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Vibration analysis and suppression in robotic boring process

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ABSTRACT

The industrial robot, due to its flexibility, is considered as a promising option to accomplish the fine boring work of the aircraft intersection holes. However, the robot has a relatively low stiffness and is easily subjected to chatter vibration in the boring process, resulting in difficulty in guaranteeing the machining quality. In this article, the mechanism of the vibration in the robotic boring process is analyzed, and a novel vibration suppression method based on the pressure foot is proposed. First, a robotic boring system is presented. Based on its cutting characteristics and stiffness characteristics, the mechanism of the vibration is analyzed, followed by the study of the tool path during the boring operation. It is found that in the robotic boring process it is the robot itself vibrates rather than the boring bar, which usually vibrates in the traditional CNC machine tools. And the type of the vibration is found to be a forced vibration with a displacement feedback. Furthermore, a novel method making use of the pressure foot is proposed to suppress the vibration of the robot. Finally, large numbers of boring experiments have been conducted and the results verify the correctness of the vibration mechanism and the effectiveness of the vibration suppression method.

1. Introduction

The key connection holes on the aircraft, such as wing–body connection holes, vertical tail and fuselage connection holes, and landing gear and fuselage connection holes, can be collectively called the aircraft intersection holes. During the assembly of large aircraft components, fine boring of intersection holes is necessary to eliminate the parts manufacturing error and assembly error so as to ensure the pose accuracy of intersection holes. As intersection holes are distributed widely on the aircraft and the working space of the assembly site is narrow, it is difficult to use the traditional computer numerical control (CNC) machine tools that are inflexible as well as require large installation space to accomplish the machining work. In view of this situation, industrial robots that are being widely used in the aerospace industry [1–3] can reach each intersection hole conveniently due to their flexibility. Therefore, it is a promising option to accomplish the fine boring work with the industrial robot and dedicated boring end-effector.

However, compared with the CNC machine tools, the serial structure of industrial robot has a much lower stiffness, resulting in difficulty in guaranteeing the machining quality [4,5]. It is found from boring experiments that under the same machining parameters, it is stable to work with a CNC machine tool, while chatter vibration is created when working with a robot. Chatter vibration will cause not only damages on the tool and robot structures but also bad accuracy and surface quality of the intersection holes, which will affect the performance of the whole aircraft. Consequently, it is important to study the vibration mechanism and also the vibration suppression method in the robotic boring process.

In fact, chatter vibration has been a topic of industrial and academic interest in manufacturing for many years. A great deal of research has been carried out to solve the chatter problem, including how to identify, detect, prevent, and suppress chatter [6–10]. Nevertheless, these studies are almost always based on the traditional CNC machine tools and they are not fully applicable to the robot. With regard to robotic machining process, chatter vibration has not been paid enough attention. This can be explained by the following two principal factors: (1) the application of robot in machining is mainly focused on the field of drilling in which chatter vibration seldom occurs [1–3,11], and (2) the complex serial structure of articulated robot brings great difficulties to the robotic chatter research. Only a few scholars have studied the chatter problem in the robotic machining process. Pan et al. [12] analyzed the chatter mechanism in the robotic milling process and found that the type of chatter was mode coupling chatter rather than regenerative chatter that always occurred in traditional CNC machine tools. In the robotic turning process, Ozer et al. [13] presented a novel semi-active controller to delay chatter vibrations to improve the cutting performance and the tool life. Currently, Wu et al. [14] introduced two methods to suppress the robot machining chatter, namely, passive vibration control method

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and active vibration control method. For the passive vibration control method, a parallel mechanism was presented to increase the stiffness of the robot; for the active vibration control method, a hybrid control method combining a feed-forward controller and a nonlinear feedback controller was introduced for chatter suppression. For the boring process, however, there is almost no report about the application of robot in this field up to now, let alone the robotic chatter vibration research.

In this article, we first analyze the vibration mechanism in the robotic boring process, taking into account both its cutting characteristics and stiffness characteristics. Furthermore, we also propose a novel method based on the pressure foot to suppress the vibration of the robot so as to improve the boring quality and efficiency. The article is structured as follows. In Section 2, a robotic boring system is presented, followed by the analysis of its characteristics with respect to the traditional CNC machine tools. In Section 3, the vibration mechanism in the robotic boring process is studied intensively, and then the tool path that affects the final contour of the hole to be bored is also analyzed. In Section 4, a vibration suppression method is proposed based on the pressure foot. In Section 5, experiments to verify the vibration mechanism and vibration suppression method are described. Finally, the article is concluded in Section 6.

2. Robotic boring system

As shown in Fig. 1, the robotic boring system is composed of an ABB IRB6600-175/2.55 robot, a dedicated boring end-effector, a Kistler 9257B dynamometer and a workpiece. The boring end-effector is a critical component to accomplish the boring work. As shown in Fig. 2, it consists of a robot flange interface, two air cylinders, a pressure foot, a feed screw, a spindle, a boring tool system and so on. In the boring process, the tool rotates with the spindle, and moves along the feed screw to achieve the cutting motion. The boring tool system mounted on the spindle includes a shank, an extension, a boring head, and an insert. The pressure foot can be pressed against the workpiece under the action of air pressure in the cylinders so as to suppress the chatter vibration. Its mechanism is explained in further detail below. In the boring experiments, the carbide inserts are used to machine the TC4 titanium alloy workpieces. The dynamometer is used to measure the cutting force components in three orthogonal directions.

Compared with the traditional CNC machine tools, robotic boring system has the following characteristics: (1) its cutting way is that the workpiece keeps still while the tool rotates and feeds with the spindle. This means that the robot will be subjected to dynamical cutting forces whose direction vary periodically even though the boring process is stable, that is, the cutting depth remains unchanged. (2) Due to its relatively low stiffness, the robot itself is the main source of flexibility in the boring system. This is significantly different from the CNC machine tools in which the boring bar is regarded as the dominant source of flexibility [15–18].

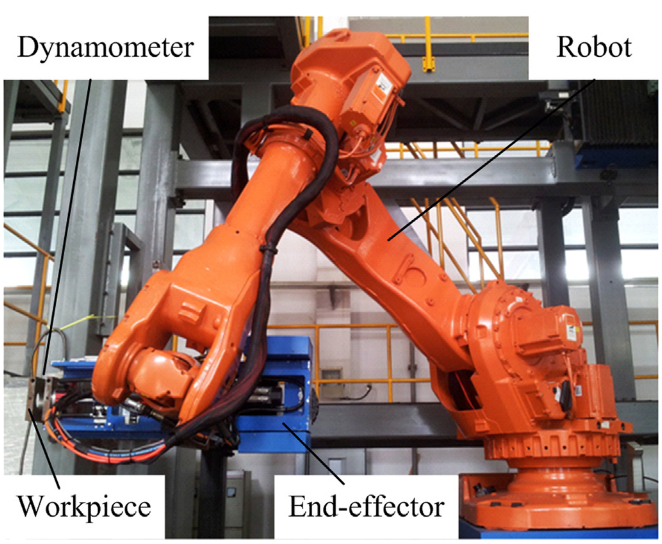

Fig. 1. Robotic boring system.

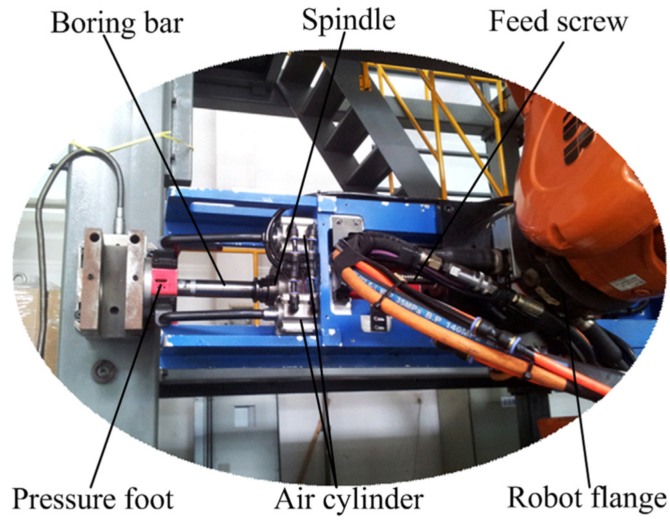

Fig. 2. Robotic boring end-effector.

3. Vibration analysis

3.1. Mechanism of the vibration

According to Ref. [6], chatter vibration can be generally classified into two categories: primary and secondary. Primary chatter is caused by the cutting process itself, including frictional chatter (caused by friction between the tool and the workpiece), thermo-mechanical chatter (caused by thermo-mechanical effects on the chip formation), and mode coupling chatter (caused by mode coupling). Secondary chatter is caused by the regeneration of waviness of the workpiece surface, and it is often called regenerative chatter. Among them, the regenerative chatter is the most common and most destructive type of chatter. For this reason, it has become a convention and been followed by a lot of publications in which 'chatter' only refers to regenerative chatter. The chatter in the boring process using the CNC machine tools usually refers to the regenerative chatter [15,17,18]. However, due to the different cutting way and study object, the regenerative mechanism does not apply to the chatter vibration in the robotic boring process. In this section, based on its own characteristics of robotic boring process, we will study the vibration mechanism intensively.

In the boring process, the cutting force can be represented by the tangential force, radial force, and feed force [19]. As the tool rotates with the spindle during the robotic boring operation, the directions of the tangential and radial forces vary periodically while the direction of the feed force remains unchanged. So the robot will be subjected to dynamical cutting forces in the plane perpendicular to the feed force, while be subjected to static cutting forces in the direction of the feed force. Based on this knowledge, the boring process could be simplified to a two-degree-of-freedom (2-DOF) problem.