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Ontology-based human–machine integrated design method for ultra-precision grinding machine spindle

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ABSTRACT

This paper proposes an ontology-based design method which integrates human's knowledge and experience with computer's inference and computational capabilities for the spindle of ultra-precision grinding machine. A complete design framework is initiated based on a unify ontology base, which is built to integrate human's experience with computer's database. The spindle's bearing and drive type are automatically selected by defining the experience-based fuzzy inference rules, and applying the similarity-based instance search method. After the geometric model and finite element model are conducted, the static, dynamic and thermodynamic behaviors of the spindle are optimized. Consequently, the design indices of the spindle of an ultra-precision grinding machine have been satisfied successfully.

1. Introduction

Ultra-precision spindle is the core component of large ultra-precision machine tools, and its performance directly affects the production efficiency of the machine and the surface quality of the workpiece. With the increasingly fierce competition in the market, the precision and efficiency of the machine tools are growing continually, imposing more and more harsh requirements on the spindle's performance, especially for the spindles serving optical mirror manufacturing, where a high speed, a high stiffness, a high accuracy and a large required torque need to be guaranteed simultaneously. It is quite difficult to accomplish this task purely depending on either human's experience or computer's analyses, due to the long design lead time, the high cost and the big risk. Therefore, it has become an urgent problem of how to integrate designers' knowledge and experience with computer's powerful computation and deduction ability, so that the advantages of the both can be utilized to enhance the efficiency as well as the success rate of designing ultra-precision spindles.

Spindles can be classified into different types according to the bearing mechanism (e.g., rolling, hydrostatic, aerostatic, etc.) or transmission mode (gear, belt-pulley, direct-coupling, motorized, etc.). Up to present, extensive studies have been conducted on the design and optimization methods of various types of spindles, mainly focusing on the structure design of bearing and drive mechanism, and thermodynamic optimization. Cao and Altintas [1] simulated the concentric and eccentric forces of a ball bearing with nonlinear finite element method, and established a dynamical model of the spindle, based on which the natural frequency, bearing stiffness and deformation of the spindle system were obtained. The design of hydrostatic bearing mainly focuses on journal bearing [2], thrust bearing [3] and restrictor [4]. Several computer-aided design tools have also been developed to relieve the designers of the tedious computation burden and to improve design efficiency. Cavdar [5] designed a computer software system integrating multi-objective optimization algorithm, which automated the design process from requirement definition to parameter selection of the journal hydrostatic bearing. Cheng and Rowe [6] also presented a design strategy for hydrostatic bearing design to automate the parameter selection process, including bearing type, configuration, material, etc. Liang et al. [7] proposed an expert system for hydrostatic bearing design, and divided the total design process into logical selection and optimization, thus enhancing the design efficiency. However, a systematic design method for ultra-precision spindle covering the whole process from customers' requirements to structure parameters is far from complete. More importantly, the existent computer-aided design tools have not effectively introduce designers' knowledge and experience into the design process, especially for the most uncertain conceptual design phase. Thus, there is still a large room for the design efficiency to be improved.

In order to integrate designers' experience into computer-aided design, first a unified and unambiguous knowledge representation and management method needs to be established. Designers' experience is highly personalized, fuzzy, and hard to be put into

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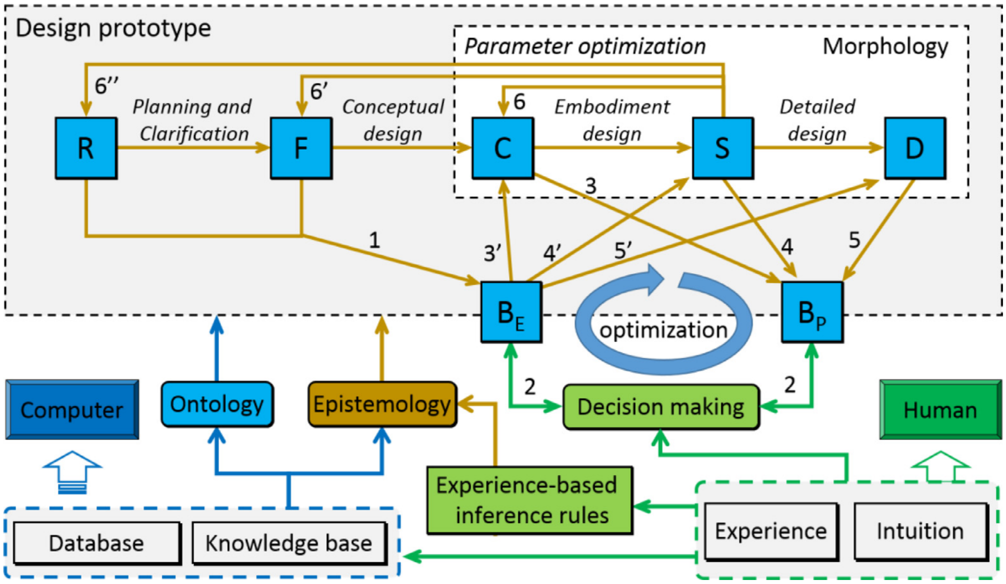

Fig. 1. Ontology-based human–machine integrated design framework.

formulas. Moreover, the descriptions of the same knowledge from various designers may take different forms of language and vocabulary, resulting in ambiguity and polysemy during knowledge representation. As a representation form with unambiguous semantics, ontology can eliminate the semantic contradictions among different knowledge representation forms, thus helping to build a unified knowledge base [8]. Originating from the philosophical concept of "Ontology", ontology here is defined as a specific, formalized and standard description for sharing conceptual models. Domain knowledge with specific semantics [9–11] can be constructed by defining a set of concepts and their semantic relationships. The key feature of ontology is its reusability and consistence, based on which the relations among different domain knowledge can be established via semantic relationships.

The motivation of this paper is to propose an ontology-based human–machine integrated design method for the spindle of ultra-precision grinding machines, aiming at fully integrates human's knowledge and experience with computer's powerful inference and computation capabilities. First, the human–machine integrated design framework was presented, with a well-structured ontological knowledge base, which is composed of function, behavior and morphology. Second, in order to realize the automated inference ability of computers in selecting the bearings and drive types of spindles, the experience-based fuzzy inference rules and similarity-based instance search method are developed. Third, the static, dynamic and thermodynamic behaviors of the spindle are optimized after the geometric model and finite element model are conducted. Finally, the design indices of the spindle of an ultra-precision grinding machine have been satisfied successfully.

2. Ontology-based human–machine integrated design methodology

2.1. Human–machine integrated design framework

The design of ultra-precision spindle is not only a process from customer requirement analysis to the specification of structural parameters of all the parts, but also a cognition process of the interaction among interdisciplinary knowledge. By combining the advantages of Pahl and Beitz's traditional design framework [12] and Gero's FBS design prototype [9], a human–machine integrated design framework is proposed, as shown in Fig. 1.

Originating from requirement (R), four results defined as function (F), configuration (C), structure (S) and details (D) are generated by planning and clarification, conceptual design, embodiment design and detailed design respectively. Parameter optimization happens at the kinematic (procedures 3, 2 and 3′), dynamic (procedures 4, 2 and 4′) and geometry (procedures 5, 2 and 5′) levels, when the physical behavior (Bp) is unqualified with the expected behavior (Be) after comparison (procedure 2). Wherein, physical behavior is derived from the generated configuration (procedure 3), structure (procedure 4) and details (procedure 5), meanwhile expected behavior is deducted from the requirement and function by the computer (procedure 1). Different levels of reconfiguration happen when local optimization cannot satisfy the design goal (procedures 6, 6′ and 6′′). Ontological modeling builds a well-organized architecture of domain knowledge for design, and provides a normative logical foundation for automatic epistemological deduction by computer. Human experience and knowledge are participated when qualitative information and uncertainties are involved, especially in conceptual design and decision-making during parameter optimization. Three core stages, including planning and clarification, conceptual design and parameter optimization, which determine the effectiveness of the design, are described as follows.

2.1.1. Planning and clarification

This process refers to the conversion from requirements to functions. The design requirements are usually determined by the operating conditions defined by the customers. It is essential to set up a requirement list acting as a guideline during design and a standard for evaluation. Furthermore, requirement is described as the spindle's function and behavior, which act as the direct principle for the design. The joint discussion of designers and customers is necessary for the requirement definition process, because clearly defined requirements would effectively suppress the uncertainties during subsequent design, thus raising the design efficiency and success rate. For grinding machine spindle, the operating conditions involved in the design include workpiece material, grinding feed speed, cutting depth, grinding force, installation form, etc. The design requirements of the spindle include rotating speed, stiffness, torque, damping, weight, cost, etc. This process will not be detailed discussed in this paper, as it is relative simple and formal in spindle design.