Contactless excitation and response system for analysis of high precision rotor dynamic properties

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Abstract

The spindle system is a critical part of a machine tool structure and its dynamic properties are important for the performance of the whole machining system. Currently the only way to extract the dynamic properties of a given structure is via experimental modal analysis. This approach, however, can only be employed on idle systems and is performed with the assumption that the dynamics of a system are independent of rotational speed. The latter assumption cannot be applied to spindle systems. This paper introduces a novel testing system for analysing machine tool spindles dynamic properties, consisting of real-time recursive estimation of modal and operational dynamic parameters, employed alongside a contactless excitation and response system. The presented approach allows analysing the spindle system condition and dynamic properties not only at discrete rotational speed intervals but also during continuous sweep of rotational speed.

1 Introduction

The introduction of knowledge based manufacturing in machining, where an increased understanding about material properties and structural loading and improved analysis and design techniques, have led to the development of new optimized machine tool designs [1]. Such designs in combination with high cutting feed and cutting speeds have led to machining systems often excited by high-energy sources which can create intense vibration excitation problems as, for instance, modern machine tool design results in systems with high stiffness and low mass (low inherent damping).

One of the critical parts of a machine tool structure is the spindle system which supplies the necessary power to the cutting process. The spindle is a high precision component which comprises several parts, e.g. rotor shaft, bearings and clamping system. All these components need to be in a perfect balance in order to achieve high accuracy at elevated rotational speed and by this high material removal rate under stable conditions. As in many mechanical systems, various design and performance factors, such as fits between the bearings and the shaft/housing, preload, lubrication, and rotational speed, influence both stiffness and damping. For instance, the stiffness of an angular contact bearing decreases while damping increases with increasing amplitude of vibratory force [2].

The estimation of the dynamic properties of spindles are usually time consuming and traditional analysis methods, such as experimental modal analysis (EMA) with impact hammer and accelerometers, are performed with the assumption that the dynamics of a tool-spindle system are independent of rotational speed. This assumption is however not valid for high-speed milling spindles where the effect of the gyroscopic moments and centrifugal forces must be considered [3, 4].

The aim of this paper is to introduce a contactless excitation and response system (CERS) alongside a model-based identification method for evaluating a machine tool structure and in particularly spindle unit dynamic properties. This approach allows obtaining realistic data in off-operational conditions as the analysis of the dynamic properties can be carried out while continuously changing the spindle rotational speed [1, 5].

In this study, model-based identification is used to represent machine tool and spindles under operational condition. Model-based identification, based on parametric models, can be divided into two categories: off-line or batch identification (e.g. based on autoregressive moving average ARMA models), and on-line or recursive identification. Off-line identification means that a batch of data is collected from the system and subsequently – as a separate procedure – this batch of data is used to build a model. An off-line method gives only an average behaviour and cannot give detailed information about the time variable of a system. If the model, however, is needed to evaluate and control a system during operational condition, e.g. a spindles under continuously sweep of rotational speed, it is necessary to deduce the model at the same time as new data is acquired [1]. In this study, the RPEM is used to represent a spindle system under operational condition. The model structure is represented by the recursive autoregressive moving average (RARMA) model structure [1].

2 Contactless excitation and response system

The CERS system consists of three major parts; a mechatronic excitation and response unit; an actuator and sensor control system; and specially developed rotor (Figure 1).

The excitation and response unit is an active magnetic bearing (AMB) that is usually employed as rotor support bearing. The AMB is equipped with inductive displacement sensors capable of registering the rotor displacement in both X and V directions. The excitation and response unit is clamped on the machine tool table.

The control system delivers an adjustable bias current of 0.3-1.3 A and a superpositioned excitation current (random signal). The force applied to the rotor in the X direction (analogous in the V direction) is expressed in terms of the stator coil current (measured current of top and bottom quadrant) and the instantaneous air gap. The excitation of the cutting tool is provided by electromagnets fed by random signal coil current – thereby introducing a magnetic force which acts on the rotor.

The rotor is a modified milling cutter. The modification consists of a laminated structure to reduce energy losses due to eddy current effects and to minimize the air gap between the magnets and the tool. The effective gap is 150 μm. The advantage with the modified tool is that both the magnetic excitation and response measurements as well as cutting tests can be performed with the same tool which simplifies coupling of dynamic characteristics into theory of metal cutting stability.

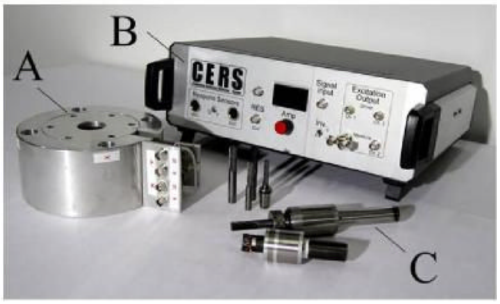

Figure 1: The contactless excitations and response system CERS: (A) actuator hardware with on-board displacement sensors; (B) actuator and sensor control system; and (C) specially developed cutting tools.

3 Testing spindle under loaded condition

In this study the dynamic behaviour of a machine tool spindle system has been evaluated employing the proposed model-based identification approach. This task has been carried out by:

1. Identification of dynamic characteristics via acoustic imaging.
2. Evaluation of frequency response function (FRF) and dynamic parameters via traditional EMA at spindle idle state.
3. CERS has been employed to excite the same system during idle state. Batch identification was used to evaluate dynamic parameters.
4. CERS has been employed to excite the same system during spindle rotation. Recursive identification was used to evaluate dynamic parameters.

The machine used in this study was a 5-axis hybrid parallel kinematics machine tool (PKM) with a 24000 rpm spindle (45 kW). The spindle rotor is supported by four 25° angular contact ball bearings (preloaded with 1.28 kN).

3.1 Acoustic imaging for identification of the dynamic characteristics of a machine tool

Acoustic imaging has historically been successfully used in finding acoustic sources [8]. In this work acoustic imaging was employed to visually and quickly identify the effect of the excitation introduced by the CERS. By using an array of microphones, in this case 48 microphones arranged in a circle with a video camera in centre, Figure 2, the direction to the source can be calculated and a representation of the acoustic pressure can be displayed on an image or a video.

The presented case study in which a machine tool spindle modal characteristics were investigated, the acoustic camera was used to visualize vibration patterns of the investigated spindle system. The changes in dynamic characteristics were evident. The figure visualizes the sound pressure in the frequency interval of 1 kHz to 1.6 kHz. As can be seen the highest level of sound pressure is identified at the spindle - tool holder connection.

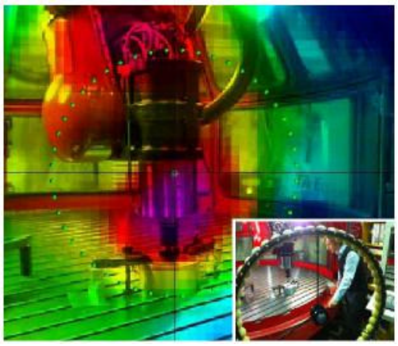

Figure 2: Image from acoustic camera. In the lower right corner of the figure the microphone array is displayed. The array is pointed directly to the spindle and CERS. The scale of the sound pressure is ranging from the dark blue (49dB) to purple (55dB).

3.2 Dynamic properties evaluation at spindle idle state

The EMA has been performed using impact hammer and five accelerometers, three placed on the tool and two on the spindle. The test has been carried out in the machine tool X and Y directions at idle state.

The CERS allows exciting the tool with a broadband force (0 to 5 kHz) of random nature. The excitation is provided by the electromagnets while the inductive displacement sensors register the tool position in the X and V directions. However, in this case the response has been measured with a tri-axial accelerometer placed on the spindle casing at the location corresponding to the front bearings. This choice was made in order to capture not only the rotor vibration mode but also those of the bearing frequencies. The dynamic behaviour at the tool tip has been estimated by employing batch identification.

The natural frequencies and damping ratio of each mode of the system identified via EMA and batch identification (called Ident in Table 1) are presented in Table 1. As can be seen, the two methods give results very close to each other.

Table 1: Summary of natural frequencies $_{fmod}$ [Hz] and respective damping ratios $_{\xi mod}$ [%] in X and V direction.

Frequency				**Damping ratio**			
EMA	Ident	EMA	Ident	EMA	Ident	EMA	Ident
$(fmod)^x j$,	$(fmod)^x j$	$(fmod)^y$j	$(fmod)^y$j	$(\xi mod)^x$ j	$(\xi mod)^x$j	$(\xi mod)^y$j	$(\xi mod)^y$j
390	400	502	512	3.3	4.2	4.6	4.6
531	502	800	800	3.2	5.1	4.2	3.6
807	820	974	970	7.1	6.1	7.0	4.7
932	1020	1240	1747	5.9	4.2	7.2	5.4
1710	1690	2280	2237	5.9	5.9	5.0	3.1
2160	2330	-	-	4.8	3.7	-	-
2315	4000	-	-	2.8	-	-	-

3.3 Dynamic properties evaluation at continuously varying spindle speed

In order to take into consideration the influence of unbalances and bearings' dynamics, the CERS was employed for excitation of the spindle while the rotational speed was swept from 0 to 18000 rpm in 67 seconds. Doing so, one could also find out if, with respect to dynamic properties, there was a range of speed resulting in lower vibratory amplitude. By applying the proposed model-based identification in a recursive scheme (the model order was p=6, q=5 determined by final prediction error method [6]) on a selected frequency band it is possible to track the evolution of the respective modal damping ratio in time.

In Figure 3 the two key observations about the damping ratio are that (1) it globally increases with the spindle speed, and (2) some locally decreasing behaviour is noticeable. The locally decreasing behaviour can be explained by the fact that the frequency of the excitation coming from sources, such as bearings and unbalances, coincides with the structural natural frequency. The global increases behaviour can partly be explained by the increase of oil injected in the ball bearings during the experiment.

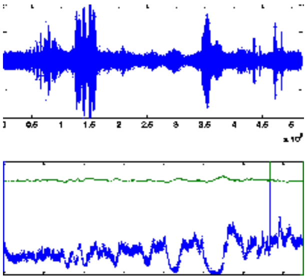

Figure 3: Damping ratio and natural frequency. Recursive identification on accelerometer signal in Y-direction

4 Conclusions and discussion

Dynamic characteristics of a machine tool system are to a large extent determined by the spindle performance. A special test system has been developed to allow contactless excitation of the spindle system. By batch identification it was possible to identify modal characteristics of the investigated machine tool spindle. The frequency and damping characteristics analysed with CERS and EMA show close results between the two methods.

The model-based identification can be used to take a discrete ‘finger’ print of the spindle system dynamic characteristics. However, as the spindle´s static and dynamic behaviour changes depending on, amongst others factors, rotational speed, the system needs to be tracked in time to get a complete picture of the system static and dynamic behaviour. This can partly be done by continuously repeating the measurement at discrete spindle speed intervals to capture data. The limitation of this approach is that transition states between different vibratory levels will not be captured as the spindle has to be stopped during data acquisition. This limitation can be overcome by using the proposed recursive identification method in combination with CERS enabling continuous sweep of spindle speed.

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