Mechanical Amplifier for Translational Kinetic Energy Harvesters

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Abstract. This paper reports the design, optimization, and test results of a mechanical amplifier coupled to an electromagnetic energy harvester to generate power from low-amplitude (±1 mm) and low-frequency (<5 Hz) vibrations in the presence of large static displacements. When coupled to a translational kinetic energy harvester, the amplifier boosts small vibration amplitudes by as much as 4x while accommodating translational displacements of more than 10x of vibration amplitudes. A complete electromagnetic energy harvester using this mechanical amplifier produces 16x improvement in output power (30 mW vs 1.9 mW without amplifier at 5 Hz), and a high power density of 170 µW/cm^3.

1. Introduction
There is a growing interest in using ambient vibrations as an alternative energy source for power consumer electronics. However, kinetic/vibration energy harvesting becomes challenging in low frequency environments (human motions, bridges, buildings, and some automotive/avionic systems) [1]. To address this challenge, different approaches have been proposed: using a resonant oscillating mechanism [2], deploying mechanical frequency up-conversion [3], or using rotational movement of an eccentric mass [4]. The performance of many of these systems degrades in the presence of non-axial loads, large static displacements, aperiodic vibrations, and low-amplitude stimuli [5].

While most of the aforementioned works propose inertial harvesters which transfer kinetic energy into a resonant proof mass tuned to resonate at source vibrations, an alternative is to deploy direct-force harvesters where source vibrations are directly applied on the proof mass. Although such systems tend to generate less power relative to resonant harvesters, they inherently remain operational over a wider excitation bandwidth. However, a real challenge to generate useful amounts of power arises when working at low-amplitude and low-frequency vibrations. To address this issue, this paper proposes a new approach of coupling a mechanical amplifier with direct-force kinetic energy harvesters to increase the amplitude of source vibrations. To investigate the impact of the mechanical amplifier on the generated power, a macro-scale electromagnetic energy harvester was used for.

This paper is organized as follows: in section 2 the design concept of the entire harvesting system is presented. Next in section 3 different design architectures are analyzed and refined to prototype the mechanical amplifier. After discussing experimental results in section 4, section 5 presents conclusions and future work.
2. Design conception

The operation principle of electromagnetic power generators is based on Faraday’s law of induction which relates the electromotive force $\varepsilon$ to the changing rate of magnetic flux $d\Phi_B/dt$ passing through a closed conductor as follows:

$$|\varepsilon| = \frac{d\Phi_B}{dt}$$  \hspace{1cm} (1)

When considering Ohm’s law and Kirchoff’s law for an electric circuit with source resistance of $R_{coil}$, the generator’s output power $P_{out}$ becomes proportional to:

$$P_{out} \propto \left\{ \left( \frac{d\Phi_B}{dz} \right)^2 / R_{coil} \right\} \left\{ (dz / dt)^2 \right\}$$  \hspace{1cm} (2)

where $dz/dt$ is the magnet-coil relative velocity.

To increase $P_{out}$ both expressions on the right-hand side of (2) should be at their maximum. Regarding the first expression, previous work [6] presented an optimization procedure to adjust coil dimensions and position relative to a given magnetic structure in a way to meet the optimum ratio of flux linkage to coil resistance.

It is also essential to maximize the second expression, the vibration velocity which itself varies with vibration amplitude and frequency. When using frequency-up conversion or resonant mechanism in inertial harvesters, more power is generated via the increase in frequency and/or vibration amplitude. In direct-force energy harvesters other mechanisms should be implemented to enhance the output power.

As figure 1 illustrates, this energy harvester consists of two main parts: A) an electromagnetic transducer composed of an assembled stack of custom-made NdFeB magnets which remain stationary and a copper coil which moves axially relative to magnets, B) the mechanical amplifier consisting of three elements: 1) the base which is connected to the same frame as the transducer’s stationary part, here the magnets, 2) the input member to receive ambient (source) vibrations, 3) the output member to drive the mobile part of the energy transducer, here the coil, at increased vibration amplitudes.

The mechanical amplifier should ideally provide both a high mechanical gain for small dynamic vibrations, and a high capacity to accommodate large static/dynamic displacements to prevent structural damage of the harvester. In other words, the challenge is twofold: at the same time that small input vibrations are amplified as much as possible, very large static inputs, i.e. more than 10x of small vibrations, should be attenuated by the amplifier. Besides, depending on the application field, other criteria like weight, size, or damping force may also be taken into account in the design of the amplifier.

3. Amplifier architecture

In this section few designs of the amplifier based on mechanical linkage are examined and compared to each other. It should be mentioned that the objective of this work is to study the coupling effect of the mechanical amplifier with energy harvesters. The comprehensive study of all different configurable types of amplifiers lies beyond the scope of this paper.

In rotary energy harvesters higher output power can be generated by modifying the pitch diameter of the engaged gears [7]. As this concept remains incompatible with translational harvesters, other design architectures should be investigated. A very basic type of amplification is the lever mechanism composed of one link and one pivot point (figure 2-a). Despite its simple structure, it is not an ideal translational amplifier. Indeed, for input amplitudes much smaller than the link length the
amplification can be estimated as translational; however, due to the rotational movement of the link about the fulcrum axis, it inherently provides rotational motions. Amplifiers based on the scissors linkage (figure 2-b) appear as a solution to obtain complete translational amplification. In spite of this advantage, the mechanical gain and the input capacity remain unchanged relative to the lever system.

By coupling two rack-pinion mechanisms together, linear motions are converted to rotational motions and vice versa. As Figure 2-c shows, the amplification takes place when both pinions are locked on the same shaft and the pitch diameter of the driven pinion is set larger than the driving pinion. This mechanism accommodates unlimited input amplitudes; however, the output amplitudes remain also unlimited. Except for applications where the harvester volume is not a design criterion, the unlimited output strokes become a major drawback to conceive a compact harvester unit.

Figure 2-d depicts a mechanical amplifier using one rack-pinion mechanism paired with one disk-crank mechanism providing piston-like motion. In such a system, after converting the linear motion into the rotational motion, while the angular velocity remains the same, the linear velocity increases for the disk of larger diameter than the pinion. Then, via a slider-crank linkage the rotational motion is converted back into linear motion. This assembly, furthermore, provides the advantage of accepting infinite input amplitudes while confining the output strokes within the disk diameter.

\[
G = \frac{R}{r}
\]

\[
\text{Input}_{\text{Max}} = 2r
\]

\[
\text{Output}_{\text{Max}} = 2R
\]

Figure 2. (a) Schematic view of different amplifier design conceptions with indicated mechanical gain \(G\) and input and output capacities: (a) simple lever, (b) scissors linkage, (c) two rack-pinion joints, (d) rack-pinion paired with piston-like motion

Figure 3-a shows detailed schemas of the developed mechanical amplifier based on figure 2-d design concept. Two solid plates are used as amplifier’s backbone on which all components are mounted. Linear bearings/sliders are deployed to limit both the rack (the amplifier’s input member) and the coil rod (the amplifier’s output member) to one translational degree of freedom along the x-axis. To size the amplifier, trade-offs were set between device volume, mechanical gain, and friction. In this way the pinion pitch diameter and the disc diameter were set at 0.6 cm and 2.5 cm respectively \((R/r = 4)\). As for the crank, a smaller length produces a higher mechanical gain. On the other hand, to meet the design requirement of high input load capacity, a minimum crank length equal to the disk radius \(R\) is necessary to succeed disk complete revolution \((0–360^\circ)\). Besides, as tested, very short-length cranks impede smooth functioning of the system unless using 4 cm or longer cranks.

Figure 3-b shows the finished amplifier prototype with a copper coil, 0.6 kΩ, attached to the output member and a spherical rod end screwed to the input member to decouple angular motions from linear motions of the vibrating source. The amplifier prototype was fabricated by mounting brass machined
parts and off-the-shelf stainless steel rack & pinion with 120 diametral pitch and 20° pressure angle. Set screws and E-rings were also used to adjust and hold in position the movable components. This prototype weighs 130 gr and occupies 40 cm³.

4. Results and discussion
To characterize the developed mechanical amplifier two series of tests were carried out: static measurements on the amplifier alone and dynamic tests on the complete energy harvesting system.

4.1. Static measurements
Referring to figure 2-d, it is noticed that the mechanical gain varies not only with disk-pinion radius ratio $R/r$ (here 4) and the crank length $L$ (here 4 cm), but also with the crank-disk angle $\theta$. The mechanical gain between input and output displacements was measured and traced in figure 4 as a function of crank-disk angle. In good correlation with simulation results, the presence of two identical peaks defining the optimum operation zone is noticeable. The width of dotted zones (~30° in disk rotation) corresponds to ±1 mm input amplitude and their height to ±4 mm output (a gain of 4). Two dotted zones are identical because the rod slider and the disk are centered about the same x-axis.

4.2. Dynamic measurements
Dynamic tests were performed at low-frequency low-vibration amplitudes (±1 mm) using APS 113 Electro-Seis shaker. While the energy transducer alone generates 1.9 mW power at 5 Hz, once incorporating the mechanical amplifier, the output power is boosted to 30 mW. As figure 5-a shows, after a transient regime, the generated power rises by as much as 16x when using a 4x-amplifier. The total damping force increases up to 8 N, 2.5 N of which is estimated to be caused by friction. Despite the increased total volume of the harvester when integrating the amplifier, the power density is quadrupled and reaches 170 $\mu$W/cm³. The improvement can also be observed when comparing the
resulting 43 mW/cm$^3$/g$^2$ normalized power density with other reported electromagnetic energy harvesters in figure 5-b. An inset of the complete energy harvesting system integrated into 4 cm wide tube is also illustrated in figure 5-b.

Figure 5. (a) Measured output power and gain factor at 1 mm vibration amplitude using source-load matched resistance, (b) normalized power density as a function of frequency for this work and other electromagnetic energy harvesters, an inset of fabricated energy harvester incorporating mechanical amplifier

5. Conclusion
This work studies the design of a translational mechanical amplifier and its impact on the generated power once coupled to an electromagnetic energy harvester. Several design concepts based on mechanical linkage were analyzed to obtain large mechanical gain and high load capacity to accommodate static/dynamic displacements much larger than vibration amplitudes. After refining the design architecture for the most attractive mechanism (a rack-pinion paired with a piston-motion mechanism), amplifier prototypes with 4x mechanical gain were built and tested.

Dynamic measurements showed when coupling the developed mechanical amplifier to a direct-force electromagnetic energy transducer, 30 mW power is generated from vibration amplitudes as low as 1 mm at low-frequencies. With mechanical amplifier integrated, the output power rises by as much as 16x and the power density quadruples up to 170 µW/cm$^3$. The design concept of the detailed mechanical amplifier remains compatible with other types of kinetic energy harvesters, e.g. piezoelectric or electrostatic. With the goal of size reduction and efficiency improvement, future work will investigate other mechanisms using pneumatic or hydraulic means.

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