How to cite this article:
Authors: Piotr Szulewski, Dominika Śniegulska-Grądzka, Mirosław Nejman
Title of article: „Aktywne systemy monitorowania procesu skrawania dla Przemysłu 4.0" ("Active systems for monitoring the cutting process in the Industry 4.0 concept")
Mechanik, Vol. 91, No. 3 (2018): pages 183-189
DOI: https://doi.org/10.17814/mechanik.2018.3.34

Active systems for monitoring the cutting process in the Industry 4.0 concept

Aktywne systemy monitorowania procesu skrawania dla Przemysłu 4.0

Piotr Szulewski
Dominika Śniegulska-Grądzka
Mirosław Nejman *

The paper illuminates and discusses selected technical solutions related to increasingly popular systems for monitoring and supervising the machining process. The basic sensors and elements of the measurement path responsible for conditioning the acquired signals are presented. An analytical strategy for self-excited vibrations is given. The solutions of commercial monitoring systems and their capabilities available on the market are indicated.
KEYWORDS: machine-tools monitoring and supervision, vibrations, sensors, signal conditioning

At a time when the customer market demands that manufacturers offer products in a wide range, but personalized and at least affordable, a widespread introduction to production and management of information technology is necessary. The promoted idea of Industry 4.0 (being a conglomerate of technology, system and digital techniques) is not limited to the creation of a unique production structure based on "digital automation outlets". For its implementation, it is necessary to adopt a holistic way of thinking, which - along with the systematically introduced digitization - will revolutionize production [1]. It will be possible only if full communication is ensured between machine tools and technological machines, assuming that each of them has an independent monitoring system of its condition and the process being carried out. This means that one should strive for a situation where each of the machine tool components has built-in intelligence and a set of sensors that allows it to participate effectively in the process of active monitoring of production [2].

In the broadly understood machining (including turning, milling, drilling) many of the phenomena that have an adverse effect on the final result (workpiece) are perceived as particularly troublesome by oscillations of the OUPN system (machine tool-holder-workpiece-tool).

Three independent strategies can be distinguished to avoid the occurrence of adverse vibrations during machining. These are:

- selection of cutting parameters with regard to the stability limit,
- self-excited vibration detection and active (online) modification of cutting parameters (adaptive control),
- use of new materials, tools or components of machine tools with a special design, enabling reduction of the risk of vibrations or effective dampening.

Acquisition of signals and their application for monitoring

A number of factors have an impact on the machining process. Four main sources can be identified, namely:

- workpiece: type of material, geometry, hardness, surface structure, mass, susceptibility of thin walls,
- machine tool: method of fixing the object, kinematic structure of the machine, coolant, technical condition, temperature, spindle rigidity,
- tool: geometry, size, coating, cutting material, rotational speed, feed, blade condition, overhang,
- environment: programming errors, poor machining operations, operator reactions.

Due to the multi-parameterization and complexity of the cutting process, in order to achieve optimal conditions for its implementation, it is necessary to use active forms to monitor the process parameters and condition of the tool [2]. The goal is to provide a quick response to unexpected problems. The result is a significant increase in productivity and efficiency of machine tool utilization, maximization of permissible feeds, shortening of the machining cycle, improvement of machining quality, longer tool working time, optimization of cutting parameters and constant supervision over machine safety. In addition, downtime is reduced, energy is saved, and the costs of maintaining and servicing the machine are reduced. It avoids the necessity of corrections or reprocessing of the object and the risk of producing an object outside the limits imposed by tolerance [3]. Tab. II presents the current possibilities of remote supervision over the machine tool, tool, object and process.

* Dr inż. Piotr Szulewski (maxer@cim.pw.edu.pl), dr inż. Dominika Śniegulska-Grądzka (dominika.gradzka@pw.edu.pl), dr inż. Mirosław Nejman (m.nejman@zaoios.pw.edu.pl) – Instytut Technik Wytwarzania Politechniki Warszawskiej

TABLE I. Ranges for monitoring the machine and the process [4]

Monitoring	Turning	Milling/drilling	Rifling
Tool	Break Blade wear No tool Wrong tool Non-axial attachment of the tool in the frame	Break Blade wear No tool Wrong tool Unbalance Non-axial attachment of the tool in the frame	Break Blade wear No tool Wrong tool Thread depth deviation Non-axial attachment of the tool in the frame
Process	Spindle torque Axial force Spindle vibrations Coolant utilization Spindle rotational speed Changes made by the operator Condition of the workpiece Temperature Cutting force	Spindle torque Axial force Spindle vibrations Coolant utilization Spindle rotational speed Changes made by the operator Condition of the workpiece Temperature Cutting force	Strength momentum in the tool holder Axial force Vibration of tool holder Coolant utilization Spindle rotational speed Changes made by the operator Condition of the workpiece Temperature Hole diameter Thread depth
Optimization	Tool life period Feed rate, cutting speed (adaptive control) Work time Detecting deficiencies Statistical analysis of the machining process	Tool life period Feed rate, cutting speed (adaptive control) Work time Detecting deficiencies Statistical analysis of the machining process	Tool life period Feed rate, cutting speed (adaptive control) Work time Detecting deficiencies Statistical analysis of the machining process
Condition of the machine tool	Drive load, vibrations Spindle vibrations Spindle rotational speed Coolant utilization and pressure Fixing the workpiece Statistical analysis	Actions taken for all types of machine tools. Monitoring systems can be used together to observe the process and condition of the machine. Data collected from built-in sensors (vibration, acoustic emission, torque, force, temperature) and the NC controller are constantly analyzed, saved and presented on the operator's monitor. The machine state changes noted are used to predict service activities.	
Machine tool protection	Collision detection and minimizing losses Avoiding harmful vibrations Spindle extension compensation Spindle temperature	The alarm statuses of individual signals are delivered to the NC controller and after the analysis enable a preventive response. In the event of a collision, immediate stoppage of all controlled axes allows minimizing damage, repair costs and downtime.	

TABLE II. Sensors and their application [5]

Parameters	Description
Momentum	DTA (digital torque adapter) - sensorless method of measuring and transmitting data from the drive power supply (digital control) with the current moment being developed by the spindle and used machine axes. The high sampling rate of the current value and precise information on the current position of the driven axes enable the accurate determination of the instantaneous torque value
Supplied power	*In the case of traditional machine tools, not equipped with digital drives and communication buses, it is possible to measure the power supplied using Hall effect sensors (spindle drive current measurement)*
Force	Tensometers or piezoelectric sensors combine to obtain high sensitivity, precision of measurement and a wide range of measured force. They are embedded in the machine body, tool holders, tools or placed in the spindle
Force and momentum	Threading tools, pipe drills and broaches have a very large contact surface with the material being processed and are usually characterized by a significant depth of cut. This is associated with the occurrence of very high friction forces and the ease of sudden damage or destruction of the tool. It is necessary to observe the moment being developed by the tool to detect its growth or a sharp drop. The best place to place the sensor is the tool itself or its holder
Vibrations	To reduce the load on the bearings and the spindle, it is necessary to minimize vibrations and unbalance of the tool. Sensors are placed in the spindle housing and the machine tool body. Displacement and acceleration sensors are used. In a collision situation, measured signals allow you to stop moving components in milliseconds, reducing losses
Coolant	Pollutants, metal filings, chips that enter the coolant circuit, can effectively limit its expenditure (reducing the active cross-section of the supply lines) and in extreme cases lead to a significant increase in cutting resistance and even damage (dulling) of the tool (especially small). The flow and pressure sensors installed in the power circuits effectively monitor the pressure and ensure that the proper cooling conditions are maintained
Deformations	Movement of the spindle - due to the temperature or cutting force - changes the position of the tool (cutting surface), which negatively affects the geometry of the workpiece, especially during precision or finishing machining. Non-contact displacement sensors allow detection of even nanometric strains. This information is sent to the NC controller, where the offset values of the machine axis position are generated
Acoustic emission	Sensors are installed on the spindle or workpiece holder. They allow registration of a wide range of frequencies (bandwidth) of signals; they are characterized by high sensitivity to damage to the material structure. They are used to detect contact of the blade with the work material, chipping of the cutting blade, collision and bearing damage

Sensors for monitoring

Tab. II presents selected sensors used to monitor the machine tool, tool condition and cutting process.

Acquisition and preliminary preparation of signals

The key issues in the construction of monitoring systems are the proper design and implementation of the measurement path. The number and price of sensors are not as important as the fit to the monitored process, the proper location of the sensor, correctness of the installation, proper wiring and power supply. Frequent problems include noise and power disturbances as well as lack of grounding or incorrect grounding. During the registration, mistakes can be made by choosing inappropriate filters and insufficient speed of analog-digital conversion [6].

Typically, sensors used in measuring lines are not generative, and therefore require dedicated, voltage-stabilized power supplies. Because the cheapest are pulse power supplies, the first choice can go to them. Usually the result of this is the appearance of very short pulses in the measured signal. A good practice is to use a separate power supply for measuring lines. Often, connecting digital devices of the type to the same power supply ends with signal interference (fig. 1).

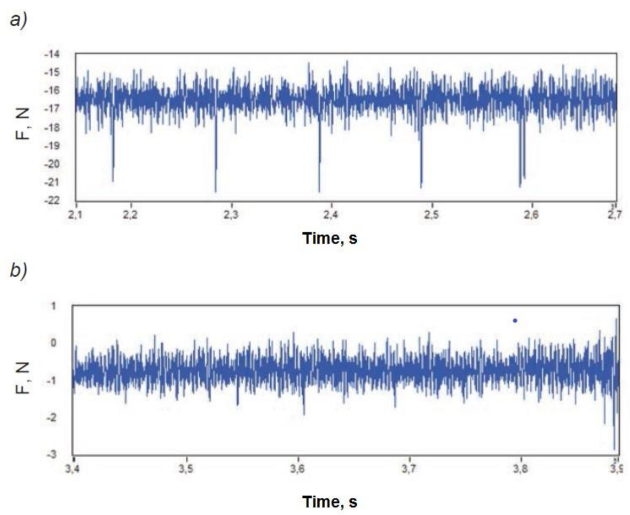

Fig. 1. Signal from the dynamometer: a) with disturbance and b) after removal of the disturbance

Filters are another important element of the measuring path. As a rule, it is interesting to monitor various mechanical phenomena, which in nature rarely cause oscillations exceeding 1 kHz. On the one hand, sensors should be selected that will allow to record the whole band of the observed phenomenon, on the other hand the selection of the pre-amplification system called pre-amplifier is important. Its task is to power the sensor, amplify the signal and possibly filter. As mentioned above, sensor transducers are usually not generative, but only convert the physical quantity into voltage or current. The characteristic of such preamplifier is important, so that it does not introduce changes in the field of amplitude, frequency or phase shift. Most preamplifiers work correctly.

It is not a standard to offer signal filtering by preamplifier manufacturers. Lack of signal filtering may mean the need to use high sampling frequencies in analogue-digital converters; on the other hand, if filters with different characteristics or even cut-off frequencies are used in measuring lines, this may make it difficult to perform proper time analysis of signals in online mode. The use of many sensors without filtering signals ends with the use of Cloud or Big Data technology, which suggests that the creator of the measurement system does not know what information he is looking for in the measurement signals, and therefore he acquires a lot of excess information and needs the application cloud computing and data processing.

Manufacturers of machine tools offer retrofitting machines with additional sensors [2, 3]. However, they do not really want to boast about which mathematical analyzes (or other) they use to conduct monitoring. They claim that they offer a cloud application that will analyze this data, or that such processing is under development. On the other hand, manufacturers of diagnostic and monitoring systems, e.g. Brankamp or Montronix, base their strategies on measurements from one or two sensors, based on single measures, and achieve effectiveness in the case of large-scale production.

The huge area of unit, small- and medium-series production is still the most difficult to monitor. At least two groups can be distinguished:

- monitoring of machine tools (mainly: degradation, wear of parts),
- monitoring of the production process.

Machine monitoring is usually a slow-changing process; includes observation of: temperature, drive power, average value of bearing vibrations, vibration bands or simple statistical analysis of the process and detection of the presence of subsequent manufactured parts. The monitoring of processes concerns fast-changing signals - forces, vibrations, and acoustic emission. It is necessary to conduct an online analysis, based on the current signal tracking and searching for anomalies. Such complex analyzes can no longer be programmed in the machine's control. Most often, a computer with a typical operating system can not handle them. For such applications you will need either a real-time computer or a device with an FPGA.

Another problem is building communication with the machine tool. The monitoring system will not work blindly, without knowing what the machine is doing. It is desirable to signal the program cycle on, the information which cycle (machining program) has been started, the duration of work and set-up movements, speeds and directions of movements. Thanks to this, you do not need to collect redundant data, and the analysis can take place locally. Only the monitoring results are gathered in the cloud and enable monitoring of the whole production line. Many controllers have at least free digital or analog input/output, which can be assigned to a simplified communication [2, 6]. A better solution is to use the RS-232, Ethernet and PROFIBUS ports for said communication.

In machine tools and other machines, not only sensors start to appear, but so-called agents that using OPC servers, MTConnect or other technologies can transfer information for further processing and analysis [7].

Vibration monitoring

One of the undesirable factors in machining are self-excited vibrations, especially in high-speed and high-speed machining. Such vibrations affect the deterioration of the work surface, faster wear of the machine tool and increase the noise level. Therefore, the need to eliminate self-excited vibrations is not subject to discussion, so that the process proceeds correctly. This can be achieved by setting the stability boundary and determining stable work areas (machining).

If the machine is equipped with an accelerometer or a dynamometer, and in the controller it is possible to set the pulsation of the rotational speed, you can design a system that online monitors whether there is a self-excited vibration. If so, the speed pulsation procedure starts. A simpler alternative is to observe whether during the cutting there are self-excited vibrations and then for selected operations, you can mark the pulsation of the rotational speed in the machining program.

The next direction of development is the monitoring of the spindle condition and bearing vibrations. The aim is to plan the machine tool service in a timely manner, without exposing yourself to the production of objects outside the tolerance limits, and in extreme cases - avoiding machine tool breakdowns.

Determination of the stability boundary

It is good practice when designing the technological process and selection of cutting parameters to take into account the stability limit, i.e. plotting the bag curves determining the dependence of the maximum depth of the cutting layer on the spindle speed. Determination of the stability limit requires knowledge of the dynamic cutting process characteristics (DCPS) and the mass-elastic-damping system (MST) of the machine tool. This is due to the fact that self-excited vibrations are nothing more than the occurrence of feedback between the MST system and the cutting process (PS). DCPS is defined as the dependence of the cutting force [8, 9]:

- on instantaneous values of the thickness of the cutting layer changing due to changes in relative displacements between the workpiece (PO) and tool (N) (in the direction perpendicular to the cutting edge) rt and waves on the surface treated in the previous pass r_T,
- on the speed of these movements r_t ':

$$F_r = F_{rk}(h) + F_{rc}(r_t'), \qquad F_t = F_{tk}(h) + F_{rc}(r_t') \tag{1}$$

$$h = h_0 + h_d = h_0 - r_t + r_T \tag{2}$$

where:
F_{rk}, F_{tk} - component cutting forces dependent on relative displacements between the tool and the workpiece, on the directions *r* and *t*,
F_{rc}, F_{tc} - component cutting forces dependent on the relative velocities of the N-PO system oscillations,
h - thickness of the machined layer,
h_0 - static thickness of the machined layer, h_d - dynamic component *h*,
$r_t = r(t)$ - internal modulation h,
$r_T = r\ (t - T)$ - external modulation *h*, *T* - blade transition period.

Thus, the F_r and F_t forces can be written [9-12]:

$$\begin{cases} F_r = b[k_{rd}(-r_t + r_T) - h_{er}\dot{r}_t] \\ F_t = b[k_{td}(-r_t + r_T) - h_{et}\dot{r}_t] \end{cases} \tag{3}$$

where: *b* - width of the machined layer; k_{rd}, k_{td} - dynamic resistance to cutting; h_{er}, h_{et} - coefficients of damping of the cutting process.

The dynamic resistance of cutting through linearization at the working point ($h = h_0$) can be saved:

$$k_{rd} = \left|\frac{dF_r}{dh}\right|_{h=h_0} = (1 - m_r)C_r h_0^{-m_r} \tag{4}$$

where: C_r, m_r - permanently determined experimentally.

The formula (4) will be analogous to the direction *t*, with the correspondingly determined constants C_t, m_t.

The mass-elastic-damping system of the machine tool is created by the OUPN system. Because this system is complex, with many degrees of freedom, it is therefore easiest to characterize its characteristics experimentally by performing modal analysis. Modal analysis allows the determination of modal parameters - i.e. natural frequency, attenuation, stiffness and modal mass - for each form of vibration. For the empirical determination of modal parameters, the impact energy of a modal hammer is used [10, 11].

In considering the example of orthogonal turning and the impact of PS on the MST system with two degrees of freedom, the input signals to the MST system are radial cutting forces (F_r) and tangent cutting (F_t), in a matrix record [9]:

$$\mathbf{F} = \begin{bmatrix} F_r \\ F_t \end{bmatrix} \tag{5}$$

The forces F_{x1} and F_{x2}, acting along the main stiffness axes x_1 and x_2, are determined by projecting the cutting forces F_t and F_r:

$$\mathbf{F_x} = \begin{bmatrix} F_{x1} \\ F_{x2} \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} F_r \\ F_t \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} F_r \\ F_t \end{bmatrix} = \mathbf{AF} \tag{6}$$

where:

$$\mathbf{A} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \tag{7}$$

On the other hand, the output signals are displacements along the direction perpendicular to the cutting speed *r*, which determine the cutting forces. They can be obtained by projecting displacements along the x_1 and x_2 axes on the direction *r*:

$$r = \mathbf{BX} \tag{8}$$

where:

$$\mathbf{B} = [\cos\alpha \quad \sin\alpha] = [a_{11} \quad a_{21}], \qquad \mathbf{X} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \tag{9}$$

Then, the MST transition function in coordinates x_1, x_2 can be presented:

$$\mathbf{W_x} = \frac{\mathbf{X}}{\mathbf{F_x}} = \begin{bmatrix} w_{11} & 0 \\ 0 & w_{22} \end{bmatrix} \tag{10}$$

where:

$$w_{11} = \frac{\sum_{j=1}^{N_1} x_{1j}}{F_{x1}} = \sum_{j=1}^{N_1} \frac{1}{s^2 m_{1j} + s c_{1j} + k_{1j}};$$
$$w_{22} = \frac{\sum_{j=1}^{N_2} x_{2j}}{F_{x2}} = \sum_{j=1}^{N_2} \frac{1}{s^2 m_{2j} + s c_{2j} + k_{2j}} \tag{11}$$

m_{1j}, c_{1j}, k_{1j}, m_{2j}, c_{2j}, k_{2j} - modal masses, damping and stiffness coefficients for individual (*j*) form (vibration) modes in the x_1 and x_2 directions; N_1, N_2 - the number of vibration forms in the x_1 and x_2 directions.

For the stability analysis, the MST transition function is determined in the coordinates of the cutting process *r* and *t*.

$$\mathbf{W_{MST}} = \mathbf{BW_xA} = [a_{11} \quad a_{21}] \begin{bmatrix} w_{11} & 0 \\ 0 & w_{22} \end{bmatrix} \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \tag{12}$$

i.e.:

$$\mathbf{W_{MST}} = [w_r \quad w_t] = [a_{11}^2 w_{11} + a_{21}^2 w_{22} \quad a_{11}a_{12}w_{11} + a_{21}a_{22}w_{22}] \tag{13}$$

Based on equations (3, 4), the cutting process transfer function can be saved as:

$$\mathbf{F} = \begin{bmatrix} F_r \\ F_t \end{bmatrix} = -b \begin{bmatrix} k_{rd}(1-e^{-sT}) + sh_{er} \\ k_{td}(1-e^{-sT}) + sh_{et} \end{bmatrix} r = -b\mathbf{k}\, r \quad (14)$$

where:

$$\mathbf{k} = \begin{bmatrix} k_{rd}(1-e^{-sT}) + sh_{er} \\ k_{td}(1-e^{-sT}) + sh_{et} \end{bmatrix} = \begin{bmatrix} k_{rr} \\ k_{tr} \end{bmatrix} \quad (15)$$

The open system transition function is:

$$\mathbf{W_o} = \mathbf{W_{MST}F} = -b\mathbf{W_{MST}k} = -b[w_r \quad w_t] \begin{bmatrix} k_{rr} \\ k_{tr} \end{bmatrix} \quad (16)$$

$$\mathbf{W_o} = -b(w_r k_{rr} + w_t k_{tr}) \quad (17)$$

and the transmittance of a closed system is written as:

$$\mathbf{W_Z} = \frac{\mathbf{W_o}}{\mathbf{I-W_o}} \quad (18)$$

where *I* - unitary diagonal matrix.

According to [12], elements of the characteristic equation are searched, on the basis of which it is possible by analytical or numerical methods to determine the bag curves defining the stability limit:

$$\mathbf{I} - \mathbf{W_o} = \mathbf{I} + b_{lim}\mathbf{W_{MST}k} =$$
$$1 + b_{lim}(w_r k_{rr} + w_t k_{tr}) = 0 \quad (19)$$

Then, on the basis of the bag curve, for the selected rotational speed, the greatest possible depth of cut can be chosen, at which the process stability will be maintained.

Commercial examples

■ **Sandvik, PROMETEC.** The methods of avoiding vibrations are many. If it is not possible to determine the limit of stability, the easiest way is to reduce the outreach of the tool, of course if possible. When larger overhangs of tools are needed, e.g. for boring bars, the manufacturers offer frames with built-in passive and active vibration dampers. Despite the higher costs of such a frame, providing a better quality of the surface being processed is a good justification for the expense. An example of this is the cooperation effect of Sandvik and PROMETEC, which offer tools with built-in vibration dampers, sensors measuring vibrations and cutting forces (fig. 2).

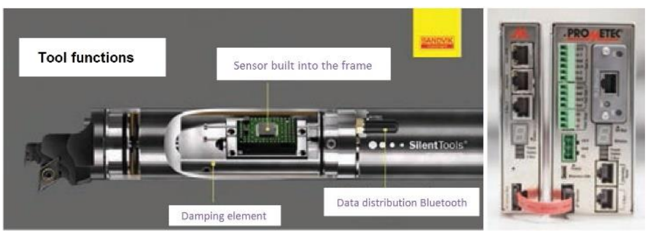

Fig. 2. Cutting process monitoring proposed by Sandvik and PROMETEC [13]

■ **Reiden Technik AG.** An effective method of avoiding adverse vibrations during processing can also be the use of special construction materials in machine tools (for bodies). An example is HYDROPOL - a unique composite of concrete and steel (steel on both sides filled with special concrete). Its properties allow for effective vibration absorption. It is also characterized by high dynamic stiffness and no need to heat the machine before work, as the coefficient of thermal expansion is constant and has a small value. Using it brings savings of about 30% of material compared to traditional iron castings, and tool loads are reduced by 15-20%. The density of the new material is 2500 kg/m³, elastic modulus - 60,000 N/mm², maximum surface pressure - up to 100 N/mm². Fig. 3 shows a graph of material susceptibility as a function of frequency.

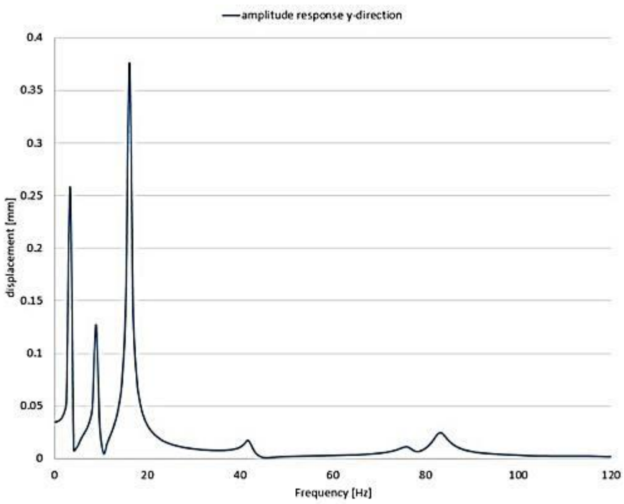

Fig. 3. Displacement value as a function of frequency for the HYDROPOL composite [14]

■ **Bimatec Soraluce.** The company offers a new, active, dynamic stabilizer DAS+ (Dynamic Active Stabilizer). Its effect improves the quality of the treated surface and reduces the risk of breaking the tools by extending their life in extreme cutting conditions. The principle of operation is based on continuous measurement of vibrations and production - through the actuator system - of shifts with the opposite return, which leads to the oscillation going out. In this way, the rigidity of the machine tool is increased. A significant increase in processing efficiency is observed (up to 300%). Fig. 4 presents the frequency range in which the active DAS+ system reaction is possible.

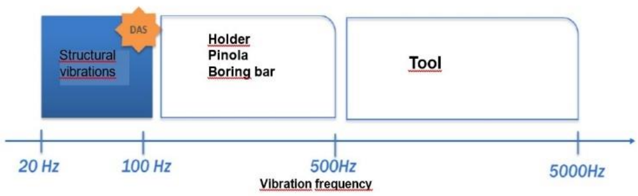

Fig. 4. Scope of the DAS+ system [15]

■ **ExactControl** system from Schmitt Industries. The device in the form of an independent controller, for the purpose of designing and monitoring the unbalancing of rotating elements, enables the connection of six independent acoustic emission sensors. It allows automatic or manual measurement of traditional bearing systems, hydrostatic bearings and acoustic signals. In addition, the system is equipped with Profibus and Ethernet network interfaces, analog and digital inputs / outputs. Standard applications include monitoring of energy, spindle load, vibration, temperature, torque and speed, as well as data exchange with NC machine controllers - the results of the system are visible on the monitor screen. All strategies are self-learning, which allows for precise adaptation to virtually all processes. Each monitoring cycle is considered and analyzed individually, and the calculated parameters form the basis for further actions.

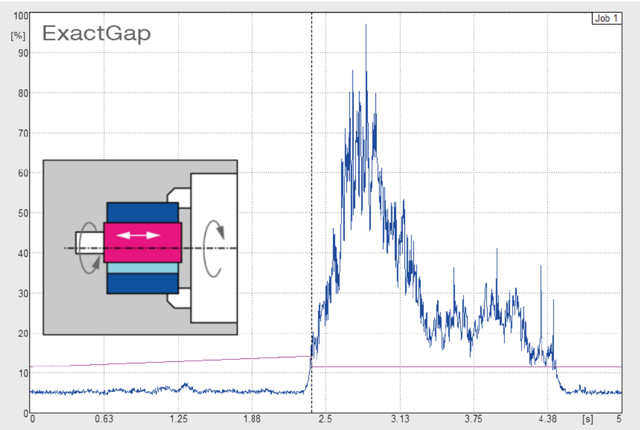

Fig. 5. Monitoring in the ExactControl system [16]

Constant recognition of the background of recorded signals (fig. 5) makes it easier to detect "air cutting" and its elimination. Thanks to the continuous analysis of the character of the signal, it is also possible to avoid the negative influence of various types of interference, caused for example by: cooling, motors, drives of controlled axes or near machine tools. As an illustration, there can be a significant increase in the volume of operating bearings caused by the technological increase of the spindle speed. Then an adaptive determination of the new level of the signal's background occurs without generating an alarm of exceeding the limit value.

It is also possible to record signal patterns (e.g. for a characteristic machining fragment, machine or tool state) and to compare the current value with the selected pattern. In case of non-compliance, an appropriate alarm or stopped machining will be generated.

The operator - who knows the process - can independently set ranges of acceptable signal values, which are a measure of a specific process characteristic. These ranges do not have to be rigid, because they can be subject to dynamic changes depending on the fluctuation of the observed signal related to the implementation of a specific part of the technological process.

It is also possible to indirectly observe the productivity and productivity of the machine. On the basis of the comparison of the accumulated time of tool contact with the workpiece with the other recorded times of the operation, the actual machining time is determined. In the case of differences with the pattern, a message is created stating the reasons for discrepancies together with the time values and their periods of occurrence.

When monitoring the unbalancing, it is possible to detect it up to 0.02 μm for a constant research speed of 600 rpm. The speed range ranges from 30 to 30,000 rpm. The range of registered vibration accelerations is 50 μg ÷ 1.25 g (g = 9.80 m/s^2). The vibration measurement resolution is 0.001 μm. It is permissible for the user to set individual strategies for filtering the acquired signals in order to analyze them more accurately and to avoid false alarms.

■ **Montronix.** Montronix offers a range of sensors and signal analysis software. One of the propositions is a three-axis accelerometer with a built-in analog-to-digital converter and a Wi-Fi transmitter (fig. 6). This is one of the few commercial proposals for wireless sensors. Wireless is a great asset of the system, because - if the machine has no built-in sensors - it is almost impossible to encourage the manufacturing company to an additional machine tool service to add sensors. The problem is also the design of the machine tools and its multi-axis character. Necessity of using measuring cables makes it possible to install the sensor quite a distance from the cutting zone on the first non-moving element, which often causes the suppression of relevant information from the cutting process.

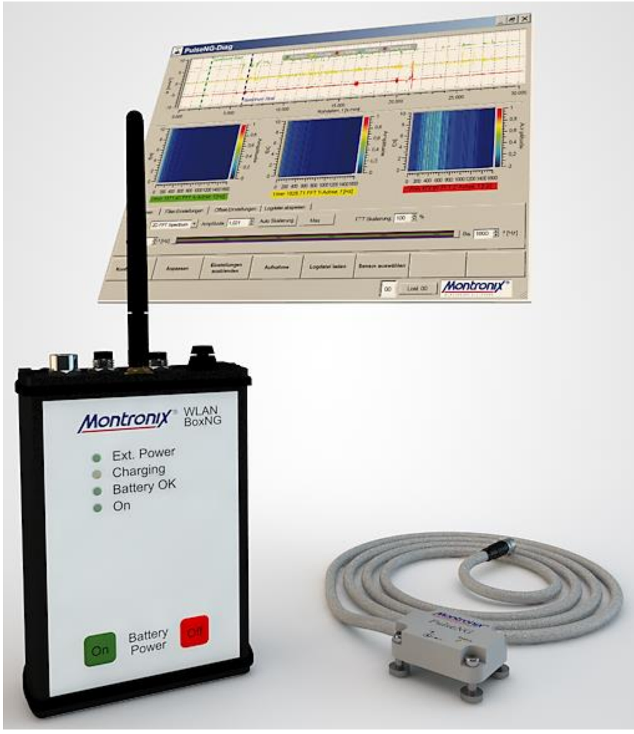

Fig. 6. Montronix wireless acceleration measurement system [17]

The PulseNG-hmi software for monitoring signals can be added to the sensor range. It offers simple measures such as average values, threshold overruns and FFT analysis in real time.

■ **Brankamp.** Another interesting proposal is collision detection. Starting a new technological process involves the risk of taking wrong account of the tool's projection or oversight related to the geometry of the machining holders. According to specialists from Brankamp, the typical reaction time of an employee to an unpredictable collision can be from 1 to 10 s, another delay of the control system - from 20 to 200 ms and physical stopping of the drive - from 100 to 500 ms. The CMS system is to replace and shorten the operator response to 1 ms. The ECO700 system (fig. 7) additionally displays the waveforms of selected signals, from sensors and measures the maximum force value, exceeding the limits and a few other simple signal measures, among others in the machining application.

Fig. 7. Brankamp cutting process monitoring system [18]

Conclusions

As shown in the examples of commercial devices and theoretical considerations, the issues of monitoring vibrations and counteracting their negative impact on the resulting quality of machining are not straightforward. The key is the ability to obtain useful information about the process status and the machine tool as well as the controller communication with the monitoring system. However, it seems that, despite the complexity of this process, it is now an absolute necessity for the actual implementation of the Industry 4.0 concept.

The project is co-financed by the European Union under the European Regional Development Fund and the National Center for Research and Development - No. Innolot /I/10/NCBR/2014 - INNOGEAR.

REFERENCES

1. Szulewski P. „Koncepcje i elementy inteligentnej fabryki przyszłości". *Mechanik*. 90, 2 (2017): pp. 98–102.
2. Śniegulska-Grądzka D., Szulewski P. „Systemy automatycznego monitorowania drgań w obrabiarkach". *Mechanik*. 90, 3 (2017): pp. 170–175.
3. Szulewski P. „Nowoczesne funkcje diagnostyczne we współczesnych sterownikach NC". *Mechanik.* 89, 1 (2016): pp. 5–12.
4. http://www.marposs.com/application.php/eng/milling_machine_monitoring (dostęp: 22.11.2017).
5. http://www.artis.de/en/company/the-tool-monitoring-company (dostęp: 4. 12.2017).
6. Nejman M., Śniegulska-Grądzka D., Jemielniak K. „Wpływ charakterystyki toru pomiarowego na bezpośredni pomiar siły skrawania w czasie występowania drgań". *Mechanik.* 87, 8–9 (2014): pp. 400–407.
7. Szulewski P. „W kierunku samoorganizujących się środowisk wytwórczych". *Mechanik.* 90, 7 (2017): pp. 494–500.
8. Eynian M., Altintas Y. „Chatter Stability of General Turning Operations With Process Damping". *Journal of Manufacturing Science and Engineering*. 131 (2009): pp. 041005.1–041005.10.
9. Jemielniak K., Nejman M., Śniegulska-Grądzka D. „Wyznaczenie dynamicznych współczynników sił skrawania poprzez bezpośredni pomiar siły skrawania w czasie występowania drgań". *Mechanik.* 87, 8–9 (2014): pp. 31–38.
10. Bąk. P.A., Jemielniak K. „Zastosowanie automatycznej analizy modalnej w diagnostyce wrzecion frezarek". *Mechanik*. 88, 3 (2015): pp. 101–108.
11. Altintas Y. „Machining process Modeling, Machine Tap testing and Chatter Vibration Avoidance". *Manufacturing Automation Laboratory*. Vancouver (Canada): University of British Columbia, 2002.
12. Downey J., Bombiński S., Nejman M., Jemielniak K. „Automatic multiple sensor data acquisition system in a real-time production". *Procedia CIRP.* 33, 6 (2015): pp. 215–220.
13. http://www.equip-prod.com/outil_coupant/proposer une-solution-complete-pour-couvrir-tous-les-besoins-de-lindustrie-4-0 (dostęp: 14.12.2017).
14. www.reiden.com (dostęp: 2.01.2018).
15. www.soraluce.com (dostęp: 4.01.2018).
16. http://www.grindingcontrol.com/wpcontent/uploads/ExactControl en.pdf (dostęp: 10.01.2018).
17. https://www.montronix.com/en/products/functionality/interface/wlan-boxng-en.html (dostęp: 12.01.2018).
18. http://www.brankamp.com/en/data/files/products/prospekt_cf_eco700_en.pdf (dostęp: 5.01.2018). ■

Translation of scientific articles, their computer composition and publishing them on the website www.mechanik.media.pl by original articles in Polish is a task financed from the funds of the Ministry of Science and Higher Education designated for dissemination of science.

Ministry of Science and Higher Education

Republic of Poland