THREE-DIMENSIONAL VIBRATION ANALYSIS FOR ON-LINE MONITORING OF MILLING PROCESS AND SPINDLE BEARINGS

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Vibration analysis has long been used for detection and identification of the machine tool condition. Considering the current importance of machining process regarding the quality and the productivity imposed by the market, the appearance of vibration is inevitable, more so in the milling process. This paper proposes a method to monitoring and diagnosis for milling process and also for spindle bearings condition. The method used refers to an advanced three-dimensional vibration analysis to obtain the answer on quality of the milling process and to identify various defects. In order to reach to objective, an experimental device designed to obtain dynamic information provided by the dynamic system machine-tool/tool/workpiece. The focus will be on Synchronous Envelope Vibration Analysis (SEVA) in order to obtain a frequency spectrum in direct connection with the quantity and the uniformity of each tooth own energy and how it is transmitted to the workpiece. During the cutting process the vibration level of bearings and the appearance of defects are take in account and processed to the predictive maintenance process.

Keywords: milling, analysis, monitoring, envelope, spindle

1. Introduction

The current market imposed a developing trend of machine tool in order to provide in the shorts time the high quality for workpieces whit the minimal cost. Thus the development and application of new processing technologies require special attention on dynamic behaviour, both in terms of tool and workpiece and in terms of machine tool spindle respectively. The paper aims to create a system that relies on dynamic link between the machines behaviour and the cutting process. Optimization of cutting conditions for the multitude of existing materials is strongly penalized by the influence of machine tools stiffness on the dynamic stability of cutting process [1], [2], [3]. The research proposed in this paper aims coupling of cutting vibrations behaviour and spindle state monitoring [5], [6].

Using a vibration analysis associated with on-line monitoring provides consistent data for spindle diagnosis and cutting process. By its nature the milling process is a three-dimensional process with mechanical actions on the three directions and the use of three-dimensional vibration analysis is absolutely necessary. Vibration analysis is based on the Synchronous Envelope Vibration Analysis (SEVA) method developed for qualitative evaluation of the tool/workpiece contact during the milling process.

Intensification of industrial activities in the automotive led, also to the development of high speed machining, respectively, the use of CNC machine tools in increasingly complex configurations that are equipped with motor spindles or with precision shafts with high speed. High Speed Machining (HSM) technology is still relatively new to many unknowns generated by work processes and dynamic behaviour unpredictable situations, and power. Safety and reliability of processing are strongly penalized by imperfections dynamic and thermal performance of motor-spindles after contact between tool / chip / piece becoming the main issue for both machine dynamics and the quality and quantity of its operation.

Therefore using a model that takes into account on the hand the dynamic behaviour of the machine, spindle, through monitoring and diagnosis and on the other hand the dynamic characteristic of the cutting process for stability optimization process can be an outstanding success [6], [7]**.**

This research proposes the development of complex methods of monitoring the cutting process, tool and spindle implicitly using a series of advanced signal processing techniques measured via high speed acquisition modules. A key element in the proposed method is the determination at any time the dynamic position of the tool during the cutting process. Although theories concerning the processing of HSM they are published for many years [8], [9], [10] their effective introduction of advanced processing together took place quite late. Current problems include issues of tooling, balancing, thermal and dynamic behaviours, and reliability of machine tools [7]. In contrast to the traditional detection of tool conditions (TCM- Tool Condition Monitoring), the approach is that machining processes are being continuously monitored via sensing devices to quantify the process performance or provide information for process optimisation using sensors [7], [8].

The understanding and the control of these difficulties have lead to a lot of scientific researches, concentrated mainly on the instability of the cutting process in particularly on the self-exited vibrations, the more their importance in milling is overwhelming [9], [10].

The dynamic influence of the vibrations over the motor spindle is severe and needs a detailed attention of the mechanical components. The vibrations appear in the cutting process due to: the interdependence between the cutting force and the relative displacement between the tools and the work piece; the variations of the friction process at the interface tool/chip, etc., [1]. The originality of the method consists in quantifying the impact of the milling teeth with the workpiece and processing the signal by demodulation it can then be analyzed. Important results were obtained by an advanced analysis of vibration, spectral envelope analysis based on a Hilbert transform to identify mechanical defects and obtaining a better response on the milling process quality [11], [12].

2. Research scope

The main objective of the research is to achieve an integrated real-time monitoring and diagnosis system responding on the processing conditions on conventional CNC machine tools and especially the high-tech technologies. A successful diagnostic and monitoring solution depends on the ability of the system to identify process abnormalities and respond in critical time with the appropriate feedback actions [12].

The method used for real-time monitoring and diagnosis is based on synchronous vibration enveloping using the Hilbert transform. This method allows the evaluation of incipient faults both spindle and tool [6], [13]. Vibration signals generated during the cutting process are impulsive milling is possible to collect them through an accelerometer on obtaining the frequency response of the dynamic system. Current methods for monitoring not only refer to a part of dynamic parameters we can measure simultaneously highlight and main shaft and cutting process. Synchronous Envelope Vibration Analysis (SEVA) represents a new approach based on Hilbert transform [11] applies both cutting process and spindle analyzed at each rotation.

3. Proposed method

To understand the dynamic phenomena due to the milling process the present method consist in the correlation between vibration and mechanical actions in an experimental way. A complex experimental protocol is designed and realized to highlight the three dimensional vibration behavior of the milling tool during the cutting process.

3.1 Method description

The method used in this research refers to an advanced monitoring and vibration analysis, SEVA method is based on a Hilbert transform [11], to identify mechanical defects and obtaining a better response on the milling process quality [13]. Envelope vibration is a technique to extract the modulation signal to understand the fault behaviors which occur at high frequency. The envelope vibration detection is used on three-axis to highlight the three-dimensional characteristic of the milling cutting process.This application has the following features: acquisition, processing and analysis in real-time and long-term continuous recording of signals, high-resolution FFT analysis buffer up to 32,768 samples and speed acquisition up to 50,000 samples / sec., Filtration, integration and derivation in the time domain and frequency harmonic analysis synchronously with continuing resolution, spectral analysis of variable frequency signals, multiple option tachometer synchronous, simultaneous analysis of vibration parameters and process parameters, specific functions for testing bearings, harmonic identification and tracking multiple references (multi-axis processing and order tracking), connecting remotely via the local network or the Internet. The research consists in addressing complex cutting process by integrating the cutting mechanical action with vibrations into a monitoring and diagnosis method.

The central point of the research is highlighted by the development of numerical signal processing algorithms rely on domain Hilbert transform both linear and nonlinear. The core of this is the development of the analysis SEVA method in order to provide real-time information of tool cutting evolution and motor-spindle condition monitoring in terms of diagnosis by analyzing faults and processing quality. The method consists of two main parts (figure 1): on the one hand the low frequency domain and on the other hand the high frequency domains. The signal processing is divided into two for a clear dissociation between forced vibration generated by the cutting system (unbalance, misalignment, looseness, electric faults, etc.) and defects that occur at high frequencies, such as: bearings fault, tool teeth wear, tool under loaded, etc.

Fig 1 shows a tool system monitoring which include the first step concerning signal acquisition by sensors and transducers and then signal processing and analysis. To understanding the dynamic behavior of the milling tool at high speed is performed the low frequencies analysis to identify the high level energy vibration. In the second phase the signals are processed via Fast Fourier Transform (FFT) synchronous, filtering resonance frequencies followed by Hilbert Transform (HT) and then returning to time via Inverse Fast Fourier Transform IFFT and then using SEVA method in both time and frequency domain to identify critical impact frequency of cutter teeth and bearing spindle. Also the harmonics and inter-harmonics are highlighted to find their distribution and repeatability. Finally there is identification of defects and quality of milling process [13]. The Hilbert transform $\hat{x}(t)$of a real time $x(t)$ is defined as:

$$\hat{x}(t) = H\big(x(t)\big) = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{x(\tau)}{t-\tau} d\tau \quad (1)$$

The signal $x(t)$ is the impulse response function of the Hilbert transform. The Hilbert transform in time domain is subject to the Fourier transform to obtain the demodulated frequencies after applying the band pass filter.

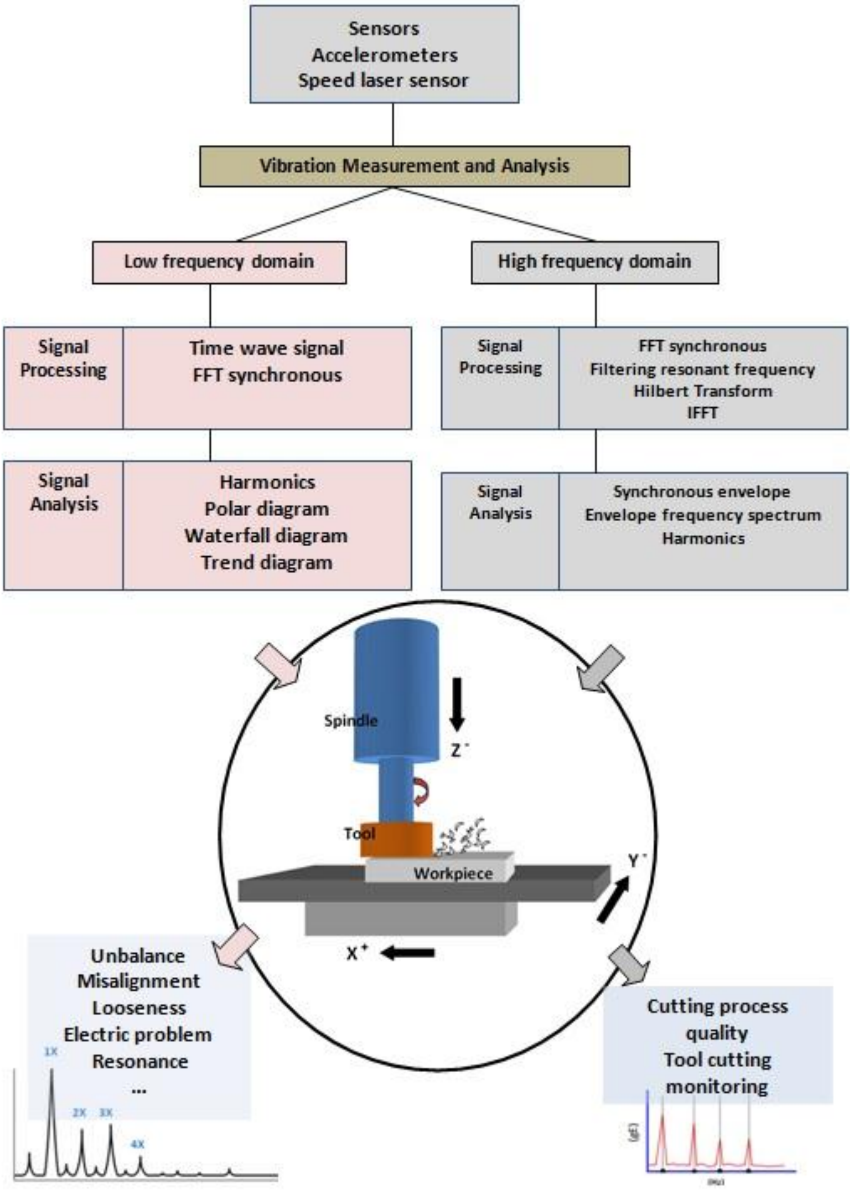

Figure 1: Research synopsis

3.2 Experimental setup

The tests have been carried out on 3-axis CNC First MCV 300 machining milling center by mounting an experimental device (figure 2) based on a National Instruments NI USB-6216 analogical/digital data acquisition board associated with Fastview software. For mechanical actions signal measurement it is used a Kistler 9257B stationary dynamometer for and for vibration measurement it was used two accelerometers, one for spindle/tool and other for workpiece. The speed was monitored using a laser speed sensor. The tool is a milling cutter with 6 teeth, type Sandvik Coromant R365-080Q27, diameter 80 mm with BT40 tool holder. The tests were performed on aluminum material with the feed movement on the X direction. The study is focused on dynamic analysis of the entire milling system spindle/tool/workpiece during the cutting parameters: cutting speed 344 m/min with 1368RPM spindle speed, the feed rate 0.1mm/tooth and depth of cut 1mm.

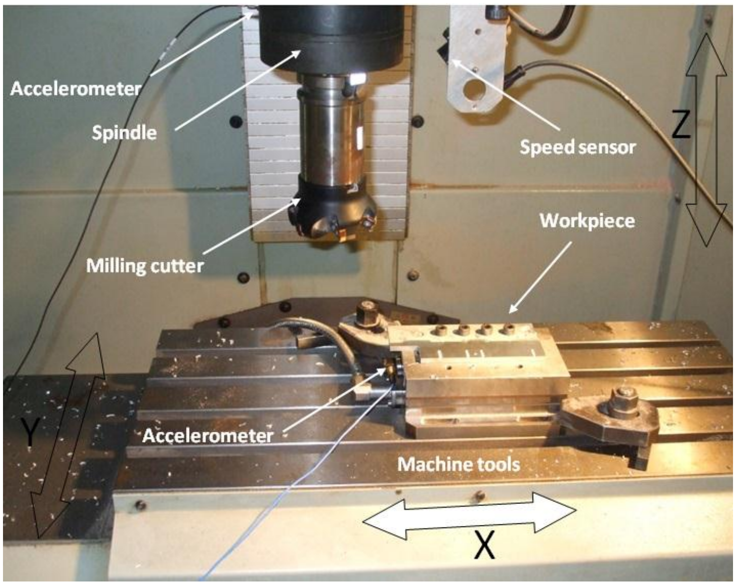

Figure 2: Experimental setup

4. Results and analysis

Knowing the dynamic behaviour of the tool in the milling process can be applied the enveloping synchronous vibration method (SEVA) to evaluate the quality of the cutting process. The aim is to give to accurately determine the energy transfer at the contact between tool and workpiece and its harmonics. The vibration signals are acquired simultaneously with speed that is necessary to obtain qualitative synchronizations. Having the acceleration signal on the three directions and knowing the frequency range of the tool, the filtering of interest frequencies by band pas filter are applied (Figure 3). Using the SEVA method the high frequencies are demodulated and the acceleration envelope ensures precision of the mill cutter to identify type and amplitude of asymmetry and wear (Figure 3).

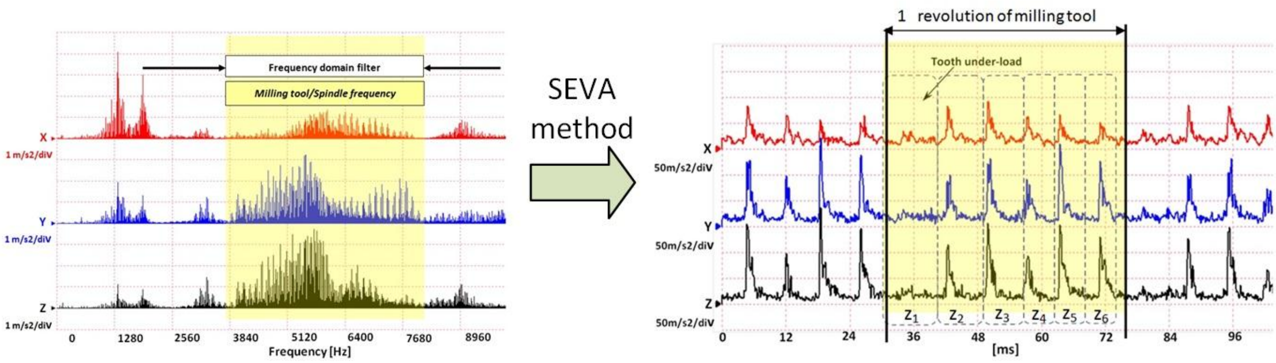

Figure 3: Envelope time signal

Each cutter tooth asymmetry is automatically qualified through the harmonic components with a lower frequency than the principal frequency equivalent teeth number. The same method can be applied in the case of forces, highlighting the quality of cut and obtained the similarly results with the vibrations [6], [13].

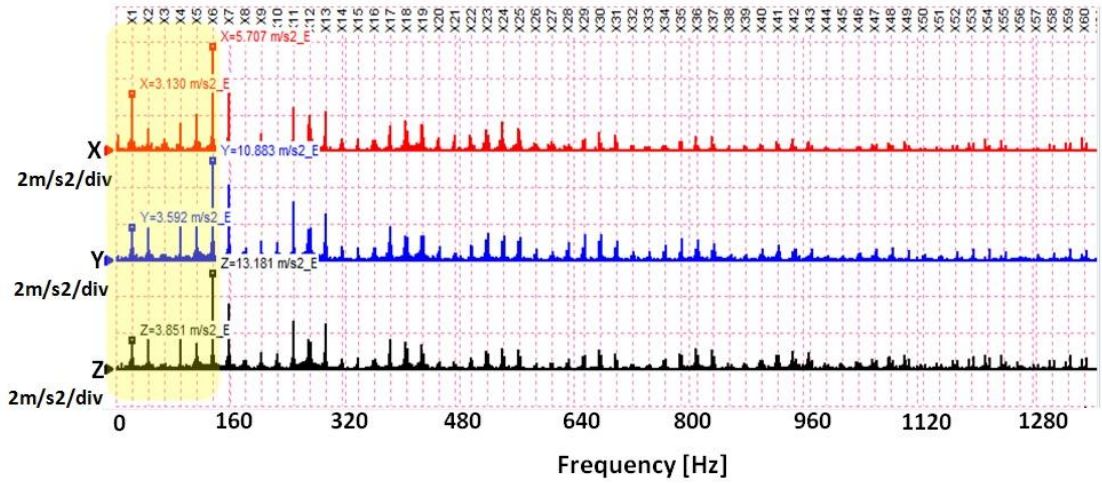

Figure 4: Envelope frequency spectrum

In figure 4 we can see the 6 order harmonics which is equivalent to the number of teeth, given by relation, f_z=*z·n/6,0* were f_z are the fundamental frequency of the milling cutter, *z* represent the number of teeth and *n* rotational speed. The asymmetry of the tool evolution during the milling process is presented by the frequency harmonics 1x which represent one tooth is under load in compared to other teeth. This situation shows the existence of an incipient degree of wear. For on-line monitoring can be entered limit level both in terms of the amplitude and frequency appearance.
Synchronous analysis of vibration envelope provides quantitative information directly related to the tools and bearings' quality and leads to automated decisions regarding the interventions means and methods [13].

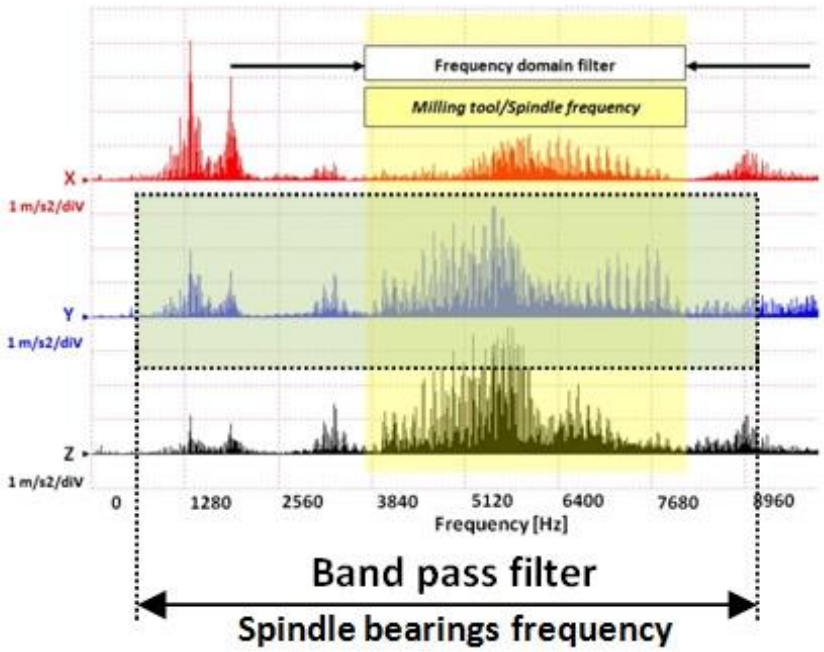

Figure 5: Band pass filter frequency for bearing status

The method presented aims to detect the status of bearings spindle. Vibration signal is the same, provided by the same accelerometer just as filtering frequencies in the band pass filter (figure 5) is processed on a different frequency range. The frequencies filter range it is based on the delta cursor method so that it can filter out the frequency range of interest. These methods provide a mobile filter compared to method based on filtering fixed band used depending on the speed [14]. When filtering band is fixed it is a risk of filtering and enveloping certain frequencies that are unrelated to bearings spindle or tool. In this situation can be electrical frequency of converter that occurs in the frequency range of 500-10000 Hz. Concerning the bearing status the unit of acceleration will be in *gE* (figure 6) considering that most levels of acceleration limit for bearing enveloping [14].

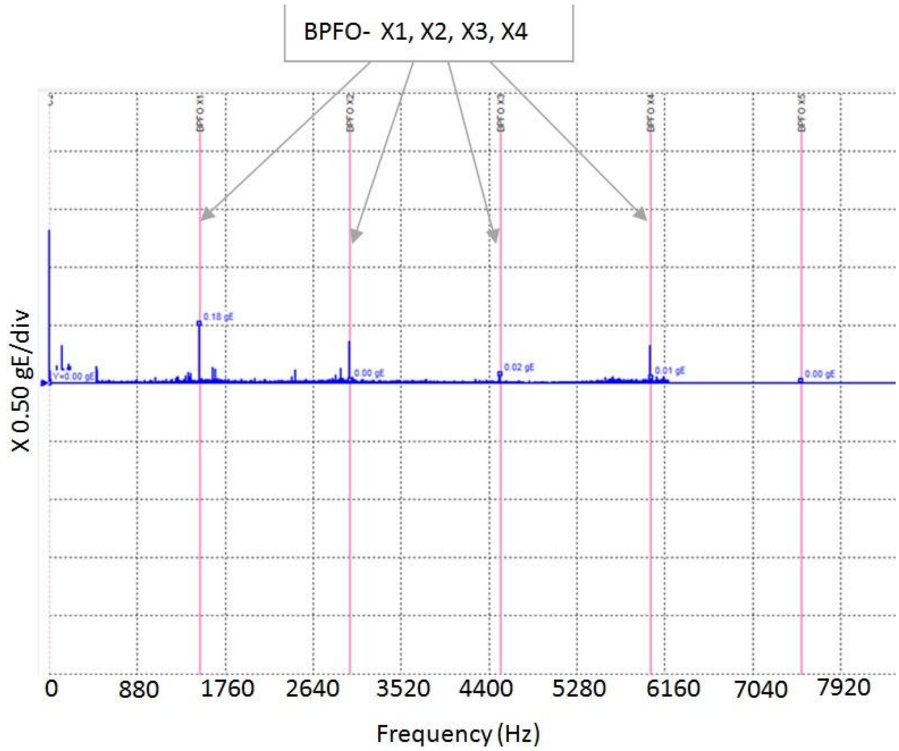

Figure 6: Enveloping acceleration spectrum

The vibration analysis for bearings defect monitoring is applied on x-direction, the direction with the lowest stiffness. Using envelope spectrum of acceleration (figure 6) can be seen the harmonic components X1, X2, X 3 and X4 equivalent with the bearing fault. With the serial number of bearing: 7014 CETNH-HCP4A-QBCA, it can be observed the identification between the defect markers for BPFO (Ball Pass Frequency Outer ring) with the harmonic envelope spectrum.
The results show efficient use of the SEVA method both for cutting process and tool analysis and for spindle bearings fault state.

5. Conclusion

Workpiece machining by removing material occupies a predominant role in getting the finished parts. Both conventional machining and especially high speed machining still has many unknowns. In the last decade due to increased productivity and cost reduction new on-line methods for monitoring have been integrated [13]**.** But problems can occur in the cutting process, related to the instability of the process and producing a poor surface finish, reducing dimensional accuracy, increasing the rate of tool wear and potentially leading to the breakage of the spindle - tool unit.

The development method is based on synchronous envelope analysis using Hilbert transform for good accuracy in amplitude and a complex algorithm of digital resembling for a high accuracy in frequency. The vibration signal incurred by the mill cutter is periodic impulsive signal in time domain and is a signal given by accelerometer transducer. The signal processing using SEVA method is used to identify mechanical faults that have on amplitude-modulating effect on the acceleration signal of a tool or spindle bearings.
The paper serves to highlight a number of elements needed for analysis and identification of the dynamic behaviour of the current machining system. For this reason an experimental protocol was

designed to implement the SEVA method for online monitoring and diagnosis. For on-line monitoring directly linked to machining the warning and danger limit level are set depending on the optimal performances of the machine tool and the parameters enveloping trend, and they are followed over time. The methodology resulted can be implemented on any machine tool, conventional or with numerical control and consists of using one or two accelerometers depend on the spindle configuration, an acquisition board and SEVA algorithm for signal processing and analysis.

Acknowledgement

This work has been funded by University Politehnica of Bucharest, through the "Excellence Research Grants" Program, UPB –EXCELLENCE–2016 Research project GEX no. 36/26.09.2016.

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