MAINTENANCE AND TECHNICAL DIAGNOSTICS OF MACHINE TOOLS

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DOI: 10.17973/MMSJ.2016_11_2016167

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The article deals with the maintenance and technical diagnostics of machine tools. The basic knowledge about maintenance, distribution of maintenance and also important facts about the diagnostics are provided. Attention is focused on the possibility of using technical diagnostics as an instrument to improve maintenance. Article is describing an experiment in the engineering company. It proceeds from the current state of maintenance and suggests a plan of innovation. This proceeds from FMEA and FMECA analysis and the vibrodiagnostics is submitted as one of the possible methods of improving maintenance of machine tools. The article describes and evaluates the experiment and carry out recommendations for specific conditions in described company.

KEYWORDS

maintenance, technical diagnostics, vibrodiagnostics, current and predictive diagnostics, neural network

1. INTRODUCTION

Currently, the industrial practice is increasingly addressing maintenance and related issues.

Maintenance is an integral part of management of tangible assets; it is one of the supporting processes in production and affects the productivity of production and its efficiency across the organization. Performance of maintenance processes is influenced by many factors, such as strategies, personnel, standards, availability of spare parts, financial resources, legal provisions, company culture, etc. Maintenance is different in different areas; it is crucial whether it is a continuous operation or a single shift operation. Maintenance must be understood in the interdisciplinary sense; it is a process which is a combination of all technical, technological, managerial, economic and administrative activities. These must aim at maintaining or restoring a condition in which tangible assets fulfil all the required functions. Maintenance benchmarking shows that the annual maintenance cost is approximately 3% of annual sales. This is not a negligible sum and, of course, any reduction is welcome by the companies. [Legat 2013], [Sherwin 2000], [Opocenska 2015].

Especially lately, an indispensable part of maintenance has been technical diagnostics, a science about the condition of, in this case, machines. An increasing emphasis is laid on prevention of operational problems due to technical failures. Therefore, the development of technical diagnostics is directed from finding the causes of failures to continuous automatic monitoring of machine technical condition. The current trend in companies is focused on the effect of diagnostics and maintenance within the integrated system of company management.

The present paper seeks to respond to the above mentioned issues and to show the possibilities of application and combination of diagnostics and maintenance. The workplace of authors has been involved in diagnostics and maintenance for quite many years, and currently it can offer the experience in assessing the condition of machines (Fig.1) in engineering industry. [CSN 2010], [Blecha 2014]

Figure 1. Example of machine tool

2. GENERAL FACTS ABOUT MAINTENANCE AND TECHNICAL DIAGNOSTICS

Maintenance can be, according to CSN EN 60300-3-11, defined as a combination of all technical, administrative and managerial actions during the life cycle of the object aimed at maintaining it in the condition or returning it to the condition in which it can perform a required function. [Sherwin 2000]

Basic classification of maintenance can be seen in Fig. 2. [Legat 2013]. Fig.2. refers to some terms that are more or less known.

After-the-failure maintenance - the oldest type of maintenance that was and still is justified for objects that have a minimal effect on the readiness of the equipment. It represents a disadvantage in the form of unplanned and sometimes longer operational shutdowns of the equipment, which may be connected with large financial costs.

Preventative maintenance with pre-determined intervals – usually includes check-ups, inspections, ETA. This type of maintenance represents a high level of planned work and usually leads to a reduction in costs compared to the costs of after-the-failure maintenance.

Preventative maintenance based on technical condition – is based on monitoring of characteristics or parameters, uses technical diagnostics.

Proactive maintenance – is similar to preventative

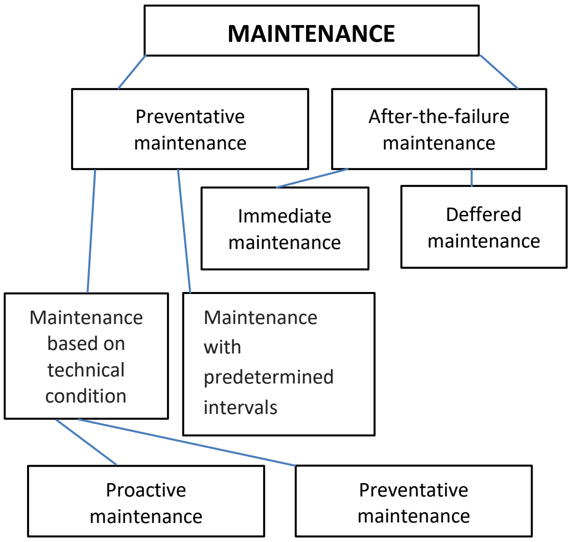

Figure 2. Basic classifacation of maintenance

maintenance based on technical condition. It highlights a proactive approach to ensure the required functionality while spending optimal costs. [Legat 2013]

In various companies, a variety of ways to maintenance is applied and various maintenance strategies are used. It can be said that a routine after-the-failure maintenance and preventative maintenance with predetermined intervals are the most common. Recently, however, efforts have been made to implement a preventative maintenance based on technical condition or proactive maintenance.

Technical diagnostics is an independent branch of science that deals with the methods and means for determining the technical condition of the object under monitoring. The use of methods of technical diagnostics is necessary for the early identification of equipment failure conditions. These are non-invasive and non-destructive methods. Information on the monitored object is then obtained by evaluating its external manifestations. [Legat 2013]

Technical diagnostics is divided according to different criteria. The most common criterion is that of monitored diagnostic variable. According to this criterion, technical diagnostics is divided into the following highlights:

thermodiagnostics,
acoustic (noise) diagnostics,
pressure diagnostics,
deformation diagnostics,
vibrodiagnostics,
diagnostics of acoustic emission,
electrodiagnostics,
defectoscopic diagnostics,
tribodiagnostics,
flow diagnostics,
level diagnostics
heat diagnostics,
concentration diagnostics.

The nature of the above diagnostics is suggested by their names; therefore, the respective methods are not further discussed and described. [Hammer 2015], [Hammer 2016]

It is still possible, in various literature, to find the term of remote diagnostics (used for machines) or multi-parameter diagnostics when the condition is evaluated e.g. by two diagnostic methods or within a single diagnostic method by two or more variables. Classification of diagnostics that is also still used involves the actual diagnostics (evaluates the condition of the object in the particular – actual condition) and the predictive diagnostics (prediction of future condition using advanced mathematical techniques, such as neural networks, fuzzy systems, etc.).

Using a particular diagnostic method depends on the particular technical object. For diagnostics of machine tools, considering their maintenance, the most commonly used diagnostics are vibrodiagnostics, thermodiagnostics, electro-diagnostics and acoustic diagnostics; they are used both individually and as a multi-parameter diagnostics. To diagnose some specific machines, there are extra standards or regulations for their assessment, e.g. for machine tools, it is a set of standards designated as CSN 230 ISO-x. These are the following standards:

CSN ISO 230-1 Test code for machine tools - Part 1: Geometric accuracy of machines operating under no-load or quasi-static conditions

CSN ISO 230-2 Test code for machine tools - Part 2: Determination of accuracy and repeatability of positioning in numerically controlled axes

CSN ISO 230-3 Test code for machine tools - Part 3: Determination of thermal effects

CSN ISO 230-4 Test code for machine tools - Part 4: Tests of circular interpolation for numerically controlled machine tools

CSN ISO 230-5 Test code for machine tools - Part 5: Determination of noise emissions

CSN ISO 230-6 Test code for machine tools - Part 6: Determination of positioning accuracy on body and walls diagonals (Diagonal displacement test)

CSN ISO 230-7 Test code for machine tools - Part 7: Geometric accuracy of axes of rotation

CSN ISO 230-10 Test code for machine tools - Part 10: Determination of measuring properties of sensor systems of numerically controlled machine tools.

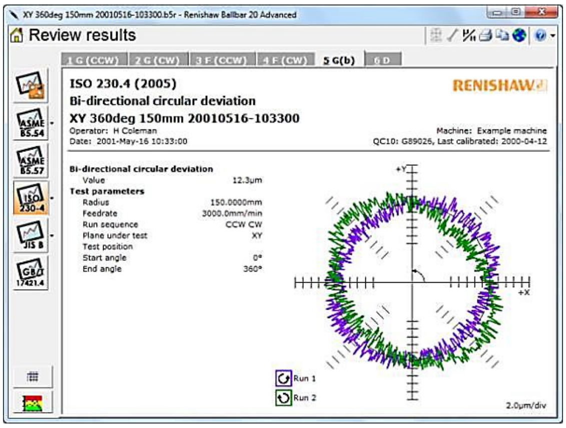

Figure 3. Example of measurements of bi-directional circular deviation by the program Renishaw 30 [Team 2016]

3. PARTICULAR FACTS ABOUT MAINTENANCE AND TECHNICAL DIAGNOSTICS

This section firstly describes an example of preventative maintenance based on technical condition.

In the engineering company, automatic five-axis lathes were assessed, see Fig. 3. These were the machines produced in 2013 and differed only by hours of deployment in operation. After becoming familiar with the real workplace, a maintenance proposal was initiated; it was based on the fact that the described company used only after-the-failure maintenance and preventative maintenance with predetermined intervals. Given that these were the machines with a relatively short service life, failures were only rare and were addressed mostly by outsourced company from abroad. This company had a fairly good level of preventative maintenance with predetermined intervals. Below is a brief overview (examples):

Inspection daily
Putting into operation after turning the power on
Entering the amount of coolant
Checking the inlet pressure

Inspection 1x a week (Monday)
Entering the amount of oil in the main spindle
Removing and cleaning the side spindle

Inspection 1x a month (1st week of the month)
Cleaning up the sliding guidance and the chuck (main spindle)
Checking the damage of pressure gauge

Inspection every two months (every odd month)
Contamination of cooling fan

Inspection 2x a year **(**March / September**)**
Greasing the toggle lever

It was therefore an ideal situation where it will be soon possible to consider a preventative maintenance based on technical condition, to design this maintenance for the company and assist to implement it into practice.

First, based on documentation and technical reality, a machine - system was broken down into subsystems and components. An example is schematically shown in Fig.4. This was followed by the implementation of FMEA (Failure Mode and Effects Analysis) and FMECA (Failure Mode and Effects and Criticality Analysis) according to CSN EN 60812 [CSN 2009]. Evaluation of FMECA showed that the most critical component in the monitored machine tool is a main spindle, and specifically a bearing. Therefore, vibrodiagnostics was selected as a diagnostic method. Vibration measurements were performed on two machine tools. These machines were of the same type having the same manufacturer. Both machines were measured by two sensors connected in the axial direction at the point of expected vibration of the main spindle (Fig. 4). As a measurement analyzer, we used a four-channel universal signal analyzer of CMXA80 type marked Microlog (Fig. 4 - top photo).

Measurements were then carried out at a gradual change in speed within the range of 500 - 5500 rpm, followed by reduction of speed to 4000 rpm, with the step of 500 rpm. Measuring time during one step was approximately 10 sec. We measured diagnostic variables of vibrations according to [Jankovych 2015],

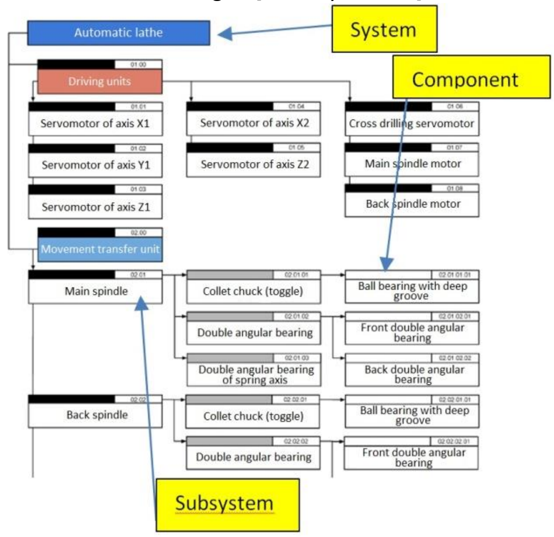

Figure 4. Example of machine breakdown [Team 2016]

the particular ones are specified in the headings of presented graphs. An analysis of measured data was conducted in the ARM program (Analysis and Reporting Manager) [SKF 2015]. This software from the company SKF is a computer supportive application for Microlog, which provides an automatic transmission, display, and analysis of measurement data generated by the application modules of the tools. For measurements, sensors were used (Fig. 5 - lower photo - sample wiring of sensor CMSS 2011):

- CMSS 2011

sensitivity 100 mV/g, frequency range 0.5 – 10 000 Hz

- CMSS 732AT (high-frequency)

sensitivity 10 mV/g, frequency range 0.5 – 25 000 Hz

Figure 5. Lathe examined in preparation for diagnostics (top photo) and mounting of sensors (bottom photo) [Team 2016]

4. ANALYSIS OF EXPERIMENT

Using the known data, a spectral analysis was conducted; this basically consists in the conversion of the reference signal from the time domain to the frequency domain. This creates a frequency spectrum. This conversion is performed by computational algorithm of Fast Fourier Transform (FFT).

The frequency spectrum of the measured machine (designated as 1) can be seen in Fig. 6. From the graphic display, we can read a staircase shape of amplitude caused by changing the speed, and further, we can see that the maximum amplitude deflection arose at an approximate frequency of 91.8 Hz, which corresponds to a maximum speed achieved by the machine with a value of 5500 rpm.

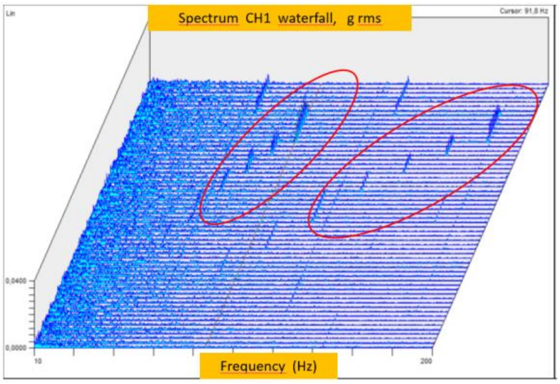

Figure 6. Frequency spectrum of machine №.1 [Team 2016]

From the displayed frequency spectrum of measurement data of the machine №.2 (Fig. 7), we can again determine the highest amplitude at the highest speed of 5500 rpm, which corresponds to a frequency of 91.8 Hz. The amplitude of the machine №.2 in comparison with that of the machine №.1 is slightly higher. Higher vibrations can be caused e.g. by a longer service life of the machine №.2.

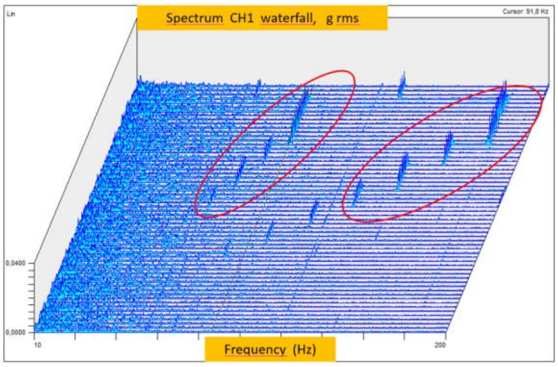

Figure 7. Frequency spectrum of machine №.2 [Team 2016]

The basic standard for vibration diagnostics of rotating machines (not only for bearings) is CSN ISO 10816-1. It sets four vibration bands for machines of different power ratings (Table 1), starting from the effective value of vibration speed (called RMS). The band is dependent on the frequency of machine rotation; a detailed explanation is given in the standard.

Explanation of some of the data from the table:

Band A: In this band, vibrations of new machines should be found.

Band B: Machines in this band can be operated indefinitely.

Band C: Machines in this band are not designed for continuous operation, but can be operated until the remedy is needed.

Band D: Machines operating in this band are considered dangerous, vibrations can damage them.

<table>
<tr><th>Effective value of vibration [mm s^{-1}]</th><th>Class I</th><th>Class II</th><th>Class III</th><th>Class IV</th></tr>
<tr><td>0.28</td><td rowspan="3">A</td><td rowspan="4">A</td><td rowspan="5">A</td><td rowspan="6">A</td></tr>
<tr><td>0.45</td></tr>
<tr><td>0.71</td></tr>
<tr><td>1.12</td><td rowspan="2">B</td></tr>
<tr><td>1.8</td><td rowspan="2">B</td></tr>
<tr><td>2.8</td><td rowspan="2">C</td><td rowspan="2">B</td></tr>
<tr><td>4.5</td><td rowspan="2">C</td><td rowspan="2">B</td></tr>
<tr><td>7.1</td><td rowspan="5">D</td><td rowspan="2">C</td></tr>
<tr><td>11.2</td><td rowspan="4">D</td><td rowspan="2">C</td></tr>
<tr><td>18</td><td rowspan="3">D</td></tr>
<tr><td>28</td><td rowspan="2">D</td></tr>
<tr><td>48</td></tr>
</table>

Table 1. Vibration bands for machines of different power ratings

Class I. Individual parts of motors and machines are integrally connected with the entire machine under normal conditions. A typical example is an electric motor with a power output of up to 15kW.

Class II. Medium-sized machines (typically electrical motors with an output from 15kW to 75kW) without special foundations, steadily mounted motors or machines (with an output of up to 300kW) on special foundations.

Class III. Large primary driving units or other large machines with rotating masses, attached to steady foundations that are relatively rigid in the direction of vibration measurement.

Class IV. Large primary driving units and other large machines with rotating masses mounted on foundations that are relatively soft in the direction of vibration measurements (for example, turbo-generators or gas turbines with an output greater than 10 MW).

From the evaluation of measurement data according to CSN ISO 10816-1 for both CNC machines, it can be concluded that these machines were during the measurement in good technical condition. The analysis of measurement data did not reveal any extreme values indicating a failure. It is also possible to state that based on the described measurements of two machines and also other machines in other companies, vibrodiagnostics is a considerably sensitive method for assessment of the machine condition. [Team 2016]

In the following part of the present article, attention is drawn to the possibility of predicting the condition of technical systems. An important part of machine tool spindles are bearings; therefore their predictive diagnostics is described below. Again, we worked with vibrodiagnostics that was used, in this case for laboratory conditions, for accelerated testing [Kutalek 2015]. Some parameters of vibration (acceleration and speed of vibrations, acceleration envelope, etc.) were measured at regular intervals and their progress was monitored during the test. Theoretical progress of bearing defects over time is shown in Fig. 8. The above figure shows the dependence of general diagnostic variable on time. Here, the use of individual specific methods of vibrodiagnostics is also shown [Bilos 2012]; the following methods are suitable for the progress stage of bearing defects:

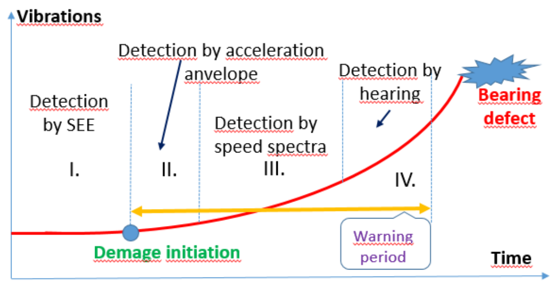

Figure 8. Progress of bearing defects

detection by acoustic emission (SEE) [Kopec 2008], use of acceleration envelope, use of speed and also detection by hearing. Acoustic emission records the structural defects of material caused by wear. The frequency range for acoustic emission is from 1 kHz to 100 MHz, typically 100 kHz. Therefore, it is not a pure vibration signal; it is more of ultrasound propagated by the bearing material. Other terms are commonly known.

For predicting of bearing condition from the data obtained in laboratory conditions, the neural network RBF (Radial Basis Function) was selected; its general scheme is shown in Fig. 9. This network is suitable for prediction of data based on historical data. The network was learned and then used to predict the values of vibration parameters. [Hammer 2009], [Demuth 2001]

The results are shown in Fig. 10. This figure shows a considerable agreement of real and predicted data for the entire duration of accelerated tests.

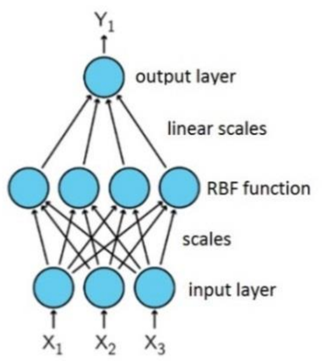

Figure 9. Neural network for prognostics [Hammer 2009], [Demuth 2001]

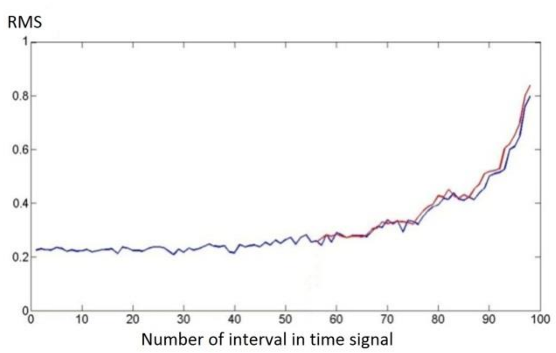

Figure 10. Relationship between real (measured) and predicted data

CONCLUSIONS

The authors of the present article focused on the issues of maintenance and diagnostics, with the aim of analysing the possibility to apply the technical diagnostics in maintenance. It is a problem of considerable importance, since the above mentioned is associated with the economic aspect. The article describes the specific case focused on machine tools. There is a considerable number of companies that use these particular machines for their activities and solve the above problem. Companies do not focused on machine tools. There is a considerable number of companies that use these particular machines for their activities and solve the above problem. Companies do not provide maintenance of the same level. A promising approach for the area of maintenance of machine tools appears to be vibrodiagnostics, which was highlighted in this article. Further, as a possible solution, it is suggested to predict the condition of critical parts of machine tools, such as spindles and bearings. This approach is entirely new and promising. Of course, it must be supported by further experiments and evaluations.

As already mentioned, in most companies, machine tools currently undergo the preventative maintenance, namely the maintenance with predetermined intervals, irrespective of the technical condition of the machine. This system of maintenance, according to the results of the FMECA analysis and the evaluation of vibration measurements, is still insufficient. For the machine tools, based on the past experience, the current system of maintenance can be recommended to retain and to further consider the implementation of predictive maintenance system, i.e. the maintenance based on technical condition of the machine. For machine tools, a proactive maintenance could be further considered; i.e. the use of regular monitoring of machine condition and visualization of measured data. [Team 2016] The last but not least, it is also possible to consider the implementation of any up-to-date approach to maintenance, such as TPM (Total Productive Maintenance) [Hartmann 1992], [May 2009], [Reitz 2009] and RCM (Reliability Centred Maintenance) [CSN 2010].

ACKNOWLEDGEMENT

This work has been supported by Brno University of Technology, Faculty of Mechanical Engineering, Czech Republic (Grant No. FSI-S-14-2401).

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[Team 2016] Team 2016. A Project under the specific Research at the Faculty of Mechanical Engineering, Brno University of technology.

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