THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Conjoined piezoelectric harvesters and carbon supercapacitors for powering intelligent wireless sensors

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COVER: "From blueprint to reality"
Energy sources for intelligent wireless sensors, where a backfolded conjoined piezoelectric energy harvester is packaged together with a supercapacitor pack and a power management module, ready to be connected and deliver power to an intelligent wireless sensor.

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Abstract
To achieve total freedom of location for intelligent wireless sensors (IWS), these need to be autonomous. To achieve this today there is a need of broadband piezoelectric energy harvesting and a long-lasting energy storage. The Harvester need to be able to provide sufficient amount of energy for the intelligent wireless sensor to perform its task. The energy storage needs to fulfill the requirement of a large number of charge discharge cycles and contain sufficient power for the intelligent wireless sensor.

The biggest issue with piezoelectric energy harvesting today is the bandwidth limitation. Solutions today to achieve larger bandwidth make a tradeoff where the output is decreased. The biggest issue for energy storage today is the limitation of energy density for supercapacitors and the lack of sufficient life cycles for batteries.

This thesis aims to realize piezoelectric energy harvesters with broad bandwidth and maintained power output. Moreover, for energy storage in the form of supercapacitors realize an electrode material that has a high effective surface area, good conductivity not dependent on a conductive agent and can be used without a binder. This thesis cover background and history of the two fields, discussion of technologies used and presents solutions for piezoelectric energy harvesting and carbon based supercapacitor storage.

A Backfolded piezoelectric harvester was made of two conjoined piezoelectric cantilevers, one placed on top of a bottom cantilever. By the backfolded design this thesis show that by utilizing the extended stress distribution of the bottom cantilever a maintained power output is achieved for both output peaks. By introducing asymmetry where the top cantilever have 80% length compared with the bottom cantilever the bandwidth was increased. An effective bandwidth of 70 Hz with voltage output above 2,75 V for 1 g is achieved.

To achieve further enhanced bandwidth a piezoelectric energy harvester with selftuning was designed. The selftuning was achieved by a sliding mass on a beam, which is conjoined, to two piezoelectric cantilevers in a backfolded structure. By introducing length asymmetry, the effective bandwidth was enhanced to 38 Hz with a power output above 15 mW, for 1 g, which is sufficient for an intelligent wireless sensor to start up and transmit data.

To utilize the positive output effect from conjoined cantilevers a micro harvester was fabricated. The design was based on the same principle as for the backfolded, but for fabrication reasons the design was made in one plane. The harvester contain two outer cantilevers conjoined to a backfolded middle cantilever. Due to fabrication difficulties, only a mechanical characterization of the harvester was possible. The result from the characterization looks promising from a harvesting point of view, by showing a clear peak that seems to be somewhat broadband.

Energy storage for an autonomous intelligent wireless sensor (AIWS) needs to be able to charge and discharge during the lifetime of the AIWS. Therefore the choice fell on supercapacitors instead of batteries. Over time the supercapacitor due to its superior amount of charge and discharge cycles, outperform a battery when energy density is compared.

Increasing the energy density for supercapacitors gives the advantage to prolong the providing of power to the IWS. One such electrode material is conjoined carbon nanofibers and carbon nanotubes. The material is not dependent on conductive agents or binders. The effective surface area can be expanded through a denser structure of CNF, where more CNT can grow. In combination with activation, which will yield more micropores, hence an increased capacitance. The presented synthesized (not activated) material yielded 91 F/g with an effective surface area of 131 m².

There is many challenges to power an IWS on a gasturbine. This thesis cover challenges like vibrations on cables, placement issues and the charge of a supercapacitor by harvested energy that comes in small chunks. Solutions for these challenges are offered.

The presented work in this thesis shows how the bandwidth for piezoelectric energy harvesters can be broader by asymmetric implementation of conjoined resonators. In addition, the advantages of conjoined carbon electrode materials to be implemented as electrode material in supercapacitors. Both harvester and storage are intended to be used as energy sources for intelligent wireless sensors.

Keywords: Intelligent wireless sensor, Supercapacitor, electrode material, carbon nanomaterials, Kinetic harvesting, piezoelectric energy harvesting, selftuning, coupled resonators
“A parent's energy is harvested in full from the one given by their children”

To Nelly & Noah
List of appended papers
This thesis is based on the work in the following appended papers:

Paper I
SIMULATION AND EXPERIMENTAL DEMONSTRATION OF IMPROVED EFFICIENCY IN COUPLED PIEZOELECTRIC CANTILEVERS BY EXTENDED STRAIN DISTRIBUTION
L G H Staaf, E. Köhler, D. Parthasarathy, P Lundgren and P Enoksson

Paper II
IMPACT OF DESIGNED ASYMMETRIES ON THE EFFECTIVE BANDWIDTH OF A BACKFOLDED PIEZOELECTRIC ENERGY HARVESTER
L G H Staaf, A Smith, E. Köhler, P D Folkow, P Lundgren and P Enoksson
Submitted

Paper III
ACHIEVING INCREASED BANDWIDTH FOR 4 DEGREE OF FREEDOM SELF-TUNING ENERGY HARVESTER
L G H Staaf, A Smith, E Köhler, P D Folkow, P Lundgren and P Enoksson
J. Sound Vib., vol. 420, pp. 165–173, 2018

Paper IV
EFFECTIVE PIEZOELECTRIC ENERGY HARVESTING BANDWIDTH ENHANCEMENT BY ASYMMETRY AUGMENTED SELF-TUNING OF COUPLED CANTILEVERS
L G H Staaf, A Smith, P D Folkow, P Lundgren and P Enoksson
Submitted

Paper V
A MICRO-MACHINED COUPLED-CANTILEVER FOR PIEZOELECTRIC ENERGY HARVESTERS
A Vyas, L G H Staaf, C Ruso, T Ebefors, J Liljeholm, AD Smith, P Lundgren and P Enoksson
Micromachines 2018, 9(5), 252; https://doi.org/10.3390/mi9050252

Paper VI
PRESENT AND FUTURE SUPERCAPACITOR CARBON ELECTRODE MATERIALS FOR IMPROVED ENERGY STORAGE USED IN INTELLIGENT WIRELESS SENSOR SYSTEMS
L G H Staaf, P Lundgren and P Enoksson

Paper VII
HIERARCHICAL CELLULOSE- DERIVED CNF/CNT COMPOSITES FOR ELECTROSTATIC ENERGY STORAGE

Paper VIII
PIEZOELECTRIC ENERGY HARVESTING AS ENERGY SOURCE FOR AUTONOMOUS INTELLIGENT WIRELESS SYSTEMS ON GAS TURBINES
L G H Staaf, E Köhler, J Kemp, M Allen, S Zenkic, A Lindblom, M Christodoulou, J Roberts, P Lundgren and P Enoksson
EVI-GTI and PIWG Joint Conference on Gas Turbine Instrumentation, 2016, p. 4 (17 .)-4 (17 .)
Papers not included due to overlap or being outside scope of this thesis:

CAPACITIVE EFFECTS OF NITROGEN DOPING ON CELLULOSE-DERIVED CARBON NANOFIBERS
Volodymyr Kuzmenko, Olga Naboka, Henrik Staaf et al

HIGH TEMPERATURE ENERGY HARVESTER FOR WIRELESS SENSORS
Elof Köhler, Richard Heijl, Henrik Staaf et al
Journal of Smart Materials and Structures. Vol. 23 (9), p. Art. no. 095042-

SUSTAINABLE CARBON NANOFIBERS/NANOTUBES COMPOSITES FROM CELLULOSE AS ELECTRODES FOR SUPERCAPACITORS
Volodymyr Kuzmenko, Olga Naboka, Mohammad Mazharul Haque, Henrik Staaf et al

VERIFICATION OF SELF-TUNING 4DOF PIEZOELECTRIC ENERGY HARVESTER WITH ENHANCED BANDWIDTH
Henrik Staaf, Elof Köhler, Anderson David Smith et al
PowerMEMS 2017, The 17th international conference on Micro and Nanotechnology for Power Generation and Energy Conservation Application, November 14-17, Kanazawa, Japan

SELF-TUNING ENERGY HARVESTER BY SLIDING WEIGHT
Henrik Staaf, Elof Köhler, Peter Folkow et al
Svenska Mekanikdagarna 2017, 12-13 juni, Uppsala, Sverige

MINIATURIZED SUPERCAPACITORS FOR SMART SYSTEMS
Qi Li, Volodymyr Kuzmenko, Mohammad Mazharul Haque, Henrik Staaf et al
Smart Systems Integration 2017, 8 - 9 March, Cork, Ireland

SMART DESIGN PIEZOELECTRIC ENERGY HARVESTER WITH SELF-TUNING
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NANOCOMPOSITE MATERIALS FOR MINIATURIZED SUPERCAPACITORS
Qi Li, Volodymyr Kuzmenko, Mohammad Mazharul Haque, Henrik Staaf et al

SUPERCAPACITOR WITH INCREASED CAPACITANCE AT 200°C
Elof Köhler, Henrik Staaf, Peter Enoksson
IET Conference Publications. EVI-GTI and PIWG Joint Conference on Gas Turbine Instrumentation; Berlin; Germany; 27-29 September 2016 (CP693)

PROOF OF CONCEPT THERMOELECTRIC ENERGY HARVESTER POWERING WIRELESS SENSOR ON GAS TURBINE
Elof Köhler, Henrik Staaf, J. Kemp et al
EVI-GTI and PIWG Joint Conference on Gas Turbine Instrumentation, Berlin, Germany, 27-29 September 2016 (CP693)
FREESTANDING CARBON NANOFIBERS/GRAPHENE COMPOSITE ELECTRODES FOR SUPERCAPACITORS
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The World Conference on Carbon - Carbon 2016, July 10-15, State College, PA, USA

PIEZOELECTRIC ENERGY HARVESTING AS ENERGY SOURCE FOR AUTONOMOUS INTELLIGENT WIRELESS SYSTEMS ON GAS TURBINES
Henrik Staaf, Elof Köhler, J. Kemp et al
EVI-GTI and PIWG Joint Conference on Gas Turbine Instrumentation, Berlin, Germany, 27-29 September 2016 (CP693)

SMART DESIGN FOR MEMS PIEZOELECTRIC HARVESTER
Agin Vyas, Henrik Staaf, Peter Enoksson
Micronano System Workshop MSW 2016, 17-18 May, Lund, Sweden

HIERARCHICAL CELLULOSE-DERIVED CARBON NANOCOMPOSITES FOR ELECTROSTATIC ENERGY STORAGE
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Henrik Staaf, Elof Köhler, Manuel Soeiro et al

SUSTAINABLE SUPERCAPACITOR COMPONENTS FROM CELLULOSE
Volodymyr Kuzmenko, Arun Bhaskar, Henrik Staaf et al

CARBON NANOTUBES/NANOFIBERS COMPOSITES FROM CELLULOSE FOR SUPERCAPACITORS
Volodymyr Kuzmenko, Muhammad Amin, Olga Naboka Henrik Staaf et al
16th European Conference on Composite Materials, ECCM 2014; Seville; Spain; 22 June 2014 through 26 June 2014

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Edoardo Trabaldo, Elof Köhler, Henrik Staaf et al

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Volodymyr Kuzmenko, Muhammad Amin, Olga Naboka, Henrik Staaf et al
The World Conference on Carbon (Carbon2014), June 29 - July 4, Jeju, South Korea. Vol. ORT6-54

NITROGEN-DOPED CARBON NANOFIBERS SYNTHESIZED FROM ELECTROSPUN CELLULOSE AS SUPERCAPACITOR ELECTRODE
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Henrik Staaf, Muhammad Amin, Gert Göransson et al

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Elof Köhler, Richard Heijl, Henrik Staaf et al

FUTURE ELECTRODE MATERIALS FOR SUPERCAPACITORS IN INTELLIGENT WIRELESS SENSOR SYSTEM
Henrik Staaf, Peter Enoksson, Per Lundgren
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Lindome, oktober 2018

Henrik Staaf
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1 INTRODUCTION

1.1 BACKGROUND

When autonomous intelligent wireless sensors are mentioned, you may start thinking about advanced technical gadgets equipped with AI, like a drone able to perform tasks. But back in time, in a way, the first intelligent wireless sensor node was a beacon with a scout on a peak at a coastline. Set up in a network along the coast, these beacons when lit, were warning people of approaching enemies. In this ancient case, we the humans, where the autonomous intelligent sensor and the beacon was acting as a transmitting system and put together with a chain of beacons the direct translation for today would be an intelligent wireless sensor network. Imagine that these scouts stood there for hours, days, weeks, months looking at the horizon. Surveying from the coastline, waiting, and if they saw a ship had to decide if it was a friendly or a hostile, using optical sensors, the eyes. This was not a one man task, since it was very tedious and sleep is needed, a number of men had to be assigned to each beacon. It took humanity until recently, when wireless sensors started to be used as forest fire detectors [1], [2] to replace humans as overseers. Solutions for autonomous wireless sensors by energy harvesting windmills are investigated [3] to make these nodes completely autonomous. These fire detectors have the ability to cover a huge area and replace human watchtowers and video surveillance, making it more cost efficient and easier to oversee.

Further, intelligent wireless sensor systems are beginning to be used to monitor numerous things in our surroundings. Where an intelligent wireless sensor (IWS) gathers data, processes the data and transmits the result to a monitoring device. Together with an energy harvester converting ambient energy to electricity it becomes an IWS system that can work autonomously [4]–[9]. Being able to monitor the health of buildings [10], structures [11], machines [12], human body [13], conditions of roads [14] etc. (Figure 1.1). This will have a positive impact on our lives, since with more efficient monitoring, energy consumption can be reduced. Examples of this are the warming and cooling of houses [15] and fuel consumption for example airplanes [16], which properly monitored and controlled will use less energy resources and will generate less pollution.

Today we are mostly limited by the quantity and length of cables that have to be used for the sensors, or the lifetime of batteries, which have to be replaced in IWS. These boundaries limiting the possibilities to place a sensor or an IWS anywhere, to be operational for a very long time [17].
One of the main challenges for IWS systems is the power consumption where a great deal of research has been done over the last years to compress the transmitting data, hence consume less power [18]. Also, progress in low power circuits technology makes it easier to craft IWS systems for more applications. Despite these efforts, 2-3 mW is used to transmit data wirelessly [19], [20].

The wireless transmission is not usually continuous but occurs in intervals while the energy harvester scavenges energy to be used for the transmissions. An even bigger challenge is the powering of the startup sequence for the wireless transmitter which consumes most power about 8-240 mW [21], which is far from reachable directly for most harvesters today. Therefore, a smart power manager has to be used combined with a storage device, that first store the energy and then release enough energy for first the startup sequence of the RF interface and then supply enough power for the RF interface to be able to send data intermittent.

For more data and further accurate data reading numerous IWS are connected in a network called a wireless sensor network (WSN). By using many IWS in a WSN the readings get more accurate and the IWS can transfer data between each other and do not have to have a direct connection to the gateway (Figure 1.2) [22].

---

**Figure 1.1** An overview of different possible ambient energy sources available for energy harvesting to provide power to Intelligent wireless sensor systems.
1.2 SCOPE AND OUTLINE

The scope and outline of this thesis is to investigate power sources for intelligent wireless sensors, primarily on gas turbines. These power sources are divided into energy storage and energy harvesting.

In chapter 1, intelligent wireless sensor systems are described, including an overview of the components that such a system contains; energy storage and energy harvesting solutions for these systems are presented.

In chapter 2, piezoelectricity and its mechanism and how to harvest energy with a piezoelectric harvester are described. The development of novel designs with conjoined cantilevers for a piezoelectric harvester to be used for a gas turbine sensor application is presented (Figure 1.3, Paper I – V). The impact of a conjoined design with two cantilevers and with selftuning is investigated for further improvement in power output and for reaching a wider bandwidth. A micro harvester with conjoined cantilevers in one plane is also presented.

In chapter 3, supercapacitors are presented. The background theory and the specifications of electrode materials for supercapacitors used in IWS systems are presented. Results from recent research on carbon allotropes as electrode material are presented and evaluated to find a way
towards new and better electrode material (Paper VI). Further is a conjoined carbon electrode material based on CNFs and on CNTs grown on CNFs presented (Paper VII).

In chapter 4, measurements in an authentic commercial test environment on a gas turbine is presented along with a discussion on remaining challenges and potential solutions (Paper VIII).

The 5th and final chapter comprises discussion, conclusion and suggestions for future work based on the results from previous chapters in the thesis.

Figure 1.3 Schematic of an intelligent wireless sensor and its components. Presented is also the research areas for this thesis, marked as Paper I – VIII.

1.3 COMPONENTS OF AN INTELLIGENT WIRELESS SENSOR SYSTEM

An autonomous intelligent wireless sensor (AIWS) system is assembled from different components and needs an ambient source of energy. The IWS itself holds the sensor, CPU and RF interface. Where the sensor is used for collecting nearby data that the central processor unit (CPU) will process, and the RF interface sends and receives data. A power manager distributes the energy between the sensor, the CPU, the RF interface and the energy storage. For the AIWS system, a harvester is added, that will harvest enough energy for the AIWS to start up and manage its dedicated task (Figure 1.3).
1.3.1 DC converter and power manager
The harvested energy that is converted into electricity often comes in the form of an AC signal, while low power circuits needs a DC power supply. The input AC goes through an AC/DC converter and the DC goes through a power manager circuit that either directly is feeding the sensor, RF interface or the CPU, any residual energy is forwarded to the energy storage. Due to the often stochastic feed from the harvester, small chunks of energy come to the power manager which needs a clever algorithm to be able to distribute the energy properly. The power consumption is often a limiting factor and the power manager repeatedly needs to gather enough energy from the harvester to power the onboard RF interface, which is sending in intervals [23].

The MIDE EHE004 is the energy harvesting power manager used with the piezoelectric energy harvesters in this thesis. It has a full wave rectifier with charge management and DC conversion. The output can be chosen to the following settings: 1.8 V, 2.5 V, 3.3 V and 3.6 V, where 3.3 V is the choice in this thesis due to the input demand from the RF interface used. It also has the option of connecting auxiliary energy storage where enough power can be stored to start up the RF interface or act as a backup if there is a period where no ambient energy is present.

1.3.2 The intelligent sensor
An intelligent sensor interprets the collected data from the sensor by a microprocessor which makes calculations and analyses the data from given boundaries. If the analyzed result needs to be transmitted, the data is compressed and the information will be sent to a central unit. The sensor and the microprocessor have to be one physical unit to be called an intelligent sensor. A sensor where the only function is to detect and send an unprocessed signal to an external system, which then performs some action, is not considered intelligent. To make the intelligent sensor more effective, a network of sensors can be setup that works together is in a so called wireless sensor network (WSN) as mentioned in paragraph 1.1 [24], [25].

An intelligent sensor can be defined as:
“A smart sensor provides various functions beyond those necessary to generate better decision making or better controlled quantity. The intelligence aspect is improved in a networked environment” [26].

Is an intelligent sensor smart and or intelligent? Or is it just a label we describe them with, since an intelligent sensor is monitoring something, all the time. By putting many sensors together, the decision pattern can mimic something we would call an intelligent pattern where the outcome is to perform a (for a human) simple task. In addition, more important where do we, humans, draw the line for tasks being performed based on decisions made, established on intelligent sensors input. It is nice and comfortable to hand over tedious monitoring tasks to intelligent sensor systems, but questions remain, if we cross that line, will intelligent sensor based systems have hiccups? Like not passing on vital information, not due to malfunction, but decisions based on input from the intelligent sensors, which might cause death [27]. We are not there yet, and answers about the future is not easy to predict. However, as long as we implement advanced intelligent wireless sensor systems based on a proper investigation, we hopefully will not find ourselves surrounded with systems deciding what is best for us and not the other way around.
An example where many sensors are used to perform a simple task is a robotic vacuum cleaner, shown schematically in Figure 1.4. In order to be able to conduct cleaning, the robot has to navigate in rooms with obstacles in the vicinity. Mechanical bumpers, in the front, can be used to detect when the robot touches a wall or an obstacle. Proximity sensors that utilize infrared or ultrasound can also be used for the same purpose. Under the robotic vacuum cleaner, you will need sensors to detect the absence of surface (cliff sensors), like when encountering a stair. For localization and mapping there are different options to choose from:

- Cameras
- Ultrasound sensors
- Laser rangefinder
- Wheel encoders

Then there is the task of cleaning, for which you need sensors that sense the bin level, battery level, brush being stuck and detecting dust on the floor [28], [29]. All sensors put together with the task to clean and charge itself, actually make the robotic vacuum cleaner an advanced autonomous intelligent sensor system.

![Figure 1.4 Schematic of a robotic vacuum cleaner with sensor positions, top (left) and bottom (right) view.](image)

1.3.3 Energy storage

1.3.3.1 Batteries

Today batteries are the main energy source for IWS [30]. The advantages of batteries are their high energy density, as presented in the schematic Ragone plot [31] in Figure 1.5. The foremost drawback when using primary batteries is that they have to be replaced when depleted. If secondary batteries are used in conjunction with a harvester, the number of rechargeable cycles are still very limited (<1000) [17] and thus they too eventually have to be replaced. The increasing amount of
disposed batteries is also a major environmental concern, as recycling still is very low even though loads of research on recycling for the hazardous components in batteries are performed [32]–[37].

1.3.3.2 Supercapacitors
Supercapacitors, also named ultracapacitors have attracted attention because of their capability of fast power intake and release (Ragone plot in Figure 1.5), their long cycle life and that they are eco-friendly. Supercapacitors are used as backup power for computers, power booster for forklifts, and power source from brake energy recovery for brake systems in hybrid vehicles among many other applications [38]–[43]. Despite its lower energy density, the supercapacitor is a good choice compared to batteries due to its high number of recharge cycles \(10^6\). Therefore, over its lifetime, it reaches a higher accumulated energy density than batteries, as shown in Paper VI.

![Figure 1.5 Schematic Ragone plot for energy storage and conversion devices. The indicated areas are rough guide lines between the different storage techniques. The Y-axis indicates how fast an energy storage can unload or load its power and the X-axis indicates how much energy it can store.](image)

1.3.4 Energy harvesting
To gain greater strength than the human body could muster, or have energy for long tedious tasks, humanity had to scavenge energy from its surroundings and convert it into usable energy. Hence the first harvesters were born in the shape of the waterwheel and the windmill [44]. Humanity has since continued to harvest energy from ambient renewable sources and today primarily converts it to electric power by e.g. water turbines, wind turbines, photovoltaic cells and thermoelectric converters.
Figure 1.6 An overview of energy harvesting from different ambient energies with conversion to electricity.

Depending on the location of the AIWS system, different ambient energy sources can be utilized to power it (Figure 1.6). Small AIWS are used for applications such as:

- Environmental monitoring
- Surveillance
- Structural monitoring
- Interaction and control
- Medical remote sensing
- Military applications
- Aerospace
By applying powering through energy harvesting in such AIWS applications, benefits will arise in the terms of the AIWS becoming maintenance free. Then it can be placed in inaccessible sites where operability else would be impossible due to impractical cable length or that the AIWS is permanently built into a structure. Smart choices of energy harvesting and energy storage will increase the operability of the AIWS. By substituting batteries with energy harvesters, we will have a big cost saving by not having to replace batteries, eliminating also the need to handle their chemical disposal [32]–[37].

In a specific case, a gas turbine, two main ambient sources of energy are found: heat and vibrations. Thus, energy can be harvested by thermal harvesters and by kinetic piezoelectric harvesters. On a test site, the number of sensors is counted in hundreds and the cable length per sensor is hundreds of meters. Reducing the usage of cables on test sites will make the testing much easier and faster. In the future, reducing the amount of cables to sensors, on the gas turbine mounted to an airplane, will make the engine weigh less and therefore also use less fuel. To prolong operation time of the AIWS the main challenge today is to replace batteries with energy harvesters [45], [46].
2  PIEZOELECTRIC VIBRATION ENERGY HARVESTING

In this chapter, piezoelectricity is scrutinized. By its mechanism and how to harvest energy with mechanically coupled resonators, in the shape of a piezoelectric harvester are described. The development of new designs for piezoelectric harvesters to be used for gas turbine applications is presented. The impact of conjoining two cantilevers is covered, which utilizes extended stress distribution, and is presented on: a backfolded harvester, a self-tuning harvester and a micro harvester.

2.1  PIEZOELECTRICITY

In 1880 Jacques and Pierre Curie demonstrated the piezoelectric phenomena [47] based on their knowledge in pyroelectricity and of the basic crystal structures to forecast the behavior of crystals with piezoelectric properties [48]. Piezoelectricity is an electric charge that is accumulated in crystals [49], some ceramics [50], can be found in DNA [51], [52] and specific proteins [53], when a mechanical stress is applied. The first application to utilize piezoelectricity was a sonar device developed by Paul Langevin 1917 in France [49]. It was used to detect submarines and was made of a transducer, which was composed of thin quartz crystals, packaged in glue between two steel plates. It was connected to a hydrophone, which detected the echo that was returning from the submarine. By measuring the time until the echo was heard, the distance to the submarine could be calculated. Today a popular application for piezoelectric ultrasound transducers is to mount them on the rear of many cars and help the driver to conclude if any object is directly behind the car and therefore not visible to the driver [54].

![Figure 2.1 Overview of direct piezoelectric effect; (a) Piezoelectric material after poling under no impact of strain, (b) Energy generation under compression, where the voltage has the same polarity as poling voltage (c) Energy generation under tension, where the voltage has polarity opposite of poling voltage.](image)

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2.2 MECHANISM OF PIEZOELECTRIC MATERIALS

Piezoelectric effects are closely related to the existence of electric dipole moments in solid materials [55], [56]. The dipole polarization is calculated for crystals by adding the dipole moments per volume of the crystallographic cell [57], [58]. Each dipole is a vector and the dipole density \( P \) is a vector field. Dipoles near each other can be aligned in regions called Weiss domains. These domains are usually oriented in random order but can be aligned by using a process called poling. Poling is a process where a strong electric field is applied across the material, usually at elevated temperatures [59], [60].

A key importance for the piezoelectric effect is the change of polarization, \( P \), when an external mechanical stress is applied and cause a re-orientation of molecular dipole moments, Figure 2.1. Piezoelectricity will be produced depending on the variation of the polarization strength, the direction or both. It depends on:

- The orientation of \( P \) within the crystal.
- The crystal symmetry.
- The applied mechanical stress.

Piezoelectric materials also show the opposite effect, called converse piezoelectric effect, where the application of an electrical field forms mechanical deformation in the crystal. The combined effect of material behavior gives the piezoelectricity (2.1), (2.2). First effect:

\[
D_i = \varepsilon_{ij} E_j \quad (2.1)
\]

where \( D \) is the electric charge density displacement, \( \varepsilon \) is permittivity and \( E \) is the strength of the electric field. Second effect is Hooke’s law:

\[
S_{ij} = s_{ijkl} T_{kl} \quad (2.2)
\]

where \( S \) is strain, \( s \) is compliance and \( T \) is stress.

These two material effects are combined in coupled equations where the strain-charge in matrix form is:

\[
\{S\} = \{s\} \{T\} + \{d^1\} \{E\} \quad (2.3)
\]
\[
\{D\} = \{d\} \{T\} + \{\varepsilon\} \{E\} \quad (2.4)
\]

where \( \{d^1\} \) is the matrix for the converse piezoelectric effect and \( \{d\} \) is the matrix for the direct piezoelectric effect. Equation 2.3 represents the connection for the converse piezoelectric effect and 2.4 the direct piezoelectric effect [61].

2.3 PIEZOELECTRIC CANTILEVER HARVESTING:
DEVELOPMENT AND CHALLENGES

To utilize the direct piezoelectric effect, piezoelectric crystals may be packaged in thin films for attachment on a cantilever at the clamped end, where the stress/strain is highest, as presented schematically in Figure 2.2. By applying vibration to these cantilevers, an AC voltage is obtained. The energy produced is usually in \( \mu \)-mW range and is too small for large electrical applications.
depending on power demand but yield enough power for a small electronic system like an intelligent wireless sensor [62]. It is hard to directly compare piezoelectric vibration harvesters, since they employ different techniques and since the variation in sizes. Between a couple of μm for MEMS fabricated harvesters up to meter size for macro harvesters, make them behave radically differently [63]. A defined standard figure of merit (FOM) would be beneficial. However, none of the several FOMs that have been suggested have resulted in any standardization [64].

![Piezo-material](image)

**Figure 2.2** A SDOF schematic piezoelectric cantilever with piezoelectric material attached at the fixed end. In the graph, a high-power output peak with the typical narrow bandwidth for the lowest eigenfrequency is presented. The green arrows present the output curve’s change if the bandwidth increases. The dotted red line is a schematic representation of stress along the cantilever.

The main problem for piezoelectric single degree of freedom (SDOF) cantilever harvesters is ending up with the main power carrying frequency residing outside the optimized narrow frequency range of the harvester. The output power drops dramatically outside the range of the lowest eigenfrequency resonance peak of the cantilever, presented generally in Figure 2.2. The placement the of piezo material is at the clamped end, where the stress is highest on the cantilever; the stress decreases rapidly towards the free end of the cantilever and only a small part of the cantilever is actually used for energy harvesting as presented schematically in Figure 2.2. Over the years several methods have been suggested on how to broaden the bandwidth of piezoelectric cantilever harvesters, without significantly sacrificing the output power [65]. These different approaches can be classified into:

- Multimodal harvesting [66]–[68].
- Self-tuning [69]–[71].
- Resonance tuning [72]–[74].
- Nonlinear technique [75]–[77].

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In this thesis, multimodal and self-tuning harvesting is covered. Improved approaches have been covered in the literature on multimodal energy harvesting, where some have made comparable systems using an array of cantilevers combining different lengths and weights to cover a broader bandwidth. By tuning each one for a different frequency as presented in the schematic Figure 2.3 [78]–[80] a broader bandwidth is achieved. Using an array of cantilevers where only one cantilever will be able to harvest effectively, each at the time, the design will become bulky in size if the array is to be able to harvest over an extensive bandwidth.

![Schematics of an array of piezoelectric cantilevers, able to yield a power output over a broader bandwidth, compared to a single cantilever. Only one cantilever at the time is able to effectively target the applied frequency, hence to target an extensive bandwidth the design quickly becomes immense.](image)

An example of multiresonance energy harvester developed by Qi et al. (2010) [81], has arrays of cantilevers attached to a single beam in the middle. Even though the design is cunning, the bulk and weight of the harvester limits its power density and therefore its usability.

An alternative to the array structure is the multiple degrees of freedom (MDOF) energy harvester that was developed by using a single beam [82]. One case of MDOF is the two degrees of freedom (2DOF) that has two masses on a cantilever as presented in Figure 2.4. By this design two modes are obtained, but the two peaks are still too far away from each other to be considered a broadband harvester [83]. An enhancement of the 2DOF design was made using a dynamic magnifier; this magnified the power output from the piezoelectric outer beam in the two-beam system, where the inner beam acts as a magnifier for the outer beam [84]. Most designs for multimodal energy harvesters have the resonance frequencies separated from each other and usually the second peak has lower power output than the first one as presented schematically in Figure 2.4. The frequency spacing between the peaks is also a problem and you should have the secondary peak closer to the primary peak so that the range in between the peaks can be used for energy harvesting.
H Wu et al. (2012) [85] proposed a 2DOF piezoelectric energy harvester with a cut-out design where the two modes are near each other and the second mode also has a good energy conversion. This design looks very promising considering the energy density. However, the design only utilizes one cantilever with piezoelectric material at the attached coupled end and the design is also bulky.

Challenges for vibration energy harvesting using piezoelectric cantilevers:

- Only a small part of the cantilever is used for energy harvesting.
- The harvesting bandwidth is narrow.
- Solutions to broaden the bandwidth tend to increase the size of the harvester.
- Solutions to broaden the bandwidth tend to decrease the power output.

This thesis attend to and make proposals toward solutions to these challenges.

2.4 ACHIEVING BANDWIDTH AND POWER ENHANCEMENT

To be able to utilize the benefits of an IWS it has to be practical in size to fit in small places like on an engine or a gas turbine. All electrical components in the IWS are small and naturally the space available in the neighborhood of a gas turbine is limited, therefore the harvester has size constraints. In order to meet those constraints using conventional commercial piezoelectric cantilevers, new harvester designs are needed. Such as structures which could utilize more of the cantilever bulk, not only the fixed end where it is attached, to harvest energy. This would make the harvester able to decrease in size and might have a maintained or even increased power output.

A new structure based on 2DOF principles was presented in Paper I. Previously, cantilever harvesters have utilized a primary cantilever to enhance a secondary one (Figure 2.4). In Paper I, the primary cantilever is piezoelectric as well as the secondary cantilever (Figure 2.5). Instead of
placing the two cantilevers in the same plane, the secondary cantilever is backfolded over the primary cantilever as presented schematically in Figure 2.5. By this design, the projected area becomes smaller compared to a 2DOF harvester in one plane. Even though the design becomes somewhat higher, it requires less operational volume than a 2DOF harvester in one plane due to shorter cantilevers and less displacement compared to a 2DOF with longer cantilevers in total. The piezoelectric cantilevers used in the design are off the shelf (OTS) and manufactured by MIDE. The choice of OTS beams was based on their availability, small enough size and that they would be used in a gas turbine demonstrator, where components are demanding robustness and that the demonstrator can easily be reassembled.

The design was simulated in finite element analysis, (using the finite element analysis COMSOL software). Measurements on the MIDE cantilever was compared with simulation data to have a reliable model to be able to simulate the behavior of the backfolded design. When the backfolded design was simulated, the first result was that the output voltage was different from a general 2DOF system. The primary output peak had the same behavior, but the secondary peak had a maintained voltage output comparable to the primary peak, presented schematically in Figure 2.5. To get a better benchmark comparison, the design in Paper I was compared with two tuned single cantilevers, since the general 2DOF only have one patch of piezo material, while the backfolded design has two. One single cantilever was tuned to the primary peak and one to the secondary peak. The two single cantilevers where added together for a total simulated open voltage output and compared with the backfolded, as presented in Paper I. The simulated backfolded harvester outperformed the two single tuned cantilevers.

![Figure 2.5 A schematic 2DOF harvester compared with the schematic backfolded design. In the graph the green line represents the general output voltage from the backfolded design. The secondary peak has a maintained voltage output comparable with the primary peak.](image-url)
In order to understand this effect, stress data from simulations were compared for the single cantilever and the backfolded harvester. In Figure 2.6 the different plots of the general stress, depending on design, is presented schematically. For the single cantilever, the stress is highest at the attached end (dotted red line). For the enhanced harvester based on 2DOF it shows the same behavior (dot-dot-line orange line), but it is higher compared to the single cantilever. For the backfolded design, the top cantilever shows the same behavior as for single and 2DOF (green line). The big difference is when we examine the bottom cantilever of the backfolded design, there we can see that the stress curve is extended and distributed over the whole cantilever (blue line). The elevated stress explains why the backfolded design has a higher output. As presented in Paper I, the measured output correlated with the simulated.

Even though the power output was maintained for the secondary peak on the backfolded design, the primary and secondary peaks have a separation, ΔHz (from peak to peak), that is too large and needs to be decreased to utilize a broader bandwidth effect. When the two peaks have a small ΔHz the valley will effectively rise between the peaks and yield an increased power output which leads to a broader bandwidth presented schematically in Figure 2.7 indicated by the blue arrow. The backfolded design was extensively measured for in total 144 different combinations to provide data for a simplified numerical model used in Paper II. From the data it became clear that for the three different clamping positions of the bottom cantilever (presented in Paper II) three distinct groups of ΔHz between the two peaks were identified. Within these three groups the two masses (m_1 and m_2 in Figure 2.7) were altered. For all design combinations the ΔHz was still too high for the peaks...
to be bridged (Figure 2.7). In Paper II, the numerical model predicts that the peaks will have a lowest $\Delta Hz$ if the top cantilever is approximately 20% shorter than the bottom cantilever where $m_1 = m_2$. Which was confirmed by measurements. However the configuration yielding the closest $\Delta Hz$, did not yield the best output from a harvesting point of view. Clarifying the difficulties with conjoined cantilevers as energy harvesters.

![Figure 2.7](image)

*Figure 2.7* By shortening the length of the top cantilever, the primary and secondary peaks get a decreased $\Delta Hz$ and the output voltage in between them gets higher (indicated by the blue arrow). Hence the backfolded harvester gains a broader bandwidth.

### 2.5 INCREASED BANDWIDTH BY NON LINEAR SELF-TUNING HARVESTING

To achieve broad bandwidth the concept of self-tuning can be applied. A self-tuning piezoelectric harvester has the ability to adjust its eigenfrequencies to match the applied ambient frequency. When the eigenfrequency shifts for the harvester, the high Q-value is maintained. This means that the power output remains significant over a broader bandwidth, where the structural eigenfrequencies adjusts to the applied ambient frequency. The change in eigenfrequency can be performed during ongoing harvesting or in between when no harvesting is done. Preferably, the eigenfrequency is automatically adjusted during harvesting. This can be done using electric adjustment systems [86]–[88] or by using mechanical solutions [10], [11], [30]–[32]. Mechanical solutions are slower to adjust to the eigenfrequency compared to electrical ones, but they have the positive trait of no power consumption, which tends to be a problem for electrical self-tuning solutions [92]. The choice to use resonance tuning by automated mechanical self-tuning is preferable if the main frequency mode is changing slowly over time, like in an engine. A harvester that has self-tuning uses input from the ambient vibration to adjust its frequency. It can for example be a rotational acceleration force [69] or a bistable system that can change between two stable states [70]. A mechanical tuning effect was demonstrated by Miller et al. [93], presenting that for a given excitation at a certain frequency, a sliding proof mass will move on a beam until it reaches a position where the mode of vibration has a resonance behavior. This was presented experimentally...
for a double clamped beam [93], where the proof mass could alter its position (marked as sliding mass in Figure 2.8), as the driving frequency changes, in order to maintain resonance.

![Image](image1.png)

**Figure 2.8** To the left the clamped-clamped beam with a sliding weight, to the right the self-tuning harvester based on the backfolded design and the sliding mass phenomenon.

![Image](image2.png)

**Figure 2.9** To the left top is the backfolded design presented in Paper I and II, below is the self-tuning harvester which utilize the extended stress distribution in Paper III and IV. To the right a schematic graph shows the stress curvature for the two harvester’s individual cantilevers.

In order to utilize the demonstrated sliding mass phenomenon as a mechanical self-tuning effect, the backfolded design from Paper I and II was put together with a beam having a sliding mass, as presented in Figure 2.8. By using the backfolded design, the first trait was that the harvester size could be small. The second trait was that the extended stress distribution could be maintained for both piezoelectric cantilevers. In Figure 2.9 the backfolded design (Paper I and II) stress curvature for the top and bottom cantilever is compared schematic with the stress curvature for the self-tuning harvester (Paper III and IV). As presented, the two piezoelectric cantilevers stress curves (purple...
line) from the self-tuning harvester behaves similarly like the bottom cantilever from the backfolded design (blue line).

The self-tuning design was presented at PowerMEMS 2015 [94], where conducted COMSOL simulations predicted that the eigenfrequency was shifting, depending on where the mass was positioned on the middle beam. This is somewhat similar to an array of cantilevers, but much smaller in size as presented schematically in Figure 2.10. Experiments verified that the bandwidth became broader when the mass was sliding compared to being fixed on the middle beam. Comparison between a short and a long middle beam showed that the power output was higher for a harvester setup where the middle beam was longer as presented in Figure 2.11. Experiments also showed that there was no difference in bandwidth between the short and long middle beam as presented in Figure 2.11.

The two measurements cases with short and long middle beam were referred to as M1 and M2 with data tabulated in Table 2.1. The difference in length between M1 and M2 indicates that the middle beam has different eigenfrequencies. A rough estimation of the clamped-clamped middle beam eigenfrequency is presented in Table 2.1. Since the output was increased when the middle beam had a lower eigenfrequency, three thicknesses (Test 1 – 3, Table 2.1) for the middle beam were tuned to match the harvester eigenfrequency. Experiments showed that the 0.35 mm middle beam gave the highest output (Table 2.1). The quite narrow bandwidth of 12 Hz (compared to Miller et al [93] with wide mechanical bandwidth of 95 Hz) was maintained for all three tests.

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>Width (mm)</th>
<th>Length (mm)</th>
<th>Calculated eigenfrequency (Hz)</th>
<th>3dB Bandwidth (Hz)</th>
<th>Measured maximum voltage output (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>1</td>
<td>3</td>
<td>16</td>
<td>2974</td>
<td>12</td>
</tr>
<tr>
<td>M2</td>
<td>1</td>
<td>3</td>
<td>27.5</td>
<td>1006</td>
<td>12</td>
</tr>
<tr>
<td>Test 1</td>
<td>0.7</td>
<td>3</td>
<td>27.5</td>
<td>760</td>
<td>12</td>
</tr>
<tr>
<td>Test 2</td>
<td>0.35</td>
<td>3</td>
<td>27.5</td>
<td>380</td>
<td>12</td>
</tr>
<tr>
<td>Test 3</td>
<td>0.175</td>
<td>3</td>
<td>27.5</td>
<td>190</td>
<td>12</td>
</tr>
</tbody>
</table>

*Table 2.1 Tabulated structure data for the middle beam.*
Figure 2.10 Schematically an array of cantilevers with different eigenfrequencies compared with a selftuning harvester is presented, where the sliding mass is marked with corresponding color and number for matching each cantilever on the array harvester.

Figure 2.11 Open circuit voltage comparison between M1 and M2 with fixed and sliding mass for both. The output in M2 is 11.7 V and has a 3dB bandwidth of 12 Hz.
Since length and height modifications on the middle beam did not have any impact on the bandwidth, a numerical investigation on what modifications on the harvester that would have an impact on the bandwidth was started. The measurements from M1 and M2 were the foundation towards a numerical model, presented in Paper III. The model predicted that the highest impact regarding bandwidth was to introduce an asymmetry by different lengths for the piezoelectric cantilevers. The numerical model handled the beam system from a mechanical view and the predicted mechanical bandwidth was 60 Hz. The numerical model also indicated that the sliding mass was moving along the middle beam according to where the zero-slope was positioned ($x_n$) as presented in the schematic Figure 2.12 and $a$ is the distance between the position of the sliding mass and the zero slope while $\eta$ is the position of the mass on the middle beam. The zero-slope position itself is dependent on the applied frequency.

$\eta$ and $a$ are shown in Figure 2.12: For the first mode, the outer masses move in the same direction and the position of the sliding mass ($\eta$) can be related to the position ($x_n$) with zero slope of the middle beam where the distance $a = |x_n - \eta|$.

The numerical model calculated the eigenfrequency depending on where the mass was located on the middle beam. For these eigenfrequencies it is interesting to see the mode shape of the middle beam. In Paper IV the mode shapes for one case L3 with mass configuration C1-C4 (Table 2.2) were presented and a brief discussion about the correlation was presented. Aiming at a deeper understanding of the phenomenon, the model prediction for the sliding mass position and its behavior, configuration L3/C1 will be examined more closely (on cross section L3/C1 marked in green in Table 2.2). For L3/C1 the sliding mass shifts from a position to the left of the middle beam to a position near the right side of the middle beam, during the frequency sweep as presented in Figure 2.13. Looking at the output curve the self-tuning effect is visible between 194 Hz – 201 Hz. Above 201 Hz the sliding mass has a stable position up to 213 Hz and in this range, we have a clear power peak for the harvester system. From the numerical model presented in Figure 2.14, the calculated mode curves for L3/C1 describes where the zero slope is positioned for a certain position of the sliding mass at an eigenfrequency. In the numerical model the fixed mass position is in some cases not the position where the sliding mass will stay, if the zero slope is located at another position. In the numerical model when the sliding mass is located at $\eta = 0$ on the middle beam, the zero-slope position is at $x_n = 1$ on the middle beam (Table 2.3 and Figure 2.13), where $\eta$ and $x$ start at 0 on the left side of the middle beam (Figure 2.12 and 2.14). This indicates that the mass wants to slide towards the right side ($x = 1$) as presented in table 2.3. The sliding mass is placed in four different positions on the middle beam, yielding four eigenfrequencies and three different zero slope positions ($\eta$), where $\eta$ corresponds to the measured values $x_m$ as presented in Figure 2.13.
Comparing the zero slope $\eta$ with $x_m$ (sliding mass position during measurement) in Figure 2.13 we can see that both have similar position behavior. The change in position is from 0 on the middle beam towards 1 and then back to 0 again. The numerical model has slightly lower eigenfrequencies for the sliding mass position compared with the measurement but gives a decent correlation to measurement, considering that the numerical model is a simple beam, point mass construction. Both the utilization of a self-tuning mechanism and the ability to predict its behavior are a key to achieving a broader bandwidth. I believe that self-tuning in combination with conjoined asymmetric cantilevers is a viable challenger to harvesters used today.

<table>
<thead>
<tr>
<th>Measurements configurations</th>
<th>C1 No added mass</th>
<th>C2 One added mass on bottom cantilever (m)</th>
<th>C3 Two added masses on bottom cantilever (2m)</th>
<th>C4 One added mass on top cantilever (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1 top/bottom</td>
<td>18 / 18</td>
<td>18 / 18 (m)</td>
<td>18 / 18 (2m)</td>
<td>18 (m) / 18</td>
</tr>
<tr>
<td>L2 top/bottom</td>
<td>20 / 16</td>
<td>20 / 16 (m)</td>
<td>20 / 16 (2m)</td>
<td>20 (m) / 16</td>
</tr>
<tr>
<td>L3 top/bottom</td>
<td>22 / 14</td>
<td>22 / 14 (m)</td>
<td>22 / 14 (2m)</td>
<td>22 (m) / 14</td>
</tr>
<tr>
<td>L4 top/bottom</td>
<td>24 / 12</td>
<td>24 / 12 (m)</td>
<td>24 / 12 (2m)</td>
<td>24 (m) / 12</td>
</tr>
</tbody>
</table>

Table 2.2 Mapped measured configurations for the self-tuning harvester. The marked green configuration L3/C1 with top piezoelectric cantilever 22 mm and bottom piezoelectric cantilever 14 mm is examined.

<table>
<thead>
<tr>
<th>Numerical model sliding mass position</th>
<th>Zero-slope position</th>
<th>Measured sliding mass position close to numerical eigenfrequency</th>
<th>Numerical model eigenfrequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>------</td>
<td>$\eta = 0$</td>
<td>$x_n = 1$ $x_m = 0$</td>
<td>$f = 179.5$ Hz</td>
</tr>
<tr>
<td>........</td>
<td>$\eta = 0.5$</td>
<td>$x_n = 1$ $x_m = 0$ (50 – 194 Hz)</td>
<td>$f = 192.8$ Hz</td>
</tr>
<tr>
<td>.........</td>
<td>$\eta = 0.8$</td>
<td>$x_n = 0.55$ $x_m = 0.5$ (201 Hz)</td>
<td>$f = 202.5$ Hz</td>
</tr>
<tr>
<td>...........</td>
<td>$\eta = 1$</td>
<td>$x_n = 0.1$ $x_m = 0.3$ (213 Hz)</td>
<td>$f = 205.5$ Hz</td>
</tr>
</tbody>
</table>

Table 2.3 Presenting numerical model: eigenfrequency, mass position ($\eta$), zero slope position ($x_n$), measured sliding mass position ($x_m$) and eigenfrequencies.
Figure 2.13 Presenting the output power for the configuration L3/C1, with marked sliding mass positions (white rectangles) and the black rectangle has an intermittent sliding behavior. The zero-slope position (green) from the numerical model is also marked.

Figure 2.14 Presenting the numerical mode curves with different positions of the zero slope (x) depending on the mass position (η) on the middle beam.

2.6 CONJOINED CANTILEVER MICRO HARVESTER

Circuits are decreasing in size and new ways of implementing intelligent sensors are ascending in the field of Internet of Things (IoT) [95]. Even though the gadgets are smaller, the problem with batteries that needs to be recharged or replaced remains. Harvesting energy for shrinking gadgets requires harvesters that also have to decrease in size. A micro energy harvester needs to be able to utilize all possible available area to be able to convert as much energy as conceivable. Different design approaches have been made but the most common MEMS design is to use a single cantilever. The reported frequency span is between 243 – 2300 Hz and the power output is between 0,471 – 2,7 μW [96]–[99]. Other designs used is a bent cantilever [100], circular spring [101], multiple cantilevers [102] and rectangular spring [103], where the multiple spring report the highest power output of 66,75 μW.
Figure 2.15 Presenting a planar backfolded design based on the top/bottom backfolded design. The planar design utilizes the extended stress distribution on the outer cantilevers and has a trapezoidal shape on the backfolded middle beam.

In the macro case (described earlier in chapter 2), it is of utmost importance to utilize as high amount of the available area as possible of the harvester. Due to fabrication issues a backfolded two layer design like in Paper I and II is hard to achieve. A similar concept but confined in one plane, is obtained by conjoining three cantilevers. In parallel with the backfolded design (stacked on top of each other) tests were made on a backfolded planar design. A planar design is desirable for micro production. As presented schematically in Figure 2.15 the planar backfolded harvester has two outer cantilevers and, in the middle, there is a backfolded piezoelectric cantilever. This design is possible to fabricate in micro size. To achieve a higher power output for the middle cantilever it uses a trapezoidal shape, which also yields a broader bandwidth [104], [105].

The design presented in Paper V looks promising for a micro harvester. Due to fabrication processing challenges, only a mechanical characterization of the harvester could be conducted (Figure 2.16). The primary peak was as predicted by simulations (Paper V), the secondary peak was a bit higher due to over etching of the backfolded middle beam mass. Despite the fabrication problem faced, I believe that conjoined cantilever harvesters are a good way to utilize as much available area as possible and show us a path towards upcoming more power efficient micro harvesters.
Figure 2.16 Measured mechanical characterization of the micro backfolded harvester.
3 SUPERCAPACITOR AS ENERGY STORAGE

In this chapter the supercapacitors are described by background theory and the specifications on electrode materials for supercapacitors used in IWS system. Electrochemical characterization by cyclic voltammetry and galvanostatic charge discharge is described and results of the electrode materials CNF and CNT, CVD grown, on CNF are presented.

3.1 BACKGROUND AND THEORY

A supercapacitor is an electrochemical capacitor with a very high capacitance. Supercapacitors, sometimes called ultracapacitors or electric double-layer capacitors (EDLC), do not have a conventional solid dielectric. Instead they use an electrolyte. In 1957, a patent filed by General Electric [106] explained the manufacturing of a device that used porous carbon electrodes with sulfuric acid between the electrodes [107]. After further development supercapacitors have been used since the mid-seventies as energy storage for backup computer memories [108]. Furthermore, supercapacitors have become useful for wireless communications and are used as power devices for different applications like recovering brake energy to improve energy efficiency in a hybrid battery/diesel system [40]. The energy density of a supercapacitor depends on the capacitance and voltage, if either or both are raised the energy density will be improved. In the following equation we have the energy density \( E \), specific capacitance \( C \), charge density \( Q \), and voltage \( V \) [109]:

\[
E = \frac{CV^2}{2} = \frac{QV}{2} \tag{3.1}
\]

The power density of a supercapacitor defines how fast it can be discharged and depends on the voltage and the equivalent series resistance; the latter is to be kept to a minimum for high power density. We introduce the power density \( P \) and equivalent series resistance \( R_s \) [109]:

\[
P = \frac{V^2}{4R_s} \tag{3.2}
\]

Supercapacitors can be classified into three types as shown in Figure 3.1. Electrochemical double layer capacitors (EDLC), pseudocapacitors and a mix of EDLC and pseudocapacitance called hybrid capacitors.

The EDLC supercapacitor has a very high-power density because it mainly stores its energy electrostatically, utilizing the double layer. Storing energy in this fashion, the supercapacitors can be charged and recharged for over \( 10^5 \) times and in theory infinite numbers. The downside of this storage mechanism is that the energy density is much lower compared to batteries. Batteries on the other hand have an energy storage based on Faradic charge transfer. A Faradic charge transfer is a charge that is transferred across an electric interface as a result of an electrochemical reaction [110]. The Faradic charge transfer can also be used as storage mechanism for supercapacitors and is called pseudocapacitance [110]. To enhance the energy density, abundant amount of research are ongoing on pseudocapacitive electrode materials.
Pseudocapacitance behaves like capacitance when characterized with voltammetry but occurs from an electrochemical reaction. The pseudocapacitance has been studied and tested for electrode materials using transition metals and electrically conductive polymers [111]. Both these methods show good result concerning energy density, but so far lack the number of charge-discharge cycles that can be sustained without serious detrimental impact on the device performance needed for it to utilize as supercapacitor electrode material in an IWS system as shown in Paper VI. Due to, so far a very limited number of life cycles for pseudocapacitors, a hybrid supercapacitor, might be a better solution [112].

![Diagram of supercapacitors classification](image)

*Figure 3.1 Classification of supercapacitors in three major groups EDLC, hybrid and pseudocapacitors with examples of electrode material for each group.*

A hybrid supercapacitor has one half cell utilizing the double layer and the other half cell is based on pseudocapacitance. By that combination, the power density is higher compared to batteries and the energy density is higher compared to other types of supercapacitors [112].

Even though supercapacitors have inferior instantaneous energy density, over time with their huge cyclability, over their life time the supercapacitors can provide more stored energy than batteries can, shown in Table 3.1 from Paper VI. The life cycles for supercapacitors are $10^5$ and higher and during the life time of an IWS system with an energy harvester this high number of cycles is needed.
since the supercapacitor will be charged and recharged continuously with intermittent harvested energy.

<table>
<thead>
<tr>
<th></th>
<th>Supercapacitor</th>
<th>Battery LiPo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wh/kg per cycle</td>
<td>9</td>
<td>250</td>
</tr>
<tr>
<td>Maximum number of cycles</td>
<td>100000</td>
<td>1000</td>
</tr>
<tr>
<td>Accumulated energy density for total number of cycles</td>
<td>900000</td>
<td>250000</td>
</tr>
</tbody>
</table>

Table 3.1 Energy density accumulated over the number of charge cycles shows that supercapacitors will deliver a higher energy density of nearly 4 times over time versus batteries. The approximation for the battery is overestimated since it does not take into account that the battery energy density decreases over time due to loss of active electrode material [113].

### 3.2 ELECTRODE MATERIALS FOR SUPERCAPACITORS

The commercial EDLC supercapacitors are mainly using active carbon as electrode material today [114]. The main reasons are that of the low production cost and easy production techniques of activated carbon. In Paper VI recent years of carbon electrode material research in the literature is compared; by looking at surface area versus capacitance for different carbon allotropes, conclusions regarding what electrode materials look promising can be drawn (Figure 3.2). The black line is based on an ideal model carbon electrode material with maximum active area, which only considers the double layer. Every electrode material would have lower value regardless of their surface area and structure since the model material is perfect in that sense. The material with highest capacitance per gram is the group called composites of carbon. These materials are combinations of carbon allotropes that enhance the surface area or the structure or both and therefore have better performance. Three measured electrode materials have values above the model maximum, these electrode materials are either measured with 6 M KOH or 0.1 M Na₂SO₄ as electrolyte instead of 1 M KOH which the rest are characterized with or are combinations with materials that uses the pseudocapacitance mechanism. From a more detailed look at the composite materials, the most promising electrode material is made of N-doped graphene nanosheets, Paper VI. The N-doping makes a part of the storage mechanism change from double layer to pseudocapacitance, which makes the capacitance higher and therefore also the energy density higher. The structure of the material, by implementing graphene nanosheets, is that the surface area is greatly enhanced and accessible for the electrolyte. Hence, the way to develop new materials is either by aiming at a more ordered structure, or to enhance the energy density by implementing pseudocapacitance.
3.3 SUPERCAPACITORS IN IWS SYSTEM

An electrode material suitable for a supercapacitor in an IWS with energy harvesting needs to fulfill the following conditions:

- Sufficient number of charge and discharge cycles without deterioration during the lifetime of the device.
- High value of capacitance per gram and per volume, hence a possibility to scale it down for usage in e.g. Micro Electrical Mechanical System (MEMS) IWS.
- A low self-discharge.

The high number of cycles is needed because the harvested energy comes discontinuously and thus constantly charges and the IWS periodically discharges the supercapacitor typically when transmitting data. The AIWS has to be operational for a long time and supercapacitor have more than 10⁶ cycles and a life expectancy over 20 years [115], [116]. A high number of life cycles entails that the super capacitor will not be the crucial part of the AIWS functionality over time.

A high value of specific capacitance is needed when the IWS system is scaled down to MEMS size or if the sensor needs a high amount of energy and therefore the size and weight of the supercapacitors becomes an issue.

A low self-discharge is also needed if the IWS system is in standby and is not able to harvest energy for a longer period and also if the harvester delivers low power it is also critical to have low losses or no energy will be stored. If a wireless system can harvest energy more or less continuously, the self-discharge time for a supercapacitor will not be reached. If the system fails to harvest the self-discharge is between 5-60% over a period of two weeks [117].

As presented in Table 3.1 from Paper VI the amount of cycles presented for tested electrode materials, does not show the high amount of cycles needed for long time IWS usage. Many are also reporting high degradation of the capacitance compared the first to the last cycle measured, meaning that the electrode material might break down due to degradation. Therefor life cycle measurement is crucial to verify for new usable electrode materials.
Figure 3.2 Capacitance per gram plotted against surface area per gram for electrodes with different carbon structures or composite carbon structures based on table 2.2, showing that a larger surface area doesn’t necessarily give a higher capacitance. And that that electrode materials with pseudocapacitance or with a very well-ordered structure gives a higher capacitance with a smaller surface area, from Paper VI.
<table>
<thead>
<tr>
<th>Allotrope</th>
<th>Surface area m²/g</th>
<th>F/g</th>
<th>Electrolyte other than 1M KOH</th>
<th>Number of cycles</th>
<th>degradation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composites of carbon</td>
<td>2231</td>
<td>1071</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Composites of carbon</td>
<td>1059</td>
<td>524</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Composites of carbon</td>
<td>3012</td>
<td>385</td>
<td>2500</td>
<td>-6%</td>
<td>-</td>
</tr>
<tr>
<td>Composites of carbon</td>
<td>1626</td>
<td>378</td>
<td>2000</td>
<td>-4.6%</td>
<td>-</td>
</tr>
<tr>
<td>CNF</td>
<td>3000</td>
<td>371</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Activated carbon</td>
<td>2100</td>
<td>355</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Composites of carbon</td>
<td>517</td>
<td>349</td>
<td>6 M KOH</td>
<td>5000</td>
<td>+8%</td>
</tr>
<tr>
<td>Activated carbon</td>
<td>3200</td>
<td>320</td>
<td>2500</td>
<td>-31%</td>
<td>-</td>
</tr>
<tr>
<td>Composites of carbon</td>
<td>810</td>
<td>310</td>
<td>1000</td>
<td>-3%</td>
<td>-</td>
</tr>
<tr>
<td>Activated carbon</td>
<td>2570</td>
<td>300</td>
<td>10000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Templated carbon</td>
<td>1295</td>
<td>284</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Templated carbon</td>
<td>1650</td>
<td>260</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Graphene</td>
<td>1050</td>
<td>258</td>
<td>2000</td>
<td>+1%</td>
<td>-</td>
</tr>
<tr>
<td>Graphene</td>
<td>1654</td>
<td>255</td>
<td>2000</td>
<td>-5.9%</td>
<td>-</td>
</tr>
<tr>
<td>Templated carbon</td>
<td>4000</td>
<td>250</td>
<td>10000</td>
<td>-2%</td>
<td>-</td>
</tr>
<tr>
<td>Carbon aerogel</td>
<td>2119</td>
<td>250</td>
<td>5000</td>
<td>-24%</td>
<td>-</td>
</tr>
<tr>
<td>Templated carbon</td>
<td>1600</td>
<td>220</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Activated carbon</td>
<td>1012</td>
<td>218</td>
<td>1000</td>
<td>-3%</td>
<td>-</td>
</tr>
<tr>
<td>Composites of carbon</td>
<td>274</td>
<td>212</td>
<td>2 M KOH</td>
<td>2000</td>
<td>-16%</td>
</tr>
<tr>
<td>Activated carbon</td>
<td>674</td>
<td>210</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CNF</td>
<td>529</td>
<td>202</td>
<td>3000</td>
<td>-3%</td>
<td>-</td>
</tr>
<tr>
<td>Activated carbon</td>
<td>3326</td>
<td>190</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Graphene</td>
<td>1400</td>
<td>180</td>
<td>2000</td>
<td>-5.9%</td>
<td>-</td>
</tr>
<tr>
<td>Composites of carbon</td>
<td>830</td>
<td>154</td>
<td>1000</td>
<td>-20.4%</td>
<td>-</td>
</tr>
<tr>
<td>Carbon aerogel</td>
<td>3431</td>
<td>152</td>
<td>8000</td>
<td>-1%</td>
<td>-</td>
</tr>
<tr>
<td>Graphene</td>
<td>2600</td>
<td>132</td>
<td>1000</td>
<td>-14%</td>
<td>-</td>
</tr>
<tr>
<td>Composites of carbon</td>
<td>481</td>
<td>128</td>
<td>1500</td>
<td>-1%</td>
<td>-</td>
</tr>
<tr>
<td>CNF</td>
<td>500</td>
<td>128</td>
<td>100</td>
<td>-17%</td>
<td>-</td>
</tr>
<tr>
<td>CNF</td>
<td>1120</td>
<td>122</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Templated carbon</td>
<td>1250</td>
<td>120</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CNT</td>
<td>120</td>
<td>79</td>
<td>0,1 M Na2SO4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CNT</td>
<td>871</td>
<td>57</td>
<td>5000</td>
<td>-2%</td>
<td>-</td>
</tr>
<tr>
<td>Activated carbon</td>
<td>2900</td>
<td>44</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Templated carbon</td>
<td>400</td>
<td>35</td>
<td>300</td>
<td>-2%</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3.2 Carbon allotropes compared by surface area, F/g, number of cycles and degradation, all crucial markers for a good electrode material suitable for supercapacitors in IWS systems (references are presented in Paper VI).
3.4 ELECTRODE MATERIAL CHARACTERIZATION FOR SUPERCAPACITORS

For the characterization of an electrode material for supercapacitors, one commonly used method is the three-electrode measurement. The three-electrode test cell contains a work-, counter- and reference electrode. The electrochemical performance of the electrode material is evaluated by cyclic voltammetry (CV) and galvanostatic charge-discharge (GCD).

CV studies the current response of the electrode material as a function of applied potentials [32]. The mass specific capacitance of the electrode from a CV is given by:

$$C = \frac{\int i \Delta V}{m v \Delta V}$$  \hspace{1cm} (3.3)

where $i$ is the response current, $\Delta V$ is the electrochemical potential range of the CV, $v$ is the potential scan rate and $m$ is the mass of the electrode. The CV for an ideal EDLC electrode material is rectangular in shape and is marked with 1 (black dash dash dot line) in Figure 3.3. The current immediately switches sign when the potential sweep is reversed. The energy storage mechanism is here pure electrostatic. If there is resistance in the capacitor, the CV curve gets the shape marked by 2 (blue line) in Figure 3.3. And if the electrode material contains pseudocapacitative contributions the shape goes from rectangular to a deviation form marked as 3 (green dash line) in figure 3.3.

Figure 3.3 CV shapes for ideal EDLC electrode material and how the CV behaves when carbon is used as electrode material and the impact of redox reactions.
Cyclic charge discharge (CCD) studies the potential change for an electrode material as a function of time when a constant current is applied while charging and discharging [118]. The supercapacitor is charged at a constant current as presented schematically in Figure 3.4. The CCD curve is divided into two parts, first the charge of the supercapacitor and then the discharge. At the start of the discharge sequence there is a voltage change ($V_{\text{drop}}$) due to equivalent series resistance (ESR). In Figure 3.4 the $dE$ is the change in voltage during discharge and $dt$ is the discharge time.

Figure 3.4 CCD schematically presented for an ideal electrode material.

The mass specific capacitance from CCD is calculated by:

$$C = \frac{i}{m \left( \frac{dE}{dt} \right)} \quad (3.4)$$

where $i$ is the constant current and $dE/dt$ is the slope of the discharge curve.

CV is used to characterize how the material behaves and if it is suitable as electrode material. CCD is used to see how the electrode material behaves after cycling or break down during cycling and how affected the material is by degradation. A good material suitable as electrode material needs to be stable while cycling where the degradation is kept to a minimum or ideally is nil between first to last cycle.
3.5 CONJOINED CARBON COMPOSITE: CNT CVD GROWN ON CNF

3.5.1 Electrode material structure and the impact of pores
As suggested in Paper VI, to ensure a high cyclability and to increase the energy density, new electrode materials based on composites of carbon allotropes and/or enhanced by pseudocapacitance are beneficial. A more well-ordered structure and enhancing the usable surface area is an indicated way to be able to obtain these better electrode materials. An important part of the structure is the pore distribution. There are three different types of pores in an electrode material: macro-, meso- and micro-pores. Macropores are above 50 nm, mesopores are between 2 – 50 nm and micro-pores are smaller than 2 nm [119]. The pores have different roles in the electrode material. Macropores add to the power density of the supercapacitor; however, macropores take a lot of valuable space, where more material could be built in. Mesopores add to the power density and since they are smaller than macro-pores they don’t take as much place from the electrode material, hence they are better suited to carry the electrolyte in the electrode material [120]. The micropores are adding to the effective surface area where ions can attach to the electrode material [121]-[122]. Some carbon materials have very high densities of micro-pores, like carbon aerogel, but due to poor material structure many of these find themselves in closed cavities and can therefore not add to the active surface area [123]–[127]. A good electrode material has connected mesopore corridors with adjacent easily accessible micropores, a conjoined carbon on carbon electrode material can be fabricated with these traits.

3.5.2 Cellulose based carbon nanofibers
Carbon nanofibers (CNF) constitute a fascinating material and can be made from several different sources. Cellulose is a source that is renewable and environmental friendly [128]–[130]. Cellulose based CNF is made from cellulose acetate (CA) which by electrospinning can give fibrous mats. In this thesis the mats were placed in 50 ml of 0,1 M water solution of NAOH so the CA is hydrolyzed into regenerated cellulose. After carbonization, the fibrous mats consist of thin CNF with well-ordered mesoporous structure as presented in Figure 3.5. The CNF fibers have a diameter from tens of nanometers up to several hundred nanometers. From a supercapacitor perspective, as electrode material, CNFs have a fairly high surface area with a good, stable charge and discharge cycle life-time [131]–[134] and mechanical stability.

Figure 3.5 SEM image of CNFs.
3.5.3 Carbon nanotubes
Carbon nanotubes (CNT), are in this thesis made by chemical vapor deposition (CVD), cylindrical nanostructures [135]. These cylindrical structures have a wrapped graphene sheet as wall. The CNTs are on the nanometer scale and their diameter is ranging from 1 – 20 nm. CNTs can be single walled, double walled or multiwalled. CNTs have good thermal and electrical properties, which make them suitable for being an electrode material in supercapacitors. To increase the effective surface area, CNTs can be grown vertically aligned in a dense pattern [118], [136], [137].

3.5.4 Conjoined carbon electrode material
Two different carbon allotropes can be merged together in pursuit of an increased specific capacitance. In Paper VII we investigated cellulosed CNF as base structure for CVD CNTs. CNF has a well-ordered structure with a large amount of mesopores for electrolyte transportation. CNT, due to the small diameter, has a higher effective surface area compared to the CNF. In Paper VII, CNTs are CVD grown on CNF. In Figure 3.6 the clearly visible border between pure CNF and CVD grown CNT on CNF is presented. Figure 3.7 present TEM images of the CNTs at different magnifications, where Figure 3.7 A shows a close look at a single CNT grown on one CNF fiber. Figure 3.7 B reveals that some catalytic particles are inside the CNT closer to the base than the tip. Figure 3.7 C shows that the CNTs are multiwalled. By conjoining CNF and CNT, the surface area is increased 3 times (Table 3.3). The capacitance is nearly doubled for CNF/CNT compared to CNF and the retention loss is only -3.4 % after 2000 cycles.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Surface area (m²/g)</th>
<th>Electrode capacitance (F/g)</th>
<th>Capacitance retention (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNF</td>
<td>45</td>
<td>46.5</td>
<td>88.7</td>
</tr>
<tr>
<td>CNF/CNT</td>
<td>131</td>
<td>91.5</td>
<td>96.6</td>
</tr>
</tbody>
</table>

Table 3.3 Presenting data for the difference between pure CNF and CNF/CNT. Capacitance retention given after 2000 cycles.

Figure 3.6 SEM image of the border between pure CNF and CVD grown CNT on CNF.
As presented in Paper VII, the surface area of 131 m$^2$/g is rather low but still yields a specific capacitance of 91 F/g and placed in the model in Paper VI, the result is above the theoretical material. Compared with CNT and CNF, CNT are reported to have 79 F/g with a surface area of 120 m$^2$ [137] and activated CNF is reported to have 370 F/g with a surface area of 3000 m$^2$ [138] (Table 3.2). CNF/CNT compared to activated CNF, has a small surface area. Compared with electrode materials in Table 3.2, the low surface area indicates that the capacitance result is good, by merging these two carbon materials together. The structure of CNF is well-ordered which makes wetting easy for the electrolyte. Denser structure for the CNF will yield more area to grow CNT and increase the effective area of the CNF/CNT and the capacitance further.

The cycling stability, where degradation decreases and flattens out (presented in Paper VII), indicates that CNF/CNT will have the lifetime of $10^6$ cycles desired for a supercapacitor in an IWS system.

Activated carbon is cost effective and is mainly used today for commercial supercapacitors. Tailored electrode materials are a better choice from an energy density perspective, but are more expensive to produce. Compared to active carbon they are not dependent on binders and conductive agents to work as an electrode material. The tailored electrode material like conjoined CNF/CNT
has also the advantage of an effective surface area, easily accessible for ions. This structural control is a beginning of making efficient electrode materials with high energy density. Conjoined carbon electrode materials, in the long run, show tremendous promise in outperforming today’s commercial electrode materials in supercapacitors.
4 ENERGY HARVESTING ON GAS TURBINES

This chapter will present measurements in an authentic commercial test environment on a gas turbine. Challenges will be presented along with solutions both published and not published. At the end a complete IWS system powered by energy harvesting is demonstrated.

4.1 ENERGY HARVESTING ON GAS TURBINES

The importance of health monitoring on a gas turbine is significant from an environmental point of view. By better sensing the safety margins in a gas turbine used currently can increase and performance rises. For example, 10 °C uncertainty on the turbine entry temperature can have an impact on fuel consumption by 0,2 % and a change in the turbine tip clearance by 0,2 mm has an impact on the fuel consumption by 0,4 %. By more accurate sensing technology over 1,5 million tonnes of CO₂ could be saved [139]. Further health monitoring applications are gearbox sensing and strain/stress sensing on the attachment between the wing and the gas turbine. Today these sensors are cabled, the advantages of using an intelligent wireless sensor on a gas turbine is the removal of cabling and contacts for these.

4.2 HARVESTER OUTPUT ON GAS TURBINES, CHALLENGES

The environment close to a gas turbine contains; heat and vibrations. Both these ambient energies can be converted by harvesters, however both also are challenging to master when energy is to be converted. The heat around and close to a gas turbine during the combustion and exhaust sections, shown in Figure 4.1, are above 400 °C which is too high for a piezoelectric harvester and the circuits used for power management, measurements and transmission. Therefore, a piezoelectric energy harvester has limitations regarding its placement. At the air intake section, the gas turbine has much lower temperatures, which is more suitable for a piezoelectric energy harvester to be placed. The other challenge, vibrations might at first glance seem to be contradictive, since the piezoelectric energy harvester are to convert vibrations to electricity. However, the power density spectrum (PSD) for a gas turbine contains a wide spread of frequencies and high values of accelerations. For vibration harvesting two major challenges arises;

- Cabling between harvester and circuits
- Placement of harvester on the gas turbine which have an impact on the energy harvester output

The cables within the IWS needs to be properly attached and have multiple cores as presented in Figure 4.2. Multicore cables damp the vibrations in the cable hence the strain on soldered ends, which to our experience tends to break for single core cables.
Figure 4.1 Schematic of a gas turbine, where the cold section is to the left where piezoelectric energy harvesters are more suitable and to the right the hot section where thermal harvesters are more suitable [140], [141].

Figure 4.2 Multicore cable usable in harsh vibration environment.

The placement of the harvester on the gas turbine is an important issue to take under consideration. On a test site the gas turbine is attached to a dampening frame. Hence placing the harvester on that frame is futile due to damping. As presented in Figure 4.3 the box containing the harvester is strapped closely to the gas turbine by plastic zip ties. This solution is not a viable option for long term usage on test sites and plastic zip cords also has a damping effect via the transition between the gas turbine and the boxed harvester but it is easy to apply and considered good enough.

Figure 4.3 Boxed harvester attached to the mounting frame for the gas turbine by zip ties.
Considering only the placement of the harvester on the gas turbine, have in some cases a large negative impact on the output of the harvester. Presented in Figure 4.4 is a tuned backfolded harvester with output measured on a shaker table during a frequency sweep 50 to 400 Hz with actuation amplitude of 0.2 g. The same tuned harvester showed a different output when put on a gas turbine, presented in Figure 4.5. This is an example where the placement and the harvester axis direction have an impact of the output. The difference between the two measurements can be explained by looking at the three first modes of the backfolded harvester. In Figure 4.6 the three first modes are presented, where the first two modes are along the Y axis, while in the third mode is along the Z axis. The gas turbine on the test site is fixed to a frame, which is attached to the floor. By this fixture the vibrations from the gas turbine is damped inline with the Y axis. Calculated voltage output from simulations in COMSOL, presented in Table 4.1, shows that there is electric output for all three modes. Because of the gas turbine fixture with its damping on the Y axis it is reasonable to believe that the output from the harvester only is obtained for the third mode, as shown by the measured values in Figure 4.5.

Figure 4.4 Open circuit voltage output from a backfolded harvester (inlet picture) on shaker table.

Figure 4.5 Open circuit voltage output from a backfolded harvester on a gas turbine.
Table 4.1 Tabulated COMSOL calculated open voltage for the three first eigenfrequencies on the backfolded harvester with 1g.

<table>
<thead>
<tr>
<th>Eigenfrequency</th>
<th>Output voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>114</td>
<td>3,3</td>
</tr>
<tr>
<td>191</td>
<td>3,3</td>
</tr>
<tr>
<td>456</td>
<td>3,2</td>
</tr>
</tbody>
</table>

Figure 4.6, The three first modes of the backfolded harvester is presented. Mode 1 and 2 are under impact from vibrations in y axis, while the third mode is moving along the z axis.

4.3 CHARGING OF SUPERCAPACITORS BY HARVESTED POWER

The choice of supercapacitor as energy storage in an IWS is based on a life cycle perspective as presented in Paper VI. To be able to use the supercapacitor the difference between batteries and supercapacitors has to be examined. Batteries have an internal chemical potential difference between the electrodes with a charge transfer that creates an output voltage. While charging and discharging the voltage is relatively constant as presented schematically in Figure 4.7.
The EDLC supercapacitor (in this thesis) stores the energy electrostatically and when charged the voltage increases linearly and during discharge the voltage decreases linearly as presented schematically in Figure 4.7. To be able to deliver energy to the sensor and Wi-Fi transition a power management module is needed. In this thesis a MIDE EHE004 is used. To be able to deliver energy, the power manager charges the supercapacitor up to the $V_{in}$ rising voltage limit, presented in Figure 4.8. And when the $V_{in}$ rising voltage limit is reached, EHE004 delivers energy until the $V_{in}$ falling voltage limit is reached, as presented in Figure 4.8. The energy density for a battery is much higher compared to a supercapacitor. Due to the supercapacitor linear discharge behavior compared to the constant discharge behavior of batteries, energy density difference is increased, presented schematically in Figure 4.7 by the green dash-dot-dot line. The whole constant discharge from the battery is above the output line while half of the discharge from the supercapacitor is above the output line.

The Wi-Fi startup sequence for the used RF interface ZigBee is the most single power consumption task for the IWS system. The supercapacitor needs to have enough power for a startup sequence of 8 mW. This is achieved by a 20 mF supercapacitor. However, a 20 mF supercapacitor takes a long time to charge when a harvester is used, up to 3 hours even from an optimized harvester on the shaker table. This is because the current is not constant and the power from the harvester comes in small chunks. In Figure 4.8 the difference between ideal charge and harvester charge is demonstrated schematically. The charge time with power from the harvester, blue dash-dot-dot line in Figure 4.8, becomes logarithmic in nature and reaching the $V_{in}$ rising level for the power management takes very long.
To counter the charge time problem the supercapacitors were connected in series. In Figure 4.9 two 20 mF supercapacitors were connected in series and in parallel to demonstrate the difference in charge time. The two 20 mF connected in series (green solid line Figure 4.9), charge much faster compared to the two in parallel (dotted line Figure 4.9). However, connected in series the total capacitance is decreased, which was solved by using larger supercapacitors to have enough energy...
to start up the Wi-Fi. In this thesis four 320 mF supercapacitors are connected in series, with a total capacitance of 80 mF. Connected in series, in the critical zone between start voltage and cut off voltage, a near linear behavior is achieved, presented with a black line in Figure 4.10 between \( V_{\text{in rising}} \) and \( V_{\text{in falling}} \). By this solution the charge time is decreased considerably from up to 3 hours down to 1 minute on a shaker table.

![Figure 4.10 schematic of output voltage from supercapacitors connected in series where the charge from the harvester shows a near ideal behavior in the voltage window between \( V_{\text{in rising}} \) and \( V_{\text{in falling}} \)](image)

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### 4.4 WIRELESS INTELLIGENT SENSOR SYSTEM TEST ON A GAS TURBINE

There are many challenges that you encounter when you are to harvest energy to power a wireless sensor system on a gas turbine. The biggest challenge turned out to be to cover the right frequencies since there is an amount of many different resonances, in different directions on a gas turbine. In my case, in this thesis this occurred because we were not able to put the harvester directly on the gas turbine itself. In the end we found a protruding rectangular metal plate where the harvester could be attached. The protruding rectangular metal plate itself has an eigenfrequency, which naturally shifted, when the package with the harvester was attached to it. In the end an array of harvesters was used to be able to cover the wide range of possible frequencies where energy could be harvested, due to limited time access of the gas turbine, this turned out to be the quickest and best solution from a harvesting perspective.

The harvester was screwed directly to the protruding rectangular metal plate, depicted in Figure 4.11. Shown in Figure 4.11 is also the Wi-Fi transmitter (ZigBee), the power management module (EHE004) and the supercapacitor pack containing four 320 mF connected in series. After some on-site tweaking, the supercapacitor was charged from 0 V to 5.13 V within 3.5 minutes. Which is a reasonable time, considering that under normal conditions the supercapacitor will be above 0 V
when power is starting to be harvested. In figure 4.12 the supercapacitor voltage under continuously transmitting power consumption is presented; the red ring indicates the startup sequence power consumption for the Wi-Fi transmitter. During harvesting the ZigBee was powered for 67 seconds, while broadcasting continuously.

Analyzing the supercapacitor voltage output data, a scenario for transmitting with 0 - 10 second interval was calculated (Figure 4.13). The result was that the harvester would be able to power the ZigBee if the ZigBee was broadcasting with 1 second interval. The specified demand was to transmit gearbox health data every 10 second, as discussed in Paper VIII, which by this demonstration is achieved. I believe that wireless sensors are very useful on test sites and later also on gas turbines mounted on airplanes. To be able to have a more effective output from the harvester its placement and attachment would be taken into consideration when designing new harvester and gas turbines.

Figure 4.11 The final setup up components where the harvester was able to provide sufficient energy to power the wireless system.
Figure 4.12 Supercapacitor voltage during startup (marked by the red circle) and continuously transmitting.

Figure 4.13 Voltage change due to Wi-Fi transmission interval. Broadcasting every second will be possible since the net harvested energy is positive.
CONCLUSIONS

In this thesis, I have focused on two vital components in an AIWS, the energy harvester and the energy storage. The choice of energy harvester in this thesis covers piezoelectric cantilevers. Since my main application, gearbox surveillance on gas turbines, vibrations are an ambient source of energy due to placement on the gas turbine. Energy harvesting by heat conversion is not covered in this thesis. For the energy storage component, the choice in this thesis was supercapacitors, since they can be charged and discharged over $10^5$ times, which is vital to be able to power an IWS over many years. To be able to utilize energy harvesting as an alternative or in combination with an energy storage it needs to be broadband, yield a sufficient power supply, have a reasonable size, which utilize available space to the fullest.

In the second chapter of this thesis I presented vibrational piezoelectric harvesting and the main challenge of obtaining a broad bandwidth and a maintained power output. To solve these challenges, I presented two macro harvesters and one MEMS harvester.

The first macro harvester, called backfolded, with two conjoined cantilevers, has a higher output compared with two single cantilevers. The backfolded also has two output peaks with maintained power output. The main reason for this effect is that the bottom cantilever has an extended stress distribution over the whole cantilever and therefore it is more effectively utilized compared to a cantilever attached in one end. Conjoining two cantilevers vertically on top of each other, compared to traditional 2DOF in one plane, gave higher energy output and I showed that it is possible to decrease the gap between the two output peaks, introducing length asymmetry. By achieving this, a broader bandwidth is obtained. The backfolded structure also is space-effective compared to other piezoelectric solutions with the same power output.

The second macro harvester, called self-tuning harvester with a sliding mass, is made up of two piezoelectric beams placed on top of each other with a connecting center beam between them. This design maintained the positive trait of extended stress distribution for both piezoelectric cantilevers, compared to the backfolded harvester where only the bottom cantilever achieved this trait. A broad bandwidth of 12 Hz is achieved by the mechanical self-tuning phenomena of sliding mass, the position of which on the middle beam changed the eigenfrequency of the system in total. In order to achieve broader bandwidth (37 Hz) with maintained power output (150 mW) the solution was to use asymmetric lengths of the piezoelectric cantilevers. The asymmetric solution was predicted by a numerical model of the system. In Paper IV the numerical model prediction was verified and examining one measured case closely, the sliding mass movement prediction correlated well with measurements.

The micro size harvester is also utilizing the trait of extended stress distribution by conjoining cantilevers. Here the cantilevers are in one plane with two outer cantilevers connected to a backfolded cantilever in the middle. This design is due to MEMS fabrication reasons, where a planar structure is easier to fabricate in contrast to a design where the cantilevers are on top of each other. Utilizing as much of the available device area as possible for harvesting is a crucial benefit.
for conjoining cantilevers with extended stress distribution. This will make harvesters more space efficient and non efficient to be used in real life applications.

In this thesis I have schematically shown the difference between other harvester solutions and my solutions to achieve broader bandwidth and maintained power output. The reason I choose not to compare numbers is twofold; the absence of a standard FOM and wanting to clearly show the difference between my solutions and other solutions in the literature. Regarding the FOM, so far many have tried to create one, but the result is up to now that there are many different FOMs [64]. In order to benchmark my harvesters, I used an effective bandwidth, which was defined from the power I needed to provide for the IWS. I am aware that this need differs from application to application, but so is the design and tuning of the piezoelectric harvesters depending on where they are used. This implies that it is hard to compare different harvester solutions straight off. In the end the harvesters that can provide sufficient power will be the ones that we might be able to create a FOM from.

In the third chapter I presented that the best energy storage for IWS are supercapacitors. Compared to batteries, supercapacitors have a much longer life cycle, but inferior energy density, which shifts over the life time in favor for supercapacitors due to their high amount of charge and discharge cycles. To solve the challenge of the energy density, new electrode materials have to be developed. One such material is CNF conjoined with CVD grown CNT. This material provides positive traits such as a well-ordered structure with large amount of mesopores. The reported active surface area is $131 \text{ m}^2/\text{g}$ and the capacitance is $91 \text{ F/g}$ (without activation, which would yield a higher F/g)

The fourth chapter is dedicated to measurements in an authentic commercial test environment on a gas turbine and the challenges you encounter when to harvest energy on a gas turbine. The live test was finally successful after solving the following challenges:

- Cables breakage, due to ambient vibrations.
- Placement of the harvester.
- Charging supercapacitors.

The final goal was to show that it was possible to charge a supercapacitor within a reasonable time and provide harvested power for the IWS to broadcast data every 10 seconds. Both conditions were achieved while harvesting on a gas turbine. I am sure that autonomous IWS will be used more on various applications in the future. The development of harvesters is in its infancy, but it goes fast in the right direction with broader bandwidth and sufficient power. The development of ambient energy harvesters will have a positive impact on our environment, since we will be able to use less non-renewable resources for power and cables.
References


[34] L. L. Gaines and J. B. Dunn, Lithium-Ion Battery Environmental Impacts. 2014.


[140] “gnu.org,”.


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Appended papers
Paper I

SIMULATION AND EXPERIMENTAL DEMONSTRATION OF IMPROVED EFFICIENCY IN COUPLED PIEZOELECTRIC CANTILEVERS BY EXTENDED STRAIN DISTRIBUTION
L G H Staaf, E. Köhler, D. Parthasarathy, P Lundgren and P Enoksson
Simulation and experimental demonstration of improved efficiency in coupled piezoelectric cantilevers by extended strain distribution

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A B S T R A C T
A piezoelectric energy harvester design is proposed, which will achieve a wider bandwidth without compromising energy conversion efficiency for future use in e.g. gas turbines. By coupling two cantilevers where the tip of the bottom one is attached to the base of the upper one, the harvester will have a wider bandwidth and a higher power output compared to two optimally tuned single cantilevers, which to a large part is the effect of an extended strain distribution in the bottom cantilever in the coupled configuration. The design is compact, using only half the area compared to two parallel single cantilevers at the price of only a small increase in height. The coupled harvester displays approximately five times higher power output than two tuned single cantilevers.

1. Introduction

Piezoelectric energy harvesting from vibrations is cost efficient and environmentally friendly compared to batteries with limited lifetime, which make them a good alternative for powering, e.g., intelligent wireless sensors inaccessibly integrated into harsh industrial environments like engines or machines with inherent vibrations [1,2].

A single piezoelectric cantilever used in vibration harvesters can be tuned to the most abundant vibration frequency in its environment but it will be at risk of providing insufficient electrical power if the vibration spectrum shifts or fluctuates beyond the narrow window of optimal tuning. One fundamental challenge in cantilever design is thus to widen the bandwidth without sacrificing the power output [3].

Gas turbines constitute an interesting but challenging environment for wireless sensing with high temperatures and high amplitude vibrations. The space available for harvesters to power sensors is limited, putting constrains on their total size. The harvestable frequencies change dynamically with the turbine’s rotational speed. It is a design challenge to find a minimum size harvester that can utilize the broad and varying spectrum of vibrations in the whole range from startup to cruise conditions of the gas turbine.

There is a significant amount of research reported on approaches to widen the bandwidth and gaining higher harvested energy from piezoelectric cantilevers. Li et al. [4] proposed an array of structures with a different resonant frequency for each structure. Soliman et al. [5] used an amplitude limiter to gain broader bandwidth. Petropoulos et al. [6] used coupled oscillators; Spreemann et al. [7] used magnets to achieve a non-linear harvester resulting in broader bandwidth. Ramlan et al. [8] tested bi-stable structures, and Zhu et al. [3] used a large mass (large device size) with a high degree of damping.

Another interesting way to increase the harvested energy and the bandwidth has been proposed by Zhou et al. [9] exploiting a primary beam multimode magnifier. In this design the secondary beam multi-mode energy harvester is attached to the primary beam multimode dynamic magnifier and this has a broader bandwidth and the harvested energy is greatly improved. To further enhance this effect Wu et al. [10] describe two degrees of freedom piezoelectric energy harvester, where the secondary beam is cut inside the main beam. This makes the design less bulky, results in a broader bandwidth with two closely spaced peaks, and gives a high power output from both beams.

The harvester design presented in this paper is realized using commercial components and is a combination of a magnifier and two degrees of freedom harvester having a magnifier in the shape of a bimorph piezoelectric cantilever, where the secondary cantilever is also a bimorph piezoelectric cantilever. This design enhances the harvested energy and gives a broader bandwidth than an array of two tuned single cantilevers. The design gives a small increase in volume but utilizes the bottom beam more efficiently for higher...
power output, much due to the improved and extended strain profile of this beam.

2. Design realization and simulation of single and coupled cantilevers

The theory of piezoelectric cantilevers in the literature mainly covers single cantilevers. An extension to the single cantilever theory has to be applied in order to describe two connected beams as a couple for enhanced power output. Zhou et al. [9] extends the single cantilever theory to cover two coupled beams with a multimode design. This design is proved to yield a higher power output and to broaden the bandwidth. Our improved alteration of their design utilizes two piezoelectric cantilevers folded over each other (Fig. 1) instead of extending in the same plane. This design will enable harvesting from both cantilevers with stress profiles, which differ significantly from those of single beams. This design is also built with industrial components and will consume only half the area compared to two single cantilevers.

The height is slightly increased but in total the design provides a conveniently manageable harvester. A model of a single MIDE v21b cantilever [11] was built within COMSOL Multiphysics. The real MIDE v21b is a bimorph piezoelectric cantilever with five layers (Fig. 1): FR4, piezo material, Espanex, piezo material and FR4 [12]. FR4 is a glass epoxy thermoset laminate, and ESPANEX is a copper-clad polyimide laminate used for flexible circuit boards.

The length and width for the layers were measured with calipers and the thicknesses of the layers were measured in a microscope (Table 1). The length, width, and thickness were transferred over to COMSOL where the built model cantilever has the resonance frequency 274 Hz in 1 atm, which is the specified resonance frequency without tuning weight from MIDE datasheet [11]. Since the simulation correspond closely enough to the true values of the v21b specifications, the mass, size, and spring values in the simulation corresponds to the real cantilever and need no further adjustment. The coupling made of the plastic Polytetrafluoroethene (PTFE) might, however, introduce extra mechanical damping for the whole system.

With the single cantilever as starting point another (top) cantilever of the same geometry is added by attaching it at the free moving tip of the first (bottom) one, so that the top one extends out over the bottom one (Fig. 1). For comparison, two single harvesters were tuned so that each one showed resonance at one of the resonance frequencies of the coupled harvester (Fig. 2). The voltage responses as a function of frequency for the two differently tuned cantilevers were then added together. The coupled harvester simulated output is compared with the double single simulated output in Fig. 4. The power is proportional to the square of the output voltage: by integration of the voltage square of the curves in Fig. 4, the output power in the frequency range 50–200 Hz is 4.7 times higher for the coupled compared to the double single harvester (Table 3). It can also be seen in Fig. 4 that the bandwidth for the coupled harvester is wider than for the double single harvester.

Looking further in the simulation data for explanation of the higher power output for the coupled harvester, it can be seen that the stress on the bottom cantilever is significantly higher in the first mode at 102 Hz (Fig. 3A1), compared to the single cantilever, over the cantilever surface (Fig. 5A). The stress for the coupled top cantilever is, however, lower compared to the single cantilever at the first mode at 102 Hz. The stress profile on the bottom cantilever resembles that of a single clamped beam with a weight (the top cantilever) at the free end, since the top cantilever does not add stress to the bottom cantilever at this mode. It appears that the bottom
Table 1
Materials and constants used in the simulation for the MIDE v21b cantilever.

<table>
<thead>
<tr>
<th>Material properties</th>
<th>Young's modulus ($E_i$, Pa)</th>
<th>Piezoelectric constant ($d_{31}$, mV/Pa)</th>
<th>Dielectric constant ($e_{31}$, Fm$^{-1}$)</th>
<th>Density ($\rho$, Kgm$^{-3}$)</th>
<th>Poisson’s ratio</th>
<th>$L \times w \times t$ (mm $\times$ mm $\times$ mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PZT</td>
<td>$63 \times 10^9$</td>
<td>$-190 \times 10^{-12}$</td>
<td>$830 \times 10^{-10}$</td>
<td>7800</td>
<td>0.3</td>
<td>$36 \times 15.2 \times 0.18$</td>
</tr>
<tr>
<td>FR4</td>
<td>$22 \times 10^3$</td>
<td>-</td>
<td>$1920$</td>
<td>1300</td>
<td>0.28</td>
<td>$36.5 \times 17 \times 0.18$</td>
</tr>
<tr>
<td>Spanex</td>
<td>$3.2 \times 10^3$</td>
<td>-</td>
<td>$1920$</td>
<td>1300</td>
<td>0.34</td>
<td>$36 \times 17 \times 0.09$</td>
</tr>
<tr>
<td>Damping material</td>
<td>$3.5 \times 10^3$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.28</td>
<td>$5 \times 17 \times 0.01$</td>
</tr>
</tbody>
</table>

Fig. 4. Coupled harvester simulation and double single (the two single power output is added, hence double single) simulation of power output vs. Hz, where the simulated coupled harvester performs 4.7 times better than the double single harvester by comparing power output by voltage square.

cantilever would be the highest power output contributor for the coupled harvester at the first resonance mode. For the second mode at 175 Hz (Fig. 3A2) the coupled top cantilever has its highest stress at the fixed end (coupled to the bottom beam) (Fig. 3B). The stress is higher over the whole distance compared to the single cantilever. For the coupled bottom cantilever there is high stress at the fixed end, lower in the middle and higher towards the coupled fixture. This extended stress profile enables piezoelectric action over the whole length of the bottom beam. By the magnification at coupled end the strain profile is similar to as if the bottom cantilever be fixed in this end. And due to the similar strain profile as fixed at the coupling end and the regular strain profile at the fixed end the bottom cantilever has a higher strain in total and therefore can deliver a higher power output. In Fig. 3B1 and B2 we can see the corresponding single cantilever mode shapes for 102 and 175 Hz.

3. Measurement setup

A prototype couple harvester was built by two v21b MIDE piezoelectric cantilevers (Fig. 6). The bottom cantilever is attached to a metal box by a piece of PTFE. The top cantilever is attached at the other end of the bottom cantilever via a piece of PTFE as coupling fixture with PTFE screws and nuts to attach the cantilevers. Very thin cables are soldered to the top cantilever to minimize the mechanical influence. All protecting plastic and contact materials on the top cantilever are removed to reduce weight. The assembled coupled harvester is placed on a shaker table. The shaker table is connected to a function generator from which the frequency output is controlled and the amplitude kept constant. The output from

Fig. 6. The double harvester prototype containing two MIDE v21b cantilevers and the polymer bottom attachment and the polymer coupling with screws and nuts.

Fig. 5. (A) Single cantilever normalized stress applied to the coupled harvester cantilevers where bottom cantilever has a higher stress over distance (36 mm) for the cantilever than the single cantilever for the first mode of resonance. The top cantilever has a lower stress than the single cantilever. (B) Single beam normalized stress applied to the coupled harvester cantilevers for the second frequency mode, where the top cantilever has a higher stress over the distance (36 mm) for the cantilever. The bottom cantilever has higher stress at the ends and lower in the middle due to that it is attached on the left end and has the attached coupling on the right end.
the coupled harvester is measured by a multimeter and the frequency output is measured by a second multimeter. Both outputs are stored via USB connections to computers.

4. Result

The single and coupled cantilevers were tested in the experimental setup in the frequency range 50–200 Hz. The resonance modes for the prototype are 85.2 and 135.5 Hz with a relative deviation of 20.5% and 26.6%, respectively compared to the initial simulations (Table 2). The measured output power is lower than the simulated output power. Fig. 7 shows the voltage squared output power from the double single and coupled harvesters. The coupled harvester has 5.4 times higher power output than the double single harvester by integration of the curves in Fig. 7, in the frequency range 50–200 Hz. The measured double single harvester performs significantly worse than in simulations and is possibly affected more by damping when a tuning weight is attached compared to the coupled harvester, which is shown by the power output ratio comparison in Table 3.

The difference between the initial simulations and the measured resonance frequency modes is significant; in order to reduce the gap between simulated and measured modes, more damping was added in the simulation and was adjusted until the resonance modes in the simulation match the measurements. The damping on the prototype originates from mechanical losses for both the fixture attaching the bottom cantilever and the coupling fixture to the top cantilever and is the factor that is most difficult to estimate prior to measurements. The mass and spring constant are given by specifications whereas the damping is treated as an unknown (fitting) parameter. In order to model the damping in the simulation, thin blocks of soft damping material (Table 1) in the connection areas between the PTFE pieces and the cantilevers are used (Fig. 8). The thin blocks were taken as 0.01 mm high and were given a Young’s modulus of 350 kPa compared to the 750 MPa of PTFE. The simulated resonance frequencies can be made to differ by only 1.1% and 2.1%, as presented in Table 2.

Through the added damping, the simulation can be used to further enhance the prototype, by looking on the impact on the output from the damped simulation. In Fig. 9 the first simple simulation is compared to the measured values and the simulation with damping. The power output for the simulated damped coupled is 7.4

<table>
<thead>
<tr>
<th>Mode 1 couple harvester</th>
<th>Mode 2 couple harvester</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated</td>
<td>Measured</td>
</tr>
<tr>
<td>102.7 Hz</td>
<td>85.2 Hz</td>
</tr>
<tr>
<td>Simulated damped</td>
<td>84.3 Hz</td>
</tr>
</tbody>
</table>

Fig. 7. Measured coupled and double single harvester vs. frequency response; the coupled harvester has a higher output around the modes and between, the coupled harvester has 5.4 times higher power output.

Table 3
Integrated power output ratios comparison.

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>simulated couple vs. simulated double single</td>
<td>4.7</td>
</tr>
<tr>
<td>damped simulated couple vs. damped simulated double single</td>
<td>6.3</td>
</tr>
<tr>
<td>measured couple vs. measured double single</td>
<td>5.4</td>
</tr>
<tr>
<td>damped simulated double single vs. measured double single</td>
<td>6.3</td>
</tr>
<tr>
<td>simulated double single vs. measured double single</td>
<td>14.5</td>
</tr>
<tr>
<td>damped simulated coupled vs. measured couple</td>
<td>7.4</td>
</tr>
<tr>
<td>simulated coupled vs. measured coupled</td>
<td>12.7</td>
</tr>
</tbody>
</table>

Fig. 8. The thin damping blocks are marked by red on the model in COMSOL. There are three attenuation zones between the cantilevers and the PTFE pieces (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Fig. 9. Measured prototype (blue line) compared with simulated damped coupled (green long dash) and simulated non-damped couple (red dashed) of voltage output vs. frequency, where the added damping shows that the bandwidth decrease as does the power output (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).
times higher (Table 3) compared to the measured power output. The damping on the prototype influences both the power output and the bandwidth. By adding damping in the model we see what kind of changes to the prototype that are likely to improve the power output and to enhance the bandwidth; reduction of damping appears to be critical for our harvesting system.

The first simple model indicated that the design with the coupled harvester would have a higher power output than two single cantilevers. The measurements on the prototype showed a big difference in the frequency modes and in the power output. With better attachment, better fixture and stronger coupling for the coupled harvester will yield a higher power output, supported by findings of theamped simulations.

5. Conclusion

A compact and broadband coupled harvester based on two mechanically coupled cantilevers, intended for powering of wireless sensors in physically constrained environments has been designed, simulated, built, measured, and compared to two single cantilevers that are tuned to display the same resonance frequencies as the coupled. In simulations the coupled harvester yielded 4.7 times more harvested power than two single cantilevers, to a large part an effect of an extended stress distribution for the bottom cantilever in the couple design. Measurements on prototypes showed that the coupled cantilever outperformed the two optimally tuned single cantilevers by 5.4 times in terms of power output.

The ongoing design optimization is directed towards an application in gas turbines, where the compact design for sufficient broadband operation is a critical issue and will require further reduction in damping for the coupling fixtures in particular. Hence another material with less damping and higher stiffness like aluminum and thin screws will be a viable option to choose. The elevated temperature in the gas turbine will tend to increase the damping impact of the PTFE even further, wherefore replacing this material has a high priority."

Acknowledgments

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References


Biographies

Henrik Staaf received his master’s degree in physics and his teaching degree for the Swedish high school in 2003. In 2007 until 2012 he was appointed IT-pedagog within a corporate group in IT-Gymnaset Sweden AB, where the focus was to enhance the usage of IT in the classroom and to use virtual platforms as pedagogic support and to implement new platforms. From 2008 till 2012 he was a teamleader on IT-Gymnaset Göteborg. He has worked as a full time teacher until 2012, when he started his Ph. D. studies at Chalmers University of Technology through the Swedish Education Initiative and sponsored by the Swedish Council of Science. The Ph. D. studies focus on energy sources for Intelligent Wireless Sensors which is divided into energy storage and energy harvesting, where the main focus on harvesting is from piezoelectric and thermal energy harvesters and the energy storage focus on supercapacitors.

Elof Köhler is a Ph. D. student in the Micro- and Nanosystems group at the department of Microtechnology and Nanoscience at Chalmers University of Technology. He has a bachelor degree in applied physics and a master degree in nanoscience, both from Chalmers University of Technology. The main focus in his Ph. D. work is energy harvesting with high temperature thermoelectric energy harvesting as his favorite pet.

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Peter Enoksson received the Ph. D. 1997 from the Royal Institute of Technology, KTH, Sweden. 1997 he became assistant professor and 2000 was appointed professor at KTH. He was appointed Professor of MOEMS 2001 at Chalmers University of Technology, Gothenburg, Sweden. In 2002 he was appointed vice dean of School of Electrical Engineering and 2003 head of the Solid State Electronics Laboratory. Currently he heads the Micro-and Nanosystems group at the department of Microtechnology and Nanoscience, MC2. His research focus on combining MEMS/NEMS with other sciences in novel dedicated and advanced systems. Prof Enoksson has published more than 200 research journal and conference papers and ten patents. He is initiator of spin-off companies, winner of the Innovation Cup, referee for several journals and also a member of the editorial board of Journal of Micromechanics and Microengineering, the steering committees of MicroMechanics Europe and of company and projects boards.
Paper II

IMPACT OF DESIGNED ASYMMETRIES ON THE EFFECTIVE BANDWIDTH OF A BACKFOLDED PIEZOELECTRIC ENERGY HARVESTER
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Submitted
IMPACT OF DESIGNED ASYMMETRIES ON THE EFFECTIVE BANDWIDTH OF A BACKFOLDED PIEZOELECTRIC ENERGY HARVESTER

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Abstract

For the successful realization of autonomous wireless sensors, they will have to be able to harvest energy from their surroundings. Vibrational energy harvesting offers a possible power supply in many environments, since vibrations are an abundant power source. In order to make vibrational energy harvesters more useful, a broad bandwidth is desirable since many vibrations are stochastic in nature. In this paper we implement asymmetry to a backfolded piezoelectric energy harvester to achieve broader bandwidth with maintained power output. Asymmetry based on different lengths of the conjoined cantilevers is experimentally and numerically shown to have the largest impact on the bandwidth, compared to the impact of modified mass loadings. A developed numerical model is used to explain the voltage output, showing that small changes in length of the cantilevers yields significant differences in the output.

Introduction

With growing interest in wearables [1], the health of buildings [2], monitoring of structures [3], failure prevention check on machines [4] and state of health check on the human body [5], autonomous wireless sensor systems [6], [7] play a vital part. All these devices consume power and this is usually solved by using a rechargeable battery. The focus on a solution, that can power the device over a long time without any physical replacement of batteries, is greater than ever. A longer lasting energy solution should furthermore have superior capacity, be integrated and scalable. Batteries today are limited by their lifetime, regarding charging and discharging. One attractive alternative to batteries would be to use energy harvesters in conjunction with supercapacitors. Supercapacitors are inferior in energy density compared to batteries, but have a very long cycle lifetime [7]. The lower energy density is alleviated by the pairing with a vibration energy harvesting device, which recharges the capacitor, as it is drained. Both supercapacitors and vibration harvesters are scalable which open the potential for self-powering miniaturized systems which can be put into wearables [8]–[10].

For a self-powering system based on vibrational harvesting, an energy harvester needs to be a mechanical structure with high output and broader bandwidth than single cantilevers or comparable concepts. The system architecture involves an intrinsic sensor, actuator and control mechanisms. The system should respond to a stimulus and then return to its original state after the stimulus is removed. Stimuli can for instance be stress, strain, light or electric field. The choice of material for such energy conversion structure is for example piezoelectric material, as in our case where we have stress from vibrations. The main challenge for a piezoelectric cantilever is that a simple beam has a very narrow bandwidth Various approaches have been investigated to attempt to achieve both a higher energy output and a broader bandwidth.

A way to enhance the power output is to change the rectangular cantilever to other different geometric shapes, since only the part closest to the attached end of the cantilever is utilized. Instead a trapezoidal shape has been presented to extend the stress over a larger part of the cantilever, hence yielding a higher output [17].
An additional mass can be used to adjust the eigenfrequency of the cantilever, so that the harvester could be modified to match different ambient vibrations. The applied mass also makes the harvester more broadband with the undesirable consequence of sacrificing the output [11]. By combining several cantilevers with different eigenfrequencies in an array, a broader bandwidth is achieved at the expense of space, since the array solution tends to become large to cover a broad bandwidth [12].

Another solution for broader bandwidth is to apply two masses on a cantilever and by that using the part of the cantilever closest to the attachment (primary cantilever), to enhance the outer part of the cantilever (secondary cantilever), called two degree of freedom (2DOF) harvesters. The masses can be applied on one cantilever or the primary and secondary cantilever can be of different rectangle size. The first mass is applied between the primary and secondary cantilever and the other mass is applied at the outer free tip of the secondary cantilever [13][14][15][16]. This solution is more space efficient compared to previous solutions and yields a good power output. However, these solutions yield broader bandwidth at the expense of power output and have two output peaks separated from each other, where the first output peak has a usable output but the second output peak has a much lower output.

The aim of this paper is to utilize conjoined piezoelectric cantilevers to achieve broader bandwidth without having to compromise the voltage output. Different drilled patterns on single piezoelectric cantilevers, to mimic a trapezoidal shape, are investigated by their voltage output impact. To achieve broader bandwidth and maintained voltage output, different configurations with variations in plate lengths, drilled hole patterns and applied masses are tested on the whole system. By altering these parameters for a backfolded harvester (see Method below) various levels of asymmetry are achieved.

Method

Systems with two beams coupled in the same plane have previously been thoroughly investigated [14], [18]–[22]. In contrast, our system has a secondary plate backfolded on top of the primary plate. This configuration not only enhances performance but also conserves space. Our performance investigation is based on empirical measurements of various combinations of configurations; (couplings k(1-4), weights w(1-4)), stiffness (bottom cantilever b(0-2) and top cantilever t(1-2)) (Figure 1) for our plate system. The system is analyzed by a simplified numerical model for guidance in how to select parameters for output enhancement, which is subsequently confirmed by measurements. All these configurations have an asymmetric impact on the harvester, where some parameters have a larger impact on both bandwidth and output.

Measurement setup

The harvester contains a bottom piezoelectric cantilever that is conjoined via an aluminium coupling with a backfolded top piezoelectric cantilever (Figure 1). The top cantilever t(0-2) has two different geometrical patterns that lower the stiffness, hence lowering the eigenfrequency somewhat. The top cantilever t0 is just a plain cantilever. Top cantilever t1 has drilled holes in rows (Figure 1A). The number of holes is increasing towards the free end and the distance between each row is constant. Top cantilever t2 also has holes drilled; the holes have a slightly larger diameter towards the attached end and are overlapping each other (Figure 1A). The holes change the area size of the cantilever and strives to mimic a trapezoidal shape, which has been shown to yield a more distributed stress over the cantilever, hence yielding a higher output [23], [24].

The mechanical coupling between the bottom and top cantilever, called k(2-4), are presented in Figure 1B. The differences between the couplings are their heights and weights (Table 1). The biggest impact from the couplings is that they are differing in mass. At the unattached free end of the top cantilever, t(0-2), four different weights, w(1-4), are placed. The weights used are the same as the couplings k(2-4). In Table 12 the weights and open lengths are presented. The open length is the space between the clamping position,
b(0-2), and the coupling at the outer end of the bottom cantilever. The open length is the same for the three top cantilevers, t(0-2). Coupling k1 could not be used due to its low height.

The bottom cantilever b(0-2) has three different clamping positions for the attachment (Figure 1C-D). These clamping positions make the cantilever stiffer, allowing it to gain a higher stiffness and consequently a higher eigenfrequency, closer to the top cantilever eigenfrequency.

The measurement is carried out on a shaker with 0.2 g sinusoidal excitation signal. An NI-USB-6210 data acquisition (DAQ) instrument collects the data.

![Figure 1](image)

**Figure 1.** A, The different cantilever configurations that are used. B, The couplings k2-3 also used as weights w1-4. C, Actual setup of the harvester. D, Schematic setup of the system

<table>
<thead>
<tr>
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<th>Height (mm)</th>
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<th>Open length (mm)</th>
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<td>3</td>
<td>1.83</td>
<td>-</td>
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<tr>
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<td>5</td>
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<td>k3, w3</td>
<td>7</td>
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<td>9</td>
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<td>t2</td>
<td>-</td>
<td>1.690</td>
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**Table 1.** w1 – w4 are the masses, k2 –k4 are the couplings uses to conjoin the top and bottom cantilever, b0 – b2 are clamping positions for different open lengths on the bottom cantilever and t0 – t2 are top cantilevers with different geometric patterns.
Measurement result; top cantilever with differently drilled patterns

The three top cantilevers were measured with the four masses (w1–w4) as single cantilevers without coupling. The open circuit output voltage is presented in Figure 2. The eigenfrequency for the cantilevers differs within 10 Hz for each mass (w1–w4) applied on the cantilevers. The top cantilever, t0, has the highest eigenfrequency for all four masses. The top cantilevers, t1 and t2, with different patterns, have lower eigenfrequencies (t1 slightly lower than t2). Regarding the voltage output between all measurements on the top cantilevers, t0 and t1 perform similarly and t2 has the highest output for all masses. The different drilled patterns show only a small difference in eigenfrequency. However, for the pattern on t2, we can see an increased peak voltage output of 2 V compared to the patterned t1 and non-patterned t0. This increase can be attributed to having a larger part of the piezoelectric material on the cantilever being under strain (and converting mechanical power) during the excitation.

Figure 2. Voltage output and eigenfrequency comparison between t0-2 with weight w1-4. The t2 cantilever with overlapping drilled pattern yields the highest voltage output.
Measurement result; bottom cantilever

The bottom cantilever has three different clamping positions, which make the open length shorter and hence the eigenfrequency higher. In Figure 3, the bottom cantilever open voltage for the three different clamping positions, b(0–2), are presented. The measurements are performed without a tip mass. The position, b2, has the shortest open length (table 2) and, b0, has the longest open length (table 2). As seen in Figure 3, the clamping position has a big impact on the eigenfrequency, as expected.

Figure 3, Open voltage output over frequency for the clamped bottom cantilever without tip mass.

Measurement result; conjoined backfolded harvester

Figure 4, Output open voltage for configuration b0 t0 k(2-4) w(1-4).
In Figure 4 the output open voltage for configuration b0 t0 k(2-4) w(1-4) is shown. This is only one of the subsets in the measurement series, and it shows the typical output behavior of two distinct peaks with a low voltage output in-between. The rest of the measurements are covered later in the paper. Parameter changes for the system are three different couplings, k(2-4), and four different weights, w(1-4). The left resonant peak is called peak 1 and the right resonant peak is called peak 2 in this paper. In each subfigure in Figure 4, the total open voltage output for bottom plus top cantilever is presented. As seen in Figure 4, when the weight increases horizontally, the output also increases visibly for peak 1 but very little for peak 2.

In Figure 5, the frequency separation ($\Delta Hz$) between peak 1 and peak 2 is presented. By comparing different configurations (b(0-2), t(0-2) k(2-3), w(1-4)) we see two general trends for the harvesting system, when the stiffness for the bottom cantilever is increased. The first trend is that the measured data is divided into three major groups where all three groups are clustered around each clamping position on the bottom cantilever (b0, b1, b2). In Figure 5, b0 has the lowest $\Delta Hz$ with 50 - 65 Hz and b2 has the highest with $\Delta Hz$ 180 - 215 Hz. The second trend is that the impact by mass from the coupling seems to lower the $\Delta Hz$. However, that impact tends to decrease for b0 compared to b1 and b2.

![Figure 5](image)

*Figure 5. Frequency separation ($\Delta Hz$) between the first and second peak for all configurations (b(0-2), t(0-2) k(2-3), w(1-4)). The three distinct groups of $\Delta Hz$ are each primarily based on where the bottom cantilever is clamped. The group with lowest $\Delta Hz$ has the bottom cantilever clamping position b0.*

In Figure 6, we compare three different clamping positions on the bottom cantilever where each is conjoined with the three different top cantilevers. The coupling and tip mass on the top cantilever is fixed (configurations; b(0-2) t(0-2) k4 w4). The coupling and weight settings are selected as optimal from the results given in Figure 4.

The eigenfrequencies (the red bars in Figure 6) for peak 1 (dash dot red bar) are similar for all nine configurations, while the eigenfrequency for peak 2 is increasing from b0 to b2. The same eigenfrequency data is repeated for the graphs of the top- and bottom cantilever respectively.

For the top cantilever voltage output (blue bars in Figure 6A), there is a change in the output. Configuration b0 t(0-2) has the lowest voltage output for the peak 1 (blue lined bar) and peak 2 (dotted line bar). Configuration b1 t(0-2) has the highest voltage output for peak 2 and similar voltage output for peak 1 compared to the b2 t(0-2) configuration.
For the bottom cantilever a similar pattern as for the top cantilever can be distinguished (blue bars in Figure 6B). Configuration b0 t(0-2) has the lowest voltage output and b1 t(0-2) and b2 t(0-2) have similar voltage output for peak 1 (blue lined bar in Figure 6B). Configuration b1 t(0-2) has the highest voltage output for peak 2 and similar voltage output for peak 1 compared to the b2 t(0-2) configuration. The eigenfrequency behavior is near identical to that of the top cantilever, due the coupling effect where the top and bottom cantilever affect each other.

Combining the voltage output from both cantilevers for peak 1 and peak 2 respectively, the total voltage output for b0 t(0-2) for peak 1 is consistently lower (Figure 6C). For peak 2 the total output is more similar between the nine configurations. The largest trend is that the eigenfrequency becomes larger with the shorter open length on the bottom cantilever. Hence, to achieve smaller ΔHz between the two peaks, the configuration with b0 clamping position seems to be the most favorable (Figure 5 and Figure 6); however, the voltage output becomes lower in total when ΔHz decreases (Figure 6).

Figure 6, 6A) the output and eigenfrequencies for peak1 and peak 2 for the top cantilever are presented. 6B) the voltage output and eigenfrequencies for peak 1 and peak 2 for the bottom cantilever are presented. 6C) the total voltage output for peak 1 and peak 2 plus the ΔHz between the two peaks are presented.
Measurement result; conjoined cantilevers configurations based on numerical prediction

To find options for further decreasing the peak separation and for obtaining a higher voltage output between the peaks, a numerical model of the conjoined backfolded harvester system was constructed based on previous work. In the model, different cantilever lengths were compared, the mass for the coupling and the weight was kept constant (k3, w3) as a typical case, since the observed behavior for different masses was similar. The optimal simulated length configuration for the lowest ΔHz between the two peaks was found to occur when the top cantilever had an asymmetric configuration of 80% of the length of the bottom cantilever, for this case with constant masses.

To verify the numerical prediction, measurements were conducted where the top cantilever was consecutively shortened by 2 mm at a time (Table 1). The coupling and outer tip mass on the top cantilever was k3 and w3. The different lengths are mentioned as -2 for 2 mm shorter open length, down to -10 which is 10 mm shorter open length. By shortening the top cantilever length, the frequency separation between the two peaks was expected to be shorter. Five measurements with a shortened top cantilever are presented in Figure 7. As seen in Figure 7, the valley between the two peaks has an output close to 3 V when the top cantilever was shortened. This is a significant difference compared to previous measurements, where the output between the two peaks was quite low (below 0.5 V).

![Figure 7. Open circuit voltage output for backfolded harvester with shortened top cantilever from -2 mm to -10 mm.](image)

![Figure 8. Measured ΔHz between the first output peak and the second output peak for backfolded harvester with shortened top cantilever from -2 mm to -10 mm. The measured backfolded harvester with configuration -4 mm has the lowest ΔHz for both experiment and simulation. The blue line is the numerical prediction, which correlates with the measured values of ΔHz in shape.](image)

In Figure 8 the frequency separations between the peaks are presented. The configuration with the smallest ΔHz of 44.5 Hz is when the top cantilever is shortened with 4 mm. Shorter or longer measured top cantilever
gives a larger $\Delta H_z$ as presented in Figure 8. Compared to the numerical prediction of a length correlation of 4/5 between top and bottom, -4 mm yields a length correlation of 83%, which is very close to the optimum predicted from the numerical model.

In Figure 9, the -4 mm configuration for the top, bottom and total voltage output is presented in more detail. For the first peak, the bottom cantilever is dominant compared to the voltage output from the top cantilever. When the frequency sweep moves up around 105 Hz, the voltage outputs become equal. When the frequency sweep continues, the voltage output dominance shifts. For the second peak, the output from the top cantilever is almost 4 times higher compared to the bottom cantilever.

In Figure 10, the measured output for top and bottom cantilever and total voltage output is presented. The configuration in Figure 10 has an 8 mm shorter top cantilever and the voltage output is the highest for the second peak and for the voltage output between the peaks. Analyzing the voltage output for top and bottom cantilevers, the output from the bottom cantilever dominates the first peak. For the second peak, the top cantilever output is somewhat higher than that of the bottom cantilever.

The frequency where the top and bottom cantilevers contribute equally to the output is different between the two shown in Figures 9-10. The configuration -8 mm has a higher voltage in the valley between the two peaks, but -4 mm has a smaller peak separation. The effective bandwidth in our case with highest output is determined by the value of the highest voltage output point for the valley between the two peaks. For configuration -8 mm with the highest voltage output in the valley compared with the other measurements, the bandwidth is 70 Hz from 92 – 162 Hz, where the voltage output is above 2.75 V.

For further understanding of the different voltage outputs between the -4 mm and -8 mm configuration, their modes were calculated. The peak 1 modes for -4 mm and -8 mm configuration have the same curve for the bottom cantilever and opposite curve with more or less the same magnitude of inflection on the top cantilever, Figure 11 A and B. This explains the similar voltage output for peak 1 for both -4 mm and -8 mm configuration. In the peak 2 mode there is a symmetric S-shape on the bottom cantilever for -4 mm, presented in Figure 11C, hence the voltage output is lowered due to different polarizations of the piezo
material in the bottom cantilever. While in the peak 2 mode for the -8 mm, Figure 11D, a large distinct curvature of the bottom cantilever is visible with an extended stress distribution; at the attached end a small asymmetric S-shape can be distinguished on the bottom cantilever, but its magnitude is very small. The peak 2 mode shape in Figure 11D shows why the output for the -8 mm configuration for the bottom cantilever (Figure 10) has a 4 times higher voltage output for peak 2 compared to the -4 mm configuration.

Figure 11, 11A) present the peak 1 mode shape for -4 mm configuration. 11B) presents the peak 1 mode shape for the -8 mm configuration. 11C) present the peak 2 mode shape for -4 mm configuration. 11D) presents the peak 2 mode shape for -8 mm configuration. The largest difference in output is between the peak 2 mode for -4 mm and -8 mm, where the S-shape for the -4 mm configuration explains the low voltage output.

Discussion

For the backfolded piezoelectric harvester proposed in this paper, various configurations with different clamping positions on the bottom cantilever in combination with different masses were tested. Our initial assumption was that the higher stiffness achieved by a shorter bottom cantilever open length would reduce the resonance peak separation of the system. This strategy however turned out to have the opposite effect; the frequency range between the two peaks became larger (Figure 5). Even though the voltage output for the first peak increased markedly (presented in Figure 6) the valley between the two peaks had a very low voltage output.

The impact of different masses on the top cantilever outer tip and different masses on the couplings between the bottom and top cantilever had a small but clear impact on lowering the frequency separation between the two peaks. However, the ΔHz for both b2 and b1 was significantly higher than for b0. For b0 the impact on ΔHz from the masses was very small (Figure 5). Hence increasing the eigenfrequency for the bottom cantilever does not yield a broader bandwidth.
A numerical model of the backfolded beam system predicted that the lowest ΔHz was to be achieved by a length correlation between the top and bottom cantilever, where the top cantilever optimal length would be 80% of that of the bottom cantilever where the coupling and weight is constant (k3, w3). This prediction was verified by measurements. However, even though the configuration with a -4 mm shorter top cantilever (matching the model prediction) had the smallest peak separation, the configuration with -8 mm shorter top cantilever, in total, over the whole voltage output range, displayed a higher output, hence a broader effective bandwidth. Scrutinizing the modes for these two configurations we see that the difference can be explained by a pronounced S-shape on the bottom cantilever in the -4 mm case. Future investigations will show if it is possible to be rid of the S-shape entirely. From an energy harvesting point of view, a match of large bandwidth and high voltage output is needed for optimum design choices.

**Conclusion**

In this paper, we present an investigation on various forms of asymmetry for a backfolded piezoelectric energy harvester with the aim to find the best way to design for large bandwidth and higher voltage output. To achieve a higher output, drilled patterns on the piezoelectric cantilevers were tested. The cantilever called t2 with an overlapping drilled pattern yielded 2 V higher output compared to another drilled pattern and an unaltered cantilever. By applying length asymmetry for both bottom and top piezoelectric cantilever, the conclusion is that by shortening the top cantilever, the separation in frequency between the two output peaks becomes smaller and the voltage output between the peaks becomes higher. Different masses and achieving an asymmetry by mass difference proved to have a small impact compared to applied length asymmetry. By optimizing a backfolded piezoelectric cantilever by length asymmetry, in our case setting the top cantilever length to 80% of the bottom cantilever length, a harvester with a broad effective bandwidth without compromised power output is achievable.

**Acknowledgement**

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**References**


Paper III

ACHIEVING INCREASED BANDWIDTH FOR 4 DEGREE OF FREEDOM SELF-TUNING ENERGY HARVESTER
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Achieving increased bandwidth for 4 degree of freedom self-tuning energy harvester

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ABSTRACT

The frequency response of a self-tuning energy harvester composed of two piezoelectric cantilevers connected by a middle beam with a sliding mass is investigated. Measurements show that incorporation of a free-sliding mass increases the bandwidth. Using an analytical model, the system is explained through close investigation of the resonance modes. Resonance mode behavior further suggests that, by breaking the symmetry of the system, even broader bandwidths are achievable.

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1. Introduction

Over the last decade, the topic of self-powered systems has received increasing attention, especially with the appearance of wearable devices [2]. Instead of pure battery dependency, self-powering systems incorporate an energy storage component as well as an energy harvester. Energy harvesters can power devices by converting ambient energy sources (such as heat, light and vibrations) into electrical energy. Sources of vibrations for energy harvesting can be transportation vehicles, construction equipment and the human body.

A kinetic (vibration-based) energy harvester needs to have an operating frequency that matches the frequency of prevalent ambient vibrations in order to achieve a desirable power output [3]. Single piezoelectric cantilevers typically operate over a narrow bandwidth and, therefore, an appropriate design must be employed for the targeted vibrational source. However, in real-life applications, vibrational sources are intrinsically frequency-variant — sometimes over a broad bandwidth. To overcome the narrow bandwidth of conventional single piezoelectric cantilevers, various approaches have been reported as summarized below.

Ferrari et al. used multiple harvesters, each working at different resonance frequencies, forming a multi frequency energy converter [4]. Zhou et al. and Aldraihem et al. developed a double-beam configuration where a wide beam enhances the power and bandwidth of a connected shorter and thinner beam that contains the piezoelectric material [5,6]. Ou et al. placed two tip masses on a beam as a simple solution to enhance the bandwidth and derived a generalized model for a beam with any number of tip masses [7]. Additionally, Wu et al. (2012, 2014) proposed a two Degrees of freedom (DOF) design that is composed of a...
main beam and an inner secondary beam [8,9] and Erturk et al. proposed an L-shaped beam structure [10]. They were able to tune the first two natural frequencies of the structures to be relatively close to each other, achieving broadening of the bandwidth. Tang et al. included magnets in their energy harvesters where non-linearities were utilized in order to enable the harvesters to adapt to the variable input frequency by tuning the harvesters resonance frequency [11]. As a bonus, the magnets can act as tip masses that also create a Faraday's effect with auxiliary inductive coils [12] for broader bandwidth.

Another concept that enables a broader bandwidth for an energy harvester is to use a self-tuning resonator. This type of device adapts its resonance frequency to the source of vibration over a wide range of frequencies. Boudaoud et al. demonstrated a free to slide mass on a vibrating metal string, actuated by an oscillating magnetic field, which can self-adjust the system to certain input frequencies [13]. The free sliding mass adds one degree of freedom to the system. A different approach uses a bead inside a hollow cylindrical cantilever [14]. A more recent study from Miller et al. also achieved a self-tuning harvester behavior through a fixed-fixed beam and a sliding mass configuration [15,16].

Our self-tuning harvester consists of two piezoelectric cantilevers; both fixed and static in one end and free to move in the other end. For each cantilever, a tip mass is attached to utilize the concept of extended stress distribution [17]. A middle beam of aluminum, containing the sliding mass for self-tuning, connects both tip masses and acts as a mechanical coupling. By using a middle beam to host the sliding proof mass, the design space for the self-tuning is less restricted by the specific properties of the piezoelectric cantilevers. In previous modelling efforts for simpler systems of a moving mass on a cantilever [18] or a moving mass on a double clamped beam [15], the mathematical expressions for the motion of the beam and of the proof mass become challenging to interpret directly—even with simplifying assumptions. The general argument to explain the self-tuning mechanism, as given by Miller et al. [15], is that for a given excitation at a certain frequency the proof mass will move on the beam until it reaches a position where the mode of vibration has a resonance with the driving frequency. As has been shown experimentally for the double clamped beam [15], the proof mass can alter its position, as the driving frequency changes, in order to maintain resonance. The numerical modelling of Khalily et al. [18] results in a continuously lower resonance frequency as the proof mass approaches the non-clamped end of the cantilever. In contrast, the lowest resonance in the double clamped system is given by having the mass near the beam center [18]. It is, however, not obvious from previous results how proof mass motion is expected to influence the resonance frequency in our more complex structure.

In this paper, we derive a tailored analytical model that adequately describes the observed measured frequency response of our self-tuning device. Our model can explain both the observed movement of the sliding mass and the impact on system performance through altering the length of the middle beam.

2. Method

The self-tuning harvester is intended to provide power for an intelligent wireless sensor (IWS). The IWS will collect temperature data and transmit the data via Wi-Fi. The data will be collected from a gas turbine where the self-tuning harvester will convert vibrations into power.

The self-tuning harvester is measured with two different lengths of the middle beam, called Short Beam (SB) and Long Beam (LB) [19]. From a harvesting perspective, the LB had the most interesting result. Therefore, the analytical investigations were focused on the LB configuration. The output difference between SB and LB are explained by the results of the analytical calculations.

3. Experimental setup

The harvester consists of two mechanically coupled piezoelectric cantilevers connected via a middle beam (Fig. 1). The piezoelectric cantilever MIDE v21b [20] is an industrial standard cantilever composed of two layers of lead zirconate titanate
(PZA-5A), two layers of FR-4 and a layer of Espanex (a copper clad laminate using low thermal expansion polyimide) produced by Nippon steel & Sumitomo metal [21] (Fig. 2). All couplings, attachments, the middle beam and the sliding mass are made of aluminum 3003-H18.

The characterization of the harvester was carried out on a shaker table with a sinusoidal excitation. The tested frequency range was 330–410 Hz. The selected measuring range is broader than the range for which the harvester is intended (365–380 Hz). The applied frequency was increased by steps of 1 Hz and was not changed until the system was stable. The cantilever electrodes were connected to USB equipped multimeters measuring the open circuit voltage. The top and bottom cantilever output is converted to DC and added together as a total output for the system. The harvester was tested upright and then tilted 90° where the same measurements were repeated (Fig. 3).

We define the “open length” as the lengths of the cantilevers and middle beam with the parts containing couplings and attachments excluded. In the SB configuration, the top and bottom cantilevers have an open length of 14 mm and 12 mm respectively. The coupling weight is in total 3.87 g, consisting of the middle beam, the two couplings and the sliding mass (where the sliding mass weight is 0.87 g). The middle beam is 1 mm thick, 3 mm wide and has an open length of 11 mm.

In the LB configuration, the top cantilever has an open length of 23 mm and the bottom cantilever open length is 21 mm. The middle beam is 1 mm thick, 3 mm wide and has an open length of 25 mm. The coupling remains the same with the same weight for both SB and LB (Table 1).

4. Experimental results

We measured fixed weight and a free sliding weight with middle beams of different lengths. The length of the piezoelectric cantilevers differs in length between SB and LB in order to achieve the same resonance frequency.

For the SB case, the difference between sliding and fixed weight is a broadening in bandwidth. The fixed weight has 3 dB at 8 Hz and the sliding weight has 3 dB at 12 Hz. The peak open circuit voltage is more or less the same for fixed (3.26 V) and sliding (3.12 V) (Table 2).

For the LB case, the difference between sliding weight and fixed is a broadening in bandwidth. The fixed weight has 3 dB at 8 Hz and sliding weight has 3 dB at 12 Hz. The peak open circuit voltage is more or less the same for fixed (11.5 V) and sliding (11.7 V) (Table 2).

The open circuit voltage output for the LB is 3.8 times larger than for the SB, hence the 3 dB open circuit voltage output is also higher in the LB (Table 2).

There is no visible difference of the sliding mass movement, despite the shorter movement of the mass in the SB case [19]. When comparing fixed and sliding mass behaviour, SB and LB behave similarly and we can see bandwidth broadening resulting from the sliding mass compared to a fixed weight (Fig. 4). The 3 dB bandwidth for both SB and LB is 12 Hz. Apparently, little is affected by the beam length differences (Fig. 4). The effective bandwidth for our ex-service gas turbine wireless intelligent sensor application is defined by a voltage output above 5.13 V [1]. The effective bandwidth for the LB sliding mass is 22 Hz (Fig. 4).

When the driving frequency is applied, the mass slides towards either edge of the middle beam (given that it starts out in the center of the beam). The sliding pattern is the same regardless of the direction that the mass slides. In the two tests with asymmetric setup (i.e. SB and LB) with different lengths of the top and bottom piezoelectric cantilevers, the sliding mass moves from the center to an outer position but also has intermittent sliding behaviour during the frequency sweep where the sliding is unstable. The unstable sliding is clearly visible with the mass moving back and forth (approximately 3 mm along the middle beam at 362–366 Hz). In Fig. 5, the mass position on the middle beam is presented with the corresponding applied frequency. The observed behaviour of the sliding mass is not affected by turning the harvester 90° to have gravity acting along the width instead of along the thickness of the beam (Fig. 3).

When observing cases with the same length for the top and bottom cantilevers (symmetric setup), the mass only slides from the center to an outer position (without observed unstable sliding behaviour).

4.1. Simplified finite element analysis of the system

The main objective behind developing a simplified model is to derive computationally efficient codes or even closed form solutions that enable comprehensive investigations of variation in geometrical and material parameters. To this end, the system is studied using Euler-Bernoulli theory for isotropic beams with additional point masses [22]. The electromechanical

![Fig. 2. Off-the-shelf cantilever MIDE v21b cross-section.](image-url)
coupling effects for the piezoelectric cantilevers are neglected as they are of minor importance for the overall structural eigenfrequency response. Moreover, the laminated structures of these beams are modeled as homogeneous beams using

**Table 1**
Material parameters used in the harvester’s different configurations.

<table>
<thead>
<tr>
<th></th>
<th>Open length (mm)</th>
<th>Weight (g)</th>
<th>Thickness/height (mm)</th>
<th>Width (mm)</th>
<th>Young’s modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short beam (SB)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Middle beam</td>
<td>11</td>
<td>1</td>
<td></td>
<td>3</td>
<td>69</td>
</tr>
<tr>
<td>Top cantilever</td>
<td>14</td>
<td>0.89</td>
<td></td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Bottom cantilever</td>
<td>12</td>
<td>0.89</td>
<td></td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Long beam (LB)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Middle beam</td>
<td>25</td>
<td>1</td>
<td></td>
<td>3</td>
<td>69</td>
</tr>
<tr>
<td>Top cantilever</td>
<td>23</td>
<td>0.89</td>
<td></td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Bottom cantilever</td>
<td>21</td>
<td>0.89</td>
<td></td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Coupling</td>
<td></td>
<td>3.87</td>
<td></td>
<td>25</td>
<td>69</td>
</tr>
<tr>
<td>Sliding mass</td>
<td></td>
<td>0.87</td>
<td></td>
<td>14</td>
<td>69</td>
</tr>
</tbody>
</table>

**Table 2**
Comparison of measurement 1 (SB) and measurement 2 (LB).

<table>
<thead>
<tr>
<th></th>
<th>Primary mode (Hz)</th>
<th>Peak open circuit voltage (V)</th>
<th>3 dB open circuit voltage (V)</th>
<th>3 dB bandwidth (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SB sliding mass</td>
<td>375</td>
<td>3.12</td>
<td>2.2</td>
<td>12</td>
</tr>
<tr>
<td>SB fixed mass</td>
<td>378</td>
<td>3.26</td>
<td>2.3</td>
<td>8</td>
</tr>
<tr>
<td>LB sliding mass</td>
<td>372</td>
<td>11.7</td>
<td>8.3</td>
<td>12</td>
</tr>
<tr>
<td>LB sliding mass</td>
<td>374</td>
<td>11.5</td>
<td>8.1</td>
<td>8</td>
</tr>
</tbody>
</table>

**Fig. 3.** The harvester containing: Couplings (A), sliding mass (B), attachments (C) and piezoelectric cantilevers (D).

**Fig. 4.** Measurement 1 (SB) open circuit voltage output over 340–400 Hz, compared with measurement 2 (LB).
effective material properties. As for the sliding mass, it is assumed to be fixed at various positions along the middle beam. This assumption simplifies the analyses considerably while having little effect on the system’s eigenfrequency (demonstrated in Fig. 4). Here, the measurement with fixed mass has an eigenfrequency that is close to the measurement with sliding mass. At their respective eigenfrequencies, the mass is at the same positions for both measurements.

The harvester is converted to a beam structure using a simple finite element (FE) model. In the present self-tuning system, the first two eigenfrequencies are found to be rather close to each other whereas the eigenfrequency for the third mode is much higher. It is thus important that the model adequately captures the two lowest eigenfrequencies. In our case, a system using only three beam elements with three point masses was chosen — resulting in a four DOF problem. By adopting a Guyan reduction [23] of the two nodal rotational degrees of freedom, $u_d$, the reduced $2 \times 2$ equations of motion system for the active nodal displacement DOF, $u_a$ is given by Equation (1).

$$\ddot{M}u_a + K u_a = 0.$$  \hspace{1cm} (1)

The elements of $\ddot{M}$ and $K$ consist of polynomial expressions in terms of the geometrical and material parameters. Consequently, the two lowest eigenfrequencies and the corresponding eigenmodes may be expressed in closed form involving only algebraic equations.

Schematic illustrations of the two first modes are presented in Fig. 6. Fig. 6a depicts the middle beam in a bending motion (mode 1), whereas the middle beam is almost straight in Fig. 6b (mode 2). For the long middle beam, LB, mode 1 is the dominant mode, while the opposite holds for the short middle beam, SB. Mode 2 gives significantly less power output compared to mode 1 due to smaller bending of the piezoelectric cantilevers. In mode 1, the vertical displacement and the curvature of the piezoelectric cantilevers are more pronounced compared to mode 2. Additionally, for mode 1, the position of the sliding mass can be related to the position with zero slope of the middle beam - the distance, $a$, in Fig. 6a. In the LB case, the distance, $a$, may be given between the mass and zero slope point, while in the SB case there is no such point with zero slope. Hence, the piezoelectric cantilever bending is less evident, which may explain why the output is lower in the SB case than in LB case. For mode 2, the sliding mass is close to the neutral position (distance, $b$, close to zero) and thus does not move much vertically as the system vibrates.

Given the higher voltage output for the LB case (Fig. 4), and the more pronounced bending effects for mode 1, we will base our analyses and behavioral explanations below on the LB structure in the mode 1 configuration.

The first case we analyze is a symmetric setup in order to investigate the impact of the length of the middle beam. The system eigenfrequency depends on the sliding mass position (Fig. 7) where the upper and lower piezoelectric cantilever lengths are 22 mm (similar to LB). Here, three different middle beam lengths are considered: 22 mm, 25 mm and 28 mm,

![Fig. 5. The position of the mass on the middle beam is shifting, depending on applied frequency on the system.](image1)

![Fig. 6. The first two eigenmodes.](image2)
where \( x \) is the position of the middle beam mass measured from the lower coupling to the top coupling, expressed in terms of the fraction of the middle beam length where the mass can move.

The short middle beam (dominated by mode 2) renders higher eigenfrequencies than the long beam. The result is symmetric with respect to the \( x \) coordinate. For the two longer beam cases, the system eigenfrequencies decrease as the sliding mass is moved further away from the midpoint. However, due to complex beam dynamics, it is difficult to generally state how the position of the sliding mass affects the system inertia for all these cases. Since the effect of the sliding mass position on system behavior is difficult to predict, investigations in other design criteria (such as middle beam length) may offer more readily achievable improvements in bandwidth.

The results shown suggest that a slightly longer middle beam could increase the potential impact of the sliding mass on our resulting bandwidth (from 3 Hz up to 7 Hz). In addition to longer middle beams, there are many other possible ways to alter the eigenfrequency span, such as varying beam geometries (length, thickness, width), modifying beam materials or point masses. Among these, the perhaps easiest is to change the effective beam lengths. Interestingly, one efficient way to influence the effect of the position of the sliding mass is to disturb the system’s symmetry properties. For example, different lengths for the upper and lower piezoelectric cantilevers can be used. Fig. 8 represents an asymmetric case with middle beam length 25 mm and uses different outer piezoelectric cantilever lengths.

The solid blue curve in Fig. 8 are identical to the results illustrated as the dotted red curves in Fig. 7. Note that the symmetry with respect to the \( x \) coordinate has now disappeared. Here, higher eigenfrequencies are obtained as the sliding mass position \( x \) is increased. For the LB case (dotted red curve), the bandwidth is about 25 Hz while the dashed green curve has roughly 45 Hz compared to the 4 Hz bandwidth for the solid blue curve (symmetric case).

To further investigate the difference between the symmetric beam cases illustrated in Fig. 7 and the asymmetric beam cases in Fig. 8, investigations were performed into their respective eigenmodes. One interesting measure is the influence of \( a \), as illustrated in Fig. 6a. For each position \( x \) of the sliding mass, the corresponding eigenfrequency and eigenmode can be calculated. Here, \( a \) is the distance \( x \) to the sliding mass minus the distance to the zero slope position for that specific eigenmode. These results are illustrated in Fig. 9, where Fig. 9a corresponds to Fig. 7 cases, while Fig. 9b corresponds to Fig. 8 cases. Consequently, the red dotted curve in Fig. 9a is also seen in Fig. 9b as a solid blue curve. For the symmetric cases in Fig. 9a, the parameter, \( a \), is generally quite small. Here, \( a = 0 \) when \( x = 0.5 \) and the magnitude of \( a \) generally increases as the sliding mass approaches the ends. For the asymmetric cases illustrated in Fig. 9b, the parameter, \( a \), is more pronounced.

---

**Fig. 7.** Eigenfrequencies for different positions \( x \) of a fixed mass. Middle beam length is: 22 mm (solid blue), 25 mm (dotted red), 28 mm (dashed green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Fig. 8.** Eigenfrequencies for different positions \( x \) of a fixed mass. Upper/lower beam lengths are: 22/22 mm (solid blue), 23/21 mm (dotted red), 24/20 mm (dashed green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
By studying the red dotted LB curve more in detail for increasing eigenfrequencies, the lowest eigenfrequency (as seen from Fig. 8) is for low x values. Here, and for most other x positions, the a value is negative (Fig. 9b) and thus the coordinate for the zero slope position is larger than the sliding mass position, x. Hence, it seems that the sliding mass would travel towards the left end (higher x values). At x about 0.9 (that is about 371 Hz in Fig. 8), the parameter, a, approaches 0. Increasing x further causes a to become positive, and thus the coordinate for the zero position is less than the sliding mass position x. This may cause the sliding mass to travel in the right direction. Hence, these analyses may, to some extent, explain the behavior illustrated in Fig. 5.

Generally, for both Figs. 7–8, it is interesting to note that the local max/min points for eigenfrequencies are for x positions where a = 0 (the specific modes where the sliding mass is at the zero slope position as shown in Fig. 9). Another interesting feature is that a higher bandwidth seems to correspond to greater magnitudes for the, a, parameter (Fig. 9).

5. Discussion

In this paper, we show how a sliding mass works as a passive self-tuner for a 4DOF energy harvesting system. Further, we aim to improve both the bandwidth and power output.

In order to observe self-tuning, the driving conditions need to be appropriate for the given mechanical structure – the frequency range and the range of magnitudes of acceleration that result in self-tuning are limited. Fortunately, by downsizing the beam dimensions, the acceleration required for self-tuning can be reduced. In our design, the device needs to operate in the frequency range 360–400 Hz. The results of observing and modeling the self-tuning of a string with a moveable mass [13] show that the frequency range is reduced when the proof mass weight is reduced (relative to the string mass). The same conclusion was drawn from the clamped-clamped beam experiments with varying proof mass to beam mass ratios [15]. In our case, the geometry is more complex which makes the conclusions from the simplified analytical models more tentative.

We claim that the main mechanism behind the bandwidth broadening (the change of position of the sliding mass with excitation frequency) is sufficiently described in the model to make it useful for behavioral predictions.

From the measurements of the SB and LB, we see that the sliding mass gives a broader bandwidth compared to a fixed mass for the energy harvester. Hence, our sliding mass does have an impact on the bandwidth. Different lengths on the middle beam show a difference in open circuit voltage output, while the bandwidth is not measurably affected.

The output difference between the SB and LB can be explained by the higher stiffness of the shorter middle beam in SB. Since the piezoelectric cantilevers bend less in this case, they will yield lower output.

Regarding the movement of the sliding mass, we can see the following from the analytical derivation: if there is a zero slope on the middle beam (Fig. 6a, mode 1) the sliding mass will move towards it.

The zero slope position is dependent on the applied frequency and the sliding mass will move accordingly. In order to achieve the bandwidth broadening, we need the sliding mass to change its position along the middle beam as the excitation frequency changes.

In order to enhance the bandwidth, many other parameters than the length of the middle beam can be considered. From the analytical model, a simple way to modify the system to gain broader bandwidth is to enhance its asymmetry. By making the top piezoelectric cantilever differ in length from the bottom piezoelectric cantilever, the bandwidth is predicted to be significantly enhanced (Fig. 8). As we inferred from Fig. 6, mode 2 yields much lower power output due to less bending than mode 1. Therefore, the bandwidth modification should be directed to affect mode 1, just as the sliding mass is seen to have more effect on mode 1 than on mode 2.

6. Conclusion

By using a sliding mass on the connecting beam for two coupled piezoelectric cantilevers, the bandwidth of the harvesting system becomes broader due to self-tuning. In order to optimize the power output, the length of the middle beam should be

![Fig. 9. a, Symmetric as in Fig. 7 b, Asymmetric as in Fig. 8.](image-url)
adjusted. In our case, a longer middle beam results in a significantly higher output with a design for maintained resonance frequency. Our analytical model shows that an asymmetric system is a favorable design for further bandwidth improvement. An easy way to make the system asymmetric is to have different lengths of the piezoelectric cantilevers. This change can have a large beneficial impact on the bandwidth.

Acknowledgement

The Swedish Research Council, the European Horizon2020 projects STARGATE and smart-MEMPHIS, and Sweden’s innovation agency Vinnova (within the frames of the UDI energy harvesting toolkit project) are graciously acknowledged for their financial support.

Appendix A

The structure in Fig. A1 is modeled using three beam elements. The parameters for the top cantilever beam and coupling mass have subscript “t”, the parameters for the bottom cantilever beam and coupling mass have subscript “b”, while the parameters for the middle beam and sliding mass have no subscript. Here, no a priori assumptions are stated for the various parameters (i.e. same material parameters for both cantilever beams). The simple FE formulation for the structure motion thus becomes a $4 \times 4$ equation system

$$M \ddot{u} + K u = 0.$$  \hfill (A1)

By using the node displacement ordering $u = [u_1, u_3, u_2, u_4]^T$, the elements of the symmetric stiffness matrix $K$ may be scaled and written

$$K_{11} = \frac{12}{L_t^3} + 12 \gamma_t \frac{L_t}{L^3} \quad K_{12} = -\frac{12 \gamma_t}{L^3} \quad K_{13} = \frac{6}{L_t^3} - \frac{6 \gamma_t}{L^2} \quad K_{14} = -\frac{6 \gamma_t}{L^2}$$

$$K_{22} = \frac{12 \gamma_t}{L^3} + \frac{12 \gamma_t}{L_b^3} \quad K_{23} = \frac{6 \gamma_t}{L^2} \quad K_{24} = \frac{6 \gamma_t}{L^2} + \frac{6 \gamma_t}{L_b^2}$$

$$K_{33} = \frac{4}{L_t} + \frac{4 \gamma_t}{L} \quad K_{34} = \frac{2 \gamma_t}{L} \quad K_{44} = \frac{4 \gamma_t}{L} + \frac{4 \gamma_t}{L_b \gamma_b}$$

where $\gamma_t = EI/E_t l_t$ and $\gamma_b = EI/E_b l_b$.

The mass matrix $M$ could be written as a sum of two parts; one part for the beams $M_A$ and one part for the point masses $M_B$. The symmetric beam mass matrix $M_A$ is scaled according to

$$M_{A,11} = \frac{156(L_t^2 \alpha_t + L \alpha \gamma_t)}{420} \quad M_{A,12} = \frac{54 L \alpha \gamma_t}{420} \quad M_{A,13} = \frac{-22 (L_t^2 - L^2 \alpha \gamma_t)}{420} \quad M_{A,14} = \frac{13 L^2 \alpha \gamma_t}{420}$$

$$M_{A,22} = \frac{156 (L_b \alpha \gamma_b + L \alpha \gamma_t)}{420} \quad M_{A,23} = \frac{-13 L \alpha \gamma_t}{420} \quad M_{A,24} = \frac{-22 (L_b^2 \alpha \gamma_b + L^2 \alpha \gamma_t)}{420} \quad M_{A,34} = \frac{-3 \alpha \gamma_t}{420}$$

$$M_{A,33} = \frac{4 (L_t^2 \alpha_t + L^2 \alpha \gamma_t)}{420} \quad M_{A,44} = \frac{-3 \alpha \gamma_t}{420} \quad M_{A,44} = \frac{4 (L_b^2 \alpha_b + L^2 \alpha \gamma_b)}{420} \quad M_{A,44} = \frac{-3 \alpha \gamma_t}{420}$$

where $\alpha_t = \rho_t A_t/El_t$, $\alpha = \rho A/EI$ and $\alpha_b = \rho_b A_b/E_b l_b$.

The symmetric point mass matrix $M_B$ is scaled according to

$$M_{B,11} = \beta_t \gamma_t + \beta(3 - 2 \eta) \gamma_t^2 \quad M_{B,12} = \beta(3 - 2 \eta)(-1 + \eta)^2 \gamma_t \quad M_{B,13} = L \beta(3 - 2 \eta)(-1 + \eta)^2 \gamma_t$$

$$M_{B,14} = L \beta(3 - 2 \eta)(-1 + \eta)^2 \gamma_t$$

where $\beta_t = m_t/El_t$, $\beta = m/EI$ and $\beta_b = m_b/E_b l_b$. Here the parameter $\eta$ states the normalized position of the sliding mass. Hence the distance to the sliding mass from the bottom coupling mass is $\eta L$. 

The mass matrix

$$M = \begin{bmatrix}
M_A & M_B \\
M_B^T & M_B
\end{bmatrix}$$
In the Guyan reduction [23], write \( \mathbf{u} = [a, \mathbf{u}_d]^T \) where the active DOF are the displacements \( \mathbf{u}_a = [u_1, u_3]^T \) while the dependent DOF are the rotations \( \mathbf{u}_d = [u_2, u_4]^T \). Introducing \( 2 \times 2 \) submatrices \( K_{ij} \) and \( M_{ij} \) turns the structure’s stiffness and mass matrices to

\[
\mathbf{K} = \begin{bmatrix}
K_{aa} & K_{ad} \\
K_{da} & K_{dd}
\end{bmatrix}, \\
\mathbf{M} = \begin{bmatrix}
M_{aa} & M_{ad} \\
M_{da} & M_{dd}
\end{bmatrix}.
\]

Adopting static condensation on the bottom row submatrices, the dependent DOF \( \mathbf{u}_d \) are eliminated, and the equation of motion (A1) is reduced to the \( 2 \times 2 \) equation system

\[
\mathbf{M}_{aa} \mathbf{u}_a + \mathbf{K}_{aa} \mathbf{u}_a = 0.
\]  

(A2)

Each of these matrix elements are long and complicated and not presented here.

![Fig. A1. The structure is modelled using three beam elements, top, middle and bottom beam.](image)

References


EFFECTIVE PIEZOELECTRIC ENERGY HARVESTING BANDWIDTH ENHANCEMENT BY
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Submitted
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cTIVE PIEZOELECTRIC ENERGY HARVESTING WITH BANDWIDTH ENHANCEMENT BY ASSYMETRY AUGMENTED SELF-TUNING OF CONJOINED CANTILEVERS

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Abstract

Vibrational energy harvesting offers a potential power supply for future intelligent wireless sensors. In order to make vibrational energy harvesters more useful, a broad bandwidth is desirable since many vibrations are stochastic in nature. In this paper we use a piezoelectric self-tuning energy harvester to demonstrate the importance of designing for asymmetry in a system of conjoined cantilevers. Asymmetry is achieved by varying the piezoelectric cantilever lengths as well as the proof mass weights. In addition to bandwidth broadening, a self-tuning effect is experimentally demonstrated by a sliding mass. The measurement results confirm previous model predictions.

Introduction

Over the last decade, the interest for autonomous intelligent wireless sensors (AIWS) has increased substantially. Accompanying that expanding interest, the issue of powering these sensors has been the subject of increased attention [1]–[3]. Despite significant research effort, the biggest remaining challenge is substituting a conventional battery solution with a power source that does not need to be replaced. Energy harvesters show promise as alternative power sources. To be able to replace a conventional battery solution, an energy harvester needs to be able to deliver sufficient power. Depending on the intended use of the AIWS and its corresponding surroundings, different energy harvesters can be used (such as photovoltaic, thermal and kinetic). In our case, we consider a vibration source and therefore a piezoelectric (kinetic) energy harvester solution is chosen. Piezoelectric energy harvesting in this paper is achieved by usage of cantilevers containing thin layers of piezoelectric material. The piezo material is poled along the 31-mode coupling and when the cantilever is vibrating, the deformation of the piezo crystals along the 31-mode yield a voltage output [4]. The primary problem for a piezoelectric energy harvester is the bandwidth, which is usually quite narrow and makes the harvester ineffective in most real-life applications. To counter this problem, previous works implement an array of cantilevers, with the drawback of increased space. Additionally, this space requirement grows dramatically for each cantilever added to the harvester [5]. Another solution is to utilize coupled cantilevers in a 2 degrees-of-freedom (2DOF) solution where the bandwidth is somewhat broadened, but combining the two peaks in these solutions to one extended peak remains as a challenge [6], [7].

To enhance the bandwidth and power output, a bistable system could be utilized as an energy harvester. A bistable system has two equilibrium states which represent two resonance frequencies in vibrational energy harvesters. The equilibrium points are local minima, in terms of potential energy, with a local maximum in between. Depending on the applied vibration input, the system is in either of the equilibrium states or in between the two where there is an unstable equilibrium [8]. Realistic vibrational patterns are often stochastic, spread over multiple frequencies, and vary over time. A nonlinear structure, as a bistable structure, has a broader effective frequency range compared with a linear system with its more narrow effective frequency range [9].

Bistable harvesters that utilize mechanical properties have been demonstrated using a bistable composite plate with bonded piezoelectric patches [10]. Another solution is a mechanical bistable harvester which is made of a metal shell with two stable configurations [11]. The electrical output from a bistable system can be problematic for harvesting applications when the system is switching from one steady state to the other. This occurs when the applied frequency is in the unstable equilibrium range.
frequency range for the bistable system. The resulting electrical output will vary chaotically at a constant excitation frequency [12]. For an effective harvester, this chaotic range has to be minimized in relation to the interwell motion.

Another way to make the harvester achieve a larger effective bandwidth is by dynamically tuning the system’s eigenfrequency and thereby utilizing an intrinsically narrow bandwidth with its high Q-value in an efficient way. Self-tuning is achieved either by an adjustment of the eigenfrequency between harvesting cycles or while the harvesting is ongoing. A simple way to tune the eigenfrequency is to apply a mass on the free tip of the piezoelectric cantilever. The effect of the applied mass is a lower eigenfrequency and using this mode of tuning has been presented to result in a higher energy output [13].

Instead of adding a mass and altering the weight, Wu et al (2008) proposed another method, where they relocated the center of gravity on a piezoelectric cantilever by shifting a moveable part (a screw) in a fixed proof mass. When the screw was shifted towards the clamped end of the cantilever, the eigenfrequency had its highest value. Shifting the screw furthest away from the clamped end the harvester had its lowest eigenfrequency [14].

Research has also been carried out by altering the stiffness of the cantilever before frequency excitation [15]–[19]. These mechanical tuning methods give a high tunability, but are difficult to alter and adjust when the harvester is operating. When a mass is applied there is also damping in the system to take into account.

A more direct way of self-tuning is to change the eigenfrequency of the system to match the applied excitation frequency during the ongoing energy conversion for the harvester. Lallart et al. [20] used a tuning mechanism proposed by Guyomar et al. [21] where a piezoelectric sensor element is connected with a tuning element and both are connected to the harvesting piezoelectric element in a three layer cantilever. This self-tuning method increased the bandwidth from 4 to 17 Hz.

An alternative active self-tuning approach was presented by Challa et al. [22], where an array of four piezoelectric cantilevers were used. On the outer free tip, magnets were placed and the cantilevers were attached to a frame which was moveable vertically by a motor. The movement adjusted the distance from the magnets on the cantilevers to fixed magnets on an outer frame. By adjusting the distance, the magnetic force impacted the cantilever’s eigenfrequency. This self-tuning system only cost energy when the motor adjusts the distance with the advantage that, once tuned, the magnets are not using any harvested energy.

These and other approaches [23]–[26] on active self-tuning are shown to be effective for tuning the eigenfrequency towards more broadband harvesters with a maintained power output.

Previous attempts at self-tuning were accomplished by a sliding mass. [27], demonstrating that, for a given excitation at a certain frequency, the sliding proof mass will move on the beam until it reaches a position where the mode of vibration has a resonance with the driving frequency.

We present a self-tuning energy harvester using a sliding mass on a middle beam acting to conjoin two piezoelectric cantilevers. The novel design concept for this 4DOF piezoelectric harvester was reported at PowerMEMS 2015 [28], where the resulting voltage output was augmented through an extended stress distribution over the length of the piezoelectric cantilevers [29]; this study further demonstrated that a sliding mass results in a broader bandwidth than if the mass was fixed on the middle beam.

In this paper we now experimentally confirm the prediction of the previously developed numerical model [30] that an applied asymmetry will enhance the bandwidth. The verification is carried out by measurements on devices with different piezoelectric cantilever lengths and added masses. In total, 16 different configurations are investigated, a subset of which are analyzed numerically in more detail. The interrelationship between applied asymmetries and self-tuning is highlighted.

**The harvester setup**
The harvester consist of a top piezoelectric cantilever (MIDE PPA-2014), connected to a back folded middle beam via a coupling. On the middle beam, a sliding mass is placed. The other end of the beam is connected to a bottom piezoelectric cantilever of the same type via a second coupling. The harvester is presented schematically in Figure 1. The couplings and middle beam are made of aluminum. Specifications for the couplings, mass and middle beam are listed in Table 1. The length given for the cantilevers and middle beam is the open length, which are the lengths between attachments and
Numerical model

Based on a numerical harvester model was developed on previous measurements on the harvester, where the sliding mass on the middle beam was either fixed or free to slide [31]. Additionally, this model is governed by Euler-Bernoulli theory for homogeneous and isotropic beams [30] with additional point masses [32]. The harvester model is transformed to a beam structure using a simple finite element (FE) model. In Figure 2, the first mode of oscillation is presented, where ‘a’ is the distance for the sliding mass to the position of zero slope of the middle beam. The sliding mass changes its position according to where the zero slope of the mode on the middle beam is located. The mode position is shifting due to the applied frequency excitation, which entails that the sliding mass is shifting its position accordingly. When the sliding mass shifts position, the eigenfrequency for the whole system also shifts, which entails that the bandwidth becomes broader since the harvester can cover a wider applied frequency range. The numerical model gives a clear prediction that if an asymmetry for the harvester is introduced, by altering the lengths or/and the tip masses of the piezoelectric cantilevers, the bandwidth broadening due to the sliding mass will be increased. The numerical model comprised this as follows: top/bottom cantilever lengths (in mm); 22/22, 23/21 and 24/20. In Figure 3, the difference in bandwidth between symmetric 20/20 (blue line) and 24/20 (green dashed) is presented. The asymmetric 24/20 yields a theoretical mechanical bandwidth of 60 Hz, an order of magnitude more than in the symmetric (22/22) setup. The curves in Figure 3 show the system eigenfrequency as a function of the position of the sliding mass on the middle beam [30].
Experimental setup

Four measurement series with different open length configurations of the top and bottom piezoelectric cantilevers are named: L1, L2, L3 and L4. The open length is altered from a symmetric starting point in L1 where both top and bottom piezoelectric cantilevers have a length of 18 mm. In L2 the top cantilever is 20 mm and the bottom piezoelectric cantilever is 16 mm. In L3 we have a top length of 22 mm and a bottom length of 14 mm; for L4 the corresponding lengths are 24 mm 12 mm respectively. By adding and subtracting 2 mm on each piezoelectric cantilever, the total area is the same for all configurations and can be utilized for energy conversion. All combinations are schematically presented in Table 2. The top and bottom attachment is presented in Figure 4, where the front wall has been removed, so the vital part of the harvester is visible. The outer walls are attached to a plate, which is attached to the shaker table.

Within each measurement series four different cases are tested. C1 has no added mass, C2 has added mass on the outer tip on the bottom cantilever, C3 has two added masses on the outer tip of the bottom cantilever and C4 has one mass added on the outer tip of the top cantilever. These case configurations are presented in Figure 4 and Table 2. A fifth case was also tested, with two masses added to the top cantilever, since the sliding mass behavior though was behaving exactly as in C4 and with equal output, it is not reported in this paper. Regarding the position of the sliding mass, it was placed on stochastic arbitrary locations on the middle beam before applied vibration excitation. Regardless of placement and case (C1 – C4), the sliding mass immediately started to slide towards the side of the middle beam where the coupling was attached to the top cantilever. Before data collection, we swept the frequency several times to mitigate hysteresis in the measurement. While recording data, the frequency was increased by 0.1 Hz each time, from 100 – 300 Hz (1 g), and was not changed until the mass was either stable or moved to a new position on the middle beam. Changes in the mass position occurred rapidly (within 1 to 2 seconds) when the frequency was changed. During the measurement sweep, the movement of the sliding mass was recorded.

<table>
<thead>
<tr>
<th>Measurements configurations</th>
<th>C1 No added mass</th>
<th>C2 One added mass on bottom cantilever (m)</th>
<th>C3 Two added masses on bottom cantilever (2m)</th>
<th>C4 One added mass on top cantilever (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1 top/bottom</td>
<td>18 / 18</td>
<td>18 / 18 (m)</td>
<td>18 / 18 (2m)</td>
<td>18 (m) / 18</td>
</tr>
<tr>
<td>L2 top/bottom</td>
<td>20 / 16</td>
<td>20 / 16 (m)</td>
<td>20 / 16 (2m)</td>
<td>20 (m) / 16</td>
</tr>
<tr>
<td>L3 top/bottom</td>
<td>22 / 14</td>
<td>22 / 14 (m)</td>
<td>22 / 14 (2m)</td>
<td>22 (m) / 14</td>
</tr>
<tr>
<td>L4 top/bottom</td>
<td>24 / 12</td>
<td>24 / 12 (m)</td>
<td>24 / 12 (2m)</td>
<td>24 (m) / 12</td>
</tr>
</tbody>
</table>

Table 2. All the measurements configurations are schematically presented.
The four different cases C1 – C4 are presented, in all four cases different open length configurations of the piezoelectric cantilevers are applied. The open length is marked in every case. In C1 there is no alteration of mass. In C2, a mass is added to the bottom cantilever (marked with red ellipse). In C3, two masses are added to the bottom cantilever (marked with blue ellipse). In C4, a mass is added to the top cantilever (marked with green ellipse).

Measurement results

In order to compare the model with the behavior of the real device, we make a comparison between the model mechanical bandwidth and the power output bandwidth of the real device. This is accomplished by benchmarking the measurements data against a Defined Effective Bandwidth (DEB); the effective bandwidth is based on the RMS power output. For an intelligent wireless system (IWS) (a real example used on a gas turbine), the harvester has to provide a startup power of 8 mW and for continuous transmitting provide 2 mW for the IWS to perform its task [33]. The power level chosen to benchmark the measured data is 15 mW since it is conducted on a shaker table without disturbances such as white noise, which usually lowers the effectiveness of the harvester. The DEB is calculated from the difference between the highest frequency with power above 15 mW and the lowest frequency with power above 15 mW. Hence, the whole frequency range for the effective bandwidth has power above 15 mW. The power that is harvested above 15 mW can be stored in a supercapacitor to be used when the harvester temporally does not yield enough output.

The harvested power curves are presented for each length configuration with the four mass cases. Under the power graph is a corresponding schematic figure for each case presenting the behavior of the sliding mass on the middle beam. The given frequency is the frequency where the sliding mass slides to a new stable position. The mass on the middle beam is referred to as a sliding mass, also in the cases where it does not actually change position. A stable position for the sliding mass refers to a position on the middle beam where it remains until it moves to another stable position due to a change in applied frequency. If the sliding mass does not slide the schematic has two figures presenting the starting applied frequency and the final applied frequency and where the sliding mass is located on the middle beam (stable position). The brown lines represent the piezoelectric cantilevers. The grey squares are the added masses. The location and number of additional of masses are presented in the schematic figure below the power graph in Figures 5-8.
In L1, the first measurements series, the symmetric length configuration (where the top piezoelectric cantilever has 18 mm open length and the bottom piezoelectric cantilever has 18 mm) presented some variances for the four different cases. C1 has the highest eigenfrequency and, when an additional weight is added, the eigenfrequency is lower (Figure 5). The asymmetric configurations C2, C3 and C4, have a broader bandwidth (Figure 5) compared with the symmetric C1, as predicted by the numerical model. Interestingly, the sliding mass does not slide during these measurements (no self-tuning impact), even if extra masses are added to the configuration and hence an asymmetry by mass configuration is achieved for C2 – C4. The eigenfrequency for C2 and C4 are close to each other which is presented in Figure 6. The difference between them is that the weight is attached to the bottom cantilever in C2 and to the top cantilever in C4. The effective bandwidth for both are also nearly the same around 29.2 Hz. Consequently, the symmetric length setup seems to respond in the same way whether a mass is attached on either top or bottom cantilever. C3 with its two extra weights attached to the bottom cantilever has the highest peak power output and the broadest effective bandwidth of 32.58 Hz. Note that the sliding mass slides towards the same side in the tests, presented in Figure 6. The sliding mass position is on the same side as the coupling to the top cantilever. Since the mass position is stable to one side, no impact from the self-tuning effect can be observed.
The harvester power output in the graph for C1 – C4, configuration L2, for each case the sliding mass (white square) positions are presented with the corresponding frequencies, when the mass slides to a new position. The attached masses added for asymmetry is marked with grey squares. When the sliding mass has an intermittent sliding behavior, it is marked with a black square instead of a white one. Intermittent sliding behavior is presented by different outputs for the same frequency presented in the inset.

In L2, the second measurement series, the asymmetric length configuration is 20 mm on the top piezoelectric cantilever and 16 mm on the bottom piezoelectric cantilever as presented in Figure 6. In C1, the sliding mass moves to different positions depending on the applied frequency. On the power output curve, a major peak is visible around 206 Hz but also a smaller peak around 200 Hz, presented in Figure 6. The small peak around 200 Hz has a shifting output in amplitude due to the sliding mass’ intermittent sliding behavior around this frequency. This intermittent behavior entails the shift in power output since the eigenfrequency for the harvester is shifting with the position of the sliding mass. In C2, we observe different positions for the sliding mass. The output curve has a flattened top (Figure 6) which correlates with the positions of the sliding mass. Here we have two influential aspects, both the asymmetric lengths and the added mass to the lower cantilever. This has a net positive effect on the bandwidth, which is broader compared to C1 and C4. However, the sliding mass slides over a narrower frequency span, compared to C1, which might be due to the damping effect of the added mass. The effect we observed in the first measurement series (L1) with symmetric configuration, where C2 and C4 behaved nearly the same (Figure 5), differs somewhat in the second measurement series. Since the sliding mass is shifting positions, a self-tuning effect on the power output in C2 is observed with a flatter top and broader bandwidth (Figure 6). This can be compared with the output curve in C4, with no sliding behavior, and a symmetric shape around the eigenfrequency. C3 has, despite its lack of sliding mass behavior (no self-tuning impact), the highest peak power output and the broadest bandwidth of 33.87 Hz, as presented in Figure 6.

Figure 6
In L3, the third measurement series, the asymmetric lengths are 22 mm (top open length) and 14 mm (bottom). For C1, the sliding mass is shifting positions (Figure 7) and the output curve has a clear peak and flattened slope (195 - 200 Hz) at frequencies below the eigenfrequency. On the flattened slope, the sliding mass has an intermittent behavior (196 - 199 Hz) where the output is shifting. For C2, the mass is shifting positions (Figure 7) and the damping effect from the added mass on the bottom cantilever in combination with the asymmetric length configuration gives the curve a long flattened peak. Hence, the output curve is a combination of all three major factors that can have an impact on the harvester system, asymmetric cantilever length, asymmetric mass configuration and the position of the sliding mass. C3 has the highest output peak and the broadest bandwidth in the third measurement series. There is no stable position change for the sliding mass. Around 165 – 167 Hz (Figure 7), the mass has an intermittent sliding behavior at the outer end of the middle beam. This sliding behavior is visible on the output curve around 165 – 167 Hz as changes in amplitude on the output. Around these frequencies, since the mass is moving intermittently and lacks a stable position, the system might have a bistable behavior where the middle beam is between two modes that are close to each other in frequency. C4 has the lowest bandwidth (Figure 7) and the added mass to the top cantilever again seems to dampen the movement of the sliding mass which stably resides to the left during the whole measurement.
Figure 8, The harvester power output in the graph for C1 – C4, configuration L4. For each case the sliding mass (white square) positions are presented with the corresponding frequencies, when the mass slides to a new position. The attached masses added for asymmetry is marked with grey squares. When the sliding mass has an intermittent sliding behavior, it is marked with black square. Intermittent sliding behavior is shown by different outputs for the same frequency presented in the inset.

In L4, the fourth measurement series, the top length is 24 mm and the bottom length is 12 mm. For C1, there are two distinct peaks presented in Figure 8, and the sliding mass has several different positions between these two peaks, indicating the sliding mass self-tuning effect on the system. The lowest point between the two peaks is just above the effective bandwidth power limit of 15 mW. The appearance of two peaks are apparently a consequence of the large length asymmetry between the top and the bottom cantilevers. For C2, the power output has a clear peak with a lower output around 180 – 195 Hz. In this area we can see a clear correlation between the power output and the shifting position for the sliding mass. At 186 Hz, the mass slides to a new position and the power output is directly lower. As the applied frequency increases, the power output also increases until 190 Hz, where the mass slides to a new position and the power output decreases. Even though the power output decreases when the mass is sliding to a new position the effect in total yields a broader bandwidth for the harvester. Around the eigenfrequency peak of the harvester in C2 the sliding mass starts to slide intermittently between 196 – 203 Hz. For C3, it is the first time we see the sliding mass behavior in the measurements series when two weights are applied to the bottom piezoelectric cantilever. , hence the combination of open length asymmetry and two weights on the bottom piezoelectric cantilever seems to be an advantageous combination. The highest power output peak is around 175 Hz and it is also here the mass starts to slide to a new position, resulting in a small power output drop. The sliding mass is shifting its positions when the applied frequency is increased and the power output has a long broad peak, which is typical for the cases where the mass is sliding on the middle beam. For case C4, the sliding mass behaves as in previous measurement series for the same case, with no stable change in position. In C4, for this open length configuration of top 24 mm and bottom 12 mm, we have an intermittent sliding between 164 – 169 Hz, which is visible around the peak on the power output (inset of Figure 8).
Comparing all bandwidths (Figure 9), L1 to L4 with its four cases (C1 – C4), we can conclude that for C1, C2 and C3 there is an improvement of the bandwidth when asymmetry is applied on the system. However, for C4, the bandwidth decreases slightly with increased length asymmetry (Table 3). For each configuration, C3 has the largest bandwidth followed by C2 and C1. The difference between C1, C2 and C3 is a consecutively increased mass at the bottom cantilever coupling. Therefore, from the mutual arrangement for each length configuration L1 – L4, we can see that the added mass asymmetry, as expected, makes the bandwidth wider in each such configuration.

For the specific case, C3, there is no sliding mass behavior (i.e. no self-tuning impact on the bandwidth in L1, L2 and L3), only the asymmetry from the length configurations and the added mass that has an impact on the bandwidth. It is interesting to see that in L1 – L3, when the sliding mass is not moving, the increase in bandwidth decreases slightly with every configuration compared to C1 and C2. Therefore, the added mass without self-tuning impact does not add bandwidth as effectively compared to the effect from the self-tuning sliding mass. In L4, where the mass is sliding, there is a large increase in bandwidth due to the impact from self-tuning. The total increase in bandwidth from the symmetric setup L1, C1 (with configuration top piezoelectric cantilever open length 18 mm and bottom piezoelectric cantilever open length 18 mm) to L4, C3 (with asymmetric configuration top piezoelectric cantilever open length 24 mm and bottom piezoelectric cantilever open length 12 mm and two masses on the bottom cantilever) is 46%.

Comparing peak output eigenfrequency for the four cases, presented in Figure 10, we see that for C1, the eigenfrequency first increases but in L4 it decreases. In L4, we have a very large length configuration asymmetry, where the long piezoelectric cantilever might start to lower the eigenfrequency for the whole system. For C4, the eigenfrequency seems to decrease as asymmetry...

**Figure 9.** Bandwidth trends for the four cases, filled markers are where the sliding mass is changing position during measurement.  

**Figure 10.** Peak output eigenfrequency trend for the four cases, filled markers are where the sliding mass is changing position during measurement.

<table>
<thead>
<tr>
<th>Top/bottom</th>
<th>C1 (Hz)</th>
<th>C2 (Hz)</th>
<th>C3 (Hz)</th>
<th>C4 (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1: 18/18</td>
<td>26.0</td>
<td>29.2</td>
<td>32.6</td>
<td>29.3</td>
</tr>
<tr>
<td>L2: 20/16</td>
<td>28.6</td>
<td>30.7</td>
<td>33.9</td>
<td>29.5</td>
</tr>
<tr>
<td>L3: 22/14</td>
<td>30.8</td>
<td>33.9</td>
<td>34.6</td>
<td>29.0</td>
</tr>
<tr>
<td>L4: 24/12</td>
<td>33.7</td>
<td>36.6</td>
<td>37.9</td>
<td>28.7</td>
</tr>
</tbody>
</table>

*Table 3. The 15.0 mW DEB is tabulated for each configuration (L1 – L4) and case (C1 - C4). The largest bandwidth is obtained in L4, C3 and is 37.9 Hz.*
increases. For both C2 and C3, the eigenfrequency is increasing while the asymmetry increases.

Analyzing relative bandwidth, defined by \( \Delta f / \delta \) (\( \delta \) is the center frequency of the bandwidth), we see that for C1 the length asymmetry clearly yields an enhanced relative bandwidth along with the self-tuning effect (marked with filled markers in Figure 11).

For C2, we can see a small increase in relative bandwidth, hence an added mass on the bottom cantilever does not yield a huge impact on the relative bandwidth even though the self-tuning by sliding mass is working for C2: L2, L3 and L4. As expected, the relative bandwidths for C2 and C4 are similar, since both have the same mass applied in total on the system.

In C3, for L1 – L3, the relative bandwidth does not increase. L4 is where the self-tuning seems to have a positive effect on the relative bandwidth. For C4 we observe a small linear increase in relative bandwidth for L1 – L4.

It is interesting to see that C1, C2 and C4 seems to correlate at the same relative bandwidth in L4, where C1 has no mass attached.

Scrutinizing relative bandwidth, from a self-tuning perspective, between the 16 different configurations, the implication is that the configuration change that has the highest impact on self-tuning for our system is to adjust the piezoelectric cantilever length. Adding one mass has some impact on the bandwidth. Adding two masses yields a higher output and bandwidth but in three configurations of four, the sliding mass is not changing position. In the fourth configuration, where the self-tuning mass changes position we see a broader relative bandwidth, compared with L1 – L3.

Figure 11, Relative bandwidth comparison between all length configurations and mass configurations.

**Sliding mass behavior explanation by numerical model**

The sliding mass, that adds self-tuning by sliding on the middle beam, is not sliding for all our measurements and scrutinizing L3 (with open length configuration top 22 mm and bottom 14 mm), the mass is sliding for C1 and C2. It has an intermittent sliding behavior without stable position change in C3 and in C4 the mass is stable at one end all the time during measurement. Here, in L3 we have two cases of sliding mass behavior, one case of intermittent sliding only and one case where the sliding mass is not moving at all. Mode curves were investigated for each of the cases in order to shed additional light on the sliding mass behavior throughout L3.

The numerical model [30] gives an eigenfrequency for the system depending on where the sliding mass is positioned (\( \eta \)) on the middle beam as presented in figure 2. The zero slope does not necessarily have to be \( \eta = x_0 \) (where \( x_0 \) is location for zero slope on the middle beam). If the zero slope is \( \eta \neq x_0 \), in the model, it indicates that the sliding mass is inclined to move towards the zero slope position. The numerical model, by studying the modes, gives answers to why the sliding mass is moving or not along the middle beam by the distance between model (fixed) sliding mass position and the position of the point of zero slope on the middle beam. For the real device, the correlation between applied frequency, zero slope position and sliding mass position is verified by measurement data and can be compared with
and further explained by the model.

In Figure 12, for $\eta = 0$ (placement of sliding mass to the left), the zero slope is located near the right ($x = 1$) which makes the mass willing to move to the right (this is also true for $\eta = 0.5$). For $\eta = 0.8$, the zero slope on the middle beam changes position to be located more in the middle of $x$, which suggests that the mass stops moving to the right. For $\eta = 1$, the zero slope is located to the left which makes the sliding mass willing to move left. Comparing the eigenfrequencies for each mode and the movement of the sliding mass with observed measurement (Figure 7) we can conclude that the model gives the same picture as the measurements. The sliding frequency window for C1 is 26 Hz from $\eta = 0$ to $\eta = 1$.

In Figure 13, for $\eta = 0$, the zero slope is located close to $x = 1$ and the mass tends to slide to the right. When $\eta = 0.5$, the zero slope is shifting towards $x = 0.4$, which makes it clear that the mass stops and tends to slide towards the left. For $\eta = 1$, it slides left since the zero slope is located near $x = 0$. Compared to C1 the zero slope is located at the left at lower $\eta$, which results in the sliding mass having a smaller frequency window for sliding in C2 of 22 Hz from $\eta = 0$ to $\eta = 1$. Compared with measurements, the model gives more or less the same result (Figure 7) where C1 and C2 are both close to the other end.

In Figure 14 we can see for $\eta = 0$, the mass tends to move to the right since the zero slope is located close to $x = 1$. But already towards $\eta = 0.2$, the zero slope is changing position towards $x = 0.3$, which makes it clear that the mass stops and tends to slide left. For $\eta = 0.5$ and $\eta = 1$ the zero slope is located near $x = 0$ so the slides left. By looking at the modes the zero slope starts to change clearly towards a low $x$ already around $\eta = 0.2$. Comparing with the measurements for L3, C3 we see that the mass has an intermittent sliding behavior around the same frequencies as the model predicts. The intermittent sliding, observed from measurement, occurs when the zero slope is shifting between two stable positions, which might be a bistable behavior of the harvester. The frequency window for the sliding mass due to the placement of the zero slope seems to be too small for the mass to slide during measurement, which also is seen for the measured case (Figure 8).

In Figure 15 the zero slope position for different $\eta$ is positioned around $x = 0$, hence the sliding mass will be stationary at that position. The eigenfrequencies for $\eta$ are reversed compared to C1 – C3. The behavior described by the model is the same as we observed during measurement (Figure 8), the sliding mass does not change position on the middle beam.

<table>
<thead>
<tr>
<th>Sliding mass position</th>
<th>Eigenfrequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta = 0$</td>
<td>$f = 179.5$ Hz</td>
</tr>
<tr>
<td>$\eta = 0.5$</td>
<td>$f = 192.8$ Hz</td>
</tr>
<tr>
<td>$\eta = 0.8$</td>
<td>$f = 202.5$ Hz</td>
</tr>
<tr>
<td>$\eta = 1$</td>
<td>$f = 205.5$ Hz</td>
</tr>
</tbody>
</table>

**Figure 12**, Presenting the mode curves with different positions of the zero slope ($x$) depending on the mass position ($\eta$) on the middle beam C1/L3.
Case C2 and top/bottom: 22 / 14 mm, L3, one additional mass at the coupling of the bottom cantilever

<table>
<thead>
<tr>
<th>Sliding mass position</th>
<th>Eigenfrequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta = 0$</td>
<td>$f = 177.5$ Hz</td>
</tr>
<tr>
<td>$\eta = 0.5$</td>
<td>$f = 188.3$ Hz</td>
</tr>
<tr>
<td>$\eta = 1$</td>
<td>$f = 199.2$ Hz</td>
</tr>
</tbody>
</table>

**Figure 13,** Presenting the mode curves with different positions of the zero slope ($x$) depending on the mass position ($\eta$) on the middle beam C2/L3.

Case C3 and top/bottom: 22 / 14 mm, L3, two additional masses at the coupling of the bottom cantilever

<table>
<thead>
<tr>
<th>Sliding mass position</th>
<th>Eigenfrequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta = 0$</td>
<td>$f = 167.3$ Hz</td>
</tr>
<tr>
<td>$\eta = 0.2$</td>
<td>$f = 169.4$ Hz</td>
</tr>
<tr>
<td>$\eta = 0.5$</td>
<td>$f = 177.3$ Hz</td>
</tr>
<tr>
<td>$\eta = 1$</td>
<td>$f = 188.0$ Hz</td>
</tr>
</tbody>
</table>

**Figure 14,** Presenting the mode curves with different positions of the zero slope ($x$) depending on the mass position ($\eta$) on the middle beam C3/L3.

Case C4 and top/bottom: 22 / 14 mm, L3, one additional mass at the coupling of the top cantilever

<table>
<thead>
<tr>
<th>Sliding mass position</th>
<th>Eigenfrequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta = 0$</td>
<td>$f = 177.7$ Hz</td>
</tr>
<tr>
<td>$\eta = 0.5$</td>
<td>$f = 175.6$ Hz</td>
</tr>
<tr>
<td>$\eta = 1$</td>
<td>$f = 158.6$ Hz</td>
</tr>
</tbody>
</table>

**Figure 15,** Presenting the mode curves with different positions of the zero slope ($x$) depending on the mass position ($\eta$) on the middle beam C4/L3.

In Figure 16, a comparison of measured eigenfrequencies for L3 is compared with a calculated mean value eigenfrequency from the numerical model. The mean value is calculated from the predicted eigenfrequencies for the different position ($x$) of the sliding mass. The measured values are within the standard deviation of the calculated mean values and thus the numerical model demonstrates a good matching.
Figure 16, Eigenfrequencies from measurement series L3 compared with calculated mean value eigenfrequencies. The filled markers are where the sliding mass has a self-tuning impact on the harvester.

Using the numerical model, we can see when the point of zero slope changes position, due to changes in the applied frequency, the sliding mass is thus predicted to move to a new position. It is interesting to see that by just applying a mass for more asymmetry does not give the sliding mass ability to slide and self-tune the system. In case C3, the two added masses on the bottom piezoelectric cantilever lower the eigenfrequency for that cantilever, hence actually lower the asymmetry in the system, since the mass is applied on the short cantilever. Which leads to that it might be an optimum asymmetry achieved by length configurations and added masses, to accomplish further self-tuning impact from the sliding mass to achieve even broader bandwidth.

Conclusion

A harvester with broad bandwidth and sufficient output is one key to achieve successful autonomous intelligent wireless sensors. In this paper, we present a harvester with enhanced bandwidth accomplished by self-tuning, where the measurement results confirm important aspects of previous numerical model predictions. The self-tuning is achieved by an asymmetric setup, where both lengths of the piezoelectric cantilevers are altered and where additional masses are applied. Considering length asymmetry alone, there is a clear effect on the system and the sliding mass is acting as a self-tuner. When we add masses to the system, the self-tuning by sliding mass does not work in all cases. The mass dependence on the self-tuning, which allows for a sliding mass in some configurations but not in others, present an interesting topic for future exploration.

Acknowledgments

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References


Appendix A

The structure in Figure A1 is modelled using three beam elements; the parameters for the top cantilever beam and coupling mass have subscript “t”, the parameters for the bottom cantilever beam and coupling mass have subscript “b”, while the parameters for the middle beam and sliding mass have no subscript. Here no \textit{a priori} assumptions are stated for the various parameters (i.e. same material parameters for both cantilever beams). The simple FE formulation for the structure motion thus becomes a $4 \times 4$ equation system

$$
M \ddot{u} + K u = 0. \quad (A1)
$$

By using the node displacement ordering $u = [u_1, u_3, u_2, u_4]^T$, the elements of the symmetric stiffness matrix $K$ may be scaled and written

$$
\begin{align*}
K_{11} &= \frac{12}{L_t^4} + \frac{12\gamma_t}{L_t^3} \\
K_{14} &= -\frac{6\gamma_t}{L_t^2} \\
K_{24} &= \frac{6\gamma_t}{L_t^2} + \frac{6\gamma_t}{L_t^2\gamma_b} \\
K_{44} &= \frac{4\gamma_t}{L} + \frac{4\gamma_t}{L_b\gamma_b} \\
K_{12} &= -\frac{12\gamma_t}{L_t^3} \\
K_{22} &= \frac{12\gamma_t}{L_t^3} + \frac{12\gamma_t}{L_t^3\gamma_b} \\
K_{33} &= \frac{4}{L_t} + \frac{4\gamma_t}{L} \\
K_{34} &= \frac{2\gamma_t}{L}
\end{align*}
$$

where $\gamma_t = EI/E_t I_t$ and $\gamma_b = EI/E_b I_b$.

The mass matrix $M$ could be written as a sum of two parts; one part for the beams $M_A$ and one part for the point masses $M_B$. The symmetric beam mass matrix $M_A$ is scaled according to

$$
\begin{align*}
M_{A,11} &= \frac{156(L_a a_t + L a\gamma_t)}{420} \\
M_{A,13} &= -\frac{22(L_t^2 a_t + L^2 a\gamma_t)}{420} \\
M_{A,22} &= \frac{156(L_b a b + L a\gamma_b)\gamma_t}{420\gamma_b} \\
M_{A,24} &= \frac{24(L_t^2 a b + L^2 a\gamma_b)\gamma_t}{420\gamma_b} \\
M_{A,34} &= -\frac{3 a\gamma_t}{420} \\
M_{A,12} &= \frac{54 L a\gamma_t}{420} \\
M_{A,14} &= \frac{13 L^2 a\gamma_t}{420} \\
M_{A,23} &= -\frac{13 L^2 a\gamma_t}{420} \\
M_{A,33} &= \frac{4(L_t^2 a b + L^2 a\gamma_b)\gamma_t}{420} \\
M_{A,44} &= \frac{4(L_t^2 a b + L^2 a\gamma_b)\gamma_t}{420\gamma_b}
\end{align*}
$$

where $a_t = \rho_t A_t / E_t I_t$, $a = \rho A / EI$ and $a_b = \rho_b A_b / E_b I_b$.

The symmetric point mass matrix $M_B$ is scaled according to

$$
\begin{align*}
M_{B,11} &= \beta_t + \beta(3 - 2\eta)^2\eta^4\gamma_t \\
M_{B,13} &= L\beta(3 - 2\eta)(-1 + \eta)\eta^4\gamma_t \\
M_{B,22} &= \left(\beta(-1 + \eta)^4(1 + 2\eta)^2 + \beta\gamma_b \gamma_b\right)\gamma_t \\
M_{B,24} &= L\beta(-1 + \eta)^4\eta(1 + 2\eta)\gamma_t \\
M_{B,34} &= L^2\beta(-1 + \eta)^2\eta^4\gamma_t \\
M_{B,12} &= \beta(3 - 2\eta)(-1 + \eta)^2\eta^2\gamma_t \\
M_{B,14} &= L\beta(3 - 2\eta)(-1 + \eta)^2\eta^3\gamma_t \\
M_{B,23} &= L\beta(-1 + \eta)^3\eta^2(1 + 2\eta)\gamma_t \\
M_{B,33} &= L^2\beta(-1 + \eta)^2\eta^4\gamma_t \\
M_{B,44} &= L^2\beta(-1 + \eta)^4\eta^2\gamma_t
\end{align*}
$$

where $\beta_t = m_t / E_t I_t$, $\beta = m / EI$ and $\beta_b = m_b / E_b I_b$. Here the parameter $\eta$ states the normalized position of the sliding mass. Hence the distance to the sliding mass from the bottom coupling mass is $\eta L$. 

\[\text{Equation for stress and strain}\]
In the Guyan reduction [23], write $\mathbf{u} = [\mathbf{u}_a, \mathbf{u}_d]^T$ where the active DOF are the displacements $\mathbf{u}_a = [u_1, u_3]^T$ while the dependent DOF are the rotations $\mathbf{u}_d = [u_2, u_4]$. Introducing $2 \times 2$ submatrices $K_{ij}$ and $M_{ij}$ turns the structure’s stiffness and mass matrices to

$$K = \begin{bmatrix} K_{aa} & K_{ad} \\ K_{da} & K_{dd} \end{bmatrix}, \quad M = \begin{bmatrix} M_{aa} & M_{ad} \\ M_{da} & M_{dd} \end{bmatrix}. $$

Adopting static condensation on the bottom row submatrices, the dependent DOF $\mathbf{u}_d$ are eliminated, and the equation of motion (A1) is reduced to the $2 \times 2$ equation system

$$\ddot{\mathbf{M}}\mathbf{u}_a + \ddot{\mathbf{K}}\mathbf{u}_a = \mathbf{0}. \quad (A2)$$

Each of these matrix elements are long and complicated and not presented here.

Figure A1, The structure is modelled using three beam elements, top, middle and bottom beam.
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A Micromachined Coupled-Cantilever for Piezoelectric Energy Harvesters

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Abstract: This paper presents a demonstration of the feasibility of fabricating micro-cantilever harvesters with extended stress distribution and enhanced bandwidth by exploiting an M-shaped two-degrees-of-freedom design. The measured mechanical response of the fabricated device displays the predicted dual resonance peak behavior with the fundamental peak at the intended frequency. This design has the features of high energy conversion efficiency in a miniaturized environment where the available vibrational energy varies in frequency. It makes such a design suitable for future large volume production of integrated self powered sensors nodes for the Internet-of-Things.

Keywords: piezoelectric micro-energy harvester; lead zirconate titanate; bandwidth broadening; coupled cantilevers; enhanced stress distribution; finite element modeling; microelectromechanical systems (MEMS)

1. Introduction

With recent advancements in the field of micro electro mechanical systems (MEMS), sensors have been miniaturized with increasing functionality [1]. These sensors, due to their size, can easily be placed in exotic or unreachable locations, unthinkable before to convey useful information. These smart devices need power supplies to function, which are usually provided by batteries and chemical fuels [2]. However, once the fuels run out, the sensors need to be retrieved and provided with a new power supply. Since many of the sensors are often placed in remote and/or harsh environments, the task of carrying out the change in batteries becomes expensive. Having a miniaturized power supply that recharges itself on the basis of the energy present in the surroundings will give the future internet-of-things (IoT) access to several relevant and challenging locations—inside machines, constructions or in living tissue.

Miniaturization of devices is essential for the design and fabrication for IoT applications. Micro-machining fabrication techniques have been used in manufacturing complementary metal-oxide-semiconductor (CMOS) devices, sensors, actuators, and also energy harvesters at a large scale. The simplest design for micro-energy harvesters is a single cantilever with a thick proof mass hanging at the free end. Table 1 refers to several single cantilever designs explored in literature along with their dimensions, resonant frequencies and voltage and power outputs. The problem with these
single cantilever based energy harvesters is the absence of active piezoelectric area along the free ends of the beam. Another serious drawback in single cantilever designs is their small bandwidth. Their performance depends on matching the resonance frequency with the vibration frequency of mechanical excitation of the object or surrounding environment whose energy is to be harvested. Even a slight shift from resonance reduces the power output drastically. There is a need for broader bandwidth devices in order to account for the random shifts of vibrational frequency. Thus, solutions that increase the range of working frequencies of a device and which can subsequently be assimilated in a MEMS structure are required.

<table>
<thead>
<tr>
<th>Device</th>
<th>Size (mm)$^2$</th>
<th>Thickness (µm)</th>
<th>Res. Freq. (Hz)</th>
<th>Vpp (V)</th>
<th>Power (µW)</th>
<th>Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lee et al. [3]</td>
<td>3 x 5</td>
<td>10</td>
<td>575</td>
<td>0.81</td>
<td>0.471</td>
<td>Single Cant.</td>
</tr>
<tr>
<td>Shen et al. [4]</td>
<td>4.8 x 0.4</td>
<td>36</td>
<td>461</td>
<td>0.16</td>
<td>2.15</td>
<td>Single Cant.</td>
</tr>
<tr>
<td>Muralt et al. [5]</td>
<td>1.2 x 0.8</td>
<td>5</td>
<td>870</td>
<td>1.60</td>
<td>1.4</td>
<td>Single Cant.</td>
</tr>
<tr>
<td>Lee et al. [6]</td>
<td>3 x 1.5</td>
<td>500</td>
<td>255</td>
<td>2.7</td>
<td>2.7</td>
<td>Single Cant.</td>
</tr>
<tr>
<td>Isakorn et al. [7]</td>
<td>1 x 2.5</td>
<td>15</td>
<td>2300</td>
<td>0.27</td>
<td>13</td>
<td>Single Cant.</td>
</tr>
<tr>
<td>Kim et al. [8]</td>
<td>3 x 1</td>
<td>21</td>
<td>243</td>
<td>0.3</td>
<td>2.15</td>
<td>Single Cant.</td>
</tr>
<tr>
<td>Park et al. [9]</td>
<td>3 x 2</td>
<td>18</td>
<td>115</td>
<td>-</td>
<td>-</td>
<td>Bent Cant.</td>
</tr>
<tr>
<td>Leuke et al. [10]</td>
<td>-</td>
<td>-</td>
<td>226</td>
<td>-</td>
<td>0.69</td>
<td>Circ. Spring</td>
</tr>
<tr>
<td>Yu et al. [11]</td>
<td>3 x 2.4</td>
<td>50</td>
<td>234</td>
<td>-</td>
<td>66.75</td>
<td>Multi Cant.</td>
</tr>
<tr>
<td>Zhang et al. [12]</td>
<td>6 x 6</td>
<td>-</td>
<td>&lt;11</td>
<td>0.0075</td>
<td>-</td>
<td>Rect. Spring</td>
</tr>
</tbody>
</table>

Among potential solutions to the bandwidth and power problem are nonlinear generators with bistable structures. Stanton et al. [13] incorporated a magnetic nonlinearity with the help of two magnets strategically placed in a linear system. Wu et al. [14] and Erturk et al. [15] arrived at a similar solution of obtaining a broad bandwidth. Mann et al. [16] investigated nonlinear systems that utilized magnetic levitation to produce an oscillator with tunable resonant frequencies. Mahmoudi et al. [17] proposed a double clamped cantilever beam with a movable magnetic proof mass which is excited by oppositely polarized magnetic fields at the top and bottom. Furthermore, Yang et al. [18] designed a triple proof mass-magnet system to develop a multifrequency generator. The magnetic fields from the copper coils acted on the proof masses induced different modes of vibration in the cantilever beam which led to three close eigenfrequencies and improved bandwidth. Similarly, Sari et al. [19] demonstrated a microcantilever array consisting of 35 cantilevers of varying resonant frequencies acting in presence of a magnetic field. The relative motion between a magnet and coils fabricated over the cantilevers generated power, while the array provided the wideband harvesting frequencies. Abed et al. [20,21] expounded on the multimodal equilibrium techniques by theoretically analyzing doubly clamped cantilevers coupled with a magnetic array to develop a non-linear magnetic stiffness in the beams. Although the above described techniques could provide enhanced bandwidths, the magnets are usually large and require an auxiliary support structure that cannot be easily placed in a MEMS design. Similarly, Blystad [22] and Liu [23] suggested amplitude limiters, where a mechanical stopper is used to limit the displacement of the cantilevers. Soliman et al. [24] experimented on such a structure with a single stopper and showed a 240% improvement in the power output bandwidth of the device. Although these devices offer improved bandwidth, in practicality, a lower maximum output power and fatigue-induced failures in such designs make their incorporation harder in microstructured harvesters.

An effective approach to bandwidth broadening is using two-degree-of-freedom (2DOF) structures and reducing the gap between the first two natural frequencies. To devise natural frequencies that are closer together, Jang et al. [25] (2011) developed a 2DOF piezoelectric energy harvesting device which exploited the structure’s translation and rotation vibration modes. The device showed two-peak power output and displayed 31.8% bandwidth improvement at the power level of 155.6 mW compared to the conventional single-degree-of-freedom (1DOF) device. Kim et al. [26] (2011) demonstrated the performance comparison between a 2DOF and conventional 1DOF device at 10.9 Hz, with the the
former exhibiting a 280% increase in bandwidth at a voltage level of 55 V/g. Wu et al. [27] proposed a “cut-out” 2DOF harvester with a secondary beam enclosed within the main beam, which achieves two close resonances with significantly large amplitudes. Improvement of bandwidth through 2DOF structures can be enhanced by increasing the distribution of stress on these cantilever beams. Studies by Staaf et al. [28,29] provide an assessment of using parallel cantilevers coupled to one another at one end. This improves the stress distribution patterns and the bandwidth through coupled resonance at frequencies near the natural excitation. Thus, using a 2DOF structure with a highly distributed stress can support a larger bandwidth of harvestable frequencies.

In recent years, the focus of the vibrational microenergy harvester research has shifted to fabrication of specialized designs to improve the bandwidth of the energy providing frequencies. Park et al. [9] designed an intrinsically stress-induced bent silicon cantilever to study on the principle of proportional dependence of the output power on the bending moment. They also shaped the cantilevers in a trapezoidal form to improve the distribution of stress on the beam. Leuke et al. [10] fabricated a set of folded spring structures for reduction of the operational frequency of the microstructures. The folded beam shape reduces the overall stiffness of the design and thus bring the natural frequency of the system down to 30–300 Hz. Yu et al. [11] designed a five cantilever system with a single large proof mass. The fabricated generator had plates and a silicon proof mass. A similar concept was also employed by Zhang et al. [12] where, instead of rectangular folded springs, they used circular annular rings, each attached to the central proof mass.

Based on the review of techniques, it is evident that usage of a 2DOF structure for bandwidth improvement with coupled cantilevers designed in a form that enhances stress distribution is desirable. The aim of this study was to complement and translate these macro-concepts into a micro-energy harvester. An M-shaped micro-design was analyzed, simulated, and fabricated (Figure 1). It incorporates the advantages of a 2DOF design in a trapezoidal shaped middle beam coupled with rectangular cantilevers in a single structure. The M-shape is optimized to achieve a compact structure with a uniquely uniform stress distribution across the beams and a higher bandwidth of utilizable frequencies through reducing the gap between the first two natural frequencies. Fabrication of the coupled resonators with a lead zirconate titanate (PZT) layer was performed and assessed. PZT was chosen as the piezoelectric material as it has more than ten times higher figure-of-merit than AlN or ZnO [30]. The feasibility of using micromachining to realize the M-shape design has been demonstrated by continuous evaluation of the progress during the fabrication process and by matching the observed mechanical behavior of the device to numerical simulations and to a simple analytical model.

**Figure 1.** Schematic image of the M-shape harvester design. Table 2 outlines the dimensions of the design.

**Table 2.** Characteristic features for simulated and fabricated M-shape device.

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>$l_s$</th>
<th>$w$</th>
<th>$l_m$</th>
<th>$w_{m1}$</th>
<th>$w_{m2}$</th>
<th>$\Delta f_{1,2}$</th>
<th>$\Delta \Omega_{1,2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>2900</td>
<td>1000</td>
<td>2700</td>
<td>500</td>
<td>100</td>
<td>222</td>
<td>0.14</td>
</tr>
<tr>
<td>Fabricated</td>
<td>2908</td>
<td>1001</td>
<td>2746</td>
<td>481</td>
<td>98</td>
<td>487</td>
<td>0.30</td>
</tr>
</tbody>
</table>
2. Theoretical Design and Simulation

2.1. Theory

Piezoelectric energy harvester cantilevers are normally modeled as a spring–mass–damper system. The harvester design in Figure 1 can be translated into the schematic in Figure 2a, which is a conventional 2DOF lumped parameter model used for the analysis of the M-shape designs. In this model, \( m_1 \) and \( m_2 \) are masses of the primary side beams and secondary middle beam structures, respectively; \( k_1, k_2 \), and \( \eta_1, \eta_2 \) are their respective spring constants and dampings. When the system is in a base excited configuration, the initial displacements of the base, primary, and secondary proof masses are \( y_0, y_1 \) and \( y_2 \), respectively. The model is elaborated further by Tang et al. [31]. On solving the equations of motion for negligible damping, the dimensionless difference in eigenfrequencies \( (\Delta \Omega_{1,2A}) \) is calculated as:

\[
\Omega_{1,2A} = \sqrt{(1 + \mu)\lambda^2 + 1} \pm \sqrt{(1 + \mu)\lambda^2 + 1} \pm \sqrt{\frac{(1 + \mu)\lambda^2 + 1}{2}} - \frac{4\lambda^2}{2} \tag{1}
\]

where \( \mu = \frac{m_2}{m_1} \) and \( \lambda = \frac{\omega_2}{\omega_1} \). \( \omega_1 \) and \( \omega_2 \) are the natural frequencies of the two systems vibrating separately which are calculated as \( \omega_{1,2} = \sqrt{\frac{k_{1,2}}{m_{1,2}}} \). It is evident that the closeness of the first two natural frequencies depends on the parameters \( \mu \) and \( \lambda \). The minimum values for \( \Delta \Omega_{1,2A} \) are demonstrated for \( \mu, \lambda < 1 \). However, considering the fabrication restraints in designing a 2DOF miniaturized cantilever, \( \lambda \) will typically be greater than 1, as the middle beam is always shorter than the primary beams. Therefore, for COMSOL analysis, the dimensions are considered in a way that they lie within the window \( 1 < \lambda < 2 \).

Fabrication design considerations for a distributed stress structure also limit the values of \( \mu > 1 \) as the volume of the middle beam is higher. Figure 3 shows the region in the contour plot of \( \Delta \Omega_{1,2A} \) vs. \( \mu \) and \( \lambda \) from Equation (1). The trend given from this simple analytical analysis is that values of \( \mu \) and \( \lambda \) approaching 1 would yield a small separation of the coupled structures resonance peaks. According to Tang [31], the damping (\( \eta_1 \)) in the primary part is more influential in the outcome amplitudes at the resonant frequencies. The effect of damping will need to be taken into account when evaluating the harvesting efficiency once we start extracting electrical power from the system. The next section describes the simulation results in COMSOL (version 5.2, COMSOL, Inc., Stockholm, Sweden) based on this window of operation for \( \mu \) and \( \lambda \).

![Figure 2. Typical lumped equivalent mass–spring–damper model for two-degree-of-freedom (2DOF) cantilever design.](image-url)
2.2. Cantilever Design

The 2DOF microenergy harvester was numerically simulated in COMSOL to acquire the optimal dimensions for the realization of enhanced stress distribution and to make the bandwidth broader. Several different topologies were investigated. However, keeping manufacturability as a core issue, a single design named M-shape was explored in more detail. Figure 1 shows the schematic of the generalized harvester in COMSOL. The big block was taken as the fixed support in the simulation. This is used as a simulation tool for the support structure that was included in fabrication to improve the robustness of the design. To complete a MEMS piezoelectric energy harvester, the design structure consists of silicon combined with piezoelectric material which is chosen to be PZT-5A. The five main dimensional parameters that play an important role in determining natural frequencies are the length and width of the side beams, $l_s$ and $w$, respectively; the length of middle beam, $l_m$; and the widths of the middle beam at the attached and free ends, $w_{m1}$ and $w_{m2}$, respectively. The thickness of the device is decided by the device layer in the silicon on insulator (SOI) wafer used, i.e., 20 $\mu$m. The thickness of the proof mass was 100 $\mu$m for each design so that they could be fabricated in a single process plan.

With the proof mass thickness 100 $\mu$m as a fabrication design parameter, the dimensions $l_s$ and $w$ govern the natural frequency of the system. They were chosen as $l_s = 2900$ $\mu$m and $w = 100$ $\mu$m such that the device resonance frequency is in the range 1.2–1.5 kHz and it has enough area for the middle beam compartmentalization. The simulation gives $\omega_1 = 1619$ Hz for the generated primary structure (side beams with proof mass).

The $\mu$ values were obtained using $m_1$ and $m_2$, the masses of the side and middle cantilevers respectively. The masses were calculated as $\rho V$, where $\rho$ is the density of the material (silicon) and $V$ is the volume from the structure shown in Figure 1. This forms the basis for the dimensions $l_m = 2300$, $w_{m2} = 300$, and $w_{m1} = 600$. Figure 4 shows the effect of $l_m/l_s$, $w_{m1}/w$ and $w_{m2}/w$ on $\Delta \Omega_{1,2}$, where $\Delta \Omega_{1,2} = \Delta \Omega_{1,2}^{A}$. In Figure 4b,c, the datapoints for $l_m$ and $w_{m2}$ in the region $\Delta \Omega_{1,2} < 0.16$ are in the range 2440–2700 $\mu$m and 160–260 $\mu$m, respectively. The value for $w_{m1}$ was chosen to reduce the stress between the side beams and the trapezoidal middle beam. The chosen dimensions are shown in Table 2. The simulation for $\Delta \Omega_{1,2}$ shown in Figure 4 suggests a significant difference in the order of magnitude with the acquired values in Figure 3, since the values calculated for $\mu$ and $\lambda$ in the design are $\mu = 1.22$ and $\lambda = 1.48$, which gives a simulated $\Delta \Omega_{1,2}$ of 0.14, and an analytical $\Delta \Omega_{1,2A}$ of...
1.52. Despite this fact, we see the same trend for optimizing $\lambda$ and $\mu$ from the simulations. Therefore, although the representation of the actual structure into a lumped 2DOF model would require more elaboration to be faithful, the simple model presents a useful starting point for design considerations.

![Graphs showing simulated variation of $\Delta\Omega_{1,2}$ with respect to different parameters.](image)

Figure 4. Simulated variation of $\Delta\Omega_{1,2}$ with respect to: (a) $w_{m2}$, width of the free end; (b) $w_{m1}$, width of fixed end; and (c) $l_m$, length of the middle beam. The blue circle denotes the values of $M$-shape on the respective graphs.

2.3. Simulation Results

The results for the eigenfrequency simulations are shown in Figure 5. For the $M$-shape, the first and second eigenfrequencies are observed at 1257 Hz and 1479 Hz, i.e., $\Delta\Omega_{1,2} = 0.14$. The normalized stress gradient suggests that the vibration of the middle beam enhances the distribution of stress on each of the two side beams. The middle beam does not act as a dormant proof mass; it has its own characteristic vibrational mode. The presence of stress on the middle beam is coupled with the side beam’s stress, which leads to a larger area acting under stress. Figure 6 displays the distribution of stress on the outer edge of the cantilever side beams compared to a single cantilever at the same resonance frequency of 1257 Hz. The free end of the beam is at $x = 0$. The boundary conditions for each design were kept constant. The single cantilever has the maximum stress at its fixed end. There is negligible stress on the beam at its free end. In contrast, the $M$-shape displays a different characteristic curve where the stress is significant over its whole length.
Figure 5. Mode shapes of (a,b) M-shape at the first and second natural frequencies. The gradient on the side displays the normalized von Mises stress on the cantilever beams without the lead zirconate titanate (PZT) piezoelectric layer.

Figure 6. Stress distribution on M-shape across the side beam length compared to a single cantilever at the same natural frequency of 1257 Hz.

3. Fabrication

The process plan used in our fabrication is explained in two main parts: layering and patterning of the electrodes and piezoelectric layers, and etching of the silicon substrate to create the cantilever design. The electrodes and PZT were prepared by SILEX Microsystems (Jarfalla, Sweden) on an 6” silicon-on-insulator (SOI) wafer.

3.1. Process

Fabrication began with a 500 µm silicon-on-insulator (SOI) wafer. A layer of thin 500 nm SiO$_2$ was thermally grown onto the SOI wafer. The SiO$_2$ layer was then patterned using a standard photolithographic process. The uncovered SiO$_2$ was etched away with a mixture of CHF$_3$ and O$_2$. A 20 nm layer of titanium and a 100 nm layer of platinum were sputtered to create the bottom electrode. A buffer layer of LaNiO 20 nm was deposited on top of the bottom electrode. Then, a lead zirconate titanate (PZT) layer of 1.1 µm was deposited by a sol-gel process on the buffer layer.

The electrode stack was patterned, one layer at a time. The wafer was initially preheated and MicroChem ma-N1410 resist (MicroChem, Westborough, MA, USA) was spin coated with post softbake, exposure and development in ma-D33 (Figure 7a). Thin films of platinum and titanium of 100 nm and 20 nm, respectively, were deposited on the wafer surface through evaporation (Figure 7b). The resist
was lifted off in mr-REM 400 bath in ultrasonic environment for 1 h (Figure 7c). The 1.1 µm PZT and 100 nm buffer were wet etched in a 1:1:20 solution of hydrogen fluoride (HF)(7%):HNO₃(6%):H₂O [32] (Figure 7d,e). The bottom electrodes had to be etched at a high 400 W radio frequency (RF) power in 10 mTorr pressure at 25 sccm argon flow rate. Thermally grown SiO₂ of 500 nm below the electrodes was etched along in the same process. The wafer was processed in the load lock chamber for 25 min in total, 5 min for Ti etching, and 20 min for SiO₂ (Figure 7f,g).

The cantilever structures were created by etching 20 µm of silicon from the front side, and 100 µm and 280 µm etching from the backside. To create the cantilevers in the 20 µm device layer of the SOI wafer, AZ4562 thick resist (MicroChemicals GmbH, Ulm, Germany) mask was developed. The exposed surface was etched to 21.6 µm in Centura II (DPS and MxP, HD Pacific, Inc., Mukilteo, WA, USA) (recipe in Table A2) deep reactive ion etching tool (Figure 7h). The wafer was then treated from the backside to realize the proof masses and release the structure. A hard mask of aluminum was created to make the support frame. A 0.5 µm aluminum layer was sputtered and etched out through a resist mask aligned to the top side using the backside alignment technique (Figure 7i). Aluminum was etched using H₃PO₄ at 40 °C in 3 min and 30 sec(Figure 7k). The initial thermally grown SiO₂ layer was then etched.
using CHF$_3$/Ar at 250 W. A thick resist mask of AZ4562 was patterned for the proof masses. With the resist mask, the exposed backside silicon was etched in STS-ICP DRIE (MechSE-Illinois, Urbana, IL, USA) chamber to 100 µm (Figure 7i). The etch recipes are shown in Table A1 in Appendix A. Resist was stripped in mr-REM400 under ultrasonication (Figure 7m). A thermal tape was used to attach the substrate to a carrier wafer. The remaining 280 µm of handler SOI wafer was etched (Figure 7n). The wafer was then mechanically cleaved into small chips each containing one micromachined design (Figure 7o).

3.2. Challenges in Fabrication

This section describes the experiments and challenges experienced in the microfabrication of the M-shape energy harvesters.

The first challenge was the fabrication of the electrodes. Platinum, being an unreactive metal, cannot be easily removed from the substrate through conventional reactive ion etching recipes. The top electrode was deposited with ease through a lift-off process. However, for the bottom electrode, dry etching was the only alternative. Wet etching of bottom electrodes is ill-advised as it could potentially etch the PZT through the sides and lift the entire stack off. Therefore, a 400 W high-energy argon etching recipe was created in PlasmaTherm RIE that had an etch rate of 11 nm/min. Figure 8a shows the electrode stack created after lift-off of top electrodes, wet PZT etching, and dry etching of bottom electrodes. The dark blackish-grey region in the image is the unashed resist from the resist mask used. Figure 8b displays the bond-pads after electrode fabrication. The left side bond-pads are for the side beam on left, and likewise for the right side contact pads. Spacings of 35 µm and 30 µm were created between the top electrode and the PZT pattern, and PZT and bottom electrode pattern respectively. The argon 400 W recipe is an efficient recipe to remove nearly any sort of thin film. During the bottom electrode etching, the wafer was subjected to the machine for 35 min. During this time, the recipe went through 100 nm platinum, 20 nm of titanium and 400 nm of SiO$_2$ without affecting the resist in any considerable way. The only observable change in the photoresist was its color and transparency.

The second challenge in the fabrication was observed in the topside silicon etching. This was due to the uneven heating of the substrate during the deep reactive-ion etching (DRIE) process in Centura II. Centura II machine parameters can be found in Table 2. Typically, in a DRIE process, the wafer is cooled at the carrier to maintain a constant etch rate. The backside of the substrate was mounted on an 8” wafer through a thermal tape. The formation of bubbles between the tape and substrate interface led to an uneven cooling of the wafer, which resulted in evaporation of photoresist at the heated surfaces before the whole etching was completed. This led to a deviation in the thickness of the beams. The areas which were protected by the electrode pads were etched until the buried SiO$_2$ layer, while the areas exposed after resist evaporation had a depth of around 8 µm to 16 µm depending on the area’s position on the 6” wafer. In Figure 8, images taken under an optical microscope demonstrate the extent of destructive processing carried out during DRIE silicon etching. There are areas on the wafer which are underetched (Figure 8c) and some areas where the buried oxide layer is visible (Figure 8d). Although the non-uniform etching severely affected the yield on the wafer, in the end, the wafer could still be processed further on to create the coupled cantilever structure. The dimensions accrued from optical characterization were as follows: $l_s = 2908$ µm; $w = 1001$ µm; $l_m = 2746$ µm; $w_{m1} = 481$ µm; $w_{m2} = 98$ µm.

The final challenge encountered during the wafer processing was the backside etching. The details for the STS machine parameters can be found in Table 2. This process step, as explained previously, involved two DRIE etching steps, one to create the proof masses of 100 µm thickness and another to etch through the full wafer thickness, i.e., 280 µm. The proof masses were etched, and their optical image is shown in Figure 8e. Their thickness was measured in a Dektak Profiler (Bruker Corporation, Billerica, MA, USA). During the final etching process, the exposed silicon surface was etched taking the proof mass design downwards (Figure 8f). The most significant challenge experienced in this
process was the uneven etching of the outer edges of the wafer compared to the inner. Their etch rates were 4.1 µm/min and 3.25 µm/min, respectively. Thus, the outer proof masses differed up to 21% in thickness from the inner ones. Furthermore, after the backside etch, the wafer system comprising of the main wafer taped to the carrier wafer is heated to 120 °C which led to a difficulty in releasing the cantilevers.

![Image](image.png)

Figure 8. (a) Electrode layout after the top electrode fabrication process steps under an optical microscope for a single cantilever; (b) Contact pads for each side beam of M-shape cantilevers. The intention is to connect the two electrodes in series; (c) Presence of unetched silicon due to uneven etching of the wafer; (d) Areas where SiO\textsubscript{2} is visible after topside etching; (e) Proof mass on M-shape realized after the first backside etch process; (f) Etched proof mass connected to topside cantilever structure after wafer-through etch.

An scanning electron microscope (SEM) image of M-shape is shown in Figure 9. The shiny surface on top is the top electrode of platinum which is not covering the PZT surface completely, especially on the side beams. A step-like structure was created during the topside etching, which is visible at the interface between the electrode stack and silicon on the middle beam. Insets on the right side show the proof masses at the bottom. The top surface and intended structure of proof masses were well preserved. However, the side profile shows the troughs created in silicon through DRIE etching.
The notching effect at the side beams, visible in the insets, are formed by over-etching of silicon through the etchant gases. With no end-point detector for SiO$_2$ in the machine, the charged ions deflect at the insulator interface towards the silicon surface leading to a sideways etching. This phenomenon has been described by Laermer et al. [33]. The SEM images demonstrate that the design can be fabricated with the above-described processing steps. However, they require optimization for a better yield.

Figure 9. Scanning electron microscope (SEM) image of M-shape at 25× magnification. Insets contain the backside processed images of the primary and secondary proof masses, and the PZT layer on the bottom electrodes on the side-beam cantilevers.

4. Results and Discussion

4.1. Mechanical Characterization

The fabricated designs were measured for mechanical characterization in a laser doppler vibrometer (LDV) setup. An LDV uses monochromatic light to measure the velocity of a moving object by scattering light off the surface of the object and measuring the frequency shift in the reflected light. This detection is made interferometrically and leads to very accurate velocity measurements. The motion is excited by a shaker which is driven by the LDV internal signal generator and an amplifier. The fact that the shaker excitation is phase locked to the detection implies that phase sensitive measurements can be carried out, showing how different parts of the structure moves relative to each other.

Figure 10 shows the velocity response in the measured frequency domain for the free end of the M-shape device. In the first graph (Figure 10a), the response is recorded under a Gaussian white noise excitation across a frequency spectrum of 3.5 kHz. The first eigenfrequency of the design is measured at 1294 Hz, which is very close to the result of the simulation. The second peak, however, resides higher in frequency than predicted at 1781 Hz. Figure 10b shows the device when it is subjected to a periodic chirp of excitation across 3.5 kHz.

4.2. Discussions

The fabricated structure’s first eigenfrequency is well predicted by simulations. However, the second peak displayed in simulations at 1479 Hz has the actual second eigenfrequency at 1781 Hz. The fabricated device thus has a higher $\Delta \Omega_{1,2} = 0.3$ compared to the simulated $\Delta \Omega_{1,2} = 0.14$. The trend in Figure 3 suggests that a significant increase in $\lambda$, i.e., the ratio of the two separate eigenfrequencies $\omega_2/\omega_1$, causes the gap between the natural frequencies of the device to widen. An increase in $\lambda$ could occur through the misalignment of proof masses with respect to the cantilever structure. When the middle proof mass shifts towards the coupling end of the cantilevers, the stiffness $k_2$ increases, leading to a higher $\omega_2$ and a higher $\lambda$. 
Figure 10. Characterization of M-shape in a laser doppler vibrometer (LDV) setup in different excitation signals: (a) Gaussian white noise of 0.1 V amplitude; and (b) periodic chirp voltage of 0.1 V. Both measurements show the same resonance frequencies.

Table 2 compares the values of the simulated and fabricated device. Applications of the proposed energy harvester can be envisaged in gas turbines and conventional machine tools. Such sources exhibit vibrations over 1 kHz while being operational. Thus, mounting the energy harvester on such sources can power wireless sensors for information gathering and condition monitoring.

5. Conclusions

An M-shaped 2DOF cantilever for energy harvesting was designed based on the principle of closing the gaps between the first two natural frequencies to achieve a broad bandwidth and improved stress distribution. The design was fabricated using micromachining techniques and was investigated for dimensional and mechanical characteristics. Dimensional analysis showed the feasibility of the fabrication process. Mechanical evaluation further demonstrated that the device behavior is close to what was intended in the design. In addition, the demonstrated M-shape micro-cantilever design shows harvesting capabilities in beam vibrations ranging from 1293 Hz to 1781 Hz, which can be attributed to the coupling mechanism in a single structure.

Future work can be directed towards two main features: (1) creating designs in the kHz range with minimal $\Delta\Omega_{1,2}$ based on the influence of masses and spring constant accrued from the design; and (2) formulating an improved process plan for better yield and design conformity for the middle beam in particular.

Author Contributions: The design was conceptualized by H.S. and A.V.; A.V. and H.S. modeled and simulated the design; The wafers with PZT were fabricated by J.L. and T.E.; A.V. performed the fabrication. The mechanical characterization was carried under C.R.; Analysis of measurements were described by A.V. and H.S.; A.D.S., P.L. and P.E. contributed in the paper manuscript and revisions.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Etch recipes used in the STS-ICP plasma etcher.

<table>
<thead>
<tr>
<th>STS-DRIE</th>
<th>SF6</th>
<th>C4F8</th>
<th>Pressure (%)</th>
<th>RF (W)</th>
<th>Platen (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI_FASTO</td>
<td>130</td>
<td>85</td>
<td>7 + 0.5</td>
<td>55</td>
<td>600</td>
</tr>
<tr>
<td>SI_SLOWO</td>
<td>130</td>
<td>85</td>
<td>7 + 0.5</td>
<td>55</td>
<td>600</td>
</tr>
</tbody>
</table>
Table A2. Overview of the etch details in Centura II (DPS & MxP).

<table>
<thead>
<tr>
<th>Centura II Parameters</th>
<th>Deposition</th>
<th>Breakthrough</th>
<th>Etch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (s)</td>
<td>1.2</td>
<td>1.3</td>
<td>1.5</td>
</tr>
<tr>
<td>Pressure (mTorr)</td>
<td>55</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Bias Power (W)</td>
<td>5</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>125</td>
<td>125</td>
<td>125</td>
</tr>
<tr>
<td>Source Power (W)</td>
<td>1900</td>
<td>1900</td>
<td>1900</td>
</tr>
</tbody>
</table>

References


30. Dubois, M.A.; Muralt, P. Measurement of the effective transverse piezoelectric coefficient \( e_{31t} \) of AlN and Pb \((Zr_{x} Ti_{1-x})O_{3}\) thin films. *Sens. Actuators A Phys.* 1999, 77, 106–112. [CrossRef]


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PRESENT AND FUTURE SUPERCAPACITOR CARBON ELECTRODE MATERIALS FOR IMPROVED ENERGY STORAGE USED IN INTELLIGENT WIRELESS SENSOR SYSTEMS
L G H Staaf, P Lundgren and P Enoksson
REVIEW

Present and future supercapacitor carbon electrode materials for improved energy storage used in intelligent wireless sensor systems

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KEYWORDS
Carbon; Electrode; Supercapacitor; Intelligent wireless sensor

Abstract
In this paper we argue that supercapacitors are the best choice for energy storage in an intelligent wireless sensor system. Furthermore we present recent research on carbon allotropes used as electrode. To compare these materials we introduce a theoretical model to estimate the maximum surface area and maximum capacitance obtainable for carbon electrodes. The purpose of the model is to elucidate what material features are crucial for obtaining a higher energy density in electrochemical double layer capacitors which will particularly benefit energy storage in wireless intelligent sensor systems since a supercapacitor will deliver a higher energy density over time and will have a longer lifespan than a battery. The result of the comparison is that composite materials especially nitrogen-doped graphene nanosheets show great promise with their high capacitance compared to other carbon allotropes.

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Introduction

This review will cover supercapacitors from an intelligent wireless sensor point of view. The basics of supercapacitor operation will be explained and particular attention will be given to electrochemical double layer capacitors (EDLC). Recent research on carbon allotropes as supercapacitor electrode material will be presented and evaluated in relation to a theoretically derived maximum capacitance achievable for carbon electrodes. This will give us a roadmap on which materials look most promising today and might give us better supercapacitors tomorrow. The review is structured so that we begin by explaining what an intelligent wireless sensor is and why it is better to be powered by a supercapacitor (see (Intelligent wireless sensors)). We move on to explain the theory of supercapacitors (see (Supercapacitors)), and in Electrode material requirements section we continue by looking at crucial material properties for electrodes. Carbon electrode materials section covers carbon allotropes and their traits as electrode material for EDLC. Maximum theoretical surface area and capacitance for EDLC and Difficulties of comparison of carbon allotropes sections give a theoretical model in comparison with experimental results and a discussion on future electrode materials respectively. Brief conclusions are given in the final part.

Intelligent wireless sensors

An intelligent wireless sensor (IWS) is an autonomous device with internal computing capability and wireless communication which can be combined with energy harvesters that scavenge energy from the environment or which can use stored energy. Today we have battery powered or wired sensors which can provide us different kinds of data from our surrounding. In the near future we want to place several of these sensors in remote places or incorporate them in structures which will make them hard to maintain [1]. The solution for powering these wireless sensors has so far been to rely on batteries, fuel cells or supercapacitors. These solutions give them a limited lifetime and the sensors will mostly send data if it is really necessary to save energy and by that extending their lifetime.

Energy sources with a higher energy density will enable the IWS to perform its task longer. The development of electrode materials that increase the energy density is needed for IWS that need high energy output, like a chemical sensor in the exhaust of a car [2]. Here size and weight is crucial and a rechargeable energy supply with higher energy density will take less space and will weigh less.

A conventional sensor is wired and could be positioned in an airplane, in a car or in a structure like a bridge. In a car you have many sensors and hence a great deal of wires which makes the car more expensive to produce; different sensors also need different wire lengths depending on where they are placed which add up to the pile of cables that is required. The drawbacks of batteries, with limited lifetime, and cable consumption make the idea of a wireless intelligent sensor with a self-preserving power source very attractive from many environmental points of views.

An IWS contains different energy supply parts which are one or several different energy harvesters and energy storage which are connected to a power manager (Figure 1). The power manager either provides the converted energy to the sensor or stores it in a supercapacitor or battery. This setup requires an energy storage which can deliver enough energy directly during the IWS lifetime, which makes a demand for a high accumulated energy density and an energy storage that does not reach end of life due to aging.

Energy harvesting can exploit different energy sources and one has to consider the environment for the IWS in which energy or energies to harvest to get an optimized or at least sufficient output.

Vibration energy harvesting uses vibrations and typically a cantilever optimally tuned for the vibration frequency. Since the frequency is often shifting and unstable, research has been conducted to broaden the bandwidth to obtain a higher power output from these harvesters. The power available for harvesting from ambient vibrations is often relatively low so it has to be accumulated and stored. The advantage of vibration harvesting is that it is available almost everywhere, usually in the low frequency domain [3-7].
Radiofrequency harvesting can be done by piezoelectric cantilevers but faces problem of harvesting a narrow bandwidth which needs widening for a higher power output [8-10]. The power also decreases with distance from the source [11].

Electromagnetic energy harvesting can be suitable if an IWS is near a rotating wheel using a wheel speed harvester. The power output is high and could be connected to a sensor that needs high power to operate [12].

Thermal harvesting can be done if a temperature difference is present using the Seebeck effect [13-16]; a steady power is delivered in the magnitude of 10-18 μW [17,18]. Research is ongoing regarding higher temperatures with new materials that will yield a higher amount of power than compared to materials used today [19].

For storing the harvested energy for the wireless sensor, the energy storage needs to fulfill following properties:

- Sufficient number of charge and discharge cycles without deterioration during lifetime of the device.
- High value of capacitance per gram, hence a possibility to scale it down for usage in Micro Electrical Mechanical System (MEMS) IWS.
- A low self-discharge.

Possible candidates for energy storage are micro fuel cells, batteries and supercapacitors. Micro fuel cells have a good energy density and low self-discharge and there are ideas on how to recharge them [20]. The main problem is low voltage and current outputs [21]. A battery has a good energy density but limited amount of cycles, in the absolute best case 1000 [22] and will not sustain usage for a sufficiently long time. Supercapacitors have a fair energy density and the electrochemical double layer capacitors have a very long lifetime; they can be charged and discharged more than $10^5$ times. The lifetime requirement of an IWS depends on where it is placed, in a bridge for example. it could be up to 100 years or longer. During that time the electrode material of a battery will be depleted [23], while the supercapacitor still will be intact and functioning. An IWS system for structural health monitoring would benefit from long lifetime and the number of recharge cycles for electrical energy storage would need to be high. A supercapacitor can have the ability to match the number of cycles required and also the possibility to still function after 100 years of usage.

The self-discharge for a supercapacitor is an aspect of concern, but if a wireless system can harvest energy more or less continuously, the discharge time for a supercapacitor will not be reached. If the system fails to harvest the self-discharge is between 5 and 60% over a period of two weeks [24], which will be enough for most IWS applications.

The continued development of new electrode materials with higher value for capacitance per gram used as energy storage also gives supercapacitors the ability to be scalable and be fitted into MEMS devices and still be able to hold enough energy.

If operated in a short lifespan a battery will be more suitable for the IWS system but looking at a longer lifespan the supercapacitor will be a better choice, due to its high number of cycles before failure (Table 1).

**Table 1** Energy density accumulated over the number of charge cycles shows that supercapacitors will deliver a higher energy density of nearly 4 times over time versus batteries. The approximation for the battery is over-estimated since it does not take into account that the battery energy density decreases over time due to loss of active electrode material [23].

<table>
<thead>
<tr>
<th></th>
<th>Supercapacitor</th>
<th>Lithium polymer battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wh/kg per cycle</td>
<td>9</td>
<td>250</td>
</tr>
<tr>
<td>Maximum number of cycles</td>
<td>$10^5$</td>
<td>$10^1$</td>
</tr>
<tr>
<td>Accumulated energy density for total number of cycles</td>
<td>$9 \times 10^5$</td>
<td>$2.5 \times 10^5$</td>
</tr>
</tbody>
</table>

**Supercapacitors**

A supercapacitor is an electrochemical capacitor with a very high capacitance. Supercapacitors, sometimes called ultracapacitors or electric double-layer capacitors (EDLC), do not have a conventional solid dielectric. Instead they use an electrolyte. This section will cover the history and theory of how a supercapacitor stores its energy.

In 1957 a patent filed by General Electric explained the manufacturing of a device that used porous carbon electrodes with sulfuric acid between the electrodes [25]. After further development, supercapacitors have been used since the mid-seventies as energy storage devices in clock chips and for computer memories. Furthermore, supercapacitors have become useful for wireless communications and are used as power devices for different applications like recovering brake energy to improve energy efficiency in a hybrid battery/diesel system [26]. The energy density of a supercapacitor depends on the capacitance and voltage; if either or both are raised the energy density will be improved. In the following equation we have the energy density ($E$), specific capacitance ($C$), charge density ($Q$),
and voltage (V) [27]:

$$E = \frac{CV^2}{2} = \frac{QV}{2}.$$  \hspace{1cm} (1)

The power density of a supercapacitor defines how fast it can be discharged and depends on the voltage and the equivalent series resistance; the latter is to be kept to a minimum for high power density. We introduce the power density (P) and equivalent series resistance ($R_s$) [27]

$$P = \frac{V^2}{4R_s}.$$ \hspace{1cm} (2)

Supercapacitors can be divided into two different types [28]: (1) Electrochemical double-layer capacitors which store their energy electrostatically at the interface between an electrode and an electrolyte and (2) supercapacitors based on pseudocapacitance which relies on the adsorption of active ions or arises from a Faradaic redox reaction which takes place at a transition metal oxide surface or in a doped electrically conducting polymer [27]. These two storage methods are more easily described one by one even though both act concurrently, depending on the design of the supercapacitor, one is more dominant than the other.

**Electrochemical double layer capacitors**

An electrochemical double layer capacitor (EDLC) stores its charge electrostatically [27]. Hence there is no transfer of charge between the electrolyte and electrode. The earliest model of the electrical double layer was made by Helmholtz [29]. He treated the double layer as similar to a conventional capacitor, which are two layers of opposite charges that form at the interface of the electrode and electrolyte, separated by a distance at the atomic scale. For an EDLC the electrolyte is either an aqueous or non-aqueous liquid, or a solid material like a conducting polymer. The charged ions are ordered in an array at the electrode surface according to Helmholtz. The model was modified by Gouy [30] and Chapman [31] who looked at the continuous distribution of cations and anions in the electrolyte. The distribution is determined by thermal motion and this layer is called the diffusion layer. The Gouy-Chapman model of the double layer overestimated the capacitance of the electrochemical double layer capacitor, due to the assumption of point charges at the electrode surface. Later Stern [32] was treating this problem by suggesting the combination of the Helmholtz and Gouy-Chapman models, giving an internal Stern layer (which is a Helmholtz layer) and an outer diffuse layer (Figure 2). This model states that ions have a finite size, hence sets a geometrical limit to the region of adsorption in the Helmholtz layer and the total capacitance is a series of capacitances for the layers where the smallest capacitance has the biggest impact [33]

$$\frac{1}{C_{dl}} = \frac{1}{C_H} + \frac{1}{C_{diff}}.$$  \hspace{1cm} (3)

**Pseudocapacitance**

Supercapacitors using pseudocapacitance instead of storing the energy electrostatically implies energy storage by a different mechanism which is of Faradaic origin. In this case we have charge transfer across the double layer at the electrode surface [34]. Three different types of pseudocapacitances in electrochemical capacitors have been used. The first is surface adsorption of ions from the electrolyte and the second is redox reactions that involve ions from the electrolyte. These two processes are mostly dependent on a surface mechanism and therefore rely on the surface area as one factor for a large capacitance; the other is the permittivity of the material. The third type is doping and undoping of electrically conducting polymers in the electrode. Conducting polymers are less surface dependent and

![Figure 2](image_url)
rely more on micropores so the ions can be distributed through its bulk.

EDLCs and pseudocapacitors have different advantages which depend on their ways of storing energy. The EDLCs has a very high power output and although a pseudocapacitor has a higher energy density than EDLCs. Today the EDLCs have a much longer lifetime than pseudocapacitors due to their material limitations, which makes the EDLCs more suitable for IWS.

Asymmetric supercapacitor

To gain a higher energy density, different electrode materials that have good anode or good cathode properties can be used [35-38]. Asymmetric supercapacitors consist of one EDLC side and one side with a pseudocapacitive material like a transfer metal or a polymer. If you have a symmetrical setup the total capacitance ($C_T = C_1 + C_2$) will be

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} \rightarrow C_T = 0.5C_1$$  \hspace{1cm} (4)

If one electrode uses EDLC ($C_1$) and the other is pseudocapacitive ($C_2$) with high capacitance then you will have a supercapacitor with higher capacitance due to [38]:

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} \rightarrow C_T \approx C_1$$  \hspace{1cm} (5)

From an IWS point of view a higher energy density is attractive as long as the long lifetime is not shortened. Unfortunately so far cycles up to only 1000 have been reported [39].

Electrode material requirements

In this section requirements for electrode material will be examined in terms of which material traits will be beneficial for supercapacitors in IWS. The impact from pores and from the electrolyte will be discussed.

Materials used as electrodes in supercapacitors for IWS systems are required to have some important properties [26]:

- Long stable lifetime (>10⁵ charge/discharge events).
- High active surface area (>10⁵ m² g⁻¹).
- Controlled pore size and distribution in the material.

Long stable lifetime is needed since the harvester in the IWS will typically provide only 10 µW·1 mW [18,40] of ambient energy, so the supercapacitor will face the need to be intermittently fully discharged by the sensor when it is transmitting data, and then to be recharged for the next IWS transmission. A long stable lifetime will handle this kind of continuous charge and discharge.

A high active surface area gives a higher capacitance and hence a higher energy density. Present IWS using supercapacitors have enough energy (~1700 µJ) to power a sensor using ~70 µJ to transmit data [40] but higher active surface area will give supercapacitors that weigh less and take less space. A higher active surface area will also make supercapacitors available for use in future IWS with chemical sensors that need a high power density and a high energy density. A NO₂ sensor in the car exhaust system will be able to harvest a high amount of energy from thermal energy in that region, but this also requires a supercapacitor that withstands those thermal conditions.

The pore size needs to be controlled and adjusted to the electrolyte and thus to the ion size that will be used. A tailored pore size will enable us to reach an optimally high active surface area. The control of the pore distribution is also needed to avoid closed cavities since the active surface area needs to be accessible.

Pores and their impact

There are three different types of pores for the electrode that have distinguishable impact on the capacitance. Macropores have a size of more than 50 nm and are to a lesser extent useful for the electrode and electrolyte. A significant disadvantage is that macropores take up valuable volume where additional surface area would be a better option through smaller pores. Mesopores are 2-50 nm in size and have an important role since they provide good conductivity for the electrolyte [41]. An electrolyte with high viscosity is dependent on an ordered mesopore structure for a high energy density. Micropores have a size less than 2 nm and studies show that micropores are important for a high surface area which leads to a higher energy density [42]. Depending on how the electrode is manufactured different pores are favored. For some carbon materials micro- and mesopores get closed for the electrolyte due to the structure of the material. The importance of pores cannot be underestimated for future electrode materials and research is required on optimized pore distribution in combination with a way to controllably obtain this distribution.

Electrolytes

Electrolytes can be aqueous liquid, nonaqueous liquid or solid. An aqueous electrolyte has a low viscosity and therefore it has a high mobility and can easily gain access to the micropores in the electrode. The main disadvantage is that aqueous electrolytes only can sustain a voltage up to 1 V [27]. To raise the voltage for the supercapacitor, nonaqueous aprotic solvents electrolytes, which cannot donate hydrogen, have been tested and a voltage of 2.5 V has been reported [39]. The aprotic solvent has a high viscosity and a low dielectric constant so the capacitance is low. Ionic liquids or room temperature molten salts have shown voltage results above 3 V [43] and are non-toxic, nonflammable and they are cheap to produce. Their disadvantage is high viscosity and low ionic conductivity at room temperature thus further research is needed to make ionic liquids more suitable for normal environments.

The electrolyte controls the voltage and depending on its viscosity it needs a well ordered pore distribution of the electrode material. It also needs an ion size that is optimized for the dominant pore size of the chosen electrode material.
Carbon electrode materials

This section will explore positive and negative traits of different carbon allotropes and also present recent measured capacitance results. The research on supercapacitors has grown rapidly and in 2013, some 7200 papers were published in the field (Figure 3). Also shown in Figure 3, the ratio indicates that the research output regarding supercapacitors is growing faster than for batteries.

To utilize the double layer in an EDLC optimally an electrode material needs to be well ordered in structure and yield a high surface area. Those two features are desirable not only for supercapacitor electrodes but for lithium polymer batteries and for hydrogen storage as well [44].

For an electrode material used in a supercapacitor in an IWS we will analyze each carbon electrode material from these parameters:

- Sufficient number of charge and discharge cycles without deterioration during the device lifetime.
- High value of capacitance per gram, which makes it possible to scale it down for usage in IWS small devices e.g., MEMS.

A high number of charge and discharge cycles is very important for an IWS, since the harvested energy is stochastically intermittent and the supercapacitor has to be continuously cycled during a long time, which is a very demanding condition on the electrode material.

![Figure 3](image)

**Figure 3** The number of published articles for batteries and supercapacitors are shown on the left axis. The ratio between published supercapacitor and battery papers is shown on the right axis and indicates that the research on supercapacitors is increasing relatively more than for batteries.

Activated carbon

Activated carbon is the most used electrode material commercially today. Activated carbon has a high surface area and is easy to produce at a low cost compared to other materials and carbon variants. Activated carbon contains all three pore sizes; micro-, meso- and macropores [45]. The micro- and mesopores are the ones contributing to the capacitance [46]. Zulamita et al. used activated carbon electrodes which were derived from different novel carbon sources such as argan seed shells [47] yielding 355 F/g and with a surface area of 2100 m².

Xu et al. used poly(vinylidene fluoride)-derived ultramicroporous carbon which had a specific surface area of 1012 m²/g [48] yielding 264 F/g for 6 M KOH but only 7 F/g for 1 M Et4NBF4/PC, due to the pore size being too small to be accessible even for the desolvated ions in the non-aqueous electrolyte.

Shen et al. used phenol-melamine-formaldehyde resin which was synthesized by the condensation polymerization method [49] yielding specific capacitances up to 210 F/g. The advantages of this material are that it is easy and fast to synthesize; it is commercially available, raw materials are very cheap and it has a high electrochemical performance.

Activation of different carbonized materials results in different structures and pore size distributions. Activated carbon yields a capacitance of 150-355 F/g where the electrolyte plays an important part depending on molecule size in the electrolyte so it is compatible to the activated carbon pore size [50]. The research into novel carbon sources is motivated by the outlook of low cost, easy preparation, reliable performance and minimum detrimental impact on the environment.

The drawback of activated carbon is its limited energy density due to low F/g compared to more expensive carbon alternatives. This is because of limited control of pore structure and pore size when manufacturing activated carbon compared to other fabricated carbon allotropes.

- Activated carbon has 10⁵ [51] charge and discharge cycles without deterioration, due to the EDLC energy storage.
- Activated carbon is in the middle range of the carbon allotropes with regards to specific capacitance per gram and thus is scalable.

Templated carbon

One way to control the pore size and distribution is to use templated carbon. By using different silicon templates, different pore structures can be manufactured with a better control of which pore size is dominant. Hence it can be tailored to fit an electrolyte more properly than activated carbon. Yan-su et al. successfully prepared a mixture of thermoplastic precursor pitch with MgO precursors (magnesium acetate and citrate) yielding 284 F/g with a 0.3 M KOH electrolyte [52]. The templated carbon was carbonized under a nitrogen atmosphere by stepwise heating at 800 C for 3 h and then activated by KOH. The high result is probably due to the doping of MgO where the pseudocapacitative part becomes larger.
By using templates different electrodes for either high conductivity by well-structured mesopores or high energy density by a high number of micropores, can be contrived. Different kinds of supercapacitors can be targeted like microcapacitors where Berenguer-Murcia et al. produced thin films of zeolite-templated carbon which yielded 100-120 F/g [53] and is useful to store energy for IWS where volume is restricted and energy storage has limited space. Flexible supercapacitors have been shown by Gaoa et al. using electrospun titanium carbide (TiC) nano-felts converted into carbide derived carbon (CDC) yielding up to 135 F/g [54] useful to store energy in cloth fabrics powering built-in IWS.

The main drawback with templated carbon is that it is costly to produce and needs lengthy preparations during its manufacturing process [25]. Templates also consume twice the weight in carbon, so cheap template materials that are available on the order of tons is necessary to keep the production cost down [44].

- Templated carbon has 300 [115] reported charge and discharge cycles without deterioration, but doping the templated carbon with nitrogen and utilizing pseudocapacitance will have to be tested.
- Templated carbon is on the lower half of the carbon allotropes of specific capacitance per gram and due to that templated carbon is less scalable.

Carbon aerogels

Carbon aerogel (CAG) is a 3D nanostructure solid network containing meso- and micropores with a high specific surface area and good electrical conductivity [55,56]. CAG is made by using hard or soft templates, expensive chemicals and has to be dried with supercritical drying where all liquid is removed and solid carbon aerogel is left.

Wu et al. used an alternative process method and produced CAG from biomass derived sponge carbonaceous hydrogels and aerogels originally from biomass (watermelon) [57]. This environmentally friendly hydrothermal treatment produces an electrode material that yields 322 F/g with a stable performance of 96% up to 1000 cycles of charging-discharging.

Another method is to activate carbon aerogels by using KOH or CO₂. Liu et al. used activated carbon aerogels that contained a hierarchically porous structure resulting in high specific surface area [58]. This activated carbon aerogel was prepared via CO₂ and KOH activation processes which yield 250 F/g and 198 F/g respectively in 6 M KOH. This electrode material has a long lifetime, good power density and good cycle life.

Liu et al. produced carbon aerogel based on resorcinol-formaldehyde and activated by CO₂ [59]. This aerogel had a surface area of 3432 m²/g and yields a capacitance of 152 F/g. This electrode material shows good cycling stability of over 8000 cycles.

Carbon aerogel has a very high number of micropores and shows great promise as an electrode material. In order to be able to use all the micropores the carbon aerogel is dependent on an open structure where there is a small number of closed cavities.

- Carbon aerogels have been proved to have over 8000 charge and discharge cycles without deterioration.
- Carbon aerogel has a high specific capacitance per gram among the carbon allotropes and is considered scalable.

Carbon nanofibers

Carbon nanofibers (CNF) are chemically vapor deposition grown carbon nanofibers which are a cylindrical nanostructure with graphene layers arranged as stacked cones, cups or plates. They benefit from a highly accessible specific surface area. Xu et al. have produced polyacrylonitrile fibers using aqueous, non-aqueous and novel ionic liquid electrolytes and the result yielded 371 F/g in 6 M KOH, 213 F/g in 1 M LiClO₄/PC and 188 F/g in ionic liquid [60].

The drawback with a high surface area in general is that it suffers from low high concentration of functional groups which can lead to stability problems under prevalent cycling and may result in poor life cycle performance [25]. Kim et al. used polyacrylonitrile/poly(methyl methacrylate) which contained graphene and was electrospun to fibers and became carbon nanofiber electrode after heating with a mesopore structure yielding a high power density. These CNF become hierarchically porous nanofibers. The surface area was ~ 500 m²/g and the material yielded 128 F/g [61]. The stability of this material was a decrease of 17% after 100 cycles in 6 M KOH.

Yun et al. prepared hierarchically porous carbon nanofibers with a surface area of 2862 m²/g and thermal treatment with melamine with 9.1% nitrogen and this material showed a stable life cycle above 5000 cycles [62].

Jung et al. prepared CNF by electrospinning and thermal treatment of poly(acrylonitrile-co-vinylimidazole). After activation the surface area was 1120 m²/g and the material yielded 122 F/g [63].

Ma et al. prepared microporous carbon nanofibers by electrospinning from resole-type phenolic resin. By controlling the KOH concentration during the electrospinning process the fiber diameter could be controlled which greatly enhanced the surface area and the capacitance obtained was 256 F/g [64]. Also N-doped electrospun cellulose shows promising results even without activation [65].

CNF can be prepared in different ways, has a high surface area and a large number of mesopores which makes it a good candidate for power consuming applications where a high power density is needed, as for a NOx sensor.

- CNF has 5000 reported charge and discharge cycles without deterioration.
- CNF is in the middle of carbon allotropes with its values of capacitance per gram and is scalable.

Carbon nanotubes

Carbon nanotubes (CNT) are cylindrical nanostructures with extraordinary thermal conductivity, mechanical and electrical properties, carbon nanotubes find applications as additives to various structural materials. Nanotubes are members of the fullerene structural family [66]. CNT can be described as http://en.wikipedia.org/wiki/Graphene graphene sheets rolled at specific and discrete angles, the combination of the rolling angle and radius decides the nanotube properties. Carbon nanotubes can be either single
walled (SWCNT) or multiwalled (MWCNT). To be used as an electrode material for supercapacitors, research on vertically aligned carbon nanotubes, grown as dense as possible to yield a higher surface area, is conducted [67]. Their high electrical conductivity and very good mechanical and thermal stability is particularly beneficial for high power densities [68,69].

Since CNT are expensive to produce, alternative scalable techniques have been researched and Reit et al. fabricated vertically aligned carbon nanotubes which increased the surface area due to the higher number of nanotubes allowed by the controlled vertical alignment and yielded a capacitance of 30-79 F/g depending on growth time of 5-25 min [70]. Reit et al. along with the results show an effective methodology for the growth of vertically aligned carbon nanotubes on aluminum foil substrates and display that maintaining the uniform porosity is granted by alignment of carbon nanotubes, which can be helpful for others in the research field. These CNTs were cycled 500 times and showed little retention. This fabrication method on metal substrates claims to be scalable and therefore is promising for future EDLC electrode.

CNT can also be used as a substrate for unstable pseudocapacitive materials that suffer from mechanical degradation and they can also be combined with carbon aerogels to open access to closed cavities with micropores [82].

- CNT has 500 reported charge and discharge cycles.
- CNT has compared to other carbon allotropes, a low value of capacitance per gram and it is less scalable.

**Graphene**

Graphene is one layer of carbon atoms that are arranged in a regular hexagonal pattern. Graphene has a high electrical conductivity, high chemical stability and excellent mechanical stability [71]. Early research on graphene as an EDLC electrode showed a capacitance of 200 F/g [72]. It can also be used as a supporting substrate and has been bundled with polypyrrole giving a specific capacitance of 249 F/g [73]. The drawback of graphene is the cost and the challenge in producing high quality graphene sheets. Different approaches have been tested: cutting and unzipping multiwalled CNT into curved graphene nanosheets shows result of 256 F/g [74]. Wang et al. used large scale synthesis of single layered graphene which yielded 233 F/g with 5000 cycles reported and by using a zeolite Ni-MCM-22 as catalyst template, graphene sheets are easily produced [75].

Ning et al. used gram-scale synthesis of nanomesh graphene built on porous MgO layers, this unique pore structure yielded 235 F/g [76].

Li et al. used graphene oxide synthesized by multistep intercalation and reduction. This high electrical conductivity material gave 180 F/g [77].

Wu et al. used graphene hydrogels modified with 2-aminonaphthoquinone molecules yielding 258 F/g [78]. The material benefits from a good pore structure for charge transfer and electrolyte diffusion and claims long cycle life without showing any cyclic number.

Graphene is a very suitable electrode material for ionic liquid (IL) as electrolyte and shows a wide voltage window and good stability. Fu et al. showed in 2010 by using IL that the energy density was enhanced and reached 143 Wh/kg [79].

To enhance the capacitance for graphene, recent tests have been made by nitrogen doping. The nitrogen atom replaces a carbon atom in the hexagonal structure of the graphene sheet. Measurements yield 280 F/g but the underlying chemical mechanisms for these results are still unknown [80].

- Graphene has 5000 charge and discharge cycles without deterioration, but a cycle test with nitrogen doped graphene has to be conducted.
- Graphene is on the lower half considering value of capacitance per gram compared with other carbon allotropes thus considered less scalable.

**Composite electrode materials**

Composite electrode materials can be pseudocapacitive when a carbon allotrope is combined with transfer metals or a polymer. If a carbon allotrope is combined with another carbon allotrope the energy storage is EDLC. By coating polymers on different carbon structures the mechanical resilience is improved, which theoretically will increase the lifetime of the polymer, alternatively a transition metal can be coated on a carbon substrate [81]. Another way of using combined carbon electrode materials to gain higher energy density is to get a higher surface area and by that raising the capacitance.

Bordjiba et al. used carbon nanotubes bundled with carbon aerogel [82]. This gives a high surface area of 1056 m²/g and a measured capacitance of 524 F/g. This promising composite needs more research on preparation procedures since it is difficult to prepare today. Fang et al. made free-standing Ni-microfiber supported carbon nanotube aerogel [83], which by the added Ni-microfiber utilizes the pseudocapacitance. The CAG and CNT open structure and a high surface area yields 359 F/g only losing 5% of the capacitance the first 300 cycles and then is almost stable through 1000 cycles.

Zheng et al. used a glucose solution that contained CNT [84]. The solution was hydrothermally carbonized and turned into a “tube-in-activated carbon” when activated by KOH. This material had a surface area of 1626 m²/g and a capacitance of 378 F/g and only a loss of 4,6% after 2000 cycles.

Xu et al. used nitrogen doping of porous carbon from gelatin with high surface area. The doping utilizes the contribution of the pseudocapacitance and yields 385 F/g with a surface area of 3012 m²/g and claims good cycle durability but do not show any numbers [85].

To utilize the pseudocapacitance to enhance the energy density by a wider voltage window makes the supercapacitor more competitive to batteries. Early research showed limited device cyclability which recent developments seem to be able to handle [86]. Zhao et al. used graphene oxide where nickel ions where adsorbed on both sides. Electrostatic interactions forms a monolayer graphene/NiO sheet which yields 525 F/g with a surface area of 134.5 m²/g and capacitance retention of 95.4% after 1000 cycles proving that composite materials utilizing pseudocapacitance begin to compete with batteries charge/recharge cycles but still
need more development to be able to compete with carbon-based EDLC.

In the effort to obtain larger active surface area different approaches have been taken, using different carbon structures as described previously. Graphene nanosheets are a composite material where known carbon structures are being enhanced by different procedures that add flakes of graphene sheets. This enhancement leads to a higher surface area and hence in most cases a higher capacitance. The storage of hydrogen utilizes the same condition for being a good carbon storage material as a good carbon electrode material and Kuchta et al. presented a model of a new hypothetical material [87]. This open carbon framework (OCF) consists of slit-shaped pores obtained by fragmentation/truncation of graphene sheets and reaches theoretical surface areas of 3800-6500 m²/g. This model might explain why new materials based on graphene nanosheets show a high capacitance. Nandhini et al. used activated carbon that by high energy graphite ball milling was coated with electrophoretic deposition on titanium substrate. The pores contain 95% of 20-100 Å pores and yields 1071 F/g and a surface area of 2231 m²/g. The simple process and the excellent capacitance performance make this a very promising way of producing carbon electrodes for supercapacitors [88].

Yan et al. presented a high performance supercapacitor electrode based on a method that is rapid, scalable and has a low cost [89]. They used carbon black and polytetrafluoroethylene mixing in a mass ratio of 75:20:5 and dispersed it in ethanol. The mix was coated onto nickel foam and dried at 100 °C for 12 h and subsequent capacitance measurements reached a capacitance of 349 F/g. Zhou et al. used graphene-beaded carbon nanofibers prepared by electropinning with a solution containing graphene nanosheets and polyaniline. Electrochemical measurements showed that the material had high electrical conductivity, a large specific surface area and resulted in a capacitance of 263.7 F/g [90].

- Carbon composites have 2000 charge and discharge cycles reported without deterioration in many cases, but pseudocapacitive combinations seem not to be able to reach a sufficient number of cycles.
- Carbon composites show the highest value of capacitance per gram among the carbon allotropes and seem to be a good candidate for scalability.

All the electrode materials from the different references in Sections Activated carbon to Composite electrode materials are compared and presented in Table 2 and Figure 4.

Pseudocapacitive electrode materials

A transition metal can be coated on a carbon substrate and charge transfer will take place if a voltage is applied. This reversible chemical reaction behaves like a capacitance and is cyclic. A great deal of research has been done on ruthenium oxide (RuO₂) which shows a very high capacitance and would be a good choice if not for the cost of the metal. Therefore research has been aimed at other transition metals, among which manganese oxide (MnO₂) shows the most promising results of 698 F/g, and compared to RuO₂, manganese oxide is far less expensive [91]. The research on transition metals has only been focusing on a few metals and for those only cycles of 1000 have been reported. They also have shown problems with corrosion of the collector and poor low temperature performance [92].

Electrically conducting polymers (ECP) can be coated on a substrate as a thin film and can function as the electrode. Charge transfer will take place within the polymer and as a consequence of charging and discharging the ECP will swell and shrink. This fast volume swelling and shrinkage is a source of instability suffered by these materials and reduces their lifetime significantly. Their advantage is their reasonable price (e.g., 3,4 ethylenedioxythiophene) and their ability to accumulate a high capacitive charge throughout the whole volume which makes them less surface reliant compared to carbon based electrode materials where the energy storage is at the surface. Research is made on improving their lifetime by supporting the ECP with CNT [68].

- Pseudocapacitve electrode materials face the same problems as battery electrodes and lack a sufficient number of charge and discharge cycles without deterioration.
- Pseudocapacitive electrode materials have a high value of capacitance per gram compared with some carbon composites and are considered scalable.

Maximum theoretical surface area and capacitance for EDLC

The structure of activated carbon can be illustrated as a fullerene-related structure, built with rings containing 5-7 atoms where the ring forms a micropore [31]. Assuming that 1 g of carbon could be arranged in an optimal fashion, how large could the active surface be? One way of modeling this has been suggested for hydrogen storage simulations [87]. The van der Waal bonding radius is 170 pm. The surface area of a single carbon atom using that radius will then be approximately: \( A = 3.6 \times 10^{-19} \text{m}^2 \) [94]. For 1 g of carbon the total surface area would amount to: \( A_0 = 18,208 \text{m}^2 \) which is a theoretical maximum if the carbon atoms have no bonds with each other. If a theoretical material where one carbon atom has bonds with two other carbon atoms is assumed to preserve half of the theoretical maximum active surface, the resulting total area would be 9104 m².

This material will look like a long string of connected atoms, with a structure that has optimal surface area. If this material were to be used as electrode material in an EDLC we would have:

\[
C = \frac{\varepsilon_0 \varepsilon_r A}{d} = 3746 \text{ F/g} \tag{6}
\]

\( \varepsilon_r = 9.3 \) for 1 M KOH, \( \varepsilon_0 = 8.85 \times 10^{-12} \text{F/m} \), \( d = 2 \times 10^{-10} \text{m} \) (distance of the double layer [27]), \( A = 9104 \text{m}^2 \) (theoretical maximum active area). A theoretical maximum surface area of 9104 m² gives a maximum theoretical capacitance of 3746 F/g if aqueous 1 M KOH is used as electrolyte calculated by Eq. (6). With these parameters we assume that all atoms are accessible for the electrolyte and that the electrolyte has a sufficient number of ions. Likewise if the carbon material is built as graphene or carbon nanotubes
there will only be one axis of accessible surface area and we will have a theoretical maximum area of 4052 m$^2$ and a maximum capacitance of 1873 F/g, which is much higher than measured results shown in the open literature. In Figure 4, based on Table 2, measured capacitances with 1 M KOH as electrolyte are plotted against measured surface areas. The theoretical maximum according to our model is the highest value. As seen, different carbon electrode materials with high surface area do not necessarily yield a higher capacitance.

The composite carbon materials (purple circle) and carbon nanostructure (yellow dot) show a promisingly high capacitance. From our model we have a diagonal line which shows the maximum specific capacitance per surface area for 1 M KOH and EDLC. Some values are above the theoretical max. These electrode materials are measured in 6 M KOH or have been doped. Intercommunion between the double layer capacitance and the pseudocapacitance is always present. By N-doping the pseudocapacitative part is amplified and hence the capacitance values can get higher than the theoretical max due to the limitation of our model which only handles the double layer part of the capacitance.

The red dotted line is where commercial supercapacitors are today. The value is calculated from a supercapacitor from Skeleton Technology with 320 F and a weight of 56 g. The weight is halved for the calculation of specific capacitance due to assumed packaging weight. The green dotted line is what a Li ion battery would have in capacitance converted from its energy density and a voltage of 1.5 V. Our theoretical estimate for the highest possible EDLC capacitance gives a lower energy density than for a commercial battery today using KOH as electrolyte which limit us to 1.25 V due to the water electrolysis. To develop EDLC supercapacitors, the triangle above the line for commercial supercapacitors today and under the diagonal theoretical line is the area available for development. Even though a very high surface area does not yield proportionally more capacitance a well ordered pore structure with pore sizes matched to the electrolyte will yield a high capacitance [60].

### Table 2  Different carbon electrode allotropes sorted and compared by surface area and F/g measurements carried out by 3-electrode systems.

<table>
<thead>
<tr>
<th>Allotrope</th>
<th>Surface area m$^2$/g</th>
<th>F/g</th>
<th>Electrolyte other than 1 M KOH</th>
<th>Number of cycles</th>
<th>Degradation</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composites of carbon</td>
<td>2231</td>
<td>1071</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>[96]</td>
</tr>
<tr>
<td>Composites of carbon</td>
<td>1059</td>
<td>524</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>[82]</td>
</tr>
<tr>
<td>Composites of carbon</td>
<td>3012</td>
<td>385</td>
<td>2500</td>
<td>-6%</td>
<td>[85]</td>
<td></td>
</tr>
<tr>
<td>Composites of carbon</td>
<td>1626</td>
<td>378</td>
<td>2000</td>
<td>-4.6%</td>
<td>[97]</td>
<td></td>
</tr>
<tr>
<td>CNF</td>
<td>3000</td>
<td>371</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>[60]</td>
</tr>
<tr>
<td>Activated carbon</td>
<td>2100</td>
<td>355</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>[47]</td>
</tr>
<tr>
<td>Composites of carbon</td>
<td>517</td>
<td>349</td>
<td>6 M KOH</td>
<td>5000</td>
<td>+8%</td>
<td>[89]</td>
</tr>
<tr>
<td>Activated carbon</td>
<td>3200</td>
<td>320</td>
<td>2500</td>
<td>-31%</td>
<td>[98]</td>
<td></td>
</tr>
<tr>
<td>Composites of carbon</td>
<td>810</td>
<td>310</td>
<td>1000</td>
<td>-3%</td>
<td>[99]</td>
<td></td>
</tr>
<tr>
<td>Activated carbon</td>
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<td>300</td>
<td>10,000</td>
<td>-</td>
<td>[50]</td>
<td></td>
</tr>
<tr>
<td>Templated carbon</td>
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<td>284</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>[100]</td>
</tr>
<tr>
<td>Templated carbon</td>
<td>1650</td>
<td>260</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>[101]</td>
</tr>
<tr>
<td>Graphene</td>
<td>1050</td>
<td>258</td>
<td>2000</td>
<td>+1%</td>
<td>[78]</td>
<td></td>
</tr>
<tr>
<td>Graphene</td>
<td>1654</td>
<td>255</td>
<td>2000</td>
<td>-5.9%</td>
<td>[76]</td>
<td></td>
</tr>
<tr>
<td>Templated carbon</td>
<td>4000</td>
<td>250</td>
<td>10,000</td>
<td>-2%</td>
<td>[51]</td>
<td></td>
</tr>
<tr>
<td>Carbon aerogel</td>
<td>2119</td>
<td>250</td>
<td>5000</td>
<td>-24%</td>
<td>[58]</td>
<td></td>
</tr>
<tr>
<td>Templated carbon</td>
<td>1600</td>
<td>220</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>[102]</td>
</tr>
<tr>
<td>Activated carbon</td>
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<td>218</td>
<td>1000</td>
<td>-3%</td>
<td>[103]</td>
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<tr>
<td>Composites of carbon</td>
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<td>212</td>
<td>2 M KOH</td>
<td>2000</td>
<td>-16%</td>
<td>[104]</td>
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<tr>
<td>Activated carbon</td>
<td>674</td>
<td>210</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>[49]</td>
</tr>
<tr>
<td>CNF</td>
<td>529</td>
<td>202</td>
<td>3000</td>
<td>-3%</td>
<td>[105]</td>
<td></td>
</tr>
<tr>
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<td>190</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>[106]</td>
</tr>
<tr>
<td>Graphene</td>
<td>1400</td>
<td>180</td>
<td>2000</td>
<td>-5.9%</td>
<td>[76]</td>
<td></td>
</tr>
<tr>
<td>Composites of carbon</td>
<td>830</td>
<td>154</td>
<td>1000</td>
<td>-20.4%</td>
<td>[107]</td>
<td></td>
</tr>
<tr>
<td>Carbon aerogel</td>
<td>3431</td>
<td>152</td>
<td>8000</td>
<td>-1%</td>
<td>[108]</td>
<td></td>
</tr>
<tr>
<td>Graphene</td>
<td>2600</td>
<td>132</td>
<td>1000</td>
<td>-14%</td>
<td>[109]</td>
<td></td>
</tr>
<tr>
<td>Composites of carbon</td>
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<td>128</td>
<td>1500</td>
<td>-1%</td>
<td>[110]</td>
<td></td>
</tr>
<tr>
<td>CNF</td>
<td>500</td>
<td>128</td>
<td>100</td>
<td>-17%</td>
<td>[61]</td>
<td></td>
</tr>
<tr>
<td>CNF</td>
<td>1120</td>
<td>122</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>[63]</td>
</tr>
<tr>
<td>Templated carbon</td>
<td>1250</td>
<td>120</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>[52]</td>
</tr>
<tr>
<td>CNT</td>
<td>120</td>
<td>79</td>
<td>0.1 M Na$_2$SO$_4$</td>
<td>-</td>
<td>-</td>
<td>[84]</td>
</tr>
<tr>
<td>CNT</td>
<td>871</td>
<td>57</td>
<td>5000</td>
<td>-2%</td>
<td>[111]</td>
<td></td>
</tr>
<tr>
<td>Activated carbon</td>
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<td>44</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>[112]</td>
</tr>
<tr>
<td>Templated carbon</td>
<td>400</td>
<td>35</td>
<td>300</td>
<td>-2%</td>
<td>[113]</td>
<td></td>
</tr>
</tbody>
</table>
Difficulties of comparison of carbon allotropes

From the model (Figure 4) we can see that an EDLC based supercapacitor cannot reach the same energy density as a commercial battery today with aqueous electrolyte, but EDLC can still be developed for higher energy density to successfully be used in IWS systems like a NO$_x$-sensor that needs up to 20 W. An electrode for a supercapacitor used in a wireless sensor system would benefit from a well-ordered pore structure that utilizes the double layer for a higher capacitance combined with a composite electrode material, which will yield a higher energy density.

Measurements of electrode materials can be performed in different ways. Electrochemically a two electrode or three electrode systems can be chosen and most commonly 1 M KOH is used as electrolyte, sometimes 6 M KOH is used which yields higher capacitance values and therefore it is hard to directly compare samples measured with different electrolytes. But if all referenced measured in 1 M KOH would be measured in 6 M KOH they probably would show a higher capacitance and their communion order would likely be the same.

For an IWS a high number of cycles are preferred, only activated carbon among the carbon allotropes has reported cycles up to $10^5$. Carbon electrode materials utilize the double layer as energy storage and a higher number of cycles would be possible and desirable to publish.

A two electrode system has a structure that is very similar to a prototype capacitor device and also gives a realistic result when measuring capacitance which is comparable to commercial supercapacitors. It is also possible to make lifetime measurements in a more realistic manner. The methods for measurements of electrode materials are not standardized and the different ways of measuring make it hard to compare results with each other [95]. Figure 4 displays surface area per gram versus capacitance per gram which gives an indication of which materials are more favorable than others. Trends within materials can be seen, like if a higher surface area really gives a higher capacitance.

Conclusions

An electrode made of carbon utilizes the double layer for energy storage. Commercial EDLCs today use different carbon structures as electrodes since carbon has a number of good traits: cost effective as material, cost effective to produce as activated carbon, and the electrostatic energy storage gives a long lifetime.

The shortcoming of carbon as electrode material is that since it uses the double layer it has a poor energy density compared to batteries. Research shows that micropores contribute to the energy density and therefore the carbon electrode material research has been concerned with achieving a larger surface area to increase the capacitance and hence the energy density. Even though the theoretical and measured surface area is very high for some carbon varieties the measured capacitance is much lower than expected. A considerable amount of today's research on supercapacitors is aimed at obtaining higher energy density using pseudocapacitance; although that is good direction in general it is not a direct benefit for a wireless sensor system since the lifetime is significantly lower for a
pseudocapacitive supercapacitor compared to a double layer based one. Many wireless sensor systems will need to have an energy source that lasts for a substantial amount of time of more or less constant charging and discharging. In this case energy density can be traded for lifetime. Considering the last years of research, results indicate that electrodes constituting one single kind of carbon material are unable to yield a higher capacitance in proportion to the increased surface area. In contrast, a composite containing carbon on carbon, like carbon aerogel and CNT yields higher capacitance and N-doped carbon nanostructures yield even higher results and seem to survive a very high number of charge/discharge cycles.

An IWS system that will be able to operate under a long time needs an optimized energy harvester and an energy storage solution that can be charged and discharged many times over a long period of time. An carbon based EDLC with its formidable lifetime will deliver nearly four times the energy density over time and will have a longer lifespan than a battery. The research on supercapacitors aimed for energy storage. Hence composite electrode construction especially of N-doped graphene nanosheets shows great promise with its high surface area and high capacitance.

Acknowledgments

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References


Henrik Staaf received his master's degree in physics and his teaching degree for the Swedish high school in 2003. In 2007 until 2012 he was appointed IT-pedagogy within a corporate group in IT-Gymnasiet Sweden AB, where the focus was to enhance the usage of IT in the classroom and to use virtual platforms as pedagogic support and to implement new platforms. From 2008 till 2012 he was a teamleader on IT-GymnasietGöteborg. He has worked as a full time teacher until 2012, when he started his Ph.D. studies at Chalmers University of Technology through the Swedish Education Initiative and sponsored by the Swedish Council of Science. The Ph.D. studies focus on energy sources for Intelligent Wireless Sensors which is divided into energy storage and energy harvesting, where the main focus on harvesting is from piezoelectric and thermal energy harvesters and the energy storage focus on supercapacitors.

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Prof Enoksson has published more than 200 research journal and conference papers and ten patents. He is initiator of spin-off companies, winner of the Innovation Cup, referee for several journals and also a member of the editorial board of Journal of Micromechanics and Microengineering, the steering committees of MicroMechanics Europe and of company and projects boards.
Paper VII

HIERARCHICAL CELLULOSE- DERIVED CNF/CNT COMPOSITES FOR ELECTROSTATIC ENERGY STORAGE
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Hierarchical cellulose-derived CNF/CNT composites for electrostatic energy storage

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Abstract
Today many applications require new effective approaches for energy delivery on demand. Supercapacitors are viewed as essential energy storage devices that can continuously provide quick energy. The performance of supercapacitors is mostly determined by electrode materials that can store energy via electrostatic charge accumulation. This study presents new sustainable cellulose-derived composite electrodes which consist of carbon nanofibrous (CNF) mats covered with vapor-grown carbon nanotubes (CNTs). The CNF/CNT electrodes have high electrical conductivity and surface area: the two most important features that are responsible for good electrochemical performance of supercapacitor electrodes. The results show that the composite electrodes have fairly high values of specific capacitance (101 F g⁻¹ at 5 mV s⁻¹), energy and power density (10.28 W h kg⁻¹ and 1.99 kW kg⁻¹, respectively, at 1 A g⁻¹) and can retain excellent performance over at least 2000 cycles (96.6% retention). These results indicate that sustainable cellulose-derived composites can be extensively used in the future as supercapacitor electrodes.

Keywords: supercapacitors, carbon nanocomposite, electrodes, cellulose

(Some figures may appear in colour only in the online journal)

1. Introduction

One of the ways to fulfill the requirements of a future sustainable society is using new efficient technologies that can satisfy our growing needs and remain environmentally friendly at the same time. Today hazardous primary and secondary batteries with relatively short lifetimes are substantial contributors to a tremendous amount of landfill. This rising problem leads to the necessity of using long-lasting and, even more importantly, environmentally safe energy storage devices such as supercapacitors [1, 2].

Contemporary supercapacitors still need to be improved in terms of capacitance, energy density and cycling stability. The supercapacitor’s performance is mostly influenced by its main constituents, electrodes, which are typically made of carbon nanomaterials [3]. Many different forms of carbon have been utilized as electrode materials for supercapacitors [4]. Among them carbon nanofibers (CNFs) with well-developed mesoporosity, high mechanical and electrochemical stability are seen as prospective materials for the electrostatic energy storage inherent to electrical double layer (EDL) capacitors. The mesoporous structure of CNFs allows a substantial uptake of an electrolyte solution with the subsequent unrestricted diffusion of electrolyte ions into electrode cavities, which is very important for the high power performance of a storage device [5, 6]. Moreover, nowadays CNFs can be produced in a convenient way through the carbonization of electrospun polymeric precursors. The resulting flexible CNF sheets have freestanding nature (they can be used without a polymeric binder) with a controlled fiber diameter below one micrometer [7, 8].
On the other hand, CNF materials derived from electrospun polymers have rather low specific surface areas (due to the fairly large diameter of fibers) and mediocre electrical conductivity (due to the amorphous carbon structure with many defects) [9, 10]. These flawed properties can be diminished by functionalization with much smaller and more conductive carbon nanotubes (CNTs). According to recent studies, there are three major techniques for making efficient CNF/CNT composite electrode materials for use in supercapacitors: (1) the addition of dispersed CNTs into polymeric solution prior to electrospinning followed by the carbonization of composite fibers [10–13]; (2) the addition of dispersed CNTs onto fibers after electrospinning followed by the carbonization of composite fibers [14]; (3) chemical vapor deposition (CVD) of CNTs on top of the carbonized electrospun fibers [15–17]. All of these suggested methods were successful in improving the electrochemical performance of CNF materials with the addition of CNTs (the highest shown values of specific capacitance were 417 F g⁻¹ at 0.5 A g⁻¹ [13] and 185 F g⁻¹ at 0.625 A g⁻¹ [15] for three- and two-electrode systems, respectively). Though CNF/CNT composite electrodes produced using the third method have slightly lower rate capability and cycling stability (possibly due to their complex hierarchical structure), their resistance is lower as well (this can be explained by the better contact between the electrode surfaces and collectors). Moreover, CVD is a highly adjustable technique in terms of the density and thickness of CNT deposition, and requires no complicated preparation of CNT dispersions.

Nevertheless, the abovementioned works are mostly concentrated on composites that consist of unsustainable components, whereas very promising composite electrodes derived from sustainable renewable resources have only recently found their application in supercapacitors [11, 14, 18–20]. Despite their lack of high bulk conductivity, non-carbonized ‘conductive’ mats have exceptional mechanical properties and tailorability suitable for wearable electronics [18, 19], while carbonized cellulose precursors result in highly conductive materials suitable for energy storage devices [11, 19, 20]. In this study, cellulose-derived freestanding hierarchical CNF/CNT composite materials with desirable properties for electrostatic energy storage were evaluated as electrodes with potential use for novel on-chip supercapacitors [21]. Owing to the continuously increasing demand on carbon nanomaterials, in the near future vast raw material resource such as cellulose should start replacing the currently used, non-renewable and globally detrimental coal tar pitch and synthetic polymers as precursors for the synthesis of carbons. Our study is envisioned to accelerate this process.

2. Experimental

2.1. Fabrication of composite electrodes

The composite CNF/CNT electrodes were produced via chemical vapor deposition of CNTs on top of cellulose-derived CNFs. Initially, CNF sheets were fabricated by executing the following three consecutive steps: cellulose acetate electrospinning (17 wt% solution of the polymer in 2:1 solvent ratio of acetone and dimethylacetamide), cellulose regeneration (in 0.1 M water solution of NaOH) and carbonization (in a quartz tube furnace with N₂ flow by heating up to 800 °C with the heating rate of 5 °C min⁻¹) according to [9]. Subsequently, CNTs were thermally grown on CNF substrates at 700 °C for 10 min using acetylene as a carbon source, 2 nm thick iron layer as a catalyst and hydrogen as a carrier gas (in AIXTRON Nanoinstruments Black Magic 2 inch machine). Finally, prior to electrochemical measurements, the CNF/CNT composites were dipped into a mixture with equal volumetric proportions of 1 M nitric and sulphuric acids to remove catalytic particles, and thoroughly washed afterwards with DI water to avoid contamination with dissolved ions.

2.2. Material characterization

The morphology of the composite materials was observed using high resolution scanning electron microscopy (SEM) (Leo Ultra 55 FEG SEM, Zeiss) in a secondary electron mode at an acceleration voltage of 3 kV. For transmission electron microscopy (TEM), as-grown CNF/CNT samples sandwiched between two Cu-grids (Athena G204, 400 mesh) were placed in a single tilt sample holder and further examined in a JEOL (JEM 2100) TEM equipped with a LaB₆ cathode and a Gatan (SC1000 Orius) digital cyclic charge–discharge (CCD) camera. Imaging was done using an electron acceleration voltage of 80 kV, in order to stay below the threshold for knock-on damage and to minimize electron-beam induced damages in the CNTs [22].

The surface area of the materials was measured using the Brunauer–Emmett–Teller nitrogen adsorption method, and mesopore size distribution was quantified by the Barrett–Joyner–Halenda method using an adsorption isotherm (TriStar 3000 V6.04 A surface area and pore analyzer). The samples were degassed under vacuum at 225 °C for 4 h prior to the measurements.

The x-ray photoelectron spectroscopy (XPS) was performed on a Quantum 2000 scanning ESCA microprobe (Physical Electronics) to assess the presence of catalyst residues in the samples. An Al Kα x-ray source (1486.6 eV) with a beam size of 100 μm was used. The area analyzed was about 400 × 500 μm² with a depth of 4–5 nm. The results were evaluated using MultiPAK 6.1A software.

X-ray diffraction (XRD) analysis was made using a Philips X’Pert Materials Research Dif-ractometer with an x-ray tube with Cu anode (Kα radiation, λ = 1.541 84 Å) as a radiation generator at 45 kV and 40 mA. Phase analysis was carried out with X’Pert HighScore 3.0 (PANalytical BV).

Raman spectroscopy was implemented to evaluate the microstructure of vapor-grown CNTs. Raman spectra were obtained using a 638 nm laser source on a Horiba XploRA spectrometer equipped with an Olympus BX41 microscope. Spectra were analyzed with LabSpec software.

The electrical conductivity of the materials was evaluated using a four-point probe system (CMT-SR2000N, AIT). Five different measurement spots were taken for analysis of each sample.
2.3. Electrochemical analysis

Electrochemical performance was measured in a Swagelok supercapacitor cell consisting of a symmetrical two-electrode system with CNF-based carbon nanomaterials as working electrodes, electrospun cellulose as a separator, and 6 M aqueous solution of KOH as an electrolyte. The working electrodes and separators were cut to a circular area of 0.5 cm$^2$ to fit current collectors. Before starting the measurements, the electrodes were immersed in the electrolyte solution for 24 h. Electrochemical measurements were performed with Gamry Reference 3000 potentiostat/galvanostat/ZRA and data were analyzed with Gamry Echem Analyst. A voltage range between 0 and 1 V was used for CV (cyclic voltammetry) measurements at five different scan rates (5, 10, 20, 100 and 200 mV s$^{-1}$), while GCD (galvanostatic charge–discharge) tests were performed at six different current densities (0.5, 1, 1.5, 2, 5 and 10 A g$^{-1}$). EIS (electrochemical impedance spectroscopy) was completed at an open circuit potential with an AC amplitude of 5 mV over a frequency range from 100 kHz–10 mHz. Electrochemical stability tests were performed by CCD for 2000 cycles with a current density of 1 A g$^{-1}$.

3. Results and discussion

3.1. Morphology and surface properties

Freestanding CNF mats with a thickness of 25–40 μm were obtained via carbonization of electrospun cellulosic precursors. The mats consist of fibers with 50–250 nm diameters. The continuous fibers are randomly oriented and have a smooth topography (figure 1, bottom right corner). The morphology of the composite material is rather different (figure 1, top left corner). After chemical vapor deposition, the bigger CNFs were densely covered with much smaller uniform CNTs (5–10 nm tube diameters), thus forming a hierarchical nanocomposite material. A straight boundary line between the pristine CNF region and the region with deposited CNTs validates the reliable space controllable deposition of iron catalytic particles.

Figure 2(A) reveals slightly uneven growth of CNTs on different sides of the CNF, which could be due to the heterogeneous distribution of heat or catalytic particles within a CNF substrate during CNT growth. A closer look at the CNTs (figure 2(B)) exposes catalytic particles which are commonly seen inside the tip of the CNTs but occasionally also remote from the tip, still inside the tube walls but further towards the tube base. In such cases, the tip could sometimes be curled up, indicating that the direction of growth is less straight once a tube grows past a catalyst particle. The number of tube walls typically varied between three and eight, with rare occurrences of single- and double walled tubes (figure 2(C)). Measurements were taken in several different distances from the CNT base, both near the CNF on which they were grown, as well as close to the CNT tips, and the distribution of outer and inner diameters was found to be fairly homogeneous. The measurements revealed outer tube diameters $d_o$ in the span of 5–10 nm and inner diameters $d_i$—3–5 nm, resulting in a normalized thickness $t_n = \left(\frac{d_o - d_i}{d_i}\right)$ of 0.4–0.55. The range of $t_n$ is in the lower region of typical values for CVD-grown CNTs and considerably lower than for CNTs grown by arc-discharge (where typically $t_n$ is much larger than 0.5) [23].

Figure 3(A) shows a nitrogen adsorption isotherm and pore size distribution for the CNF/CNT material. The shape of the isotherm is characteristic for meso- and macro-porous (pores with a size range of 2–50 and >50 nm, respectively)
materials without a developed microporous structure [24], which is in accordance with figures 1 and 2. Meso- and macro-porosity of the composite are very important for electrostatic energy storage as they provide sufficient access of electrolyte ions to the surface, support charge propagation and accumulation, and, as a result, increase the power capability of a supercapacitor [25]. Besides this, pore size distribution points to the presence of pores with a diameter below 10 nm, which makes a substantial contribution to the total surface area of the synthesized composites (table 1). Pores of this size should be attributed to the CNTs which are much smaller than the CNFs and thus have much higher specific surface area [14].

The XPS analysis (figure 3(B)) confirmed that both the pure CNF material and the CNF/CNT composite almost completely consist of carbon with predominant C–C bonds (a peak at 284.5 eV). The pure CNFs contain slightly more oxygen which can be due to their more amorphous nature in comparison to the CNTs. It should lead to faster oxidation of CNFs when they are exposed to air.

The XRD analysis was used to evaluate the crystalline structure of the composite CNF/CNT material (figure 3(C)). It is hard to differentiate a graphitic peak around 25°, which is usually attributed to CNTs [12], as it overlaps with a broad amorphous peak around 18° which is a characteristic peak for cellulose-derived carbons obtained after carbonization at temperatures below 3000 °C [24].

The Raman spectra (figure 3(D)) shows two broad bands at ~1320 cm⁻¹ and ~1590 cm⁻¹ that can be respectively assigned to amorphous sp²-bonded carbons with structural defects (D-band) and crystalline sp²-bonded carbons (G-band) [26]. \( I_D/I_G \) ratio for the composite material was calculated to estimate the level of disorder in the carbonaceous structure. This ratio is 1.07, which confirms the prevalence of an amorphous CNF part.

The conductivity values for the CNF/CNT composite are more than 15 times higher than for pure CNFs (table 1). This is due to the dense coverage of the CNF material with the highly conductive CNTs, which is enough to reach a critical electrical percolation threshold [27]. Effective combination of high electrical conductivity and appropriate morphology, i.e. the intrinsic properties of the synthesized CNF/CNT composite, is necessary for effective performance of carbon electrode materials used in supercapacitors [16].

### 3.2. Electrochemical performance

Various electrochemical measurements were used to evaluate the performance of the CNF/CNT composites as electrode materials in a supercapacitor device.

![Figure 2. TEM images of the vapor-grown CNTs on top of a CNF at different magnifications.](image)

Table 1. Material properties of the composite material in comparison with the pure CNF material.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Surface area (m² g⁻¹)</th>
<th>Carbon content (%)</th>
<th>Electrical conductivity (S cm⁻¹)</th>
<th>Electrode capacitance (F g⁻¹)</th>
<th>Energy density (W h kg⁻¹)</th>
<th>Power density (kW kg⁻¹)</th>
<th>Capacitance retention (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNF</td>
<td>45</td>
<td>97.4</td>
<td>4.2</td>
<td>46.5</td>
<td>1.24</td>
<td>1.73</td>
<td>88.7</td>
</tr>
<tr>
<td>CNF/CNT</td>
<td>131</td>
<td>99.3</td>
<td>69.4</td>
<td>91.5</td>
<td>10.28</td>
<td>1.99</td>
<td>96.6</td>
</tr>
</tbody>
</table>

*Measured at a scan rate of 10 mV s⁻¹.

*Measured at a current density of 1 A g⁻¹.

The conductivity values for the CNF/CNT composite are more than 15 times higher than for pure CNFs (table 1). This is due to the dense coverage of the CNF material with the highly conductive CNTs, which is enough to reach a critical electrical percolation threshold [27]. Effective combination of high electrical conductivity and appropriate morphology, i.e. the intrinsic properties of the synthesized CNF/CNT composite, is necessary for effective performance of carbon electrode materials used in supercapacitors [16].
Figure 4(A) shows the dependence of capacitance on a scan rate for the composite CNF/CNT electrode. The CV curves have a moderately rectangular shape, which indicates an EDL capacitive behavior [28]. Distortion of the rectangular shape at higher scan rates (100–200 mV s\(^{-1}\)) happens because of the lack of time for electrolyte ions to penetrate completely inside the electrode, whereas for lower scan rates (5–20 mV s\(^{-1}\)) the ions reach the inner surface of the electrode providing higher accumulative charge [5]. For each electrode, the evaluation of the specific capacitance \(C_s\) was made according to equation (1),

\[
C_s = \frac{\int I(V) dV}{m(dV/dt)\Delta V} \tag{1}
\]

where \(I(V)\) is the voltammetric current obtained from the integrated area of the CV curves, \(m\) is the total mass of carbon materials in two electrodes, \(dV/dt\) is the scan rate, and \(\Delta V\) is the voltage range [10, 11]. The comparison of the CV curves of two different CNF-based nanostructured materials is presented in figure 4(B). The composite electrodes show about two times higher values of capacitance in comparison to the pure CNF electrodes. Addition of CNTs has a big influence on the performance of the CNF-based electrodes as CNTs significantly increase their surface area and electrical conductivity (table 1), which are key factors in making electrostatic charge accumulation process more efficient [14].

The GCD curves show an almost triangular shape specifying EDL behavior as well (figure 5(A)). From the GCD test,
power and energy density values were calculated using equations (2) and (3) respectively,

\[ E_d = \frac{C_s(\Delta V)^2}{2} \]  
\[ P_d = \frac{E_d}{t} \]  

where \( C_s \) indicates the specific capacitance, \( \Delta V \) is the potential difference excluding the IR drop and \( t \) is the discharge time [29]. From the GCD test power and energy density values were found to be reasonably high for the composite electrode materials. A fast current–voltage response proves that an electrode material has a high power density [24]. Figure 5(B) shows the dependence of the specific capacitance on current density. For the composite CNF/CNT electrode, at 0.5 A g\(^{-1}\) the capacitance is about 1.5 times higher than at 2 A g\(^{-1}\) and about 10 times higher than at 10 A g\(^{-1}\). At the higher current density many electrolyte ions cannot diffuse fast enough to an electrode surface and occupy available sites, which negatively effects accumulation of charges, i.e. decreases the capacitance [30].

According to EIS the equivalent series resistance (ESR) of a system is defined as the initial intercept of a plot with the X-axis in the high frequency region (figure 6(A)). ESR mostly comprises of bulk electrolyte resistance and interfacial resistance between an electrolyte and an electrode material. The composite electrode and the pure CNF electrode have low ESR values (0.57 and 0.38 \( \Omega \), respectively), which is good for effective electrochemical performance. A slightly lower value for the pure CNF material can be explained by its better wettability with the aqueous KOH electrolyte due to the higher amount of hydrophilic oxygen-containing groups (according to the XPS analysis). In contrast, charge transfer resistance, expressed as the intercept of a semicircle in the mid-higher frequency region, is lower for the CNF/CNT electrode compared to the pure CNF electrode (\( \approx 0.5 \) and \( \approx 1 \) \( \Omega \), respectively), which verifies enhanced conductivity of the composite [12]. Moreover, the verticality of the Warburg line, the slope of the 45° segment of the curve in the low and medium frequency regions, validates sufficient pore accessibility for electrolyte ion diffusion [31].
The long term exploitation of electrode materials is validated through their ability to withstand a large number of charge-discharge cycles and retain capacitance. The CNF/CNT electrodes retained 96.6% of the initial capacitance after 2000 cycles (figure 6(B)), which is a very good stability for an energy storage device such as a supercapacitor, as it has to deliver the harvested energy through quick charging and discharging many times [32]. High capacitance retention indicates excellent stability of the composite electrode material and confirms strong adhesion of vapor-grown CNTs to CNFs.

4. Conclusions

Freestanding cellulose-derived carbon nanocomposites were fabricated by chemical vapor deposition of CNTs on top of CNF mats. The resulting hierarchical carbon materials performed well as electrodes for supercapacitors. They showed fairly high capacitance (91.5 F g$^{-1}$), indeed satisfactory energy and power density ($\approx$4W h kg$^{-1}$ and $\approx$10 kW kg$^{-1}$, respectively), and remained electrochemically stable over 2000 charge-discharge cycles. The composite materials have an advantageous combination of two properties that are essential for supercapacitor electrodes. Owing to the deposition of CNTs, the electrodes have high electrical conductivity, i.e. the electrode’s ability to transfer charges, and increased surface area, i.e. the electrode’s ability to uptake an electrolyte and accumulate charges. Overall, the hierarchical cellulose-derived CNF/CNT nanocomposites should be viewed as efficient sustainable electrode materials for electrostatic energy storage.

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References

[29] Zhou Z, Wu X F and Hou H 2014 RSC Adv. 4 23622–9
Paper VIII

PIEZOELECTRIC ENERGY HARVESTING AS ENERGY SOURCE FOR AUTONOMOUS INTELLIGENT WIRELESS SYSTEMS ON GAS TURBINES
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Piezoelectric energy harvesting as energy source for autonomous intelligent wireless systems on gas turbines

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Abstract:
Autonomous intelligent wireless sensor systems (AIWS) provides fast and adaptive solutions for measurements and surveillance on gas turbines, mainly because it avoids the problem of cables. To power AIWS, energy harvesting can be utilized which will broaden the usability of the AIWS compared to battery driven solutions, where the battery will have to be replaced from time to time. A viable choice of energy harvesting is to use piezoelectric energy conversion by cantilevers that exploit the vibrations from the gas turbine. The main challenge with piezoelectric energy harvesting is its often-narrow bandwidth for sufficient power output. To achieve broader bandwidth with maintained power output, coupled structures can be utilized. Coupled piezoelectric cantilevers make use of a larger active area which increases power output besides giving a broader bandwidth through the coupling. Our AIWS comprises a coupled piezoelectric harvester, a power management circuit, a supercapacitor pack and a ZigBee (802.15.4) setup on the Rolls-Royce ex-service gas turbine (figure 1). All components are off the shelf. The characterization tuning and g-force test on the piezoelectric harvester was performed at GKN, where the harvester was tuned to match the cruise speed vibrations provided by the ex-service gas turbine. The temperature sensors and wireless system is provided by Coventry University. Attached to the power management is a supercapacitor, which has enough power to start up and deliver energy for 30 seconds of continuous transmission. The power management lets the supercapacitor charge to 5.13 V before delivering power to the ZigBee. In figure 2, top graph, the red ellipse shows the start-up sequence of 8 mW; after that the ZigBee is transmitting measured temperature data continuously. When harvesting and transmitting continuously the operating time is 67 seconds. In the bottom graph in figure 2 we show analysed data of energy consumption vs transmitting rate from the ZigBee. A transmitting interval of 1 second is possible with current configuration to yield enough energy to let the ZigBee perform its tasks. Depending on what is measured, the setups of the AIWS can be altered if for instance monitoring the gearbox it will not need to transmit until there is a fault to report, which enables an even lower power consumption.

Figure 1. AIWS setup on Rolls-Royce ex-service gas turbine

Figure 2. In the top graph measured continuous transmitting on Rolls-Royce gas turbine is shown. The bottom graph shows calculated supercapacitor output voltage change vs transmission rate for the ZigBee.