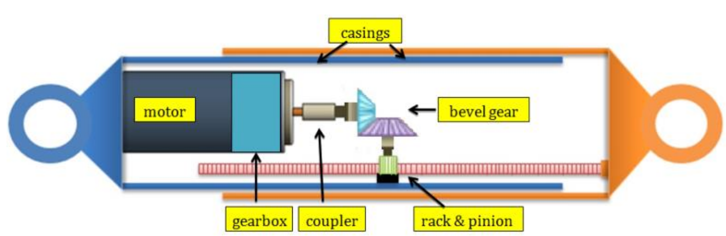


Figure 1. Traditional design of a rack-pinion based regenerative shock absorber [25]

A “motion rectifier” is created to “commutate” oscillatory motion. Its principle is showed in Figure 2. We can define the functioning of the “motion rectifier” with two working modes: positive mode and negative mode. The key components of “motion rectifier” are two roller clutches that transmit rotation only in one direction and dive the motion in two different routes. As a result, the shaft of the motor and planetary gear will move always in one direction.

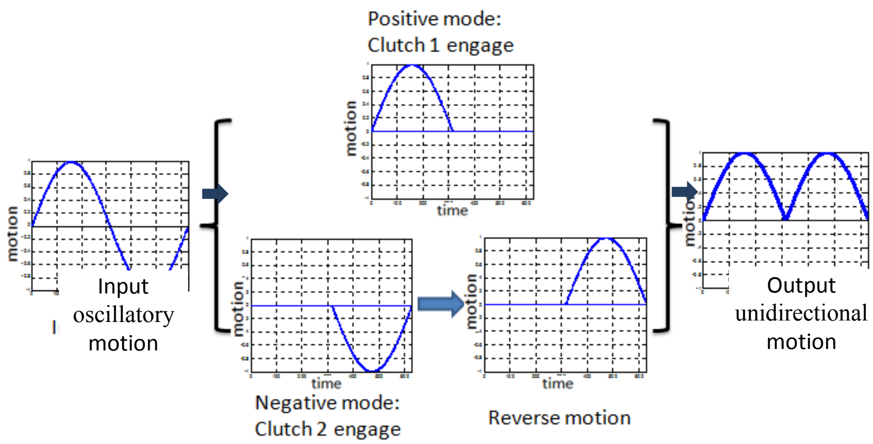


Figure 2. Principle of “motion rectifier” for oscillating motion

The mechanical motion rectifier with two roller clutches can be analogy to a full-wave voltage rectifier using a center-tapped transformer and two diodes, as shown in Figure 3. It converts the irregular reciprocating vibration into the regular unidirectional rotation. And the system inertia is equivalent to the electrical smoothing capacitor in series with the electrical load.

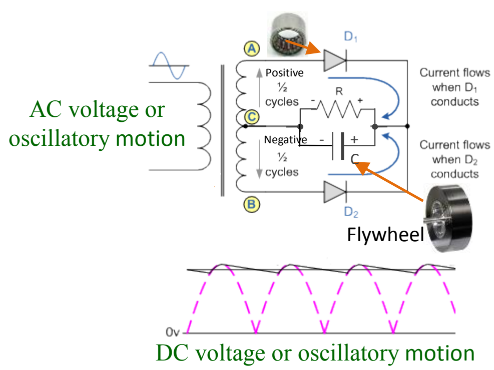


Figure 3. Electrical analogy for “motion rectifier”

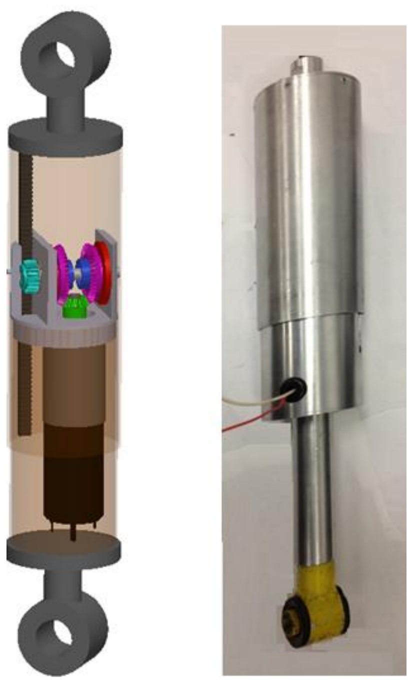
3. Design of Highly-Compact Motion Rectifier Based Harvester

A convenient design of the “mechanical motion rectifier” that directly translates the above “center-tapped transformer” into the mechanical domain may involve one input like double-side rack as the primary coil and two outputs like two pinion gears as two secondary coils, as in [26]. However, it needs 2-3 shafts and the overall size is too large for retrofit application of suspension. Moreover, overall efficiency is comparatively low considering every engagement like gear transmission or shaft typically has an efficiency of about 90%.

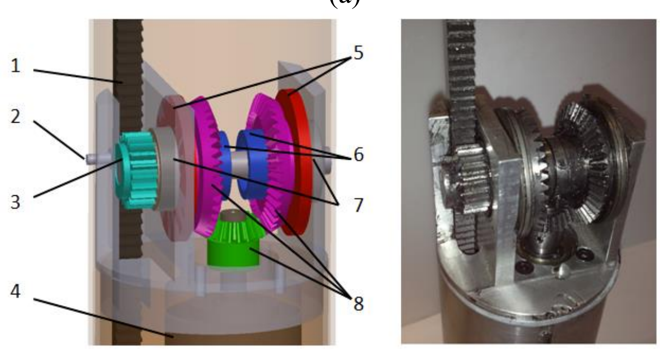
In order to keep regenerative shock absorbers compact enough, the motion transmission needs to be well organized to fit into the existing space of the shock absorber. In additional, we should decrease the number of gear pairs and shafts to improve the mechanical efficiency. Figure 4 shows the new design we proposed. In this design we use a pair of rack and pinion, one shaft and three bevel gears. Two roller clutches (blue) are mounted between the shaft (gray) and the two larger bevel gears (purple), which are always engaged with the small bevel gear (green). The different size of bevel gears will give additional transmission ratio; they can be of the same size if additional transmission ratio I not needed.

When the rack moves up and down, the pinion and shaft rotate clockwise and counterclockwise directions. Due to the engagement of the one-way roller clutches, at an instant time only one large bevel gear will be engaged and be driven by the shaft; another large bevel gear will be disengaged from the shaft by the roller clutch. These two larger bevel gears will be driven in opposite direction by the shaft. Since the large bevel gears are in two opposite sides of the small bevel gears, the smaller bevel gear (and the generator) coupled to it will always be driven by either left or right bevel gears and will rotate in one direction no matter the rack goes up or down.

The assembly of the pinion, shaft, and bevel gears will be mounted to one cylinder, and another cylinder covers outside and to guide the linear motion. Similar as roller bearings, the roller clutches can't hold large thrust in the axial direction, so two thrust bearings are designed to support the thrust forces on the two larger bevel gears. In order to reduce the friction between the inner and outer cylinders, we insert Teflon rings between the two cylinders. The rack is preloaded and guided by a roller in the place opposite to the pinion. The enclosed construction of the shock absorber prevents dirt from hurting gears inside.



(a)



1 rack
2 roller
3 pinion
4 planetary gears and motor
5 thrust bearings
6 roller clutches
7 ball bearings
8 bevel gears

(b)

Figure 4. Comparison between 3D model and actual prototype, **(a)** overall view, **(b)** inner structure

4. Modeling And Simulations

4.1 System analysis

The energy-harvesting shock absorber is used to generate power from the vibration of vehicle suspension. Such a shock absorber itself is a dynamic system which includes generator, transmission gears, motion rectifier, etc, as shown in Figure 5. A dynamic modeling is necessary to guide the design and power management to achieve the maximum power harvesting efficiency. In this section, we will first analyze the parts with differential equations and then introduce the modeling of the overall system with an innovative modeling method based on the circuits.

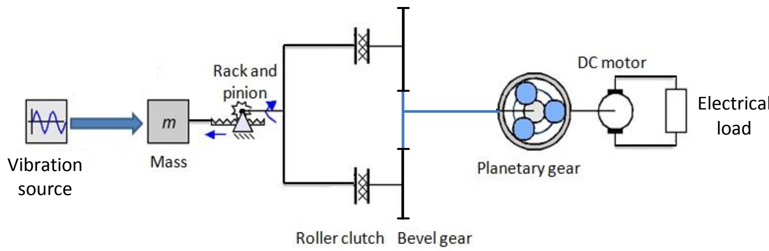


Figure 5. Simplified schematic view of the motion rectifier based energy-harvesting shock absorber

For the DC generator (Fig. 6) in our system, rotational motion will produce a back electromotive voltage V_{ef} proportional to the rotational speed ω.

$$V_{ef} = k_e \frac{d\theta}{dt} \quad (1)$$

where k_e represents the back electromotive voltage constant.

The electric current i of the motor will produce a torque τ_e following the relationship:

$$\tau_e = k_t i \quad (2)$$

where k_t represents the torque constant. From the mechanical properties of generators, we can get:

$$\tau_m - \tau_e = J_m \frac{d^2\theta}{dt^2} \quad (3)$$

where J_m is the inertia of the rotor, and τ_m is the input mechanical torque on the generator.

Based on Kirchhoff's voltage laws, we have:

$$V_{ef} - L\frac{di}{dt} - iR = 0 \quad (4)$$

By taking the equations (1)-(4) into consideration, the overall expression of the generator should be:

$$k_e \frac{d\theta}{dt} - \frac{L}{k_t}\frac{d}{dt}\left(\tau_m - J_m \frac{d^2\theta}{dt^2}\right) - \frac{R}{k_t}\left(\tau_m - J_m \frac{d^2\theta}{dt^2}\right) = 0 \quad (5)$$

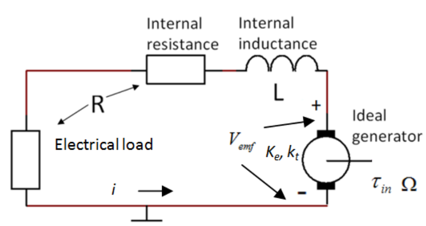


Figure 6. Model of the electromagnetic generator

The inertia of the motor J_m will be considered together with the transmission as an equivalent mass in the following. The transmission parts including rack-pinion, clutches, bevel gears and planetary gears can be taken into consideration together with a transmission ratio of i_t and efficiency of η_t.

$$i_t = \frac{1}{r} k_h k_b \quad (6)$$

$$\eta_t = \eta_r \cdot \eta_{cl} \cdot \eta_b \cdot \eta_p \quad (7)$$

where $k_h$and k_b are the transmission ratio of the planetary gear head and the transmission ratio of the bevel gears, r is the radius of the pinion gears, and $\eta_r, \eta_{cl}, \eta_b$ and η_p correspond to the efficiency of rack-pinion, roller clutch, bevel gears and planetary gears, respectively.

By taking the inertias of the motor J_m, planetary gear head J_g and the larger bevel gears J_b into consideration, we can use an equivalent mass *at the end of the rack* to represent them.

$$m_s = \frac{J_m k_h^2 k_b^2 + J_g k_b^2 + J_b}{r^2} \tag{8}$$

Note that the equation (7) we didn't take the inertia in oscillatory motion into account, including those of the shaft, pinion gears, and rack, which act differently from the inertia in unidirectional rotation. When the shock absorber is mounted in a vehicle, the inertia in oscillatory motion will be connected with the chassis or wheel rigidly. Considering such a inertia is much smaller than chassis inertia, the influences of the oscillating inertia are neglected.

4.2 Circuit based modeling

A circuit based modeling method is implemented to simulate the dynamic properties of the regenerative shock absorber. Perter C. Breedveld[27] introduced the concepts of effect and flow, which can be used to solve the multi-domain problems with the uniform format.

In this case, the regenerative shock absorber involves both mechanical and electrical domains. So it would be easier to analyze the system after transferring the mechanical elements into electrical elements.

Table 1. Corresponding elements in different domains

Mechanical element (linear)	Mechanical element (rotational)	Electrical element
Force	Torque	Voltage
Velocity	Rotation speed	Current
Spring	Rotation spring	Capacitor
Damper	Rotation damper	Resistor
Mass	Inertia	Inductor

Due to the engagement and disengagement of the roller clutches, the dynamics of the energy-harvesting shock absorber is not linear. The dynamics of such nonlinear mechanical motion system appears to be very complicated. However, if we think more about the physical insights, we can model the system by make an analogy between mechanical motion rectifier and electrical voltage rectifier.

Figure 7 shows the overall modeling of the proposed regenerative harvester system. Different from the typical center-tapped transformer with one primary coil and two secondary coils in Figure 3, in this modeling we have two primary coils and one secondary coil, where the two larger bevel gears correspond to two primary coils and the smaller bevel corresponds to the secondary coil. The two roller clutches between the shaft and the two larger bevel gears correspond to the two semiconductor diodes. The shaft is driven by the rack pinion. Only one larger bevel gear is driven in positive or negative half cycles, in a manner similar as the electrical current flow through only one primary coil. And the unidirectional rotation will occur in the smaller bevel gears, as the DC current exists in the secondary coil. Therefore, the irregular oscillatory vibration is converted into the regular unidirectional rotation by the proposed mechanical motion system. The mechanical impedance (torque from the generator and electrical load by the rotation speed) acts as the electrical impedance in the electrical circuit. Hence, we can use the well-developed principle of AC/DC power electronics [28] to model the nonlinear mechanical motion rectifier system. Note again that this motion rectifier is to regulate the motion, not just a substitute of electrical voltage rectifier.

Other elements of the regenerative shock absorber are treated as follows:

1) The DC motor can convert the electrical energy into mechanical energy. Also it can convert mechanical energy into electrical energy. It is treated as a gyrator in the circuit-based modeling,

$$U = k_e \cdot \omega \tag{9}$$

$$\tau = -k_e \cdot \frac{k_t}{k_e} \cdot i = \eta_g \cdot k_e \cdot i \tag{10}$$

where the gyration resistance $R = k_e$, efficiency $\eta_g = \frac{k_t}{k_e}$.

2) The transmission ratio including rack-pinion $\frac{1}{r}$, bevel gear ratio k_b and plenary gear head k_h is modeled as an ideal transformers or DC-DC converters with the a gain the same as the transmission ratio $i_t = \frac{1}{r} k_h k_b$. The "ideal transformer" can be used either as a transformer or as a DC-DC converter.
3) The two roller clutches are modeled as diodes where the forward voltage drop corresponds to the friction force. The subsystem can be modeled as a full wave rectifier.
4) The viscous damping in the mechanical system can be modeled as peristaltic resistors, but for this case, the mechanical damping is comparatively small, so they are omitted and not shown in the overall model.
5) The internal inductances of the generator are comparatively small, which can be neglected.

In this way the overall system can be modeled as a circuit in Figure 7 (a).

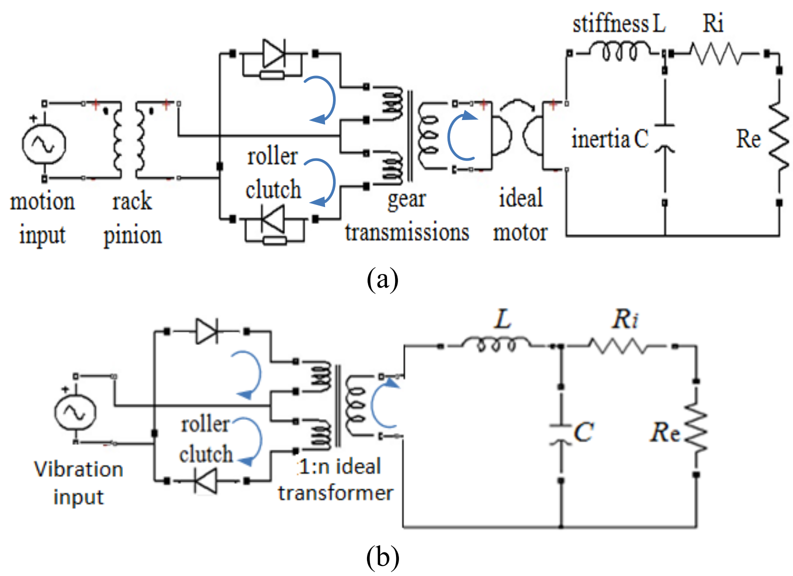


Figure 7. Modeling for regenerative shock absorber using electrical circuit: **(a)** original, **(b)** simplified

We can further simplify the system to Figure 7 (b). The value of the electrical components (for simplified circuit model) can be decided with the system's mechanical properties as the following:

Inductor $L = \frac{k_h^2 k_b^2 k_e k_t}{r^2} \frac{1}{k_s} + L_i$

Capacitor $C = \frac{1}{k_e k_t} m_s$

Transformer ratio $n = \frac{1}{r} k_h k_b k_e$

where m_s is the equivalent mass expressed in Equation (8), L_i and R_i are the internal inductance and resistance of the generator, and k_s is the stiffness of the mechanical structure, including gear teeth, shafts, etc.

4.3 Simulation

Based on this circuit based modeling method, simulations can be done with Simulink/MATLAB. Figure 8 shows that the output voltage of the generator under vibration of different frequencies. We see that the voltage is smoother when the input frequency is higher, since the effect of the motion inertia is larger at higher frequencies.

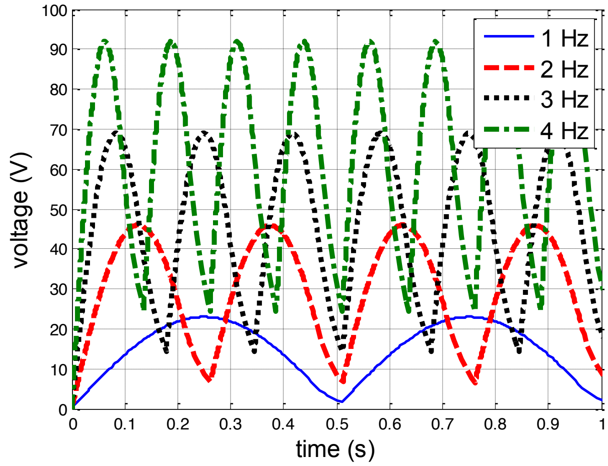


Figure 8. Voltage simulation for excitations at different frequencies with electrical load $R_i+R_e= 100\ \Omega$

The simulated voltages under different electrical load are shown in Fig 9. It can be seen that the voltage is steadier with larger electrical resistors. This phenomenon is similar as that in voltage rectifier, where smaller electrical resister needs larger smoothing capacitor to maintain a steady voltage.

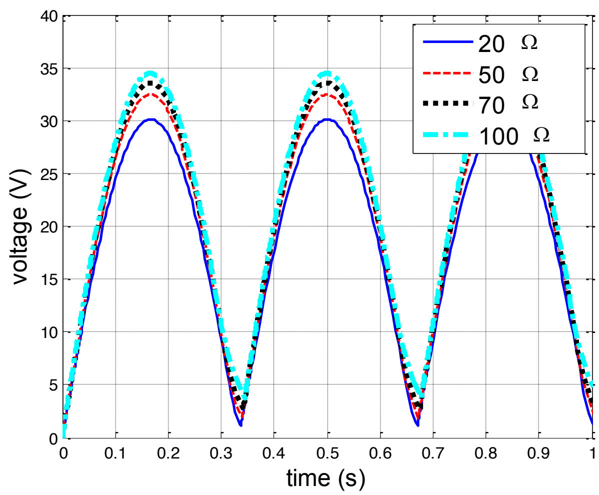


Figure 9. Voltage simulation for different total electric loads at 1.5 Hz

5. Experiments and results

5.1. Experiment Setup

The prototype was tested with the MTS 858 Mini Bionix II testing system and a dynamic signal analyzer (Hewlett Packard Model 35670A), which are showed in Fig 10. We use a sinusoidal input with comprehensive range of frequencies and power resistors to run the tests. A strain gauge was attached to measure the force variation corresponding to the displacement of the rack. The motor was hooked up to a resistor which was then connected to a dynamic signal analyzer allowing for the recording of voltage output over time. The experimental test accurately evaluated the performance of the prototype because it provided us with realistic input parameters and substantial amount of highly reliable data.

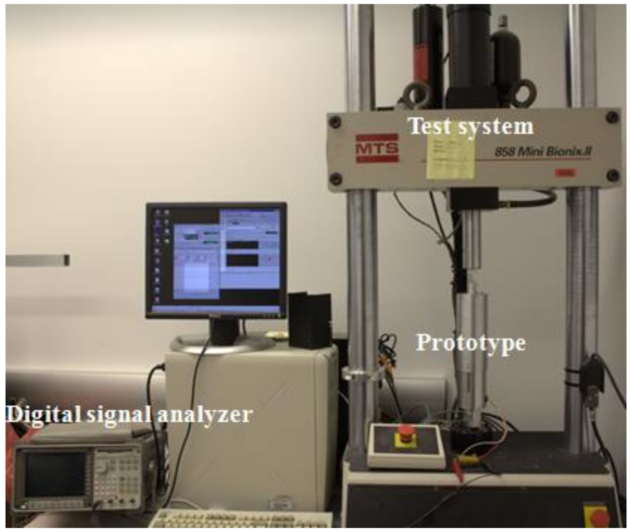


Figure 10. Complete experiment configuration for our regenerative shock absorber

5.2. Force-Displacement Damping Loops

Figure 11 is the force-displacement damping loop under harmonics excitations. The area of the loop means the mechanical work input of the shock absorber in one cycle. When there is not resistor connected (open circuit), the damping loop area is contributed by the mechanical loss such as frictions. The loop of open circuit is comparatively small, which means that the friction's work is small and high efficiency can be expected. In this figure, the forces came to zero before the displacements reach to maximum or minimum. This is because the kinetic energy stored in the motion inertia m_s is returned to the system and the roller clutch was disengaged.

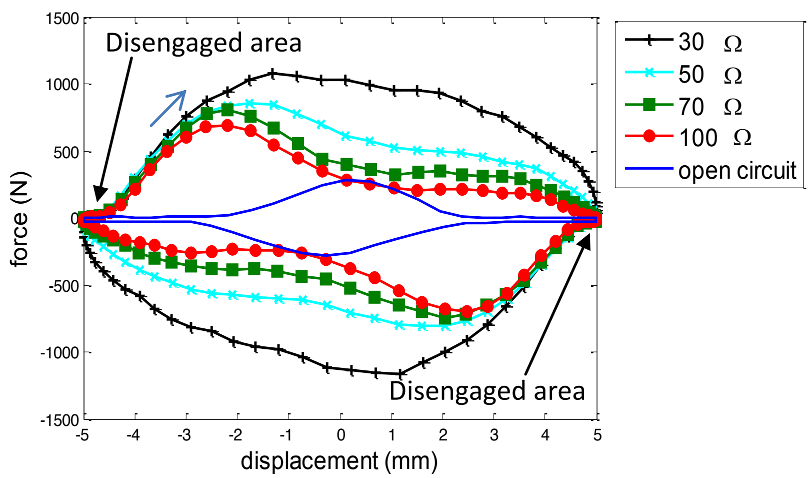


Figure 11. Damping loops for different external electrical loads under vibration input of 1.5 Hz and 5mm amplitude

Since the suspension vibration is in broad spectrum, mainly 1-10Hz, we also investigated the performance at different frequencies. Figure 12 shows the damping loops at various frequencies. The results indicate that at higher frequency the disengaged area is larger which corresponds to larger energy storage effect of motion inertia. The engagement and disengagement behaviors can be seen clearly in the recorded force during one cycle in Figure 13. It is interesting to observe that at low frequency the force reaches its maximum before the input velocity reaches the maximum, and at high frequency the force reach its maximum after the input velocity reaches the maximum. It is also noted that at high frequency the force is not zero when the displacement reaches the ends (input velocity reaches zero). The reason is the inertia force since the total force is composed on the back electromotive force proportional to the generation speed, the inertia force to accelerate the moving inertia, and possibly some friction. Note that the input force cannot decelerate the inertia in unidirectional rotation because the roller clutches.

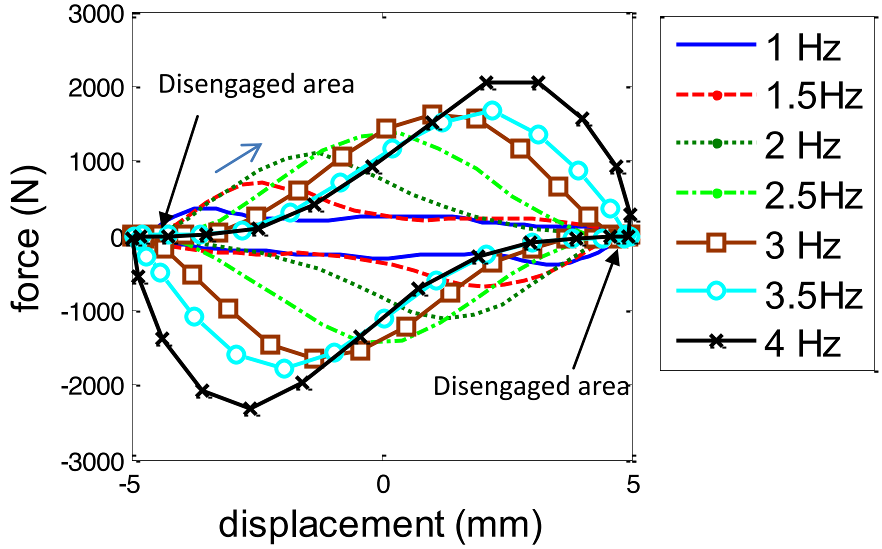


Figure 12. Damping loops for different input frequencies with electrical load R_i+R_e= 106.6 Ω

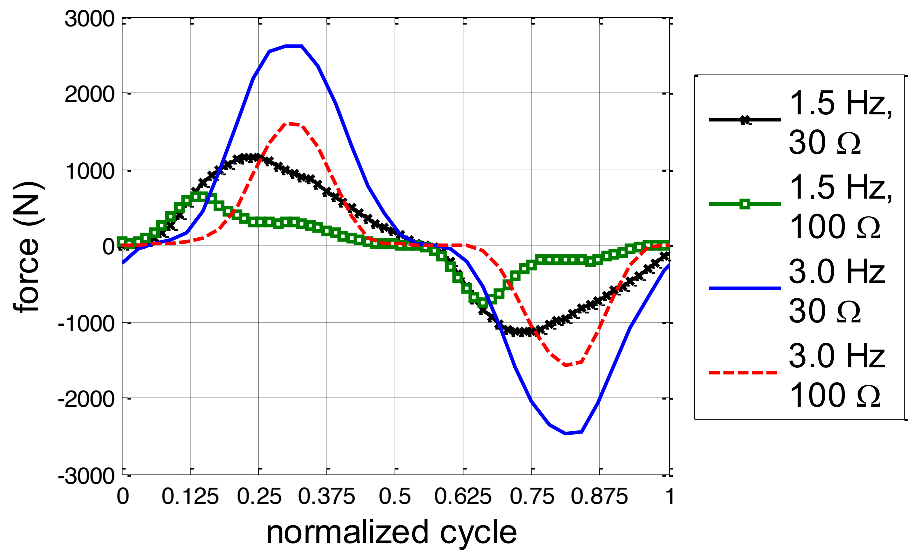


Figure 13. Measured force in one cycle for 30 Ohms and 100 Ohms external resistive loads under 1.5 and 3.0 Hz vibration inputs of ±5mm displacement.

5.3. Energy Harvesting and Efficiency

Figure 14 shows the input recorded voltage on the external resistors of 23.4 and 94.6 Ohms (internal resistor 6.6 Ohms) under harmonic excitation of 3Hz and 5mm amplitude. The recorded input velocity is also shown in Figure 14 as comparison (root mean square 0.047m/sec). Since the regenerated voltage is proportional to the output velocity of the generation, this Figure 14 actually illustrated the relationship of input velocity and output velocity of the mechanical system, which is the motion rectification. We can also find from Figure 14 that the peak voltage is lower at smaller electrical load, as predicted in the simulation Figure 9. However, compared with Figure 9, the measured voltages after the valleys didn't rise as sharp as the simulation, which might because of the engagement of the roller clutch takes some time.

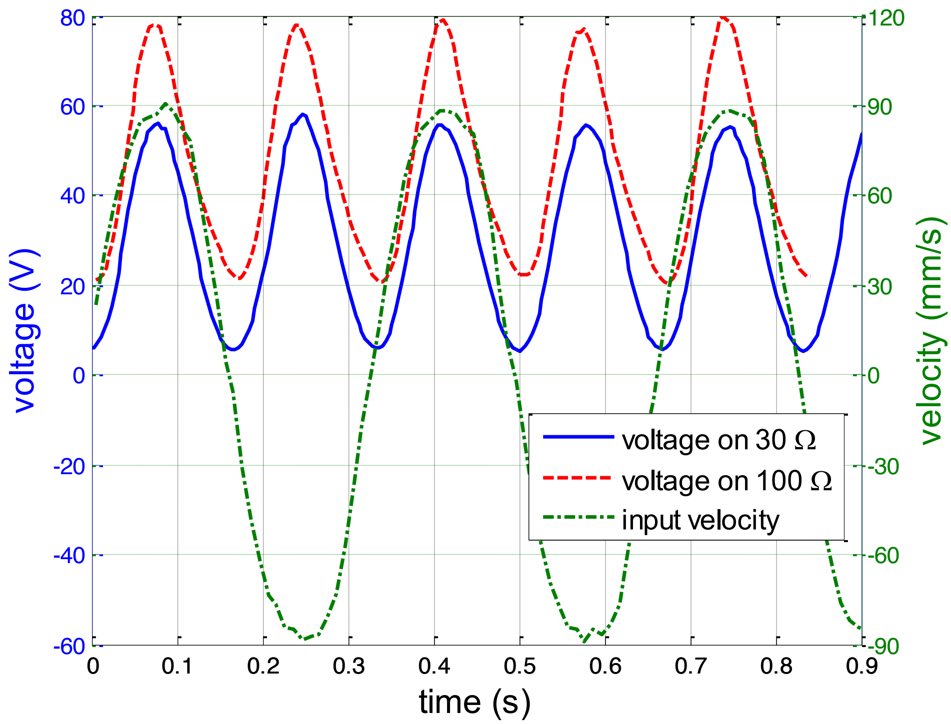


Figure 14. Measured output voltage on 30 and 100 Ω external resistive loads (total 36.6 and 106.6 Ω) under 3Hz 5mm vibration excitation, in comparison with the measured input velocity.

The electrical power can be calculated based on the voltage and resistive electrical load. Figures 15 shows output electrical power achieved with 3 Hz 5mm displacement input on 100 Ohms and 30 Ohms electrical load. It can be seen that at root mean square 0.047m/sec we harvested the peak power 62.9 Watts and 104.3 Watts, and average power 25.6 Watts and 40.4 Watts at the 100 Ohms and 30 Ohms electrical load, respectively.

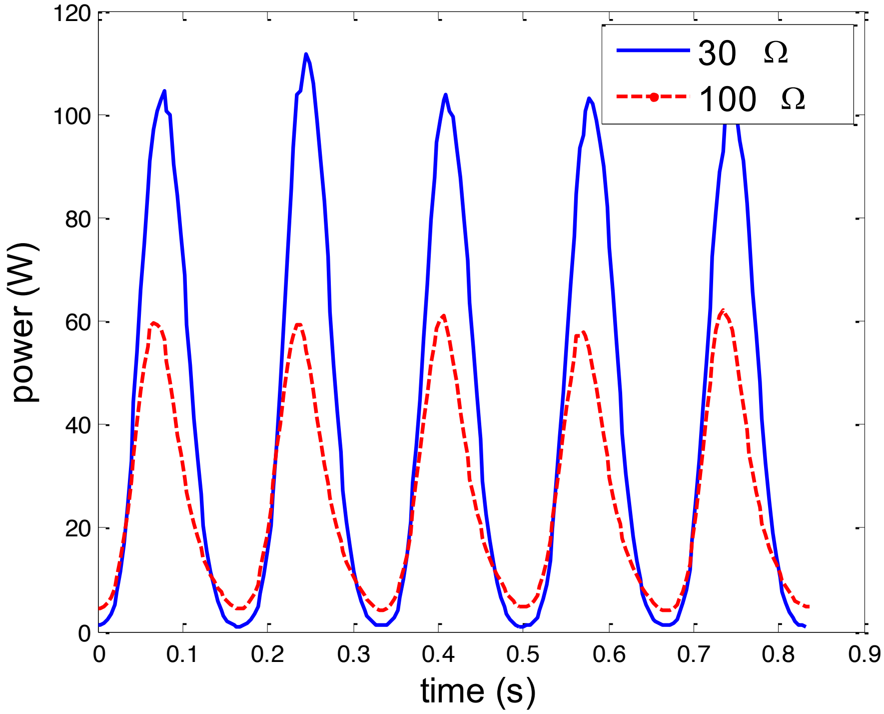


Figure 15. Measured output electrical powers on 23.4 and 93.4 Ω external resistive loads (total 30 and 100Ω) under 3Hz vibration input, where the average powers achieved is 40.4 Watts and 25.6 Watts under rms velocity 0.047m/s.

Based on the mechanical work in cone force-displacement cycle and electrical work on the external resistor, the total efficiency of the system will be obtained, which can be decomposed of electrical efficiency η_e and mechanical efficiency η_m. The electrical efficiency is the ratio of power on external electrical load and total electrical power, which is the external load resistance R_e divided by the sum of external and internal resistance R_e+R_i. The R_i of our generator is 6.6 Ω, the electrical efficiency η_e is 82%~94% for R_e=30~100Ω. The mechanical efficiencies at different electrical load R_i+R_e under 1.5Hz and 5mm amplitude vibration are shown in Figure 16. From this figure, we can find that the mechanical efficiency is around 60%. And mechanical efficiency η_m increases when the electrical resistor Re decreases.

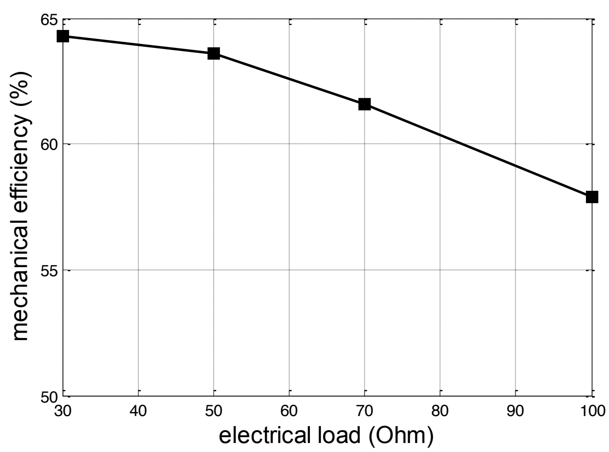


Figure 16. The mechanical efficiencies at different electrical loads under 1.5 Hz and 5mm vibration input.

The mechanical efficiencies at different vibration frequencies are plotted in Figure 17. From the figure, we can see that the efficiency tends to increase with the increase of frequency in some range. When the frequency rise up to some point, the efficiency achieves some steady value, which is around 62% in our prototype. Compared with the results of conventional regenerative shock absorber in oscillatory rotation [18], the efficiency is significantly improved at higher frequency (from 30-45% to 62%). Due to the constraint of the hydraulic test machine, we were not able to test at even higher frequencies.

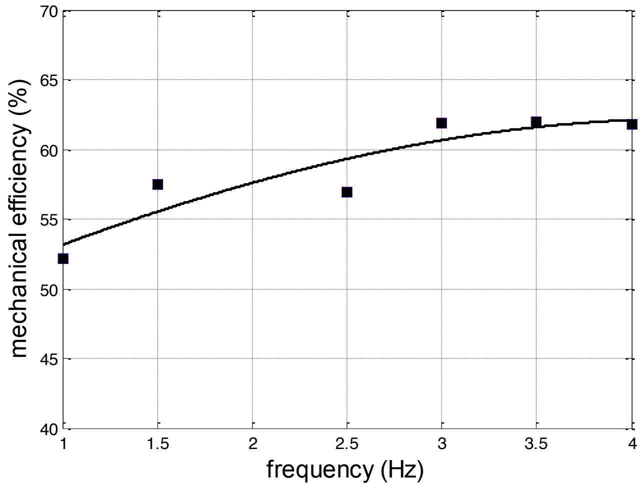


Figure 17. The mechanical efficiencies with different vibration frequency, where electrical load is R_i+R_e= 100 Ω and vibration amplitude is 5mm.

6. Conclusions

In this paper, we proposed a "motion rectifier" based design of electromagnetic energy harvester for enhanced efficiency and reliability for potential application of vibration energy harvesting from vehicle suspensions. "motion rectifier" can transfer the oscillatory motion of vehicle suspension into unidirectional motion of the electrical generator, thus enabling the generator operating in a relatively steady speed with higher efficiency. In such a design, the motion inertia will act as a filtering capacitor to temporarily storage the energy and smooth the rotation, which can decrease the influences of backlash impact and static friction.

An innovative implementation of the motion rectifier is introduced with high compactness and improved efficiency. The roller clutches are embedded in two bevel gears and the function of "motion rectifier" is achieved with three bevel gears. In addition, the mechanical-electrical system of the regenerative shock absorber is modeled with a circuit-based method to analyze the dynamic properties of the system. Finally the shock absorber is characterized with bench tests. The "motion rectifier" based design achieved a mechanical efficiency of over 60% and no obvious backlash effect. It also harvested average powers 40.4 Watts and 25.6 Watts on 23.4 and 93.4 Ω external resistive loads under vibration of RMS velocity 0.047m/s. The simulation and experiment results indicate that effect of "motion rectifier" is more important with higher input frequency, and the efficiency is higher correspondingly.

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