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Stiffness analysis and optimization in robotic drilling application

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ABSTRACT

Low stiffness characteristics limit the application of industrial robots in the field of precision manufacturing. This paper focuses primarily on the stiffness properties of drilling robots by further studying the stiffness ellipsoid model. A Cartesian compliance model is proposed to describe the robot stiffness in Cartesian space. Based on the compliance model, a quantitative evaluation index of the robot's processing performance is defined. By choosing a proper drilling posture, the performance index in the cutting tool direction is optimized. Higher accuracy of the countersink depth and hole axial direction can be guaranteed. From the perspective of the robot processing mechanism, the key role of the per-load pressing force is first indicated. By applying a per-load pressing force, the performance index on the machining plane is enhanced. Hole diameter accuracy is improved significantly. A stiffness improving factor used to evaluate the stiffness promotion degree is also proposed. Finally, experiments were conducted to verify the correctness of the proposed model. Drilling experiments were performed to investigate the effectiveness of the robot processing performance index improving methods The principle of pressing force used in engineering applications is given based on processing parameters.

1. Introduction

Recently, robots have become increasingly common in industrial fields, with the International Federation of Robotics reporting that 72.7% of all industrial robots are used for pick-and-place, welding and assembly tasks [1]. However, the operations mentioned above are simple robotic applications that are mainly used to replace repetitive manual labor. As robotics technology continues to development and progress, higher requirements for the utility of industrial robots are being proposed. High value-added operations, such as milling and drilling, are finished by robotic systems due to their high flexibility and low cost. Drilling is an excellent example. In aircraft component assembly, there are more than 1.3 million holes in a typical large aircraft [2]. Manual drilling is labor-intensive and time-consuming. Hole quality is difficult to guarantee due to human factors. Limitations including the large size of the aircraft parts and large investments make it difficult to use computer numerical control (CNC) machine tools for drilling. Industrial robots, with their good space savings and low cost, are currently being investigated for use in aircraft component assembly drilling operations. Parallel-structured robots such as Exechon and Tricept with their high accuracy and better stiffness are successfully used in aircraft assembly drilling and machining operations [3]. A limitation to widespread use of parallel-structured robots is their restricted workspace, which is difficult to fulfill the aircraft components drilling tasks in the large volume of workspace [4]. External devices must be equipped to expand the workspace, system complexity and investment will be increased significantly. Besides, fixtures with complex structures are needed during aircraft components assembly to guarantee the high stiffness and tight tolerance. Drilling operator should avoid collisions with fixtures, parallel-structured robots with 5 $^{\circ}$ of freedom (DOFs) is not possible for this processing requirement. 6-DOF serial robots benefit from their larger volume of workspace could fulfill the drilling tasks without any external devices. Function redundant DOF is another favorable feature of serial robots, which provides infinite robot postures for choosing according to the certain task. Collisions avoidance becomes easily by using serial robots. However, low position accuracy and shortage of stiffness are the main limitations of such robots in the field of precision manufacturing. Theoretical and experimental studies have shown that the stiffness for a serial robot is less than 1 N/um, while a standard CNC machine has stiffness greater than 50 N/um [5]. Static deformation may significantly reduce the robot's localization accuracy, and dynamic deformation will lead to poor machining surface quality and decreased processing efficiency [6]. Therefore, it is of great importance to understand the stiffness properties of machining robots. The compliance of links and joints is the direct reason to low robot stiffness in Cartesian space. Influence of the robot arm compliance to stiffness properties is studied by Hao et al., and a normalization-based

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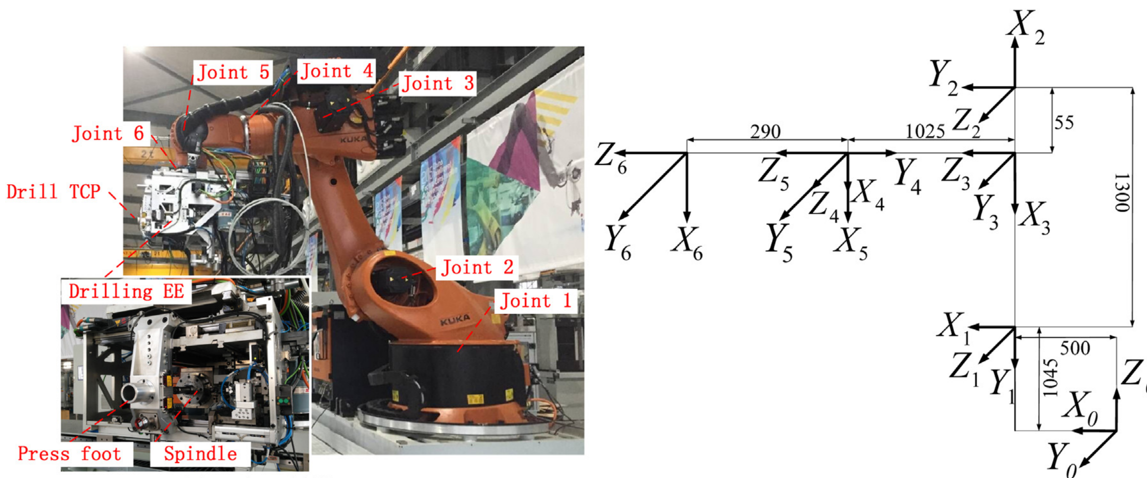

(a) Robot drilling system (b) D-H model of KUKA KR500-2 robot

Fig. 1. D-H model of the KUKA KR500-2 industry robot.

method is proposed to characterize mobility of compliant mechanisms quantitatively [7]. For 6-DOF serial robots, about 70 ~ 80% of the displacements result from the compliance of joints [8]. Hence, joint compliance contributes the most to robot Cartesian stiffness.

Stiffness analysis and optimization have been major subjects studied in the fields of robotics and machining. To understand robot stiffness properties, Chen et al. [9] developed the theory of mapping the relationship between joint and Cartesian space and proposed the conservative congruence transformation (CCT) method. By using the CCT method, Dumas et al. [8] identified the joint stiffness of six-revolute industrial serial robots, and the compliance coefficient of each joint was determined. Abele et al. [10] proposed a modelling and identification method of industrial robots used for machining applications. Second, to overcome the poor stiffness that can lead to low machining accuracy, Abele et al. [11] proposed a tool path adaption method by measuring the machining surface on the reference workpiece. Based on the optical measurement data, the robot's trajectory was revised. Vosniakos et al. [12] reduced joint torque by planning the robot's initial processing posture which resulted in better machining quality. Posture-relevance is another important characteristic of machining robots. Slamani et al. [13] found that robot machining posture had significant effects on the high speed trimming of CFRPs, which could be attributed to different stiffness properties in different postures. The methods mentioned above were focused mainly on experimental research in which qualitative results were achieved. To further understand the effects of robot stiffness and improvement of machining quality by stiffness-oriented methods, Zaeh et al. [14] measured the stiffness-parameters of a KR240 R2500 industrial robot, and the milling tool path-deviation was adjusted based on the milling force. The same method was developed by Hofener et al. [15], and an obvious increase in accuracy was achieved when repairing the composite parts. Klimchik et al. [16] identified manipulator stiffness model parameters in an industrial environment and found that by optimizing the robot's machining posture, a precision of approximately 0.2 mm under a 2.5 KN load could be achieved. For more complex situation, a Constraint-Force-Based modelling approach to model compliant mechanisms is proposed by Li et al. [17].

In aircraft assembly drilling operations, several robot drilling systems have been developed based on different task objectives [18]. To improve drilling quality, per-load pressing force is widely used in robotic drilling systems as a special processing parameter. Liang et al. [19] found that by applying a one-sided pressing force, the interlayer burr could be decreased when using a robot to drill stacked metal materials. Per-load pressing force is contributed to suppress interlayer burr size between two metal plates. However, when a robot is drilling a single metal plate, per-load pressing is also essential. The necessity of per-load pressing force in a robotic drilling system has not been explained from the robot's characteristics. In this paper, the key role of per-load pressing force is first investigated based on the characteristics of industrial robots.

There have been adequate experimental studies on robotic processing performance, and some qualitative analysis proves that robot stiffness has significant influence on machining quality. However, there have been relatively few studies evaluating and optimizing robotic stiffness quantitatively based on a certain task. This paper examines the correlation between robotic stiffness properties and drilling hole quality. The paper is structured as follows. In section 2, a robot stiffness model is studied, and a Cartesian compliance model is proposed to describe the robot stiffness in Cartesian space. In section 3, a robot stiffness character is modeled to quantitatively evaluate the processing performance index. In section 4, methods for processing performance index optimization are proposed. In section 5, experiments were conducted to verify the processing performance index, and holes were drilled to evaluate the improvement of robot stiffness by using the proposed optimized method. Finally, the paper is concluded in section 6.

2. Cartesian compliance model of a robotic drilling system

2.1. Robot compliance model

As determined by previous research, most machining damage is caused by poor robot stiffness [5]. Hence, three assumptions are proposed. First, the drilling end effector (EE) is considered as rigid body, with all of the deformations attributed to the weak stiffness of the robot. Second, it is assumed that all robot displacement is caused by the elastic deformation of the joints, and the links are considered as rigid bodies. Third, drilling process is under stable condition, and robot is keeping static during the drilling procedure. To simplify the question, effect of dynamic behavior is not considered.

Chen et al. [9] developed the theory of mapping the relationship between joint and Cartesian space stiffness by using the CCT method. The modified correlation between $\mathbf{K}$ and $\mathbf{K_\theta}$ is Eq. (1). $\mathbf{K_C}$ is the complementary stiffness matrix. When a robot has good manipulability, $\mathbf{K_C}$ can be neglected [8].

$$\mathbf{K} = \mathbf{J}^{-T} \cdot (\mathbf{K}_\theta - \mathbf{K_C}) \cdot \mathbf{J}^{-1} \Rightarrow \mathbf{K} = \mathbf{J}^{-T} \cdot \mathbf{K}_\theta \cdot \mathbf{J}^{-1} \quad (1)$$

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