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Virtual material parameter acquisition based on the basic characteristics of the bolt joint interfaces

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ABSTRACT

This work presents a joint modeling method. By adding a material of different set element, the complex elements consisting of joint are regarded equivalent to he element set without joint. Considering the influence of the different characteristics of joint surface, the parameters of virtual material can be derived by using the principle that the basic characteristic parameters of the joints equal the material strain energy. Then, when the virtual material parameters are imported into the finite element analysis software, an analytical model including joints can be obtained. The results show that the virtual material model can provide a theoretical basis for the accurate joint modeling.

1. Introduction

Mechanical joints are an important connection type used in machines as structural components to connect two or more adjacent mechanical parts [1]. A typical mechanical joint includes the adjacent mechanical joint elements and the surface contacting each other. The surface layer where the joint elements contact each other and often undergo deformation is referred to as the joint interface. Characteristics of a joint are significantly affected by the structural characteristics of a joint element along with the contact surface layer characteristics (joint interface) [2]. In addition, the presence of machine tool joints along with static and dynamic characteristics of joint also has a significant effect on the overall performance of machine. Studies have shown that more than 90% damping comes from the joint connecting elements in mechanical systems [3]. Contact stiffness of the joint between the interconnected components in force closed chain significantly influences the rigidity of the whole machine system. Therefore, during the design stage of the machine, characteristics related to the prediction of the entire structure become critical. However, characteristics of the mechanical joint such as incompatibility and nonlinearity increase the difficulty associate with joint analysis [4].

Bolt connections are among the most widely used connections between components in a mechanical system. Bolt joints are complex, composed of multiple plane joint interfaces, thread joint interfaces and multiple elements. The bolt joint under typical operating conditions is preloaded and is subjected to multi-directional loads. A coupling relationship exists between contact deformation of the bolt joint interfaces and deformation of elements. It is important to establish an accurate joint model to analyze and determine real deformation of the joint accurately. Kim et al. [5] used finite element analysis, where four different modeling methods were adopted to analyze the bolt connection. Accuracy of these models was verified by comparing the results from the simulation with experimental data. Piscan et al. [6] also analyzed bolt connections using finite element method focusing on deformation analysis under different loads. This allowed the determination and understanding of factors affecting stiffness. Williams et al. [7] used numerical calculations and analysis along with experiments to study a single bolt connection under tensile separation loads after preload. Here, the bolt joint portion in the model did not take into account the interaction between the thread, and the simulation and experimental results are consistent. Niels [8] and Pauli [9] used finite element ultra-elements to analyze the distribution law associated with contact pressure for joint interfaces. Yang et al. [10] established a parametric spiral-shaped three-dimensional finite element model for a bolt joint.

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Simulations to analyze bearing surface contact pressure distribution law for the bolt head were carried out. Based on this analysis, an effective radius and contact pressure non-uniformity distribution law for the bolt joint were obtained.

Bolt joint modeling is tedious and difficult, because of variation in the machining methods of the contact surface, surface roughness and nonlinearity in the joint surfaces resulting from the assembly. To overcome these difficulties, some researchers made the joint elements as overall model [5,6] or defined the joint stiffness as a constant value [11]. These methods ignored the effect of joint surface roughness. Stiffness of the elements has been evaluated using finite element method for bolt joint by considering the elements as linear showing elastic deformation with a fixed elastic modulus constant [12–14]. In order to reflect nonlinear characteristics of the bolt joint, Charles et al. [15] studied the impact of nonlinear dynamics of a bolt joint interface under preload and established a model with three degrees of freedom. Here, they analyzed the effect of different preload conditions on nonlinear dynamics using low amplitude modal impact test and high amplitude shock load test. Abasolo et al. [16] used the stiffness value based on four linear springs, equivalent to each bolt and established bolt joint model for analysis. Yu et al. [17] used two non-linear springs to analyze models of different stiffness values, which represented bolt joint characteristics with the screw under tension and compression loading. A set of non-linear elements can be designed to connect two contact surfaces [18,19]. Parameters (stiffness and damp) for the nonlinear elements can be obtained experimentally to achieve good agreement between the analytical and measured response. These methods seem perfect theoretically, however, spring stiffness computing is complex. Specifically, it is hard to accurately determine parameters associated with the spring when effected by multiple bolts. Moreover, accuracy of the analysis based on these models is low.

The actual contact surface of a joint consists of irregular asperities. After elements are subject to load conditions, contact first occurs at the peak of an asperity. Contact area between all asperities and the real contact area is significantly lower than the nominal area of the element surface [20]. Actual surface pressure at a contact point is higher than the average surface pressure between elements. The asperity undergoes elastic, elastic–plastic deformation [21–23], creep [24,25], etc. However, Hertz theory suggests that surface contact undergoes elastic deformation. Improved Hertz theory or statistical theory based on surface roughness [26–28] cannot accurately represent elastic–plastic and plastic deformation characteristics of the contact surfaces. Compared with these theories, fundamental parameters for the joint interface are based on varied scenarios with the mating elements of the contact surface, and they are related to the material, surface roughness, machining methods, media, etc. These parameters are always constants derived from numerous experiments and truly represent the nonlinear characteristics between joint interfaces. Our group has established a database of these basic parameters of the joint interface with data collected from numerous basic experiments [29].

In the manufacturing process of current precision and ultra-precision equipments, forecast analysis on the machine performance has to be done in machine design stage in order to reduce the design cycle. Literature review indicates that in the modeling process, bolt joints between spindle box, column and bed body were often ignored or simplified; or the forecast of the machine performance was far from accuracy, because in modeling analysis, iterative computation was not applied, resulting in low accuracy in the analysis. Therefore, the present research, taking the characteristics of bolt joint elements into consideration, puts forward that a finite element analysis model of virtual material of interface element should be built based on the bolt joint characteristic coefficient, and the model can be applied for engineering solution.

During preloading and multi-directional loading, coupling relation exists between the contact deformation and element deformation of bolt joint. It affects the results of pressure distribution analysis. The research, based on the corresponding virtual material of interface element, describes the surface characteristics of bolt joint, and embeds the elastic constants analytical solutions of equivalent material into finite element analysis, resulting in the forming of an analytical model of bolt joint and a quite accurate element deformation. Then, the joint deformation is isolated from the overall deformation, and a curve of bolt joint load-deformation caused by joint deformation can be drawn. Axial load static characteristics tests are conducted of the bolt joint according to the different preload and different element thickness, and the relative displacement between upper and lower elements can be obtained, and it is compared with the theoretical curves. As a result, the accuracy and validity of the finite element analysis of virtual material layer proposed in this research are verified.

2. Assumptions for equivalent virtual material and theoretical analysis of single bolt joint

Mechanical properties of a bolt joint such as elastic modulus, Poisson's ratio, density, etc. are reflected by elastic constants of the component materials. Fig. 1(a) shows the model of a bolt joint. Some differences exist in the binding surface morphology between two elements of a joint due to the difference in the machined surface textures [30]. Rough surface morphology of the binding surface results in a difference between the joint physical properties and the element material characteristics. Due to this, mechanical properties of the element surface cannot be directly expressed by the elastic constants of the material. Characteristics of a micro-contact between joint interfaces are equivalent to a virtual material [31]. A virtual element between two elements is selected such that it has equivalent material properties. This allows the virtual material to conform to the actual contact status of the joint interface. Virtual material layer and elements are both fixed connections. In Fig. 1(a), the 'flat joint interface A' can be simulated as a virtual material layer. The joint model containing the joint interfaces, as shown in Fig. 1(a), is equivalent to the joint model shown in Fig. 1(b) without the joint. This model ignores the plane joint interface C and threaded joint interface B. Shape of the bolt joint interface is circular, as shown in Fig. 1(c) or rectangular in shape with an inner hole, as shown in Fig. 1(d). The bolt joint interface is equivalent to a virtual material unit when the rigid part of element 1 and element 2 for the bolt joint is significantly large or the bolt joint interface A is subjected to only normal force and tangential load without moments,. When, rigid of elements of the bolt joint is small or joint interface is subjected to large moments, the bolt join interface can be considered to be equivalent to multiple virtual material units. Fig. 1(c) shows the top view of a circular bolt joint interface modeled using 8 equivalent virtual material units. Whereas, Fig. 1(d) shows the top view of a rectangular join interface with 4 equivalent virtual material units.

For the bolt joint, the force balance equation can be written as:

$$F = F_R + P + \Delta P \tag{1}$$

where, F_R is counter force exerted by joint interface A, P is pretension, ΔP is the change in bolt tension caused by change in external load.