KAUNAS UNIVERSITY OF TECHNOLOGY
FACULTY OF MECHANICAL ENGINEERING AND DESIGN

Mindaugas Kizys

RESEARCH AND IDENTIFICATION OF CHARACTERISTICS OF MANUFACTURING PROCESSES

Final Master’s Degree Project

Supervisor
Prof. Hab. Dr. Vytautas Ostaševičius

KAUNAS, 2016

KAUNAS UNIVERSITY OF TECHNOLOGY
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Final Master’s Degree Project
Mechatronics (code 621H73001)

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Identification of the characteristic of technological processes

DECLARATION OF ACADEMIC HONESTY

1 June 2016
Kaunas

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SUMMARY

The final Master’s degree project examines existing wireless sensor nodes and presents two unique and innovative types of piezoelectric generator – low-frequency for rotating tool, and high-frequency for non-rotating tool. Energy storing and transforming subsystems were perfected and an architecture and algorithm were suggested. Wireless sensors were successfully integrated in cutting and milling tools and naturals experiments were performed. Analysis of variance was performed in order to identify how characteristics of machining processes statistically effect energy generator work.

Kizys, M. Gamybos procesų charakteristikų identifikavimas ir tyrimai. Magistro baigiamasis projektas / vadovas Prof. Hab. Dr. Vytautas Ostaševičius; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas.

Studijų kryptis ir sritis: Gamybos inžinerija, Technologijos mokslai.

Reikšminiai žodžiai: *vibracijos, bevielis jutiklis, pjezoelektrinis generatorius, įrankio susidėvėjimas, tekinimas, frezavimas*.

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SANTRAUKA

Baigiamajame Magistro projekte buvo nagrinėjami egzistuojantys bevieliai jutiklių mazgai ir pristatyti unikalūs ir inovatyvūs piezoelektriniai generatoriai – aukštų dažnių generatorius nesisukančiam įrankiui ir žemų dažnių generatorius besisukančiam įrankiui. Energijos kaupimo ir transformavimo posistemės buvo ištobulintos, bei joms pasiūlyta architektūra ir algoritmas, energijos kiekio sąnaudų optimizavimui. Autonominiai bevieliai sensoriai sėkmingai integruoti į frezą ir tekinimo peilį, atlikti natūriniai bandymai. Dispersinė analizė atlikta norint nustatyti kaip mechaninio apdirbimo procesų charakteristikos statistiškai įtakoja generatoriaus darbą.

KAUNO TECHNOLOGIJOS UNIVERSITETAS
MECHANIKOS INŽINERIJOS IR DIZAINO FAKULTETAS

Tvirtinu:

Gamybos inžinerijos katedros vedėjas ____________________
(parašas, data)
Kazimieras Juzėnas
(vardas, pavardė)

MAGISTRANTŪROS STUDIJŲ BAIGIAMOJO PROJEKTO UŽDUOTIS
Studijų programa MECHATRONIKA

Magistrantūros studijų, kurias baigus įgyjamas magistro kvalifikacinis laipsnis, baigiamasis projektas yra mokslinio tiriamojo ar taikomojo pobūdžio darbas, kuriam atlikti ir apginti skiriama 30 kreditų. Šiuo projektu studentas turi parodyti, kad yra pagilinęs ir papildęs pagrindinėse studijose įgytas žinias, yra įgijęs pakankamai gebėjimų formuluoti ir spręsti aktualią problemą, turėdamas ribotą ir (arba) prieštaringą informaciją, savarankiškai atlikti mokslinius ar taikomuosius tyrimus ir tinkamai interpretuoti duomenis. Baigiamuoju projektu bei jo gynimu studentas turi parodyti savo kūrybingumą, gebėjimą taikyti fundamentines mokslo žinias, socialinės bei komercinės aplinkos, teisės aktų ir finansinių galimybių išmanymą, informacijos šaltinių paieškos ir kvalifikuotos jų analizės įgūdžius, skaičiuojamųjų metodų ir specializuotos programinės įrangos bei bendrosios paskirties informacinių technologijų naudojimo įgūdžius, taisyklingos kalbos vartosenos įgūdžius, gebėjimą tinkamai formuluoti išvadas.

1. Projekto tema Research and Identification of Characteristics of Manufacturing Processes / Gamybos procesų charakteristikų identifikavimas ir tyrimai
Patvirtinta 2016 m. gegužės mėn. 3 d. dekano įsakymu Nr. V25-11-7

2. Projekto tikslas Išvystyti bevielius jutiklius skirtus įrankio būklei stebėti frezavimo ir tekinimo procesų metu.

3. Projekto struktūra Esamų bevielių jutiklių apžvalga; energijos generatorių parinkimas skirtingo tipo procesams; energijos generatorių ir kaupimo prietaiso komponentai; piezoelektrinių keitliai ir galimybė jungti juos nuosekliai; energijos keitlių integracija įrankiuose; realių bandymų rezultatai; dispersinė procesų charakteristikų analizė.

4. Reikalavimai ir sąlygos Išvystyti savarankišką (be išorinio energijos šaltinio) bevielį jutiklį, kuris įrankio vibracijas verstų elektros energija ir perduotų informaciją apie įrankio būklę operatoriui. Atlikti dispersinę analizę, kad būtų galima įvertinti procesų charakteristikų įtaką įrankio vibracijoms.

5. Projekto pateikimo terminas 20__m. __________ mėn. __ d.

6. Ši užduotis yra neatskiriama baigiamojo projekto dalis

Išduota studentui Mindaugui Kiziui

Užduotį gavau Mindaugas Kizys __________
(studento vardas, pavardė) (parašas, data)

Vadovas Prof. Hab. Dr. V. Ostaševičius __________
(pareigos, vardas, pavardė) (parašas, data)

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INTRODUCTION

Industrial metal processing machines consume enormous amounts of energy. However, they also generate a lot of energy in vibration and heat forms which can be harvested and stored. This energy can be used for machine itself or tools' diagnostic.

Sensing-diagnostic nodes could be working completely autonomously without external energy sources, or could benefit from prolonged life time of batteries, due to harvested energy. It depends on amount of harvested energy which depends on the location of the node. Thus these sensing-diagnostic nodes must have a subsystem which could harvest electric energy, transform and store it.

The aim of this paper is to develop wireless sensors for monitoring tool condition during milling and turning operations.

The tasks carried out to implement the aim of the project:

1. Selection of energy harvesting mechanism for machining processes.
2. Development of piezoelectric generator for wireless sensor.
3. Development of architecture and algorithm of wireless sensor electronics
4. Analysis of how characteristics of manufacturing process effect tool.

1. WORLDWIDE ACHIEVEMENTS IN ENERGY SOURCES FOR WIRELESS SENSORS NETWORKS (WSNs)

A wireless sensor node usually is powered by battery and is constructed for four main tasks: sensing, data gathering, localized calculations, and wireless communication. A power generator which harvests energy from surrounding environment of the sensor can possible be used to recharge battery or autonomously power the sensor node. A common wireless sensor node can be seen in Fig. 1.1, with each block showing a subsystem with its own power requirements.

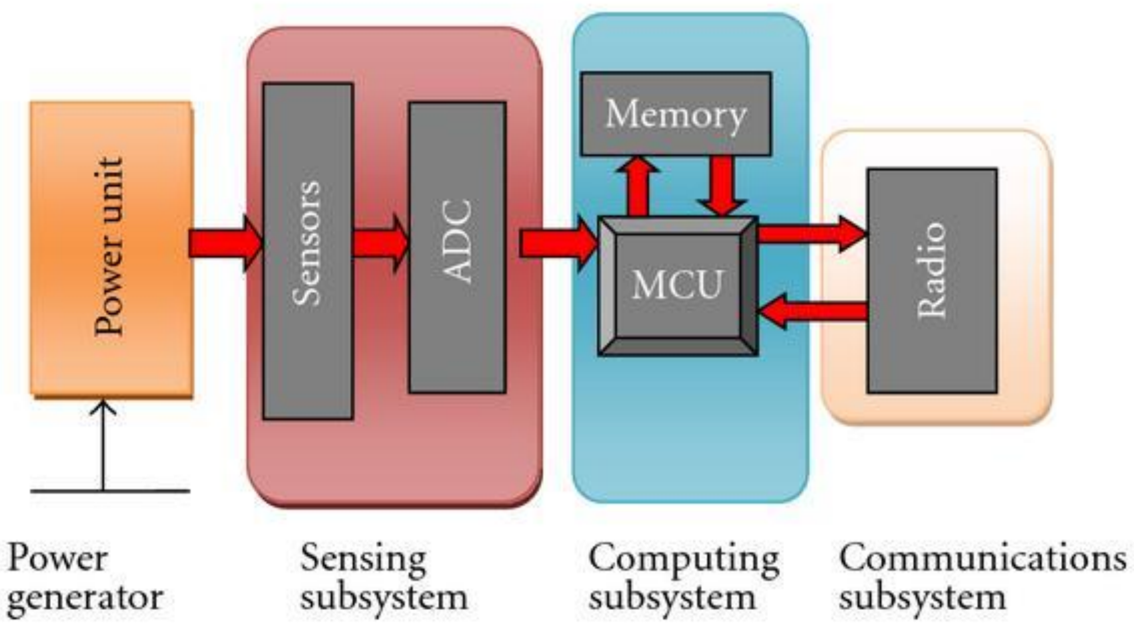


Fig. 1.1 Wireless sensor node with its subsystems

The subsystems in Fig. 1.1 basically show energy using components of the sensor node based on purpose, and Fig. 1.2 shows the common distribution of energy usage amongst these subsystems.

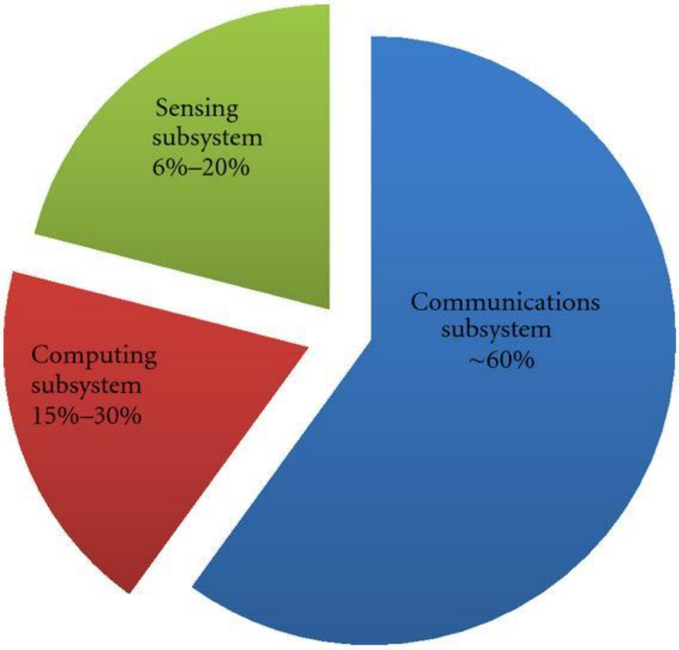


Fig. 1.2 Power consumption distribution for wireless sensor node

1.1. Piezoelectric energy harvesting from vibrations

Piezoelectricity origins from the Greek word “piezo” which stands for pressure and the word “electric” for electricity. The direct piezoelectric effect occurs when a force or stress is applied to a piezoelectric material which leads to an electric charge being induced across the material. Conversely, if charge or electric field is applied to the same material it will result in change in strain or mechanical deformation. This is called as the indirect piezoelectric effect. In energy scavenging the direct piezoelectric effect is implemented. Examples of ceramics which demonstrate piezoelectric effect are lead-titanate (PbTiO2), lead-zirconate (PbZrO3), lead-zirconate-titanate (PZT), and barium-titanate (BaTiO3). Up to now, PZT is the most often used piezoelectric material, essentially because it has high electromechanical coupling ability. However, PZT is a very fragile material. Thus this gives limitations to the strain that it can safely withstand without being damaged. Also it gives some boundaries to dimension. Polyvinylideneflouride (PVDF) is another common piezoelectric polymer which is more flexible and can be employed in energy harvesting applications.

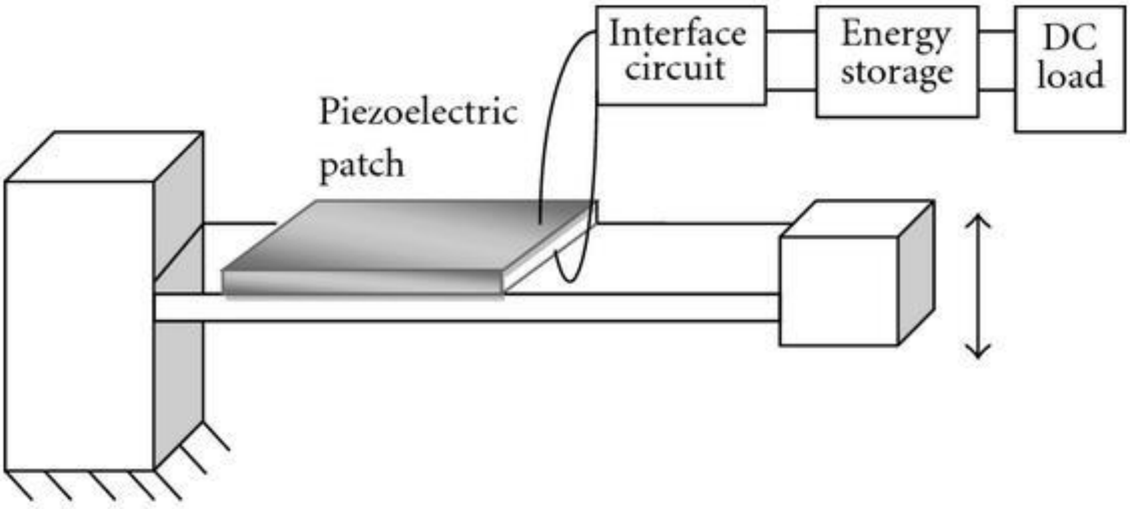


Fig. 1.3 Common piezoelectric energy harvesting system

When harvesting energy from mechanical vibration with piezoelectric, usually a mass is fixed at end of a beam which is covered with piezoelectric layer on top. When a system vibrates, the piezoelectric lever is mechanically deformed and a voltage is generated. The most popular energy harvesting elements are cantilever structures that are principally designed to operate at their resonance frequencies. Structures like these composed of unimorph or bimorph cantilevers are favored because they can withstand relatively high stresses in the piezoelectric material while reducing the dimensions of the device [1, 2, 3, 4]. Fig. 1.3 demonstrates such system created of a piezoelectric piece which is fixed to the cantilever beam face, which is affected by vibration. An alternating voltage (AC) is generated between the electrodes of piezo element when the cantilever is excited by mechanical vibration. Interface circuit transforms AC voltage into DC and stabilizes it in order to store harvested energy and use for other electronics. A summary of MEMS energy harvesters is given in Table 1.1 [5, 6].

Table 1.1 Summary of MEMS energy harvesting devices [36]

MEMS device description	Design/dimensions	Resonant frequency	Power output/voltage (reported)	Ref
AlN and PZT MEMS devices.	Piezoelectric generator located on top of a beam, piezoelectric layer sandwiched between top and bottom electrodes	300; 700 and 1000 Hz	1–100 μW	[7]
Energy harvesting MEMS device based on thin film PZT cantilevers,	Cantilever size: length = 13.5 mm, width = 9 mm, thickness = 192 μm	3 modes: 13.9; 21.9 and 48.5 kHz	2.4 V with 5.2 MΩ load, 1.01 μW	[8]
PZT-based MEMS with interdigital electrodes	Cantilever size: length = 3.000 μm, width = 1.500 μm, thickness = 22 μm	570–575 Hz	1.127 , 0.123 μW	[9]

PZT harvesters and MEMS technology	Device packaged using two wafers	1.8 kHz	40 µW	[10]
Thin film PZT-based MEMS power generator array for vibration energy harvesting, operating in d_{31} mode	Cantilever size: 2.000–3.500 µm, width = 750–1.000 µm	226–234 Hz	3.98 µW; 3.93 V	[11]
Thick film PZT free standing energy harvester operating in d_{31} mode	Cantilever size: length = 13.5 mm, width = 9 mm, thickness = 192 µm	229 Hz	270 nW at 9.81 m/s^2; 130 V	[12]
Two layered PMNZT bender devices for micropower generation	Cantilever size: length = 10 mm, width = 10 mm	120 Hz	2.0 0.5 mW	[13]
Laser machined piezoelectric cantilever devices for energy harvesting	10 cantilevers on both sides of ridge, 5 of them are placed with tip mass alternately: length = 5.74 mm, width = 4 mm	870 Hz	1.13 µW at 870 Hz through 288.5 kΩ, power density of 301.3 µW/cm^3	[14]
Multilayer unimorph PZT cantilever with micromachined Si proof mass based on SOI	Device volume (mass and beam) ~0.7690 mm^3	183.8 Hz	0.32 µW with 16.0 kΩ load; power density of 416 µW/cm^3	[15]
High performance MEMS PZT thin film energy harvester based on d_{33} mode	800 × 100 µm^2 cantilever with 10 µm thickness, proof mass of 1000 × 1000 × 500 µm^3	528 Hz	1.1 µW with 2.2 MΩ load; 4.4 operating at vibration of 0.39 g. Power density 2.8 mWcm^{-3} g^{-1}	[16]
Piezoelectric energy harvesters based on Aluminum nitride (AIN)	Cantilever devices: length = 1.31 mm–2.10 mm, width = 3.0 mm–7.0 mm	200–1200 Hz	60 µW at 572 Hz, 2 g vibration level.	[17]

1.2. Commercially available mechanical energy harvesters

There are four possible vibration energy harvesting systems – electromagnetic, piezoelectric, electrostatic and magnetostrictive. Table 1.2 compares principal features of energy harvesting systems [18]. There are no commercially available electrostatic or magnetostrictive based mechanical energy harvesters. But piezoelectric and electromagnetic devices are common to harvest vibration energy.

Table 1.2 Types of energy harvesting systems [18]

Type	Advantages	Disadvantages
Electromagnetic	No need of smart material	Bulky size: magnets and pick-up coil
	No external voltage source	Difficult to integrate with MEMS
		Max. voltage of 0.1 V
Piezoelectric	No external voltage source	Depolarization
	High voltages of 2–10 V	Brittleness in bulk piezolayer

	Compact configuration	Poor coupling in piezo-film (PVDF)
	Compatible with MEMS	Charge leakage
	High coupling in single crystals	High output impedance
Electrostatic	No need of smart material	External voltage (or charge) source
	Compatible with MEMS	Mechanical constraints needed
	Voltages of 2–10 V	Capacitive
Magnetostrictive	Ultra-high coupling coefficient >0.9	Nonlinear effect
	No depolarization problem	Pick-up coil
	High flexibility	May need bias magnets
	Suited to high frequency vibration	Difficult to integrate with MEMS

Products from major market players:

1. MicroGen Systems' BOLT^{TM} family of piezoelectric vibration energy harvesters

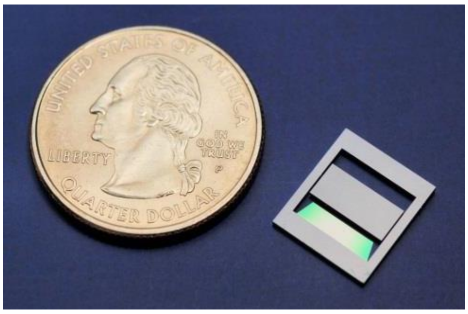


Fig. 1.4 Piezoelectric vibration energy harvester from MicroGen systems [20]

Description [19]:

- Piezoelectric energy generator based on microelectromechanical system (patent pending);
- Waste Electronic and Electrical Equipment (WEEE) compliant; CMOS compatible;
- Compliant with European Union's (E.U.) Restrictions on Hazardous Substances (RoHS);
- MicroGen Systems offer harvesters with natural operational frequencies of 100, 120, and 600 Hz. However, they can also make custom design that operates in frequency 100-1500 Hz.
- Single vibrational axis;
- Output voltage (open-circuit) is more than10 V, with output power of 25-100 µW when excited with 0.1g.

2. MicroStrain$^{\circledR}$ piezoelectric energy harvesters (PVEH$^{\mathrm{TM}}$)

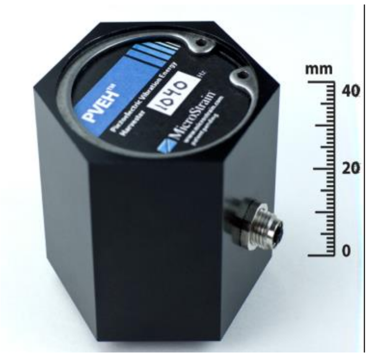


Fig. 1.5 Piezoelectric vibration energy harvester from MicroStrain$^{\circledR}$ [21]

Description [21]:

- Factory tuning is done by changing concentrated intertial mass and/or stiffness of a precision micro-machined frame, which resonates a piezoelectric stack in compression to create energy.
- Integrated 4-pin connector provides simple connection to sensor and flexibility for additional storage capacity.
- Stable DC power is provided using innovative power conversion micrlectronics and a super capacitor for power storage.
- Output voltage (VDC) is 3.2 V, with output power of 30 mW when excited with 1.5g at 1000 Hz.

3. Midé Volture$^{\mathrm{TM}}$ piezoelectric energy harvesters

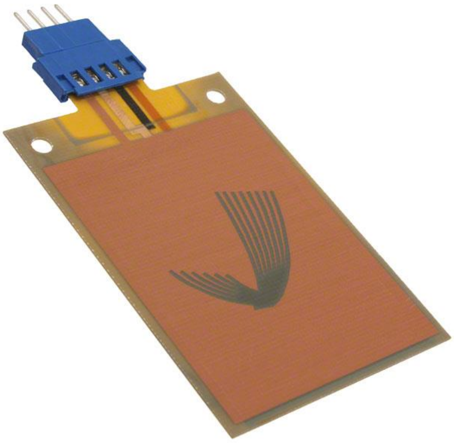


Fig. 1.6 Piezoelectric vibration energy harvester from Midé Volture$^{\mathrm{TM}}$ [23]

Description [22]

- Durable piezo packaging (patented), hermetically sealed so can be used in harsh surroundings.

- Available in different sizes to match required resonance frequency (50 Hz to 150 Hz).
- Output voltage (open-circuit): 12.8 V, output power: 1.7 mW at 1g, 180 Hz.

4. ARVENI piezoelectric mechanical energy harvester

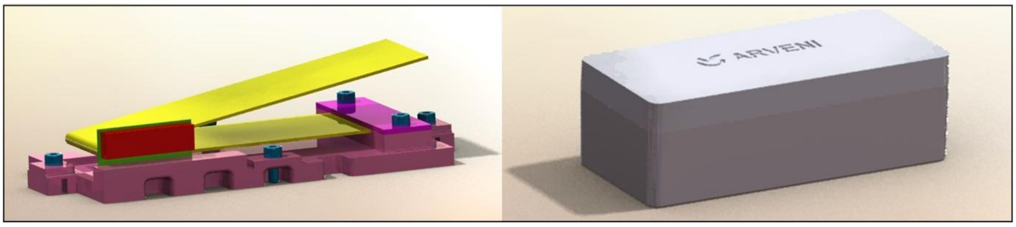


Fig. 1.7 Piezoelectric vibration energy harvester from ARVENI [24]

Description [24]:

- Arveni – the biggest adopter of energy harvesting technologies so far.
- Energy harvesting from a button pressure (switching operation).
- Applications: remote controls, wall switches for home automation and building infrastructure.
- High reliability, green technology, require no maintenance.
- A specific DC/DC interface has been designed in order to have the biggest yield as possible.
- Output power: 200 mW at 0.5g, 50 Hz.

5. CEDRAT vibration energy harvesters based on Amplified Piezoelectric Actuators (APA®)

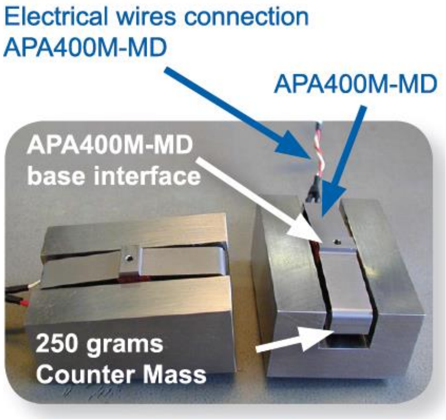


Fig. 1.8 Piezoelectric vibration energy harvester from CEDRAT [25]

Description [25]:

- Suitable for harsh industrial environment.
- Custom-built AC-DC & DC-DC electronic converter.
- Output power 95 mW at 110 Hz, vibration amplitude of 0.045 mm (peak to peak).

6. EnOcean electrodynamic mechanical energy harvester

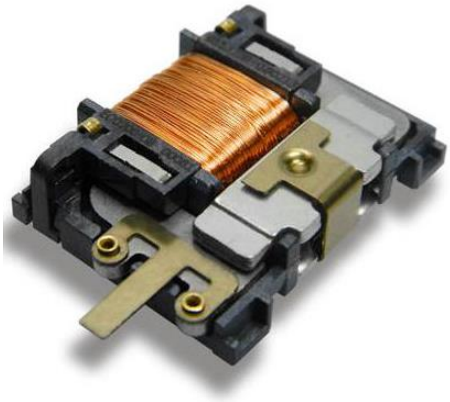


Fig. 1.9 Electrodynamic vibration energy harvester from EnOcean [26]

Description [26]:

- Energy from a switching operation (button pressure).
- Typically, can withstand more than 300k switching cycles at 25 °C. When in optimized applications more than 1M cycles are possible.
- Output energy: 120-210 µJ at 2 V.

7. Perpetuum electromagnetic vibration energy harvesters

Fig. 1.10 Electromagnetic vibration energy harvester from Perpetuum [27]

Description [27]:

- Has hazardous zone certifications: FM, CFM, ATEX and IECEx. Performs in the harshest of industrial fields.
- Combines electromagnetic vibration energy harvester with intelligent power management.
- A maintenance-free, fit and forget wireless power solution.

- 6 commercial models are available with frequencies: 25Hz, 30Hz, 50Hz, 60Hz, 100Hz, 120Hz.
- Output voltage: 5 V, output power: 27 mW.

8. FERRO SOLUTIONS electromagnetic vibration energy harvesters

Fig. 1.11 Electromagnetic vibration energy harvester from FERRO SOLUTIONS [29]

Description [28]:

- Energy harvesting devices based on unique combinations of magnetic materials and patent-pending designs
- Operational frequencies vary from 20 to 120 Hz.
- Output voltage: 3.3 V, output power 9.3 mW at 0.1g, 21 Hz.

2. ENERGY HARVESTING FROM CUTTING TOOL VIBRATION

2.1. Piezoelectric transducer for turning tool

Piezoelectric energy harvesters are most efficient while working in their resonance modes. Highest energy amount will be harvested if industrial processing machine tool and piezoelectric energy generator will have same resonance frequency. Before installing piezoelectric energy generator on turning tool it is necessary to determine mechanical vibration frequency of the tool. For this reason, experimental stand was created (Fig. 2.1). At the end of cutting tool 1 accelerometer 4 is fixed which is connected to oscilloscope 5 and computer 6.

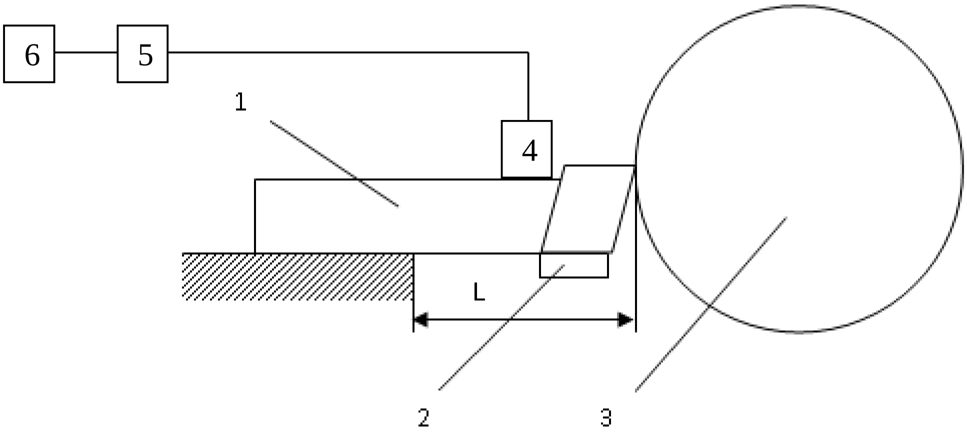


Fig. 2.1 Frequency measuring scheme for turning tool. 1 – cutting tool; 2 – energy harvesting element; 3 – workpiece; 4 – accelerometer KD 91; 5 – oscilloscope; 6 – computer; L – length of free end of shank [34].

Cutting tool impact experiments was carried out in order to excite resonance frequency vibration. Fig. 2.2 demonstrates turning tool impact test results. When the length of the free end is $L = 42\ mm$ – the resonance frequency of cutting tool is equal to 4139 Hz. More tests were done with turning lathe while changing length of free end of the shank. Experiments showed that cutting tool resonance frequency changes from 3.5 kHz to 5.6 kHz when changing length of free end of shank from 35 mm to 55 mm (Fig. 2.1).

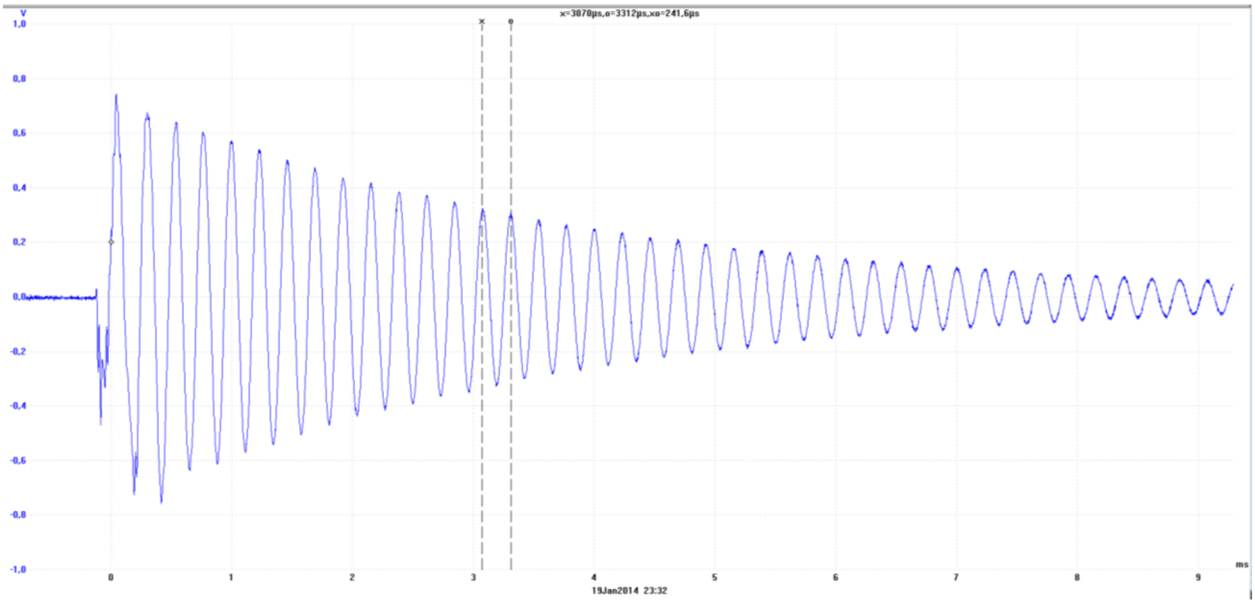
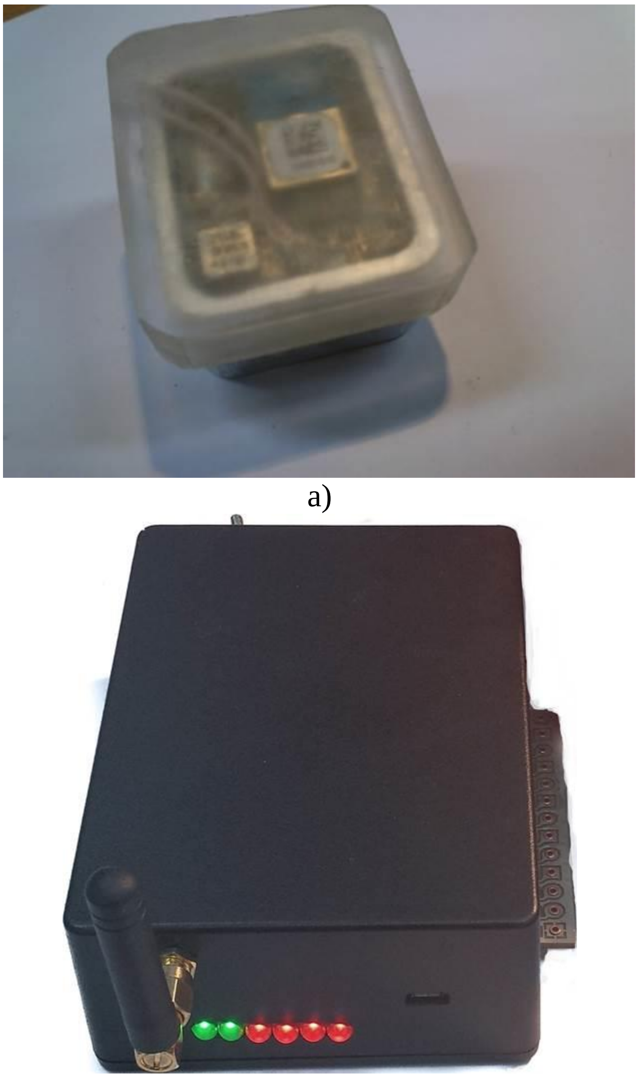


Fig. 2.2 Cutting tool impact test when free end of a shank is L=42 mm

Worldwide there are manufacturers who offers piezoelectric cantilevers for mechanical energy harvesting. However, cantilevers have all series lower natural frequencies compared with turning tools. From various piezoelectric transducer experiments it was determined that piezoelectric cantilever won't be solution for high frequencies. In order to get resonance frequencies of few kHz series cantilever should have stiff structure or length of it should be reduced. But this would give low amplitudes which leads to low electric energy generation.

2.2. Piezoelectric transducer for milling tool

There are two major groups of tools used in manufacturing processes, non-rotating such as turning tools and rotating such as milling tools. Turning tool, because of elastic deformation created by cutting force, operates at frequencies from 3.5 kHz to 5.6 kHz. However, excited vibrations with rotating milling tool does not relates with elastic properties. In order to evaluate possibility of generating enough electric energy from mechanical vibration of rotating tool, the authentic wireless signal transmitter (Fig. 2.3, a) was created. Signal transmitter consists of accelerometer, power source and wireless transmitter. Registered acceleration data is sent to wireless network receiver (Fig 2.3, b).


a)

b)

Fig. 2.3 General view of wireless accelerometer for rotating tool (a) and receiver (b) [35]

For identification of frequencies which would be efficient for generating electric energy, created wireless accelerometer (Fig. 2.3, a) was fixed on rotating end mill. End mill was working on steel workpiece in zig-zag principle with cutting feed of 600 mm/min, depth 1mm and rotating speed 3200 rpm (Fig. 2.4).

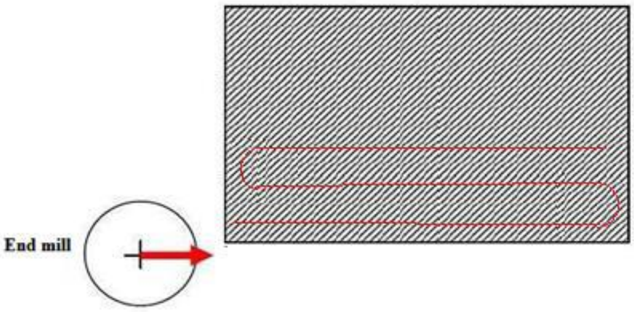


Fig. 2.4 End mill cutting path

Experiments was carried out with four teeth end mill at rotating speed of 3200 rpm. Milling process can be characterized as interrupted cutting. Accelerometer’s data shows that the collisions of end mill tooth and workpiece occurs every 6.7 ms. This gives us frequency of 150 Hz which is close to natural frequency of piezoelectric cantilever.

Piezoelectric transducer CMBP04 from Noliac was chosen. It is bimorph cantilever which converts bending moment into electric signal and is used when small acting forces creates high enough deformations. Such wireless energy generator architecture is shown in Fig 2.5 [35].

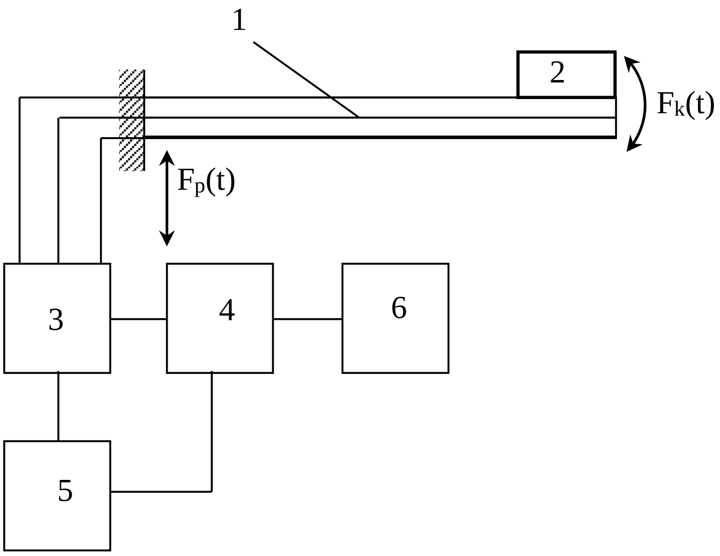


Fig. 2.5 Architecture of wireless energy generator: 1 – piezoelectric bimorph cantilever, Noliac CMBP family; 2 – concentrated inertial mass; 3 – connection unit; 4- microcontroller; 5 – storage device; 6 – wireless transmitter [35]

In order to increase generated energy amount and sensitivity of piezoelectric transducer 1, concentrated inertial mass 2 is fixed at the end of beam. Cantilever’s vibration $F_k(t)$ can be adjusted by changing weight of concentrated inertial mass making it closer to exciting vibration frequency $F_p(t)$. Also, Noliac CMBP family piezoelectric transducer is composed of two layers, so its resonance frequency can be adjusted by shunting one of the layers (Fig. 2.6).

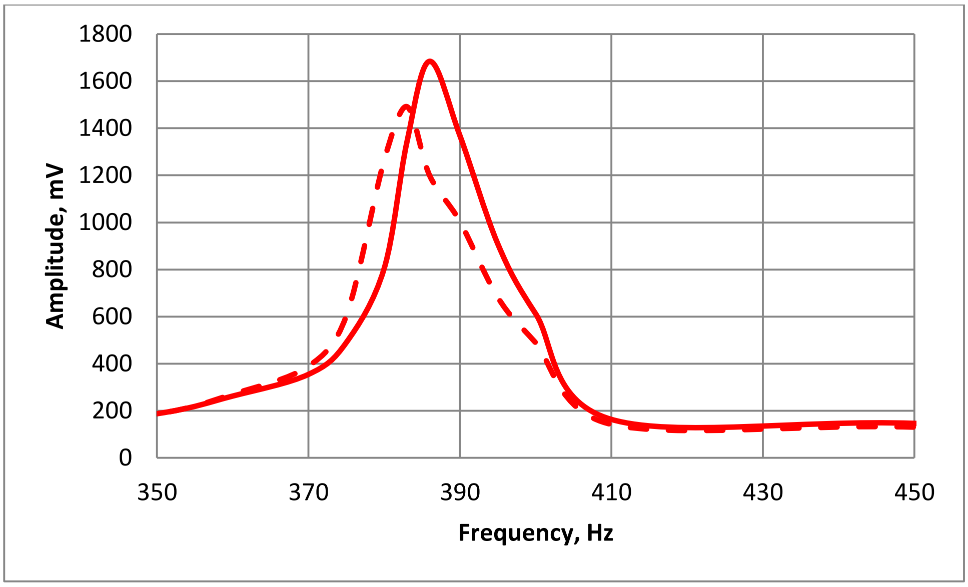


Fig. 2.6 Amplitude-frequency characteristic of piezoelectric cantilever without concentrated inertial mass when shunt resistance is infinite (*continious line* - open circuit) and when one piezoelectric layer is shunted (*dash line*)

These self-powered wireless innovative devices let to carry out experiments while testing three most often used materials in practice of manufacturing – stainless steel, steel and aluminium alloys. While identifying rotating and non-rotating tools' degree of wear it was determined that tool's wear is indirectly proportional to the time needed to fully charge capacitor up to 2 volts using tool's vibrations. When capacitor is fully charged the wireless transmitter send signal to receiver. In such way tool condition monitoring pas performed.

3. ELECTRIC ENERGY HARVESTING AND STORAGE DEVICE COMPONENTS

There are various ambient energy sources for harvesting electricity using electromagnetic wave’s energy, sun power, heat (thermoelectric), mechanical (vibration), electrostatic energy. One of the objectives of this work is to create innovative self-powered wireless sensor for industrial machine condition monitoring and failure diagnostics. It also includes tool’s wear condition monitoring which is important for obtaining higher quality of a product and reducing chances of failure. These sensors need to be placed directly on tool, thus energy harvesting and storage components need to be fixed on same tool.

For turning tool, it is possible to transform heat or vibration energy into electrical. Heat energy transformation into electrical energy is alternative energy source because during metal cutting process tip of a chip heats up too few hundreds degree of Celsius. Of course further we go from the tip of a chip the temperature drastically gets low but it is possible to get temperature differences of few dozen degree of Celsius. However, this principle was rejected because modifications of a tool would be needed. Fig. 3.1 shows position of an energy harvesting system on a cutting tool shank.

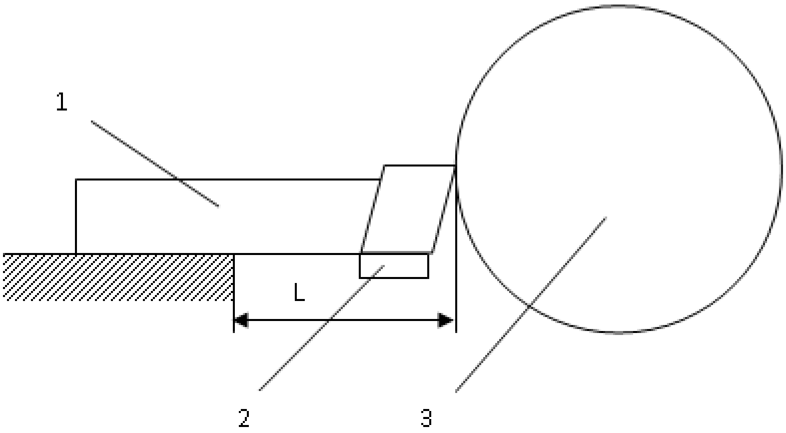


Fig. 3.1 Energy generation element position on a turning tool scheme: 1 - cutting tool; 2 - energy generator; 3 - workpiece

For energy harvesting and storing it is required to have energy generating, changing, transforming, stabilizing and storing elements, also components for protecting from overvoltage. Structural scheme of designed system is shown in Fig 3.2. In general case energy transducer or energy harvesting element is any energy transducer which transforms mechanical energy into electrical. In relatively low frequencies (few hundreds Hz) either electromagnetic or piezoelectric energy generators of cantilever form, or even hybrid, are being used [30]. All energy transducers have highest efficiency when working at their resonance frequency, this way amount of generated energy increases from 2 to 100 times.

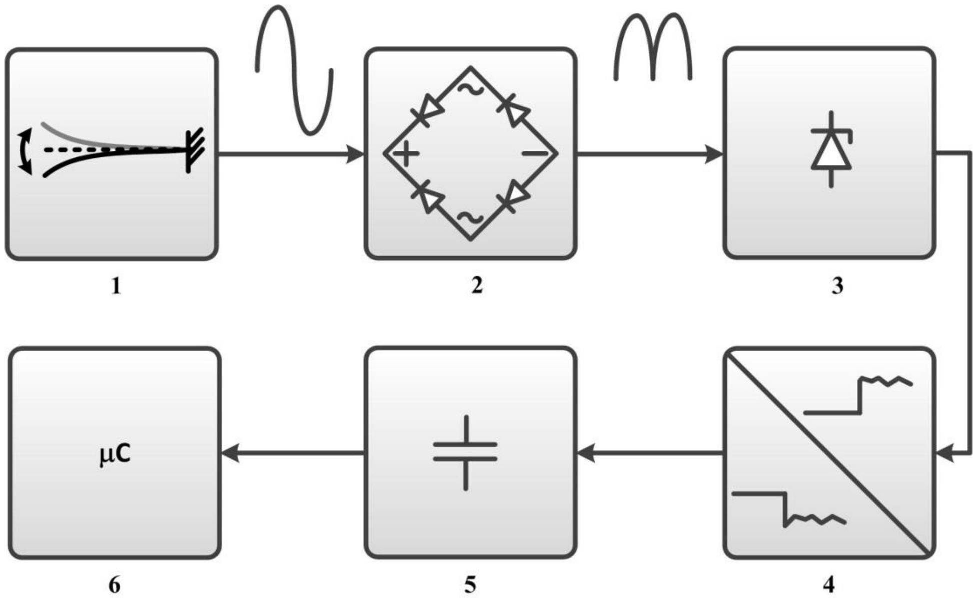


Fig. 3.2 Components of energy generating and storing elements: 1 - energy transducer; 2 - diode bridge rectifier; 3 - guard element; 4 - voltage conversion and stabilization chip; 5 - energy storage unit; 6 - powered electronics [34]

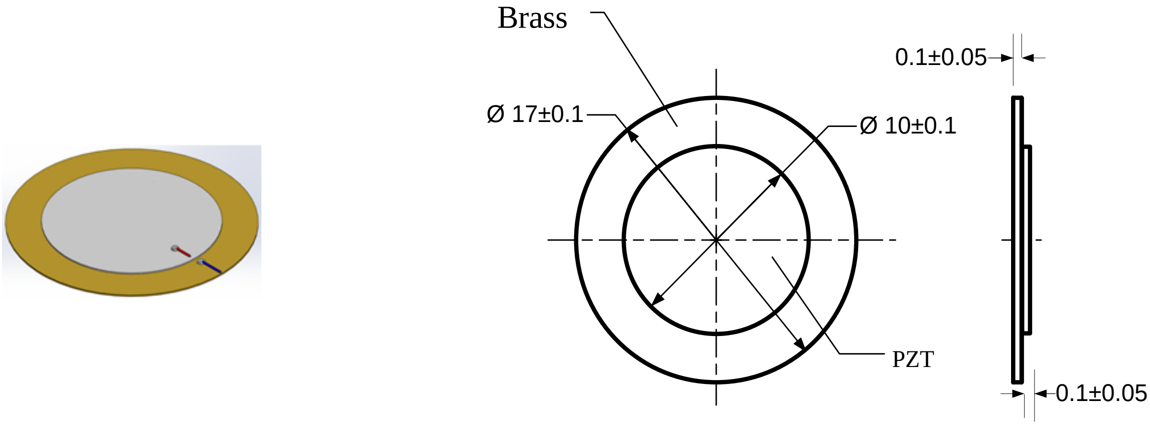
Transducer 1 generates alternating voltage (AC), thus it is necessary to have diode bridge rectifier 2 to convert it into direct current. In such bridge usually Schottky diodes are used because they are faster, have lower voltage loss (about 0.3 V) and they work better in high frequencies compared with common diodes. Element 3 protects system from overvoltage, commonly it is stabilitron (stabilizing diode). Element 4 is a chip which increases and stabilizes voltage according to requirement of electronics which will use it. In market there are already assembled chips with integrated few electronic elements which are mention above. Sometimes even all needed elements are assembled into one frame.

Energy storage unit can be standard rechargeable batteries, lithium batteries, thin film flexible batteries or supercapacitors, depending on needed amount of energy, space available and required voltage.

Latest electronic components to which generated and stored energy is supplied usually is fed with voltage 1.8 V – 3.6 V. Thus if energy transducer generated voltage amplitude is equal or more than 5 V, step-down chips are used to transform voltage into needed for powered electronics, e.g. 3 V. If generated voltage amplitude is less than 5 V, step-up chip is used in order to increase voltage up to required.

4. PIEZOELECTRIC ENERGY TRANSDUCER

Piezoelectric energy generator has to operate at its natural frequency mode. Worldwide there are many manufacturers who offer piezoelectric cantilever transducer for converting mechanical energy into electric energy. Previous test shown that piezoelectric transducer for turning tool should be bimorph piezo disk (Fig 4.1). The selected piezo element is used as buzzer while fixed in all perimeter and has resonance frequency in needed diapason (2.5…5.6 kHz). Also, price of such elements are very small (around 0.3 €/pcs).



a) b)

Fig. 4.1 General view of selected piezo disk - a; dimensions - b

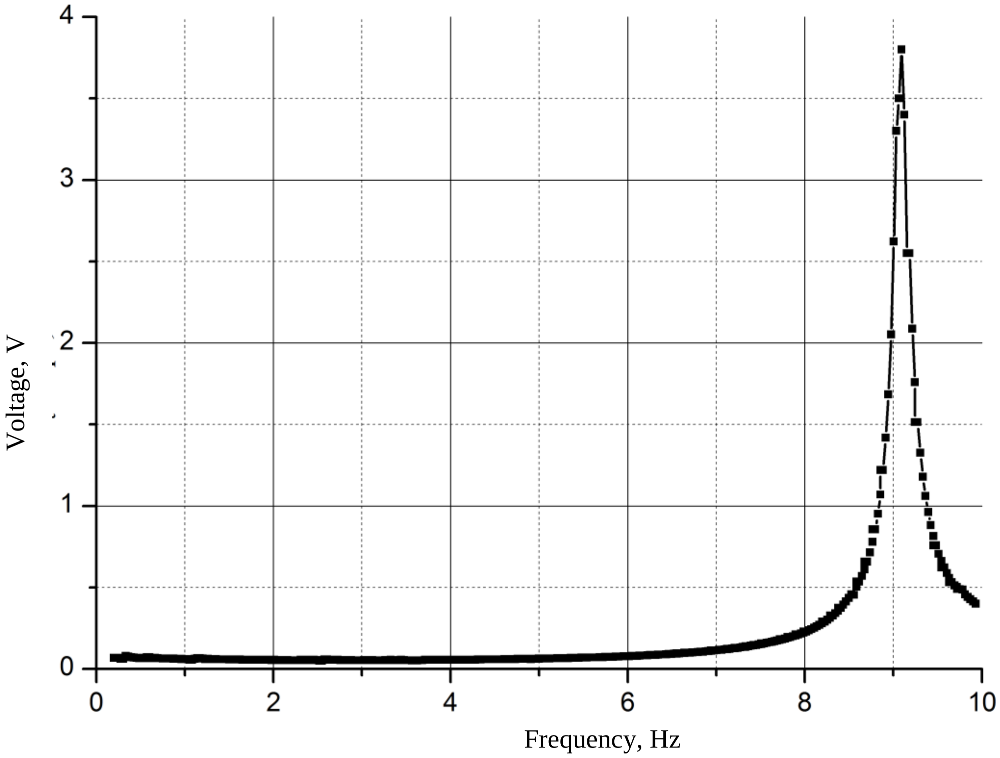
Experiments were performed testing first mode resonance frequency of same type piezo disks when they were fixed with all perimeter in constructed housing while vibrating on electrodynamic stand (model 1072, RFT, Germany). After testing five transducers of the same type it was determined that distribution of resonance frequency is significant 3.9…4.5 kHz. There are some reasons for such distribution:

- dimension tolerances of transducers i.e. brass disk and piezo material thickness and diameter deviations – tolerances;
- concentricity of brass disk and PZT layer;
- layer thickness of glue between brass disk and piezo material;
- place of wire soldering and amount of solder used;
- amount and type of glue used to fix transducer to housing.

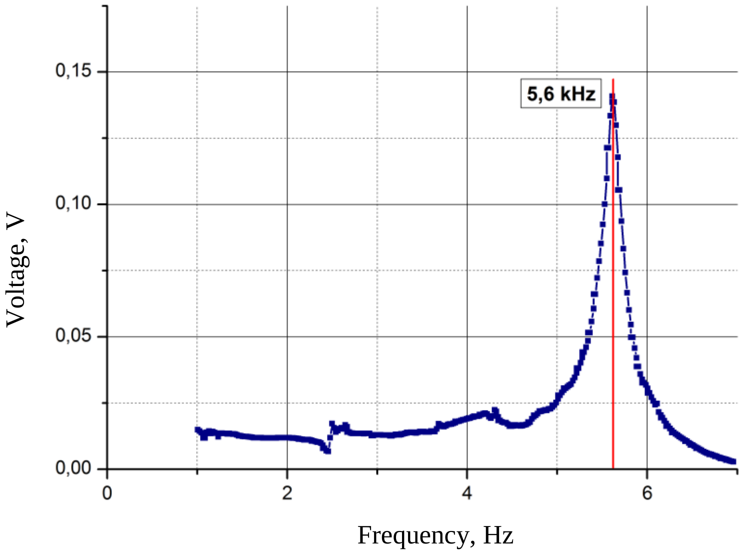
All reasons mentioned above makes smaller or bigger influence on resonance frequency which leads to significant distribution of frequencies. Piezoelectric transducer which is fixed in housing with cyanoacrylate glue frequency characteristics shown in Fig. 4.2, b. There are two possible solutions when such frequencies distribution appears:

- choose transducers which has same frequency or at least it is close enough;
- add concentrated mass at those transducers which have higher resonance frequencies.

Since transducers has to work at resonance regimes, their resonance frequency has to coincide with the turning tool first mode resonance. That’s why analysis of disc transducer first mode resonance frequency was performed. Transducers were fixed in made casing and excited on electrodynamic stand (model 1072, RFT, Germany). Electrodynamic stand and transducer frequency characteristic is shown in Fig. 4.2 a and b, respectively.



a)



b)

Fig. 4.2 Electrodynamic stand (a) and piezoelectric generator (b) amplitude frequency characteristics. (a) signal was measured usgin piezoelectric accelerometer KD35, which sensitivity is 5 m/s^2/mV

5. CONNECTING ENERGY TRANSDUCERS IN SERIES

When voltage is low and selected electronics used more than 5 volts, it is possible to connect few piezo generators in series. This way voltage is increased, but capacity is reduced. Energetically it is not a loss because when two elements are connected in series, their capacity reduces by half and voltage increases two times (in ideal case):

$$E = \frac{1}{2} \cdot C \cdot U^2 \tag{1}$$

where, *E* – generated energy by piezoelectric material, J; *C* – electric capacity of piezoelectric material, F; *U* – voltage generated by piezoelectric material, V.

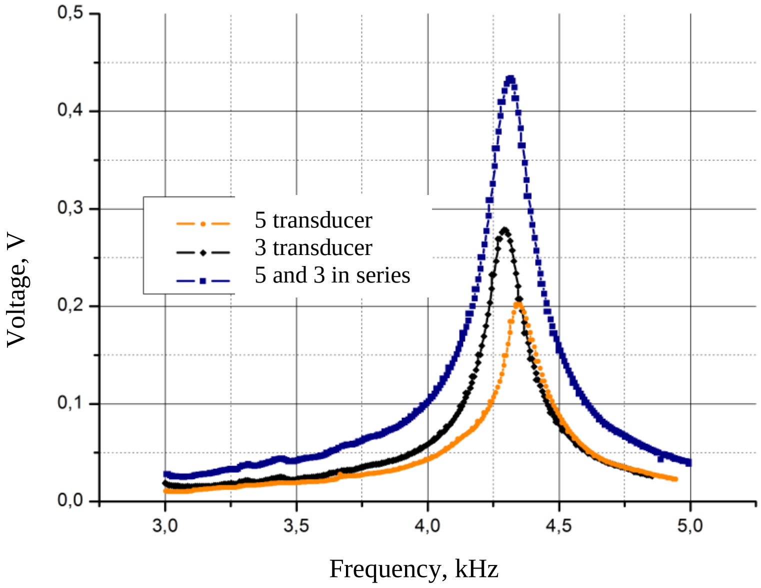


Fig. 5.1 Energy transducers amplitude frequency characteristics when connecting them in series

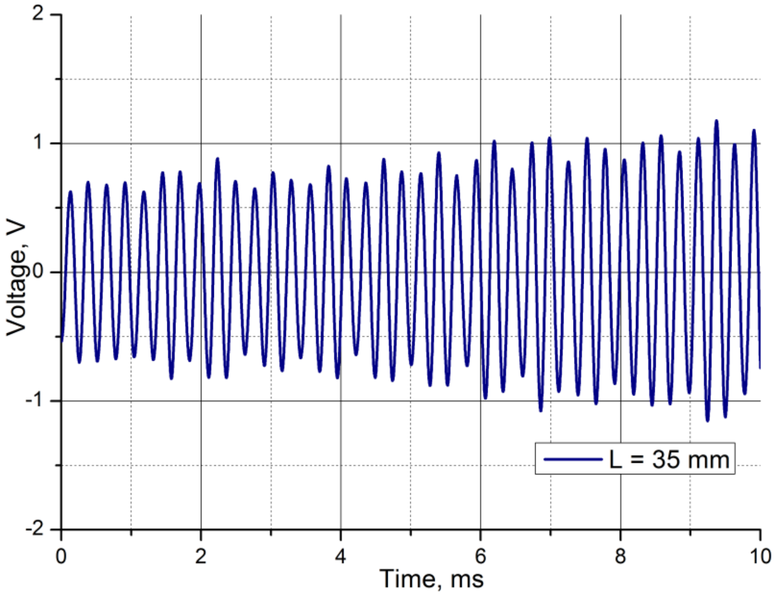


Fig. 5.2 Piezoelectric transducer vibration amplitudes when turning aluminium with tool shank length L=35 mm

It is necessary to know that phase frequency characteristic at resonance frequencies rapidly changes, thus when working with few transducers, working regime of a tool must be selected in such way that tool's resonance frequency won't be higher than transducer's which has lowest. Otherwise, transducers won't work in same phase and harvested energy amount will be lower. Mechanical construction which connects transducers in series has to be nonconducting or points where transducers are fixed have to be isolated.

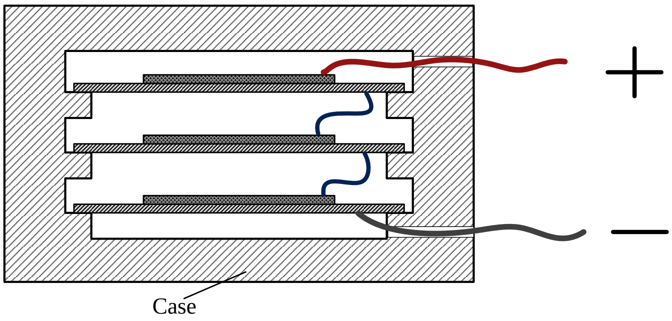


Fig. 5.3 Transducers position in case and their connection in series

Energy conversion subsystem was realized in order on convert generated electricity with energy transducer, into voltage that could be used by microcontroller (Fig. 5.4, 5.5). First transducer – piezo generator converts mechanical vibration energy into electric energy, which is alternating current (AC) and can have quite high amplitudes. Created subsystem is second transducer which converts AC to direct current (DC) and stabilizes it. Output voltage can be configured (1.8 V, 2.5 V, 3.3 V, 3.6 V). This transducer is designed using Linear Technology LTC3588-1 chip which has integrated full wave diode bridge rectifier, 20 V stabilitron (guard element for overvoltage) and DC/DC step-down converter.

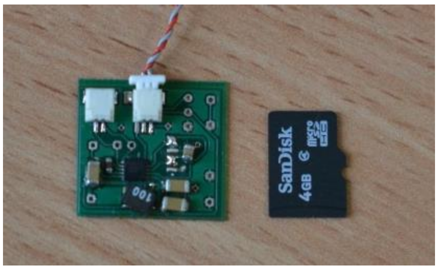


Fig. 5.4 Created energy conversion subsystem

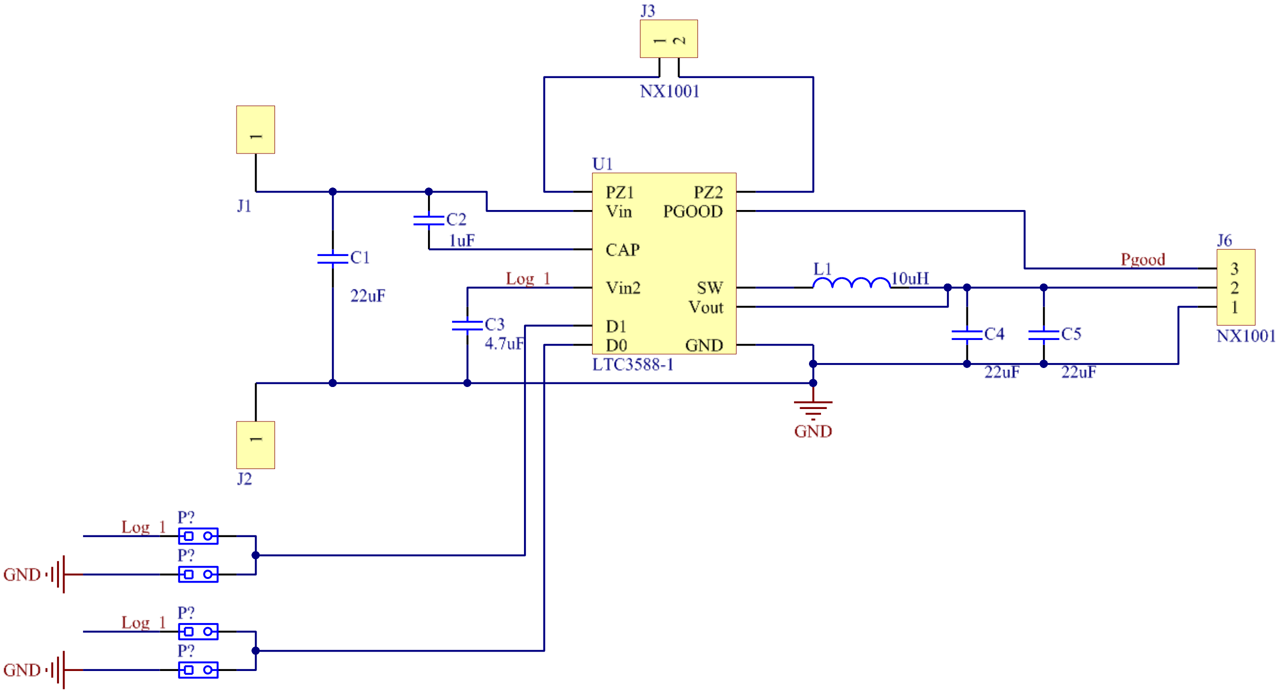


Fig. 5.5 Electric scheme of energy conversion subsystem

Two transducers connected in series generated electric energy is:

$$E = \frac{1}{2} \cdot C \cdot U^2 = \frac{1}{2} \cdot 7 \cdot 10^{-9} \cdot 6^2 = 1.26 \cdot 10^{-7} J. \qquad (2)$$

Generated power taken in account that vibration is continuous and has constant amplitudes:

$$P = \frac{E}{t} = \frac{1.26 \cdot 10^{-7}}{1} = 0.126\ \mu W. \qquad (3)$$

Energy conversion subsystem working principle is presented with removed signals while charging capacitor of 100 µF (Fig 5.6). When output voltage reaches target voltage (in this case 2.5 V), the output induces that stabilized voltage does not go out of limits. This signal is supplied to measuring electronics.

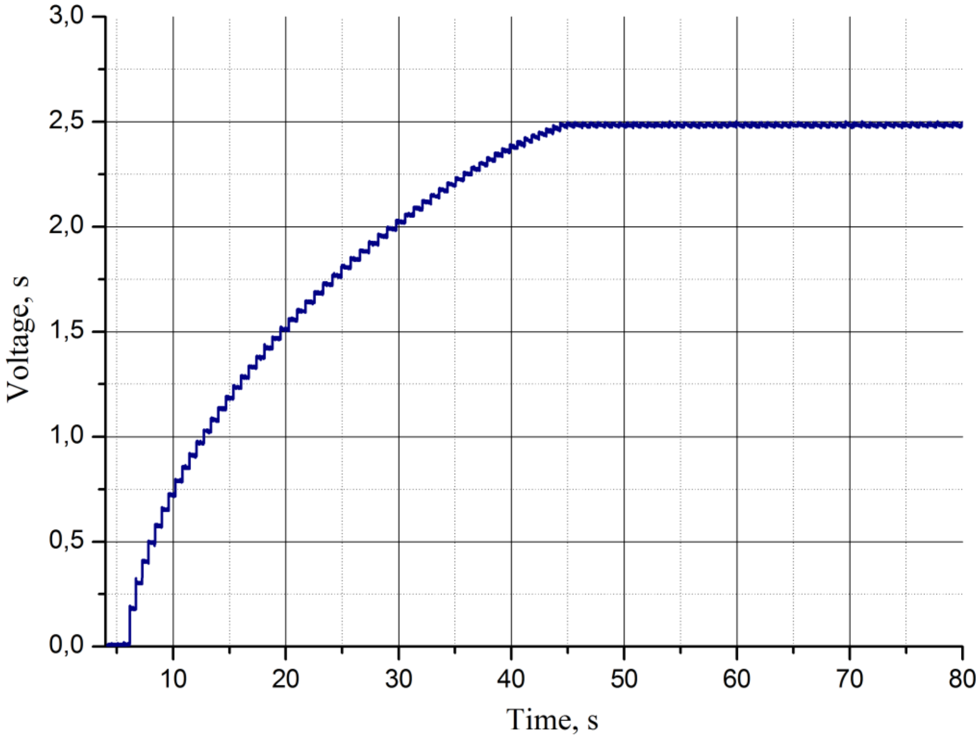
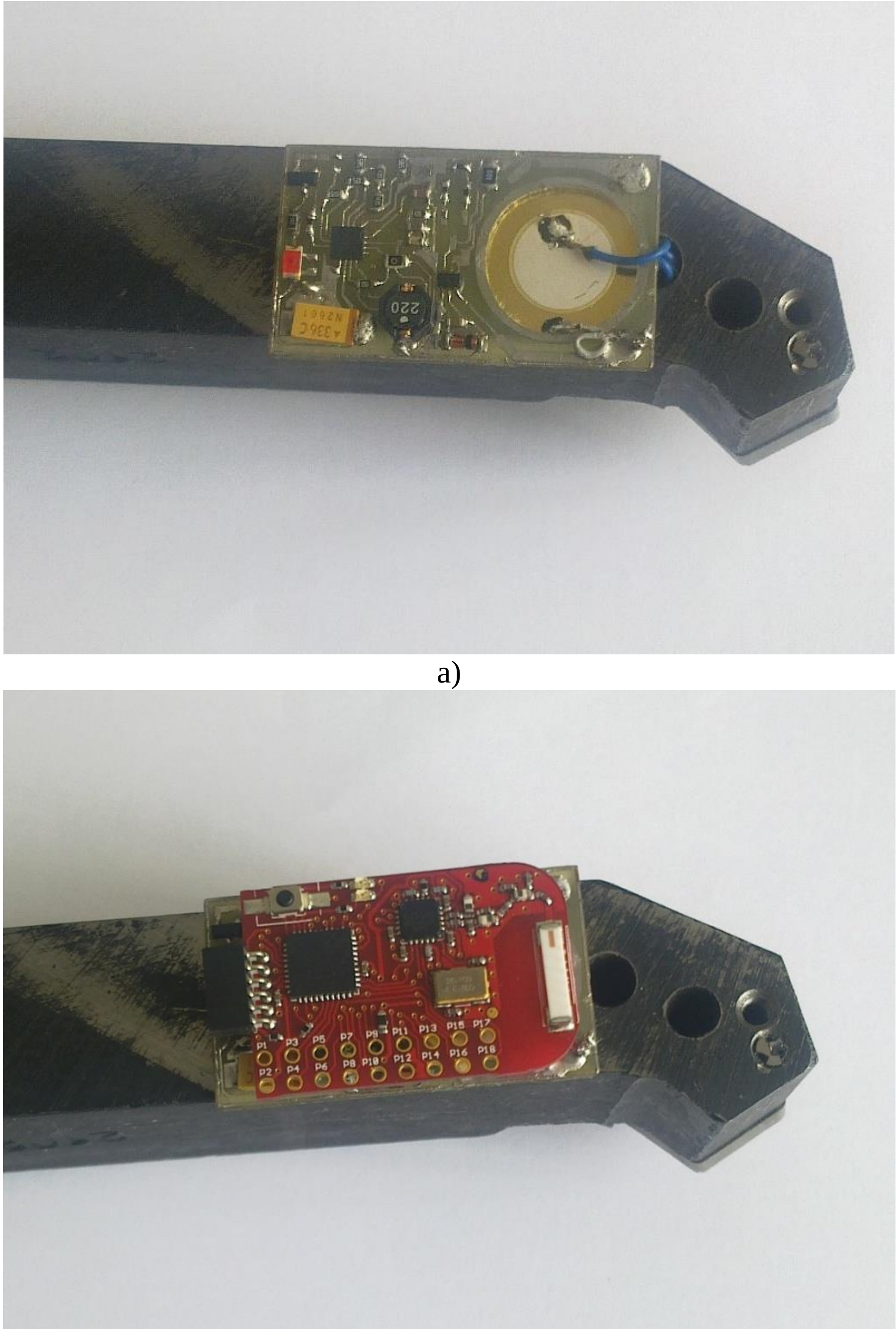


Fig. 5.6 100µF capacitor charging curve with two transducer connected in series when using energy transformation subsystem

6. ENERGY TRANSDUCER INTEGRATION INTO CUTTING TOOL STRUCTURE

Two types of piezoelectric energy transducers were created. First one with disk form piezo transducer which natural frequency of first mode is around 4000 Hz (Fig. 6.1). Second one with cantilever piezo transducer which natural frequency of first mode is about 200 Hz (Fig. 6.2).


a)

b)

Fig. 6.1 Integration of wireless energy transducer on cutting tool structure: a - energy harvesting and storing subsystems; b - data processing and transmitting subsystems

Energy generating and storing subsystems are fixed on bottom of cutting tool (Fig 6.1, a). On top of them data processing and transmitting units are mounted (Fig 6.1, b)

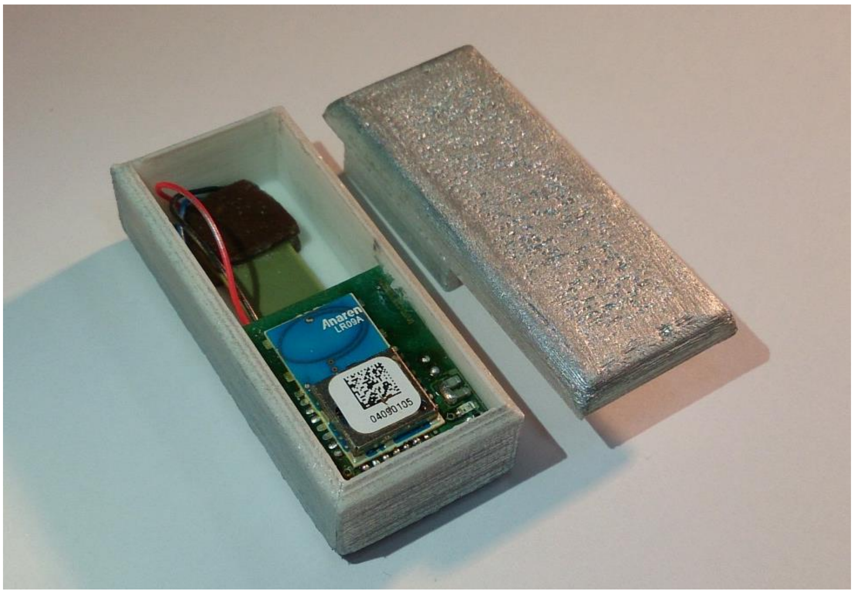


Fig. 6.2 Wireless energy generator with cantilever form piezo transducer general view [35]

Wireless energy transducer mounting scheme on rotating tool is presented in Fig. 6.3.

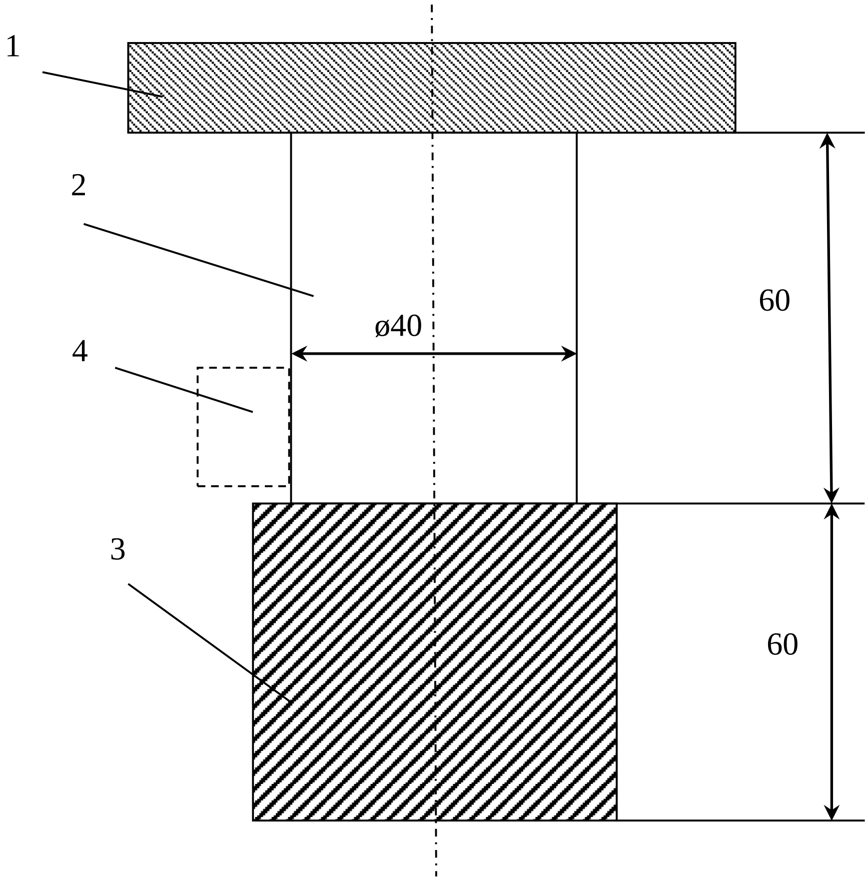


Fig. 6.3 Energy generator mounting scheme on milling tool: 1 – tool holder; 2 – mill; 3 – workpiece; 4 – wireless energy transducer.

For both cases device electronic parts architecture is presented in Fig 6.4. Advanced architecture includes ULP voltage detector which reduces energy consumption during microcontroller start-up processes. Algorithm of created wireless sensor node is shown in Fig 6.5.

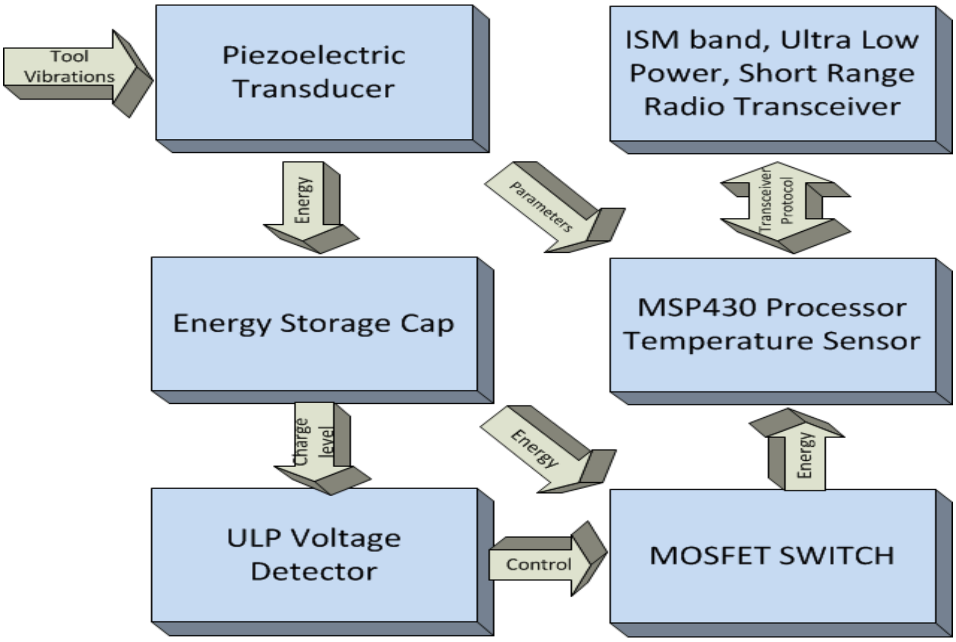


Fig. 6.4 Suggested architecture wireless sensor node with ultra-low power voltage detector [34]

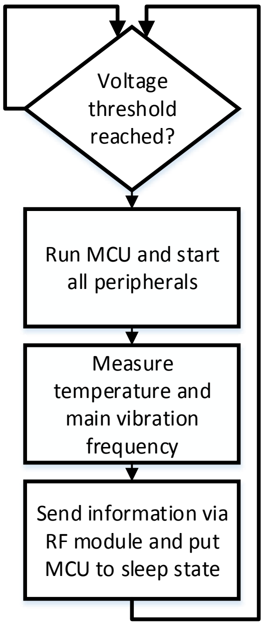


Fig. 6.5 Algorithm of created wireless sensor node [34]

7. CREATED WIRELESS SENSOR NODES NATURAL TESTS

In order to confirm assumption that tool wear has indirect proportion to time needed to charge capacitor tests were carried out with new and blunt tools. All tests were performed with same cutting regimes.

Turning with buzzer type harvester.

Table 7.1 Data provided by sensor when turning with new tool without coolant

New cutting tool. Turning without coolant			
Time	Period of timer	Period (s)	Temperature (°C)
-	-	-	-

Only one signal was received after ~35s, i.e. at the end of turning process.

Table 7.2 Data provided by sensor when turning with blunt tool without coolant

Blunt cutting tool. Turning without coolant			
Time	Period of timer	Period (s)	Temperature (°C)
10:24:16.477			39
10:24:20.125	1800	3.6	39
10:24:23.605	1851	3.702	40
10:24:34.609	5637	11.274	39

Four signals were transmitted. Time between signals varies from 3.6s – 11.2s.

Table 7.3 Data provided by sensor when turning with blunt tool with coolant

Blunt cutting tool. Turning with coolant			
Time	Period of timer	Period (s)	Temperature (°C)
10:26:08.985			39
10:26:35.315	13478	27	36

Two signals were transmitted. Time between signals – 27s

Milling with cantilever type harvester when changing processing speed – 1600 rpm and 3200 rpm. Tool was used same in both regimes.

Table 7.4 Data provided by sensor when milling at 1600 rpm

Milling at speed 1600 rpm.			
Time	Period of timer	Period (s)	Temperature (°C)
10:36:35.905			25
10:36:55.928	10256	20.512	25
10:37:15.438	9986	19.972	25
10:37:38:556	11459	22.918	25
10:37:54.154	8362	16.724	26

Five signals were transmitted. Time between signals varies from 16.7s – 22.9s.

Table 7.5 Data provided by sensor when milling at 3200 rpm

Milling at speed 3200 rpm.			
Time	Period of timer	Period (s)	Temperature (°C)
10:39:20.121			28
10:39:44.884	12679	25.358	27
10:40:04.263	9923	19.846	26

Three signals were transmitted. Time between signals varies from 19.8s – 25.4s.

These tests confirmed that tool wear has indirect proportion with time needed to charge capacitor and milling regimes do not have high influence on time needed to charge capacitor.

For determining milling tool chip wear condition and more sophisticated experiment was implemented. CNC milling lathe and additional measuring equipment was used in experiment. General view of milling lathe and experimental equipment is shown in Fig 7.1. Experimental stand consists of CNC milling lathe Optimum Optimill F150 with SIEMENS Sinumerik 828D control block and Shopmill software; four teeth end mill $D = \varnothing 50mm$ Walter Xtra-tec F4041 with changeable carbide inserts WKP35 and SK40 tool holder fixed in spindle; mill vibration sensor-power generator with integrated wireless transmitter fixed to end mill; steel 1.0037 workpiece fixed in clamps of lathe; Laptop with Docklight v1.9 software (Fig. 7.2) which receives and registers signal from sensor node through wireless receiver; surface roughness measurement device Mitutoyo SJ-201 which measures surface quality.

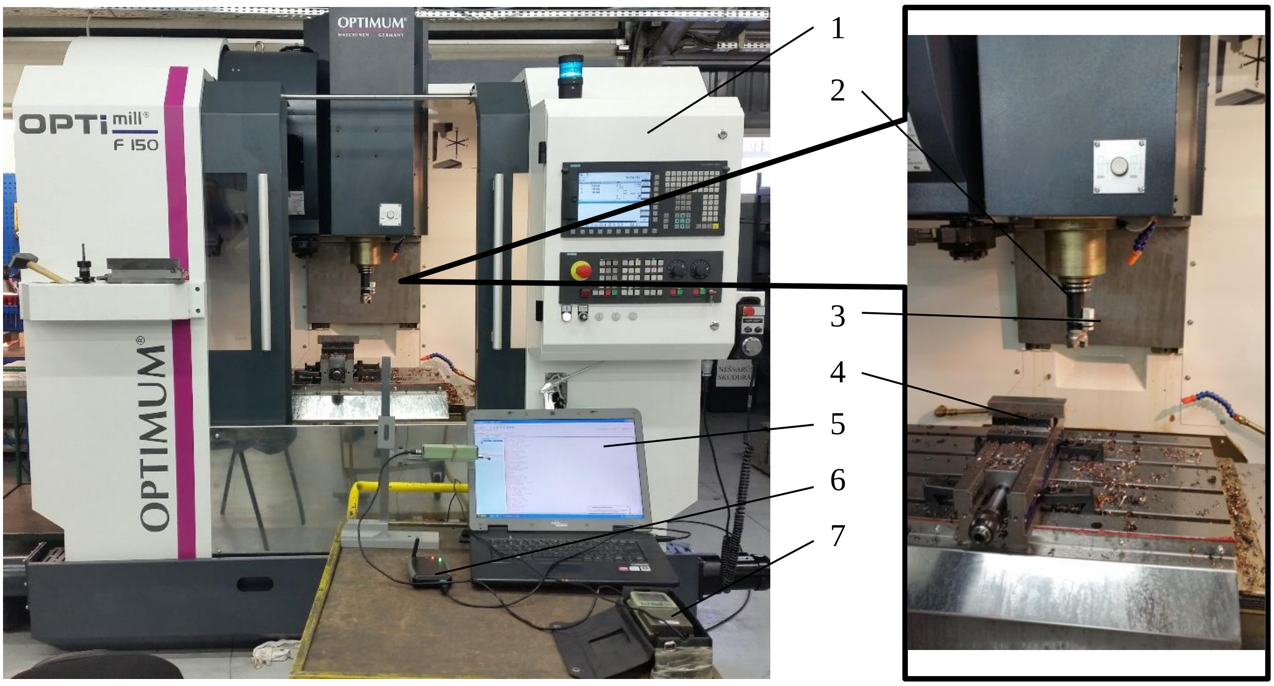
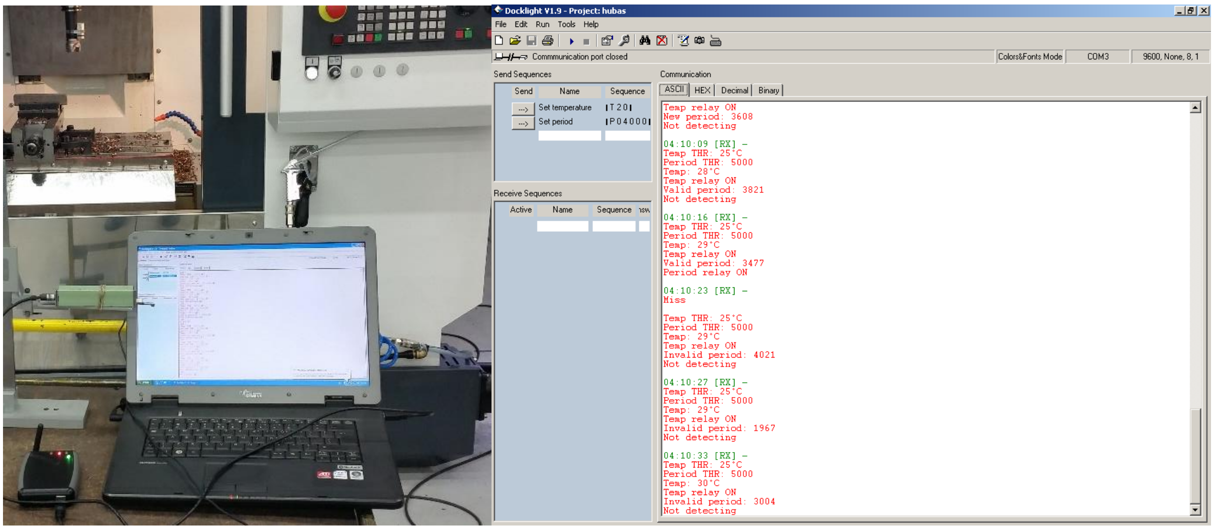


Fig. 7.1 Experimental equipment: 1 - CNC milling lathe Optimum Optimill F150; 2 - four teeth end mill; 3 - wireless sensor node; 4 - steel workpiece 1.0037; 5 - laptop with software; 6 - wireless receiver; 7 – surface roughness measuring device



Set temperature |T20|
Set period |P04000|

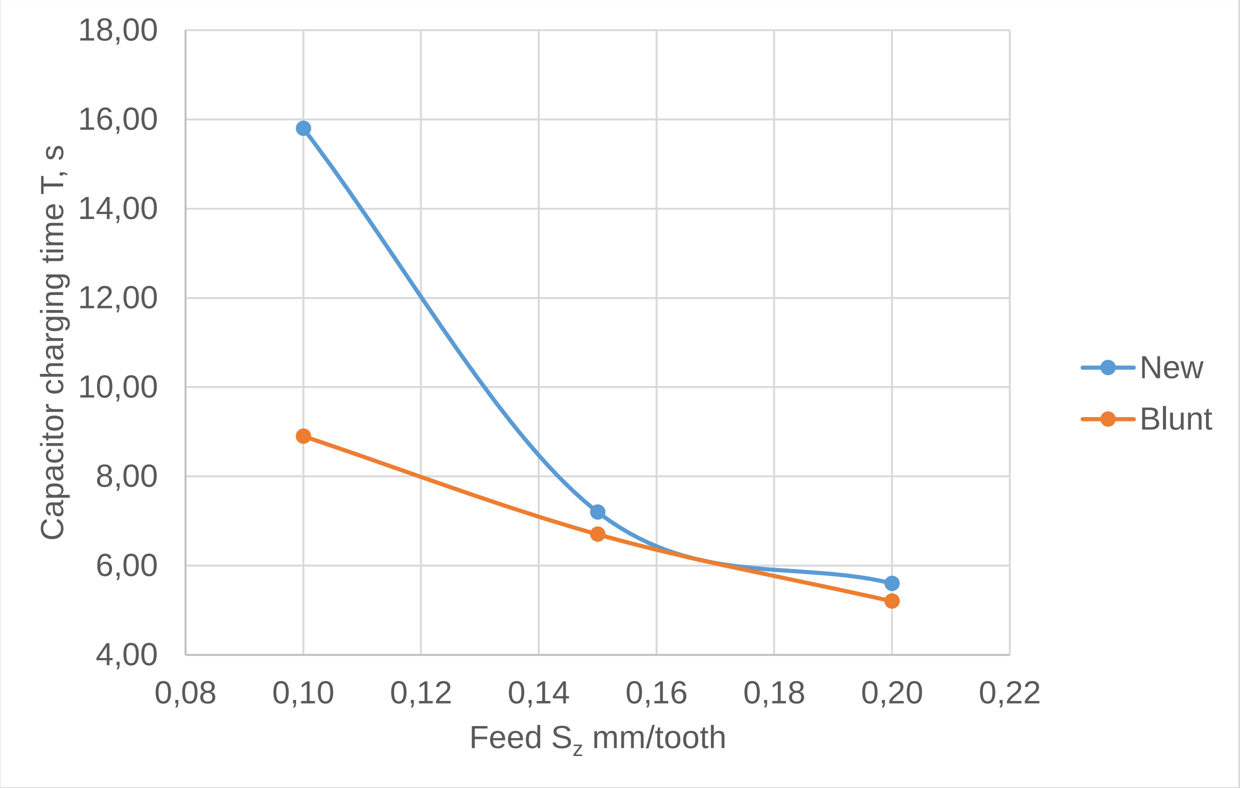
```
Temp relay ON
New period: 3608
Not detecting

04:10:09 [RX] -
Temp THR: 25°C
Period THR: 5000
Temp: 28°C
Temp relay ON
Valid period: 3821
Not detecting

04:10:16 [RX] -
Temp THR: 25°C
Period THR: 5000
Temp: 29°C
Temp relay ON
Valid period: 3477
Period relay ON

04:10:23 [RX] -
Miss

Temp THR: 25°C
Period THR: 5000
Temp: 29°C
Temp relay ON
Invalid period: 4021
Not detecting

04:10:27 [RX] -
Temp THR: 25°C
Period THR: 5000
Temp: 29°C
Temp relay ON
Invalid period: 1967
Not detecting

04:10:33 [RX] -
Temp THR: 25°C
Period THR: 5000
Temp: 30°C
Temp relay ON
Invalid period: 3004
Not detecting
```

Fig. 7.2 General view of data received from wireless sensor node during milling operation

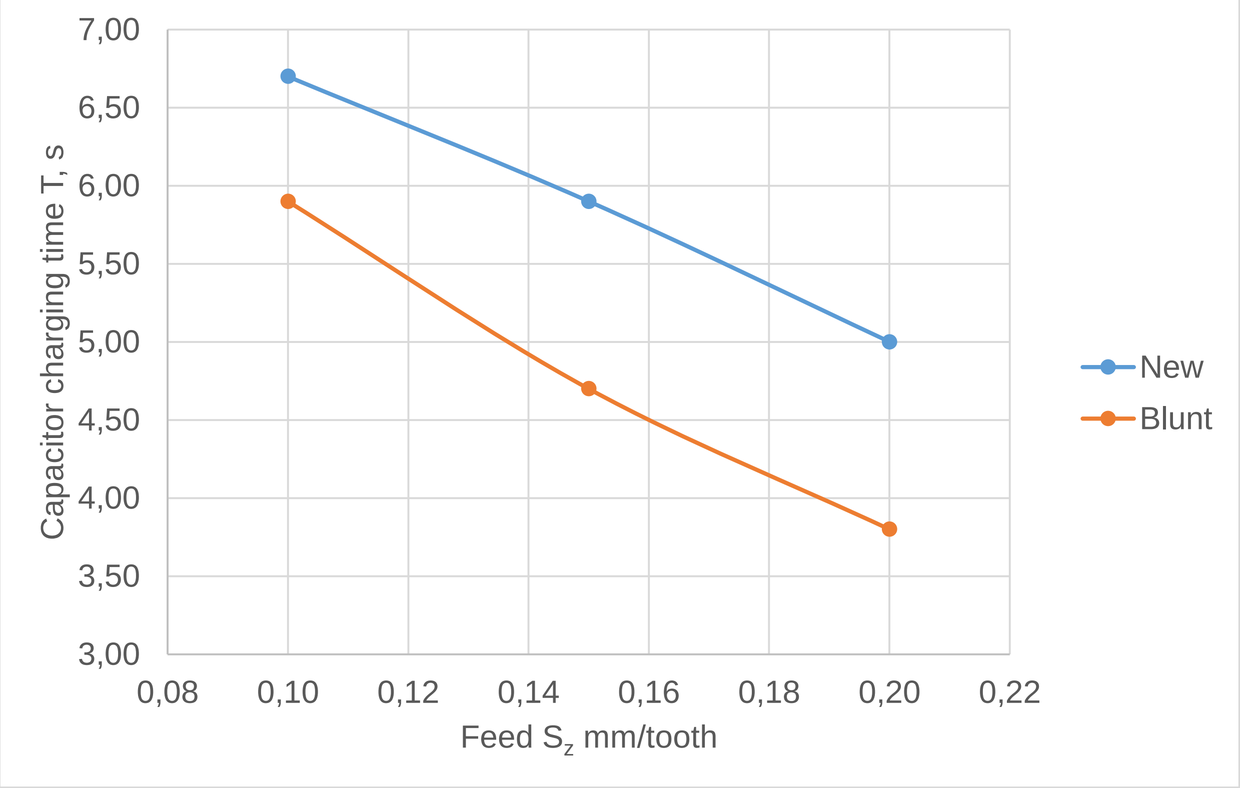
Experiments were performed with different spindle rotation speed *n*, feed S_z and cutting depth a_p, until laptop receives signal from wireless sensor. Than surface quality is determined by measuring three times and calculating arithmetical average value. Tool wear was studied with tool presetter and measuring machine Zoller Smile v300 (Fig. 7.3).

Fig. 7.3 Blunt tool measuring device Zoller Smile v300

Steel workpiece processing results of experiments are presented in Fig. 7.4



a)



b)

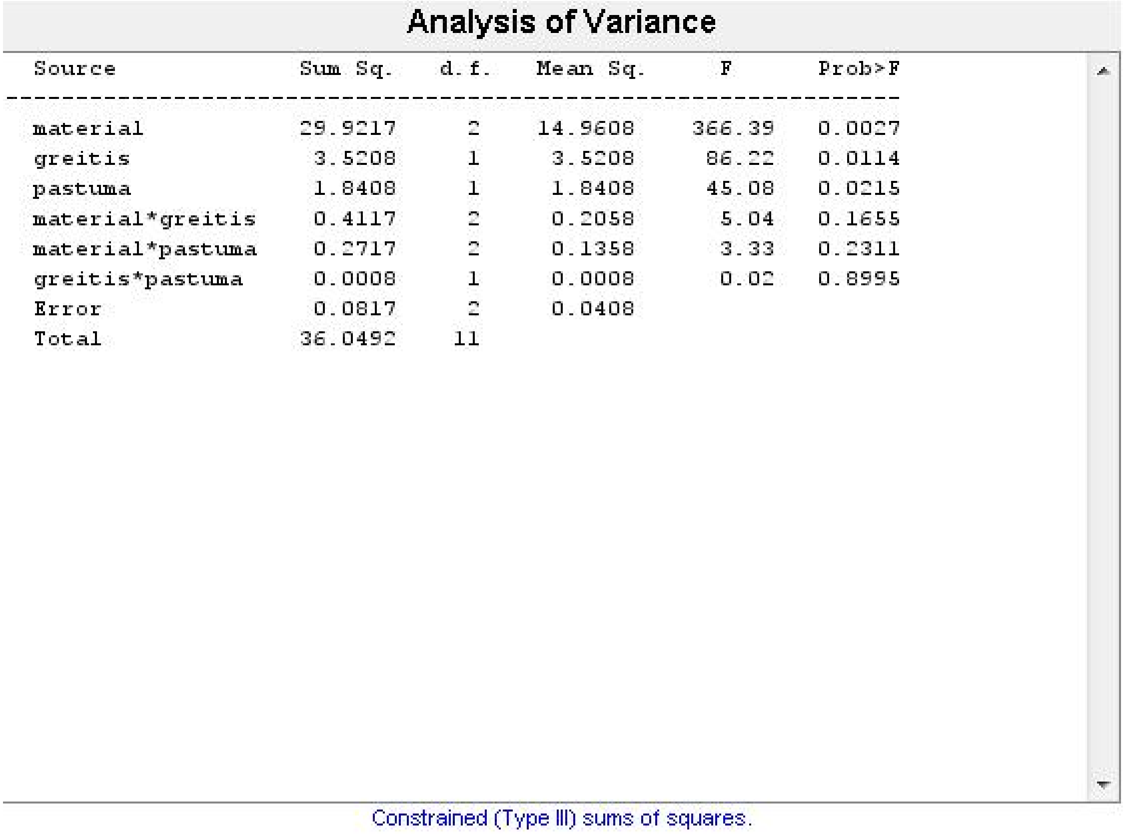
Fig. 7.4 Charging time and feed relation graphs when spindle speed n and cutting depth a_p are constant: a - n=1000rpm, a_p=2mm; b - n=1000rpm, a_p=3 mm

Graphs (Fig. 7.4 a, b) show that increase in tool insert wear leads to less time needed to charge capacitor. In order to get more accurate results, it is necessary to perform additional tests e.g. statistical analysis.

8. EXPERIMENT RESULTS STATISTICAL ANALYSIS

8.1. Variance analysis for turning operation

Turning tool identification signal formation interval of time, informing about the state of wear of the tool depends on several factors, most important of them are following: machined materials, speed (rpm) and feed rate (mm/rev). Statistical experiment consists of these three factors. Aim of experiments is to determine how these factors influence tool identification signal formation time interval. Experiment was carried out with three materials (steel 1.0037 – St37-2/S235JR and stainless steel 1.4057 and aluminium alloy), two speed values (low level 600rpm and high level 1000 rpm), two feed values (low level 0.1mm/rev and high level 0.2mm/rev). Statistical experiments were performed using a three-level two-factor ANOVA statistical method in order to determine dispersion analysis of the test results. The variance analysis provided following results of calculations: the sum of squares (Sum Sq.), their degrees of freedom (d.f.), mean sum of squares (Mean Sq.), F-statistic and its P-value. If P exceeds selected level of significance α, the null hypothesis does not object, i.e. it says that "on the basis of experimental data do not have grounds to state that factor makes effect on measuring variable". If $P \leq \alpha$, then the null hypothesis is rejected, i.e. we affirm that "factor makes effect on measuring variable". Turning analysis results presented in Fig 8.1.



Analysis of Variance

```
 Source              Sum Sq.   d.f.   Mean Sq.      F      Prob>F
------------------------------------------------------------------
 material            29.9217     2    14.9608    366.39    0.0027
 greitis              3.5208     1     3.5208     86.22    0.0114
 pastuma              1.8408     1     1.8408     45.08    0.0215
 material*greitis     0.4117     2     0.2058      5.04    0.1655
 material*pastuma     0.2717     2     0.1358      3.33    0.2311
 greitis*pastuma      0.0008     1     0.0008      0.02    0.8995
 Error                0.0817     2     0.0408
 Total               36.0492    11
```

Constrained (Type III) sums of squares.

Fig. 8.1 Turning statistical analysis results

As seen from the results, in this case, three factors – the material being processed, speed and feed – influenced the identification signal formation time interval, because P value is less than 0.05. However, in this case, statistically highest impact has type of machines material. Factors relation has not statistical effect on identification signal forming time interval duration.

Multiple comparison of population marginal means for cutting is presented in Fig 8.2, in which can be seen that material 3 marginal mean is significantly different from material 1 and material 2 marginal mean.

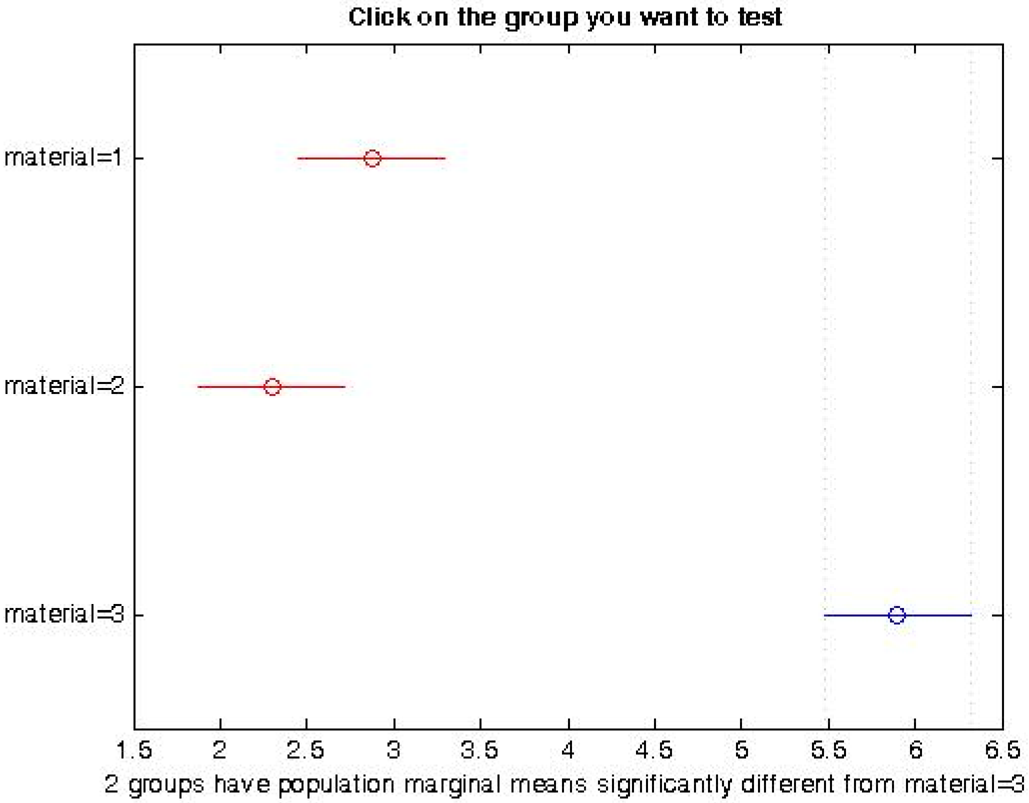


Fig. 8.2 Multiple comparison of population marginal means for cutting process

During analysis *material 1* and *material 2*, respectively are stainless steel 1.4057 and steel 1.0037 which has similar physical properties. Meanwhile *material 3* – aluminium alloy, which has different properties thus marginal mean is higher. Despite that, materials have significantly different marginal means, previous experiments showed that identification signal forming time interval duration is highly dependable on machined material. Thus, as distinctive attribute, operator would need to select only processed material code.

CONCLUSIONS

After fulfilling all the established goals which were set in order to implement the final Master's project the following conclusions are listed below.

1. After several experimental tests with piezoelectric transducers, two piezoelectric generator designs were realized: i) generator with high-frequency disk transducer, adapted to work on turning (non-rotating) tool; ii) generator with low-frequency cantilever transducer, adapted to work on milling (rotating) tool.
2. Piezoelectric generators were successfully integrated into wireless sensor nodes. Wireless sensor energy storing/transforming subsystem electronic architecture was perfected.
3. The proposed wireless sensor node architecture allowed to accumulate energy from very small sources, excite an embedded micro-systems and wirelessly transmit a signal without any additional power source.
4. Constructed innovative wireless multi-sensory diagnostic equipment (autonomous wireless sensor nodes and wireless receiver) was successfully.
5. Created devices were used to identify turning and milling tools wear condition. The proposed method is based on statistical analysis of generator signal interval duration values.
6. Performed variance analysis showed that during turning operation, statistically most influential factor as what type of material is processed. Thus, as distinctive attribute, operator would need to select only processed material code.

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