Robotics and Computer-Integrated Manufacturing 30 (2014) 107–113

Contents lists available at ScienceDirect

Robotics and Computer-Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

An expert system for hydro/aero-static spindle design used in ultra precision machine tool

Yingchun Liang, Wanqun Chen *, Yazhou Sun, Nan Yu, Peng Zhang, Haitao Liu

Center for Precision Engineering, Harbin Institute of Technology, Harbin 150001, PR China

ARTICLE INFO

Article history:
Received 25 February 2013
Received in revised form
9 September 2013
Accepted 12 September 2013
Available online 22 October 2013

Keywords:
Spindle design system
Hydro/aero-static spindle
Chatter vibration
Optimization

ABSTRACT

A novel expert hydro/aero-static spindle design system strategy is presented in this paper. It is based on the comprehensive principles of machine design, machining dynamics and metal cutting mechanics. The transmission and lubrication types of the spindle are decided by a selection system, which utilize a dedicated logical choice algorithm in the light of the specifications of both workpiece material and desired cutting condition. Hydro/aero-static spindles are designed by this system from its dynamics perspective. The chatter vibration of the spindle is automatically improved by optimizing the structural parameters of the spindle. Meanwhile, the predicted Frequency Response Function (FRF) of the spindle based on the rotor dynamics is integrated to the chatter vibration stability law. Consequently, the expert design system enables the structure of machine tools to be designed efficiently with a higher precision. The proposed system was demonstrated through an aerostatic spindle design for micro-array structures machining.

1. Introduction

Spindle is the main mechanical component in machining centers. Its performance has a direct impact on the machining productivity and surface quality of the workpiece [1]. In recent years, the hydro and aero-static spindles are widely used in precision machines due to their lower wear and friction, lower noise, as well as less contamination and higher precision [2–4]. An important feature of designing this kind of spindle is the strategy for selecting the transmission and lubrication types and choosing structural parameters of the spindle [5,6]. Selecting suitable form and structural parameters of the spindle can not only meet the processing requirements excellently, but reduce the cost sharply as well.

Considerable efforts have been devoted to the spindle and the hydro/aero-static bearing design. Jahanmir et al. [7] designed an ultrahigh speed micro-machining spindle based on the rotordynamic analysis. Eskicioglu et al. [8] developed a programming language of expert systems for the selection of spindle bearing arrangement. Cheng et al. [9] presented a selection strategy for the design of externally pressurized journal bearing, the strategy concerns the selection of bearing type and configuration, the fluid feeding device and the bearing material. Maeda et al. [1] designed an expert spindle design system for rolling bearing spindle design. In their research, the spindle drive mechanism, drive motor, bearing types, and spindle shaft dimensions were selected based on the target applications. The structural dynamics of the spindle were automatically optimized by distributing the bearings along the spindle shaft. But little attention has been paid on the hydro/aero-static spindle design systematically from the transmission and lubrication types selection to the dynamic performances prediction and structural parameters optimization. Therefore, this paper will be focused on developing a systematic and practical expert system for hydro/aero-static spindle design, which can guide to develop the hydro/aerostatic spindle in a scientific manner from the dynamics point of view [10].

The overall expert spindle design system is outlined in Fig. 1. The design system of the hydro/aero-static spindle with transmission, lubrication types selection and bearing structure optimization are automated in accordance with the requirements of machining application, expert spindle design rules, cutting mechanics, rotor dynamics and chatter stability of milling process. According to the cutting parameters such as tool geometry, workpiece material, cutting speed, depth of cut and width of cut, the transmission and lubrication types are selected by the logical selection system preferentially. Then, the structural parameters of the spindle are optimized by an optimization system in which the finite element theory and hydrostatic principle are integrated. Furthermore, considering the high rotation speed of a working spindle, rotor dynamics which contains the whirl effect are used to calculate the critical speed and the FRF, and the chatter stability is predicted by both the FRF and the cutting parameters. The expert

* Corresponding author. Tel.: +86 451 86413840; fax: +86 451 86415244.
E-mail address: chwq@hit.edu.cn (W. Chen).

0736-5845/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rcim.2013.09.006

system has been applied to design an aerostatic spindle, which proves the feasibility and practicality of the design system.

2. Expert system for hydro/aero-static spindle design

The expert system for hydro/aero-static spindle design is introduced to facilitate the design process based on the experience and the simulation algorithm. The application flowchart of this system is illustrated in Fig. 2. To begin with, the required input cutting parameters for the hydro/aero-static spindle design are entered into the inference system. Next, the inference system will compute the design requirements using the laws of cutting mechanics. Then, the design requirements are input to a logical choice system, which is established by hydro/aero-static spindle design experts according to the current level of technology.

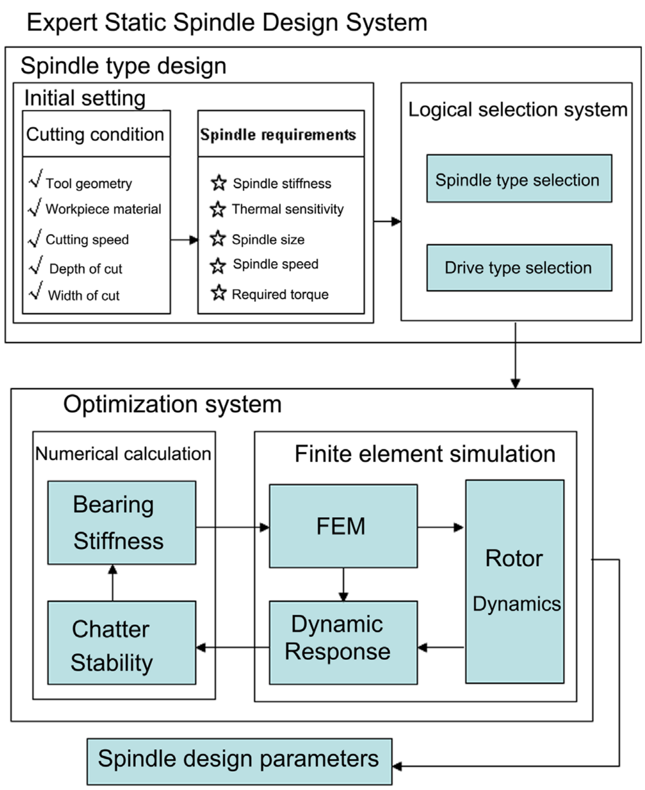

Fig. 1. Scheme of expert spindle design system.

The supervising engineer, who is permitted to maintain this logical choice system, can modify the judgment basis as the technology evolves. In this article, the transmission and lubrication types are determined using the expert system with logic algorithm first. Then, the shaft and bearing structure parameters will be optimized by the optimization system, from the interface of which results are output.

2.1. *Transmission and lubrication types selection system*

Torque has to be transmitted from the motor to the spindle shaft. There are mainly two design configurations in the precision spindle: air turbined and motorized. The transmission type is determined by the torque and rotation speed. The required input data, such as the cutting torque and rotation speed, are computed using laws of cutting mechanics as shown in Fig. 3, and are entered to the transmission and lubrication type's logical selection system.

Assuming that the maximum speed of the motor-driven spindle is 100,000 rpm and the maximum torque of the turbine-driven spindle is 50 cNm in the current level of science and technology. The process of transmission and lubrication types selection system based on the logical choice algorithm can be described as follows: if the maximum speed $(n_{max}) \geq 100{,}000$ rpm and maximum torque $(T_{max}) \geq 50$ cNm, then it cannot meet the requirements according to the current technology level, so *No Available* is output. If the $n_{max} \geq 100{,}000$ rpm and maximum torque $(T_{max}) \leq 50$ cNm, Then *Aerostatic Spindle With Turbine Driven* will be output. If the $n_{max} \leq 100{,}000$ rpm, both hydrostatic and aerostatic spindle with turbine or motorized driven may meet the requirements. The designer has to make sure which type of bearing is suitable and whether the choice of hydrostatic or aerostatic bearing is appropriate for the particular application. In order to select a more suitable form, a comprehensive judgment is adopted according to the characteristics of hydrostatic and aerostatic spindle as shown in Fig. 4.

2.2. *Simplified rating system for spindle type selection*

2.2.1. *The characteristics of hydrostatic and aerostatic spindle*

The further selection of the bearing type is based on the bearing operation requirements. In summary, the main factors affecting the choice of hydrostatic spindle and aerostatic spindle is listed as follows:

- load capacity;
- stiffness;

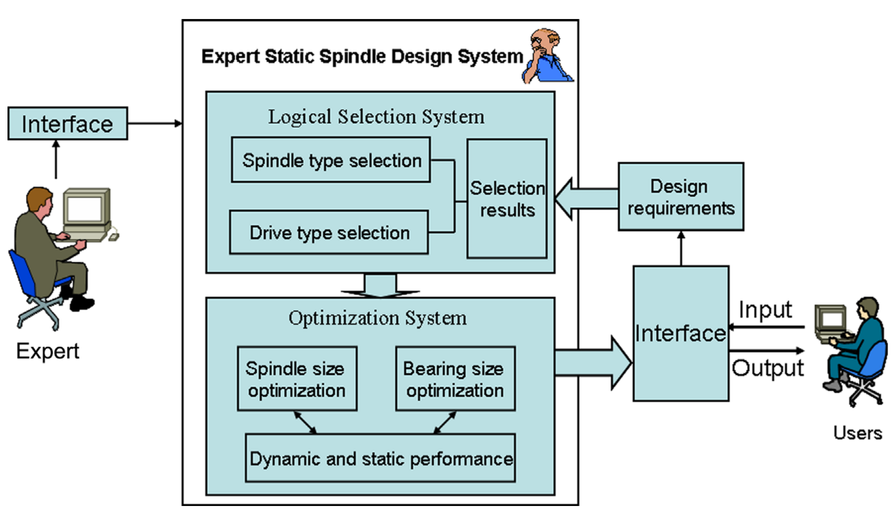

Fig. 2. Internal structure of expert system for hydro/aero-static spindle design.