QUANTITIES AND SENSORS FOR MACHINE TOOL SPINDLE CONDITION MONITORING

LUDEK JANAK, JAKUB STETINA, ZDENEK FIALA, ZDENEK HADAS

Brno University of Technology

Faculty of Mechanical Engineering, Brno, Czech Republic

DOI : 10.17973/MMSJ.2016_12_2016204

e-mail: janak@fme.vutbr.cz

The state-of-art machine tools incorporate a wide variety of sensors and associated signals that are used within the control system or as a process monitoring variables. Machine tool can also be equipped with additional sensors required by customer or manufacturer with relatively no limitation. Therefore, the key issue is in "separating the wheat from the chaff". Only those data that can be linked to machine tool failures, unintended customers' behaviour, or (exceeding) machine loading, are suitable for further implementation in machine tool condition monitoring system. This paper uses the methods formerly known from system safety and reliability analysis – namely Failure Modes and Effects Analyses (FMEA) and its Diagnostics extension (FMEDA) – to identify such data and physical quantities. The outlined approach is supported by a practical case study on machine tool spindle condition monitoring. The proposed spindle monitoring is based on noise intensity and indirect cutting force measurement.

KEYWORDS

machine tool diagnostics, condition based maintenance, sensor fusion, Industry 4.0, HUMS, FMEA, TCM

1 INTRODUCTION

The condition monitoring is a detection and collection of information and data that indicate the state of a machine [ISO 2004]. Demand for condition monitoring systems is such way that the condition monitoring shall be performed autonomously by a machine itself without the need for operator's intervention.

Computer Numeric Controlled (CNC) machine tools have been equipped with a number of diagnostic facilities since their first industrial deployments. Equipment such as simple Built-In-Tests (BIT), diagnostic tapes or other software and hardware features can be taken as an example [Keller 1982]. At the same time, the reliability studies for machine tools preventive maintenance plans have been started.

Although many years have passed, the majority of machine tools maintenance still relies on preventive or even less convenient corrective maintenance. Technical capabilities of the state-of-art machine tools provide a unique opportunity for wider application of condition monitoring systems. Those are the key enablers of condition-based maintenance which is one of the promising technologies associated with Industry 4.0 initiative.

Condition and usage monitoring of machine tools is a topic with increasing interest amongst all machine tools manufacturers. High demand for machine tool condition monitoring does not come only from maintenance point of view. The key demand for such systems from machine tools manufacturers' point of view is a systematic detection and recording on unexpected user behaviour, events and collisions. Sometimes, the machine tool condition monitoring system can be coupled with Tool Condition Monitoring (TCM) which is quite beneficial. There are a number of techniques which can be applied for a tool monitoring and predict its Remaining Useful Life (RUL) under the consideration of real workpiece processing environment [Hashmi 2014, Williams 1994]. The tool condition monitoring (TCM) can also cover and indicate catastrophic tool failure, collisions, progressive tool wear and tool chipping/fracture. [Byrne 1995]

The state-of-art machine tools incorporate a wide variety of signals that are being used within the control system or as a process monitoring variables. Machine tool can also be equipped with additional sensors required by customer or manufacturer with relatively no limitation. The amount of produced data makes a real "big-data" environment. Nevertheless, the key issue is in "separating the wheat from the chaff". Only those data that can be linked to machine tool failures, unintended customers' behaviour, or (exceeding) machine loading, are suitable for further use and evaluation.

There are a lot of Condition-Based Monitoring CBM methods which are widely respected amongst the machine tool research and development. These methods are used to mine the information about the machine technical health from measured data. As an example can be mentioned various reasoning engines such as fuzzy logic or neural networks [Elghazel 2015]. Nevertheless, these approaches, due to their extreme need for computational resources, not proven functional integrity and implementation integrity, has not currently widely implemented in state-of-art machine tools and their components.

This paper introduces the ideas outlined above on the case study of machine tool spindle condition monitoring. As a spindle is the interfacing element between the machine tool and tool (i.e. milling cutter) itself, there is an opportunity to implement a spindle condition monitoring system which will be capable of providing an information about the state of some machine tool components and the state information about the tool itself. The components to be covered by such system might include spindle housing with bearings, electric drive, and the interface between tool and drive shaft.

2 MACHINE FAILURES AND FAILURE LOCATION

The family of FMEA-like analyses proven to be the most efficient way for identifying the consequences of technical systems' failures. [SAE 1997]

Failure Modes and Effects Analysis (FMEA) and Failure Modes, Effects and Criticality analysis (FMECA) are the most suitable analytical methods for identifying the expected faults, their symptoms and associated parameter to be measured to indicate the presence of such faulty conditions. These inductive methods are widely respected in a machine safety analyses [Blecha 2008]. Above that, the Failure Modes, Effects and Detectability Analysis (FMEDA) can quantitatively evaluate the measure of diagnostic coverage of the device. FMEDA can be used to compute a rate of failure modes that can be detected by available sensors/quantities compared to number of all the identified failure modes. [Goble 1999]

Symptom → ↓ Fault	current	voltage	Resistance	partial discharge	power	torque	speed	vibration	temperature	coast down time	axial flux	oil debris	cooling gas
rotor windings	x				x	x	x	x	x		x		x
stator windings	x								x		x		x
eccentric rotor	x							x			x		
brush(es) fault	x	x			x	x			x				
bearing damage						x		x	x	x		x	
insulation deterioration	x	x	x	x									x
loss of input power phase	x	x						x			x		
unbalance								x					
misalignment								x					

Table 1. Examples of faults and associated measurable symptoms for an electric motor [ISO 2002]

Another branch of FMEA – Failure Mechanisms, Modes and Effects Analysis (FMMEA) – can be used when seeking for failure mode root-cases represented by physics-of-failure phenomena. [Pecht 2008]

All of these analyses can be performed on various levels - functional, component (piece-part), system, or any other if the analysis boundaries can be well-defined.

In the next step of analysis, the identified failure modes are matched to measurable quantities called symptoms whose change or appearance is observed while the failure mode occurs. The [ISO 2003] and more recent [ISO 2011] can be used as a reference for preparing tables that can illustrate relations of failure modes and symptoms. Example of such table prepared for the case of electric motor is shown in Tab. 1. The table can be read such way that e.g. bearing damage can be detected by the means of torque, vibration, temperature, coast down time or oil debris measurement. This table only provides "hints" on the quantities to be measured, a further evaluation of measurement location and data evaluation is needed in each specific condition monitoring task. Another example of failure precursors that might be useful in machine tools environment are precursors for cables and connector failures. Measurable parameters such as impedance changes, physical damage and high-energy dielectric breakdown are the typical examples of cable or cable connector failure precursors [Pecht 2008].

3 SENSORS

The sensors that are common and widespread in industrial machine tools environment are force, power and acoustic emission sensors. [Ambhorea 2015, Byrne 1995]

Basically, the sensors for machine tool monitoring can be divided among two categories: process monitoring sensors which are placed closely to the manufacturing process behind the cutting guard; and sensors for indirect measurements.

The requirements for process monitoring sensors are as follows [Byrne 1995]:

- measurement as close to the machining point as possible
- no reduction in the static and dynamic stiffness of the machine tool
- no restriction of working space and cutting parameters
- wear- and maintenance- free, easily changed, low costs
- resistant to dirt, chips and mechanical, electromagnetic and thermal influences
- function independent of tool or workpiece
- adequate metrological characteristics
- reliable signal transmission, e.g. from rotating to fixed machine components.

The requirement for low-costs and reliability even under harsh environments penalizes the optical systems such as digital cameras and sophisticated laser devices that are widely used in lab environment. For the same reason are beneficial the indirect and robust methods such as noise measurement, measurement of electric characteristics or other indirect methods taken an advantage of variables already implemented in CNC control system [Repo 2010].

For an industrial application and broad introduction to machine tools manufacturers' portfolio, the indirect measurement methods seem to be more promising. They are generally less expensive, easier to implement even to legacy machines, robust, function independent and reliable. As an example of such method can be taken the noise measurement [Salgado 2007, Fiala 2014] measurement of power and current in axes' drives [Drouillet 2016], or servo control signals [Koike 2016]. The cutting temperature on both tool and workpiece can be used to measure the tool wear. As the tool is exhibits wear, a higher friction is observed and the temperature of the process generally increases. The temperature measurement can be performed on both tool and workpiece, while the tool temperature measurement is more challenging since it is a rotating component. Not only the temperature increases with tool wear. Components of cutting force also exhibit measurable increase with a rising tool wear. The significance of such increase vary from process. Drilling, for example, exhibit very low cutting force changes which can be hardly used for condition monitoring. Milling and turning exhibit significant increases in feed and passive forces with increasing tool wear. [Byrne 1995]

Although they are less accurate, the indirect measurement methods proven to be a powerful utility for condition monitoring.

The machine tool faults also incorporate a number of those that are observable in the terms of spikes, steps and discontinuities in the measured data. These effects are associated with collisions, tool breakage, flanking and material fracture. Due to this fact, the acoustic emission sensors are widely used by machine tool manufacturers. [Lauro 2014]

It is strictly recommended to use the sensor type with proven record in industrial environment. Examples of such sensors include:

- microphones for sound intensity measurement
- accelerometers for measurement of vibrations
- dynamometers for measurement of cutting force components
- current sensors for monitoring drives' busbars
- acoustic emission sensors based on various physical principles
- temperature sensors.

Benefit could also be taken of a multi-sensor fusion combining any of the above-mentioned physical principles. For example, the combination of sound intensity (noise) and electric current measurement is useful for monitoring of a tool condition and wear [Salgado 2007].

Although the measurement methods for machine tool condition monitoring are generally known and established, there are still a lot of technical challenges which drive development in this area. The challenges include adaptability of sensors to tool changing, immunity and protection of cutting force sensors to overloading, or a sensitivity of sound intensity sensors to external noises.

4 CASE STUDY: POSSIBILITIES FOR MONITORING OF MACHINE TOOL SPINDLE

Spindle is one of the machine tool sub-assemblies which is required to be monitored to be kept informed about its collisions and overloading as reported by machine tool manufacturers [Abele, 2010, Byrne 1995]. A state-of-art machine tool spindle is a complex and sophisticated electro-mechanical assembly. Some of the recent spindle developments can be classified as mechatronic systems with high degree of integration [Abele 2010].

The spindle assembly consists of several items which provide a basic functionality and some custom components which vary with specific machine tool application. A generic drawing of spindle assembly with basic items is provided in Fig. 1.

A spindle head provides the interface to Z axis. The spindle itself can directly contain an electric motor for driving the spindle rotation. Alternatively, a gearbox for transferring the energy for spindle rotation from another machine tool electric motor can be provided. The drive sub-assembly encompasses bearings allowing the rotation in spindle housing, gearbox, provisions for cooling and other provisions for sensing and control of machining process. The spindle provides also an interface to the tool – a toolholder. The workpiece is not a direct part of spindle thus its drawing is provided for completeness only.

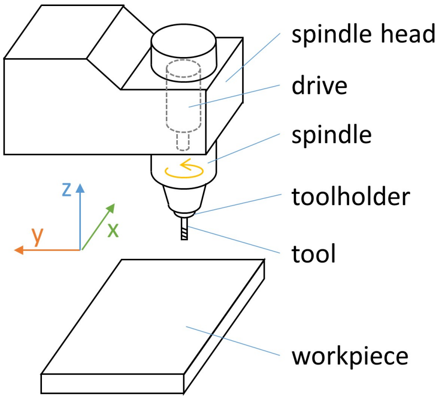

Figure 1. Schematics of a machine tool spindle with cutting tool

To assess how the spindle components, failure modes and measurable quantities relate to each another, the FMEA analysis was carried out. For the purposes of the machine tool spindle analysis was used an item-level FMEA. It means that the faults, their effects and possibilities of detection were determined at the functional boundary of spindle assembly main components - i.e. items. Examples of those are toolholder, drive, or motor with electronic control. A tool was considered as an item of the machine tool spindle too.

The simplified FMEA results listed in Tab. 3 provide a brief information about items' basic failure events. For a further assessment of how the failure modes and effect relate to each another on a higher level, the Fault Tree Analysis (FTA) or Dependence diagrams (DD) should be performed. [SAE 1996]

4.1 Examples of Quantities for Spindle Condition Monitoring

Several measurements have been taken to examine the basic ideas of machine tool condition monitoring and to acquire some first snapshot data. These measurements included the cutting force components measurement (Fig. 2) and measurement of the sound intensity induced by worn tool noise (Fig. 4).

The cutting force components data were acquired using the 9124B dynamometer from Kistler with machining conditions listed in Tab. 2. All the cutting force components have been increasing gradually as shown in Fig. 3. The milling tool wear level has been assessed along with force measurements. Tool exhibited a flank wear with VB = 0.05 mm after 10th pass. Subsequently, the tool wear increased to VB = 0.20 mm after 50th pass. These results are in good alignment with widely accepted experience that all the cutting force component trend to increasing with increasing tool wear. This behaviour can be considered in condition monitoring for assessing the tool condition and predict the remaining useful life. Nevertheless, a deeper understanding of such process and its relations to reported parameters is needed.

Figure 2. Cutting force components measurement for determining tool wear

Feed per Tooth	0.22 mm/tooth
Feed Rate	700 mm/min
Depth of Cut	2 mm
Cutting Speed	200 m/min
Width of Cut	140 mm – Symmetric Face Milling
Tool Diameter	200 mm
Workpiece Material	Steel 12 050

Table 2. Machining conditions – cutting force components measurement

Item	Failure Mode	Potential Cause / Failure Mechanism	Failure Effect	Detection Method
tool	wear	usage, overheating, overloading	nonconforming workpiece, shortened lifetime	increase in cutting force components, exceeding vibrations, noise, tool temperature, motor current/power
	chipping	usage, overheating, overloading	nonconforming workpiece, shortened lifetime	increase in cutting force components, exceeding vibrations, noise, tool temperature
	fracture	usage, overheating, overloading	nonconforming workpiece, shortened lifetime	cutting force impulse - then abnormal decrease, spike in drive motor current (power)
	tool collision	operator or SW error	tool damage, workpiece damage, spindle-level geometry defects	cutting force impulse, spike in drive motor current (power)
	unstable machining	tool chatter	nonconforming workpiece, shortened lifetime, tool damage	increase in cutting force components, exceeding vibrations, noise, tool temperature
	tool misalignment	operator error, toolholder failure	nonconforming workpiece, shortened lifetime, tool damage	exceeding vibrations, noise
spindle (miscellaneous components)	loss of cooling	cooling circuit failure	tool damage	tool temperature (overheated), spindle assembly temperature (overheated)
	insufficient cooling	cooling circuit failure	blunting of cutting edge, shortened tool lifetime	tool temperature (overheated), spindle assembly overheated
	bearing failure	abnormal wear, insufficient lubrication	increased friction of spindle shaft, spindle overheating	spindle assembly temperature (overheated), increasing motor current (power)
spindle head	collision	operator or SW error	frame deformation, defective geometry	cutting force impulse, spike in drive motor current (power)
toolholder	torque overloading	operator or SW error	inability for torque / cutting force transmission, stop of machining, tool damage	cutting force components, power or current to electric drive
	toolholder misalignment	operator error	tool misalignment, low quality workpiece, chatter	exceeding vibrations, noise
drive	overloading	Operator	excessive wear	abnormal motor current (power)
	transmission gear failure	abnormal wear, insufficient lubrication	increased friction of spindle shaft, spindle overheating	changes in motor current (power), gear temperature, unable to drive toolholder
workpiece	workpiece misalignment	inappropriate workpiece mounting	low quality workpiece, tool wear and damage	exceeding vibrations, noise
control system	performance unsatisfactory	miscellaneous HW/SW errors	increased demands for the operator, low quality workpiece	SW/HW built-in-test (BIT)

Table 3. Simplified FMEA sheet for a machine tool spindle and its monitoring (excl. Failure Rates)

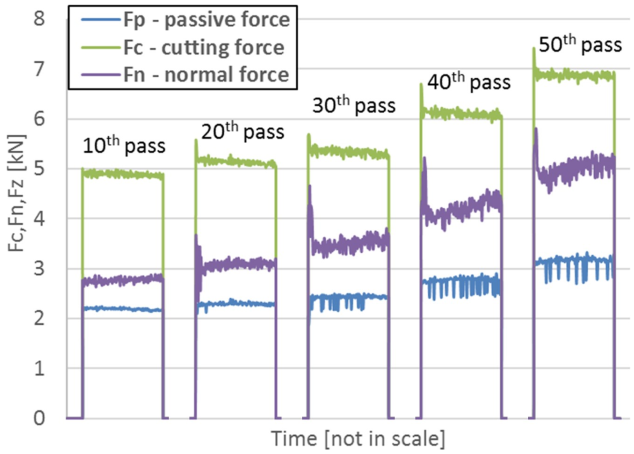

Figure 3. Cutting force components as a function of the tool wear (represented by time)

Sound intensity measurement has been another method which being examined as a proposal for a tool condition monitoring. The sound intensity measurement was acquired while milling with HSS (Al, Ti, Cr) milling cutter. Machining conditions for this case are listed in Tab. 4. Measurements were acquired using the Brüel & Kjær 4189-A-021 free-field microphone for high-precision acoustic measurements. Raw sound intensity signal was converted to frequency domain. The cutting process was stable. Measurements with unstable machining conditions as well as with new unworn tool have been also performed for reference. While under unstable conditions, the sound intensity spectra produced by tool have exhibited a high intensity noise corresponding to chatter frequency which makes this method promising for unstable machining identification.

Results for worn tool are presented in Fig. 5. It can be clearly observed that the worn tool exhibits noise associated with acoustic pressure rise on frequencies among 6-7 kHz.

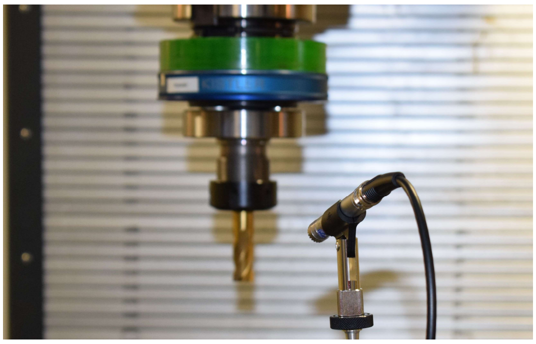

Figure 4. Sound intensity measurement for determining tool wear

Feed per Tooth	0.05 mm/tooth
Feed Rate	120 mm/min
Depth of Cut	2 mm
Cutting Speed	30 m/min
Width of Cut	16 mm
Tool Diameter	16 mm
Workpiece Material	Steel 15 260

Table 4. Machining conditions – sound intensity measurement

4.2 Failure Modes Matching to Symptoms – Spindle Assembly Example

Tab. 5 provides a list of the machine tool spindle failure modes identified by FMEA to their measurable symptoms. The table was prepared on the basis of [ISO 2011], Annex B. Note that this annex is only informative and the form how to visualise the machine faults matching to measurable variable may vary from application. Appearance of "x" indicates a symptom or parameter change that may occur if fault occurs.

The matching of failure modes to measured quantities is ambiguous. The same symtom represented by particular quantity can be affected by multiple failure modes. As a result of that, various different threshold, signal patterns or data-mining methods should be applied for identifying the each failure mode from measured data.

As an example for such approach can be taken the vibrations mesurement. The tool wear, unstable machining, and spidle misalignment failure modes can be identified from vibrations measurement. Nevertheless, each of these failure modes will exhibit on a different frequency thus can be uniquely identified. The methods for finding the failure modes in the measured data will be a case for further development.

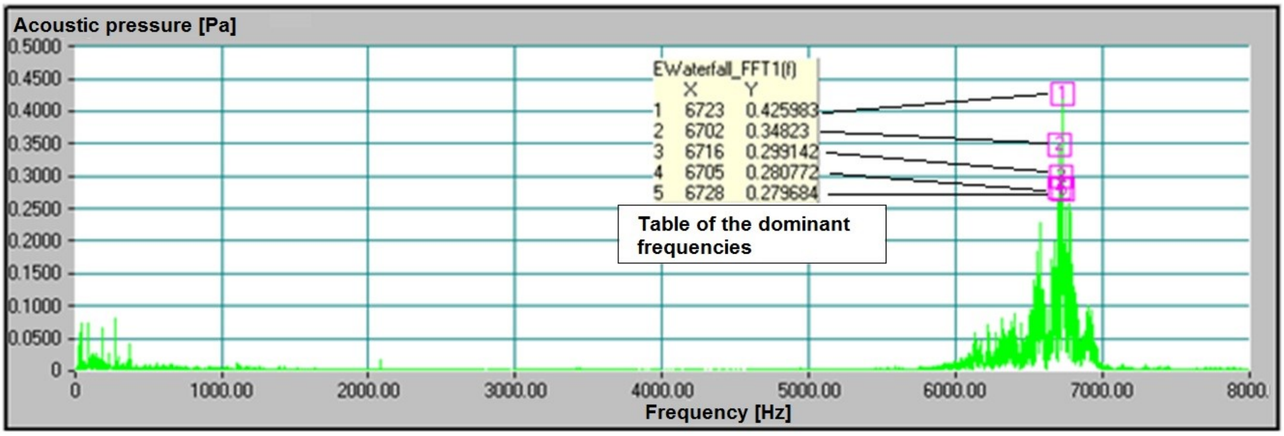

Figure 5. Acoustic pressure (noise) spectra produced by the worn cutting tool

Symptom → ↓ Failure Mode	cutting force	motor current	motor power	vibrations	sound intensity	tool temperature	spindle assemb. temperature	drive (gear) temperature
tool wear	x	x	x	x	x	X		
tool fracture	x	x	x					
tool collision	x	x	x					
unstable machining	x			x	x	x		
spindle misalignment				x	x			
insufficient cooling						x	x	x
bearing failure		x	x				x	x
collision	x	x	x					
toolholder overloading	x	x	x					

Table 5. Proposal for matching the machine tool spindle failure modes to their symptoms – prepared per [ISO 2011]

5 CONCLUSIONS

The aim of this paper was to show the basics of condition monitoring and its application to recent machine tools market.

The condition monitoring philosophy have been shown on the example of spindle condition monitoring. The analytic methods based on FMEA were presented on the spindle case study. The sound intensity measurement and cutting force measurements are used as illustrative examples on using the failure mode symptoms. The sound intensity measurement and cutting force components measurement proven to be a powerful method for a tool wear identification. Above that, both methods can be used for identification of the unstable machining.

This paper does not address the challenges associated with failure detection from monitored signals, however it provides a basic reference of how the quantities and sensor for machine tool condition monitoring could be systematically identified.

As the state-of-art machine tools contain a number of sensors tied to their CNC system, the best way to implement the condition monitoring system would be to implement the condition monitoring as software functionality without affecting any machine tool hardware and increasing the manufacturing costs.

Proposal for the signal processing, fault isolation and classification algorithm used for identifying the failure modes from measured data will be the next step in our efforts.

ACKNOWLEDGMENT

This work is an output of research and scientific activities of NETME Centre, supported through project NETME CENTRE PLUS (LO1202) by financial means from the Ministry of Education, Youth and Sports, Czech Republic under the ‘National Sustainability Programme I’.

REFERENCES

[Abele 2010] Abele, E. et al. Machine tool spindle units. CIRP Annals – Manufacturing Technology, July 2010, Vol.59, No.2, pp 781–802, ISSN 0007-8506

[Ambhorea 2015] Ambhorea, N. et al. Tool condition monitoring system: A review. Materials Today: Proceedings, November 2015, Vol.2, No.4-5, pp 3419-3428, ISSN 2214-7853

[Blecha 2008] Blecha, P. System Methodology of Risk Assessment in Machine Tools. MM Science Journal, April 2008, Vol.1, No.1, pp 1-4, ISSN 1803-1269, DOI: 10.17973/MMSJ.2008_04_20080402

[Byrne 1995] Byrne, G. et al. Tool Condition Monitoring (TCM) – The Status of Research and Industrial Application. Annals of the CIRP, November 1995, Vol.44, No.2, pp 541-567, ISSN 0007-8506

[Drouillet 2016] Drouillet, C. et al. Tool life predictions in milling using spindle power with the neural network technique. Journal of Manufacturing Processes, April 2016, Vol.22, pp 161–168, ISSN 1526-6125

[Elghazel 2015] Elghazel, W. et al. Dependability of wireless sensor networks for industrial prognostics and health management. Computers in Industry, April 2015, Vol.68, pp 1-15, ISSN 0166-3615

[Fiala 2014] Fiala, Z. et al. On the Analysis of the Sound Spectrum at Machining of the Glass-polyester Composite Material. MM Science Journal, March 2014, Vol.7, No.1, pp 458-461, ISSN 1803-1269

[Goble 1999] Goble, W. M. and Brombacher, A. C. Using a failure modes, effects and diagnostic analysis (FMEDA) to measure diagnostic coverage in programmable electronic systems. Reliability Engineering & System Safety, April 1999, Vol.66, No.2, pp 145–148, ISSN 0951-8320

[Hashmi 2014] Hashmi, S. Comprehensive Materials Processing – Vol. 13 Sensor Materials, Technologies and Applications. Amsterdam: Elsevier Ltd., 2014. ISBN 978-0-08-096533-8

[ISO 2002] ISO 13380:2002 – Condition monitoring and diagnostics of machines – General guidelines on using performance parameters. Geneva: International Organization for Standardization, 2002

[ISO 2004] ISO 13372:2004 – Condition monitoring and diagnostics of machines – Vocabulary. Geneva: International Organization for Standardization, 2004

[ISO 2011] ISO 17359:2011 – Condition monitoring and diagnostics of machines – General guidelines. Geneva: International Organization for Standardization, 2011

[Keller 1982] Keller, A. Z. et al. Reliability Analysis of CNC Machine Tools. Reliability Engineering, November 1982, Vol.3, No.6, pp 449-473, ISSN 0951-8320

[Koike 2016] Koike, R. et al. A sensorless approach for tool fracture detection in milling by integrating multi-axial servo information. CIRP Annals – Manufacturing Technology, May 2016, Vol.65, No.1, pp 385–388, ISSN 0007-8506

[Lauro 2014] Lauro, C. H. et al. Monitoring and processing signal applied in machining processes – A review. Measurement, December 2014, Vol.58, pp 73-86, ISSN 0263-2241

[Pecht 2008] Pecht, M. Prognostics and Health Management of Electronics. Hoboken: John Wiley & Sons Inc., 2008. ISBN 978-0-470-27802-4

[Repo 2010] Repo, J. Condition Monitoring of Machine Tools and Machining Processes using Internal Sensor Signals. Stockholm: School of Industrial Engineering and Management, 2010. ISBN 978-91-7415-600-3

[SAE 1996] ARP 4761 – Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment. Warrendale: SAE International, 1996

[SAE 1997] ARP 926B – Fault/Failure Analysis Procedure. Warrendale: SAE International, 1997

[Salgado 2007] Salgado, D. R. and Alonso, F. J. An approach based on current and sound signals for in-process tool wear monitoring. International Journal of Machine Tools & Manufacture, November 2007, Vol.47, No.14, pp 2140–2152, ISSN 0890-6955

[Williams 1994] Williams, J. H. et al. Condition-based Maintenance and Machine Diagnostics. London: Chapman & Hall, 1994. ISBN 0-412-46500-0

CONTACTS:

Ing. Ludek Janak
Ing. Jakub Stetina
Ing. Zdenek Fiala, Ph.D.
doc. Ing. Zdenek Hadas, Ph.D.

Brno University of Technology, FME
Technicka 2896/2, Brno, 616 69, Czech Republic
Tel.: +420 541 143 375, janak@fme.vutbr.cz
Tel.: +420 541 143 375, stetina.j@fme.vutbr.cz
Tel.: +420 541 142 420, fiala.z@fme.vutbr.cz
Tel.: +420 541 142 893, hadas@fme.vutbr.cz
www.fme.vutbr.cz