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Ultrasonic measurement of contact stiffness and pressure distribution on spindle–holder taper interfaces

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ABSTRACT

The measurement of contact characteristics of the spindle–holder taper interface is critical for the evaluation of the performance of a machine tool spindle system. In this study, an ultrasonic method was proposed to measure the contact stiffness and pressure distribution on the taper interface. The taper interface was scanned by an ultrasound transducer, and the nominal contact area was directly estimated from the resulting ultrasonic reflection coefficient. The normal stiffness distribution was determined by the spring-damper model from the reflection coefficient. On this basis, the distributed and global radial stiffness of the taper interface was calculated by the presented theoretical formulas. Meanwhile, a calibration curve was established to convert the ultrasonic reflection to contact pressure. Based on the proposed ultrasonic method, the effects of angle fitting error and clamping force were studied. The results show that the contact area, contact pressure and contact stiffness increase with the clamping force. As the angle fitting error increases, the contact area decreases, while the pressure and stiffness at the big end of the taper interface become much larger than these at the small end. In the meantime, the global radial stiffness increases first and then decreases. This result suggests that a larger angle fit error within the permissible range is better for the global radial stiffness. Moreover, the measured results confirm that a taper joint with an angle fit error larger than +36" is not suitable for practical application, because the contact pressure at the small end is too small. To compare with the ultrasonic method, the geometrical shape profiles of the contact surfaces were constructed, and FE models were also established for contact pressure predictions. The comparison shows that the ultrasound results are consistent with the surface shape profiles and the numerical predictions. Besides, one of the taper interfaces was measured three times with the same clamping force, and the results indicate that the repeatability of the proposed method is good.

1. Introduction

The tool holder of a spindle is indispensable in machine tools. The contact characteristics of the spindle–holder taper interface play a significant role in the performance of the spindle system [1]. The spindle–holder interface can account for 25–50% of the total deformation at the tool tip [2]. Furthermore, the contact stiffness of the taper interface has a significant effect on the dynamic behavior and chatter stability of the spindle systems [3]. On the other hand, the stress distribution on the taper interface also seriously affects the life of the holder and other contact characteristics of the taper interface [1]. Therefore, as machine tools are required to reach increasing high-performance machining [4,5], it is very important to measure the contact characteristics of the spindle–holder interface for the evaluation of the machining performance.

For decades, both finite element (FE) and experimental methods have been employed to investigate machine tool spindle–holder interfaces. Shamine and Shin [2] carried out an FE model of a spindle-toolholder interface to show the resulting stress distribution due to clamping force. Recently, Xu et al. [1] established an FE model to predict the stress distribution of the interface under different clamping and centrifugal forces. In addition, numerical identification of contact stiffness was also attempted. Schmitz et al. [6] presented an FE model to determine contact stiffness and damping. Similarly, Faraji Ghanati and Madoliat [7] also defined the interface stiffness and damping along the spindle–holder interface length by FE method. However, it is very hard for FE methods to consider the manufacturing errors and surface roughness of spindle–holder interface. Hence, the prediction accuracy of contact characteristics was inevitably questionable [8].

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Therefore, considerable efforts have been devoted to the experimental measurement of contact parameters.

Over the past decades, parameter identification by impact test has been widely used to obtain contact stiffness on taper interfaces. Kim et al. [9] modeled the taper joint as two linear lumped spring and damper elements, and proposed a modal parameter based method for joint parameter identification. With the similar taper joint model, Wang and Horng [10] identified the interface stiffness from the measured frequency response functions (FRFs). Agapiou [11] modeled the spindle–holder taper interface as a linear spring together with a rotational spring, and the parameters were determined by matching the experiment data to the FEM results. Xu et al. [12] modeled the taper interface as two pairs of radial spring and one axial spring, and proposed a rigid-body dynamics model for the identification of contact parameters. Özşahin et al. [13] presented closed-form expressions for the identification of dynamical contact parameters in spindle–holder–tool assemblies. In general, the above identification methods modeled the joint interface as lumped elements distributed only at the two ends or the center of the taper. However, since the contact between the holder and spindle has a considerable length, and variation in the interface stiffness is significant, so it is better to model the contact stiffness as distributed springs along the joint [7,14]. Hence, Namazi et al. [8] modeled the taper interface as uniformly distributed translational and rotational springs at the contact zone. On this basis, Ahmadian and Nourmohammadi [14] added damping coefficients to the above stiffness model to consider damping effect. Nevertheless, since the normal pressure on the taper interface is varying along the joints, the corresponding stiffness is actually not uniformly distributed. On the other hand, both of the above two approaches identified the contact parameters by minimizing the deviation between the predicted and measured FRFs. However, acquiring accurate modal data or FRFs requires tremendous efforts [15]. Furthermore, any errors in the modeling or measurement of the spindle–holder assembly will be compensated by the extracted inaccurate or incorrect interface parameters [3,16,17].

Static stiffness was also measured by applying a load at the tip of the holder or a simulated tool, and measuring the corresponding deformation [1,18,19]. Xu et al. [1] measured the axial and radial stiffness with different clamping forces using a home-made platform. Aoyama and Inasaki [19] designed an experimental equipment to measure the radial stiffness of a taper interface during high speed rotation. However, the measured stiffness is still lumped element. Furthermore, the measured radial deformation unavoidably contains a component caused by axial deformation [1]. Hence, the resulting radial stiffness is only an approximate value. From the literature reviewed above, it can be concluded that distributed stiffness of the spindle–holder interface has not been measured satisfactorily. Unlike contact stiffness, there are few reports about the measurement of contact pressure distribution on taper joint interface, due to the limitation of installment space for sensors like pressure sensitive film.

Since the measurements of contact characteristics is important for many engineering interfaces, electricity, heat, light and ultrasound have all been used for these measurements [20,21]. However, the methods based on electricity and heat require substantial modification to the component and are only useful for real contact area estimation [20,21]. The optical methods for contact area and pressure measurements require the component to be transparent [22,23]. Moreover, the optical method for contact stiffness measurement requires high-resolution digital images of a free surface orthogonal to the interface and is only suitable for flat contact surfaces [24]. Hence, the measurement methods based on electricity, heat, light cannot be used for spindle–holder interfaces. However, the ultrasonic method does not suffer from the above disadvantages. Ultrasound is partly reflected from a contact interface, and the ratio of reflected wave amplitude to incident wave amplitude (namely reflection coefficient) can be used for the contact condition estimation like contact area, contact pressure and contact stiffness [20,25–36]. Ultrasonic technique is a non-invasive method and has been used to investigate many practical contact situations, such as wheel–rail interaction, bolted joints and interference fits [20,26–32]. Nevertheless, the ultrasonic technique has not been applied to the spindle–holder interfaces due to its complex geometry.

With the above theoretical and experimental methods for the spindle–holder interface, the effects of clamping force on the contact characteristics of taper interface have been extensively studied [1,2,7–12,18]. In contrast, few researches focused on the angle fitting error of taper joint, although it has an important influence. Based on dynamic parameter identification, Wang and Horng [10] investigated the effects of both axial clamping force and angle fitting error on the dynamic parameters of taper joints. Their results show that the stiffness at the small end of the taper joints is generally much larger than that at the big end. However, the difference between the small and big ends is not consistent with the previous theoretical result in reference [7] or experimental result in reference [9]. Therefore, more detailed investigations on the effect of taper angle errors are necessary.

This paper aims to propose an ultrasonic method to measure the contact stiffness and pressure distribution on the spindle–holder interfaces. This ultrasonic method consists of reflection coefficient measurement of taper interfaces, theoretical formulas to calculate the distributed and global stiffness from the reflection coefficient, and a calibration experiment to establish the relationship between ultrasonic reflection and contact pressure. On this basis, the effects of both taper angle error and clamping force on the contact parameters are investigated. Since 7/24 tapered holders are wildly used in common machining processes, BT 40 type taper interfaces were investigated in this study. The proposed method enables the modeling and analysis of spindle system to introduce contact parameters in more details, and has the potential to be used in wear diagnosis of taper interface. The investigation about the effects of the taper angle error and clamping force is helpful for the design and manufacturing of spindle and holder.

The remainder of this paper is organized as follows. The theoretical foundation of the ultrasonic method is briefly introduced in Section 2. Section 3 provides the experiment procedure and instruments for the ultrasonic measurement of taper interface. The measurement results are presented and discussed in Section 4. The paper is concluded in Section 5.

2. Theoretical foundation of ultrasonic measurement

When an ultrasound wave is normally incident to a perfectly bonded interface, the ultrasonic reflection coefficient depends on the acoustic impedance of the materials, as shown in Eq. (1) [33]

$$R_{12} = \frac{z_2 - z_1}{z_2 + z_1} \tag{1}$$

where z is the acoustic impedance and the subscripts refer to the materials on either side of the interface. Hence, for a perfectly bonded steel/steel interface ($z_1 = z_2$), the reflection coefficient is 0, as shown in Fig. 1a. On the other hand, for an air/metal interface ($z_1 \ll z_2$), virtually all the incident wave will reflect at this interface, and the reflection coefficient is 1. Therefore, ultrasonic reflection from an interface could be used for the measurement of nominal contact area.