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Modal identification of spindle-tool unit in high-speed machining

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A B S T R A C T

The accurate knowledge of high-speed motorised spindle dynamic behaviour during machining is important in order to ensure the reliability of machine tools in service and the quality of machined parts. More specifically, the prediction of stable cutting regions, which is a critical requirement for high-speed milling operations, requires the accurate estimation of tool/holder/spindle set dynamic modal parameters. These estimations are generally obtained through Frequency Response Function (FRF) measurements of the non-rotating spindle. However, significant changes in modal parameters are expected to occur during operation, due to high-speed spindle rotation.

The spindle's modal variations are highlighted through an integrated finite element model of the dynamic high-speed spindle-bearing system, taking into account rotor dynamics effects. The dependency of dynamic behaviour on speed range is then investigated and determined with accuracy. The objective of the proposed paper is to validate these numerical results through an experiment-based approach. Hence, an experimental setup is elaborated to measure rotating tool vibration during the machining operation in order to determine the spindle's modal frequency variation with respect to spindle speed in an industrial environment. The identification of natural frequencies of the spindle under rotating conditions is challenging, due to the low number of sensors and the presence of many harmonics in the measured signals. In order to overcome these issues and to extract the characteristics of the system, the spindle modes are determined through a 3-step procedure. First, spindle modes are highlighted using the Frequency Domain Decomposition (FDD) technique, with a new formulation at the considered rotating speed. These extracted modes are then analysed through the value of their respective damping ratios in order to separate the harmonics component from structural spindle natural frequencies. Finally, the stochastic properties of the modes are also investigated by considering the probability density of the retained modes. Results show a good correlation between numerical and experiment-based identified frequencies. The identified spindle-tool modal properties during machining allow the numerical model to be considered as representative of the real dynamic properties of the system.

1. Introduction

High-speed machining (HSM) is a technology used to increase the productivity and reduce the production costs. Problems can arise during high-speed milling, related to the instability of the process and producing a poor surface finish,

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reducing dimensional accuracy, increasing the rate of tool wear and potentially leading to the breakage of the spindle-tool unit.

The unstable phenomena, known as chatter, have been widely studied [1–4]. Regenerative chatter is modelled as a feedback mechanism for the growth of self-excited vibrations due to variations in chip thickness, cutting force and subsequent tool vibration. These studies have led to graphic charts, commonly referred to as stability lobe diagrams, showing the stability information as a function of chip thickness and spindle speed.

The knowledge of the tool tip transfer function is of particular interest, since it represents the key variable in the determination of the stability limit [4]. The dynamic stiffness of eigenmodes gives rise to permissible depths of cut in stability limits theory and represents an important issue for machine tools. Numerous approaches have been addressed to elaborate the tool tip transfer function through modelling or experimental approaches [4,10–15]. Most of the previous models assume that spindle-tool set dynamics do not change over the full spindle speed range. This assumption needs to be reconsidered in high-speed milling, where gyroscopic moments and centrifugal forces on both bearings and the spindle shaft induce spindle speed-dependant dynamics changes.

The modelling approaches show that spindle dynamics are influenced by a large number of factors, including holder characteristics, spindle shaft geometry and drawbar force, and the stiffness and damping provided by the bearings [5–9]. Most of these factors are independent of spindle speed, contrary to bearing stiffness and damping, which change according to preload and spindle speed [8]. Nelson [9] presented a rotor-bearing formulation, based on Timoshenko beam theory, which included shear deformation. His formulation has been re-used for stability predictions or to validate experimental approaches like the contactless dynamic spindle testing equipment (CDST) of Rantatalo et al. [10]. In the previous work, a dynamic high-speed spindle-bearing system model was presented [11,12] based on the rotor dynamics predictions. Elements kinematics were formulated in a co-rotational coordinate frame and enabled a special rotor-beam element to be developed. Model results showed that dynamic effects due to high rotational speed, such as gyroscopic coupling and spin softening, have a significant influence on spindle behaviour. These results have been confirmed by Shuyun and Shufei [13]. The integration of the modelled speed-dependant spindle transfer function into stability analysis methods induces important variations in the stability prediction [11,12]. Hence, for accurate dynamics prediction, spindle speed-dependant modal parameters must be evaluated.

Alternative characterisation methods are provided by experimental approaches. On rotating spindles, it is most common to measure the vibration transmitted into a non-rotating part of the machine using a contacting transducer such as an accelerometer [14], but low vibration transmission can make this unreliable, especially for rotor vibrations. To be able to fully investigate the behaviour of a rotating system, such as a milling machine spindle, it is necessary to make measurements directly on the rotating part of the spindle, i.e. on the tool during rotation. This can be done either by electronically or optically based non-contact measurement methods such as capacitive displacement sensors [14,15], laser distance sensors or laser Doppler vibrometry [16].

Faassen et al. [17] and Schmitz et al. [15] proposed considering spindle dynamics speed dependency on the basis of experimental transfer function identification at different spindle speeds. The models developed by these authors predict a specific chatter-free depth of cut, which is governed by the transfer function of the tool tip. The chatter-free depth of cut is calculated for different spindle speeds, which are then plotted as a stability lobe chart.

Their method used impulse hammer excitation and contact-free (capacitive probe) response measurement of a rotating tool at different discrete spindle speeds. Experimental results revealed speed-dependant variations in spindle dynamics and hence in the stability limit. However, many conventional testing techniques prove unsuccessful at determining spindle behaviour during high-speed rotation.

Indeed, in an experimental modal analysis of a high-speed rotating shaft, the location of the hammer impact point and the sensor measurement point are not properly defined.

More recently, Tatar and Gren [16] have presented a milling tool vibration method using laser Doppler vibrometry. Based on Halkon's results [18], they showed how to overcome crosstalk between vibration components and speckle noise generated from the repeating revolution of the surface topography using a specific high-precision tool holder. Measurement analyses are presented without identifying modal parameters.

In the present study, experimental investigations into spindle-tool unit vibration during high-speed machining were carried out. The understanding of milling system dynamics during cutting requires the definition of a specific sensor platform associated with a robust identification procedure, and represents the object of this paper, focusing on the rotation-based dynamics variations in the transfer function. Thermal influences on spindle-tool dynamics variations were considered to be negligible. This assumption was taken into account through experimental precautions, especially when the spindle had attained its operating temperature.

In the second section, numerical investigations of spindle dynamics are performed based on a dedicated spindle rotor dynamics model. A specific rotor-beam element is developed in a co-rotational reference frame [11,12] associated with specific rolling bearing stiffness matrices, and is implemented. Model simulations enable specific rotating dynamics effects to be highlighted and demonstrate the need to take into account the rotating dynamics effects for accurate spindle dynamics predictions.

Section 3 describes the experimental setup that enables the vibrations in the rotating tool to be recorded as close to the cutters as possible. A specific measurement platform was designed to support two laser sensors and was fixed to the spindle head. This allows industrial machining operations to be monitored in an industrial environment. However,