Kaunas University of Technology

Faculty of Mechanical Engineering and Design

Research of Piezoelectric Vibration Energy Harvesting Intended for Powering Sensors of a Pallet Lifting and Storing System

Master's Final Degree Project

Stewen Naano

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Supervisor

Kaunas, 2019

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Mechatronics (6211EX017)

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Declaration of Academic Integrity

I confirm that the final project of mine, Stewen Naano, on the topic „Research of Piezoelectric Vibration Energy Harvesting Intended for Powering Sensors of a Pallet Lifting and Storing System" is written completely by myself; all the provided data and research results are correct and have been obtained honestly. None of the parts of this thesis have been plagiarised from any printed, Internet-based or otherwise recorded sources. All direct and indirect quotations from external resources are indicated in the list of references. No monetary funds (unless required by Law) have been paid to anyone for any contribution to this project.

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Kaunas University of Technology

Faculty of Mechanical Engineering and Design

Task of the Master's final degree project

Given to the student – Stewen Naano

Title of the project – Research of Piezoelectric Vibration Energy Harvesting Intended for Powering Sensors of a Pallet Lifting and Storing System

(In English)

Pjezoelektrinio vibracinio energijos generavimo metodo, pritaikomo palečių kėlimo ir saugojimo sistemos jutikliuose, tyrimas.

(In Lithuanian)

1. Aim and tasks of the project –

Aim is to investigate potential use and performance of a piezoelectric vibration energy harvester as micropower source for sensors integrated in specified industrial pallet lifting and storing system (PLSS). Tasks: 1. To review literature and analyse state of the art in mechanical energy harvesting with focus on piezoelectric vibration energy harvesting technologies. 2. To describe the target industrial pallet lifting and storing system, its configuration and operational conditions to identify possibilities of using one or several piezoelectric vibration energy harvesters within the specified geometrical constraints of the system. 3. To experimentally investigate vibration energy harvesting with commercially available piezoelectric transducers in order to determine dynamic excitation conditions required for harvesting electrical energy levels that are usable for powering sensors of the targeted system. 4. To propose recommendations to rationally adapt piezoelectric vibration energy harvesters to components of the pallet lifting and storing system in order to increase power output.

2. Initial data of the project –

Initial data regarding piezoelectric energy harvesting technologies for the project is revised and analysed during literature review phase where other half of known application specific information is obtained from PLS system, its working characteristics regarding components, operational speeds of the system, dimensions of parts and complete assembly.

3. Main requirements and conditions –

Requirements for experimental investigation: an experimental setup for testing of vibration energy harvesters. Conditions for experimental setup: capability to simulate same excitation speeds, positioning and plucking characteristics of the transducer as in specified PLS systems.

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	(Name, Surname)	*(Signature)*	*(Date)*
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Stewen Naano. Research of Piezoelectric Vibration Energy Harvesting Intended for Powering Sensors of a Pallet Lifting and Storing System. Master's Final Degree Project, supervisor DSc Rolanas Dauksevicius; Faculty of Mechanical Engineering and Design, Kaunas University of Technology.

Study field and area (study field group): Production and Manufacturing Engineering (E10), Engineering Sciences (E).

Keywords: lifting and storing system, energy harvesting, piezoelectric transducer, contactless magnetic plucking, mechanical frequency up-conversion.

Kaunas, 2019. 59 pages.

Summary

Research project is concerned with piezoelectric vibration energy harvesting intended for powering sensors of a lifting and storing system. A concept of energy-autonomous lift platform was proposed for detailed investigation by a manufacturer of lifting and storing systems with the aim to conduct feasibility study regarding application of piezoelectric vibration energy harvesters in heavy-payload pallet lifting and storing system in order to determine the viability of proposed energy-autonomy concept. An extensive literature review on the state of the art in mechanical energy harvesting was carried out, revealing that contactless excitation via magnetic plucking of piezoelectric transducers may be considered as a suitable vibration energy harvesting method within the scope of current project. Specified pallet lifting and storing system was examined in detail as the targeted use case for the energy harvesters in the context of implementation of energy-autonomous lift platform. Experimental investigation of the performance of the selected piezoelectric vibration energy harvesters was conducted by reproducing the actual excitation and geometrical conditions to be expected when deploying the harvesters in the specific pallet lifting and storing system. Final proposal excludes piezoelectric vibration energy harvesting because it was demonstrated to underperform under given application-specific operational conditions. As energy-autonomous concept in heavy storing system conditions proved to be insufficient, proposal was made to target low-payload storing systems instead. Although energy-autonomous solution was not achieved in heavy pallet lifting and storing system, alternative cost-effective near-energy-autonomous solutions for heavy storing systems were proposed.

Stewen Naano. Research of Piezoelectric Vibration Energy Harvesting Intended for Powering Sensors of a Pallet Lifting and Storing System. Magistro baigiamasis projektas, DSc Rolanas Dauksevicius; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas.

Studijų kryptis ir sritis (studijų krypčių grupė): Gamybos inžinerija (E10), Inžinerijos mokslai (E).

Reikšminiai žodžiai: kėlimo ir sandėliavimo sistema, energijos surinkimas, pjezoelektrinis keitiklis, bekontaktis magnetinis sužadinimas, mechaninis dažnio didinimas.

Kaunas, 2019. 59 Puslapių.

Santrauka

Mokslinių tyrimų projektas yra apie pjezoelektrinį vibracijos energijos surinkimą, skirtą kėlimo ir sandėliavimo sistemos jutiklių maitinimui. Energiją perdirbančios kėlimo ir sandeliavimo sistemos koncepcija buvo pasiūlyta bendrovės užsiimančios kėlimo ir sandeliavimo sistemų gamyba. Tyrimo tikslas yra įvertinti pjezoelektrinio vibracijos energijos surinkimo ekonominį pagrįstumą didelio svorio padėklų kėlimo ir sandėliavimo sistemoje, siekiant nustatyti pasiūlytos koncepcijos perspektyvumą. Išsami literatūros apžvalga apie naujausias mechaninės energijos surinkimo technologijas atskleidė, kad bekontaktis magnetinis pjezoelektrinių keitiklių sužadinimas gali būti tinkamu vibracijos energijos surinkimo metodu siūlomam projektui. Turima padėklų kėlimo ir sandėliavimo sistema buvo tikslingai išnagrinėta, kaip pjezoelektrinio vibracijos energijos surinkimo pritaikymo atvejis, realizuojant energiją perdirbančios kėlimo platformos koncepciją. Eksperimentinis pjezoelektrinės vibracijos energijos surinkimo sistemos charakteristikų tyrimas buvo atliktas, simuliuojant sužadinimo ir geometrines sąlygas, numatomas pritaikius pjezoelektrinę vibracijos energijos surinkimą turimoje padėklų kėlimo ir sandėliavimo sistemoje. Galutinis pasiūlymas neįtraukia pjezoelektrinės vibracijos energijos surinkimo sistemos, nes buvo parodyta, kad dėl esamos koncepcijos geometrinių apribojimų bei bekontakčio magnetinio pjezoelektrinio keitiklio sužadinimo sąlygų, pjezoelektrinis vibracijos energijos surinkimas yra nepakankamai veiksmingas nagrinėjamam projektui. Kadangi pjezoelektrinis energijos surinkimas didelio svorio krovinių kėlimo ir sandėliavimo sistemų sąlygomis pasirodė nepakankamas, buvo pasiūlyta taikyti tokio tipo energijos surinkimą mažo svorio krovinių kėlimo ir sandėliavimo sistemose. Nors didelio svorio krovinių kėlimo ir sandėliavimo sistemoje nepavyko pritaikyti pjezoelektrinio energijos perdirbimo sprendimo, tačiau, buvo pasiūlyta alternatyvių, ekonomiškai efektyvių, energijos perdirbimo sprendimų skirtų sunkių krovinių kėlimo ir sandėliavimo sistemoms.

Table of contents

List of Figures

List of tables

List of abbreviations and terms

Terms:

EH – energy harvesting.

PV – photovoltaic.

MEH – mechanical energy harvester.

VEH – vibration energy harvester.

PZT – piezoelectric material.

SMA – shape memory alloy.

TENG – triboelectric nanogenerator.

MFU – mechanical frequency up-conversion.

P-VEH – piezoelectric vibration energy harvester

PLSS – pallet lifting and storing system.

LSS – lifting and storing system.

PEH – piezoelectric energy harvester.

4MS – four magnets set.

3MS – three magnets set.

UCD – up-conversion design (including MFU belt drive system and installed P-VEHs)

CPU – central processing unit.

tx – wireless transmitter.

rx – wireless receiver.

BLE – Bluetooth low energy.

PLC – programmable logic controller.

PWR SPLY – power supply.

Introduction

It is widely known, renewable energy is currently very relevant topic while mankind moves towards to renewable energy in all fields. For lifting and storing equipment manufacturer, concept of energy harvesting process to capture small portions of energy that otherwise would be lost in vibrations or movement - appeared greatly intriguing. Ideally captured energy could serve as source of power for sensors. Thus, review of mechanical energy harvesting devices was initiated, with the aim to lead more impactful innovations in lifting and storing equipment sector. Current project focuses on manufacturer-initiated case study assignment with the aim for energy-autonomous lift platform in given PLSS device. In presented PLSS device specific conditions, conceptually energy-autonomous lift platform harnesses only one power cable for more power-hungry belt drive motors, meanwhile maintaining (self-powered) sensors and signal transmission by on-board energy harvesting and accumulation system. Initially expected criteria consequently demand a review about mechanical energy harvesting up-to-date possibilities. Exploration throughout latest trends and capabilities of vibration energy harvesting, including mechanical frequency up-conversion (MFU) possibilities took the research to piezoelectric vibration energy harvesters (P-VEH). Seemingly the most promising in terms of applicability, hence intended for use in specified industrial device: a pallet lifting and storing system (PLSS).

Given PLSS modularity is major advantage in deliverable nomenclature, one storing device can be suited for any manufacturing hall exploiting vertical space until sealing. Accompanying negative aspect appears during installment procedure where wiring for several sensors and motors demands deployment of a relatively skilled employee. Hence cost-effectiveness achieved with modularity is greatly reduced after relatively expensive installing procedures. Therefor mentioned case study was initiated. Additionally, to innovation efforts in storing systems sector, visualized energy-autonomous solution could positively influence economic efficiency of given manufactured PLSS or similar devices LSS product family.

Case study carries through task setting and detailed analysis of the proposed PLSS device, its peculiarities consequently resulting in proposals for energy harvesters integration possibilities. Proposed concept for P-VEH design complements all restrictive peculiarities while maintaining manufacturing simplicity of the EH device. Designed EH device enables to deploy several commercially available P-VEH while applying MFU.

Following experimental study acquiring measurements of harvesters performance and attainable power levels in PLSS device specific conditions were executed. Conducted analyses of received data determined further development regarding P-VEH design with deployed MFU solution.

Throughout review and research part, all manufacturer raised questions were answered, research opportunities presented and finalizing with further development proposals as requested.

1. Literature review of mechanical energy harvesting

Electrical energy is a constituent part of our everyday lives, it is indirectly in goods people buy and services they use. Energy is essential to make things happen, almost everything and any activity is dependent on energy. Our ways from production to consumption of energy have far-reaching involvement in effects that affect our economy and environment. As people are always prone to demand reliable and fair energy cost. In order to satisfy such demand, it's inevitable to possess and prudence a long-term strategy. Due to industrial development and vast growth of population, global demand for energy have risen unexpectedly during last 150 years.

Energy has various forms: chemical, electrical, nuclear, thermal, optical, mechanical and so on. If something has the possibility to produce energy, it is called potential energy, e.g. water. If this potential energy is put into use thought motion, it's called kinetic energy, as in hydroelectricity dams. It is possible to convert energy from one form to other (Fig.1). Energy used today comes from various sources what could be classified into two categories: renewable and non-renewable.[1]

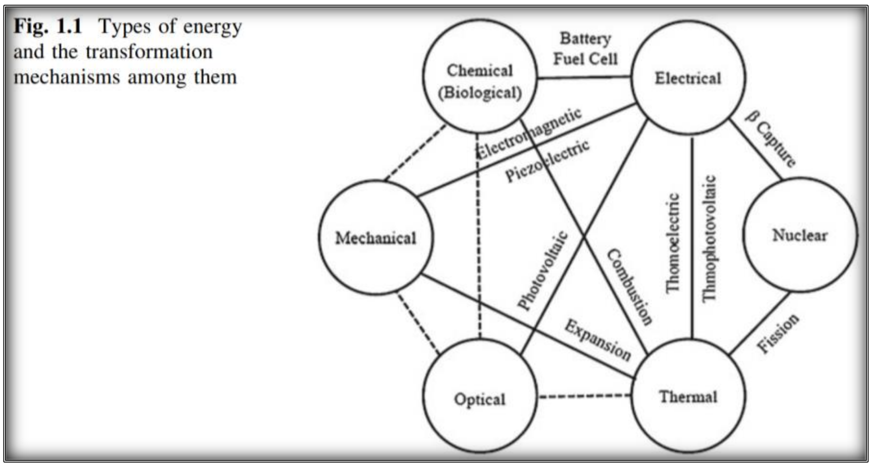


Fig.1. Types and transformation of energy [1]

Supplies for any kind of non-renewable energy are limited, therefore cannot be created again and as resources are being used the supplies are permanently consumed. Sources for non-renewable energy are coal, natural gas, oil and nuclear energy. From these, fossil fuels (oil, gas, coal) still continue as the primal source of energy for the world today. Renewable sources are these that can be regenerated again, from naturally occurring sources, which include hydro, wind, solar, geothermal, biomass and sea waves as sources. As sources are different, different technologies are needed as well.[1] As we can see, mankind has understood that conventional sources for energy are not eternal and various potential sources for renewable energy exist, hence finding out efficient alternative ways for non-renewable energy sources is a huge and still growing trend that currently makes rapid advances. Energy harvesting takes place in numerous ways, in large and small scale, transformed from many forms. As there are already existing, efficient, waste energy harvesting solutions, people are still look for more solutions in various fields to exploit potential energy around us. As windmills and hydroelectric dams might be the first and most well-known, but rather big scale solutions in renewable energy harvesting that general public is aware about. There is a growing demand on various small scale energy harvesting devices, what might not be as well-known and rather common yet, but recently emerged bigger interest of scientists and vast amounts of publications on assorted designs indicate high possibility for breakthroughs in near future.[1] Publications indexed in Thomson Reuters Web of Science from 2003 to 2013 [2], show high dominance of articles about piezoelectric generators (~2000), following electromagnetic (~650) and electrostatic articles (~300).[6]

Among small scale energy harvesting solutions, in addition to the thermoelectric and pyroelectric materials that can capture and transform energy into electrical power or directly stored as thermal energy, most auspicious energy harvesting technologies being developed also involve sound, movement and vibration what can be gathered and transformed to electrical power by employing materials with piezoelectric properties [1]. As for any portable device, they have a demand for power, due to what a trade-off between the size and the capacity of the battery has to be made, which in turn affects devices overall dimensions, operation capabilities and lifetime. Recent technologies e.g. energy harvesting have potential to efficaciously power electronic devices. Exploiting sources of motion, sunlight and temperature changes are latest examples of functioning solutions. Thus, energy harvesting can work as alternative source of energy for electronic devices.

1.1. Introduction to energy harvesting

Capturing and converting of ambient energy is a process known as energy harvesting (EH). Although there are slight differences [4], sometimes „energy scavenging“ is told instead. Energy harvesting from ambient sources is comprehensive area involving technologies on a small and large scale. In order for EH as a device to work, in basic principle it needs an ambient source (thermal, radiant, mechanical etc), an energy capture-, transduction-, power conditioning- and energy storage component (Fig.2). Depending on the systems, capture device and transducer components can be as one element, since the current might be unpredictable it requires output signal conditioning, where also the power flow from transducer is optimized, before stored or used by an electronic load.[5]

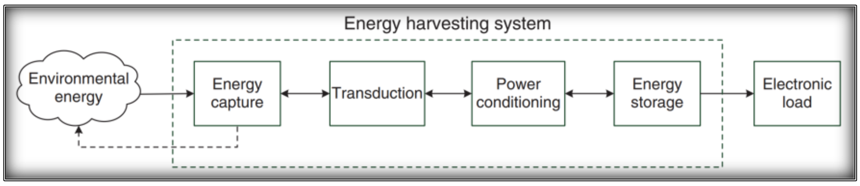


Fig.2. General energy harvesting system architecture [5]

From many forms of potential energy in ambient environment, one of the most ubiquitous sources in our surrounding for EH is mechanical energy. The source of which can be a vibrating structure, vibrations produced by air or water flow and other moving objects. As large-scale examples for air and water flow were mentioned in brief afore, consequent will reify ‘‘low-level’’ mechanical energies a.k.a. „ultra low“ vibrations and movements.[1]

If to celebrate about small scale EH applications, solar cells are the most mature solution that were successfully put to work in a device i.e. pocket calculators that are powered by photovoltaic (PV) cells (Fig.3) have been available for more than 30 years. Further development of PV cells has focused on more efficient conversion and cost, last mentioned being especially critical nuance for large scale applications. Noteworthy progress have been made in mentioned properties.[5] Past 15 years have seen great research efforts on international level regarding motion based EH, with distinct focus on inertial devices, that's a device which harnesses electrical power relatively to the motion of internal proof mass. Fundamentally the theory is established well and latest development tends to concentrate more on application specific implementations, conversion circuits and broadband operation improvement. Few recent commercial devices have been announced which seems to be a emergent business opportunity.[5] Irrespective of some devices already been launched commercially, there are numerous adverse issues related to electrochemical energy devices for example power density is low, life cycle is short and infliction of unsafe waste occurs, not to forget high costs for maintenance. In several appliances it is often economically inefficient, not reasonable or even impossible to replace empty batteries, e.g. implanted biomedical devices. Besides, batteries aren't viable solution for trustworthy long-lasting powering on portative systems meant to be deployed in rough conditions, which may also be hardly accessible. EH technologies emerged as the need for more resilient source for energy. EH technologies, as self-sustaining renewable-energy sources, might ultimately dissolve dependence on rechargeable and disposable batteries, what in turn will influence size, weight and cost of appliances. [5,6]

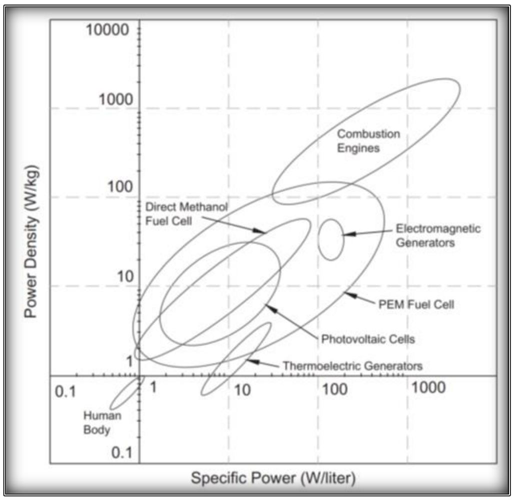


Fig.3. Comparison of power sources [3]

In ambient environment, there is array of different sources of energy what can be utilized for energy harvesting. Some of many energy forms that have already been presented for EH purposes: mechanical energy from pressure, vibration and static deformation, light energy of solar and in indoors, thermal energy, electromagnetic energy from radio frequency (sources of emissions are radio/Wi-Fi/tv and mobile transmitters), also magnetic fields [7], microbial activity [10], pH differences [13], acoustic [8] and chemical [9] and as well metabolic energy [11,12], photosynthesis artificially and reverse electrowetting.[6] Mechanical energy harvesters (MEHs) as devices can broadly be classified in to two general categories, based on smart materials and not based on smart materials (Fig.4).

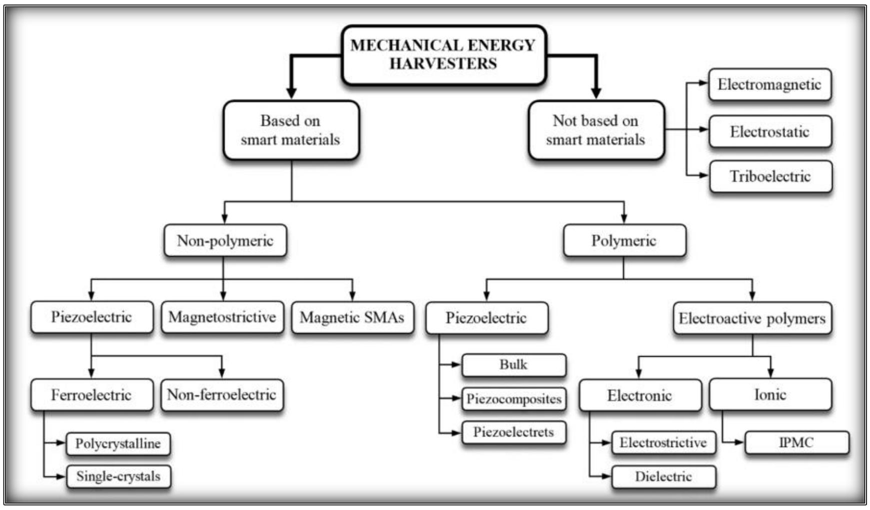


Fig.4. Mechanical energy harvester's classification [6]

As well there are numerous transduction mechanisms already employed in MEHs, yet no solution is universal, likewise there are positive and negative aspects (Fig.5). MEHs in general can be subdivided to VEHs - vibration aka kinetic-energy harvesters which relay on inertial- or direct force excitation (externally) and strain EHs what exploit surface strain vacillations to produce electrical energy. MEHs mainly apply VEHs principles. To maximize performance on energy generation, the EHs design has to be made special for distinct device while also taking into account the characteristics of input excitation, that can be harmonic, impulse, random or even a combination of these. VEHs have physical limits on power output that are specifically dependent on the volume and the mass of the device, considering miniaturization the harnessed power apodictically decreases. In general, the harnessable energy has limitations from the source of energy, in practice only a percentage of indigenous mechanical energy can be utilized to useable electrical energy.[4]

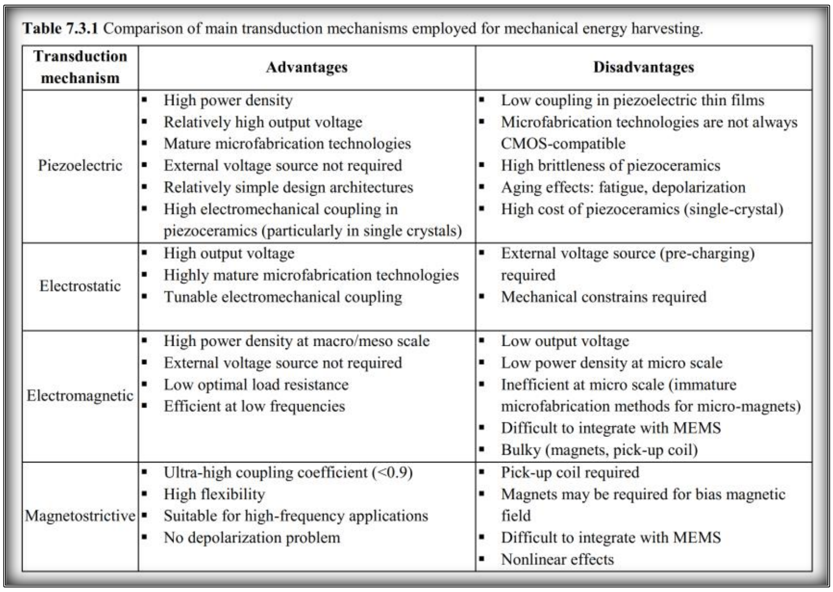


Table 7.3.1 Comparison of main transduction mechanisms employed for mechanical energy harvesting.

Transduction mechanism	**Advantages**	**Disadvantages**
Piezoelectric	▪ High power density ▪ Relatively high output voltage ▪ Mature microfabrication technologies ▪ External voltage source not required ▪ Relatively simple design architectures ▪ High electromechanical coupling in piezoceramics (particularly in single crystals)	▪ Low coupling in piezoelectric thin films ▪ Microfabrication technologies are not always CMOS-compatible ▪ High brittleness of piezoceramics ▪ Aging effects: fatigue, depolarization ▪ High cost of piezoceramics (single-crystal)
Electrostatic	▪ High output voltage ▪ Highly mature microfabrication technologies ▪ Tunable electromechanical coupling	▪ External voltage source (pre-charging) required ▪ Mechanical constrains required
Electromagnetic	▪ High power density at macro/meso scale ▪ External voltage source not required ▪ Low optimal load resistance ▪ Efficient at low frequencies	▪ Low output voltage ▪ Low power density at micro scale ▪ Inefficient at micro scale (immature microfabrication methods for micro-magnets) ▪ Difficult to integrate with MEMS ▪ Bulky (magnets, pick-up coil)
Magnetostrictive	▪ Ultra-high coupling coefficient (<0.9) ▪ High flexibility ▪ Suitable for high-frequency applications ▪ No depolarization problem	▪ Pick-up coil required ▪ Magnets may be required for bias magnetic field ▪ Difficult to integrate with MEMS ▪ Nonlinear effects

Fig.5. Comparison of general transduction mechanism deployed in MEHs [6]

Transformation of mechanical energy from ambient environment to electrical power is achieved by applying one or more electromechanical transduction mechanisms. As mentioned beforehand, MEHs can be classified in to two general categories, based on smart material or not (Fig.5).

Energy harvesters which apply smart materials work based on dynamic or static strains produced in that material. There is a big selection of different materials which demonstrate a strong magneto mechanical or electromechanical coupling that could be used effectively to convert mechanical energy to electrical energy. Piezoelectric material (PZT) energy harvesters (PEHs) are predominantly most outstanding representatives for this group and next ones are electroactive polymers. Alloys with shape memory (shortening SMA) and materials with magnetostrictive properties are currently comparatively meagre. Described group covers also hybrid energy converters where many transduction mechanisms are combined e.g. triboelectric, electrostatic, PZT and electromagnetic combined, inductive/magnetostrictive or PZT/magnetostrictive. [6]

Electromechanical energy harvesters what don´t apply smart materials for energy conversion work by the basis of displacement between coil and magnet in electromagnetic configuration or electrostatic configuration by applying capacitor plates with charge, or even through separation & contact amid materials which have different charge affinities, also called triboelectric. [6]

Triboelectric Nanogenerators

Recently mechanical EH devices have been proposed, which are known as triboelectric nanogenerators:
TENGs (Fig.6). Their operating principle is based on the contact electrification coupled effect in addition to electrostatic induction. Mechanical energy here is harvested through periodically occurring contact and separation between two materials which charge affinities are different, thus operating as a pump for charges where induced electrons are forced by electrical load to flow amid electrodes.[6]

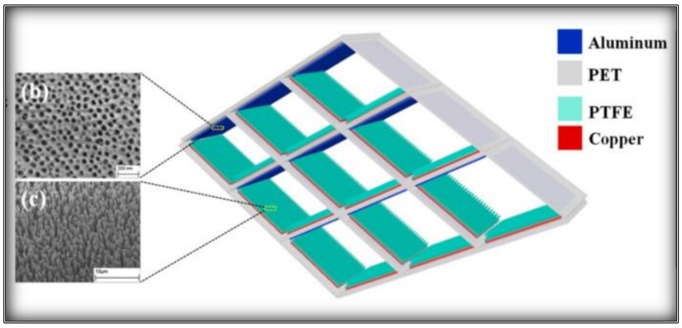


Fig.6. Triboelectric nanogenerator example [6]

However, many models have been put forward, still the contact electrification mechanism is not completely understood on fundamental level. Selection of materials to employ for TENG is immense since triboelectricity occurs widely, likewise mentioned aspect becomes advantageous in wearable, highly flexible and textile-embedded, VEHs development to exploit human motion. Main deficiency with TENGs today is rather low current output, though voltage on open circuit can gain few hundred volts. Other weak points should be addressed as well e.g. power output fluctuations, high output impedance and fragility. If these aspects are coped with, then TENGs can become expedient micropower source. To improve triboelectric charge density, a better comprehension on triboelectrification, additional endeavour in modification and contact between planes is needed. As well for textile-based TENGs concerns waiting to be solved are: breathability, washability, stretchability and softness.[6]

Micropower hybrid generators

Concepts of hybrid MEH which combine different transduction mechanisms have been studied as a possibility to improve output of power generation. For instance, VEHs exerting materials with magnetostrictive properties function on the principle of "Villari effect" combined with electromagnetic induction, by which a change in the density of magnetic flux is induced thanks to strain produced by vibrations in magnetically polarized material, where pick up coil converts vibrations into electrical current. Bigger flexibility and efficiency of conversion are main benefits of the inductive/magnetostrictive VEHs compared to PZT solutions (Fig.6).[6]

Vibrations could also be exploited for energy harvesting by magnetoelectric effect, that is generated in PZT/magnetostrictive composites and laminates. Enhanced efficiency for transduction is accomplishable if merging magnetostriction and PZT effect. Main characteristics for this union would be strong magneto mechanical coupling and great energy density. Most intriguing in this class of devices deploy multi-axial configuration (Fig.7, a) and are self-tuning EH's. Another hybridizations of MEHs combine electromagnetic+PZT, electrostatic+PZT (Fig.7, c) or even triboelectric+PZT(Fig.7, b) configuration for EH.[6]

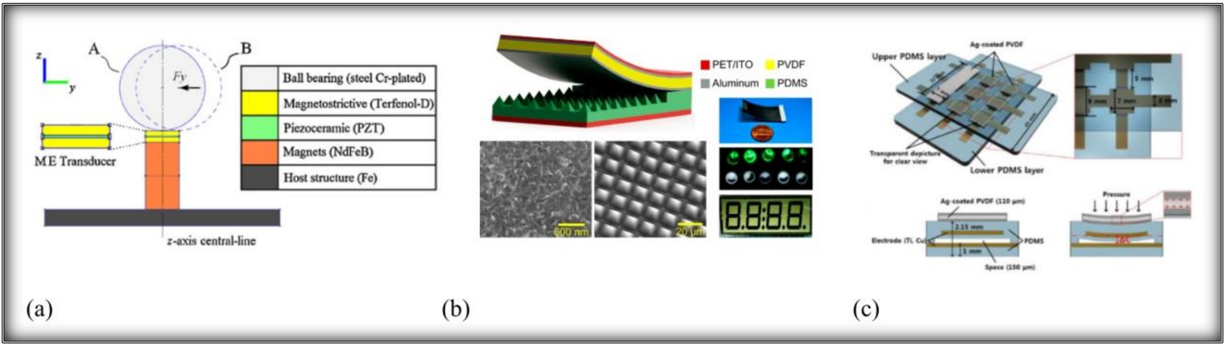


Fig.7. (a) Bi-axial magnetoelectric generator, (b) Hybrid piezoelectric-triboelectric nanogenerator (c) Hybrid piezoelectric-electrostatic generator [6]

Wideband and Nonlinear Micropower Generators.

Restrained selectivity for suitable frequency in linear VEHs is a severe obstacle what causes low efficiency in numerous real-life scenarios. From manufacturing perspective, such tight but necessary tolerances for sufficient resonant frequency in particular excitation case lead to many issues regarding production of the device. Majority of plausible vibrations sources attend to be hypothetical, multi-frequency or varying in time, hence far-reaching endeavor is needed to discover additional methods to improve the general responsiveness of VEHs. Vibrations from surroundings are mostly divided over vast range and in general case on low frequencies 0-100Hz, hence VEHs have great mechanical design challenges [14, 15]. Numerous approaches are worked at to increase the operational bandwidth[16,17]: resonance tuning [18], multi-frequency arrays [19], converting frequency up [20], using multimodal oscillators [21] or nonlinear oscillators [22].

Generally adjustable VEHs incline to underperform if excitations are swiftly varying or even random, meanwhile the need of extra power source greatly thwarts scalability and the design [23].

Mechanical frequency up-conversion (MFU) as a solution is one of the most promising techniques to enhance efficiency of energy conversion at very low frequencies <50 Hz. Main benefit is its generators resonant frequency and decoupling from excitation frequency, what causes lower sensitivity on harvesting performance to wide selection of excitation frequencies. Such standpoint is usually applied by two-stage design, so that non-resonant [24] or resonating [25] prime element corresponds to low-frequency excitation so that high-frequency oscillation is triggered impulsively by contact between PZT generators [25], non-contact [24] or hybrid [26] interaction (Fig.8). [6]

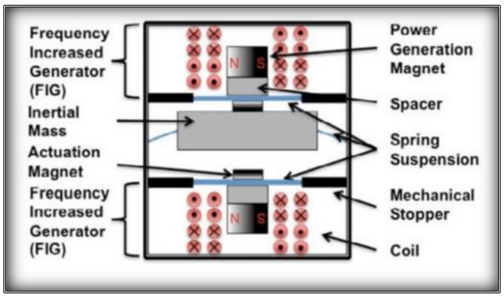


Fig.8. Schematics of electromagnetic MFU generator [6]

Common rule of VEHs that take advantage of phenomenon called “resonance amplifications” is distinguished by large output of power which is achievable by trade-off on operational bandwidth, meanwhile non-resonant applications offer large bandwidth but a lower output level. Nonlinearities in VEHs are currently very actively researched, still containing many obstacles [14,15,23]. Nonlinearity can be applied in VEHs by implementing restoring piecewise-linear forces by applying stoppers [27] or non-linear restoring forces (achievable by magnetic pull, push or by deploying buckled structures), that are then adjusted to accomplish mono-stable [28, 29], bi-stable [15,30,31] or even multi-stable [32,33] configurations. In this case, improvement of harvesting performance is vastly reliant on the characteristics and intensity of input excitation besides on preliminary circumstances. Nonlinear VEHs have very complex dynamic behavior, still involve major challenges at performance improvements in distinctive excitation conditions. Additionally, improvements regarding optimization of circuits for power conditioning are still in early stages [23].

1.2. Mechanical energy harvesters

As mentioned, energy harvesting takes place from many forms in numerous ways and scales. If to consider the growing demand on small scale energy harvesting devices, a portable, wearable or even implantable small-scale autonomous devices will be greatly needed. Among small scale EH, most promising EH technologies include vibrations and movement that can be captured by PZT materials. As we know, in small scale devices generally power source is the main challenge, regardless of numerous mechanisms already employed in MEHs, yet no universal solutions exist hence a selection considering positive and negative aspect shall be made (Fig.5). Consequently, the focus on following literature review chapters was aimed towards electrostatic, electromagnetic and PEHs.

EH generators most commonly use cantilever beam with proof mass on the beam to exploit motion (Fig.9), nevertheless many different designs also exist which are used. Designs that use proof mass are called inertial or kinetic energy harvesters, where transduction from kinetic to electrical energy typically consists of electromagnetic, piezoelectric, or electrostatic technique. Electromagnetic generation induces voltage by the displacement of a magnet relatively to a coil, PZT generator produces voltage from the straining of the material while electrostatic transduction increases the voltage of charged capacitor by changing the distance between capacitors parallel plates. [3]

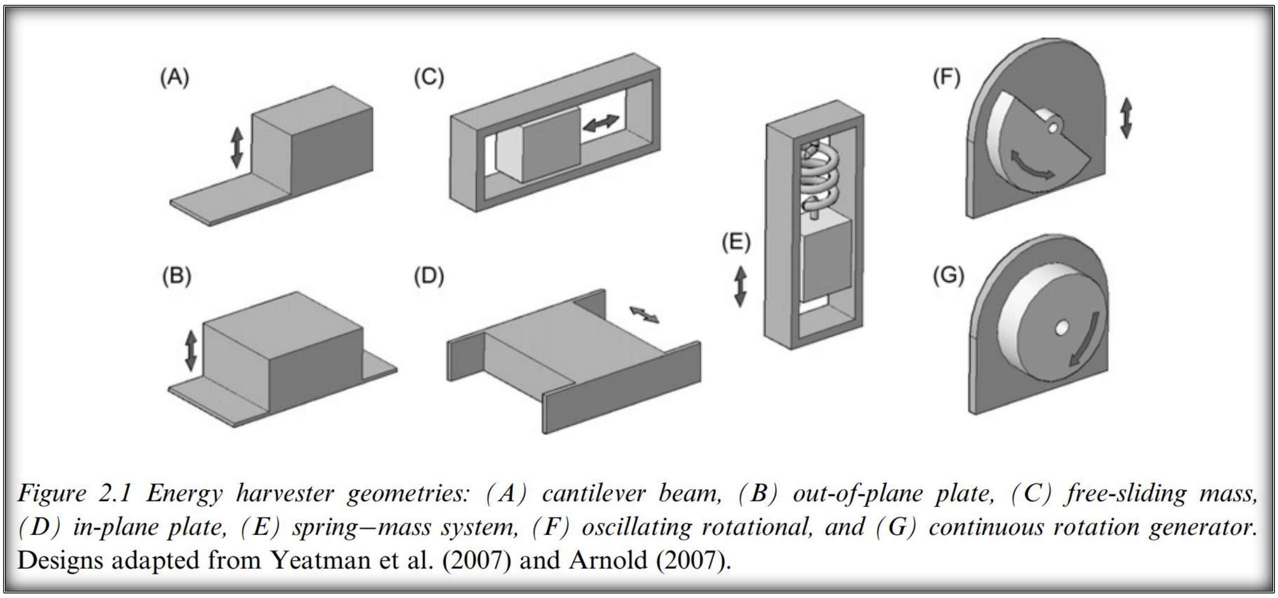


Figure 2.1 Energy harvester geometries: (A) cantilever beam, (B) out-of-plane plate, (C) free-sliding mass, (D) in-plane plate, (E) spring—mass system, (F) oscillating rotational, and (G) continuous rotation generator. Designs adapted from Yeatman et al. (2007) and Arnold (2007).

Fig.9. Different geometries of energy harvesters [3]

1.2.1. Electrostatic and Electromagnetic energy harvesters

Electrostatic VEHs function in the variable capacitor principle, which means that the electrode correlate to a suspended proof mass that oscillates while second electrode is fixed (Fig.10).[27]

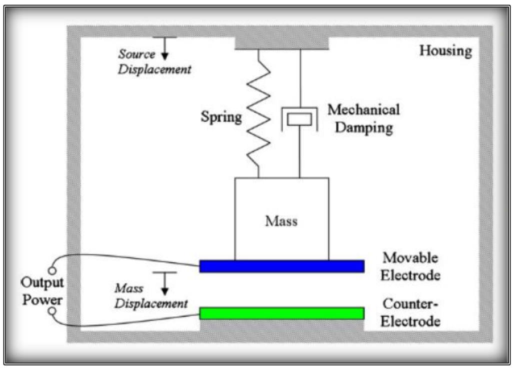


Fig.10. Electrostatic gap-closing generator [34]

On preceding Fig., the source displacement is the cause for excitation after what the force acting on the mass results the fluctuation of the distance between electrodes by what additional charges are generated at the electrodes. Such approach is called gap-closing converter, what as well may have in-plane, out-of-plane or overlapping configuration. Since every configuration type has its pros and cons, comparison should be made in between depending on application (Fig.11, Fig.12).

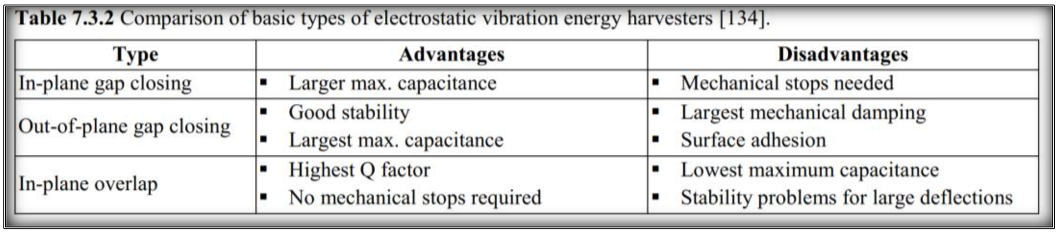


Table 7.3.2 Comparison of basic types of electrostatic vibration energy harvesters [134].

Type	Advantages	Disadvantages
In-plane gap closing	▪ Larger max. capacitance	▪ Mechanical stops needed
Out-of-plane gap closing	▪ Good stability ▪ Largest max. capacitance	▪ Largest mechanical damping ▪ Surface adhesion
In-plane overlap	▪ Highest Q factor ▪ No mechanical stops required	▪ Lowest maximum capacitance ▪ Stability problems for large deflections

Fig.11. Basic types of VEHs [57]

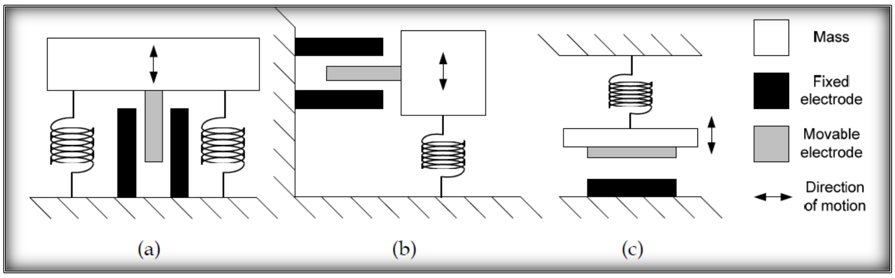


Fig.12. Electrostatic energy harvesters (a)In-Plane Overlap (b)In-Plane Gap Closing (c)Out-of-Plane Gap Closing [49]

Key deficiency of generators with electrostatic aspects is the need for initial pre-charge by external power source, this also demands complex circuitry which as well causes high electrical losses.[34] Such problem can be passed by applying electrets which use dielectric (inorganic/organic) material where quasi-permanent polarizing charge has been applied[6]. Although downscaling of electret-based appliance causes poor charge stability in long run as well have low surface potential regardless of it [36], lately emerged a electrostatic generator that needs no external power sources or electrets, that works by pumping charges which becomes possible if to apply two different materials by their work functions [37].

Electromagnetic micropower generators regardless of their size from 1cm3 and up, so far they have evolved the furthest as well most economically beneficial energy generation technology today [38]. Although there are +100 prototypes of electromagnetic generators developed since 1995 [39], being most mature with high levels of peak power output but at the same time the size in volume is 1cm3 and up, from size perspective greatly limiting if several harvesters are deployed in tight conditions as well characteristics regarding motion for energy harvesting are not directly suitable for current project hence electrostatic VEHs are not focused on in following chapters [40].

1.2.2. Piezoelectric energy harvesters

Piezoelectric (PZT) vibration energy harvesters also known as P-VEHs, typically apply mono or poly crystalline or as well piezo-active polymers to induce electrical charge as response to mechanical stresses (Fig.13). Huge popularity of PZT generators is considered to be because of their simple design, where they are easily down-scalable for applications as well as to simple to produce by MEMS technology. In comparison to electromagnetic and electrostatic versions, P-VEHs respectively have higher voltage and power density levels, as well more beneficial power scaling if to compare PZT generator $V^{4/3}$ to electromagnetic one V^2 [41].

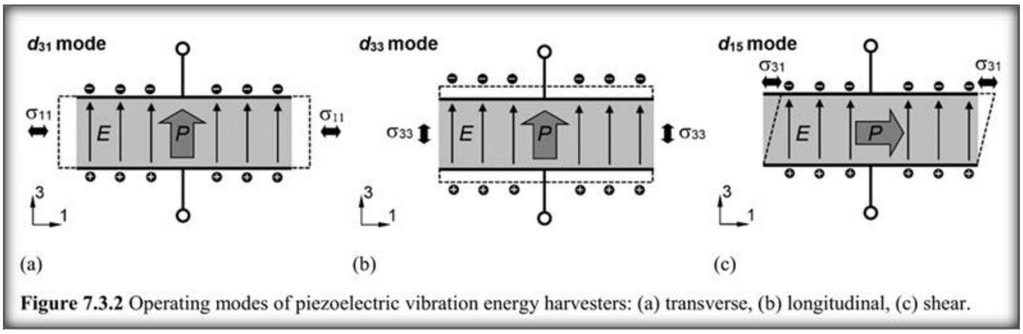


Fig.13. Operating modes of P-VEHs[6]

Typically P-VEHs are design to work in one of three coupling modes (Fig.13), what can also be distinguished by electrical field, applied strength and poling direction [38]. In most frequently used operation mode d31, the poling direction and induced field of electricity is perpendicular to applied tensile stress [42]. In less frequent operation mode d33, the poling direction and induced field of electricity is parallel to applied tensile stress [43]. Most infrequent operation mode d15, the direction of poling is parallel while direction of induced electric field is perpendicular to applied shear stress [44]. P-VEHs designs most commonly are linear oscillator in cantilever type composition, where transducer also use composite unimorph or bimorph materials and proof mass on the free end of cantilever (Fig.14) [45].

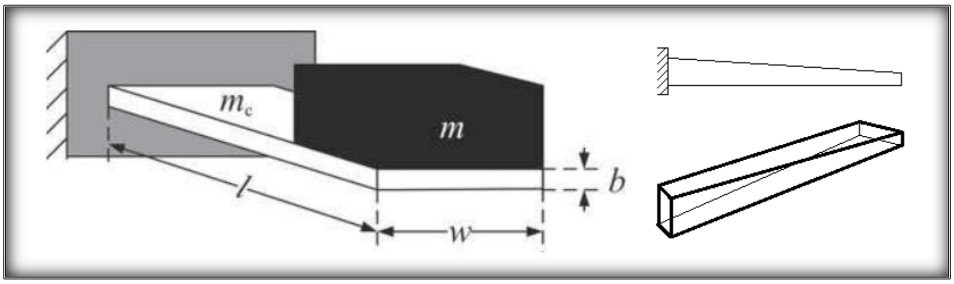


Fig.14. Cantilever with a proof mass on the free end (left) [46] tapered cantilever (right)

Cantilever architecture is favorable thanks to its high responsiveness which produces largest avarage strain for introduced portion of excitation force [47]. Tapered cantilever (Fig.14) allow homogenization of the strain stress through the structure, so minimization of weight and size in correlation to power output becomes possible [48]. Some shapes in addition to cantilevers can use ring or spiral design as well as zigzag design, these alternatives are enticing for micro size generators since they provide possibility to reach lower resonant frequencies while they still preserve high strength. Generated power output of P-VEHs is maximized only then if it is excited to vibrate as close to their resonant frequency as possible. To sustain stable excitation frequency in time in so precise range, is rather sparse in reality. Since slight fluctuation of the resonance causes decrease in performance in linear generators, hence the amount of different configurations proposed over the years to harvest nonlinearities is vast.[6] In addition, the architecture of cantilever design has also been modified so to experiment different modes and their performance in mentioned configuration (Fig.15).

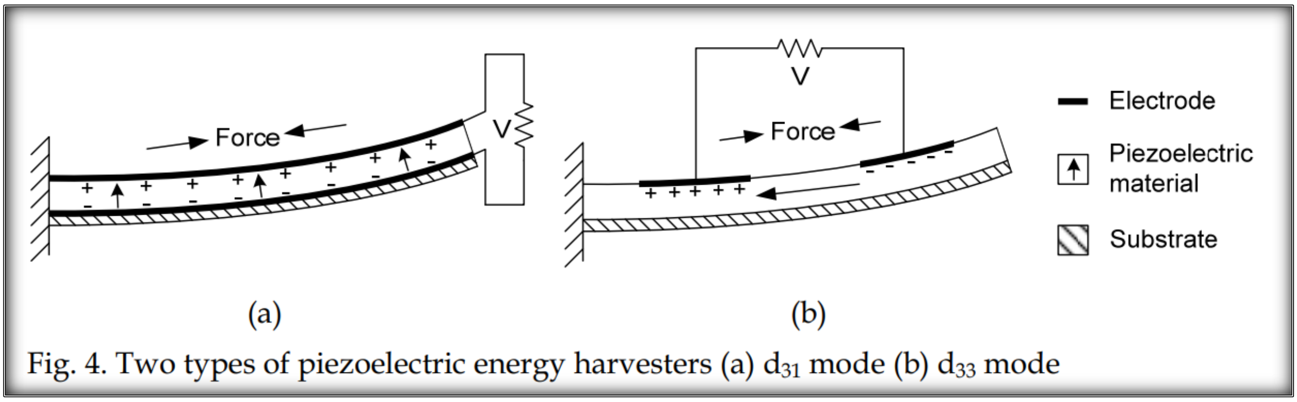


Fig. 4. Two types of piezoelectric energy harvesters (a) d_{31} mode (b) d_{33} mode

Fig.15. Two types of P-VEHs in mode d31 and d33[49]

The range of PZT materials applicable in previously described configurations is comprehensive, starting from hard and soft ceramics, non ferroelectric, with lead and lead free materials to piezoelectric polymers and composite materials. PZT are most often used thanks to its cost effectiveness and great piezoelectric properties, where noteworthy are in d31 and d33 modes reaching up to 320 pC/N and 650 pC/N [38].[6] Some commercially available PZT materials that could be but in to use in following chapters (Fig.16).

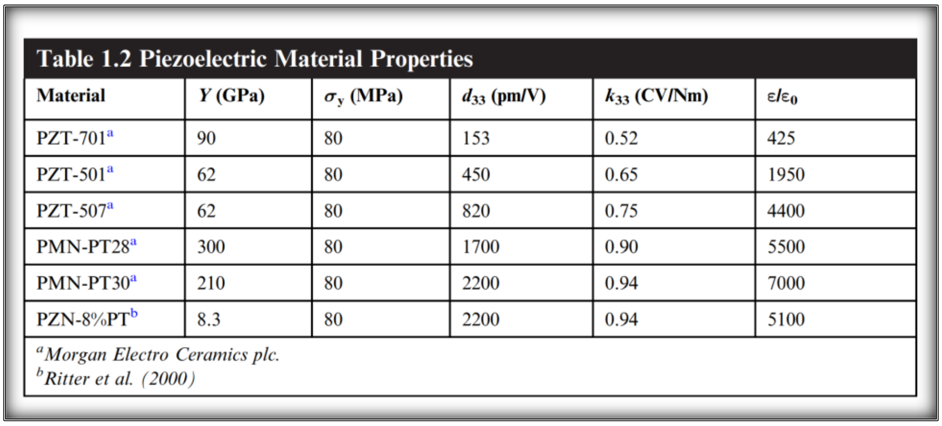


Table 1.2 Piezoelectric Material Properties

Material	Y (GPa)	σ_y (MPa)	d_{33} (pm/V)	k_{33} (CV/Nm)	$\varepsilon/\varepsilon_0$
PZT-701[a]	90	80	153	0.52	425
PZT-501[a]	62	80	450	0.65	1950
PZT-507[a]	62	80	820	0.75	4400
PMN-PT28[a]	300	80	1700	0.90	5500
PMN-PT30[a]	210	80	2200	0.94	7000
PZN-8%PT[b]	8.3	80	2200	0.94	5100

[a] *Morgan Electro Ceramics plc.*
[b] *Ritter et al. (2000)*

Fig.16. PZT materials and properties [3]

1.3. Piezoelectric energy harvesters based on frequency up-conversion

The rise of frequency up-conversion in energy harvesting is currently very promising approach to enhance the efficiency of the conversion on very low frequencies. The key benefit lies in decoupling during the excitation, where low frequency excitation triggers up-conversion which is adjusted accordingly to primary element so, that the resulting excitation frequency is close or equal resonant frequency, hence the performance of such harvester is higher. Generally, a resonant VEHs taking advantage of amplification phenomenon produce larger power output on the expense of operational bandwidth where counterpart non-resonant application provides bigger bandwidth with lower output level. Up-conversion can be achieved by contact, non-contact or hybrid interaction method.[6]

1.3.1. Contact-type excitation

In following example of contact type excitation, a cantilever configuration is used so that a plectrum causes bimorph to vibrate after released from contact (Fig.17). At first, there is a cap between bimorph and plectrum, the decreasing of distance in between is called approach phase, where following is a loading phase, which started when contact was made. Since plectrum continues its movement, the overlapping area in contact decreases until maximum deflection is reached, the same moment both elements are released (release point) and free to return to their initial undeformed position. Although the same instant, bimorph starts to vibrate as a cantilever beam on its resonance frequency, vibrations are converted and stored through the direct PZT effect to electrical energy.

Some mechanical energy is lost through different forms of damping, as in dielectric loses, material internal and air damping, hence the outcome is frequency up-conversion since numerous vibrations are generated on higher frequencies when applying single slow movement of plectrum. [1]

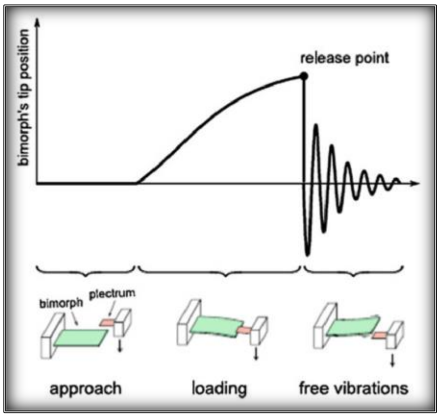


Fig.17. Illustrative graphic of contact plucking action [1]

Another application with cantilever design is following impact-driven energy harvester that employs a rigid freely sliding cylinder so that if a sliding in V direction is performed (Fig.18), the colliding tips will cause the parallelly positioned PZT bimorph to vibrate at its resonant frequency after the separation. At such configuration, the cylinder will receive the external impacts which cause it to slide and respectively causing excitation in PZT element.

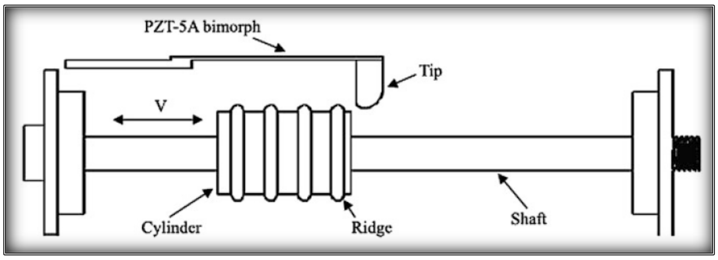


Fig.18. Schematic drawing of the impact-driven piezoelectric energy harvester [1]

Contact-type configuration may produce great power output and always operate on desired frequencies as a result to sharp and impulsive excitations although the drawback is the excessive wear of the surfaces in contact as well the impact caused material fatigue. The lifespan in comparison to contactless-type is lower as well as the operational sound level is always questionable.

1.3.2. Contactless excitation via magnetic plucking

Contactless magnetic plucking in comparison to contact-type is more robust and reciprocal to noiseless applications although the magnetic coupling is predetermined by magnets magnetic force, hence to achieve a miniaturized version that constantly performs in impulsive excitation mode is greatly challenging.[50] As this is not the only challenge that occurs in mechanical frequency up-conversion (MFU) designs in general, the trade-offs are occurring in all configurations, hence complications will be occurring no matter of the development direction. Despite the challenges, contactless MFU is by far the most interesting concept reviewed through up till now. Respectively subsequent will focus more on contactless excitation designs and magnetic plucking solutions.

Firstly, a magnetic coupling effect in a combination with cantilever, as an example how magnetic forces act on PZT element, we can see that the excitation in all variations is clearly not as sharp as in prior contact-type configuration (Fig.19).

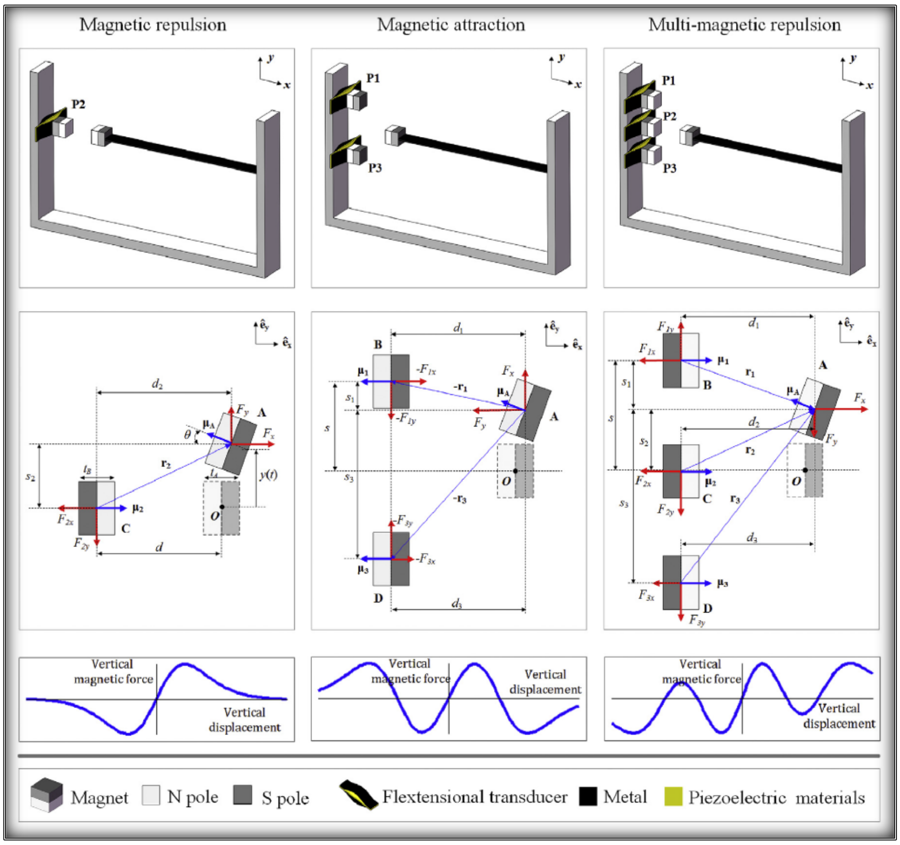


Fig.19. Schematics of magnetic repulsion in various compositions [73]

“Magnetic repulsion” employs a cantilever with magnet as a tip mass and flextensional transducer which is magnetically coupled. Such magnetically coupled flextensional transducer consists of a permanent magnet, a piezoelectric layer and two raised metal layers. By fixing magnets to a beam the flex tensional member is aligned in repulsion. “Magnetic attraction” is made up of two symmetrical magnetically coupled flextensional transducers and a cantilever with a magnet as a tip mass. The fixed magnets on a beam and flextensional transducers positioned respectively are attracting each other. “Multi-magnetic repulsion” compared to both previous versions, employs extra two magnetically coupled and symmetrically positioned flextensional transducers. By aligning the flextensional transducers and magnets fixed to the beam in repulsion, it's possible to obtain a quad-, bi- or monostable system. [51]

If to understand primary idea behind magnetic plucking as a mimicking technique to create a force profile of a peaked Gaussian curve to provide a clean release of the tip.[50] Clearly from decoupling perspective by using magnetic coupling, deliver rather obtuse excitations, if to see displacement curves (Fig.19), which will not work in favor for power output, nonetheless it is a nuance of magnets magnetic field, hence has be considered if to apply magnetic coupling in designable system. Configuration options for frequency up-conversion proposed, involving magnets, magnetic field direction and in- or out-of-plane plucking set ups can be as follows (Fig.20).

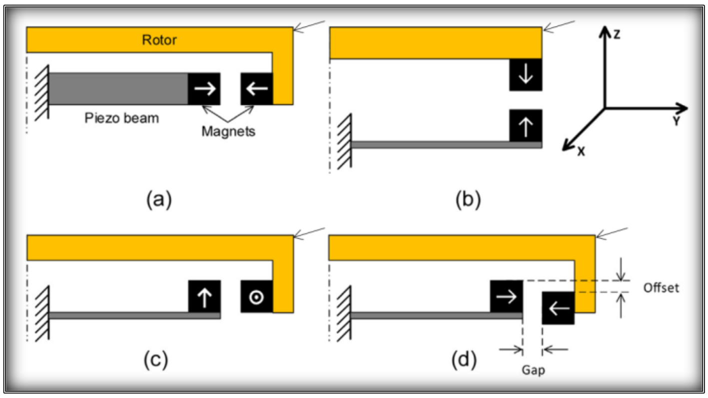


Fig.20. Magnetic plucking configurations [72]

Configuration: in-plane plucking is “a”, out-of-plane direct repulsive conFig.(known as DRC) is “b”, out-of-plane orthogonal config is (OC) “c” and out-of-plane indirect repulsive conFig.(IRC) is “d”. Driving magnet is fixed to rotor (marked: ⟵) which moves in X direction. On a schematic beam is bending in X direction while on b, c and d it bends in Z direction. [50]

If to take numerical results of preceding schematics (Fig.21), it is indisputable that transverse force Fx (a) in beam deflection direction and axial force Fz (b) in direction of the beam length seems most interesting for plucking.

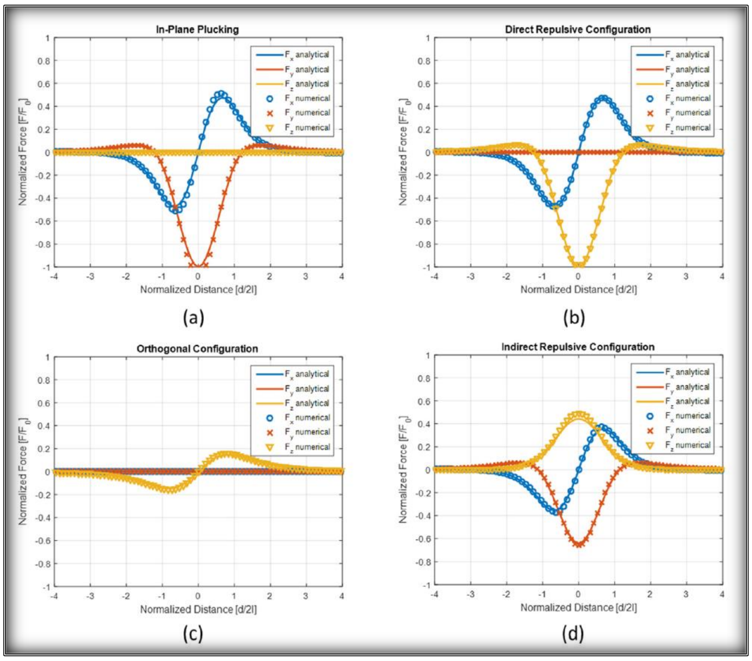


Fig.21. Static force profiles of different configurations [50]

As seen on prior Fig., the direction of Fx (transverse force) changes on zero displacement point, so the magnetic interaction causes a jump phenomenon to occur while cantilever is restoring initial position. [50] Mentioned jump phenomenon is greatly beneficial for effectively mimic the plucking of the cantilever. Currently it seems, that in-plane plucking configuration is superior to others in comparison, so to be confident in chosen design, final comparison of simulation and measured results of such configurations shall be made (Fig.22). Where continually “a – configuration” proves itself to be the best choice from discussed selection, hence a in-plane plucking configuration with PZT cantilever with permanent magnet as a proof mass on the free end is proposed for future aim, to fabricate a working model of P-VEH with contactless MFU.

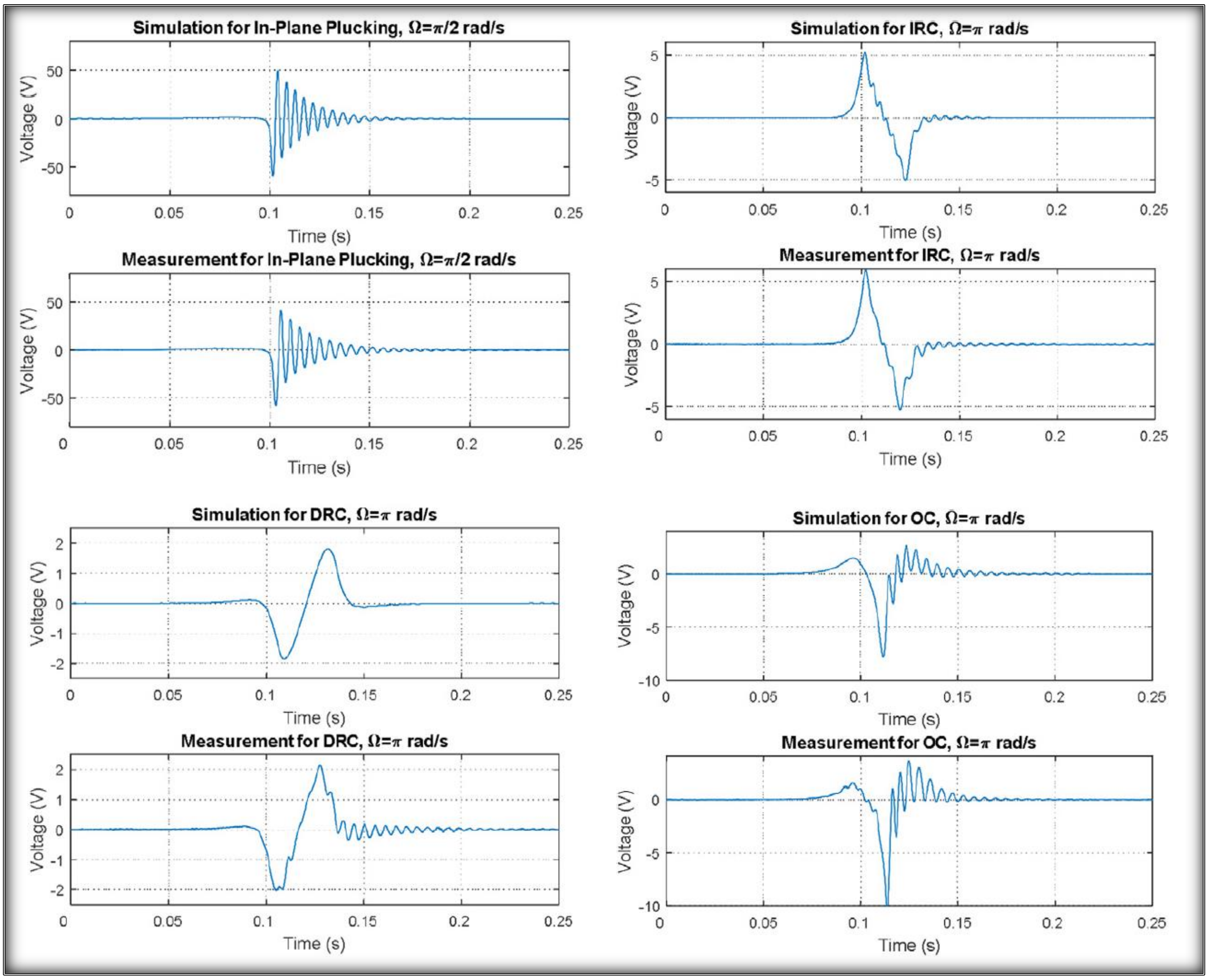


Fig.22. Simulation and measured voltage of PZT beam in previously defined configurations [50]

Chart in-plane plucking aka “a” shows the simulation-based measurement of output voltage from the PZE beam in the in-plane configuration. Chart “DRC” is the simulation-based measurement of output voltage from the PZE beam in the direct repulsive configuration. Chart “IRC” is the simulation-based measurement of output voltage from the PZE beam in the indirect repulsive configuration. Chart “OC” is the simulation-based measurement of output voltage from the PZE beam in the orthogonal configuration. [50] Considering in-plane plucking configurations outstanding performance on static force profiles (Fig.21), correlated simulation and measurement results of generated voltage (Fig.22) in comparison to other compositions, it seems most efficient option to be implemented in the scope of current project.

1.4. Summary and formulation of research aim with objectives

Considering unexpectedly risen rather vast growth of global demand for energy, as conventional sources are being used up, proportionally bigger aim to renewable sources is taken. A growing demand on small scale EH devices as well emerged bigger interest of scientists raises possibility for breakthroughs in near future. Small-scale EH solutions cover wide range of smart materials that can capture and transform energy, e.g. when capturing vibrations then materials with piezoelectric properties are auspicious. One of the most ubiquitous source for EH is mechanical energy: vibrations, in low and even ultra-low vibrations - development progress is made by deploying device specific inertial devices or MFU-based solutions. Portable EH systems are viable solution for reliable and long-lasting powering of electronic devices, especially in hardly accessible places, ideal replacement for rechargeable and disposable batteries. MEHs can be divided by based on smart and not based on smart materials, where MEHs again are subdivided into vibration-based EHs and strain-based energy harvesters. Although MEHs have physical limits depending on the volume and the mass of the device, in practice only a niggling percentage of mechanical energy can be utilized, the most outstanding representatives still are predominantly PEHs. To enhance harvesters efficiency, research on frequency up-conversion shows it to be very promising. Cantilever type design is simple and widely used which as well makes production by MEMS technology easy. Cantilevers are most often applied in two main compositions for excitation, contactless- and contact type, typically providing „d31“ or „d33“ operation mode. During contact type excitation material suffers fatigue and excessive wear as well operational sound level is questionable, in comparison to contactless type excitation, the lifespan is greatly higher and described problems are non-existent hence in further development contactless excitation could be applied along with in-plane plucking configurations which seems most efficient option if compared to other configurations from the scope of current project.

Research aim is to investigate potential use and performance of a piezoelectric vibration energy harvester as micropower source for sensors integrated in specified industrial pallet lifting and storing system.

First objective: from reviewed literature and analyzed state of the art in mechanical energy harvesting, the most promising energy harvesting solution in terms of applicability appeared to be P-VEH deploying MFU.

Following objectives do be answered henceforth:

2. Describe the target industrial pallet lifting and storing system, its configuration and operational conditions to identify possibilities of using one or several piezoelectric vibration energy harvesters within the specified geometrical constraints of the system.
3. Experimental investigation of vibration energy harvesting with commercially available piezoelectric transducers in order to determine dynamic excitation conditions required for harvesting electrical energy levels that are usable for powering sensors of the targeted system.
4. Proposals for recommendations to rationally adapt piezoelectric vibration energy harvesters to components of the pallet lifting and storing system in order to increase power output.

2. Analysis of possibilities to integrate P-VEHs in to pallet lifting and storing system

The targeted application for P-VEHs is specified as „pallet lifting and storing system“ (PLSS) (Fig.23), which is intended for vertical storing of standard size euro “E6” pallets in heavy industry. Given industrial application from EH perspective is rather specific although considering the general concept, designed solution could be also applied to other similar LSS products (in medium and low payload storing systems). The PLS-system is composed of lift platform, bottom-, shelf- and top-modules. Described PLSS device was designed by the author of this research project as separate assignment during traineeship in the company. Manufacturer stated base criteria and conceptual description, where highest priority was set on modularity. Thus, in principle it is possible to add “shelf modules” endlessly, hence the height of PLSS product vastly varies in every order, depending on the vertical height of customers manufacturing hall. According to the manufacturer, mentioned adaptability in height fulfills the demand for majority of customers thus potential cost-effectiveness of modular-LSS is generally high. However, to ensure sufficient PLSS working quality, a relatively skilled employee has to be deployed on set, so yield from product diversity is significantly reduced by high assembly and installation cost. Ideally the lift platform could be energy-autonomous (based on self-powered sensors) and be completely prepared for installment in factory, although for actuators the power cable still has to be harnessed on set. Mentioned economical aspect was one of the main motives for initiated case study. Ideally, if the custom wiring for sensors is excluded from device installment phase, a significant benefit from economic perspective is achievable (estimated to 2500-3000 €). Thus, by realizing energy-autonomous lift platform concept a significant raise of the cost-effectiveness is foreseen if proposed solution stays in budget (≤ 2000 €).

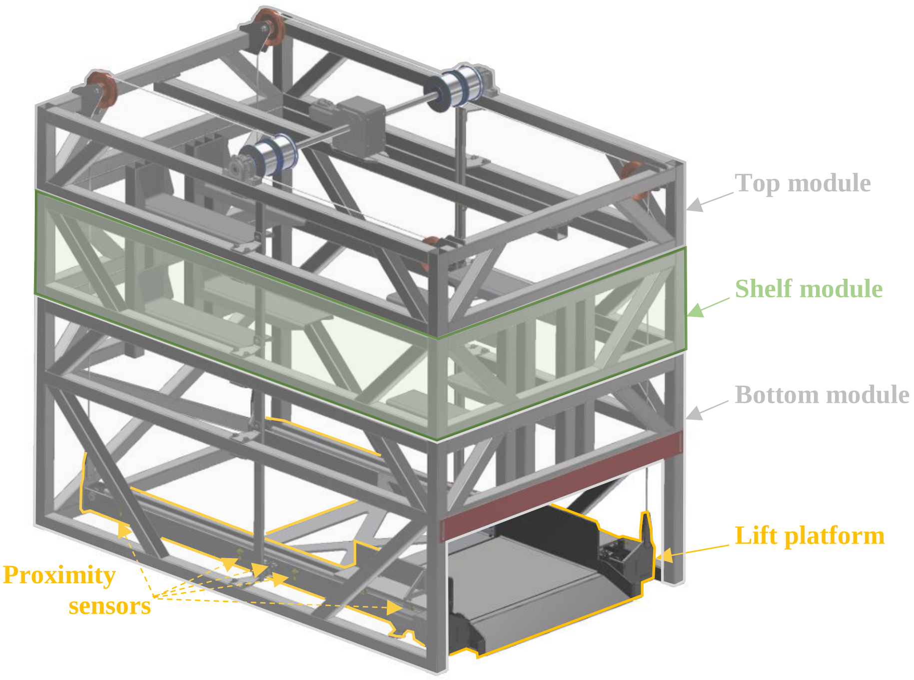


Fig.23. Euro E6 pallet lifting and storing system (PLSS)

Specified maximum allowed mass for storable pallet (including cargo) is 400kg, lift platform inside the device adds extra 100 kg due to application handles rather heavy payloads. Lifting platform is the central moving part that is responsible for delivering and storing manually inserted pallets. For such payloads the applied torque for actuation (by slider assembly motors, Fig.25) compared to possible resistance caused by contactless EH device is negligible hence the associated rotational energy can be considered for harvesting purposes. Considering the manufacturers on going product family expansion with light and medium payload systems, a case study about energy harvesting possibility for energy-autonomous lift platforms was performed in this work (Table 1).

Table 1. Case study questions

Nr.	**Manufacturer case study questions regarding EH possibilities on PLSS lift platform**
1	Is it possible to fit one or more energy harvesters in to current geometrical restrictions set by system dimensions?
2	Will energy harvester with geometrically suitable size generate power sufficiently for powering currently used sensors?
3	For sufficient energy harvesting, are changes in given PLSS application frame or other elements necessary?
4	Are there any other proposals of further development for energy-autonomous lift platform?

2.1. Task setting according to manufacturer requirements

As derived from manufacturers requirements (Table 1), the main task when analyzing the applicability of P-VEHs in the PLSS is to determine whether it is possible to obtain practically usable power levels from one or several harvesters in order to power sensors installed on the lifting platform (Fig.24) in the attempt to, achieve energy autonomy. If concluded otherwise, additional proposals can be made for further modifications to achieve energy autonomy solution another way.

Fig.24. PLSS lifting platform

In addition to previously mentioned sensors, platform also hosts actuators and belt drives to manipulate inserted payload. Due to platforms relatively simple design, only possible source of movement for EH purposes are either belt (linear) or driving/driven cogs (rotational) used for platform movement (Fig.25).

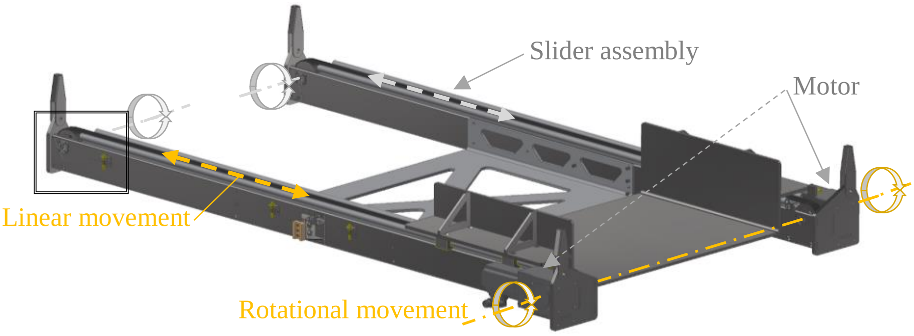


Fig.25. Lift platform (marked Fig.26 close-up)

By overviewing lift platforms assembly, best possible sources for energy harvesting are the cogwheels located on either side of the platform, where one is driving cogwheel which is equipped with an electric motor and opposite side hosts a driven cogwheel. If to consider the accessibility aspect, it is most feasible to focus on the side with a driven cogwheel. In addition to accessibility, chosen side also has more free space between the frame, no interfering fasteners and extra parts from the actuator assembly (Fig.26). Described cogwheel will be considered as a driving source in P-VEH setup to be designed later.

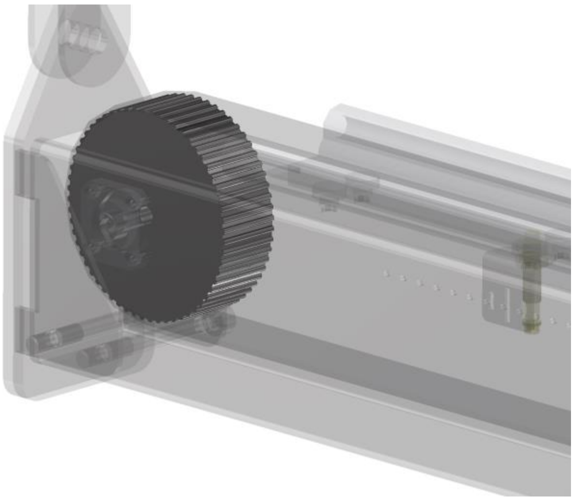


Fig.26. Driven cogwheel (close-up made from Fig.25)

Since the platform longitudinally is designed symmetrically (Fig.25). Hereafter one side will be focused on in following development and later a option remains to multiply amount of applicable energy harvesters by ×2.

2.1.1. Harvestable movement source and restricting dimensions

Previously described, chosen location for EH in given application will be the driven cogwheel positioned in the emptier end of slider assembly. The cogwheel will be considered as the source of motion energy in the considered P-VEH setup. If to examine the section view of described location in the application (Fig.27), a relatively compact P-VEH setup must be designed in order to mount it into given PLSS rather not spacious conditions. The distances between cogwheel (~12 mm) and frame are small as well the frame forms relatively tight chamber (height: 68 mm width: 54 mm) around entire P-VEH setup, in current situation the manufacturer has allowed to apply minor changes on cogwheel or frame if it’s necessary for mounting of the harvester or its elements.

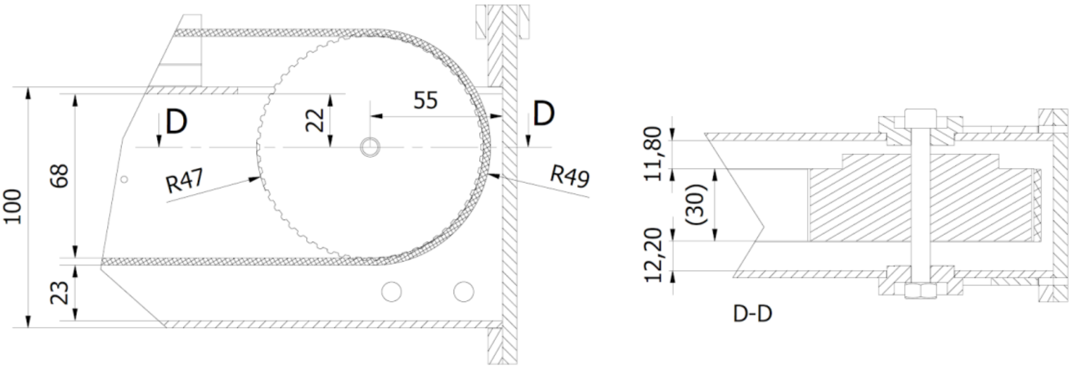


Fig.27. Section view of driven cogwheel in slider assembly

The bidirectional movement of the cogwheel is along z-axis. Belt speed after accelerating motion during start up is constant at 0.1 m/s until it comes to instant stop. Belt is driving a sled positioned on the sliders which may weight up to 500 kg in total (maximum allowed payload included). Such movement speed, if to consider the diameter of the wheel, translates to ~21 rpm (2.22 rad/s). In order to obtain best P-VEH performance, concluded result from chapter 1 shall be considered: applied configuration „a“ (Fig.20) decisively proved itself to be the best choice from considered selection (Fig.22), thus in-plane plucking configuration with PZT cantilever employing a permanent magnet as proof mass on the free end is chosen as the final designs composition. It should be emphasized that the considered motion speed (0.1 m/s) is extremely low and very challenging to exploit for energy harvesting purposes and can be classified as ultra-low speed hence a mechanical frequency up-conversion needs to be applied. Where for enhanced robustness and reliability, contactless excitation (magnetic plucking) solution shall be included.

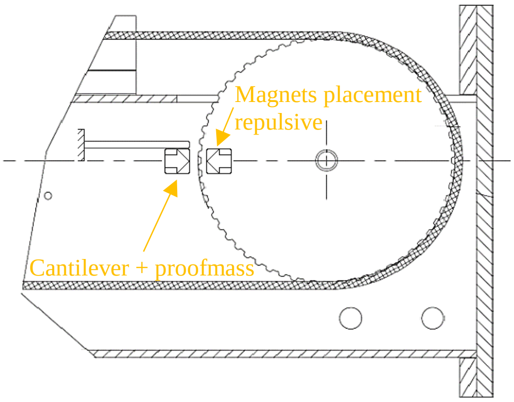


Fig.28. Configuration „a“ principle placement (Fig.20)

In order to proceed further development and concurrently conform case study questions no.1 and 3, current stage concluding remarks (Table 2) must be considered. Case study question no.2 approached in following chapter.

Table 2. Restricting dimensions and chosen properties to be considered for P-VEH setup

Dimensions / speeds / configuration	**Values/Units/Properties**
Space/area available for entire EH setup	Height:68 mm width:54 mm length: limited by slider assembly length
Movement characteristics	Rotational, bidirectional
Movement speed (driven cogwheel)	0.1 m/s (~21 rpm, 2.22 rad/s)
MFU required	Yes, proposed belt driven composition for MFU (Fig.33)
Energy harvesters configuration	In-plane magnetic plucking configuration (Fig.20)
Excitation method	Magnetic plucking (deflection and release of piezoelectric cantilever by means of magnetic coupling)

2.2. Power consumption of sensors

First prototype of PLSS at described configuration was put in to use in heavy industries welding stations, in order to test device as whole, as well conduct more specific measurements and observations. One PLSS was serving 2 welding workplaces, through 3 shift production over a longer period of time. As requested, manufacturer conducted measurements on lift platform sensors in order to acquire precise power consumption during 1 work shift (Fig.29). Currently lift platform hosts 5 proximity sensors, which results per shift can be used as reference power consumption in order to fulfill case study assignment nr. 2.

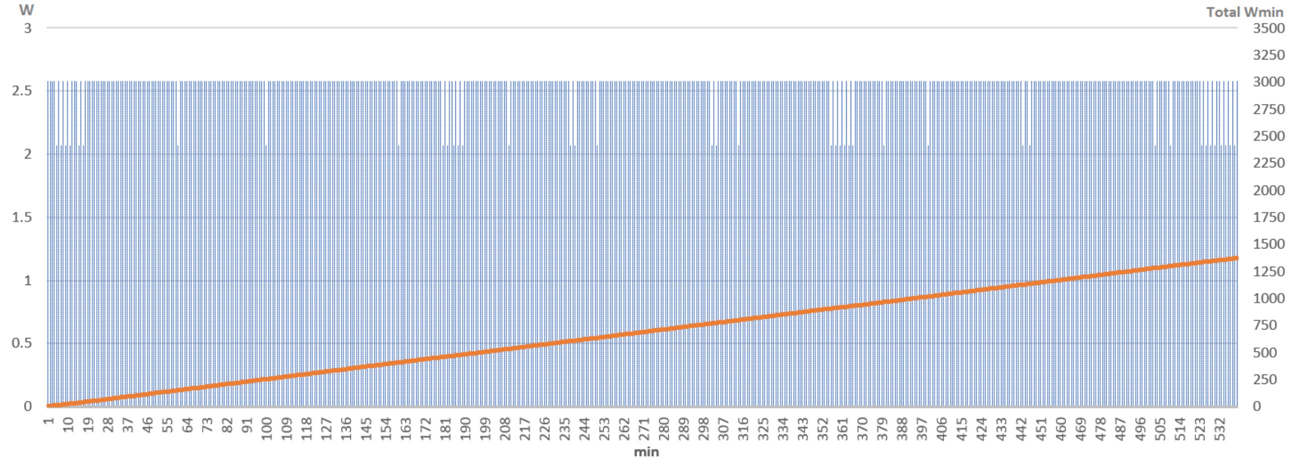


Fig.29. Lift platform sensors 1 shift power consumption (1400Wmin ≈ 23,33Wh ≈ 83988J) 540min

According to provided information, the constant idle current is ~2 W/min and cycle consumption ~2,6 W/min. During given shift storing cycle has been run 40 times, which according to manufacturer’s longer observations is the same throughout every work shift.

Considering initial concept, energy harvesting takes place on lift platform and for powering only on-board sensors, hence cycle movement peculiarities must be considered. Throughout the storing/retrieving cycle, belt drive always executes exactly the same movement, regardless of storage shelf level, the traveled distance for belt driving cog is the same (Fig.30). By knowing the movement speed and duration between cycle positions, calculated rotating time for cogwheel intended for EH purposes is 27 sec/cycle. During one shift, generally 40 cycles are made, resulting in 18 min of turning time for belt driving cogwheel.

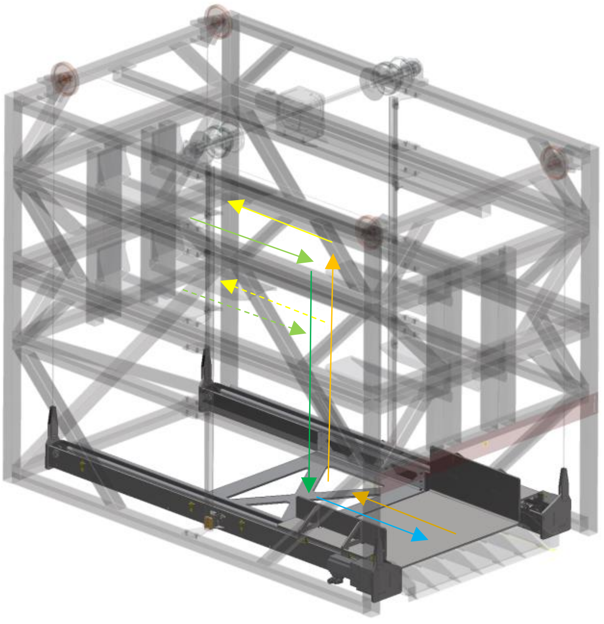


Fig.30. PLSS operation cycle movement

In order to power currently used sensors via energy harvesting, accumulated and stored energy from P-VEHs per one shift (9 h) should exceed 83988J (~9332 J per 1 hour), in order to cover operational and idle power consumption over time. In described relatively power-hungry conditions, one generator for harvesting definitely will not ensure sufficient accumulation of power during given turning time hence EH composition with several P-VEHs must be deployed.

2.2.1. P-VEH specifications

For energy harvesting purposes a piezoelectric bending transducer must be selected, where cantilever design with a magnet on the free end as proof mass would be applicable. In addition, restrictive dimensions (Table 2) must be considered in such manner that several P-VEHs would be possible to be installed in given area. Chosen configuration „a“ (Fig.28) in conjunction with restrictive dimensions require rather compact solution (Fig.31). As known from previous chapters, driven wheel movement speed is very low, hence might not provide sufficient excitation conditions if P-VEHs are directly mounted to driven wheel (Fig.31(a)). Nevertheless, one simplest option for up-conversion seems highly promising due higher amount of applicable harvesters in addition to speed (m/s) up-conversion, extra belt driven shaft in close proximity of driving cog (Fig.31-B).

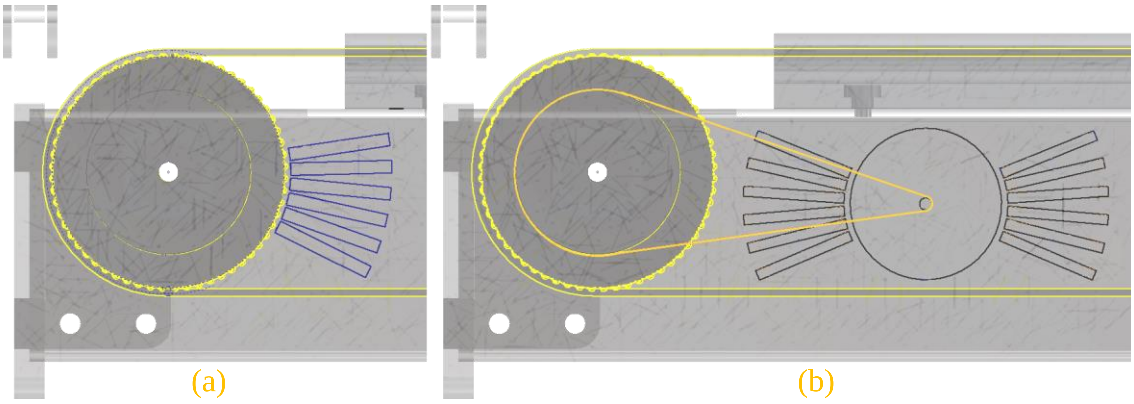


Fig.31. Reserved area 40×4 mm per PEH cantilever. A – direct-, B – up-conversion mount.

In addition to compact design, used P-VEHs must be reliable even in vastly varying temperature ranges, accordingly to readings obtained from first prototype testing at welding stations, average ambient temperature during winter season in exploited production hall varied from 2 °C to 32 °C (measured over weekends). Given conditions can’t be considered as most extreme case where PLSS may be deployed. In addition to welding stations, if same hall or in close proximity has an operating powder coating oven – the momentary temperature fluctuations can become more frequent. Powder coating in heavy industry is commonly used. Thus, wider range of temperature fluctuation must be considered, in worst case scenario, negative temperatures can occur.

2.2.2. Selecting piezoelectric energy harvester

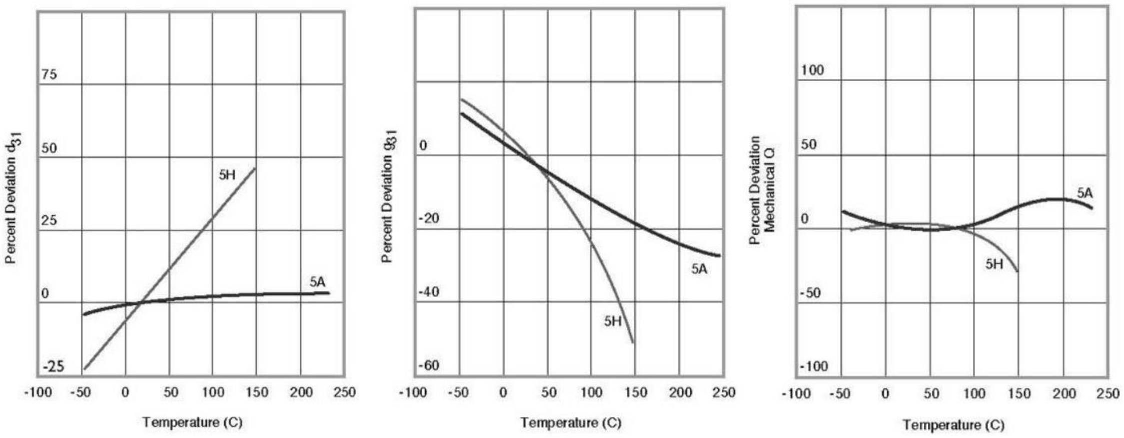
Selection criteria to be considered: a piezoelectric bending transducer, a magnet as proof mass is applicable, compact size to fit in to reserved area of 40×4 mm (Fig.31) and suitable in to environment with vastly varying temperatures.(2.2.1) For most suitable material selection, previously mentioned options (Fig.16) can be considered, in addition „Mide Technology“ is admissible [52]. To narrow down possible selection, material properties regarding temperature criteria can be considered firstly. Comparing previously discussed PZT material properties, final selection became between 3 options (Table 3).

Considering the P-VEHs size, surface area and length is the same, then „PZT-5H“ charge density compared to „PZT-5A“ is bigger by -130x10^{-12} C/N of charge produced per stress applied, however for „5A“ favor the electric field produced per stress applied is -2,1x10^{-3} m^2/C higher. Although there is a tradeoff between „charge density“ and „electric field“ produced, major argument for „PZT-5A“ advantage is its relative stability during temperature changes: at temperature between 0-50 °C, produced charge density (d31) deviation in percentage compared to „PZT-5H“ are nonexistent (Table 3-A). Produced electric field (g31) deviation in percentage is somewhat similar (Table 3-B) while the quality factor for „PZT-5A“ stays close to 0 meanwhile „PZT-5H“ value fluctuates 2...5 (Table 3-C). „PZT-5J“ is claimed as the middle option between 5H and 5A. However, to acquire more stable power generation during ambient temperature fluctuation, „PZT-5A“ is selected.

Table 3. Properties of selected piezoelectric materials [52]

Piezoelectric material	**Description**	**Properties** **Charge Density Produced / Stress Applied** **Electric Field Produced / Stress Applied**
PZT-5H	has the best piezoelectric material properties but is influenced by temperature change and has a slightly reduced temperature range	d_{31} -320 × 10^{-12} C/N g_{31} -9.5 × 10^{-3} m^2/C
PZT-5J	a compromise between 5H and 5A	d_{31} -210 × 10^{-12} C/N g_{31} -10.4 × 10^{-3} m^2/C
PZT-5A	is best for applications that have extreme temperatures and/or a widely varying temperature but the performance is desired to remain constant	d_{31} -190 × 10^{-12} C/N g_{31} -11.6 × 10^{-3} m^2/C

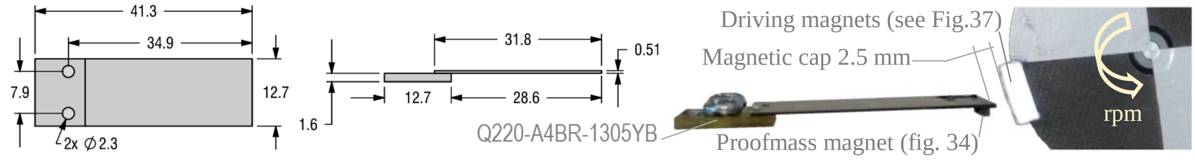
PZT 5J is not shown since it is a hybrid between PZT-5A and PZT-5H



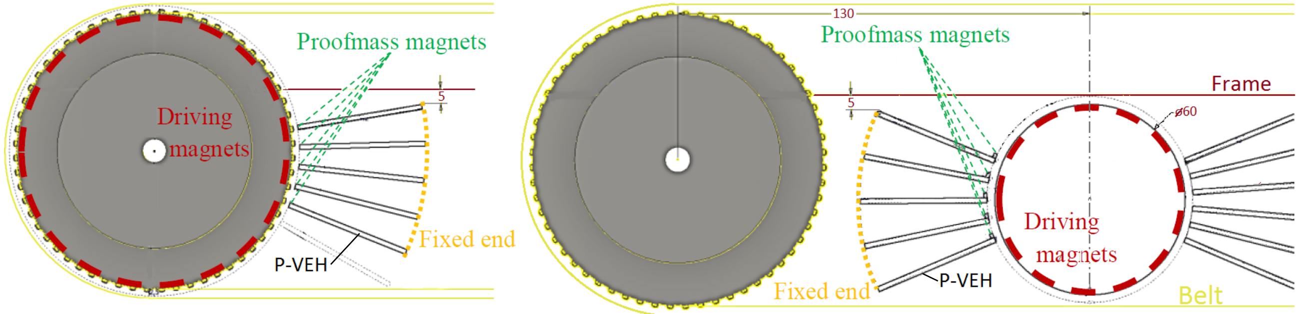
A B C

Regarding discussed P-VEHs characteristics and chosen material, final selection of cantilever dimensions came down to two suitable sizes (Table 4). Used selection criteria from available nomenclature: working mode chosen bender, with a quick mounting and material selected PZT-5A [53]. Described search resulted in two available criteria compliant bending transducers. At the time of writing, given P-VEHs were procured for research purposes however „2513YB“ was inadvertently damaged, consequently further research was carried out on „1305YB“ P-VEH. For compactness criteria „1305YB“ dimensions are excellent. Without modifying PLSS current setup at all, according to outline scheme it is feasible to integrate up to 20 P-VEHs in 1 belt driven MFU setup (Fig.33).

Table 4. Available sizes of criteria compliant piezoelectric bending transducers

Product (Manufacturer)	Product designation	Dimensions L×W×H (mm)	Mass
PZT Bending Transducer (Mide Technology)	Q220-A4BR-1305YB	41.3 × 12.7 × 1.6	1.6g
PZT Bending Transducer (Mide Technology)	Q220-A4BR-2513YB	69.9 × 31.8 × 1.6	8.0g
			[53]

Placement of P-VEHs is set 2.5 mm apart (magnetic cap) from driving wheel and tangentially aligned to ensure perpendicular placement relatively to the circular movement of driving wheel. Clearance between P-VEHs free ends on direct and MFU setup (Fig.32(a) and (b)) is left 5mm to exclude magnetic field interference between proof mass magnets. 5 mm clearance is left between frame wall on top and driving belt on bottom, in both configurations such tight conditions are greatly limiting deployable amount of P-VEHs. As shown on A and B composition (Fig.32), it is realistic to successfully mount 5 or 10 P-VEHs „1305YB“ .



(a) (b)

Fig.32. P-VEH Q220-A4BR-1305YB possible spacing and positioning in restricted area

In previously described setup, amount of PEHs can be increased, since „1305YB“ width is 12.7 mm, it is viable to mount PEHs parallel enabling to deploy 10 or 20 PEHs in shown A or B configuration. If imperative, described approach allows to notably increases mobilized amount of P-VEHs (Fig.33).

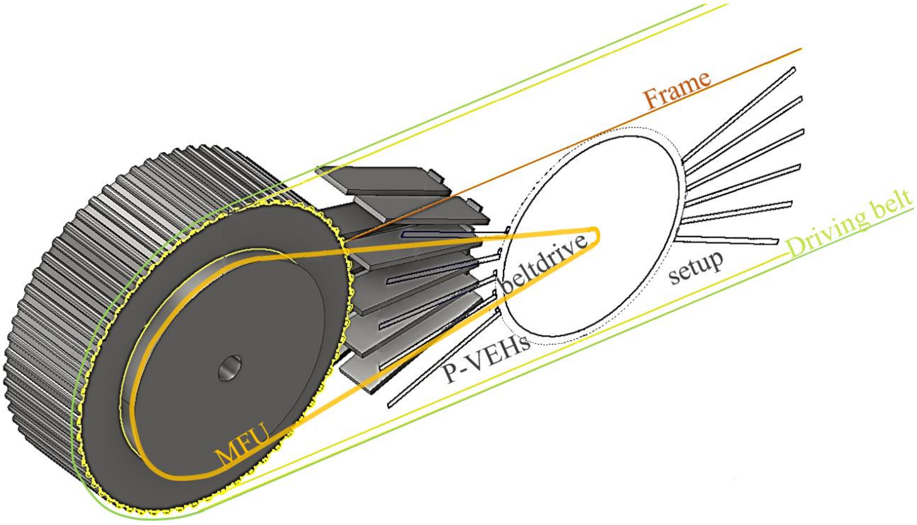


Fig.33. Outline scheme of applicable belt driven MFU parallel setup for several P-VEHs

2.2.3. Magnets selection

In order to achieve compactness of the proposed composition with maximum of 20 deployed P-VEHs, chosen magnets for contactless plucking must be sufficient and fit in assigned space between cantilever tips. As discussed, 5 mm separation between free ends makes it viable to install up to 20 P-VEHs. In addition to size restrictions, extremely small-scale magnets shall be avoided in order to ensure better manufacturability of P-VEHs setup.

Smaller magnets (Fig.32) require slower excitation speed since they generate sharper magnetic impulses, considering PLSS preliminary slow rotational motion to be harvested, given property furthermore favors magnets in small sizes. However diminutive magnets in commercially available nomenclature are, manufacturability has great influence on price hence cost-effectiveness thus must be taken into account. By assessing potential sizes, final selection was adjudicated for 5×1.5×1 mm (Fig.34), as small in size meanwhile still manufacturable without deploying magnifying glass and/or tweezers.

Material	NdFeB
Shape	Block
Size	5 x 1,5 x 1 mm
Side 1	5 mm
Side 2	1,5 mm
Side 3	1 mm
Pole faces	5 x 1.5 mm
Tolerance	+/- 0,1 mm
Weight	0,0570 g
Magnetisation	N45
Strength	approx. 140 g (approx. 1,37 N)
Max. working temperature	80°C (possibly lower) *

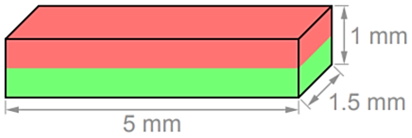


Fig.34. Chosen magnet for contactless excitation [54]

Magnet size for current project was selected inclining more on manufacturability aspect. In current scope selected magnet size supports avoiding unwanted magnetic field interferences while ensuring sufficient excitation forces, thus adequate experiment results can be obtained. Assuming finalized conclusion supports „energy-autonomous lift platform“ concept to be beneficial - a proposal as one part of further development can be derived. Magnet size hence different magnetic field characteristics affect pitch length between driving magnets (Fig.37(d)) and separation distance between driven and driving magnets. Excitation speed must be adjusted accordingly to obtain resonance when exciting over several magnets in sequence. Described amount of changing variables incorporated, conceal unknown number of plausibly efficient compositions to be investigated, hence proposed as a separate research project for the future.

2.3. Summary of P-VEH integration possibilities

The considered PLSS application case is rather specific, but the analyzed concept of energy harvesting within the lifting platform of PLSS could be applied in various similar systems and augment their functionality and energy autonomy, allowing to facilitate installation since wiring for integrated sensors would be minimized. For example, in medium and low payload storing systems, where delivery speeds are increased exponentially compared to speeds in heavy industry PLSS, additionally to ease of installation may conceal even greater effect for energy efficiency. Starting from production to installation procedures, the manufacturer expects several benefits from the energy-autonomous lift platform, not only for given PLSS as well other similar systems in the product family.

As rotational movement is widely used in all PLSS devices, energy harvesting was considered to exploit the movement of lift platform belt drive cog, with operational movement speed of 0.1 m/s. Given source of movement is positioned in rather tight conditions where free available space for EH system requires it to be compact, hence manufacturer has proposed an option to make changes in cog or frame if necessary, also possible for other elements however not preferred. Additionally, 1st PLSS prototypes are being tested where significant fluctuations in ambient temperature has been recorded – mentioned aspect was considered when selecting P-VEHs material type. PLSS device operation cycle peculiarities: harvestable movement period during one work shift (9 h) is measured around 18 min, where currently deployed five sensors over 9h consume ~83988 J of energy in total. Considering short cycle time and long power consuming idle time, energy harvesting during such a short time in comparison long work shift duration likely will not be sufficient. Hence (Nr.2, Table 1) currently used sensors must be replaced. As well proposal of applicable belt driven MFU parallel setup for several P-VEHs deployment was made (Fig.33).

Chosen piezoelectric bending transducers for further development are compliant with stated predefined technical requirements: P-VEH compact size, sustainable performance at temperature fluctuations and suitable small-size magnets for proof mass. Selected P-VEHs dimensions (41.3×12.7×1.6) are excellent for compact design of P-VEHs setup. In proposed parallel setup conditions, it is viable to deploy up to 20 P-VEHs in one integrated energy harvesting system. Complementing compactness and avoiding unwanted interferences between magnetic fields, deployable magnets sizes were chosen to maintain manufacturability without necessitating costly dedicated manufacturing equipment.

Assuming „energy-autonomous lift platform“ concept to be beneficial - a proposal as separate research project for the future was made: Since magnets with different sizes possess different magnetic field characteristics (different magnetic impulse sharpness). Separation distance between driven and driving magnets, as well pitch length between driving magnets positioned in sequence (Fig.37(d)) affect magnetic plucking characteristics. In addition, excitation speed can be adjusted to obtain resonance when excitation takes place over sequence of driving magnets. Given amount of changing variables incorporated conceal unknown number of plausibly efficient compositions for contactless magnetic plucking to be investigated.

3. Experimental study

Experimental setup (Fig.35) for mimicking and analyzing possible P-VEHs setups in PLSS was implemented. Distance between cantilever and driving magnets can be adjusted by a micrometer. Turntable rotational speed is controlled and constantly monitored by laser Doppler vibrometer 1, where piezoelectric cantilever displacement was monitored by the second laser Doppler vibrometer 2. PZT cantilever impedance was measured 6.2 kΩ (Fig.36). To obtain maximum amount of energy input and output resistance must be the same, thus resistance on resistor box in cantilever circuit was set on 6.2 kΩ.

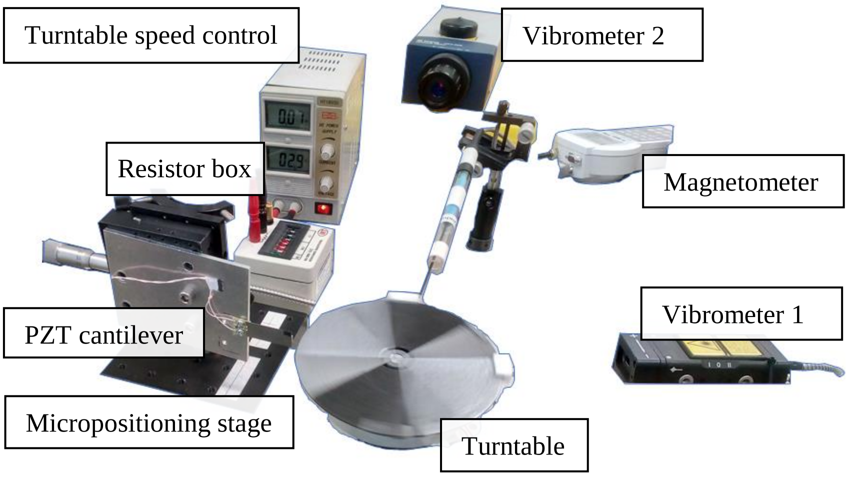


Fig.35. Experimental setup

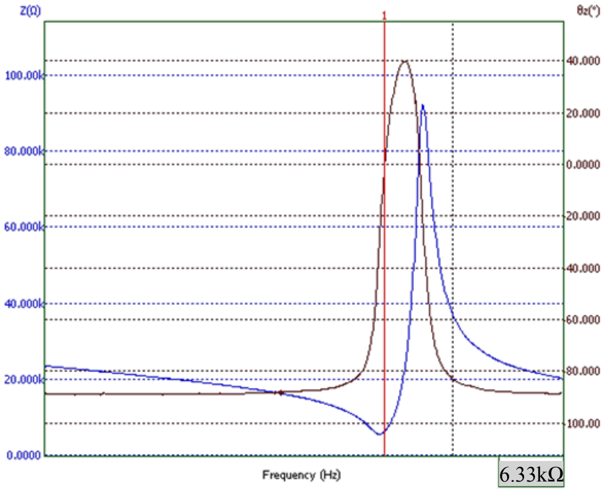


Fig.36. Q220-A4BR-1305YB PEHs Impedance measurement result 6,3 kΩ

Magnet sets on turntable and separation of magnets in sequence (Fig.37(d)) is: 4 magnets set with 3.2 mm separation (hereafter referred as: 4MS), 3 magnets set with 7.89 mm separation (3MS) and 1 single magnet (Fig.37). Diameter of the turntable is 136 mm (radius from center to magnets is 68 mm). Initial data is given in m/s, readings from vibrometer were received in rpm thus for clarity a conversion to m/s is made (Table 5).

$$rpm = \frac{60}{2\pi \times r} v \tag{1}$$

Where, rpm – revolutions per minute, r – radius [m] and v – m/s.

Table 5. Conversion between rpm and m/s

RPM	m/s	RPM	m/s
14	0.1	90	0.64
30	0.21	100	0.71
60	0.43	110	0.78
80	0.57	120	0.85

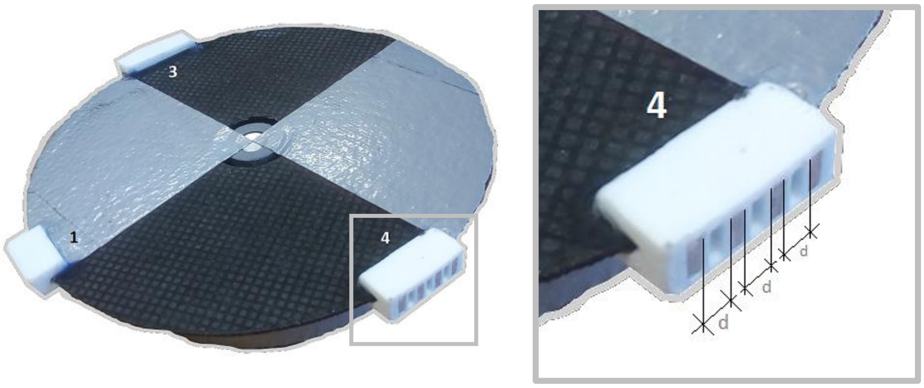


Fig.37. Turntable magnet sets: single, 3MS and 4MS (d-separation distance)

3.1. Measurement results

Measurements were carried out in the range of 10, 20…120 rpm and selection of most relevant results are presented as follows. Rpm is converted to m/s for better understanding, in same units as initial operational speeds were given (Table 5).

Preliminarily discussed harvestable speeds in discussed PLSS are too slow for direct energy harvesting. As results show, magnetic plucking on 0.1 m/s directly induces weak and shallow oscillations (displacement of PZT cantilever ±0.3 mm) correspondingly generating very low peak to peak voltage levels (highest at 1,06V)(Fig.38). Obtained diminutive amount of energy excludes option for direct energy harvesting hence MFU method must be implemented.

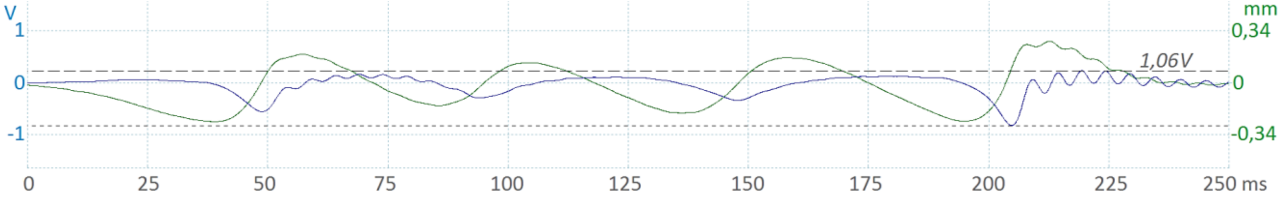


Fig.38. Initial measurements: 4MS excitation speed 0.1 m/s, measured: transient voltage(V) and displacement response (mm)

Proceeding comparison of initial measurement results to higher excitation speeds, at about 0.56 m/s an intriguing phenomenon occurred. By gradually increasing excitation speed, obtained peak to peak voltage level grew higher until a sudden drop at even further excitation speed increase. If to view 0.56 m/s excitation plot (Fig.40) in comparison to 0.64 m/s (Fig.39), mentioned occurrence might be caused by correlation between excitation speed and magnets separation 7.89 mm on 3MS (Fig.37(d)).

By inspecting displacement curve measured at 0.64 m/s, fluctuations occur in range of ±0.5 mm and no growing trend in amplitude is visible during excitation with magnets in sequence ((4MS or 3MS)Fig.39). In comparison to 0.08 m/s slower excitation speed, the displacement curve at 0.54 m/s reveals a growing trend in amplitude, ramping up to 0,65 mm of displacement (Fig.40(3MS)). Presumably magnetic coupling at each following magnet utilizes a portion of previously induced fluctuation, thus displacement curve is ramping higher over sequentially placed excitation magnets (Fig.42). Since PZT cantilever displacement directly relates to produced voltage, consequently amplitude on transient voltage curve is also showing a growing trend during 3MS excitation (Fig.40(3MS)). Hence indicated peak to peak voltage at 0.56 m/s (8,69V) is ~1,9V higher than achieved at 0.64 m/s (6,8V) (Fig.39).

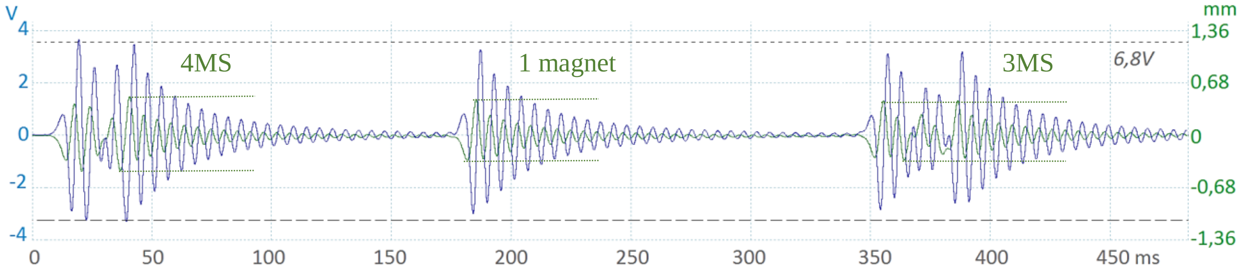


Fig.39. Initial measurements: excitation speed 0.64 m/s, measured: transient voltage (V) and displacement response (mm) peak displacements indicated by dash line

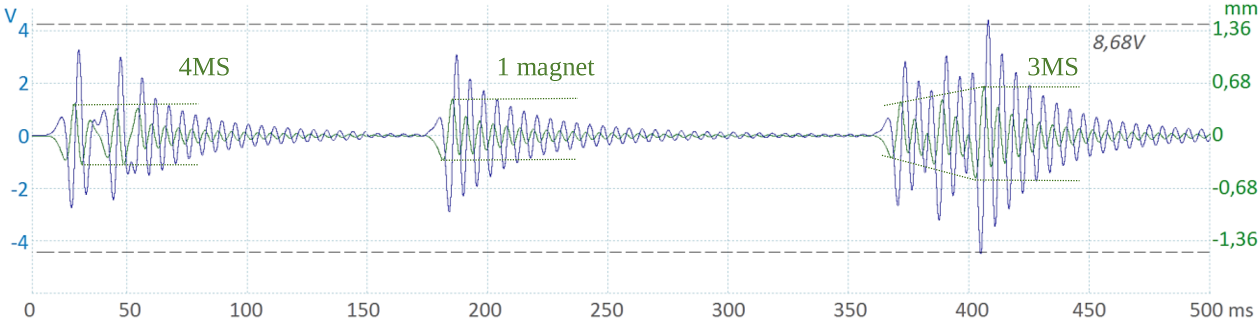


Fig.40. Initial measurements: excitation speed 0.56 m/s, measured: transient voltage (V) and displacement response (mm) peak displacements indicated by dash line, emphasized growing trend at 3MS excitation

As excitation speed during ongoing measurements were continued to increase, previously discussed phenomenon of a growing trend in amplitude started to occur again at about 0.78 m/s. Presumed correlation between excitation speed and magnets separation seems to hold true, since discussed amplitude ramping also appeared at sequential excitation by 4MS on 0.85 m/s as it did during 0.56 m/s by 3MS. From all conducted measurements, highest results were obtained at 0.85 m/s, displacement curve fluctuations occur in range of ±1.25 mm and steep growing trend of amplitude is visible during excitation with sequential magnets.(Fig.41(4MS))

One drawback of deployed P-VEHs is their fragility, since the PZT material is ceramic they are inherently brittle. Consequently, fractures at overbending are easy to occur thus on given separation (2.5 mm), highest experimented speed was left on 0.85 m/s in order to avoid incurably damaging deployed P-VEH.

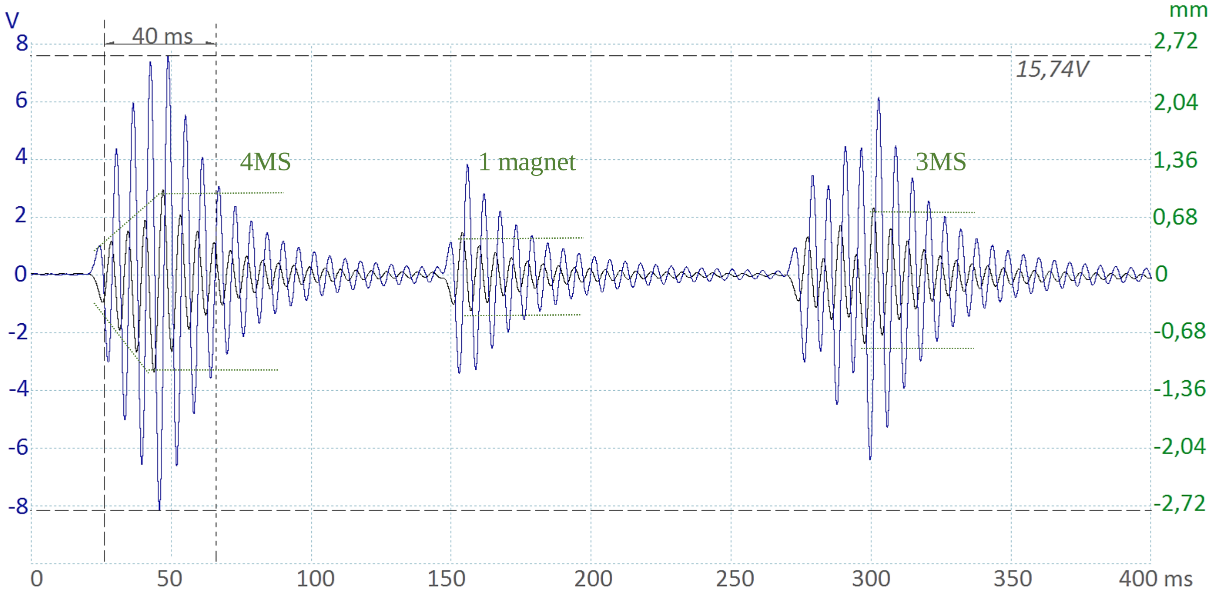


Fig.41. Movement speed 0.85 m/s, peak to peak voltage 15.7 V.

Previously discussed peak-to-peak voltage from direct readings are adequate to narrow further analyses down to fewer data sets. As it can be deduced, voltage output at slow speeds are too low for P-VEH to generate enough energy to power PLSS sensors thus measured data can be assorted accordingly. Selection for further analyses is made in Table 5, slower excitation speeds from 0.1 to 0.5 m/s are chosen for overview how amplitude of transient vibration response and correlating transient voltage changes as excitation speed was being increased. For comparison and analyses on harvestable speeds, results at excitation speed of 0.5 to 0.9 m/s are selected. (Table 5).

3.2. Analyses of generated energy at chosen excitation speeds

As discussed before, measurements were executed in the range of 10…120 rpm and at different magnetic cap size (2.5 mm and 2.3 mm). Magnetic cap: the separation between driven and driving magnets. Driving magnets were partitioned in three sets: 4MS with 3.2 mm separation, 1 single magnet and 3MS with 7.89 mm separation (Fig.37). In addition to setup properties, from initial measurement data it was inferred that slower speeds do not produce usable voltage levels from energy harvesting perspective. Thus, a selection for data to be analyzed on specific speeds was made. Starting from slower speeds 14, 30 and 60 rpm – to see how characteristics of excitations and obtained results change in constant conditions while excitation speed is increased. Judged on the basis of initial measurement data and occurred phenomenon of steep growing trend of amplitude during sequential excitation, at certain speeds the driving magnets separation (3MS and 4MS) (Fig.42) seemed to coincide with excitation speed. Readings of P-VEH displacement and resulting voltage clearly indicate the nature of excitation, by 1 or several magnets. However, it is not precisely clear on which given moment magnetic coupling actually begins hence marked fluctuation (1,2,3 and 4) are treated as presumable magnetic coupling and decoupling (Fig.42).

Discussed phenomenon occurred on 90 and 120 rpm, thus selected data range for further analyses is from 80, 90 to 120 rpm. Throughout entire experiment, the P-VEHs behavior to magnetic cap size and excitation speed changes were spectated. After reaching 120 rpm at 2.5 mm separation, by judging the intensity of excitation, it was decided to omit further speed increases in order to avoid incurably damaging deployed P-VEH. Meanwhile measurements were carried out, in comparison to highest speed readings, similar occurrence to previously discussed phenomenon appeared again at

110 rpm. As excitation speed reached 120 rpm, amplitude of transient vibration increased evidently in turn resulting in highest transient voltage readings. However in current attempt 120 rpm stayed as last recording, the question remains: would further excitation speed increase generate higher electrical output sustainably and in what extent? Regarding mentioned decision to omit further speed increase, in current projects scope >120 rpm experiments will not be conducted however a proposal for further research can be made. As higher excitation speeds might conceal beneficial aspects and greater energy levels, damage (fracture of piezoceramic) is also more likely to appear thus experimenting on the edge of high intensity and deflection, sustain questions arise.

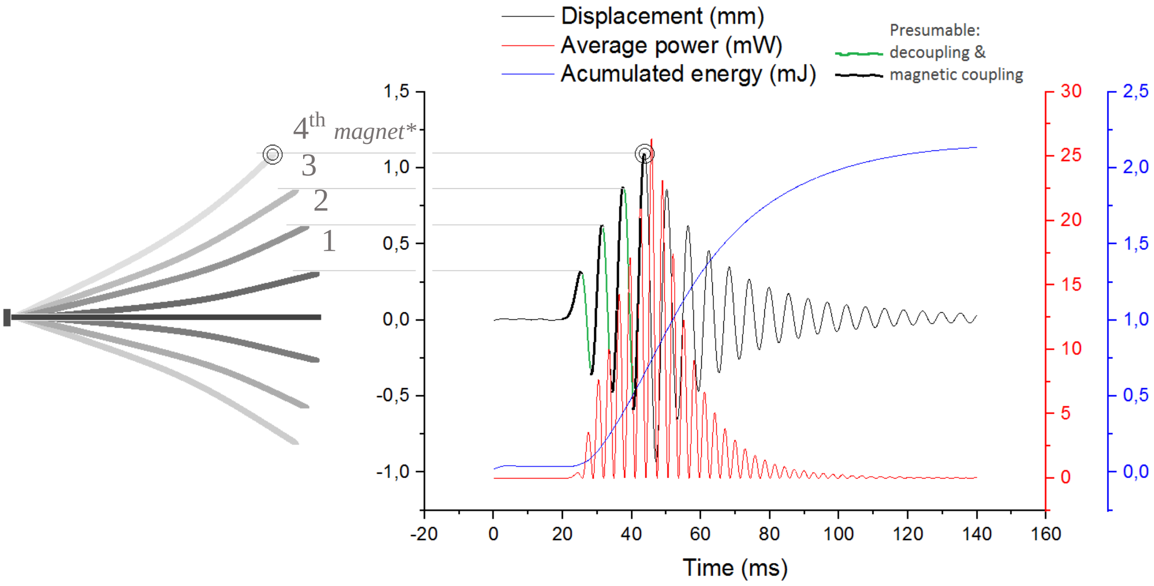


Fig.42. Presumable de-/coupling based on experiment data & observed PEH behavior

3.2.1. Generation of electrical energy at low excitation speeds

In project scope: 14, 30 and 60 RPMs (0.1, 0.21, and 0.43 m/s), are considered as low excitation speeds. Since the amplitude of transient vibration response was relatively low, generated electrical output from energy harvesting perspective is not satisfactory. However for an informational overview, how EH characteristics change and energy levels rise as excitation speed is increased, selected data is calculated ((1), (2) and (3)[55]) and results graphically plotted (Fig.43,Fig.44,Fig.45).

$$V_{rms} = \sqrt{\frac{V^2}{k}}, \tag{1}$$

$$P_{avg} = \frac{V_{rms}^2}{R}, \tag{2}$$

$$E = \frac{V^2}{R} D_t, \tag{3}$$

where: V_{rms} – root-mean-square voltage [V], V – instantaneous voltage [V], k – amount of analyzed “V” values, P_{avg} – average power [mW], R – impedance [Ω], E – accumulated energy [mJ], D_t – sampling interval [ms].

By applying described equations, RMS voltage, generated average power and accumulated energy per measured moment of time can be calculated. At low excitation speeds, electrical and dynamic peculiarities of s single operational cycle (complete transient response) are examined as a function of various excitation speeds.

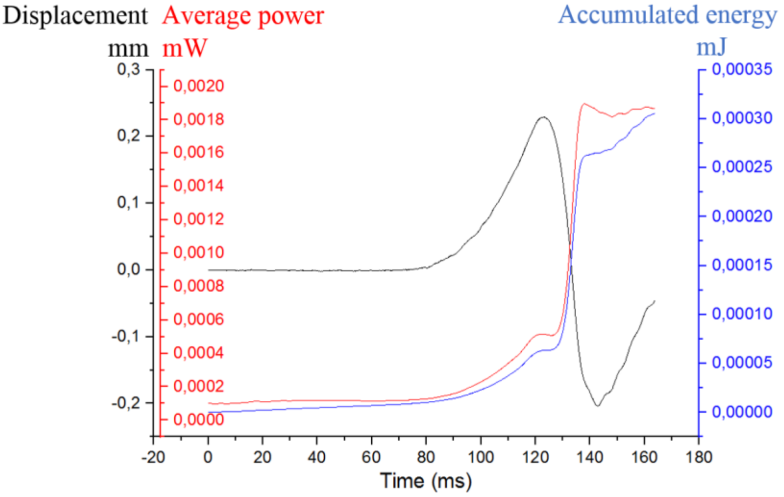


Fig.43. Generated energy at 0.1 m/s (14 rpm)

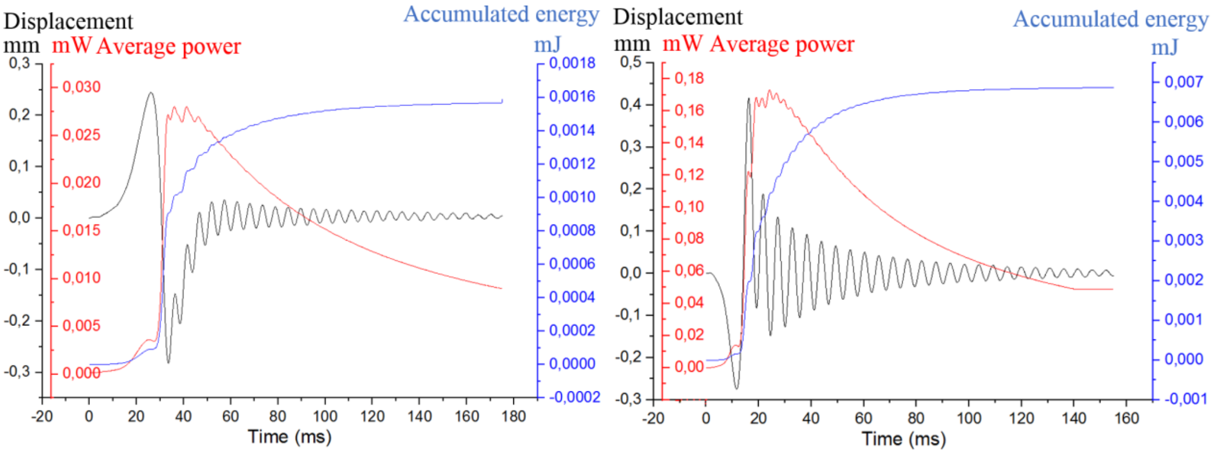


Fig.44. Generated energy at 0.21 m/s (30 rpm) and 0.43 m/s (60 rpm).

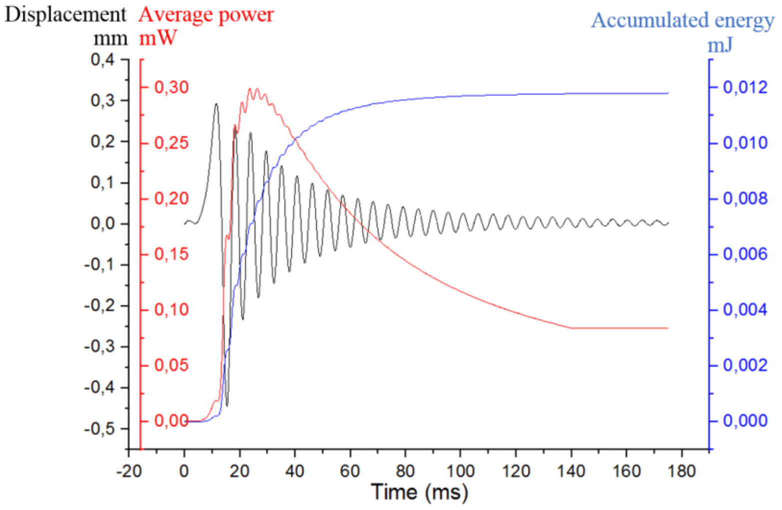


Fig.45. Generated energy at 0.57 m/s (80 rpm)

If to inspect obtained values in comparison, as plucking speed increases rather steeply, resulting displacement follows insignificantly. Considering energy generation being directly related to displacement and plucking sharpness, accumulated energy levels remain relatively low throughout 0.1-0.4 m/s.(Table 6) Clearly low excitation speeds need application of MFU method for effective impulsive excitation in order to ensure conditions for high-performance energy harvesting.

Table 6. Low speed readings tot up table

1 pluck, speed m/s	Displacement, mm		Average power peak, mW	Accumulated energy, mJ
0.10 (14RPM)	+0.22	-0.21	0.00185	0.0003
0.21 (30RPM)	+0.24	-0.28	0.0256	0.0016
0.43 (60RPM)	+0.28	-0.40	0.17	0.007
0.57 (80RPM)	+0.30	-0.44	0.28	0.012

3.2.2. Generation of electrical energy at high excitation speeds

In current project scope: 80, 90…120 rpm (0.57, 0.64, 0.71, 0.78 and 0.85m/s), are considered as high excitation speeds which produced highest amplitude of transient voltages during initial measurements thus most promising from EH perspective. Selected data for following calculations ((1), (2) and (3)) include measurement results in mentioned speed range with 3MS and 4MS excitations. For clearer overview, characteristics of measurement results at high excitation speeds gathered in Table 7 and Table 8. As calculations and analyses reveal, previous presumption of mentioned phenomenon (discussed at 3.1, Fig.40, 41) where magnets in sequence are utilizing a portion of previously induced fluctuation appears to be true. If to see 3MS excitation at 0.57 m/s, amplitude of displacement curves first oscillation is peaking at similar value 0.3 mm (single magnet excitation) as after 3MS excitation at first time moment *1** (Fig.46). Resulting oscillations after time moment *1** until second magnetic coupling event (*2**) appear akin to induced oscillation between *2** and the beginning of third magnetic coupling event (*3**). Ultimately decoupling after *3** evokes highest displacement up to ~0.6 mm, thus peaking average power generation to ~0.4 mW. In contrast to 4MS characteristics, described phenomenon do not occur (Fig.47), as well it is complex to clearly distinguish start of magnetic coupling event and end (decoupling) on displacement curve. In general, results of 4MS excitation on 0.57 m/s are chaotic, coherently magnet separation does not correlate to excitation speed hence produces lesser energy.

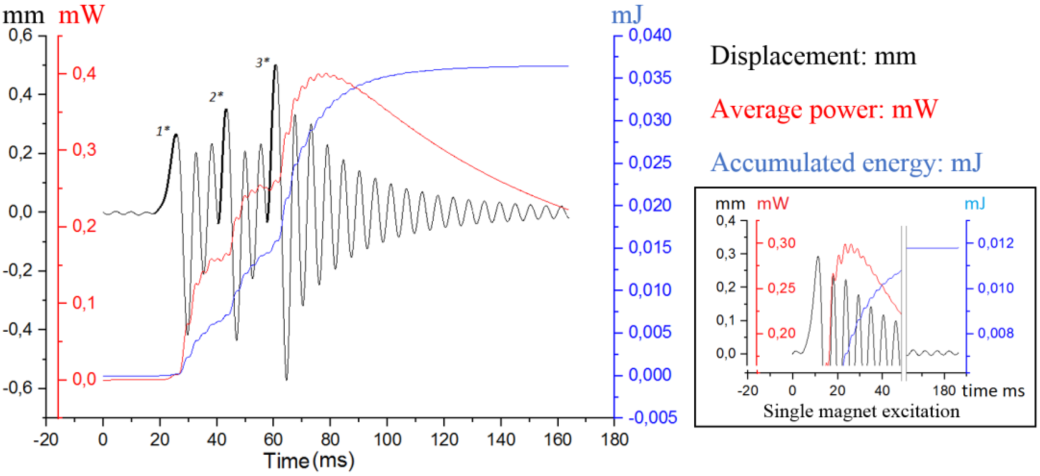


Fig.46. Generated energy at 0.57m/s (80 rpm) set of 3 magnets, *presumable** magnetic coupling

In conclusion, by deploying several magnets for contactless plucking, for increasing generated power corresponding magnet separation to excitation speed must be determined. As apparent from given 3MS & 4MS excitation example at 0.57 m/s (Fig.47), sequentially placed magnets correlating to excitation speed increase generated energy. Hence for further development, excitation speed after MFU should take advantage of correlating sequential magnet separation.

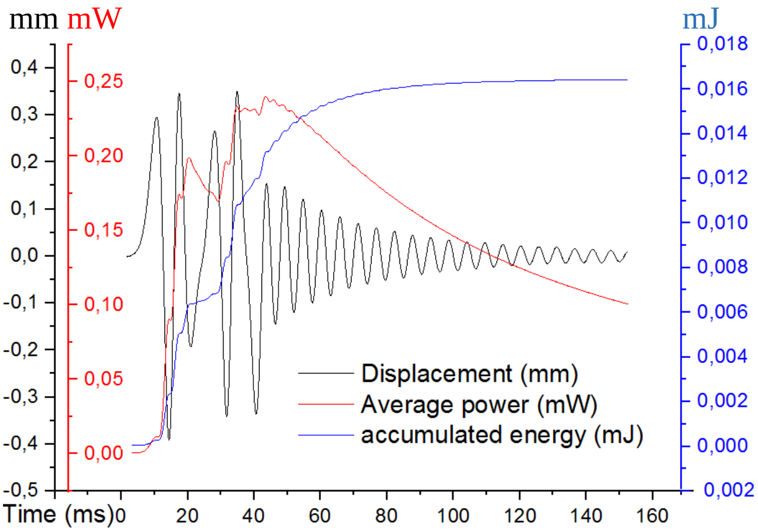


Fig.47. Generated energy at 0.57m/s (80 rpm) set of 4 magnets

If to investigate described highest result in comparison to other speeds, it becomes clearly visible that produced power and accumulated total energy is the highest. In addition, by examining displacement characteristics: on 0.64 and 0.71 m/s results are irregular with low energy generation (Fig.48Fig.49), even though 4MS at 0.71 m/s induces rather high displacement (±0.5 mm), in comparison total accumulated energy is still lower than generated by 3MS excitation at 0.57 m/s (0.029 vs 0.036 mJ)(Fig.48). Given example further supports previous statement that discussed phenomenon utilizing previously induced fluctuations should be taken advantage of for greater energy generation.

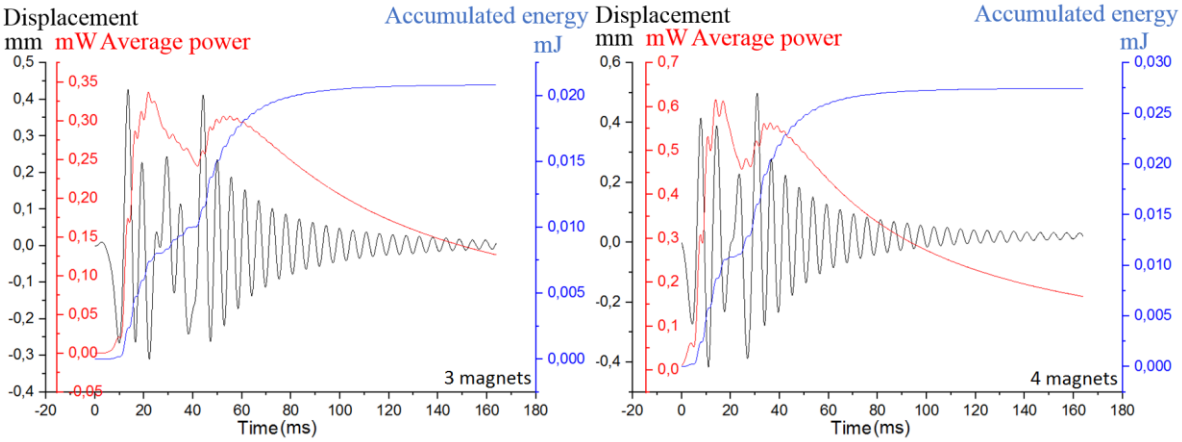


Fig.48. Generated energy at 0.64 m/s (90 rpm) set of 3 and 4 magnets

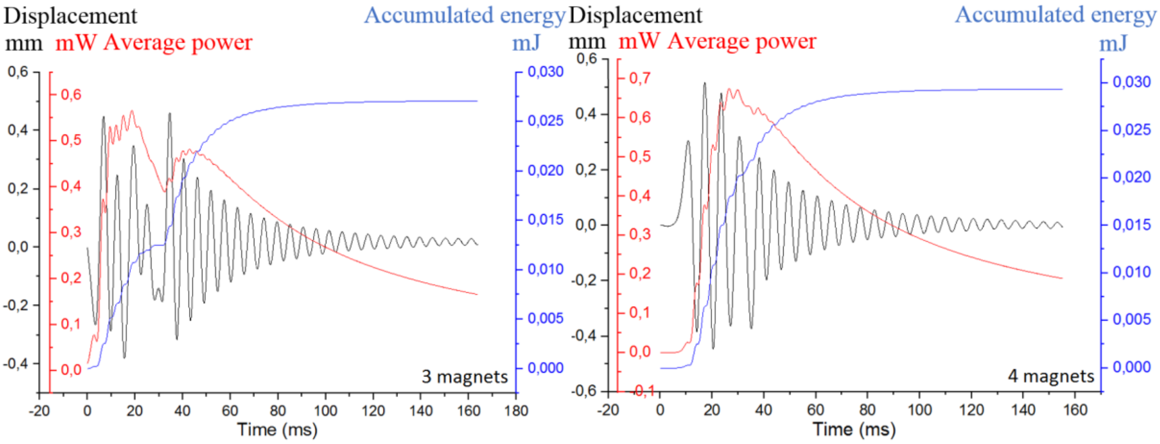


Fig.49. Generated energy at 0.71 m/s (100 rpm) set of 3 and 4 magnets

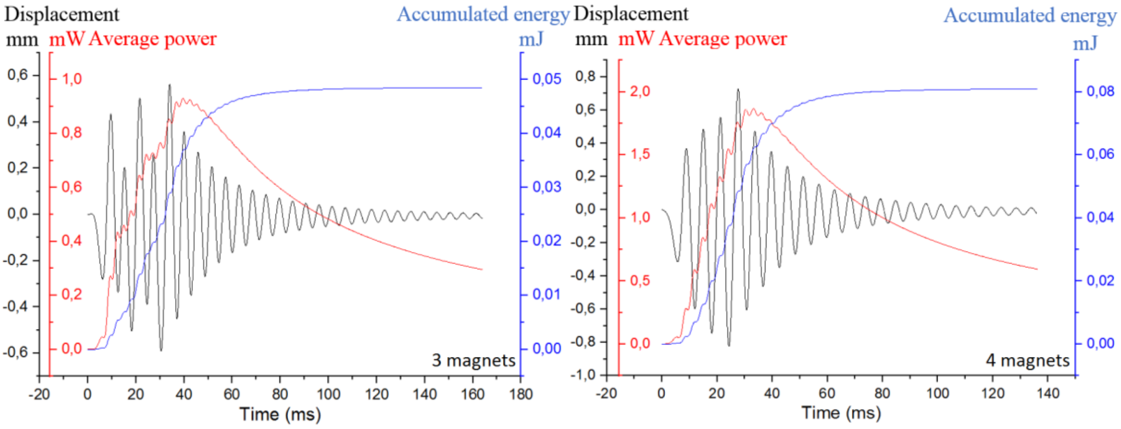


Fig.50. Generated energy at 0.78 m/s (110 rpm) set of 3 and 4 magnets

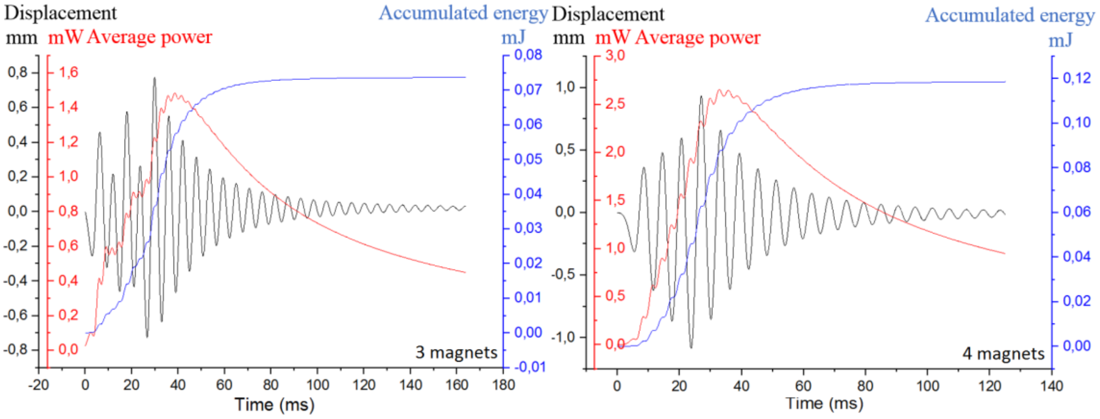


Fig.51. Generated energy at 0.85 m/s (120 rpm) set of 3 and 4 magnets

Though increased excitation speed didn't rise energy generation, 0.71m/s displacement (Fig.50) in comparison to 0.85 m/s (Fig.51) shows mild transition towards pursued phenomenon utilizing previous oscillations. In comparative scenario, speed increase of 0.07 m/s multiplied “accumulated energy” by 2.75 times (from 0.029 to 0.08 mJ (Table 8)). In attempt to extract maximum from given experiment without damaging the PZT transducer, meanwhile sustaining mentioned phenomenon - speed increase to 0,85m/s did not turn out as significant as expected yet resulted in the highest power and energy levels obtained in the experiment (Table 7,Table 8).

Table 7. High speed readings tot up table of 3MS plucking

3 set plucking, speed m/s	Displacement, mm		Average power peak, mW	Accumulated energy, mJ
0.57 (80)	+0.5	-0.6	0.4	0.036
0.64 (90)	+0.4	-0.3	0.325	0.021
0.71 (100)	+0.48	-0.4	0.55	0.027
0.78 (110)	+0.5	-0.6	0.91	0.048
0.85 (120)	+0.78	-0.78	1.5	0.075

Table 8. High speed readings tot up table of 4MS plucking

4 set plucking, speed m/s	Displacement, mm		Average power peak, mW	Accumulated energy, mJ
0.57 (80)	+0.35	-0.4	0.24	0.0165
0.64 (90)	+0.5	-0.4	0.61	0.027

0.71 (100)	+0.52	-0.48	0.65	0.029
0.78 (110)	+0.7	-0.88	1.7	0.08
0.85 (120)	+0.9	-1.1	2.7	0.12

In addition to 2.5 mm separation, measurements at the same speeds were conducted with 2.3 mm separation as well (Chapter 3.1). In order to prevent piezoelectric transducer from damage, the highest speed tested was 0.64 m/s. The acquire results underperformed 2.5 mm separation at every excitation speed. Even though the separation decrease was intended to obtain sharper plucking, no utilizing like phenomenon occurred from 0.49...0.67 m/s (70, 80 and 90 rpm) while all results under 0.57 m/s classify as low speeds. Based on amplitude of transient vibration response measured on low speeds, measurements in comparison on 2.3 mm and 2.5 mm separation– the results are similar: too low for sufficient energy harvesting. As the highest speed readings indicate (Fig.52), displacement (coupling-/decoupling) is irregular, thus generated energy levels are insufficiently low. Due to separation decrease, it is now known that even if magnetic plucking (magnetic field) intensity might increase, from sustained and efficient harvesting perspective it can have detrimental effect on bending PZT transducer. Considering poor overall performance, experiment results on 2.3 mm separation from further studies are excluded, however a proposal for further research can be made: investigate various setups with different excitation speeds and magnetic cap lengths to see their effect on P-VEHs performance and sustain.

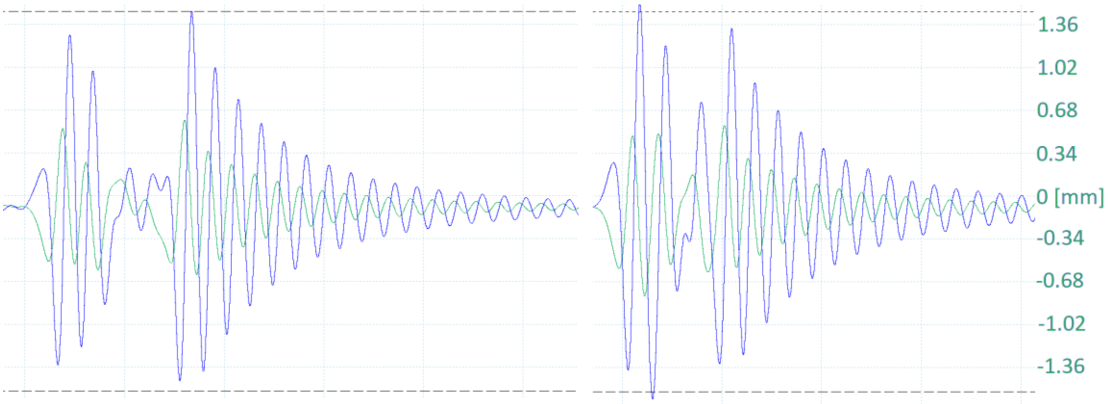


Fig.52. Movement speed 0.64 m/s (90 rpm), peak to peak displacement ±0.58 (green line)

3.2.3. Conclusion

Considering best relative performance at 0.85 m/s with 3.2 mm magnet separation, the following MFU setup can be designed accordingly. In addition to magnet wheel design regarding separation, belt drive MFU shall be designed so, that 0.1 m/s constant PLSS operation speed is converted to 0.85 m/s. Conjointly with completion of MFU setup, the case study question nr.3 can be answered as well. Since 4 magnets set at 0.85 m/s outperformed all other compositions, obtained energy levels shall be used for further calculations, regarding plausible energy generation in device dependent conditions. As understanding of harvestable energy levels are determined, options satisfying case study question nr. 4 can be proposed.

4. Further development

It is possible to fit more than 1 P-VEH device into current geometrical restrictions set by PLSS dimensions. In addition, it is realized that several P-VEHs should be deployed to generate sufficient power output. As determined beforehand, it is possible to deploy up to 20 P-VEHs in one slider assembly (Fig.25). Currently used sensors will not be fully powered by the given energy harvesting solution (Table 1- Nr.1), because mentioned sensors are too power-hungry for feasibly harvestable energy levels (Table 1- Nr.2). However, from the perspective of energy-autonomous lift platform concept, wireless transmitters and on-board system must be powered by rechargeable battery thus require more energy efficient solution. Consequently, changes in given PLSS elements regarding sufficient energy harvesting must be made (Table 1 – Nr.3). In addition to swapping sensors with more suitable ones, on board CPU with wireless transmitter/receiver and battery pack with power conditioning must be added. By the scope of current project, proposed solution including described elements for on board circuit and sensors control will not be worked out. However, calculations of attainable energy levels by proposed EH design will be conducted, so purposefulness of further development and research can be understood. In general, deployed energy harvesting setup should generate and accumulate energy sustainably - relatively to the need of feasible "energy-autonomous" system.

4.1. MFU design

In order to provide 0.85 m/s excitation speed by magnets on magnet wheel, rotational speed up-conversion from driving 0.1 m/s to driven 0.85 m/s speed must be calculated. Belt is driven at speed of 0.1 m/s. Regarding diameters of components in proposed belt-drive MFU design (Fig.54), revolutions per minute (rpm) and linear velocity (m/s) are calculated accordingly (equation (1)), results shown in Table 9.

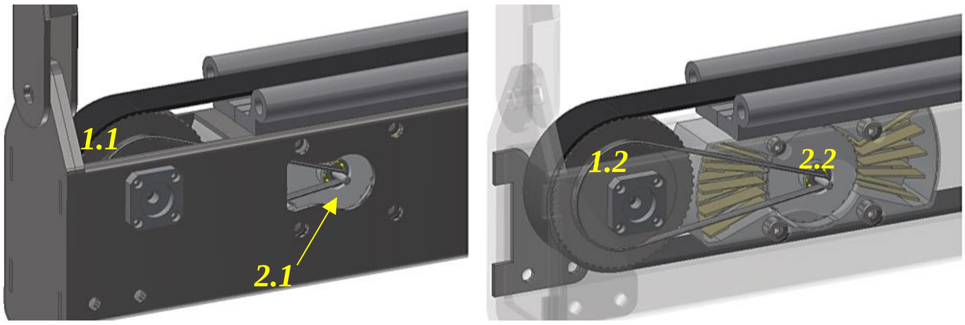


Fig.53. Manufacturable EH device "UCD" mount casing placement in slider assembly

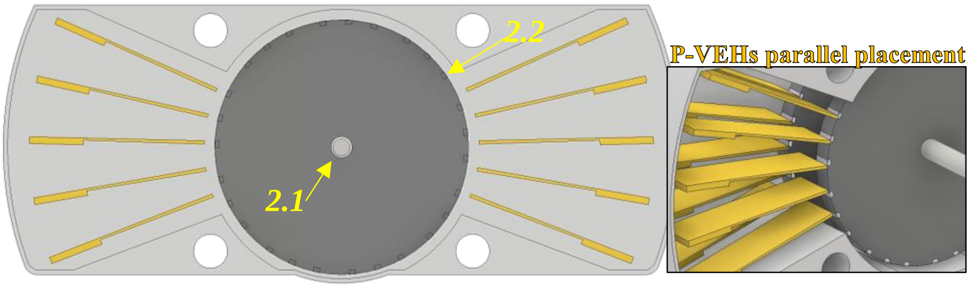


Fig.54. UCD - Internal placement of magnet wheel and "P-VEHs" (Mide Technology 1305YB)

The proposed mechanical frequency up-conversion design deploying P-VEHs (UCD) is manufacturable, capable of housing maximum 20 P-VEHs in parallel setup (Fig.54). Clearance between P-VEHs driven magnets is left 6mm. Considering peak displacements at excitation, in the worst-case scenario clearance can decrease to 4 mm, where magnetic field interference might affect harvesting performance, collision among P-VEHs is prevented. Magnet wheel is designed to hold 4MS with 5.2 mm separation hence each wheel is mounted with 9 sets. 2 mm larger separation between magnet sets is intended to accommodate free vibrations after 4MS ramping excitation.

Table 9. MFU belt-drive parameters (Fig.53)

Nr. 1.1	Main belt drive cog wheel	Axis 1	Radius= 45.925 mm	rpm= 20.793	0.1 m/s
Nr. 1.2	MFU belt wheel	Axis 1	Radius= 32.5 mm	rpm= 20.793	0.071 m/s
Nr. 2.1	Driving belt to shaft	Axis 2	Radius= 2.5 mm	rpm= 270.311	0.071 m/s
Nr. 2.2	Driven magnet wheel	Axis 2	Radius= 30 mm	rpm= 270.311	0.85 m/s

4.2. Estimation of expected vibration energy harvesting performance

The proposed belt driven MFU maximum quantity when housing 20 units of P-VEHs (Mide Technology 1305YB) arranged in parallel (Fig.54). Magnet wheels are designed to hold 9 magnet sets (Fig.37- 4MS). As stated beforehand, according to manufacturer: the minimum harvestable time to be considered, when driving wheel rotates at 0.1 m/s, during one work shift is 18 min (Chapter 2.2). According to given values, plausible generated energy by deploying the proposed MFU design can be calculated (Table 10). By taking into account the magnet wheel (Fig.54(2.2)) movement speed and 4MS excitation time with additional time for free vibrations (extra 2 mm separation)(Fig.51) – energy generation plot per single full magnet wheel rotation can be derived (Fig.55).

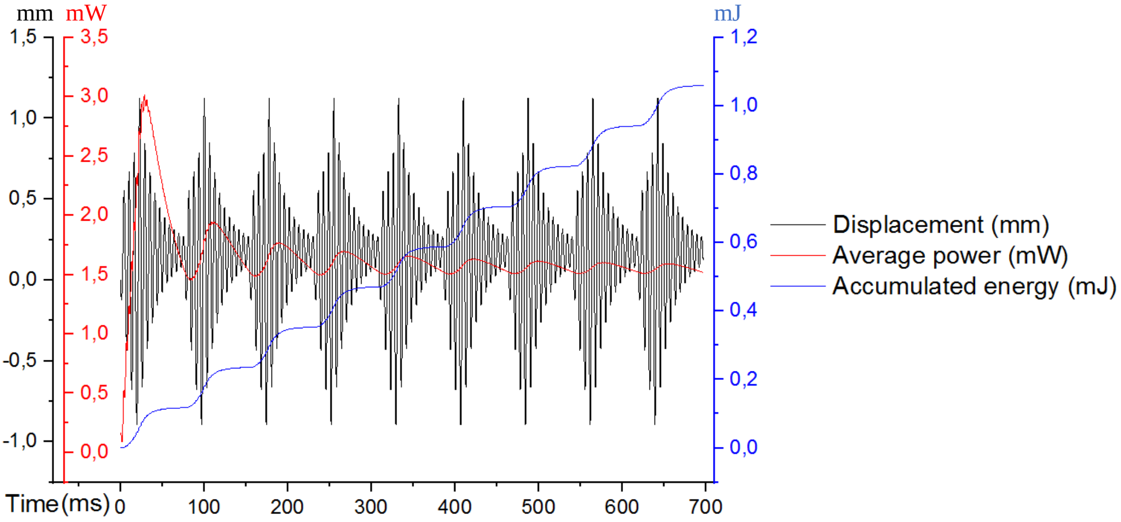


Fig.55. Estimation of energy generation at excitation speed of 0.85 m/s by 1 P-VEH per single magnet wheel revolution [mJ], displacement curve indicates each 4MS excitations (total 9)[mm]

Vibration energy harvesting results in Fig.55 predict EH performance in real-life conditions and vividly demonstrate that, despite P-VEH operation in resonance mode, the overall performance is relatively low (Table10(1)). Firstly, the available speed of 0.1 m/s needs UCD in addition. Considering heavy payload PLSS application peculiarities, slow initial speed may not become an obstacle if UCD wouldn’t have dimensional restrictions. In presented scenario, possible UCD size is greatly limited, hence achieved excitation speed trough MFU is in trade-off with the quantity of deployable P-VEHs . Geometrically magnet wheel size increase decreases amount of deployable P-VEHs and vise versa (Fig.54). The operational time available for EH in comparison to work shift duration is highly disadvantageous (Table10(3)), where work shift is measured in hours while only minutes are available for energy harvesting. It is clear that in given PLSS operational conditions sufficient and sustainable energy harvesting is not feasible (Table 10). Generated total energy levels are significantly lower than actually needed for powering of PLSS sensors, even when applying one of the most energy efficient solutions for wireless transmission (tx) available today: Bluetooth low energy (BLE). For example, a BLE capable ESP32 chip can be implemented, in general relatively energy efficient solution designed for described conditions. However, if to place ESP32 low consumption in comparison to currently proposed UCD solution, its performance becomes even more diminutive (Table 11). As one of the goals for the given project, regarding solely on the price of used 1305YB P-VEHs (Mide Technology 1305YB), achieving cost-effectiveness at given value (Table 10(9)) becomes hardly possible. In conclusion, proposed concept for “energy-autonomous lift platform” in specified heavy payload PLSS conditions did not prove itself to be viable from energy harvesting and cost-effectiveness perspective.

Main disadvantageous aspects for proposed “energy-autonomous lift platform” concept not to work in heavy payload PLS system were: low initial driving speed, UCD size restrictions causing a trade off in MFU excitation speed and amount of P-VEHs, available harvesting time ratio to work shift length (minutes to hours). Achievable cost-effectiveness when comparing current UCD cost to previous production expenses (Table10(10)), any additional components to make UCD viable in given PLSS conditions exceeds estimated budget thus not cost-efficient.Although UCD in heavy payload PLSS conditions is ineffective, as mentioned before, manufacturer could consider to implement energy-autonomous lift platform concept in other devices in LSS product family.

Operational conditions are more favorable in low payload LSS, since initial driving speeds are higher, separate UCD may not be needed if MFU is integrable in existing system. Hence EH setup less affected by dimensional restrictions and easier to achieve cost-efficiency if less additional parts are needed for complete EH solution. Above all, low payload LSS are used more frequently used e.g. in production, 1 storage device for small components and tools is used by all factory floor workers throughout the works shift thus achieved harvestable time to work shift length becomes more balanced (hours to hours). In conclusion, development of energy-autonomous lifting platform should be targeted to low payload LSS. If implemented successfully, then continue the development to medium payload systems, where achieving complete implementation may become difficult. Then still option remains to partially apply P-VEH technology so that it becomes rational to some extent for example with extensive use of rechargeable batteries, deploying ultra-low-power sensors etc.

Table 10. UCD energy generation per 1 work shift

1	Accumulated energy by 1 P-VEH per 1 revolution	1.19 mJ
2	Magnet wheel rotational speed	270 rpm
3	Rotating time per 1 work shift	18 min
4	Harvestable revolutions per one 9 h work shift	18 × 270 = 4860
5	Accumulated energy by 1 P-VEH per 1 work shift	4860 × 1,19 = 5783.4 mJ
6	Accumulated energy from 20 P-VEHs	5783.4 × 20 = 115668 mJ ≈ 115.6 J
7	Coefficient for various losses 20%	115.6 × 1,2 = 96.3 J
8	Accumulated energy per 1 mounted UCD (ch. 4.1)	**96.3 J**
9	Cost of 20 “1305YB P-VEHs”	87.5 EUR × 20 = 1750 EUR
10	Feasible residue cost: UCD and circuitry components	2000 – 1750 = 250 EUR

Table 11. ESP32 power consumption and generation comparison

ESP32 properties [56]	
Current when transmitting through BLE	130 mA ≈ 0.13 A
Operating voltage	3.3 V
ESP32 power draw (BLE tx)	429 mW ≈ 0.429 W
ESP32 total energy consumption (per one 9 h work shift)	0.429W×9h=3.861Wh (≈13899.6 J)
Energy accumulated by 1 UCD vs ESP32 total consumption	**96,3 J < 13899.6 J** (9 h work shift)

4.3. Proposal for further development

However initial concept for energy-autonomous lift platform did not prove to be viable in given PLSS device conditions. Similar products designed for lighter payloads, exploiting faster speeds over longer period of harvesting time are more likely to provide sufficient conditions for successful implementation of the described "energy-autonomous lift platform" concept. Thus, it was suggested to target the development of energy-autonomous lifting platform concept to low payload LSS instead. However, for the current heavy-payload PLSS scenario, reliance completely on P-VEHs for powering of the sensors is not a viable solution.

The following proposal (Nr. 1) will not satisfy energy-autonomy criteria as described, however an appreciable economic benefit may be achieved by reducing cabling from several sensors to one power cable. Lift platform can be equipped with wireless technology so that sensor signals will be transmitted to CPU located on ground level. In addition to actuators power cable, additional cable can be added for powering on-board circuitry and sensory system (Fig.56). Mentioned on-board system can be prepared and installed during manufacturing phase in factory. Cabling for powering devices on lift platform could be standardized in length, additionally deploying industrial cable plug connections on both ends in order to ease installing procedure. In proposed manner it will be possible to decrease described high assembly and installation cost problem (Chapter 2), meanwhile maintaining flexibility in height. In principle, cabling of several sensors is swapped for one cable. By deploying plug connectors, installation procedures become uncomplicated, since corresponding connectors will not allow false connections hence a skilled laborer is not necessary to be deployed.

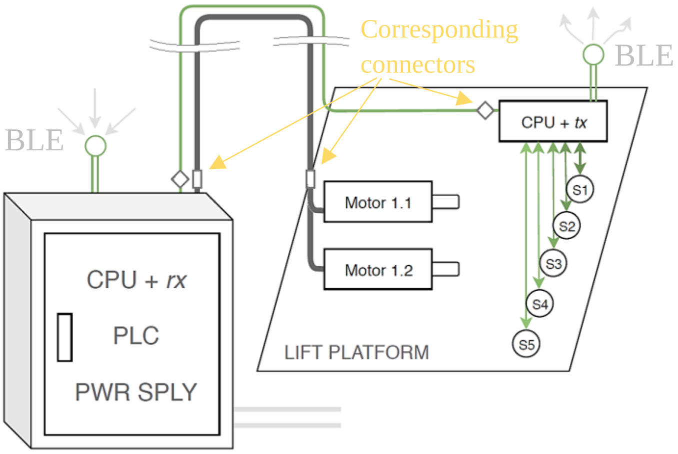


Fig.56. Schematics of on-board circuitry powered by separate cables, sensor signal transmission (*tx*) wirelessly by Bluetooth low energy to processing and power supply unit on ground level

If to consider application of wireless connection in general, then in the worst-case scenario the electromagnetic compatibility issues may arise. If to consider a situation where several PLSS devices are installed side by side, interferences in signals may occur. Biggest issue with glitches by sensor signal would be if motors continue working after stop signal is sent and not received. Considering heavy payload PLSS generally carries heavy payloads, which in case of falling may not only lethally harm workers but cause great damage to equipment and other inventory as well. Since mentioned risk accompanies wireless solutions, it is wise to tentatively avoid described risk beforehand. Thus, following proposal Nr. 2 is made.

It is known from initial information, in the “energy-autonomous lift platform” concept, the power cables for actuators will be harnessed under all circumstances. As discussed before, it is more reliable to prevent instead mitigating wireless solutions collateral risks. In view of described aspects, most reliable as well best fitting solution for resolving preliminary cause which initiated given case study, would be to exploit the capabilities of industrial multicore power cable (Fig.57).

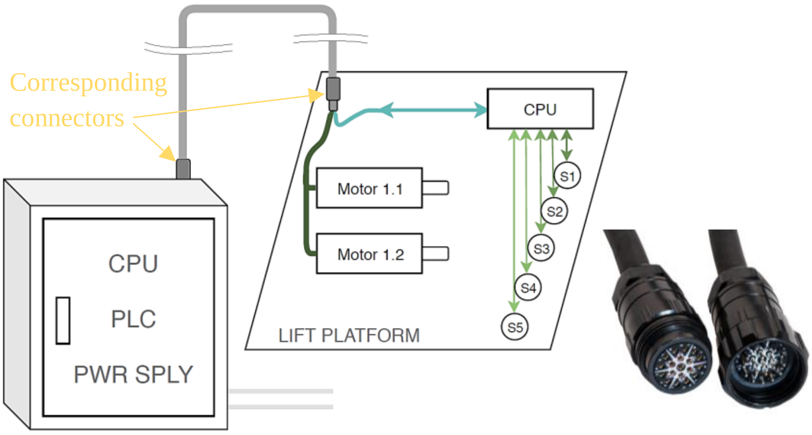


Fig.57. Multicore power cable [57]: powering & running sensors CPU signals to control cabinet

In the described approach, one cable prepared with industrial plug connectors make connecting ground control cabinet to everything on lift platform obvious and easy. Thus, henceforth it is unnecessary to deploy a skilled laborer on set for assembly and installment procedures since custom wiring for sensors is excluded from device installation phase. Additionally, product quality stays ensured in all cases, since entire lift platform along with sensors and on ground control cabinet unit can now be fully prepared in factory meanwhile corresponding connectors prevent false connections hence a skilled employee no longer needs to be deployed. Thus, a significant economic benefit strived for in given PLSS is feasible to be achieved indeed.

Conclusions

1. An extensive literature review on the state of the art in mechanical energy harvesting revealed that, contactless excitation via magnetic plucking of piezoelectric transducers (operating in the bending d31 mode) is a suitable vibration energy harvesting method within the scope of current project. Therefore, it was decided to perform feasibility study regarding application of P-VEHs for powering PLSS sensors in an attempt to determine the viability of concept of energy-autonomous lift platform in heavy-payload PLSS.
2. Based on a specific product, an industrial heavy-payload PLSS was examined in detail as the targeted use case for the P-VEHs in the context of implementation of energy-autonomous lift platform. Application-specific operational and dimensional restrictions as well as other peculiarities were specifically identified and described. Realistically feasible solution for using several P-VEHs within the specified geometrical constraints were proposed and the associated necessary modifications to the considered PLSS design were discussed.
3. Experimental investigation of the selected P-VEHs performance was conducted by reproducing the actual excitation and geometrical conditions to be expected when deploying P-VEHs in the PLSS. Maximum level of dynamic (impulsive) magnetic excitation, which precludes P-VEH damage (fracture) due to excessive deformations, was determined. The experimentally derived levels of total generated energy (0.12 mJ) and average power (2.7 mW) were found to be insufficient with respect to the predefined energy needs of the sensors used in PLSS. Consequently, further developments in P-VEHs implementation with in PLSS were discussed. The energy-autonomy as initially planned is not realistic to be achieved, hence further proposals were made, providing a feasible cost-effective solution for preliminary problem where from given case study was initially derived.
4. Final proposal for heavy-payload PLSS excludes P-VEH use since it was demonstrated to underperform under excitation conditions and constraints presented in the PLSS. Hourly harvestable energy in comparison to hourly consumption shows that feasibly accumulated energy by 1 UCD (11 J) will not be sufficient for powering of initially used sensors (9332 J) nor for one of the most energy efficient commercially available wireless transmission solutions (1544 J). Hence a cost-effective alternative solution to deploy a multicore power cable was proposed. With applied industrial cable plug connectors, false connections become impossible and installation procedures simple, thus more costly workforce is not required. Hence the cost-effectiveness of the heavy payload PLSS is reached and “near-energy-autonomous” lift platform concept implemented with a single dedicated cable.

Although, energy-autonomous lift platform concept was found to be not viable in the heavy-payload PLSS, it was proposed to target low-payload LSS instead. Since drive (excitation) speeds are higher, the proposed UCD could be integrated to achieve energy-autonomy cost-effectively. Moreover, low-payload LSS is used more frequently in industry, which provides favorable conditions for reliable powering of sensors by P-VEHs. In summary, the proposed energy harvesting concept could be feasibly implemented in low-payload LSS applications.

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