Modelling, Simulation and Analysis of a Self-healing Energy Harvester

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Abstract

The ability to harvest energy from the environment in order to provide a source of power for devices that are inaccessible and cannot rely solely on batteries is becoming an important characteristic for many sensor and health monitoring applications. Energy harvesters come in many forms, a common approach of which is to utilise environmental vibrations to generate power through the actions of the piezoelectric effect. The power generated from such devices is highly dependent upon the coupling both to the mechanical source and the electrical load of the system. Unfortunately damage to such energy harvesting devices can lead to a loss of coupling in both mechanical and electrical systems. This paper investigates an approach to ‘self-heal’ the response of an energy harvesting system once damage has occurred through the use of an anti-fuse array of ‘passive’ components to effectively re-couple the electrical load to match more efficiently and regain some loss of power generation after damage. This is first demonstrated through modelling and simulation within two state-of-the-art applications, SPICE and COMSOL and then later built into a real-world demonstrator.

Keywords: Self-healing; FEA; Energy Harvesting; MEMS

1. Introduction

The integration of embedded systems into structural assets for the use of condition-based monitoring is growing. The ability to record, track and diagnose the health of a structure or complex mechanical system such as a turbine engine provides engineers with continuous and up to date information on their performance and if necessary allows them to plan and perform any necessary maintenance. In a number of examples of structural health monitoring there is a need to power such devices without the need for wires or batteries. Wireless devices have several advantages with the flexibility, ease of implementation, and the ability to facilitate the placement of sensors in previously inaccessible locations [1]. Alternative methods for powering wireless devices include those from the field of energy harvesting. An example is kinetic energy generators, such as vibration based energy harvesters that utilize waste vibrational energy from the environment and capture this using the piezoelectric effect. There are a number of characteristics that affect the amount of energy harvested, for example the design of the system to match the source vibration frequency [2], or for the system to match the load of the sensor it is powering. Should the source vibration characteristics or the energy harvesting system change as a result of damage then the whole system will need to adapt and correct itself in order to maximize power generation.

This paper explores the modeling, simulation and analysis of a self-healing energy harvester, firstly with an overview of the two main topics of microelectromechanical systems (MEMS) and how modeling and simulation is undertaken in section 2 and a look at the field of self-healing and repair in section 3. Section 4 outlines the different modeling and simulation used to test the self-healing energy harvester approach and ends with a description of the current physical demonstrator being developed. Finally section 5 draws conclusions and presents any future work that will be pursued following this research.
2. Microelectromechanical systems

MEMS are a growing field of mechanical devices / machines built at the micro scale using fabrication techniques developed by the integrated circuit (IC) community. This class of devices is able to integrate a large number of functions by exploiting a number of phenomena, be it fluidic, chemical, thermal, magnetic or biological systems. The process of modelling MEMS devices consists of three basic steps: the modelling of the device using any number of approaches, the simulation of the behaviour of the device based on its physical characteristics and finally the analysis and visualisation of the simulation event [3].

Designers looking to build models of MEMS devices are presented with a number of abstract levels at which a designer can provide input. This hierarchical nature presents a challenge for MEMS designers of how best to approach the deconstruction of the device at the levels of modelling and analysis abstraction available. Outlined by Senturia [3] the four levels (System, Device, Physical, and Process) each contain a number of specific modelling tools and approaches, with each of these seen as a level of abstraction a MEMS device can be modelled, simulated and analysed.

The first and perhaps highest level of abstraction, the system level, focuses upon the use of lumped element circuit models, bond graphs or block diagrams to model the devices behaviour. There is also the capability to interface with mechanical elements of the MEMS device through analytical models, bond graphs or block diagrams to model the devices behaviour. This capability to connect both the mechanical and electrical allows for the ability to adjust, or tune, the resonant frequency of the energy harvester for example [9][10]. One such strategy is to build a system that resonates at a characteristic frequency. Therefore there is a limitation that such a mechanism is tied to the source vibration frequency lies within the range of around 20-300Hz, which means that in order to extract any meaningful mechanical energy requires the use of a transduction mechanism that resonates at a characteristic frequency. Therefore there is a limitation that such a mechanism is tied to a single frequency value, targeted to the source vibration frequency. In practical applications, for example those found in condition-based monitoring the healing application, that of an electronic and mechanical harvesting system maintain its match redundancy, fault-tolerance and self-diagnosis. Mechanical systems are often subject to different rules with redundancy and replacement of failing parts not an option due to cost, size and weight issues.

MEMS devices are mass fabricated, and as a result are usually very cheap to produce. So perhaps at first the idea of integrating self-healing elements into their design may seem illogical. However, most MEMS devices are integrated into bigger and more expensive systems, for example a mobile phone, and these systems require high levels of availability and reliability [12].

MEMS also inherently covers two distinct areas of self-healing application, that of an electronic and mechanical nature. As highlighted earlier for vibration based energy harvesters it is important that the system maintain its match with the source vibration frequency. In practical applications, for example those found in condition-based monitoring the source vibration frequency lies within the range of around 20-300Hz, which means that in order to extract any meaningful mechanical energy requires the use of a transduction mechanism that resonates at a characteristic frequency. Therefore there is a limitation that such a mechanism is tied to a single frequency value, targeted to the source vibration frequency, which if changed will result in a decrease or loss in energy generation function.

The design of systems which can work along a much larger frequency range have been investigated previously, for example [9][10]. One such strategy is to build a system that can adjust, or tune, the resonant frequency of the energy
harvester so that it matches the source vibration frequency should it change. This can be achieved by altering the mechanical characteristics of the transduction mechanism or the electrical load on this mechanism [9]. One approach is to use ‘Passive’ tuning, that is to tune a mechanism periodically, which uses a lower to negligible power consumption to that of an alternative approach ‘Active’ tuning which is continuously applied even after the mechanisms frequency has been restored to match that of the source vibration [9]. Continuous tuning of energy harvesters to match their resonance to a changing environment is disadvantageous due to the need to apply a continuous power supply. This is one of the reasons why an intermittent or passive strategy is more beneficial to increasing the efficiency of power output from these energy harvester systems.

Some examples of mechanical tuning of transducers include trying to change the dimensions of the device to alter its frequency, in this instance through altering the length of a piezoelectric cantilever structure [13], or by adjusting the centre of gravity of the inertial mass as demonstrated in [14]. Other methods exist and are discussed in more detail in [10].

Alternatively it is possible to electronically alter the system so as to improve matching with the target vibration frequency. A typical approach is to change the electronic damping of the system by adjusting the load, which causes the power spectrum of the energy harvester to shift. There are a number of loads that can be adjusted (resistive, inductance, and capacitance), however it is best to alter capacitive loading, where resistive loads reduce the efficiency of power transfer and the load inductances are difficult to vary [10]. An example of an electrically tunable energy harvester can be found in [15] with an overall improvement in energy efficiency of around 27%.

4. Self-healing energy harvester

A MEMS energy harvester can be constructed based upon a uni-morph cantilever design consisting of a support, piezo and proof mass material. The displacement of this cantilever as a direct result of a coupled reaction to a vibration source leads to displacement of the device and the generation of a surface potential due to the piezo effect, as shown in figure 1.

If damage should occur to the system during operation then the characteristics of the energy harvester are also likely to change as a result and no longer match the desired source frequency vibration range it was originally designed for. There are a number of ways in which such a device could fail, and these are outlined in figure 2.

Our focus is upon failure of the support or piezoelectric material and not in a catastrophic failure which renders the device completely inoperable. When such failure occurs there is an impedance matching loss, either mechanically through loss of coupling with the source vibration or electrically through electrical impedance with the source load. The approach outlined in this paper looks to incorporate passive elements that can be switched on to adjust for any electrical impedance within the circuitry after damage has occurred and essentially return partial function back to the system. This is envisioned through the use of a reconfigurable capacitive array through the use of anti-fuse technology to provide one-off additive capacitance to the system after damage has occurred as shown in figures 3 and 4.
To begin with the MEMS energy harvester has been modeled and parameterized within the multiphysics software COMSOL as a simple unimorph cantilever piezoelectric energy harvester, consisting of a support structure (Aluminium), piezoelectric material (PZT-5) and proof mass (Tungsten). The model is illustrated in figure 5, and the parameterized values are held in table 1.

A simple swept meshing is used giving a model containing around 600 degrees-of-freedom. A source frequency of 701Hz is applied to the model and its power profile for a number of resistance load values are generated and shown in figure 6.

This produces a device whose optimal resistance load matching lies at around $10^4$-$10^5$ Ohms and a power output of around $10^{-11}$ Watts. Damage was introduced into the model through the removal of some of the piezoelectric material as shown in figure 7. The resulting change in its power output profile is shown in figure 8, now generating only $10^{-14}$ Watts and an optimal resistance load of around $10^6$ Ohms. A capacitive array is introduced into the circuit to compensate for the loss from the damaged harvester and the effects upon power generation are also shown in figure 8 with the ability to shift the peak power back to its original undamaged position but with a further loss in power generation. This was expanded to include additional inductance in order to try and shift up the power curve of the damaged harvester. Figure 9 shows how this additional inductance is able to increase the power generated in this damaged energy harvester model from around $10^{-16}$ Watts back to $10^{-14}$ Watts.

Rather than focus upon a single harvester an array of harvesters was also modeled in the SPICE modeling tool, with each harvester represented as a single voltage source and capacitance value and a 1K resistance load. Setting a 1Khz frequency target source for the spice model the full energy harvester example is able to generate around 100 mV as shown in figure 10. Damaging the array but removing one of the harvesters but keeping the same load values shows a decrease once again in voltage generated, down to 87 mV as shown in figure 11. By introducing additional capacitance and inductance for each harvester in the array we are able to increase the voltage output markedly as shown in figure 12, though in reality it will be difficult to fabricate the additional inductance required on the scale of a MEMS device at this time. The modeling of the energy harvester system is a
representative approach to the effects demonstrated with the previous FEA modeling method. As a result there are drawbacks, for example its simplification of the harvester system, however it can still be used to demonstrate the effects of capacitance and inductance on the system.

Figure 8. Power generation over varying resistance loads for damaged harvester and additional capacitance (green) 1.1e-8F (red) 2.2e-8F and (cyan) 3.3e-8F.

Figure 9. Power generation over varying resistance loads for damaged harvester and additional capacitance + inductance.

Figure 10. SPICE full energy harvester array

An attempt to build a demonstrator to test this passive approach to self-healing has already begun. Using an array of four thin film piezoelectric sensors that operate at a frequency of around 180-200 Hz a simple energy harvesting array can be setup. This involves a vibration source and shaker machine and an oscilloscope used to read the output response, as shown in figure 13. By building the harvesting system to a particular resistance load value and then recording its performance, we can then remove one of the harvesters from the array and begin to test some of these passive self-healing strategies.

Figure 11. SPICE damaged energy harvester array

Figure 12. SPICE damage energy harvester array with additional capacitance and inductance.
5. Conclusions and future work

A series of modeling, simulation and experiments have been undertaken to evaluate a passive self-healing strategy for a MEMS energy harvester. This involved both FEA and circuit level models of single and arrays of piezoelectric energy harvesters. Damage was inflicted or mimicked on these models through altering the FEA model or removing one of the energy harvesters from the array completely. An original approach of using an anti-fuse capacitive array to compensate for the loss of internal capacitance as a result of damage and overcome any impedance mismatch with the circuit load was first tested, showing an ability to regain the power profile in shape but not total power output. This was improved through the addition of further passive elements in inductance, increasing the power generated above that of the damaged harvester. This was further evaluated using a SPICE model circuit of an energy harvester array showing similar results. A demonstrator is now under way consisting of an array of four thin film piezoelectric sensors set atop a vibration shaker. Evaluating and validating the passive self-healing strategy using this real world example is the next step of this research.

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References