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Surface contact stress-based nonlinear virtual material method for dynamic analysis of bolted joint of machine tool

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ABSTRACT

The components of machine tools are mainly fixed and connected by bolts. The performance of the assembly can be affected by the dynamic characteristics of the bolted joints. This paper presents a nonlinear virtual material method based on surface contact stress to describe the bolted joint for accurate dynamic performance analysis of the bolted assembly. Fractal geometry theory is used to describe the surface topography. The elastic modulus and shear modulus of one micro-contact are derived based on fractal contact theory. The equivalent elastic modulus, Poisson ratio, and density of the bolted joint can be obtained through the weighted mean method. In order to obtain the stress distribution, the contact surface is assumed flat in the macro-scale, and the uneven distribution of contact stress can be obtained by the finite element method (FEM). The contact surface can be divided into several sections, and the parameters of a virtual material layer can be determined based on the mean contact stress. Both theoretical and experimental results for a bolted joint are obtained for a box-shaped specimen under equal pre-tightening force and bending moment effect. The results show that the theoretical mode shapes are in good agreement with the experimental mode shapes. The relative errors between the theoretical and experimental natural frequencies are less than 4.41%, which indicates that the present nonlinear virtual material method is appropriate for the bolted joint in modeling CNC machine tools.

1. Introduction

Machine tools are composed of many substructures connected together by joints such as bolts, rivets, glue, and welds. Among joints, the bolted joint is mainly employed for the fixed connection of parts due to ease of repair and replacement of parts. Characteristics of the joints can affect the dynamic behavior of the machine tool, and most vibration energy loss occurs in the joint between two contact surfaces. Previous research shows that up to 90% of the system damping is provided by the joints, and 50% of the system stiffness comes from the joints [1]. For the last few decades, numerical techniques such as finite element method (FEM) have been widely used in the analysis of structure dynamics, and the mechanical characteristics of structure can be well predicted. However, the contact mechanism of bolted joints is still a challenging problem. Inaccurate modeling of bolted joints may lead to unacceptable error during analysis of the machine tool assembly. Therefore, it is necessary to study the contact mechanism and build an accurate model of bolted joints to predict the dynamic behavior of the machine tool.

Several research groups have studied the dynamics of bolted joints. One of the most widely studied methods is the identification technique, which uses stiffness and damping elements to describe the bolted joint. The primary goal of joint identification is to obtain the dynamic characteristics of the joint by analytically or numerically minimizing the discrepancy between the measured frequency response function (FRF) and the predicted FRF of an assembled structure. Tlusty [2] and Inamura [3] first reported the identification techniques to obtain the dynamic parameters of machine tools. Wang and Liou [4] identified the parameters of a structural joint directly from the noise-contaminated FRF. To reduce the effect of measurement noise or error of the FRF, a transition matrix was introduced to minimize the number of inverse operations. Ren [5] used the least square method to improve the accuracy of identified dynamic parameters for linear joints. Yuan [6] presented a unique methodology to identify the joint structural parameters of the machine tool by combining the dynamic data system (DDS) methodology with the FEM. Huang [7,8] defined the normal stiffness and damping in the unit area. Fu [9] presented an experimental investigation on the normal dynamic

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characteristics of several machined joint surfaces. Dwyer–Joyce [10,11] used ultrasonic reflection coefficient measurements to investigate the stiffness distribution of the interface for large, dry-contacting assemblies of graphite blocks under various loading conditions. Shi [12,13] conducted an experimental method based on contact resonance developed to extract the contact parameters of realistic rough surfaces under lightly loaded conditions. The parameter identification method can determine the stiffness and damping of bolted joints. However, it is difficult to describe the relationship between the dynamic performance of bolted joints and the preload, surface roughness, and material characteristics. It is difficult to apply the identified results to analyze the dynamic performance of other assemblies because the contact surface size, assembly, and machining requirements are different in most cases.

Unlike the parameter identification method, fractal contact theory can describe the micro-scale contact mechanism of surfaces. The contact stiffness and damping model of rough surfaces can be obtained based on the surface topography description and elastic–plastic deformation of contact asperities. The Greenwood and Williamson (GW) model [14] applied a contact solution for curved elastic bodies, known as the Hertzian solution to a population of asperities following a given statistical height distribution. Various extensions of the GW contact model have been developed to incorporate affects of adhesion and plastic deformation [15–19]. In order to further refine the statistical model, the effects of elastic–plastic deformation have been included by numerous researchers. Jackson and Green (JG) [20] ensured that the perfectly elastic deformation is limited to a lower load for the statistical model. With some simplifying assumptions, Archard [21] analyzed scaling effect for the elastic contact between a rough sphere and a smooth rigid flat surface. Ciavarella et al. [22] employed a similar approach but modeled the surface structure between the scales as being fractal and used a two-dimensional elastic sinusoidal model. Majumdar and Bhushan [23] developed a fractal based description of surface contact and used the asperity wavelength and amplitude to provide the radius of curvature of the deformed asperity. Jiang et al. [24] studied the contact between rough surfaces of machined plane joints under different normal loads, and concluded that the relationship between the stiffness and pressure approximately follows a power law. Other fractal-based models have also been developed by many researchers [25–31].

Compared to the stiffness and damping model of the bolted joint, the virtual material model [32] has the advantage of integrating easily with the finite element analysis software. This method may be applied conveniently to the FEM model of the assembly. An isotropic virtual material hypothesis-based analytical dynamical modeling method for immovable joint surface in machine tools was proposed by Tian [32]. The micro-contact section of two contact planes in an immovable joint surface was considered as a virtual isotropic material which was rigidly linked with two components situated on both sides of the immovable joint surface. Huang [33] adopted the virtual material method to simulate the bolt preload in modal analysis and verified the efficiency of the virtual material method for the bolted joint. Based on the structural form of the mutual contact layer of joint interfaces, Jia [34] proposed a method of modeling fixed joints based on virtual materials, in which the characteristic parameters of virtual materials were obtained by the principle of equivalence for the contact stiffness matrix of joints unit. The relationship between the stiffness of a virtual material and load or pressure can be obtained for the bolted joint, as depicted in Refs. [32–34]. However, the contact pressure was computed the ratio of the load and nominal area without consideration for uneven pressure distribution. The contact pressure can be thought of as the even pressure distribution for the case of the smaller contact area. Nevertheless, it does not correspond well with the case of a larger contact area and sparse distribution of bolts.

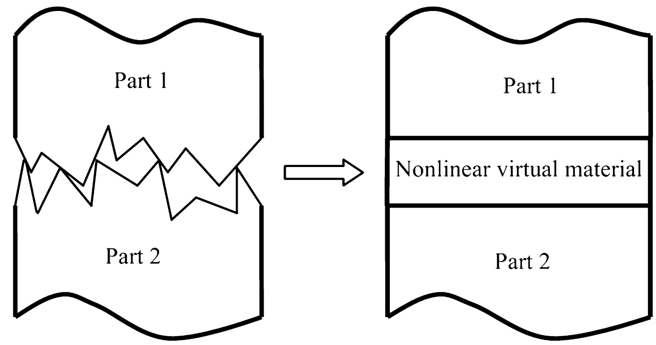

Fig. 1. Schematic diagram of nonlinear virtual material for bolted joint.

The main objective of this study is to model the bolted joint using a contact surface with unevenly distributed pressure, in which the surface contact stress-based nonlinear virtual material method is presented to obtain the dynamic characteristic of bolted joint. First, it is assumed that the contact surface of the bolted joint is flat in macro-scale, and its contact stress can be obtained by adopting the FEM. The contact surface is divided into different sections according to the distribution of the contact stress, and the local surface mean contact stress is introduced to describe the contact status of the bolted joint. Next, the equivalent elastic modulus, the Poisson ratio, and the density of the virtual material are determined according to the local surface mean contact stress. The relationship between the contact stress and the parameters of the nonlinear virtual material can be indirectly obtained by introducing the truncated area of the largest elastic micro-contact a'_L. The finite element model of the assembly with a bolted joint is created by assigning the parameters of the nonlinear virtual material according to the mean contact stress for different regions of the surface. Finally, the theoretical and experimental results, including mode shape and native frequency, are compared.

2. Nonlinear virtual material for bolted joint

The bolted assembly is composed of two parts and a flexible bolted joint where the flexible bolted joint can be replaced by a user-defined nonlinear virtual material which is rigidly connected with these two parts, as shown in Fig. 1. The contact pressure is assumed to be evenly distributed locally but unevenly distributed across the whole contact surface because of the effect of concentrated forces provided by the multi-bolts. The mean contact stress of surface for a local area is used as a variable to describe the surface contact status.

2.1. Elastic modulus, Poisson ratio and density of nonlinear virtual material

Fractal geometry theory uses scale-invariant parameters which can effectively describe surfaces of multi-scale roughness. Previous studies [22] have shown that surface roughness can be simulated by the Weierstrass–Mandelbrot (W–M) fractal function. When two rough surfaces are brought into contact, the asperities from one solid are squeezed against asperities from another solid, which make the asperities deform elastically or plastically. Two rough surfaces in contact can be represented by a surface of equivalent roughness with a reduced elastic modulus $E^* = \left(\left(1-\nu_1^2\right)/E_1 + \left(1-\nu_2^2\right)/E_2\right)^{-1}$, where ν_1, ν_2, E_1, E_2 are the Poisson ratios and elastic moduli of two surfaces, respectively, and a rigid flat surface. For one micro-contact, the equivalent radius