Available online at www.sciencedirect.com
ScienceDirect
International Journal of Machine Tools & Manufacture 48 (2008) 184–194
INTERNATIONAL JOURNAL OF MACHINE TOOLS & MANUFACTURE DESIGN, RESEARCH AND APPLICATION
www.elsevier.com/locate/ijmactool

Stability-based spindle speed control during flexible workpiece high-speed milling

I. Mañé, V. Gagnol*, B.C. Bouzgarrou, P. Ray

LaMI, IFMA/UBP-Campus des Cézeaux, BP 265 63175 Aubiere Cedex, France

Received 24 May 2007; received in revised form 9 August 2007; accepted 16 August 2007
Available online 30 August 2007

Abstract

High-speed machining (HSM) is a technology used to increase productivity and reduce production costs. The prediction of stable cutting regions represents an important issue for the machining process, which may otherwise give rise to spindle, cutter and part damage. In this paper, the dynamic interaction of a spindle-tool set and a thin-walled workpiece is analysed by a finite element approach for the purpose of stability prediction.

The gyroscopic moment of the spindle rotor and the speed-dependent bearing stiffness are taken into account in the spindle-tool set finite element model and induce speed-dependent dynamic behaviour. A dedicated thin-walled workpiece is designed whose dynamic behaviour interacts with the spindle-tool set. During the machining of this flexible workpiece, chatter vibration occurs at some stages of machining, depending on the cutting conditions and also on the tool position along the machined thin wall.

By coupling the dynamic behaviour of the machine and the workpiece, respectively, dependent on the spindle speed and the relative position of both the systems, an accurate stability lobes diagram is elaborated.

Finally, the proposed approach indicates that spindle speed regulation is a necessary constraint to guarantee optimum stability during machining of thin-walled structures.

Keywords: Spindle-bearing system; Rotor-dynamics prediction; Chatter vibration; Thin-walled structure; Stability lobes; Spindle speed control

1. Introduction

High-speed machining (HSM) is widely used in the aeronautical and automotive domains and enables increased productivity and reduced production costs. These two sectors require competitive productivity, in terms of time, number of pieces and accuracy, which HSM can deliver. During workpiece machining in these sectors, large quantities of material are removed in high-removal-rate conditions, with the risk of instability in the process. This unstable phenomenon, known as chatter, is quite critical since it produces bad surface quality and may lead to spindle, cutter and part damage.

Several studies have been conducted since Taylor first identified and described chatter in 1907, for example, by Tobias and Fishwick [1], Tlusty and Polacek [2], Merritt [3] and Altintas and Budak [4]. All these authors present a fundamental understanding of regenerative chatter as a feedback mechanism for the growth of self-excited vibrations due to variations in chip thickness and cutting force and subsequent tool vibration. These studies have led to graphic charts, commonly referred to as stability lobe diagrams (SLDs) showing the stability information as a function of chip thickness and spindle speed.

Stability studies have two important research approaches. On the one hand, many authors have studied it through machine behaviour, assuming a rigid workpiece. The tool tip transfer function is elaborated through models or experimental approaches. Somehow, most of the previous models made the assumption that spindle-tool set dynamics do not change over the full spindle speed range. This assumption needs to be reconsidered in HSM, where gyroscopic moments and centrifugal forces on both bearings and

---

*Corresponding author. Tel.: +33 4 73 28 80 19; fax: +33 4 73 28 80 85.
E-mail address: vincent.gagnol@ifma.fr (V. Gagnol).

0890-6955/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijmachtools.2007.08.018

spindle shaft induce spindle speed-dependent dynamics changes. For accurate dynamics prediction, spindle speed-dependent dynamics must be evaluated.

Faassen et al. [5] and Schmitz et al. [6] proposed considering such dependencies on the basis of experimental transfer function identification at different spindle speeds. Their method uses impulse hammer excitation and contact-free (capacitive probe) response measurement of a rotating tool at different discrete spindle speeds. Experimental results revealed speed-dependent 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 is not properly defined.

Other authors have investigated the dynamic behaviour of machine tool spindle-bearing systems through modelling. They show that spindle dynamics are influenced by a large number of factors, including holder characteristics [7], spindle shaft geometry and drawbar force, [8] and the stiffness and damping provided by the bearings [9–11]. Most of these factors are independent of spindle speed, contrary to bearing stiffness and damping, which change according to preload and spindle speed. Jorgensen and Shin [9] showed that the dynamic characteristics of the spindle system vary with speed-dependent changes in bearing stiffness, affecting chatter stability. Wang and Chang [10] performed a finite element model (FEM) analysis on a two-bearing spindle using a Rayleigh beam, without taking high-speed effects into account. Results show the importance of internal bearing contact angle variation on the vibration modes. Nelson [11] presented in 1980 a rotor bearing formulation based on Timoshenko beam theory which included shear deformation. His formulation has been reused for the purpose of stability prediction [12] or to integrate thermo-mechanical considerations [13] or also to validate experimental approaches like the contactless dynamic spindle testing (CDST) equipment of Rantatalo et al. [14]. In previous works [15,16], we have presented a dynamic high-speed spindle-bearing system model based on rotor-dynamics prediction. Element kinematics is formulated in a co-rotational coordinate frame and allows 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 the spindle behaviour. By integrating the modelled speed-dependent spindle transfer function into the chatter vibration stability approach of Altintas and Budak [4], a new dynamic SLD was predicted.

On the other hand, other research has been carried out through workpiece behaviour, assuming a rigid spindle-tool set. This assumption is relevant in specific industrial applications like very thin-walled aeronautical structures or turbine blades. Workpiece vibration is strongly dominant in comparison with spindle-tool set vibration. Thevenot et al. [17] analysed stability during the machining of a thin-walled structure and proposed a 3D lobes diagram with an additional axis characterized by the tool position along the workpiece.

These approaches have recently been extended by coupling the behaviour of the workpiece and the spindle-tool set [18–20]. The dynamic interaction of spindle-tool set and the workpiece during machining is representative of numerous industrial applications. Chatter comes from both the machine and workpiece vibration due to the similar dynamic behaviour of both the systems. Bravo et al. [19] proposed considering such applications and suggested a method for obtaining a 3D stability lobe to cover all the intermediate machining stages. Le Lan et al. [20] presented a similar approach by combining the FEM representation of a flexible automotive workpiece and the spindle-tool set. Both the approaches used the milling cutting force model formulated by Altintas and are based on the restrictive assumption that spindle-tool set dynamics do not change over the full spindle speed range.

This paper describes a method for predicting the stability of a milling process when both the machine and the workpiece vibration are in interaction. The proposed approach takes into account the dynamic interaction of a rotating spindle-tool set and a flexible workpiece by combining their respective transfer functions. The effects of the rotor gyroscopic moment and speed-dependent bearing stiffness on the dynamics of the system are taken into account. A thin-walled workpiece representative of a typical industrial application is modelled by FEM to vibrate simultaneously with the spindle-tool structure. A specific SLD is then elaborated by scanning the dynamic properties of both the workpiece and the rotating spindle-tool set throughout the machining process. Then investigations are carried out to optimize the spindle speed according to industrial constraints.

Section 2 describes the modelling approach to milling interaction. The model consists of a sub-section which describes the spindle-tool set finite element rotor model and a sub-section which describes the flexible workpiece dynamics. The dynamic interaction of both the models is then presented. Results take into account the speed dependency of the spindle model and the tool-position dependency of the machined thin-walled workpiece.

Section 3 is dedicated to milling stability prediction. Chatter is dependent on the relative vibration between the two mechanical systems that are in contact during milling. The spindle model predicts that both the speed-dependent gyroscopic moment of the rotor and the speed-dependent bearing stiffness affect the stability limit in every discrete relative tool/workpiece position. A specific SLD is elaborated which reflects the respective dynamic changes that both the spindle and the workpiece system undergo during the milling process.

Finally, Section 4 presents spindle speed control in order to guarantee optimum stable condition throughout the machining of the flexible workpiece. The regulation of