On the experimental determination of the efficiency of piezoelectric impact-type energy harvesters using a rotational flywheel

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Abstract. This paper demonstrates a novel methodology using a rotational flywheel to determine the energy conversion efficiency of the impact based piezoelectric energy harvesters. The influence of the impact speed and additional proof mass on the efficiency is presented here. In order to convert low frequency mechanical oscillations into usable electrical energy, a piezoelectric harvester is coupled to a rotating gear wheel driven by flywheel. The efficiency is determined from the ratio of the electrical energy generated by the harvester to the mechanical energy dissipated by the flywheel. The experimental results reveal that free vibrations of the harvester after plucking contribute significantly to the efficiency. The efficiency and output energy can be greatly improved by adding a proof mass to the harvester. Under certain conditions, the piezoelectric harvesters have an impact energy conversion efficiency of 1.2%.

1. Introduction
Converting low frequency vibrations (< 30 Hz) into usable electrical energy using an impact based approach, in which environmental motion is coupled to an inertial object through the physical impacts, has received significant interest. Several configurations used to couple the low frequency excitation into a piezoelectric transducer have been proposed and demonstrated [1-12]. An approach referred to as plucking (or impulse excitation) based frequency up-conversion has received significant interest as it is said to improve the electromechanical coupling and efficiency of energy harvester [7-10]. Using this approach, the piezoelectric cantilever is plucked by an inertial object, which is excited at low frequency before it is left to freely oscillate at its resonant frequency.

Theoretical attempts to determine the conversion efficiency of the impact-type harvesters have been proposed by calculating the mechanical work done on the harvester [7] or using the potential energy of the inertial object [4] as the input energy. Calculating the ratio of electrical damping to the total damping of the harvester can be also used to define the conversion efficiency [5, 11]. With these methods, however, the interaction energy (e.g. friction) between the harvester and the inertial mass is ignored.
We have previously presented a novel and compact approach for extracting the energy from a rotating gear using an AFM-like piezoelectric MEMS harvester [12]. Here, we focus on experimentally evaluating the efficiency of this approach by introducing a flywheel to quantify the mechanical input energy that is provided to the harvester, including the interaction energy between the cantilever and the inertial mass. With this method, the configuration efficiency of the impact-type harvester can be studied in terms of the plucking mechanism, the coupling geometry between the harvester and the gear, the impact speed, and the harvester stiffness.

2. Theory

A flywheel is an inertial energy storage device consisting of a heavy wheel (mass) mounted on a rotating shaft (figure 1(a)) [13]. Kinetic energy is transferred to and stored in the mass as rotational energy, where the magnitude depends on the inertia and the speed of the rotation (as indicated in Eq. 1). Flywheels are typically designed to have a significant moment of inertia to allow it to resist changes to the rotational speed (angular velocity). By applying a torque, its rotational speed is increased and kinetic energy is transferred and stored in the flywheel. As the flywheel turns, the energy stored in the mass is dissipated due to friction from the air and the bearing, as well as the transfer of energy to a coupled mechanical load, thereby reducing its rotational speed.

Figure 1. (a) Schematic diagram of the proposed concept (b) Deceleration of the rotational speed of the flywheel as a function of time for different loading conditions.

The concept proposed for measuring the efficiency of impact energy harvesters is illustrated in figure 1(a). A piezoelectric cantilever is placed directly above a rotating crown gear coupled to the rotating flywheel that is suspended by bearings. The tip at the end of the cantilever extends down between the gear teeth and is plucked as each tooth passes. The gear, which is driven by the flywheel, rotates in-plane. Exploiting the cyclical nature of the flywheel, this method can be used to determine the mechanical energy that is dissipated at each impact. The kinetic energy stored in the flywheel ($E_k$) can be calculated by

$$E_k = \frac{1}{2} I \omega^2$$

where $I$ is the moment of inertia, and $\omega$ is the angular frequency of the flywheel. The moment of inertia of a solid cylinder is given by
where \( m \) is the mass and \( r \) is the radius of the cylinder.

Figure 1(b) presents an example of the flywheel operation over time. The flywheel starts with an angular velocity of \( \omega_0 \). If the flywheel is not subjected to mechanical loading, the reduction of its angular velocity is mainly due to the friction losses from air and the bearing. The change in kinetic energy of a system at a time, \( t \), is given as

\[
E_1 = \frac{1}{2} I (\omega_0^2 - \omega_{\text{no load}}^2) \quad \text{(no load condition)}
\]

\[
E_2 = \frac{1}{2} I (\omega_0^2 - \omega_{\text{load}}^2) \quad \text{(load condition)}
\]

Therefore, the mechanical input energy can be calculated by comparing the rate of deceleration in each case,

\[
E_2 - E_1 = \frac{1}{2} I (\omega_{\text{no load}}^2 - \omega_{\text{load}}^2)
\]

Using expression in (5), the mechanical input energy used to deflect the harvester in the range of rotational speeds of interest can be quantified.

### 3. Results and discussion

The experimental setup consists of an aluminium flywheel with a diameter of 50 mm and a thickness of 10 mm. The flywheel is coupled to a crown gear with a single tooth as illustrated in figure 2. An AFM-like MEMS piezoelectric cantilever, consisting of 80 \( \mu m \)-thick PZT layer bonded to a 150 \( \mu m \)-thick silicon layer, is placed above the rotating gear such that the cantilever is plucked once per rotation. More details on the harvester dimension and fabrication process can be found in [12]. A mass weighing approximately 8 mg is added to the top of the cantilever to evaluate its effect on the performance of the harvester (figure 2(c)).

![Figure 2](image)

(a) The efficiency measurement setup showing a harvester above a crown gear which is connected to the flywheel. The laser and optical detector for detecting the velocity of the flywheel are also visible. (b) A closer view of a harvester positioned above the crown gear with a single tooth. (c) The cantilever tip / gear tooth coupling for mechanical plucking. The 8 mg proof mass is also visible.
The flywheel was charged using an electric motor to an angular frequency of 125 rad/s (~20 rps). The velocity of the flywheel was monitored by optical detection. The overlap between the tip of cantilever and the gear tooth was controlled using a micrometric stage. In the experiment, harvesters with and without a proof mass were deflected 30 µm by adjusting the tip depth into the gear wheel in order to compare the performances and efficiency of both devices. The displacement of the cantilevers was observed by the laser Doppler vibrometer (LDV).

Figure 3(a) illustrates the evolution of the angular velocity of the flywheel for different loading conditions. By adding a proof mass to the cantilever, the mechanical load on the system is increased leading to larger frictional force. Thus, a greater portion of the rotational energy stored in the flywheel is required to displace the cantilever causing the angular frequency to drop faster than when a cantilever without mass is used. However, as a result of the proof mass, more energy per pluck is transferred to the load resistance due to a decrease in the mechanical damping as illustrated in figure 3(c). The energy dissipated in the load resistance can be calculated using the following expression

\[ U_E = \sum P \Delta t = \sum \left( \frac{v^2}{R} \right) \Delta t \]  

(6)

![Figure 3](a) Angular velocity of the flywheel as a function of time. Output voltage and energy dissipated in the respective optimal load at an angular velocity of 125 rad/s (~20 rps) (b) without a proof mass, and (c) with a proof mass.

Figure 3(b) shows the output voltage and the energy generated from the harvester without a proof mass at its optimal load resistance \((R_L)\) of 5.6 kΩ. The harvester produces 0.25 µJ of electric energy per pluck at a rotational speed of 125 rad/s. After adding the proof mass to the free end of the cantilever, the resonant frequency of the harvester was reduced from 6.5 to 3.2 kHz. With the proof mass, the harvester is capable of producing an output energy of 0.4 µJ at an optimal load of 7.8 kΩ. The electrical output energy increases by more than 70% with the addition of an 8 mg proof mass. The optimal load \((R_L)\) also increases as a result of a decrease in the resonant frequency since \(R_L = 1/\omega C_p\) where \(\omega\) is the resonant frequency of the harvester and \(C_p\) is the capacitance of the piezoelectric layer.

By comparing the mechanical input energy to the electrical energy generated by the harvester, the efficiency of the harvester as a function of load resistance, and rotational speed are illustrated in figure 4. The efficiency was improved by adding a proof mass to the cantilever since the increase in the electrical output energy is greater than additional mechanical input energy required to deflect the proof mass as shown in figure 4(a). The efficiency was measured to be 1.2% for rotational speeds between 113 to 125 rad/s. However, the efficiency is reduced as the gear speed falls as shown in figure 4(b). At slow rotational velocities, the harvester is not able to freely oscillate since the tip of the cantilever simply follows the contour of the gear tooth. This occurs when the movement of the gear tooth is
slower than the natural frequency of the harvester. In this situation, less energy is generated by the harvester, and therefore, the efficiency of the system is reduced.

Figure 4. Measured efficiency (a) comparing cantilevers with and without a proof mass, and (b) as a function of rotational speed.

4. Conclusion
The experimental setup presented here is a novel approach for evaluating the efficiency of impact harvesters by implementing a rotational flywheel to quantify the mechanical input energy. Using this method, the interaction forces between the harvesters and the inertial mass, including friction, for example, are accounted for. The experimental results indicate that the efficiency can be improved by minimizing the mechanical damping ratio while increasing the rotational speed. Experiments are currently being conducted with this novel setup using various harvester configurations in order to optimize the efficiency of our harvesting system.

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