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Modelling, simulation and optimisation of a piezoelectric energy harvester

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Abstract

The power generation efficiency of piezoelectric energy harvesters is dependent on the coupling of their resonant frequency with that of the source vibration. The mechanical design of the energy harvester plays an important role in defining the resonant frequency characteristics of the system and therefore in order to maximize power density it is important for a designer to be able to model, simulate and optimise designs to match new target applications. This paper investigates a strategy for the application of soft computing techniques from the field of evolutionary computation towards the design optimisation of piezoelectric energy harvesters that exhibit the targeted resonant frequency response chosen by the designer. The advantages of such evolutionary techniques are their ability to overcome challenges such as multi-modal and discontinuous search spaces which afflict more traditional gradient-based methods. A single case study is demonstrated in this paper, with the coupling of a multi-objective evolutionary algorithm NSGA-II to a multiphysics simulator COMSOL. Experimental results show successful implementation of the schema with all 5 experimental tests producing optimal piezoelectric energy harvester designs that matched the desired frequency response of 250 Hz.

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Keywords: self-healing; MEMS; piezoelectric; optimisation; modelling

1. Introduction

In a number of applications there is a growing need to power devices or systems, which do not require the physical connection of wires or the inconvenience of batteries. Structural or condition-based health monitoring is one such application that utilizes embedded wireless sensors to provide continuous health monitoring of such assets as turbine engines or complex mechanical systems. There are several advantages to using wireless devices, such as flexibility, ease of implementation, and the ability to facilitate the placement of sensors in previously inaccessible locations [1]. In applications such as condition-based / structural health monitoring these requirements are often essential.

Kinetic energy generators, such as vibration based energy harvesters are an alternative solution to powering wireless systems. This paper is concerned with the modeling, simulation and optimisation of vibration energy harvesters based upon inertial spring and mass systems. An example of such an inertial based generator is a piezoelectric energy harvester, which is able to utilize waste vibrational energy from the environment and capture this using the piezoelectric effect. In order to maximize the efficiency of power generation it is important that the energy harvesting system should maximize the coupling between the kinetic energy source and the transduction mechanism. This can be achieved through the design of a system where the resonant frequency of the energy harvester will match the characteristic source frequency of the application environment. 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. Exploring methods of adaptation and self-healing are therefore important for devices such as these.

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This paper begins first with an overview of the field of microelectromechanical systems (MEMS), and how simulation, modeling and design optimisation occurs within it. This is followed in section 3 with an outlining of a methodology for addressing the problem of maximizing energy harvester power generation by introducing soft-computing techniques to the application of piezoelectric energy harvester design optimisation. Section 4 presents results from a simple MEMS cantilever piezoelectric energy harvester optimization case study. Next discussion of the methodology and results are given in section 5 along with a look at self-healing systems and how it is applicable to applications such as piezoelectric energy harvesters. Finally conclusions are drawn in section 6.

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 [2].

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 [2] 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, reduced order models, electrical equivalent representations of the mechanical device or hardware description language (HDL) models. This ability to connect both the mechanical and electrical allows for the ability to integrate electronic control and sensing design with the actual physical design of the device.

The next set of modelling levels, both device and physical, vary in their granularity. The device level contains methods for the 2D / 2.5D layout modelling of devices through the use of mathematical analytical representations or nodal simulators that utilize various atomic MEMS elements to build up much larger devices. Most designers choose to build analytical models of a device due to increased device behaviour that can be simulated and because of the clarity it brings with respect to other methods [2]. There are disadvantages however, often device level analytical modelling are both difficult to create and time consuming, requiring expert knowledge to do so and often the models created are 'ad hoc' and application specific. An example can be seen with the modelling of a single stage resonator, which cannot be combined to create a multi-stage resonator model and leading to a new model having to be created [3]. On the other hand nodal simulators [4] which contain a set of accurate and physically correct 'atomic' elements built upon simpler reduced order models can be used to create planar MEMS devices by joining together the elements to create ever larger components.

The physical level looks to simulate and analyse 3D models of the device through the use of expensive finite element and boundary element methods. There are a number of advantages to using this modelling level, with often more accurate and multidisciplinary analysis (fluidic / stress) open to the designer that are often not available at lower levels of abstraction. Finally the process level looks towards the creation of mask layouts and process information needed to fabricate the device and as a result provide designs that can be feasibly fabricated.

A standard approach to modelling of a vibration-based energy harvester is as a single degree-of-freedom second-order spring-mass system using a device level analytical model [5]. A transduction mechanism such as electromagnetic [6], piezoelectric [7], or electrostatic [8] can be employed to generate electrical energy by exploiting the relative displacement or strain [9].

3. Methodology

Soft computing has played an important role in aiding design automation, synthesis and optimisation in a number of industrial and commercial fields. Within this field evolutionary computation, a more unconventional method, and designed to handle complex multi-modal design search spaces have shown great success where more traditional methods have struggled.

One of the main challenges in the development of MEMS devices is their design and optimisation [10][11]. Traditional development of MEMS by silicon micromachining fabrication techniques [12] requires multiple prototypes and extensive experimentation (design process). This trial and error approach can be expensive and is dependent on the designer's experience. The application of more non-traditional approaches that can automate the process of design and optimisation could be very beneficial.

Presented in this paper is an application of evolutionary computation towards the optimisation of a MEMS piezoelectric energy harvester. As discussed previously one of the important factors in a functional vibrational energy harvester device is for its frequency response to match that of the target source vibration from the environment. Here we tie together the evolutionary algorithm (NSGA-II) [13] from the authors developed soft computing modular framework 'SoftMod' with a physical level commercial modeling and simulation tool (COMSOL)[14] to aid designers in this task.

NSGA-II is a multi-objective evolutionary algorithm aimed at evolving optimal solutions that inhabit complex multi-modal search spaces. Here the algorithm looks to evolve a population of parameterized models over a number of generations, towards some target optimal value chosen by a designer.

In this particular problem definition the MEMS device is 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 1, and the parameterized variables with their upper and lower bounds are held in table 1. A simple swept meshing is used giving a model containing around 600 degrees-of-freedom. A frequency domain sweep is applied over a range of 1-25,000Hz, with an average analysis time of 5-6 minutes.

The aim is to optimize the parameterized values of a default shape / structure so that its characteristic frequency response matches a target value. The parameters used by the NSGA-II algorithm are shown in table 2, along with the target frequency response value. The objective in this instance is calculated by running analysis of the evolved design over a frequency range, and calculating the distance of the highest peak response (Z displacement) from the target value. Lower objective values indicate solutions that are closer to our target value (i.e. source vibration frequency) and thus superior designs.

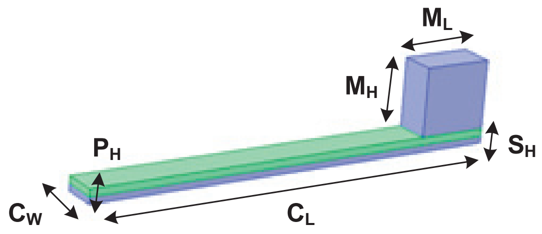

Fig 1. Piezoelectric energy harvester model

Table 1. Piezoelectric energy harvester design variables

Variable	Lower Bound (μm)	Upper Bound (μm)
Cantilever Length (C_L)	500	4000
Cantilever Width (C_W)	10	500
Piezoelectric Height (P_H)	5	50
Support Height (S_H)	5	50
Mass Height (M_H)	10	400
Mass Length (M_L)	10	200

The next section looks at the experimental results achieved through the design optimisation of a piezoelectric energy harvester.

Table 2. NSGA-II parameters

NSGA-II	Value
Probability of SBX crossover	0.8
Probability of mutation	0.05
Distribution index for crossover	20
Distribution index for mutation	20
Population size	20
Offspring size	20
Selection size	20
Generations	50
Tests	5
Target frequency (Hz)	250

4. Experimental Results

The application of our NSGA-II algorithm over the 5 separate tests has given rise to a number of experimental results. The design variables and displacement amplitude characteristics for the optimal designs found for each test are displayed in table 3 and the average frequency error of the population for each run over the course of the experiment is shown in figure 2.

The COMSOL model of the optimal design for test 1 is shown in figure 3 along with its 1^{st} mode frequency displacement response. Figures 4 and 5 show the displacement of the device over a frequency range of 2 kHz showing peak displacement at 251.24 Hz and its voltage characteristics. It should be noted that the results are all based on computational models and not physical fabrications so there is a loss in accuracy.

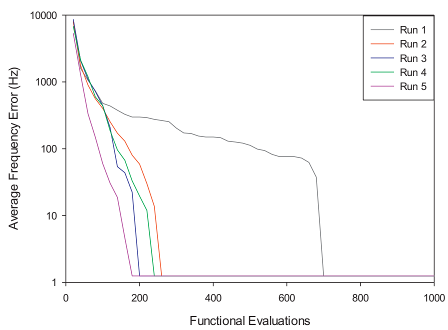

Fig 2. Average frequency error values for tests 1-5

Table 3. Optimal design variables for tests 1-5

Variable	Test 1	Test 2	Test 3	Test 4	Test 5
C_L (μm)	3747.7	2839.0	3403.5	3644.6	3477.5
C_W (μm)	45.9	396.7	218.4	45.1	34.3
P_H (μm)	14.9	8.9	6.7	5.9	6.8
S_H (μm)	5.0	5.9	7.4	7.3	8.3
M_H (μm)	376.2	386.6	314.5	175.2	189.7
M_L (μm)	155.3	158.3	93.3	90.3	152.9
Dis (μm)	3.21	8.30	7.98	1.99	1.38

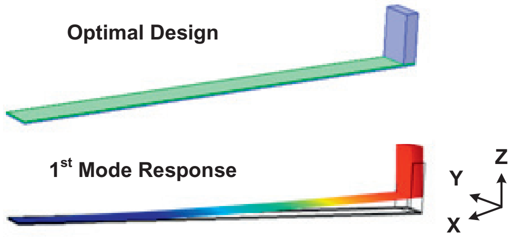

Fig 3. Test 1 optimal design and 1st mode frequency response

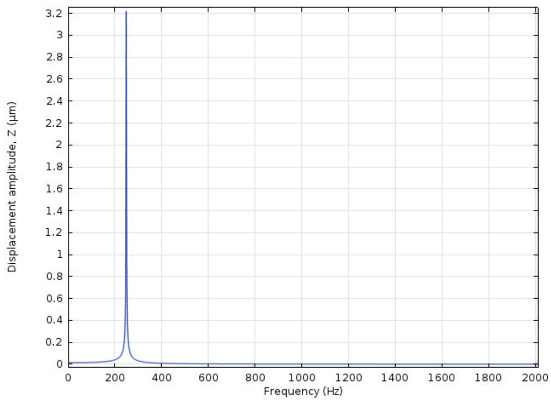

Fig 4. Test 1 optimal design displacement (Z) vs frequency

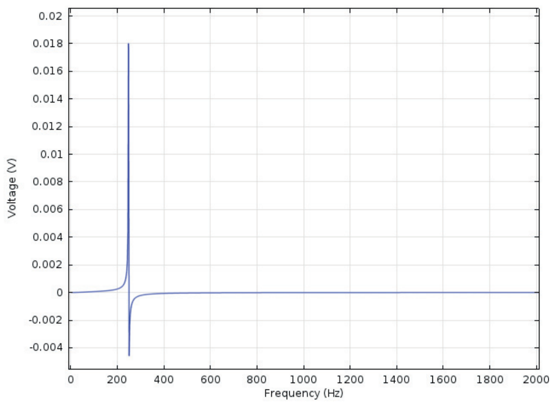

Fig 5. Test 1 optimal design terminal voltage vs frequency

5. Discussion

The design and optimisation of a simple vibration based piezoelectric energy harvester is the first step in envisioning a self-healing energy harvester capable of returning function and increasing efficiency of power generation after damage has occurred. This process begins firstly with the ability for designers to quickly and efficiently model, simulate and optimize piezoelectric energy harvesters to match their target application.

Traditional design and optimisation of MEMS can be slow, costly and often unable to actually lead to the most optimal solution. Over the recent decades the increase in the number of modelling and simulation tools has helped to automate the process of design, giving designers tools to build 'in-silica' devices which no longer have to be fabricated to be tested. However hand driven optimisation or local gradient based search algorithms are still common practice among designers. With the ever increasing complexity of MEMS design this approach will struggle. Recently there has been a shift into the use of more stochastic algorithms and given the nature of most engineering problems these are at a multi-objective level.

Within the field of soft-computing, biologically inspired multi-objective algorithms such as NSGA-II have been applied to numerous design optimisation problems and have shown to be a great success. The application to MEMS design automation and optimisation is an area of research which could also be greatly enhanced, and could lead to reduced costs and time to manufacture as well as opening up new areas of application through the creation of novel designs.

The application of NSGA-II in this instance has shown itself to be wholly successful in optimizing default designs to match target frequency characteristics, with all 5 experimental tests achieving the target goal. Examining figure 2 it can be seen that optimal designs are evolved using a relatively small number of functional evaluations for 4 out of the 5 tests, at around or under 15 generations or 300 functional evaluations. This amounts to a reduction in total error from the initial randomized population of on average 7500 Hz down to just 1 Hz.

The evolved designs, shown in figure 3 and table 3 typically consist of a larger cantilever structure in terms of length with thin piezoelectric and support material structures. The expansion of this optimisation routine to include more complex 'shape' design, rather than the current rigid cantilever 'sizing' design or introduction of constraints on maximum length may help lead to more desirable compact designs, though at a cost of optimisation complexity. Moving on from simple design optimization, the ability to incorporate technologies and architectures that can implement some degree of autonomous self-repair or increased robustness could prove to be very valuable for these kinds of devices.

The concept of 'self-healing systems' can be found in a number of research fields and activities such as electronics or mechanical design. Here we look towards systems which exhibit some form of resilience against damage, a level of redundancy in which to maintain some degree of functionality after a failure has occurred, or the ability to regain functionality through the ability of self-repair or reconfiguration [15]. A review of current progress of self-healing and self-repairing technologies can be found in [16].

The field of electronics lends itself more to self-healing strategies due to the ability to incorporate high levels of 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 [16].

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 [8][9]. 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 [8]. 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 [17], or by adjusting the centre of gravity of the inertial mass as demonstrated in [18]. Other methods exist and are discussed in more detail in [9].

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 [9]. An example of an electrically tunable energy harvester can be found in [19] with an overall improvement in energy efficiency of around 27%.

The next step involves investigating methods for passive frequency tuning after damage has occurred to the energy harvesting system through the use of an array of capacitive components. Here the authors look to implement self-healing technology that will allow a one-time reconfiguration after damage (break or deformation of material) through the use of anti or poly-fuse technology to alter the capacitive load on the electrical system.

6. Conclusions

The integration of self-healing or self-repairing technology into commercial products can both reduce the occurrence of maintenance and repair interventions, but also lengthen the lifetime of the product. Piezoelectric energy harvesters require close coupling between the source vibration frequency and its own transduction mechanism. The first step is in designing an energy harvesting system which matches its target application frequency. The next step is integrating into this design tunable or reconfigurable elements which allow the energy harvesting system to regain function and power generation efficiency when environmental change or physical damage lead to a de-coupling and loss of function.

This paper outlines a methodology for tackling the first step by the integration of a soft computing framework with a multiphysics modeling and simulation tool for MEMS design optimisation. A simple case study is used to demonstrate this approach, with the design of a cantilever based piezoelectric energy harvester targeted towards a source vibration frequency of 250 Hz. The methodology proved successful with all 5 experimental runs ending in the evolution of optimal designs which matched the target objectives utilizing only a small number of functional evaluations.

Future work now looks towards the design and integration of passive self-healing components designed to allow return of function after damage has occurred to the energy harvesting system.

Acknowledgments

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