ENERGY ANALYSIS OF ENERGY HARVESTING FROM MACHINE TOOL VIBRATIONS

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This contribution assesses the possibilities of application of Energy Harvesting technology in the field of machine tool diagnostics. These machines are on various parts more often fixed with many sensors monitoringstatus values such as deformations or temperature. However, in poorly accessible construction nodes, there is a problem with installation of both power and data cables. It could be solved by suitable application of an energy harvesting generator that would provide power supply to a specific sensor and enable wireless transfer of the measured data. In order to test the applicability of this solution, a detailed measurement and analysis of vibrations generated at defined regimes of a machinewere performed, both without machining and during power machining with the use of a demonstrator. The results confirmed the possibility to use the technology of Energy Harvesting to capture electric energy from vibrations. Although the demonstrator generated only very little power, with the use of modern communication technology it would be sufficient for selected applications with discontinuous reading of the measured characteristics.

Keywords:
Energy harvesting, machine-tools, vibration, milling, diagnostics

1. Introduction

Energy harvesting technology is defined in the publication [Mateu2005] as obtaining of electric energy from the surroundings at the point of power supply of autonomous application, without consuming any additional fuel or materials. This technology is, in rapidly evolving modern world, one of the most desirable technologies, mainly due to the development of wireless technologies, which offer a substantial reduction of energy consumption. The aim of engineers in these areas is to find suitable sources of power for wireless devices to maintain the widest possible autonomy without the need to change or recharge the batteries. In every technical system there is a large amount of waste energy that surrounds our potential autonomous application and our aim is to harvest this ambient energy for independent power supply – the source created in this way is defined as an energy harvesting system. However it is necessary to take into consideration that the density of ambient energy is very low and the devices defined in this way have the output power of up to several tens of milliwatts. Nowadays, however, it is sufficient for the whole range of modern wireless communications, security and monitoring elements.

When developing an application based on energy harvesting, it is important not only to correctly analyze and utilize the ambient energy, but also to optimize a connected wireless application. It is suitable to view the entire component as a mechatronic system and to design its development as a whole [Hadas 2010a].

Machine tools are increasingly subjected to requirements on performance and reliability of machines and production quality. New technologies offer the possibility of monitoring the variables such as temperature, displacement and deformation that serve as input information for compensation models of machines. Not always are the nodes easily accessible and sensors are also difficult to implement in the machine structure. This is also related to the location of power supply and data cables. If sufficient energy is ensured for power supply of sensors and wireless transmitter, it will be possible to in-build the sensors into the structure without any cabling.

Several suitable sources of ambient energy can be found in the machine tool; these sources can be transformed into electrical energy to power the envisaged applications. These include e.g. energy of temperature gradient or mechanical energy. In the machine tools there are often nodes where large temperature differences occur across a small area. In these nodes, the so-called thermoelectric generators (TEGs) can be placed; they are based on the Seebeck effect and can generate thermoelectric energy which can be used to power sensors. Furthermore, during machining process and passages of machine tools, vibrations of machine units occur. To use these vibrations is one of interesting ways of how to harness this ambient energy to power autonomous systems at the point of placement without the use of batteries or power supply cable. Generation of electricity from vibrations has been a concern of researchers from BUT mechatronic team for 10 years and this principle appears to be very promising in some areas, e.g. in aviation. The aim of this paper is to verify the possibility of using this non-traditional source of electricity generation in machine tools.

To verify the possibilities of energy harvesting technologies in the field of machine tools, selected technological tests with appropriate conditions for machining were carried out on the demonstrator. Measured data of vibrations were processed, and this information about vibrations obtained from the demonstrator was used for energy analysis of energy harvesting at the point of measurement. A vibration analysis on the demonstrator was held at various nodes of the machine and during various modes of operation. Simulation modelling served for verification of theoretical amount of energy gained and the results of this analysis are the core of this publication.

2. Task Formulation

2.1 Outputpower analysis of vibrations forenergy harvesting

An analysis of theoretical obtainable electric output power is the basis for assessing the feasibility of the use of energy harvesting for future autonomous application. For energy harvesting from mechanical vibrations, it is always a resonant mechanism with one degree of freedom, which is kinematicallyexcited by ambient vibrations [Hadas 2010b]. Effective is only excitation by resonant frequency.

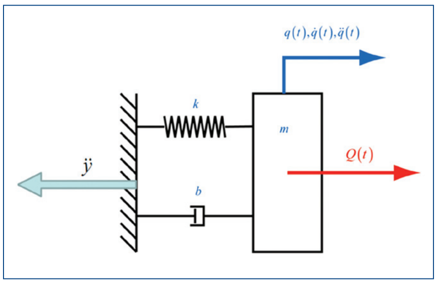

Figure 1. *Linearresonant mechanism excited by ambient vibration*

The above resonant mechanism is given by the equation of motion:

$$m\ddot{q}+b\dot{q}+kq=Q(t)=m\ddot{y}$$

where

m [kg]	resonantmass of mechanism
b [N.m^{-1}.s]	mechanicaldampingof mechanism
k [N.m^{-1}]	stiffness of mechanism
q, $\dot{q}$, $\dot{q}$ [m, m.s^{-1}, m.s^{-2}]	relative coordinates of position, velocity and acceleration
$\ddot{y}$ [m.s^{-2}]	acceleration of vibrations

In the case of the equation of motion for energy harvesting generator, it is necessary to include electric damping (armatureresponse), which is caused by consumed electricpower. The overall damping of the system (2) therefore consists of mechanical damping (b_m) and electrical (b_e) damping:

$$b = \left(b_e + b_m\right) \tag{2}$$

If we introduce the naturalfrequency of the system as

$$\Omega_0 = \sqrt{\frac{k}{m}}\,, \tag{3}$$

and further we introduce thequality of resonant mechanism (4), which corresponds to mechanicaldamping and is proportional to the size ofresonant deflection as

$$Q = \frac{m \cdot \Omega_0}{b_m} \tag{4}$$

the equation of motion for energy harvesting generator that generates useful power can be written in the following form:

$$\ddot{q} + \frac{\Omega_0}{Q}\dot{q} + \frac{b_e}{m}\dot{q} + \Omega_0^2 q = \ddot{y}\,\cdot \tag{5}$$

Anoutput power analysis of vibration energy harvesting generators has been published several times, e.g. [Mateu 2005], [Starner2005] and is based on a linear model of resonant mechanism with an integrated model of physical principle of electro-mechanical conversion, which dissipates from the system the electric power that electrically dampens the excited oscillating system. In equation (5), an electromechanical conversion is interpreted using a model of electric damperb_e. Nevertheless, for maximum resonant deflection, it is necessary to minimizemechanical damping of resonant mechanism. This mechanical damping of resonant mechanism can be smartly set using the quality parameter Q, which is inversely proportional to mechanical damping and can also be experimentally determined by the logarithmic decrement or by measuring inresonance. The maximum electricoutput power is achieved when the output power of all electrical forces during electromechanical conversion is equal to the output power of its own mechanical damping forces within the resonant mechanism. From the theory of linear vibration energy harvesting generator it is known that to obtain the highest possible output power requiresimpedance matching to be performed, i.e. tosatisfy the basic requirement for mechanical and electrical damping:

$$b_e = b_m. \tag{6}$$

Thus, a mathematically described theoretical linear model of vibration energy harvesting generator can be used for the analysis of experimentally obtained vibrations and for the assessment of maximum theoretical output power of the generator. It is not necessary to define what principle of electromechanical conversion is used here at this stage of energy analysis; we only work with theoretical output power when the vibration generator delivers the maximum possible output power. A detailed design of the entire device with the electric power generator itself should then align all the parameters of the electromechanical generator with the parameters of mechanical resonant circuit, otherwise the condition (6) is not satisfied and the achievable amount of energy is not gained.

2.2 Design of analyzed energy harvesting model

Calculation of theoretically obtainable amount of electricity requires determination of the parameters of the model of energy harvesting generator. This is essentially the mass of resonant member and the quality of the entire resonant mechanism. Since this is a fairly large machine tool and vibrations are very small, we choose to analyze the vibration mass of 150 grams and the quality of the resonant mechanism with the value of 50.

After that the Fourier transform of the measured data will enable us to obtain the frequency spectrum; we will find the most frequently occurring frequencies and then we will tune up the natural frequency of the resonant member in the vibration generator model. Then, using a simulation, this model isexcited by measured data and thus the location of vibration generator is simulated at the point of measurement.

For a few dominant frequencies from FFT analysis, a corresponding resonant mechanism is designed for this model; this mechanism has its natural frequency corresponding to the dominant frequency. Mass and quality of resonant mechanism is considered the same for all analyses. It should be noted that the results represent a maximum total electrical energy – also the one that is converted in losses in the electromechanical generator. With increasing quality of the resonant mechanism, the amount of generated power increases, but for the initial analysis it is necessary to select a constant value of resonant mechanism quality which corresponds to e.g. oscillation on a pliable beam.

The aim of modelling is to determine the output power of dissipative forces on electric damper b_e, which works in the maximum theoretical mode while maintaining the condition (6). During simulation, the model is excited by measured vibrations and theoretical output power is calculated based on the linear model of the entire mechatronic system. This output power is further integrated and the value of the energy obtained in time for the respective operating frequency of the resonant mechanism is also shown. The entire simulation model was created in Simulink and is shown in Figure 2.

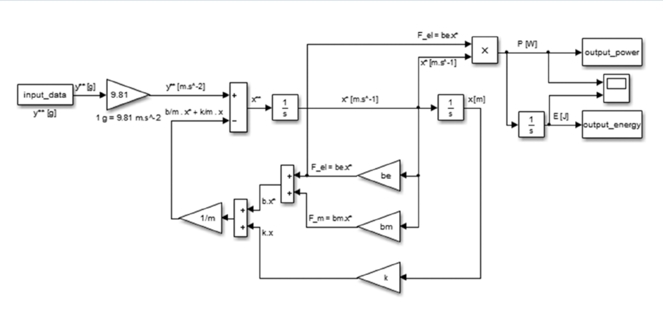

Figure 2. *Model of linear energy harvesting device excited by measured signal of vibrations*

3. Vibration analysis of the machine tool

The analysis of machine tool vibrations was performed on the demonstrator which is a horizontal milling machine tool schematically illustrated in Fig 3). Acceleration sensors were deployed on the machine at positions 1–4, which are intentionally selected with respect to the future use of energy harvesting for powering the sensors for diagnostics.

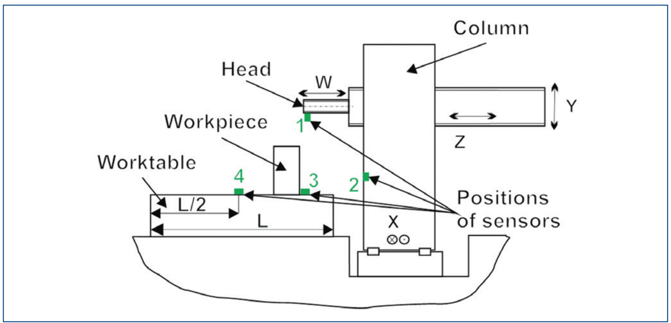

Figure 3. *Demonstrator*

In all positions, vibrations were measured when running a machine tool with given idle revolutions and then when milling a selected workpiece according to Tab. 1.

Milling	Spindle speed [rev/min]	Cutting speed [mm/min]	Depth of cut [mm]	Frequency of tool [Hz]
Climb milling	300	700	2	58.35
Conventional milling	240	700	2	46.68

Table 1. *Milling conditions*

The initial FFT vibration analysis shows that the position of sensor 1 is not appropriate for the use of vibration generator because the dominant frequency of vibration is always equal to the revolutions and the vibration generator would work effectively only at revolutions corresponding to its resonant frequency. In the position of sensor 2, dominant frequencies also varied depending on the revolutions, but the dominant frequency fluctuated around 10 Hz, which is not very suitable for energy harvesting in terms of a very flexible hinge of resonant mass. In theory, however, according to the analysed model, these vibrations provide the energy of about 2-3 mJ per milling minute.

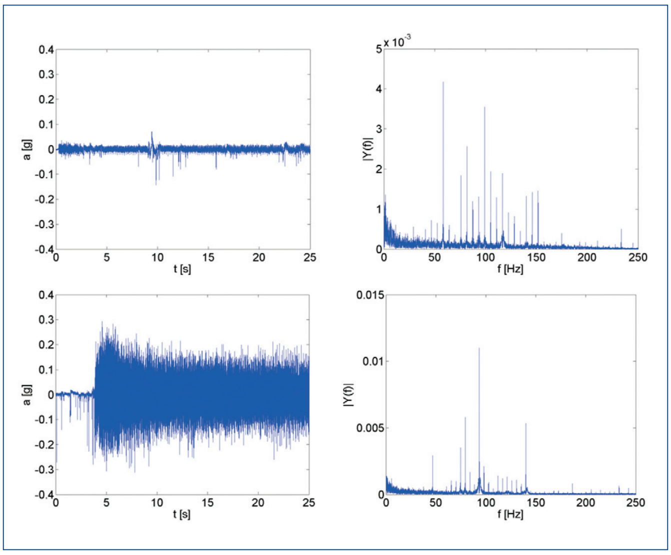

Figure 4. *Vibration and FFT analysisduring machining – Climb and Conventional milling, sensor 4*

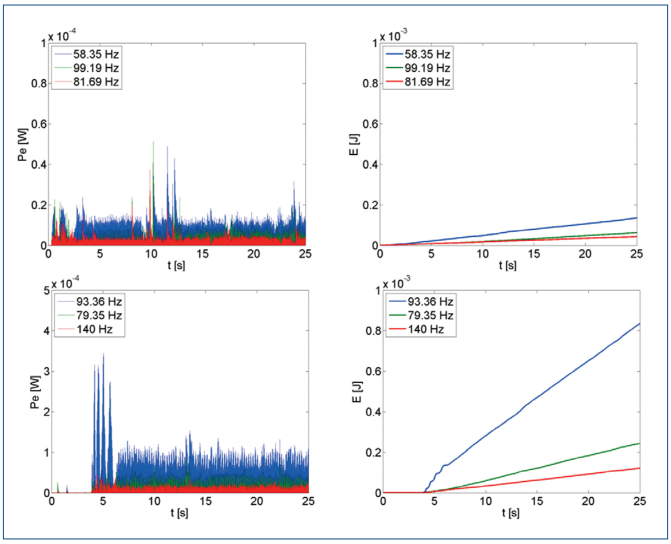

Figure 5. *Calculated instantaneous output power and total electrical power generation during machining for selected dominant frequencies – Climb and Conventional milling, sensor 4*

In terms of energy harvesting the best results were achieved when positioning the model of the vibration generator on the table, i.e. in the position of sensor 3. Assuming minute milling,electrical energy of 6 mJwas generated in conventional milling and 2 mJin climb milling.

From the theoretical output power and the amount of energy obtained from the vibration generator model, which was always tuned to the selected dominant frequency, the best results were achieved when placing the sensor at position 4. Figure 4 illustrates the waveform of vibrations and their spectrum for climb and conventional milling. It can be seen that the conventional milling transfers to the demonstrator a quantitatively greater vibration output power, and we also assume even achievement of greater obtained electrical output power. In addition to the dominant frequency given by revolutions and number of tool teeth,there are also other frequencies that are similar for both climb and conventional milling.

The results of energy analysis performed in Simulink (Fig. 2.) are shown in detail in Fig.5. There is a visible difference in obtained energy from ambient vibrations using a model of vibration generator for climb and conventional milling.

4. Discussion

One of the key goals of machine tools construction is a machine, if possible without vibrations, and therefore the energy harvesting from vibrations seems to be only applicable when placing the generator in the position with dominant frequencies identical for different types of machining operations. Given that it is not a problem in the conventional machine tool to physically implement the power supply to any sensor, this method of power supply for machine tools is not effective because environmental benefits are negligible. However, we cannot completely condemn this variant as a requirement is expected to implement a fully independent, the so-called Health and Usage Monitoring System (HUMS), which will ensure completely independent monitoringof certain parameters of machine tools for diagnostic or any other system. These requirements are quite common in the aerospace industry where energy harvesting technologiesare currently the most frequently applied.

The output power of 100–200 μWatt set by modelling can currently be used to power MEMS sensors in the so-called Burst mode where energy is obtained over a longer period of time, and then used for measuring and sending the data to the diagnostic or control unit. The output power required for such a device depends on the respective wireless technology and broadcast frequency of such application [Calhoun 2005]. Also significant is the problem of shielding the radio signal which increases energy demands.

Besides the parameters of resonant circuit that converts vibrations into electrical energy, it is also important to choose suitable electronics, the so-called power management. This electrical circuit ensures an optimal operating point of the generator according to equation (6) and during several hours by generating very littleoutput power it can gain sufficient power for wireless sensors [Amirtharaiah 2006]. The market currently offers several tens of circuit types for various generators and energy consumption, which are primarily used by super-capacitors and ThinFilm Battery for electric energy accumulation.

5. Conclusions

The above analysis was carried out theoretically from a linear model of vibration generator and the physical principle of electromechanical conversion was not solved [Poulin 2004]. For the analyzed frequencies and output power, it seems more appropriate to use the piezoelectric principle where a selected mass of 150 g will oscillate on the tuned beam with piezoelectric unimorph[Anton 2007]. The electromagnetic principle of conversion is beneficial for low frequencies (tens of Hz) and larger amplitudes of vibrations that do not occur on machine tools [Hadas 2014].

Another variant, which is interesting for machine tools, and which deserves further exploration, is the use of thermoelectric generators. These are essentially thermoelectric generators produced by MEMS technology that are now appearing on the market [Huesgen 2008]. Their output power is in the order of tens of milliwatts at a temperature gradient between the cold and hot side in the order of tens of degrees. The dimensions of these devices are in the order of mm and are suitable for integration into the scanned structure. However, here it is essential to develop the entire device as a whole with specific wireless applications.

Last but not least, it is interesting to use the solution with energy harvesting technologies for certain control and indication elements, which eliminates cabling costs, and these controls act as wireless controllers with integrated energy harvesting generator. These devices are already being spread out in intelligent buildings, where this principle is used for sensing the position of windows and doors (open or closed). These elements are developed and produced e.g. by the consortium OnOcean Alliance. Therefore some potential can be also seen with machine tools. E.g. closing the cover of the machine tool creates energy; this is converted by electromagnetic generator into electrical energy and after processing the information is sent off that the workspace is securely closed without the need to install data management for this sensor.

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