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Cutting tool vibration energy harvesting for wireless sensors applications

Vytautas Ostasevicius[a,*], Vytautas Markevicius[b], Vytautas Jurenas[a], Mindaugas Zilys[b], Mindaugas Cepenas[b], Laura Kizauskiene[c], Virginija Gyliene[a]

[a] *Institute of Mechatronics, Kaunas University of Technology, Studentu St. 56-123, Kaunas LT-51368, Lithuania*
[b] *Faculty of Electrical and Electronics Engineering, Kaunas University of Technology, Studentu 48-211 St. 27, Kaunas LT-51368, Lithuania*
[c] *Faculty of Informatics, Kaunas University of Technology, Studentu St. 48-213, Kaunas LT-51368, Lithuania*

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ABSTRACT

This paper presents a method of cutting tool vibration energy harvesting for wireless applications, the created devices and the results of the accomplished experiments. The proposed high frequency piezo generator assures energy harvesting, accumulation and appropriateness for wireless sensors applications. The proposed architecture composed from energy harvesting transducer, energy accumulating capacitor, sensors, microcontroller and RF link opens a way for wireless sensors networks in manufacturing technologies providing the effective integration of information, delivered by sensors of different nature, to achieve a wholesome description of the status of the monitored process. The elaborated algorithm and the created detector could reach no more than 100–150 nA current consumption during capacitor charging. This method makes possible the accumulation of necessary energy during turning tool vibrations. According to the experimental results, the created wireless sensor energy harvester prototype satisfies the energy needs for sensors and is capable of transmitting the information at the distance of 20 m. For cutting tool performance evaluation the limitary moment, when cutting tool starts manufacturing inappropriate quality parts, was defined experimentally and statistically.

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1. Introduction

Rapidly increasing numbers of wireless sensor nodes and their networks necessitate the development of continuously powered systems avoiding the most expensive issue of its maintenance – periodical battery replacement or recharge [1]. Capturing small amounts of energy from the surrounding vibrations, accumulating them and storing for later use is one of the perspective techniques in recent years [2], recently realized by magnetostrictive, electrostatic, electromagnetic or piezoelectric transduction mechanisms [3]. Most attractive frequencies for the harvesters are less than 100 Hz [4]. Piezoelectric transduction was chosen from the other available motion-to-electricity conversion methods due to its high energy density, favorable dynamic response as well as self-contained power generation materials [5]. Piezoelectric converters are a right choice for converting mechanical energy to electricity because energy density is more than three times higher as compared to electrostatic and electromagnetic energy generation methods. The concept of multi functionality is related to the combination of several functions in the components made from the same material. Possible system performance improvement possibilities using multifunctional materials are discussed in the paper [6]. Structural power systems, from the denoted four classes of multifunctional material systems, enabling the integration of energy storage capability with the structural function, are most interesting for applications. Energy capturing from different sources could be obligatory in cases when the amount of energy scavenged from the unique source is not sufficient for allowing the alimented system to remain online. Hybrid energy harvesting results, presented in [7] demonstrate the effectiveness of simultaneous application of piezoelectric. There are different mounting ways of piezoelectric generators, but the most common are cantilever beams [8].

The stability of a constant energy flow between the energy source and the load is a key element of the energy harvesting system. As the piezoelectric energy harvesting devices do not ensure enough current to power MEMS sensors, the development of storage devices and the enhancement of charge density

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* Corresponding author.
E-mail addresses: vytautas.ostasevicius@ktu.lt (V. Ostasevicius), vytautas.markevicius@ktu.lt (V. Markevicius), laura.kizauskiene@ktu.lt (L. Kizauskiene).

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are essential. Investigation of methods for improving electrical charge density for the circuitry and signal processing reduction are needed as well. The most fruitful efforts will likely come from hybridized power supplies, which offer both, on-board storage and energy harvesting from environmental sources. Initial research results for batteries [9] and capacitors [10], in the form of MEMS or nano generators could be considered as novel technology and new energy source for powering wireless sensor devices [11].

The possibility to increase frequencies of cantilever under low frequency excitation is shown in [12]. It is related to the utilization of vibration modes. Due to the high installation costs of wired sensor systems, the availability of sensor nodes and sensor technologies, wireless sensor systems [13] are becoming more prevalent. Wireless self-powered sensor nodes are a convenient and cost-effective solution.

Vibration in material cutting affects the machining performance, the surface finish and tool life. The self-excited vibration affects the production capacity, reliability and machining surface quality [14]. In [15] surface quality improvement is related to the intensity of tool cutting edge vibrations. The excitation of a particular vibration mode of a turning tool leads to the reduction of deleterious vibrations in the machine-tool-workpiece system through intensification of internal energy dissipation in the tool material.

Scientific work performed by several researchers in the field of machining operations' monitoring during the last two decades has highlighted the effectiveness of cognitive sensing techniques based on various aspects: acquisition, conditioning and analysis of signals, detected by sensors of different types for decision making on process conditions, cutting tool fracture, tool wear state, chip form acceptability, work material properties and work piece surface integrity [16]. A new guiding purpose of sensor monitoring research is sensor fusion technology that assures the effective integration of information, delivered by sensors of different nature, to achieve a wholesome description of the status of the process, being monitored [17]. A multiple sensor system was utilized for monitoring of Inconel 718 nickel alloy turning operations [18]. These systems are used mainly for two purposes: to continuously monitor the operating conditions during real time processing and to trigger a premature machine stop or alarm before the damage arises [19]. Thus, the risk of tool fracture can be reduced, the compliance with quality requirements can be ensured and process safety can be guaranteed.

This paper aims to develop a harvester combining advanced technology with integrated energy storage. The experimental investigation of the generator has shown, that energy harvesting from cutting vibration or from electromagnetic field of the machine tool structure or even from mobile phone was possible. The results of the cutting tool vibrational energy harvesting are published in recent research. In addition, a flexible piezo ceramic and a capacitor for the accumulation of the harvested energy is used. This assembly was tested under cutting tool excitation and also applied to accumulate the extracted energy. Electrical outputs were used for energy accumulation while charging the capacitor. Time histories are given for the harvesting tests using this energy harvesting and accumulation technique. The results are discussed as well. This innovative and low-cost "smart" wireless sensor is used for equipment condition monitoring and fault diagnostics. Tool vibration measurement sensor/energy extraction and accumulation elements are located on the tool, which is working in harsh-wet conditions. One of the paper objectives is the vibration monitoring of the industrial tool (conventional machine tools) thus increasing the quality of the products, while at the same time reducing the amount of low-quality products.

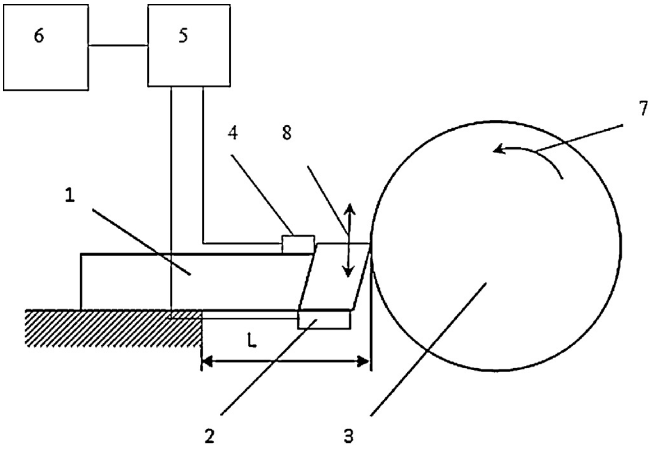

Fig. 1. Turning experiment set up: 1 – turning tool; 2 – energy harvester element; 3 – workpiece; 4 – KD91accelerometer; 5 – Pico Scope 3424; 6-PC; 7 – cutting speed direction; 8 – excited turning tool vibration.

2. Electrical energy harvester type identification

2.1. Turning tool vibrations

Machine tool chatter is a self-excited vibration problem occurring in large rates of material removal, resulting from the unavoidable flexibility between the cutting tool and workpiece. It is important to mention the turning process and turning tool, which is a flexible structure vibrating during cutting process at several natural modes. The source of vibration or chatter is related with cutting force action dependent on the regimes of manufacturing as well on the tool wear. This means that it is impossible to stop vibrations of the turning tool structure. That is why it could be useful for the energy generation. Exploiting the vibrations of machine units is one of the effective ways, allowing harnessing ambient energy for autonomous systems powering at the point of placement without the power supply cable or batteries. Integrating a harvesting system into the cutting tool structure (Fig. 1), the electrical energy can be generated from mechanical vibrations. The accelerometer KD91 was used for cutting tool vibration measurements. Some worldwide producers (Morgan Inc., Noliac A/S, Piezo system Jena GmbH, etc.) offer piezo-electric cantilevers for transmitting mechanical energy into electrical energy. Under the vibration or a change in motion (acceleration) the piezoelectric material "squeezes" and produces an electrical charge. Furthermore, the maximum amount of energy could be produced if industrial processing machine tools and piezo-electric energy generator's resonant frequencies coincided. According to the research work [15], considering several modes of elastic turning tool vibrations, it was identified that the turning tool vibrates on the main mode, depending on the clamping, i.e. the length of the tool hanging from the claim, in a range from 2.5 kHz to 5.6 kHz. It means that commercial piezo-electric cantilevers are not available for energy harvesting because of the low resonant frequency. For this purpose the circular piezo transducer bimorph, assuring the resonant frequency in the required diapason (2.5–5.6 kHz) was chosen. Turning tool impact test results presented in Fig. 2, when tool shank length is $L = 55$ mm, confirm, that turning tool vibration period presented in time domain of the tool shank is ~0.22 ms, which corresponds to 4.5 kHz.

2.2. High frequency circular piezo harvester

During the cutting process, the piezo-electric harvester, fixed on the tool tip removes energy in the form of electricity. During the research, the circular piezo transducer bimorph (model

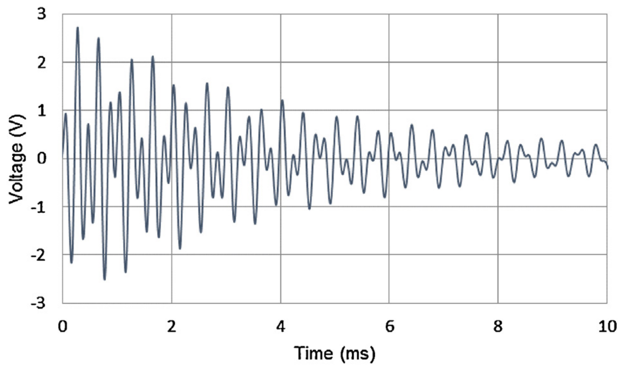

Fig. 2. Turning tool impact test, when tool shank length is $L = 55$ mm.

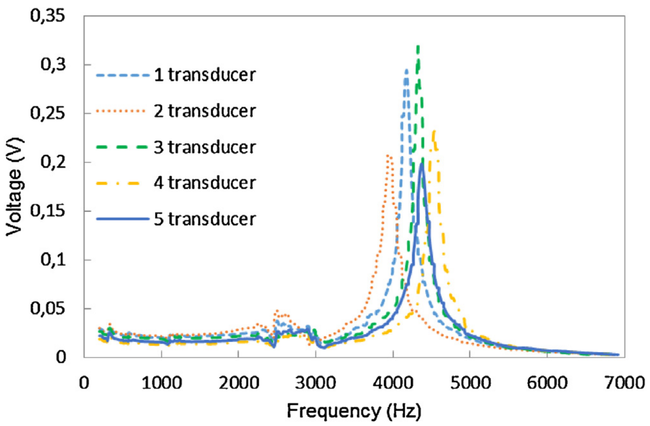

Fig. 3. Piezo-electric harvester generated voltage-frequency response under acceleration of 1 g.

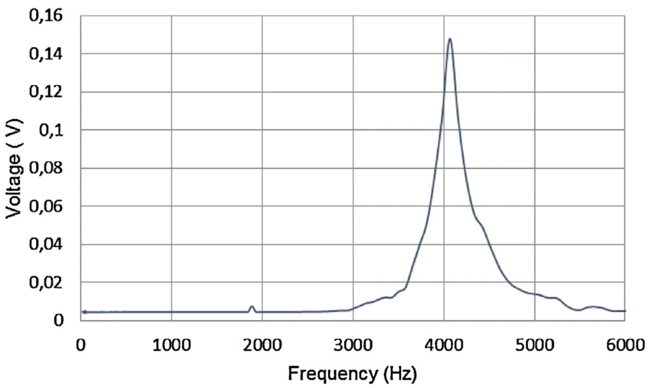

Fig. 4. Ultimate simulated piezoelectric harvester output voltage at 4.2 kHz resonant frequency.

AB1541, dimensions ø15 × 0.15 mm, resonant frequency ~4 kHz.) was used for mechanical to electrical energy conversion. The voltage-frequency characteristics for five circular piezo transducers were received vibrating on the electro dynamical stand (Fig. 3). It can be seen that there is a significant frequency distribution of the energy harvester resonance in the 3.9–4.5 kHz range.

For efficient energy harvesting the first resonance of the turning tool should be close to the resonant frequency of the piezo generator. The Finite Element model of circular piezoelectric transducer was developed with Comsol Multiphysics software which confirms that ultimate voltage is harvested at resonant frequency of 4.2 kHz (Fig. 4).

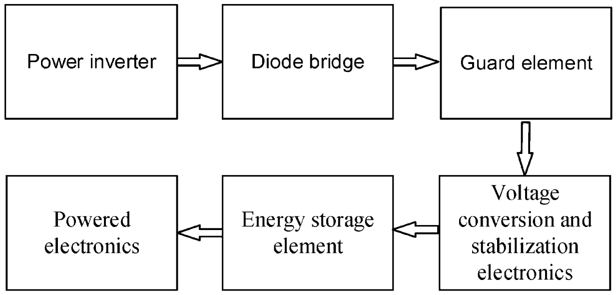

Fig. 5. Components of energy recovery and storage device: 1 – power inverter; 2 – diode bridge; 3 – guard element; 4 – voltage conversion and stabilization electronics; 5 – energy storage element; 6 – powered electronics.

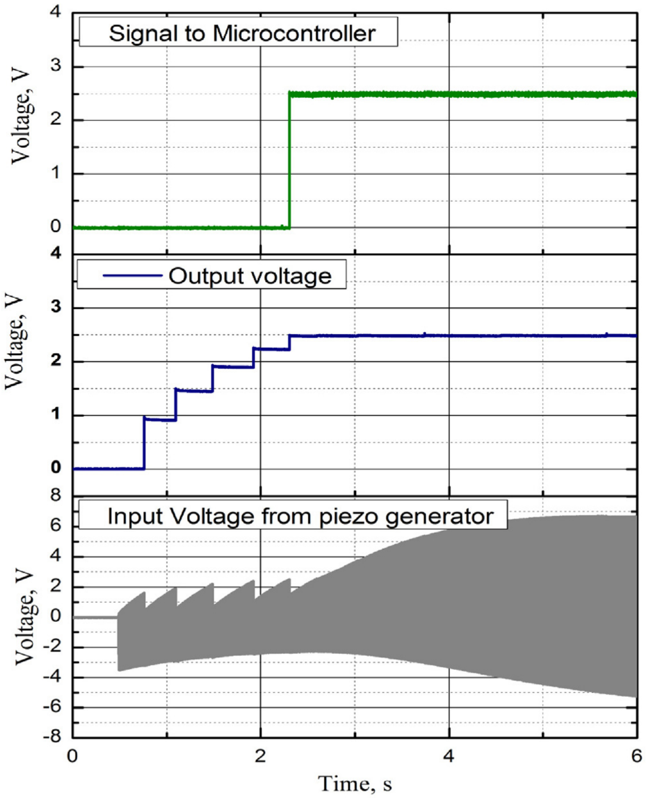

Fig. 6. Power transducer sub-system signals charging 100 μF capacitor.

3. Identification of energy harvester electrical parameters

3.1. Energy harvester block

In order to generate and store electrical energy it is required to have energy generation, transformation, stabilization and energy storage elements together with the elements from excessive surge protection (Fig. 5). Power converter or energy generating element 1 is the energy converter which transforms mechanical energy into electrical. All power converters are most efficient at resonant regime, where the amount of the generated energy increases from 2 to 100 times. Generated electric power by power converter 1 is AC current; therefore it requires the diode bridge 2, which changes the power from AC to DC. Schottky diodes are used for the diode bridge for several reasons: they are faster and they are falling on the lower voltage (approximately 0.3 V) and perform better at high frequencies compared to conventional diodes. Element 3 is an element which protects against impermissible high voltage. It is a Zener diode. Element 4 is a chip which increases voltage with a voltage

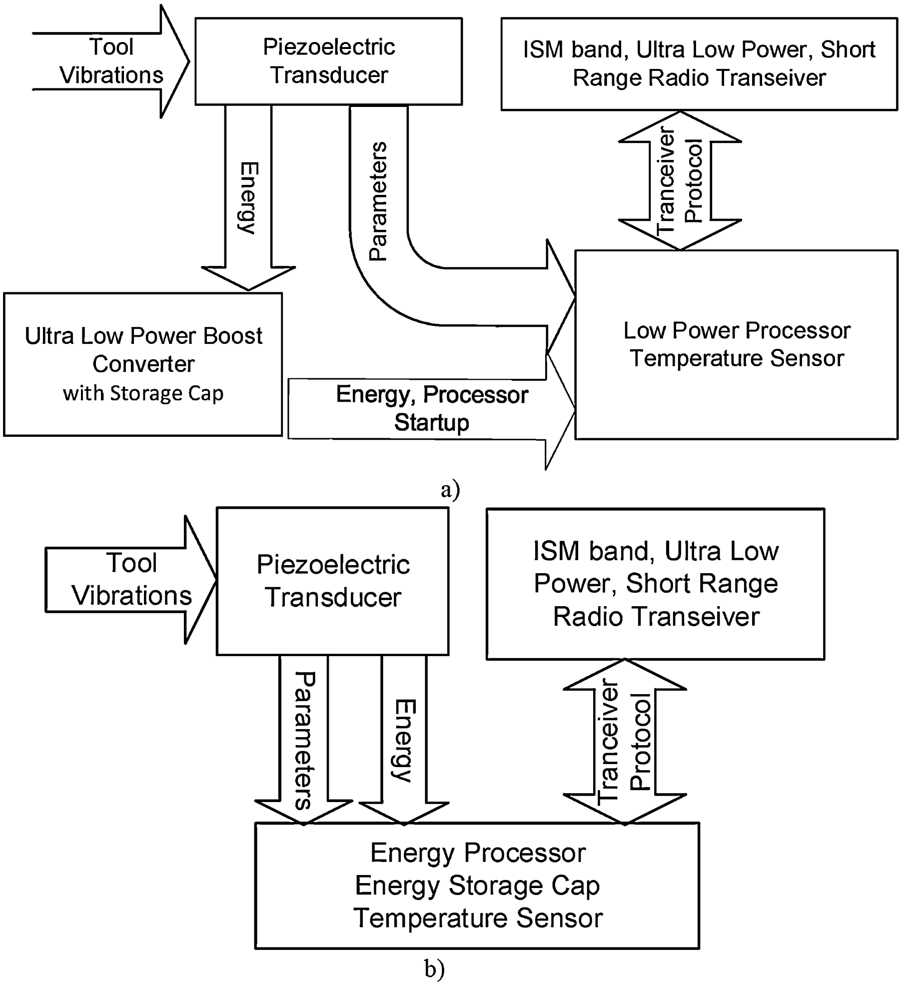

Fig. 7. Wireless sensor node design of smart tool: (a) sensor with separate low power boost converter; (b) sensor with energy processor inside.

stabilizer depending on the required stabilized DC voltage which is used to power the electronics and power inverter generated voltage amplitude. Element 5 denotes an energy storage capacitor as well as element 6 denotes the micro controller.

The subsystem of the electrical energy conversion was realized to convert electrical energy, generated by energy transducer, to micro-controller voltage level. The primary transducer – the piezo generator, converts mechanical vibrations' energy into electrical energy, which is variable and must be of sufficiently large amplitude. The created subsystem – is a secondary transducer, which converts the variable voltage into direct constant voltage, which can be modified. This transducer is designed using Linear Technology LTC3588-1 microchip, which integrates diode bridge, Zener diode and AC/DC voltage decreasing converters.

3.2. Power conversion input and output

Power conversion subsystem performance is shown with removed signals, charging 100 μF capacitor (Fig. 6). When output voltage reaches the target voltage of 2.5 V, the output induces that stabilized voltage does not go out of the constrained boundaries. This signal is fed to the measuring electronics.

As it seen from the Fig. 6 the output voltage reaches 6 V without load and 2.5 V with load. Experimental results have showed instability of high amplitude tool vibrations. In order to increase the efficiency of energy collection from piezo transducer, the system was improved and Schottky diode bridge was replaced with input voltage quadrupler.

4. Integration of energy harvester to the cutting tool structure

4.1. Wireless sensor node architecture

In order to increase the efficiency of energy collection from piezo transducer, the energy harvesting system was improved: the guard Zener diode was changed to MOSFET in order to minimize the reverse current. Possible wireless sensor node architectures, embedded into smart tool, are presented in Fig. 7.

As wireless sensor nodes operate on a tough power budget, ultra-low power (ULP) microcontroller units (MCU) are required for processing and power management. A typical MCU, like the Texas instruments MCU-MSP430, is ideal for energy harvesting for its characteristics: it has the standby current of less than 1 μA and the active current of 160 μA/MHz, a quick wakeup time of less than 1 μs, the temperature sensor inside, besides, it operates at the range of 1.8–3.6 V. After the experimental tests, the developed sensor has showed that at the beginning of the charging process of the sensor subsystem (energy converter or processor and radio transmitter) it goes to an uncertain state – power consumption strongly exceeds the current generated by the piezo transducer. This stops the charging process and the sensor is not able to switch to the measuring mode.

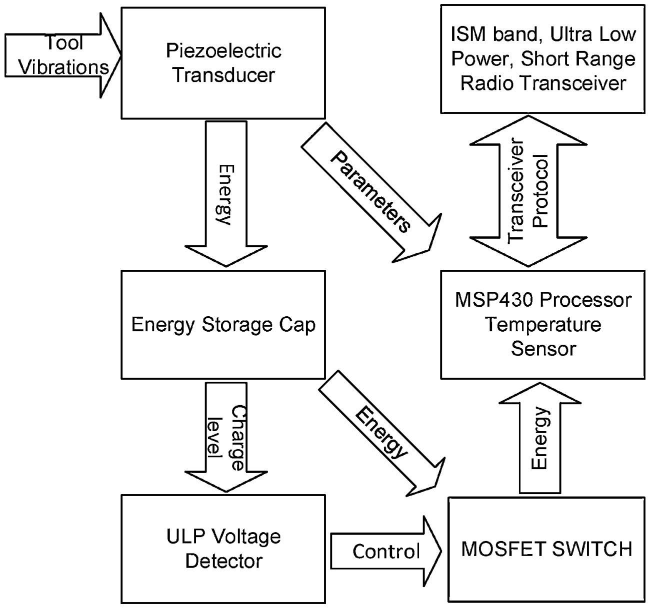

Fig. 8. The proposed advanced wireless sensor architecture with separated ultra – low power voltage detector.

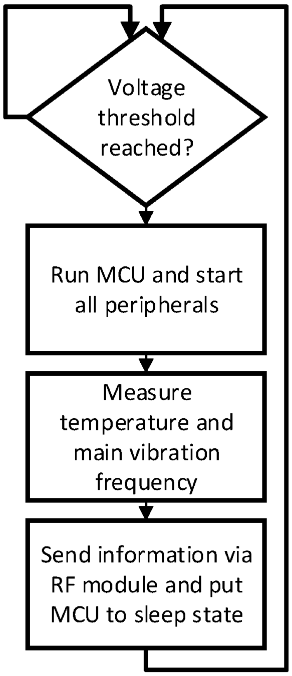

Fig. 9. Algorithm of created wireless sensor node.

4.2. *WSN architecture with separate ultra-low power charge*

The proposed advanced sensor architecture with separate ULP charge detection, denoted in Fig. 8, enabled reducing the energy consumption during MCU start-up process. The system only uses the energy for input voltage until the capacitor is fully charged. The algorithm of WSN is presented in Fig. 9. We also use MCU inside temperature sensor for tool temperature monitoring.

5. Ultra-low power consumption mode

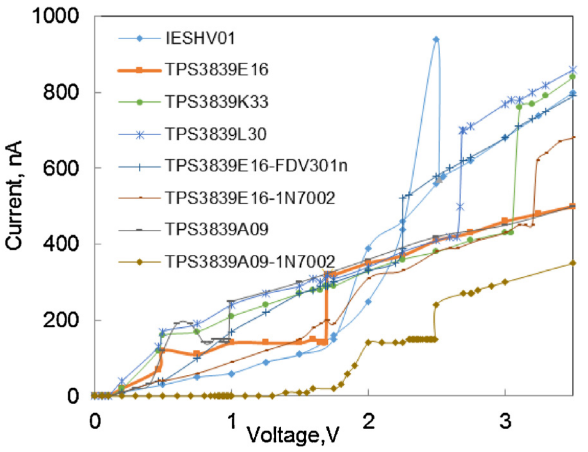

Fig. 10. Wireless sensor node energy consumption using eight different modes of charge detection.

Eight different devices of charge detection were tested and experimental results are presented in Fig. 10. Extremely low energy consumption, more than 100–150 nA current consumption could be reached only with IESV01 and TPS3839A09 1N7002 of charging detectors during capacitor charging. This method achieves the accumulation of the required energy even at low level of tool vibrations.

The proposed sensor schematics with separate ULP charge detection showed in Fig. 11. The proposed architecture for wireless sensors' nodes is presented in Fig. 12.

6. Wireless energy harvester and receiver prototypes

According to the experimental results, a prototype of the wireless energy harvester was manufactured (Fig. 13).

This prototype fully satisfies energy needs for sensors' supply and is capable of transmitting the information at the distance of 20 m for indoor environment. 10 bytes are sent each time, but there is a possibility to send max 64 bytes with accumulated energy. RF module wake up and initialization takes approximately 3 ms. Two types of transceivers for wirelessly transmitted information from sensors were elaborated (Fig. 14).

7. Experimental results

7.1. *Turning energy harvester*

Cutting vibration energy harvester concept was demonstrated for steel turning operation on CNC lathe RAYO 165. The depth of cut was 0.5 mm. The experimental energy harvesting set-up is shown in Fig. 15.

The created wireless sensor node is mounted on the CNC turning tool. Anaren RF module LR09A and the transceiver with surface-mount antenna were used in wireless sensor node. During the turning operation, the piezo harvester is excited by the high frequency vibrations. The harvested energy is accumulated by 100 μF capacitor.

7.2. *Tool wear influence on energy harvesting process*

The purpose of this experiment is to show the influence of the tool wear for the frequency of wireless transmission of the information to the transceiver (Fig. 16).

The maximum output voltage of the vibration harvester, when cutting by the new tool is 2 V (blue color). The generated harvester voltage is exponentially rising till the capacitor is fully charged and wireless signal is sent to the receiver. The signal sending time intervals are ~19 s. The accelerometer signal is shown in red color. At the

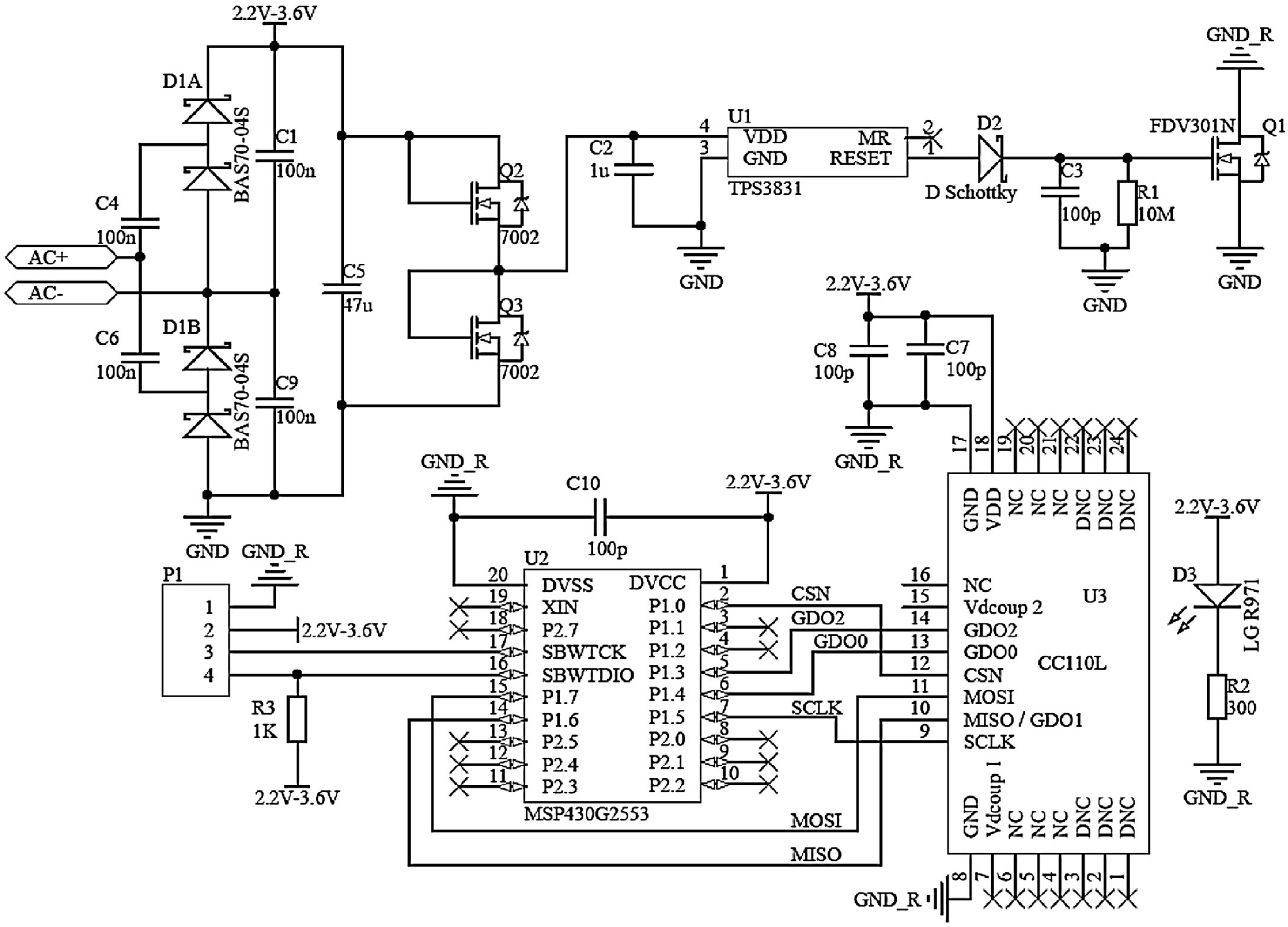

Fig. 11. Schematics of the created wireless sensor node.

end of tool life, when the tool cutting edge is worn, the accelerometer's signal amplitude increases (Fig. 17). The frequency of wireless transmission of the measured results increases too and the time interval is decreased approximately 4 times till ~5 s.

During the exploitation, the resonant frequencies of the tool and the harvester are not changing and are very close, what is the necessary condition for the energy accumulation efficiency. With the deterioration of the cutting tool technical state, the vibrations' level increases shortening the charging time of the capacitor. The capacitor's charging time is strictly proportional to the tool's vibration intensity and could be useful for the cutting tool technical state characterization.

Such statistical procedure was used for the evaluation of the experimental results: samples from the population were taken by occasional sampling method. Considering that the capacitor charging time coincides with the normal distribution law, the samples of capacitor charging for the new and the worn tool are independent. Thus, for the verification of the research results, the Student's t-test was used to check the statistical hypothesis for unknown variances (case $\sigma_1{}^2 = \sigma_2{}^2 = \sigma$). The test statistics t_0:

$$t_0 = \frac{\bar{x}_1 - \bar{x}_2 - \mu_D}{S_p\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}},$$

where:

n_1–number of samples for the new tool,
n_2–number of samples for the worn tool.

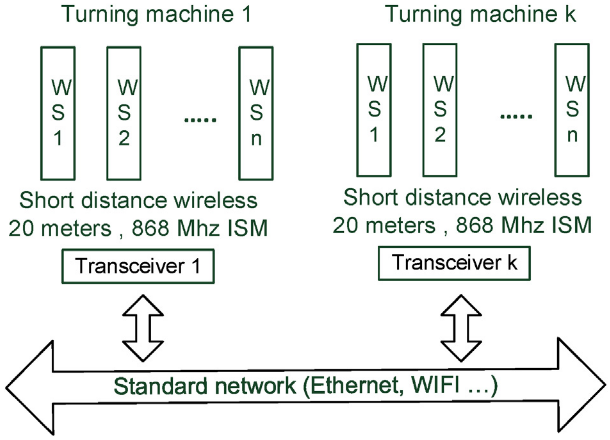

Fig. 12. Wireless sensors' nodes' network architecture.

Rating of dispersions:

$$S_p^2 = \frac{n_1 - 1}{n_1 + n_2 - 2} S_1^2 + \frac{n_2 - 1}{n_1 + n_2 - 2} S_2^2 .$$

For evaluation of the cutting tool performance it iss necessary to define the limitary moment when the cutting tool starts manufacturing inappropriate quality parts. For this purpose the statistical analysis was used. In Table 1, the energy harvesting results for the new and the worn turning tools are presented (Table 1).

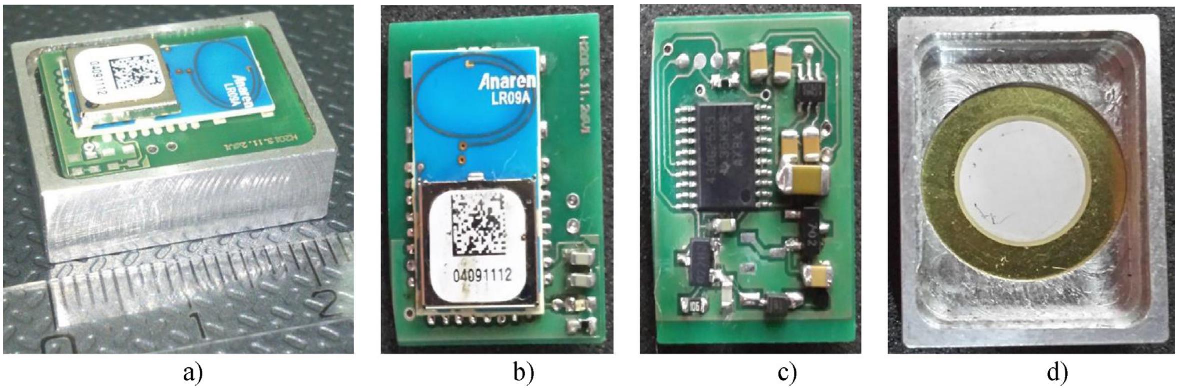

Fig. 13. A prototype of wireless energy harvester: (a) general view; (b) subsystem of information wireless transfer; (c) subsystem of energy accumulation; (d) piezo transducer.

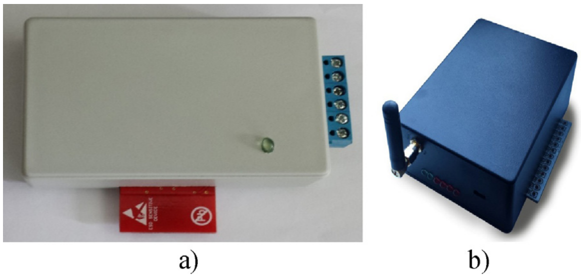

Fig. 14. Wireless sensor node transceiver prototypes: (a) surface mount antenna, (b) separate antenna.

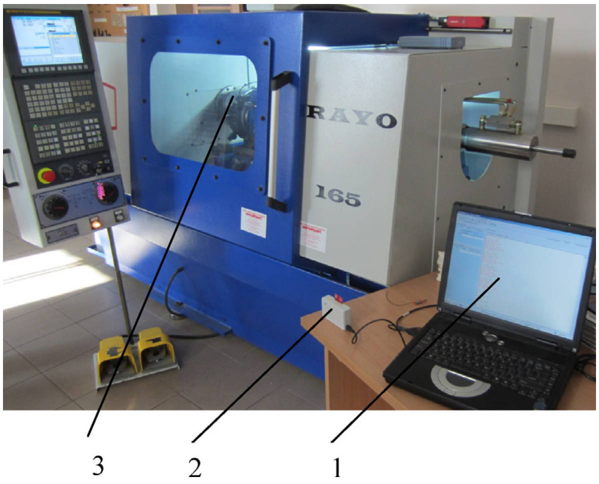

Fig. 15. General view of cutting energy harvesting set-up: 1 – personal computer; 2 – wireless receiver; 3 – CNC machine tool RAYO 165.

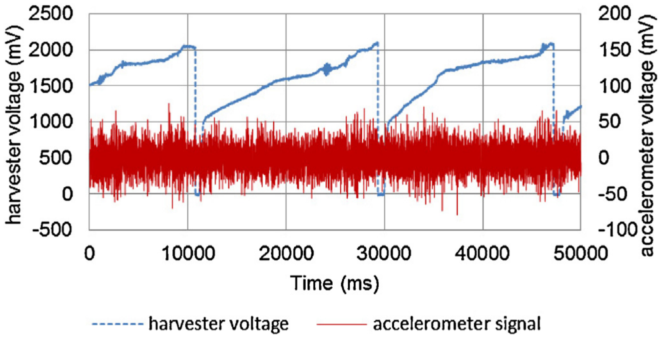

Fig. 16. Exponentially rising generated harvester voltage (upper – blue color) and the new tool vibrations (lower – red color) signals when turning steel work piece, the capacitor charge till 2 V is ~17 s. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

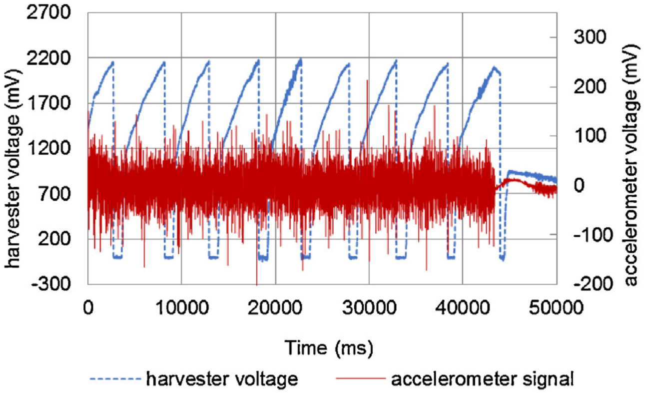

Fig. 17. Exponentially rising generated harvester voltage (upper – blue color) and the worn tool vibrations (lower – red color) signals when turning steel work piece, the capacitor charge till 2 V is ~5 s. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Energy harvesting signal formation period (s).

New tool	Worn tool
18,842	4,428
17,824	5,552
16,486	6,488
16,308	7,154
18,384	4,202
17,226	5,536
15,638	6,492
17,892	4,488
15,145	5,826
15,848	4,566
15,566	5,582
16,559	5,606
15,384	4,752
18,324	5,546
19,026	4,996
18,878	6,218
16,845	5,286
17,546	4,678
16,981	5,552
18,542	4,796
17,620	5,624

Considering that the data distribution law in the case of the new and the worn tool is normal, first of all, the tool wear influence on time interval is evaluated. Further, the hypothesis is tested, whether the difference between the means of the new and the worn turning tool is $\mu_D = 12$, with the applied significance level $\alpha = 0.05$ and the variances are assumed equal.

- The mean and variance for the sample of the new turning tool is: $\bar{x}_1 = 17.1$, $S_1 = 0.97$, $n_1 = 21$.
- The mean and variance for the sample of the new turning tool is: $\bar{x}_2 = 5.4$, $S_2 = 0.9$, $n_2 = 21$,

where n_1, n_2 – the sample size.

Then we verify if $\mu_1 - \mu_2 = \mu_D$ (where $\mu_D = 12$): μ_1, μ_2 denotes the population mean of the new and the worn tool

- H_0: $\mu_1 - \mu_2 = 12$
- H_a: $\mu_1 - \mu_2 \neq 12$ (alternating hypothesis).

The statistics of the *t*-test is marked t_0. The null hypothesis H_0 is rejected if:

$t_0 > t_{0,05.40} = 1.684$,
or if
$t_0 < -t_{0,05.40} = -1.684$.

We are calculating $S_p = 0.9$ and we receive, that the statistics of the test $t_0 = -1.1$. The t value with 40° of freedom having an area 0.05 to the right in t distribution is $t_{0.05,40} = 1.684$.

Conclusion: because $-1.684 < t_0 = -1.1 < 1.684$, null hypothesis could not be rejected. That's why in the case of new turning tool (with importance level 0.05) we could assume that the harvester signal formation interval is by 12 s longer than in the case of the worn turning tool.

8. Conclusions and future work

The proposed low power wireless sensor with energy harvesting technique has the potential ability to accurately monitor tool's condition. Standard hardware solutions are very limited for energy collection from 4 kHz piezo transducer. New technology low voltage microprocessors and transceivers allow collecting energy from piezo transducer without hardware power booster. Resonant frequencies of the chosen piezo elements scatter in the 3.9–4.5 kHz range. Real application of the vibration-based energy harvester for manufacturing purposes, able to sustain under harsh vibrations and shocks, occurring during materials' cutting, was proposed. An efficient electronic circuitry for energy harvester was developed. The experiments of the turning processes were made. The results of the experimentation have shown that the new turning tool vibration amplitudes exceed 0.5 V amplitude (sensitivity of KD91 accelerometer-0.5 mV/s^2). For the worn turning tool the vibration amplitude increases 3–4 times. The evaluation of the cutting tool performance was accomplished by measuring vibrational processes during cutting, revealing that the cutting tool wear influences the level of vibrations during this process, while the amount of the energy, harvested during cutting, increases according to the tool wear propagation. Consequently, the capacitor charging intervals decrease. For cutting tool performance evaluation the limitary moment, when cutting tool starts manufacturing inappropriate quality parts was defined experimentally and statistically. Furthermore, measuring the temperature during cutting or the vibration level introduce other possibilities. Energy harvesting from the rotating cutting tools is possible by placing the harvester on a spindle or spindle tool holder.

The developed technologies and devices in this work are practically valuable as a platform for mass production of various wireless sensor nodes and for cloud manufacturing applications.

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Biographies

Vytautas Ostasevicius graduated from Kaunas University of Technology – engineer mechanic in 1971, doctor of sciences in 1974, doctor habilitus in 1988. Director of the Institute of Mechatronics, Member of Lithuanian and and Foreign Member of Swedish Royal Engineering Academies of sciences. His research focuses on Mechatronic systems dynamics, manufacturing technologies, product development.

Vytautas Markevicius graduated MSc in1973 and received PhD in Electronics Engineering in 1983. He works at Department of Electronics Engineering, Faculty of Electrical and Electronics Engineering, Kaunas University of Technology. The leader of the research group on Interactive electronic systems. His research focuses on finding solutions for the issues related to the Interactive electronic systems, integrated information systems or WSN.

Vytautas Jurenas graduated from Kaunas University of Technology (KTU) in 1979 and received degree in Mechanical Engineering. He was awarded his PhD in 1993 in the field of Mechanical Engineering. He is a senior researcher in KTU Mechatronics Institute. His research interests include piezomechanics and diagnostics of mechanical systems.

Mindaugas Zilys graduated MSc in1996 and received PhD in Electronics Engineering in 2001. He works as a researcher at Department of Electronics Engineering, Faculty of Electrical and Electronics Engineering, Kaunas University of Technology and in industry. His research focuses on electronic system efficiency, energy harvesting, low power management and wireless smart sensors.

Mindaugas Cepenas graduated from Kaunas University of Technology (KTU) in 2012 with Master's degree in Electrical engineering. Currently, PhD study in Electrical and Electronics Department of Electronics Engineering studies KTU. Research areas - interactive design of microprocessor systems and low-power wireless networks.

Laura Kizauskiene is an associate professor at the Department of Computers, and researcher at the Real-time Computer Systems Centre at Kaunas University of Technology. She has gained doctors' degree in Technology Science in 2009. Her main research interests are multi-agent systems, artificial intelligence, wireless sensor networks, embedded real time systems and smart environments. Since 2007, she has been working at Kaunas University of Technology and has participated in several research projects, developing smart house and sensor network technologies.

Virginija Gyliene received her License Professional degree (Conception and Fabrication assisted by Computers) from the University of Maine (France) in 2001. She gained a Master degree in Manufacturing Engineering in 2002 and Ph. D. degree in 2007 from Kaunas University of Technology. Now, she is the Lecturer in the same University and her research field is numerical and experimental study of cutting processes.