The impact of impact characteristics on piezoelectric energy harvesters

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***Abstract*— In recent studies a number of new methods for energy harvesting using piezoelectric energy harvesters have been investigated, but have not made much of an impact. One of the approaches mentioned in the literature is to apply an impact to a structure rigidly connected to the energy harvester. This causes vibration of the piezoelectric material and thereby allows for energy harvesting from indirect impacts. In this paper the relation between the amount of linear momentum and kinetic energy of the impacting object on the energy output of an indirect impact-driven piezoelectric energy harvester has been investigated. A test setup has been built, which can deliver impacts to a frame to which a PZT cantilever is fixed, in order to test its output. Impacts in the range of 0.019 Ns to 0.072 Ns have been delivered by a solenoid. This was achieved by varying the speed and mass of the solenoid hammer. It has been found that that the kinetic energy of the impacting mass determines the output energy independently of linear momentum.**

I. Introduction

The usage and the range of applications of small electronic devices is increasing. These devices are decreasing in size and are often wireless, which poses challenges for their power supply [1]. A promising option for this power supply is motion energy harvesting, which is the conversion of mechanical motion into electrical energy. One type of motion energy harvesting makes use of piezoelectric material. In current literature, the emphasis lies on piezoelectric energy harvesting from forced vibrations such as [1][2][3], which is shown by Sodano, Inman and Park [4] and Saadon and Sidek [5] to require advances or innovation to increase the energy output before being able to meet the power demands of wireless electronic devices. While aforementioned literature handles forced vibration, the vibration can also be induced using impacts. In existing research on impact based energy harvesting, either the piezoelectric material itself is struck as in [6][7][8], or a structure connected to the piezoelectric material as in [9][10]. In these studies an energy harvester is designed and tested afterwards for its optimal operating range. A useful addition for designing energy harvesters would be to identify which characteristics of an impact determine its suitability for energy harvesting, as this has not been researched extensively in existing literature. This may provide insight both into what applications may be served by impact-driven piezoelectric energy harvesters, as well as how to optimize certain design parameters of these harvesters.

The objective of this study is to determine a possible relationship between the total energy output of an impact-driven piezoelectric energy harvester and the linear momentum and kinetic energy of the impacting object. Knowledge of such a relation will allow for improved identification of suitable impacts for piezoelectric energy harvesting applications. To this end, an experiment was performed in which a mass impacts the casing of an energy harvester, of which the electrical response is measured. By varying the speed and mass of the impacting object, a range of impacts with different linear momentum and kinetic energy combinations can be applied.

In order to achieve the objectives outlined in Section I, an experimental test setup that simulates impacts on the frame of an energy harvester has been built according to the design described in Section II. In section II.A a detailed description of the test setup used to perform the experiments is given. In section II.B an analysis of the test setup is performed to verify the reliability of the setup. In section III results of the executed experiments are presented. In section IV results are discussed and recommendations for further research are made. Finally, the conclusions are presented in section V.

II. Method

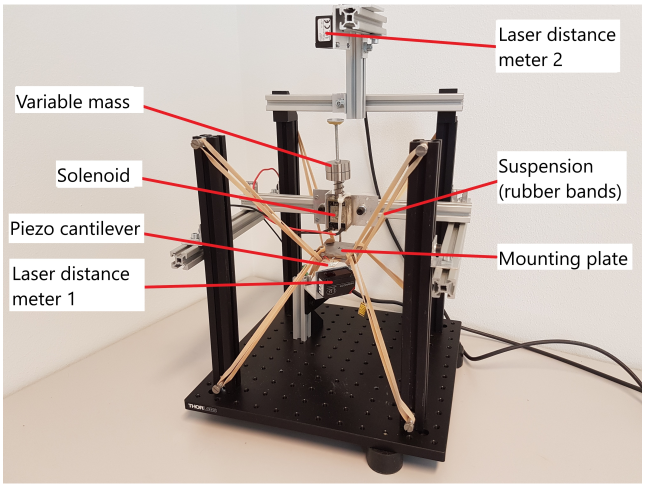

Fig. 1: Overview of test setup. Several components of the setup are labeled.

In order to measure the effect of a range of impacts a test setup was designed and built, which can deliver various impacts with high repeatability at a rate of 520 impacts per hour. This rate allows the system sufficient time to return to rest between impacts. An overview with the main components of the setup labeled is presented in figure 1. A close-up of the solenoid hammer and mounting plate is shown in 2 The impact is applied with a solenoid, where the solenoid hammer can be varied in speed and mass. The speed can be controlled by varying the voltage across the coil of the solenoid and its time of actuation. These various speeds and masses result in various kinetic energy and linear momentum combinations of the solenoid hammer. Laser distance meter 2 is used to measure the position on the solenoid hammer. The kinetic energy and linear

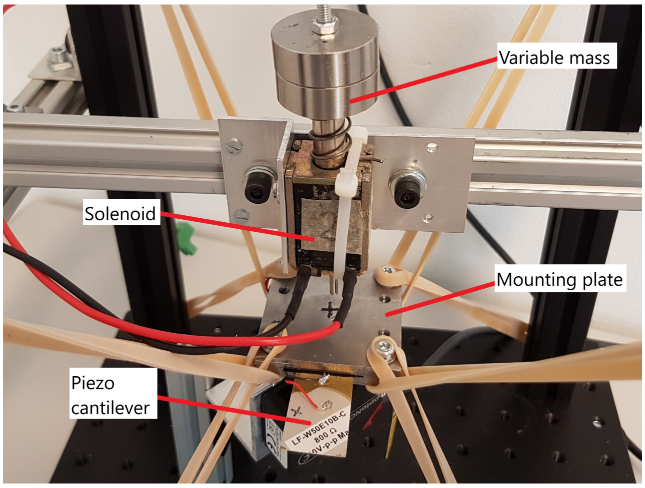

Fig. 2: Close-up of the solenoid, mounting plate and piezo cantilever.

momentum of the solenoid hammer are then numerically calculated from the position measurements. Laser distance meter 1 is used to measure the position of the mounting plate. This permits identification of the time at which the impact takes place, as well as identification of the frequency for the vertical movement of the mounting plate. Furthermore, the voltage generated by the piezoelectric cantilever is measured over a known resistance of 0.502 MOhm. This voltage response U of the piezo is then used to calculate the electrical power according to equation $P = \frac{U^2}{R}$. Integrating this over the time domain yields the total energy harvested during each run of the experiment. Relations between impact characteristics and piezo response are determined by comparing the outputs of identical piezo energy harvesters in response to different impacts. For all runs of the experiment, the same brass cantilever beam with dimensions 30.2x20.2x0.2 mm was used. It contains a 0.2 mm thick layer of piezoelectric ceramic.

A. Setup

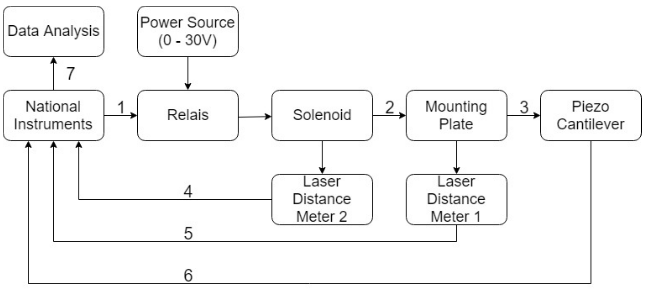

Fig. 3: Schematic diagram of test setup. 1) Solenoid controlled by NI Multifunction I/O device 2) Impact solenoid. 3) Piezo cantilever fastened to mounting plate 4) Distance between solenoid and laser 2. 5) Distance laser 1 and mounting plates. 6) Electrical output piezo. 7) Kinetic energy solenoid, kinetic energy mounting plates, linear momentum solenoid, energy output piezo.

All interactions between the main components and control system are shown in figure 3. In this section the main components are examined in further detail. The frame consists of a base-plate (300x300 mm) on which four beams (25x25x300 mm) are mounted. The rest of the setup is attached to either the base plate or these four beams. The frame was chosen to be stiff in order to minimize deformations and relative displacement of stationary components.

A construction of two steel plates is used to clamp in one end of a piezoelectric cantilever as shown in figure 2. The steel mounting plates have a thickness of 5mm in order to minimize the amplitude of vibrations resulting from the impact, and ensure their natural frequency is far higher than that of the piezo. The plates have a combined mass of 180 g, which is chosen to be much larger than that of the piezo. This ensures that the motion of the plates is minimally affected by the mass of the piezo.

The mounting plate is suspended at its four corners using pre-loaded rubber bands. The rubber bands are attached to the four beams of the frame. A total of eight pre-loaded rubber bands are used in the setup in order to maintain tension in all eight bands. This prevents swinging of the mounting plate as well as excessive movement in the horizontal plane. Due to the high damping coefficient of rubber bands the time it takes for the mounting plate to return to rest is short, thereby allowing for measurements in quick succession. The suspension is chosen with a relatively low stiffness. In combination with the large mass of the mounting plate this results in a low natural frequency of oscillation in vertical direction.

The setup simulates an impact by using a rigidly mounted solenoid to strike the centre of the mounting plate. The hammer mass and driving voltage of the solenoid can be varied to produce a range of different linear momentum and kinetic energy combinations. The experiment was performed using hammer masses of 34.5 g, 65.9 g and 98.0 g. Because an impact may be modeled as a large force over a short time, both the solenoid hammer and the mounting plate are made of steel to ensure a short duration of contact during impact.

Two laser distance meters with an accuracy of 0.5 μm and a sample frequency of 2 kHz are used in the test setup. Laser distance meter 1 measures the position of the mounting plate and laser distance meter 2 measures the position of the solenoid impact hammer. In order to process the measurements of the sensors, a National Instruments Multifunction I/O device is used which receives output values from the two lasers as well as the voltage response of the piezoelectric cantilever. During analysis, velocity data is obtained by differentiating the position data from the laser distance meters according the first order divided difference method.

B. System Analysis

In order to get a better understanding of the system behaviour a Fourier analysis has been done. Two relevant peaks at 8.7 Hz and 106.3 Hz have been found in the piezo response. From the Fourier analysis of the mounting plate position, it can be concluded that the peak at 8.7 Hz corresponds to the natural frequency of the mounting plate suspension in vertical direction. To determine the natural frequency of the piezo a Fourier transform of the piezo output has been performed where a force was directly applied to the piezo cantilever itself and subsequently released. This showed a peak at 106 Hz. From this it can be concluded that the setup will not interfere with the natural frequency of the piezo energy harvester used in this setup.

To get an idea of the robustness of the test setup a durability test has been performed. The system ran for over 60 minutes performing circa 520 impacts with constant solenoid hammer mass and solenoid actuation parameters. The results of this durability test are presented in chapter III and discussed in chapter IV.

The impact force delivered by the solenoid hammer to the mounting plate, in an ideal case, would take the shape of a Dirac delta function. In reality the contact time will not be infinitesimally short so the impact force is modeled as a scaled unit pulse over the time of contact. The time of contact between solenoid hammer and mounting plate has been measured. This was done by applying a voltage across the mounting plate and solenoid hammer and measuring the time that the circuit was closed. The contact time was found to be 124 μs, which is significantly shorter than all other elements of system behaviour. The velocity of the solenoid hammer on the moment of impact is known as well as the velocity after the impact. By determining the linear momentum transferred during the impact an approximation of the force on the mounting plate during contact can be made by using Newton's second law: $F = \frac{dp}{dt}$. In an experiment where the lightest solenoid hammer with a mass of $34.5\ g$ hit the mounting plate, the minimum velocity reached at the time of impact was $0.230\ \frac{m}{s}$. The mounting plate's linear momentum directly after impact was $0.0191\ Ns$.This is the smallest impact delivered during all experiments. When combined with the duration of impact of 124 μs and the assumption that the collision is fully elastic, this yields a mean impact force of $F_{min} = 154N$. The greatest impact was found to be 0.0720 and was delivered using the largest solenoid hammer mass of $98.0g$ with a hammer impact velocity of $0.813\ \frac{m}{s}$, which results in a mean impact force of $F_{max} = 581\ N$.

III. Results

The results of the durability test can be seen in figure 4. The red line indicates a normal distribution with $\mu = 9.5 * 10^{-8}J$ and $\sigma = 1.3 * 10^{-8}J$.

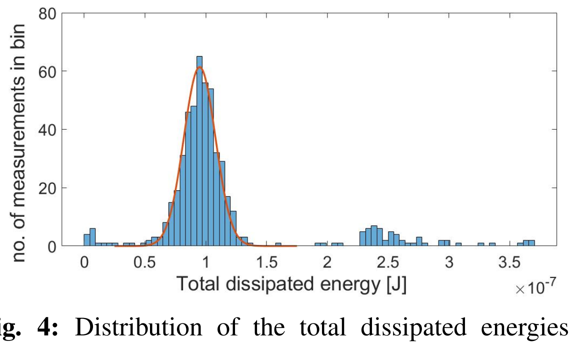

Fig. 4: Distribution of the total dissipated energies per impact for a durability test with 520 impacts

The results of the experiment are shown in figures 5-7, where each data point represents a single run of the experiment. In each figure the total energy produced by the piezo in response to the impact is plotted against respectively the velocity, kinetic energy and the linear momentum of the solenoid hammer before impact.

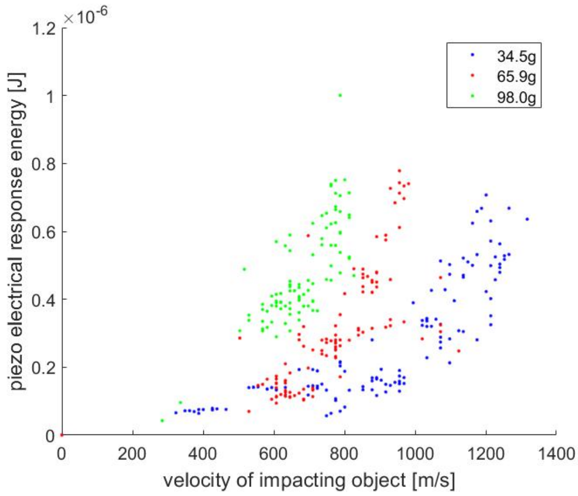

Fig. 5: Plot of the speed of the solenoid impact hammer against the piezo output voltage.

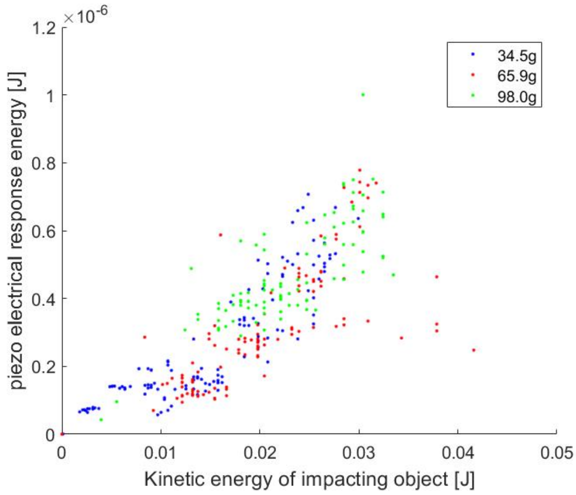

Fig. 6: Plot of kinetic energy of the solenoid impact hammer against the piezo output voltage.

IV. Discussion and Recommendations

Figure 5 shows that the response energy of the piezo increases with the square of solenoid hammer impact velocity, and also increases with increased mass, just as the kinetic energy of the solenoid would. This would seem to be confirmed in figure 6, where a linear trend can be seen between the solenoid hammer's kinetic energy at impact and the piezo response energy, though with considerable spread. Figure 7 shows that while the piezo response energy does indeed scale with the square of linear momentum for each mass individually, higher masses induce less response at the same linear momentum.

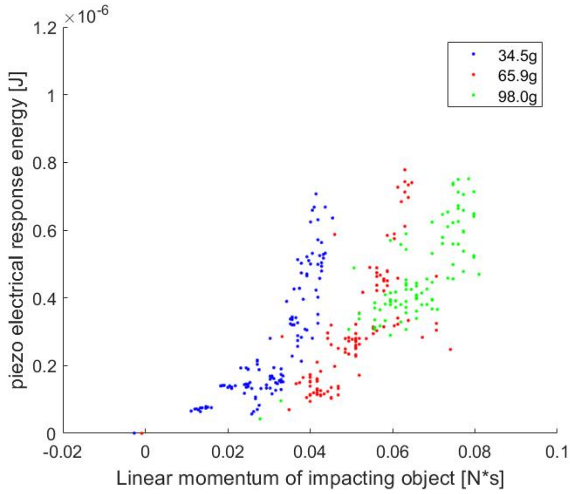

Fig. 7: Plot of linear momentum of the solenoid impact hammer against the piezo output voltage.

The second peak in figure 4 showing the distribution of total dissipated energy during the durability test can be explained by the fact that during some runs of the experiment the solenoid struck the mounting plate more than once. Disregarding these faulty measurements gives, by approximation, the normal distribution highlighted in red.

In order to improve the value of the executed research, it would be beneficial to greatly increase the range of impact velocity for all hammer masses, as well as the range of practical hammer masses. With the current setup experiments have been attempted with hammer masses up to 315 g, but this showed insufficient diversity in impact velocity. This is at least in part due to decreased stroke lengths of the solenoid for higher masses, as the mass compresses the solenoid spring under gravity such that its rest position is much lower than for lighter masses. A suitable solution might be to place the solenoid such that it strokes upward rather than downward, thereby increasing rather than decreasing the stroke length when used with greater mass. A limitation on the measurement range of the current system is that for certain conditions the solenoid strikes the mounting plate more than once. This occurs when the solenoid and mounting plates have similar oscillation times, or the duration that the solenoid is provided a voltage is sufficiently longer than the time required to strike the mounting plate. It is believed that both of these issues can be resolved by use of a feedback-controlled double latching solenoid, which would retract the hammer immediately after the impact is delivered.

Further studies can also be performed using the same test setup to verify if the findings of this paper hold for other piezo dimensions. Likewise, the setup can be used to investigate the effects of other aspects of impacts on suitability for harvesting, such as by attaching a less rigid material to the solenoid hammer to increase the time of impact. Alternatively, some aspects of harvester design may be compared to each other by subjecting different harvesters to identical impacts using the setup.

V. Conclusion

In order to identify the characteristics of impacts that determine their suitability for impact-driven piezoelectric energy harvesting, experiments have been carried out whereby various impacts were delivered to an impact-driven piezoelectric energy harvester. The objective of this experiment was to demonstrate a possible relation between the kinetic energy and linear momentum of the impacting object and the energy output of the harvester.

From the results it can be concluded that for all impacts in the measured range of linear momentum and kinetic energy combinations the piezo output energy has a linear relation with the kinetic energy of the impacting object independently of the linear momentum. The suitability of impacts for impact-driven piezoelectric energy harvesting is therefore determined solely by the available kinetic energy of the impacting object. A notable practical result of this is that energy harvesters intended to cause an impact from prescribed motion of a free moving mass at a given speed such as [9][10] will see increased energy yield if, all else being equal, the mass of the impacting object is increased. Since the devices that piezoelectric energy harvesters would typically be expected to power are small and getting smaller [4] it might be beneficial to keep the harvesters themselves small. In that case, it would be beneficial to make the free moving mass out of a dense material such as tungsten or platinum.

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