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ENERGY HARVESTING POWER SUPPLY FOR MEMS APPLICATIONS
NEZÁVISLÝ ELEKTRICKÝ ZDROJ PRO MEMS APLIKACE

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1 INTRODUCTION

For at least twenty years now there have been recorded attempts to replace the conventional power sources for low-power and ultra-low-power electronics by alternative means. One option of achieving an independent power supply is to exploit so called energy harvesting principle (sometimes called also power harvesting or energy scavenging). This term refers to obtaining electrical energy from energy of another type, available in the ambience of the energy harvesting unit. The other types of energy include solar energy, energy of thermal gradient, mechanical energy or electromagnetic (RF) energy. The range of potential applications for energy harvesting devices is increasing with the dropping power requirements of modern electronic devices. Example applications, such as wireless sensors embedded in the difficult to access parts of technical systems in aerospace or civil engineering, or modern wearable and implanted health and monitoring sensors, display a growing tendency of using MEMS (microelectromechanical systems) technology, which is characterized by very low power requirements.

In relation to recent advances in development of modern biomedical implants, namely a new generation of cochlear implants [1], the question of feasibility of using an alternative energy source for powering this implant or other wearable or biomedical MEMS application arose. Such power source, based on energy harvesting principle, would have to comply with challenging requirements regarding both its performance and dimensions in order not to compromise the user comfort. For this purpose it is essential to identify the feasible source of energy for conversion available from the ambient environment. The ambient power source feasibility can be evaluated by its ability to provide sufficient amount of energy for conversion. This amount is however dependent on the foreseen application to be powered up, good requirement specification is therefore needed for the evaluation of the perspective independent power source design. It also cannot be granted in advance that the ambient energy levels will be sufficient for powering the intended application.

Equally important to the selection of ambient energy type is the conversion physical principle selection. Especially in case of converting mechanical energy into electricity there are multiple conversion methods with different strengths and weaknesses. These unique points of particular transduction principles must be identified and the most advantageous principle must be selected in order to satisfy the specified application requirements.

The focus of this works is on a feasibility analysis and development of an energy harvesting-based independent power source for MEMS applications in challenging environments, where low frequency and magnitude mechanical excitation is available, and where size and weight constraints are severely limiting the power source parameters.
2 PROBLEM DEFINITION

2.1 FEASIBLE POWER SOURCE PROBLEM

The current strategy of powering up the wearable and biomedical electronic devices by primary or secondary batteries bears the necessity of a regular maintenance. The batteries must be periodically changed or recharged, which might be an obstacle to increasing the user comfort of such electronics. In case of wearable electronics the battery maintenance presents in most cases just a minor nuisance, unless the device stops working due to lack of power in conditions, where it is being relied upon. However, for implanted electronic devices the need for maintenance due to battery change means also a need for additional surgery, putting more strain on the user of the implant.

Multiple modern electronic wearable and biomedical MEMS applications are already in the sub-miliwatt power consumption range, as can be seen in Table 1, showing the examples of modern biomedical electronic devices with power requirements below 0.5 mW.

Table 1 Examples of low power MEMS biomedical devices

<table>
<thead>
<tr>
<th>Device</th>
<th>Reference</th>
<th>Reported power consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pacemaker</td>
<td>[2]</td>
<td>8 μW</td>
</tr>
<tr>
<td>Neural sensor</td>
<td>[3]</td>
<td>10.5 μW</td>
</tr>
<tr>
<td>Biomonitoring system</td>
<td>[4]</td>
<td>100 μW</td>
</tr>
<tr>
<td>Cochlear implant</td>
<td>[1], [5]</td>
<td>150 μW - 211 μW</td>
</tr>
<tr>
<td>Blood Pressure Sensor</td>
<td>[6]</td>
<td>300 μW</td>
</tr>
<tr>
<td>Drug pump</td>
<td>[7]</td>
<td>400 μW</td>
</tr>
</tbody>
</table>

Possible solution for the power source problem can thus be found in the field of energy harvesting. Exploiting the otherwise unused energy in the ambience of the powered application could potentially ensure theoretically continuous and unconstrained function of the electronic devices. The challenge lies in the unpredictability and variance of the ambient energy levels in the human body and its close proximity. Harvesting power from sources that can potentially directly affect the health of the harvester user (blood pressure, heart contractions) is deemed controversial and unsafe. Solar power could theoretically be utilized, but the power output of such energy source would vary significantly depending on the time and whereabouts of the user. Moreover, exploiting this technique brings necessity to have the harvester directly exposed to the light. Some publications also analyse use of thermoelectric generators for human power harvesting, but the results are not convincing. A possibility might lie in exploiting the energy of human motion. On one hand, this approach does not endanger the health of the user. On the other hand, the power output of the electromechanical energy harvester would depend on the activity levels of the user. While this might not be a problem for some wearable applications used e.g. for sport activity tracking, in biomedical sensors it could be a disadvantage, as some potential user target groups might not be very physically
active. Furthermore, if the harvester is supposed to power up the electrical application 24 hours a day, 7 days a week, it needs to be able to harvest sufficient energy from the limited period of time, when its user is being physically active. In addition to that, the size and weight of the device must not be too high, not to affect the user comfort. For this reason it is necessary to analyse the available levels of energy for conversion, and verify, whether the energy harvesting-based power source can ensure the required performance with most of the perspective users.

2.2 THESIS GOALS

Thanks to the intended placement of the independent power source – energy harvester – in the proximity of the powered application, therefore on/in the human body, there are three types of energy theoretically available for conversion: mechanical energy, solar energy a thermal gradient. Despite the challenges listed in the chapter above, the mechanical energy conversion presents the least invasive technique of powering up small electrical applications. Moreover, this type of energy has high potential for every-day use, as the amounts of available mechanical energy are directly influenced by the user behaviour, which can to certain extent be adjusted, unlike other energy sources, such as solar energy. Further work will therefore deal solely with the electromechanical energy harvesting from the human behaviour and its feasibility for powering wearable and biomedical MEMS electronic devices.

The main goals of this dissertation are twofold. Firstly, an analysis of available mechanical energy in the environment of the human body will be performed and a feasibility study of electromechanical energy harvester placed on the human body will be conducted. The least favourable placement, represented by human head, will be investigated as the worst-case scenario. For this, the acceleration in the area of human head will be measured on multiple testing specimen. This data will be used for statistical processing and to draw general conclusions regarding the feasibility of development of an electromechanical energy harvester for human power harvesting. In order to reach better harvester performance, a method that could potentially increase the amount of harvested power will be presented.

Based on the results of the initial analyses a perspective electromechanical energy conversion method will be chosen and a new design of the electromechanical energy harvester for wearable and biomedical MEMS applications will be introduced. The second goal is therefore to design, optimize, manufacture and verify the prototype of an electromechanical energy harvester for human power harvesting both in laboratory and in real life conditions. Even though the harvester is intended to be used for ultralow-power MEMS applications, due to expected low available energy levels the design of the harvester will have to properly utilize the advantages of selected energy conversion method and suppress its weaknesses in order to comply with the expected requirements.
3 STATE-OF-THE-ART

3.1 ELECTROMECHANICAL ENERGY CONVERSION

The energy harvesting power sources utilizing mechanical energy are following the same physical principles as any other electromechanical energy transducers, be it sensors or generators. The available methods of converting the mechanical energy into electricity are following:

3.1.1 Piezoelectric effect

The piezoelectric effect has been experimentally discovered in tourmaline and quartz crystals by Curie brothers in 1880. It was found, that certain materials exhibit an electric polarization when subjected to mechanical stress. This polarization is linearly dependent on the mechanical load. This effect and its inverse counterpart - deformation of the piezoelectric material when under the influence of electric field - is currently being exploited in sensors and actuators, but also for the purposes of the energy harvesting [8].

The piezoelectric effect is rooted in the fundamental structure of a crystalline network. Certain crystalline structures have a charge balance with polarization, which must be oriented in one direction to produce piezoelectric behaviour of the material. The linear piezoelectric effect is expressed a set of two constitutive equations [9], which can be written in the following form:

\[
\begin{align*}
T_p &= c_{pq}^E \cdot S_q - e_{pk} \cdot E_k \\ D_i &= e_{iq} \cdot S_q + \varepsilon_{ik}^S \cdot E_k
\end{align*}
\]

(1) \hspace{1cm} (2)

Where \( T_p \) is the stress component, \( c_{pq}^E \) is the elastic stiffness constant at the constant electric field, \( S_q \) is the mechanical strain component, \( e_{pk} \) is piezoelectric constant, \( E_k \) is the electric field component, \( D_i \) is the electric displacement component, \( \varepsilon_{ik}^S \) is the permittivity component for constant strain and indices \( i,k,p,q \) refer to different directions within the material coordinate system.

There are two operation modes of the piezoelectric material, exploitable for energy harvesting [10]: mode 33 (compressive mode) and mode 31 (transverse mode), as shown in Figure 1. In both these modes the external force is applied only in one direction, which is a common assumption in the energy harvesting devices.

![Figure 1 Implementation of piezoelectric conversion working modes: 33 (left) and 31 (right)](image-url)
3.1.2 Electromagnetic induction

The phenomenon known as electromagnetic induction was discovered in 1831 by Michael Faraday, who found that a variation of the magnetic field in time can generate an electric field. This is applicable whether the magnetic field itself changes, or the conductor is moved through it. Harvesters, exploiting the Faraday’s law of induction for generating electromotoric force (emf) on a pickup coil placed in a time-varying magnetic field (Figure 2), are essentially miniaturized versions of rotary or linear generators with a rotor moving either in line or on a circular segment path [11], [12]. Connecting an electrical load to the coil ports then causes a current to flow, generating electrical energy. The voltage (emf) induced across the coil is calculated by the well-known formula:

$$emf = -\frac{d\Phi}{dt} = -N\frac{d\Phi}{dt}$$  \hspace{1cm} (3)

Where $N$ is the number of coil turns and $\Phi$ is total magnetic flux through the coil area.

![Figure 2 Electromagnetic induction principle](image)

3.1.3 Electrostatic conversion

The principle of electrostatic energy conversion lies in exploiting a capacitor with a variable capacitance. The two electrodes of the capacitor, separated by air, vacuum or any dielectric material, move with respect to each other due to mechanical excitation. That leads to a change either in the overlapping active surface of the electrodes, or in their distance from each other, causing a variation in the capacitance [13]. The most common working cycles (Figure 3) employed are the voltage-constrained cycle and the charge-constrained cycle. A correct synchronization of the energy extraction with capacitance variation is necessary in order to exploit the relative movement of the electrodes for generating electricity.

![Figure 3 Electrostatic conversion working cycles](image)
The total amount of energy converted per cycle for charge-constrained cycle is equal to:

\[ E_{Q=\text{est}} = \frac{1}{2} Q_{\text{est}}^2 \left( \frac{1}{C_{\text{min}}} - \frac{1}{C_{\text{max}}} \right) \]  

(4)

and for voltage constrained cycle to:

\[ E_{U=\text{est}} = \frac{1}{2} U_{\text{est}}^2 \left( C_{\text{max}} - C_{\text{min}} \right) \]  

(5)

The electrostatic conversion principle is used mainly in MEMS sensors, actuators, and energy harvesters.

3.1.4 Magnetostriction

In magnetostrictive materials a mechanical strain will occur when they are subjected to a magnetic field in addition to strain originated from applied mechanical loading. This is known as a magnetostrictive, or Joule effect. Due to the inversion of this effect, known as magnetoeelastic effect, Villari effect or just inverse magnetostrictive effect, the magnetization of these materials also changes with the variation of applied mechanical stresses in addition to the changes caused by the variance of the externally applied magnetic field.

The most important mode of operation of magnetostrictive materials is the longitudinal mode 33 [14]. Linearizing the differential response of strain and magnetization to obtain the magnetomechanical coupling for this mode leads to the following set of equations:

\[ \varepsilon = S^H \sigma + d_{33} H \]  

(6)

\[ B = d_{33}^\sigma \sigma + \mu^\sigma H \]  

(7)

Where \( S^H = \frac{\partial \varepsilon}{\partial \sigma | H = \text{const}} = \frac{1}{E^H} \), \( E^H \) being the Young’s modulus at constant applied magnetic field strength, \( d_{33} = \frac{\partial \varepsilon}{\partial \sigma | H = \text{const}} \) is the magnetostrictive strain derivative (linear coupling coefficient for mode 33), \( d_{33}^\sigma = \frac{\partial B}{\partial \sigma | H = \text{const}} \) is the parameter of magnetomechanical effect for the same mode, and \( \mu^\sigma = \frac{\partial B}{\partial H | \sigma = \text{const}} \) is the magnetic permeability at a constant stress [14].

![Figure 4 Principle of a Villari effect](image)
3.1.5 Triboelectric effect

Triboelectricity has been known to humankind since antiquity, being considered mostly negative effect that needs to be prevented. The principle of this effect lies in a contact-induced charge transfer, when one material becomes electrically charged after being contacted through friction by another material. Different materials are able to either lose or accept electrons in different amounts.

The amount of the transferred charge $\Delta q_c$ is given by the product of the potential difference $V_c$ and the capacitance between the two bodies at the critical separation distance where the charge transfer is cut off $C_0$:

$$\Delta q_c = C_0 V_c$$  \hspace{1cm} (8)

The materials can be arranged by their relative polarity in an order known as triboelectric series [15].

The main obstacle for broader use of triboelectricity aside for Wimshurst machines or Van de Graaf generators was until recently seen in the limited fundamental understanding of the effect. However, recent advances in this field lead to a new type of an energy transducer being used in electromechanical energy harvesting: triboelectric nanogenerator (TENG).

Following different modes of TENG (Figure 5) are currently being used: vertical contact separation mode [16], lateral sliding mode [17], sliding or contact freestanding triboelectric-layer modes [18], and single-electrode mode [19].

![Figure 5: Different working modes of TENG](image_url)

- a) vertical contact separation mode
- b) lateral sliding mode
- c) sliding freestanding triboelectric-layer structure
- d) single-electrode contact structure
- e) contact freestanding triboelectric-layer structure
3.2 ELECTROMECHANICAL ENERGY HARVESTER CLASSIFICATION

Electromechanical energy harvesters cover a variety of different devices, utilizing the aforementioned physical principles to convert the mechanical energy into electricity. This chapter introduces some of the possible classification criteria, meant to split the electromechanical energy harvesters into categories according to their similarity in some aspect. The presented list of classification criteria is not exhaustive. Other aspects, such as device aspect ratio, presence of housing, total device weight, working frequency range or output voltage range might be used for classification purposes as well.

3.2.1 Energy extraction principle

Electromechanical energy harvesters employ a range of design principles in order to extract and convert the mechanical energy into electricity. Aside of the choice of the energy transduction physical principle, the design options include using a mechanical resonator, which works as a mechanical energy accumulation element and amplifies the displacement amplitude of the harvester when excited close to the resonant frequency. The electromechanical harvesters therefore can be classified by the type of resonator used, or its absence:

**Non-resonant devices**

Electromechanical energy harvesters that are not designed to utilize the resonance amplification effect, are mostly pulse-excited or strain-based devices exploiting the direct deformation of the transducer, caused by the advantageous placement of the harvester on the host structure. The design of these devices can be fairly simple, as they completely omit the mechanical oscillator. Non-resonant harvesters [20] also do not affect the dynamic behaviour of the host structure as significantly as the resonant devices.

**Direct resonators**

Many harvesters employ a mechanical oscillator, connected to the frame of the harvester, and therefore also to the host structure through a stiffness element. By an appropriate tuning of the stiffness constant and the seismic mass weight the natural frequency of the oscillator can be tuned to match a frequency of an exploitable component present in the excitation spectrum [21]. This leads to the resonance amplification of the seismic mass displacement, accumulating more mechanical energy in the oscillator and increasing the power output of the harvester. The seismic mass weight of the energy must be negligible compared to the weight of the hosting structure, as its oscillation introduces a dynamic feedback into the structure. This effect is however being exploited in oscillation dampers, where the oscillations of the host structure on given frequency are supressed by the function of an accordingly tuned additional oscillator.
**Parametric resonators**

Parametric resonators provide another interesting option to the direct resonance mechanism commonly used in resonant-based vibration energy harvesting. A parametric resonator (Figure 6) exploits a time dependent modulation of some of the system parameters (stiffness, damping, or moment of inertia) at a frequency equal to twice the natural frequency of the system [22]. Parametric excitation of the system is usually orthogonal to the plane of the oscillator movement. A system driven into parametric resonance can reach over an order of magnitude higher power output than the same system working in direct resonance [23].

![Figure 6 Parametrically excited pendulum](image)

### 3.2.2 Stiffness linearity

**Linear stiffness**

Many inertial harvesters are designed assuming linear properties of the stiffness [24]. Even though in reality this might not be entirely true in the whole range of the possible harvester seismic mass displacements (e.g. due to displacement limiters, magnetic springs etc.), the linear approximation of the real device allows for convenient and easy modelling and analysis of the device performance, exploiting e.g. the superposition principle for output power predictions.

**Nonlinear stiffness**

In some applications it is desirable to exploit a nonlinearity in the stiffness in order to increase the bandwidth of resonant harvesters, making it able to cope with the variations in the excitation frequency due to skewing of the amplitude-frequency characteristics [25]. However, the nonlinearity in the stiffness can trigger the system to behave chaotically under certain excitation conditions.
3.2.3 Type of movement

Linear trajectory

Devices with the linear motion of the internal element [26] fall within this category. Many of vibration energy harvesters with linear trajectory and large displacements employ nonlinear magnetic stiffness elements [27]. Some cantilevered harvesters can be included in this category as well due to very small displacements that can be approximated by a line.

Circular trajectory

Pendulum type harvesters and miniaturized conventional generators exploit oscillatory or continuous movement of the internal parts along a circular or circular segment trajectory [28]. While some devices allow for continuous rotation, others have maximum displacement limitation. Circular trajectory allows for compact devices, especially with low natural frequencies.

Other

Few electromechanical energy harvesters exploit an internal trajectory that can’t be described by the previous two types. This category includes the harvester design with free mass moving inside a spherical cavity [29] or piezoelectric cantilever harvesters with large displacements.

3.2.4 Number of DOF

By the number of degrees of freedom the electromechanical energy harvesters utilize in order to convert the electromechanical energy to electricity there are two main categories:

Single degree of freedom

Devices, which can capture and transduce vibrations or deformation into electricity in a single working direction [30]. This group contains both harvesters with linear trajectory of the proof mass and pendulum-type harvesters. Dynamics of these harvesters can be described by a single second order differential equation.

Multiple degrees of freedom

Electromechanical energy harvesters containing more than one proof mass [31], or a single proof mass that moves in multiple directions [32] fall into this category. Multiple degrees of freedom are exploited either to harvest energy from multi-directional excitation, or to extend the bandwidth of the device by using more proof masses with different natural frequency tuning. Arrays of cantilevered harvesters or frequency up-conversion mechanisms fall into this category.
3.3 ELECTROMECHANICAL ENERGY HARVESTERS MODELLING

There are two common approaches used for modelling and analysis of the electromechanical energy harvesting devices. Depending on the preferences, experience and compatibility with models of other interconnected systems (power management and storage, host structure) the following modelling techniques are employed:

3.3.1 Equations of motion

The electromechanical energy harvesters generally can be seen as spring mass damper mechanical systems with one (Figure 7) or more degrees of freedom.

\[ \frac{d}{dt} \left( \frac{dE_k}{dq_j} \right) - \frac{dE_k}{dq_j} + \frac{dE_b}{dq_j} + \frac{dE_p}{dq_j} = -\frac{dA}{dq_j} = -Q_j \]  

where \( j = 1 \ldots n \) in generalized coordinates \( q_j \) denotes each of \( n \) degrees of freedom of the device. \( E_k, E_b, \) and \( E_k \) denote kinetic, dissipative and stiffness energy of the system, respectively. \( A \) is mechanical work and \( Q_j \) stands for generalized excitation force. Each degree of freedom then adds one differential equation of motion to the set. Depending on the design of the device, the equations might or might not be coupled. This approach is the most commonly used method for modelling kinetic energy harvesters [33], [34].

3.3.2 Exploiting mechanical-electrical analogy

Another option is to exploit the analogy between Kirchhoff’s laws and Newton’s laws. Mapping the mechanical variables onto electrical one allows characterizing the whole system in the electrical domain [35]. This can be advantageous especially if the power management electronics and energy storage is being analysed together with the harvester design [36].
There are two widely used mappings (Figure 8) of mechanical variables onto electrical ones: impedance analogy (force onto voltage) [37], and rotational analogy (force onto current) [38].

The analogous differential equations for the equation of motion, impedance analogy and rotational analogy, respectively, assuming a system with one degree of freedom are:

\[
\begin{align*}
    m\ddot{q} + b\dot{q} + kq &= F \\
    L\frac{di}{dt} + Ri + \frac{1}{C}\int i\,dt &= u \\
    C\frac{du}{dt} + \frac{1}{R}u + \frac{1}{L}\int u\,dt &= i
\end{align*}
\]

The analogous elements used in these equations are summarized in Table 2.

Table 2 Analogous elements for different mechanical-electrical mappings

<table>
<thead>
<tr>
<th>Mechanical property</th>
<th>Electrical property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force</td>
<td>Voltage, Current</td>
</tr>
<tr>
<td>Velocity</td>
<td>Current</td>
</tr>
<tr>
<td>Mass</td>
<td>Inductance, Resistance</td>
</tr>
<tr>
<td>Damping</td>
<td>Resistance</td>
</tr>
<tr>
<td>Compliance</td>
<td>Capacitance</td>
</tr>
</tbody>
</table>
4 METHODOLOGY

Based on the goal definition and on the state-of-art review, it was decided to further investigate feasibility of the inertial electromechanical energy harvester, based on the electromagnetic energy conversion principle. This principle allows fairly straightforward implementation for low frequency devices, which will be beneficial for harvesting energy from human activities, where low excitation frequencies can be expected. The downside of the selected principle lies in rather low induced voltage, making the pick-up coil design a crucial part of the development to ensure usable voltage levels.

In the first step the preliminary analysis supporting or challenging the feasibility of selected energy conversion method needs to be performed. Real-life acceleration measured on a limited number of testing human subjects is to be used as energy inputs to the simulation model. The model parameters are obtained from CAD and FEM software, with the main design parameters decided by the physical constrains placed on the harvester with respect to its maximum weight and dimensions.

Next, an algorithm exploiting a principal component analysis of the acceleration is developed to process the future measurement data. Its purpose is to find the principal direction of acceleration on selected frequency, allowing for finding the most feasible orientation of the kinetic energy harvester working axis or plane in given application. A secondary purpose of the algorithm is to correct misalignments of the accelerometer during measurements to mitigate a possible source of bias in the statistical analysis.

Following the results of the first analysis, a larger scale acceleration measurements are conducted to find the statistical properties of the acceleration in the human head area. The data is processed to ensure its homogeneity and employed to model the acceleration on the head of the harvester perspective user population in order to find the theoretical power output limits of a linear kinetic energy harvester device.

Based on the results of the statistical analysis a feasibility of development of an actual kinetic energy harvester design is evaluated, and the modelling and simulation phase of the harvester development process is commenced. The design is drafted and optimized utilizing iterative simulations together with CAD and FEM modelling. An optimization algorithm for the pick-up coil design is developed during this phase to maximize the electromechanical coupling. Promising results of the model allow for taking a further step, represented by an in-house manufacture of the prototype and its testing in the laboratory.

Further tests are then conducted in the real-life conditions, where the overall performance of the novel harvester design and its feasibility to power up wearable or biomedical MEMS applications is evaluated during different activities and in various placements on the human body.
5 PRELIMINARY ANALYSES

The preliminary feasibility analysis represents the first step in the development of a new energy harvester for powering up biomedical and wearable MEMS applications.

The example application to be powered up by the developed kinetic energy harvester is represented by a cochlear implant of new generation. Its power requirements of approximately 150 μW of average continuous power are used to define the lowest expected power output of the harvester.

Acceleration during different user activities was monitored to determine the feasibility of different motions for excitation of the inertial energy harvester located in the head area, close to the cochlear implant. It was found, that most activities except for walking or jogging do not provide stable and exploitable levels of acceleration for the purposes of kinetic energy harvesting.

In order to calculate the energy necessary to supply the power to the cochlear implant for 16 hours a day, a ten months-long measurement of exploitable daily user activity was conducted (Figure 9). The data show the walking habits of an average company employee, commuting to work during the work days and occasionally going for trips during weekends.

![Figure 9 measured daily number of steps during ten months](image)

Statistical processing of this data revealed, that the average number of steps per day reached 6559 steps. Mode of the dataset, 5868 steps per day, represents the middle point of the most numerous class.

The results indicate, that average person in the productive years with semi-active life style spends only about 52 minutes a day walking, which is an activity, that can be used to harvest the energy from. The harvester would therefore have to provide 2.77 mW of average power during the assumed 52 minutes of user daily walking time, to completely satisfy the requirements of the selected application. Furthermore, this calculation does not cover the inevitable energy losses in the power management electronics and storage, which are necessary elements of the energy harvesting solution.
To get more precise results from further analyses, acceleration in the head area of five different users was measured during walking at natural and fast speeds. This data was then fed as an input to the harvester model. The model was based on a harvester design with one degree of freedom and nonlinear mechanical springs. The size, mass and magnetic circuit parameters of the model were obtained from FEM and CAD simulations (Figure 10).

The simulation model is built in Matlab/Simulink with the use of well-known motion equation of the mass-spring-damper system with one degree of freedom.

A sensitivity analysis using both harmonic and real-life excitation was performed with the goal of improving the critical parameters of the model to obtain higher power output while keeping the harvester main dimensions and displacement limits. Improved model was then fed with the measured data and the harvested power on load was observed and recorded.

The results showed large variance between different users, indicating a need for larger measurement set and for determination of the user parameters, affecting the harvester power output. Final values of the average harvested power on 6.6 kΩ resistive load are shown in Table 3.

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>Harvested Average Power [µW]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal Walk</td>
</tr>
<tr>
<td>1</td>
<td>81</td>
</tr>
<tr>
<td>2</td>
<td>84</td>
</tr>
<tr>
<td>3</td>
<td>238</td>
</tr>
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<td>4</td>
<td>61</td>
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<tr>
<td>5</td>
<td>228</td>
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</tbody>
</table>
6 SIGNAL PROCESSING ALGORITHM

During the initial measurements and analyses the question of ensuring the same orientation and alignment of the wireless accelerometer on different subjects during further planned measurements arose. Furthermore, it was found, that energy harvesting literature does not thoroughly consider the problem of the accelerometer orientation during measurements. As most of the inertial energy harvesters are devices with one degree of freedom and a single linear working axis, their correct orientation on the host system is crucial in order to maximize their power output.

An algorithm utilizing the principal component analysis of the acceleration measured in three orthogonal axes was therefore developed to solve these issues. After taking care of the uniform sampling rate of the data, the FFT is calculated. Since the measured acceleration waveforms usually contain multiple frequency components, the frequency component of interest is identified. Other frequency components are filtered out in order not to affect the further analysis.

The filtered data in time domain is then subjected to principal component analysis, which identifies the three orthogonal directions, along which the principal components of the acceleration are located (Figure 11). That means that the highest magnitude of acceleration on the selected frequency of interest is located along the first principal axis, while the smallest magnitude will be found along the third axis. It needs to be noted, that different frequency components of the acceleration may also have different principal axes depending on the source of the vibrations, so the obtained principal axes might not be aligned with the principal axes of the unfiltered dataset.

![Figure 11 Original (left) and filtered (right) acceleration measurement data in Cartesian space, with identified principal axes (in red)](image)

The method was used on measured real-life data from several different applications to illustrate the harvested power improvements. The power output comparison was then simulated, using a generic spring-mass-damper model of a linear kinetic energy harvester with a single degree of freedom. The linear 1 dof harvester model was built with Q factor of 50 and viscous damping force evenly distributed between the mechanical and electrical damping. The weight of the simulated proof mass was 10 grams and the harvester was tuned to the frequency of interest of each application.
The axis with the highest magnitude of the acceleration component at the frequency of interest was used for the excitation of the harvester model with the measured data. That ensures obtaining the maximum power output with the harvester aligned with the measurement axes of the accelerometer. Then the transformed data was used for excitation, simulating aligning the working axis of the harvester with the calculated principal axis of acceleration.

Table 4 Simulated improvements in the power output after aligning the harvester working axis with the principal component of the excitation acceleration.

<table>
<thead>
<tr>
<th>Measured system</th>
<th>Frequency of Interest (Hz)</th>
<th>Highest measured acceleration component (g)</th>
<th>First principal component of acceleration (g)</th>
<th>Harvester power output ratio (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human walking - wrist</td>
<td>1.12</td>
<td>0.269</td>
<td>0.427</td>
<td>2.72</td>
</tr>
<tr>
<td>Human walking – head</td>
<td>2.19</td>
<td>0.397</td>
<td>0.423</td>
<td>1.14</td>
</tr>
<tr>
<td>Unspecified technical system</td>
<td>62.47</td>
<td>0.188</td>
<td>0.237</td>
<td>1.40</td>
</tr>
<tr>
<td>CNC machine</td>
<td>66.7</td>
<td>0.083</td>
<td>0.099</td>
<td>1.41</td>
</tr>
</tbody>
</table>

Results (Table 4) indicate, that in many cases the measured axes of acceleration are not perfectly aligned with the principal axes of the acceleration. Therefore a simple rotation of the harvester without changing any other parameters can significantly improve the generated power output.

The described method can also be used to ensure the uniform alignment of the accelerometer while measuring acceleration while walking for different people. This can be done by adopting an assumption that the principal components of the dominant acceleration peaks will be found along the same directions normal to the lateral, transversal and sagittal plane of the human body for all the people.
The acceleration measurements and processing were split into two parts. The first phase served for comparison of different wireless accelerometer fixation styles and to identify the possible measurement subjects’ parameters that could be affecting the measured data. 30 different testing subjects were measured while walking at natural speeds on smooth and level path. The basic parameters of the subjects, such as age, weight, height and sole thickness of shoes they were wearing during the measurements, were recorded. Measured acceleration was analysed in the frequency domain, where frequencies and magnitudes of dominant acceleration peaks in different measurement axes were compared for different sensor fixation styles and then against the recorded user parameters.

Calculating the correlation coefficients between the recorded frequencies and magnitudes of first dominant acceleration peak in the axis with highest dominant acceleration magnitude indicated, that the recorded acceleration is not linearly dependent on any of the recorded parameters with one possible exception, as correlation coefficient between magnitude of the dominant acceleration peak and the sole thickness reaches value 0.4.

Since the first phase of the measurements have not shown a correlation between subjects’ parameters and measured frequencies and magnitudes, an alternative statistics-based approach was investigated during the second phase of signal acquisition and analysis. Two more sets of measurements were obtained, one of them by measuring a single testing subject multiple times, the other one measuring multiple subjects, each of them once. All the measurements were again conducted while the subjects were walking on flat level path at their respective natural speeds.

Then the data was treated using algorithm introduced in previous chapter, dynamically parsed into ten intervals in frequency domain (Figure 12), and finally reduced to ten frequency, magnitude and initial phase data triplets in each of the three orthogonal axes.

![Figure 12 Example of measured spectra in three axes with parsing intervals](image)
The preliminary analysis reveals three exploitable frequency bands providing a median of average harvested electrical power over 100 µW contained within the spectra. These bands are centred on frequencies that correspond to the most common values of first and third harmonic frequencies in Z axis, and to the second harmonic frequency in the X axis. As was shown in the previous chapters, the acceleration in Y axis contains generally lower magnitudes on the same frequencies compared to X and Z axes. The simulated harvested power results in Y axis are therefore also comparably worse than the other two axes. The design parameter Q is set in such a way, so that it maximizes the median of average harvested specific power for each of the three investigated frequencies. Figure 13 then shows the histograms and empirical cumulative distribution functions of the obtainable specific power for given model population and for selected feasible combinations of harvester working axis and working frequency (only X and Z, axis Y is omitted due to low feasibility).

![Figure 13 Estimated histograms (left) and cumulative density functions (right) of average harvested specific power for 10000 samples model population, with harvester tuned to different favourable frequencies in different axes.](image)

The empirical approximation of the complementary cumulative distribution function (reliability function) depicts the least average power that will be harvested for a given percentage of the users from the model population. Each of the following figures (Figure 14, Figure 15) depict the reliability function plots for one static and one variable design parameter in a single selected axis. This analysis can be used as a tool for improving the harvester design and for evaluating its performance, so that the lowest acceptable power is certain to be harvested by given percentage of the user population.

The reachable specific power results seem quite optimistic for the harvester being tuned to work around the dominant acceleration frequencies in each working axis. It should be noted, though, that the presented results are purely theoretical, and that the real-life harvester will have to deal with technological and spatial limitations, as well as with using a non-ideal energy transducer with nonzero inner impedance. All these factors will introduce additional energy losses into the system.
Moreover, theoretically the most promising frequency tunings are in practice difficult to exploit by a linear device due to associated large displacements of the oscillating proof mass, bringing challenges in a form of a stiffness implementation and an overall size of the device. However, exploiting higher frequencies around 3 Hz and more does not result in as high power outputs, as the lower ones. It might thus be challenging to cover the power requirements of the intended electronic application solely by exploiting the third and higher harmonic frequencies of human walking while keeping the energy harvester sufficiently small and lightweight.

The kinetic energy harvester for frequencies associated with human behaviour must overcome these challenges either by employing a nonlinear stiffness solution, or by a novel design, where the large displacements are not an issue. Such a design could take advantage of harvesting the kinetic energy from multiple directions, effectively increasing the output power, while keeping the device weight within the acceptable limits.
8 NOVEL ENERGY HARVESTER DESIGN

The previous analyses and studies indicated the feasibility of using the electromechanical energy harvesting principle for powering up MEMS electronic wearable or biomedical devices. This chapter deals with development of the kinetic energy harvester, which would be usable for harvesting human power while complying with the size and weight requirements. The target application for the harvester remains the aforementioned cochlear implant, even though the design may be universal enough to be used also for other applications with similar excitation characteristics.

The presented harvester design is based on so-called Tusi couple, which is a mathematical device proposed in 13th century by a Persian mathematician Nasir al-Din al-Tusi. The basic point of the device lies in exploiting a rolling motion of a circle inside a larger circle. The points on the diameter of the smaller circle generally travel along hypocycloidal paths. However, if the ratio of the circles’ diameters is 2:1, as in this mechanism, the hypocycloids blend with straight lines denoting the diameter of the larger circle.

This principle was exploited in the novel low frequency kinetic energy harvester design with one degree of freedom, which utilizes unlimited displacement of the proof mass and nonlinear behaviour of the pendulum-type harvester, together with springless design and compact dimensions. Furthermore, due to the nature of the proof mass movement, this design is capable of harvesting vibrations in one working plane, as opposed to conventional designs working with a single vibrations direction. An iterative principle was employed to obtain the final variant of the device, featuring 12 permanent magnets, and two coils fixed to the lids of the harvester (Figure 16).

Figure 16 Rolling mass harvester geometry and final design

A greedy search algorithm was utilized to expand the coil in the direction of the highest increment of the magnetic flux change, one turn per iteration. The algorithm stops when the cost function, defined as power on load of a linearized model of the energy harvester, reaches its maximum. The coil configurations were tested for different load resistances to compare the differences the obtained optimal coil configurations. Dimensions (height, inner and outer diameter) of the coil were then implemented into the full simulation model of the harvester.
Simulated performance of the prototype showed promising results (A5), so it was decided to manufacture and test a functional up-scaled prototype of the device. The prototype (Figure 17) was made using conventional manufacturing technology, with manually wound coreless copper coil. Testing of the prototype was performed on a linear drive, using wireless accelerometer to record the excitation waveform.

The measurements showed very good agreement with the model (Figure 18) and promising performance in context of evaluating the usability of this harvester for wearable or biomedical applications.

Considering the presented prototype dimensions 50x50x20mm and the simulated voltage output on 2kΩ resistive load, the simulated Normalised Power Density (Figure 19) of the harvester reaches values up to 230 μW/g2/cm3 depending on the frequency of harmonic excitation acceleration and the degree of nonlinear behaviour.
A comparison with other harvesters working below 10 Hz is shown in Table 5. This shows the Tusi couple design is outperforming all comparable harvesters with a single exception, which is, however, working at almost twice the frequency.

Table 5 Comparison of competing low frequency harvesters’ performance

<table>
<thead>
<tr>
<th>Reference</th>
<th>Size [mm]</th>
<th>Frequency [Hz]</th>
<th>Acceleration [g]</th>
<th>Power output [μW]</th>
<th>NPD [μW/cm³/g²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>[39]</td>
<td>20x45x?</td>
<td>2</td>
<td>0.4</td>
<td>40</td>
<td>?</td>
</tr>
<tr>
<td>[40]</td>
<td>ø17x55</td>
<td>2</td>
<td>0.5</td>
<td>300</td>
<td>96</td>
</tr>
<tr>
<td>[41]</td>
<td>ø 12x80</td>
<td>6</td>
<td>0.5</td>
<td>4840</td>
<td>2140</td>
</tr>
<tr>
<td>[42]</td>
<td>34x34x18</td>
<td>8</td>
<td>0.5</td>
<td>430</td>
<td>83</td>
</tr>
<tr>
<td>[43]</td>
<td>54x46x15</td>
<td>9.25</td>
<td>0.5</td>
<td>550</td>
<td>59</td>
</tr>
<tr>
<td>This work</td>
<td>50x50x20</td>
<td>3.45</td>
<td>0.4</td>
<td>1400</td>
<td>178</td>
</tr>
</tbody>
</table>

The simulated power outputs demonstrate the significant potential of this harvester design for use in human power energy harvesting and other very low frequency applications. Harvesters based on the Tusi couple could also present a viable alternative to current microgenerators used in wristwatches. The energy transduction method is not limited to electromagnetic induction, a similar device could be designed that uses a piezoelectric transducer that could be excited by a variable magnetic force between a magnet, fixed on the piezoelectric transducer, and the magnets on the moving proof mass.
9 EXPERIMENTAL RESULTS

An additional set of measurement data was obtained using a single test subject, measuring the power on load, delivered by the harvester prototype placed in one of four different locations on the human body during various defined activities. Head, belt, wrist and ankle were selected as feasible placements of the harvester for testing. Most of the works published by other researches use one or more of these particular fixation points, making this selection convenient for possible direct comparison with other designs.

The recorded measurements, as shown in Table 6 confirmed great variance in the output power depending both on the activity performed and on the placement of the harvester.

Table 6 RMS values of voltage and average power on load for different placements and activities

<table>
<thead>
<tr>
<th>Harvester Placement</th>
<th>Activity</th>
<th>RMS Voltage on load [V]</th>
<th>Average Power on load [μW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>Walking</td>
<td>0.34</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>Walking down the stairs</td>
<td>0.24</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>Walking up the stairs</td>
<td>0.36</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>Running</td>
<td>0.5</td>
<td>122</td>
</tr>
<tr>
<td></td>
<td>Jumping</td>
<td>0.4</td>
<td>81</td>
</tr>
<tr>
<td></td>
<td>Nodding</td>
<td>0.11</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Shaking head</td>
<td>1.35</td>
<td>905</td>
</tr>
</tbody>
</table>

Figure 20 Voltage on load and acceleration in the relevant axes with harvester placement on head during the second measurement set.
These results indicate two main points. First, the harvester is capable of delivering sufficient power output to directly power up some of the wearable or biomedical applications. Depending on the activity level of the potential harvester user, harvester placement, and application requirements, this device might be able to cover even a daily power consumption of an electronic MEMS device by accumulating the energy harvested during the user active time. Second, the current design will mostly not be able to provide enough energy to power up the originally assumed cochlear implant. The head area of the user is the least feasible location for kinetic energy harvesting purposes, which shows also in the measurement results. However, the overall usability of the device for other wearable and biomedical MEMS applications was confirmed.
CONCLUSIONS

This thesis deals with the feasibility study and the development of an energy harvesting power source for MEMS applications, with the special focus on wearable and biomedical electronic devices. After considering the available energy sources in the ambience of a human body, an electromechanical inertial energy harvester was selected as a potentially feasible solution for the defined problem situation of current unavailability of maintenance-free power source for wearable electronics.

The initial feasibility study was performed utilizing data from a ten months-long single person measurements and from five short-term measurements of different testing subjects. Promising results of the study, indicating that a useful power in the range of tens to hundreds of microwatts can be generated by a potentially implantable kinetic energy harvester model based on electromagnetic induction physical principle, showed the feasibility of the selected approach.

A signal processing method based on the principal component analysis of the excitation acceleration was then introduced. Its use lies either in improving the power output of inertial energy harvesters by alignment of their working axis with a first principal axis of the selected acceleration frequency component, or in a correction (realignment by rotation) of the measurement data to prevent measurement bias caused by misalignment of the sensor on the different measured specimen during the measurements.

Multiple sets of acceleration measurements were obtained and the data was processed to determine the properties of the acceleration obtainable from human activities, such as walking. Statistical models of acceleration in the human head area during walking were then developed in order to predict the limits of inertially excited energy harvester performance, placed in this location. It was observed that the parameters of the acceleration frequency components follow normal distributions, which can be exploited in the modelling and simulations of large harvester user populations. The simulation results further confirmed the usability of inertial energy harvester for ultra-low-power applications in the head area, so a novel concept of one degree of freedom kinetic energy harvester was introduced to exploit the observed acceleration waveforms from two orthogonal directions at the same time.

The development process was conducted with the intention of integrating the harvester as close to the powered up application as possible. Parameters and working directions of the harvester were designed utilizing the knowledge obtained from the statistical analyses and modelling. An original design of the harvester based on Tusi-couple mechanism was presented and its dynamics derived for modelling purposes. Strongly nonlinear softening characteristics of this harvester together with its unlimited circular trajectory are beneficial for applications with very low frequency of excitation acceleration and multidimensional excitation, such as human power harvesting. Comparison of the simulated results of an experimentally verified model with other low frequency harvester designs shows
superiority of the novel design with respect both to the power output and to the normalized power density performance metric.

The testing of the prototype on the various locations on human body during different recorded activities showed good potential of the device for powering some of the ultra-low power sensors. The highest average power on load of 6.5 mW was recorded while the harvester was fixed on the ankle of a violently shaking leg. The average power obtained from walking by the harvester fixed on the human head, with the working plane normal to the direction of walking reached up to 56 μW. Same activity, but harvester placement on the ankle resulted in 1.4 mW of average power on load, harvested through the duration of walking.

Aside for the focus on the human power harvesting, the harvester design attracted considerable attention within the energy harvesting industry, and over the time of writing this thesis one prototype is being evaluated by a UK-based company, which uses energy harvesting devices for powering up the wireless tags for asset monitoring.

This work presents methodology, models and physical product, which can be further developed and improved by good engineering practices. The outputs of this research are deemed to have a significant potential for larger scale utilization in the near future both in wearable and other industrial applications.
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Development of kinetic energy harvesting power sources for low excitation frequency applications
ABSTRACT

This thesis deals with the development of an independent power source for modern low-power electronic applications. Since the traditional approach of powering small applications by means of primary or secondary batteries lowers the user comfort of using such a device due to the necessary periodical maintenance, the novel power source is using the energy harvesting approach. This approach means that the energy is scavenged from the ambience of the powered application and converted into electricity in order to satisfy the power requirements of the newest MEMS electrical devices.

The target applications for the new energy harvesting device are seen in wearable and biomedical electronic devices. That places challenging requirements on the energy harvester, as it has to harvest sufficient energy from the ambience of human body, while fulfilling practical size and weight constraints.

After the preliminary requirements setting and analyses of possible sources of energy a kinetic energy harvesting principle is selected to be employed. A series of measurements is then conducted to obtain and generalize the kinetic energy levels available in the human body during various activities. A novel design of kinetic energy harvester is then introduced and developed into the form of a functional prototype, on which the actual performance is evaluated. Aside from the actual new harvester design, the thesis introduces an original way of improving the power output of the inertial energy harvesters and provides statistical data and models for the human energy harvesting usability prediction.
ABSTRAKT

Tato práce se zabývá vývojem nezávislého elektrického zdroje pro moderní nízkopříkonové elektrické aplikace. Protože tradiční řešení napájení drobných spotřebičů s využitím baterií či akumulátorů snižuje uživatelský komfort kvůli potřebě pravidelné údržby, navrhovaný zdroj využívá principu energy harvesting. Tento princip spočívá v získávání energie přímo z okolního prostředí napájené aplikace a její přeměně na energii elektrickou, která je dále využita pro napájení moderních MEMS (mikroelektromechanických) zařízení.

Potenciální aplikací vyvíjeného zdroje je především moderní nositelná elektronika a biomedicínské senzory. Tato oblast využívá ovšem klade zvýšené nároky na parametry generátoru, který musí zajistit dostatečný generovaný výkon z energie, dostupné v okolí lidského těla, a to při zachování prakticky využitelné velikosti a hmotnosti.

Po stanovení předběžných požadavků a provedení analýz vhodnosti dostupných zdrojů energie ke konverzi byla k využití vybrána kinetická energie lidských aktivit. Byla provedena série měření zrychlení na lidském těle, především v místě předpokládaného umístění generátoru, aby bylo možno analyzovat a generalizovat hodnoty energie dostupné ke konverzi v daném umístění. V návaznosti na tato měření a analýzy byl vyvinut inovativní kinetický energy harvester, který byl následně vyroben jako funkční vzorek. Tento vzorek byl pak testován v reálných podmínkách pro verifikaci simuláčního modelu a vyhodnocení reálné použitelnosti takového zařízení. Kromě samotného vývoje generátoru je v práci popsán i originální způsob zvýšení generovaného výkonu pro kinetické energy harvestery a jsou prezentována statistická data a modely pro predikci využitelnosti kinetických harvesterů pro získávání energie z lidské aktivity.