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An integrated prediction model including the cutting process for virtual product development of machine tools

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ABSTRACT

Recently activities for shortening the development time of machine tools and demands for high-value products are consistently being increased. As a result, many studies for predicting the performance in design stage have been conducted to solve these issues. So far, most manufacturers of machine tools have verified designs excluding the cutting process, even though the main performance is the machining quality of the workpiece. Therefore, it has been required to consider together the cutting process model for analyzing the machining quality before the manufacturing of the prototype. This paper presents an integrated dynamic model considering the all interaction of the machine structure, the control system, and the cutting process. The modal truncation technique using the steady-state dynamic analysis in a selected location and frequency range of interest is applied to increase the efficiency of mechatronics simulations including the cutting process. In particular, this proposed prediction model allows accurate design verifications for high-speed machines because it reflects the influences of the high inertia forces and the contour errors caused by high feed rate. Several peripheral milling applications were demonstrated in order to show the feasibility of the proposed prediction model, and we confirmed the superiority of prediction by comparing the simulated and measured results in high feed milling.

1. Introduction

Global demand for machine tools shows an increase in high-speed machine tools, which offer high productivity and the quality improvement of machined parts and high value added products. Therefore, machine tool builders require advanced analysis techniques to cope with this demand and to launch a new product faster than competitors because more accurate prediction of performance in design stage can reduce the development time until mass production, and can improve the product quality. Unlike other machines, machine tools are composed of the machine structure, the control system and the cutting process. However, most of the design verifications have been performed without considering the cutting process so far. Since they interact with each other, designers need to apply the analysis technique considering the interaction of each subsystem to predict the machining performance of the prototype in design stage [1].

Many studies have been done about structural optimization and the static and dynamic behavior of the machine structure [2,3], the performance of the control system [4,5], and the analysis of the cutting process [6,7] separately. In other cases, a coupled simulation combining the structural dynamics and control system has been applied to accomplish the design target for high-speed and complex machine tools. These studies still do not reflect in the cutting process [8–10]. Therefore, these studies are impossible to predict directly the machining quality according to variations of the cutting process, such as spindle speed, feed rate, cutting depth, and tool path. Especially, there have been difficulties to understand how the cutting process affects the accuracy and the surface roughness of machined parts. It requires a lot of time and effort to find the causality between design parameters of machine tools and the cutting process and to solve the problem. On the other hands, there have been other studies about the prediction of the cutting force to plan the tool path and cutting conditions before the real cutting and about optimization of the feed rate through the regulation of the limited cutting force to reduce the cutting time [11]. However, no above-mentioned studies have discussed the aspects of the machine design. These were only focused on the cutting processes that can be utilized by machine tool users. Also, the studies on the cutting process including the structural dynamics

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have shown the focus on the machining productivity which can be considerably improved by the setting of the optimal spindle speed through the use of stability lobes [12,13].

The need for the development of high-speed machines is increasing, but most of these studies have been done about the roughing condition at the low feed. In high feed milling, the inertia force in addition to the cutting force excites the whole machine. In this case, the control system, which reflects the dynamic behavior of the feed drive and controller, plays another important role to affect the machining quality. The effect of inertial forces due to high acceleration and deceleration can be easily transferred onto machined parts. Thus, it is necessary to include the behavior of control system with dynamic cutting model to predict accurate machining quality at the high feed rate.

This paper presents the integrated dynamic model considering the all interaction of the machine structure, the control system, and the cutting process. Especially, the proposed model can more accurately predict the quality of machined parts in high feed milling.

2. Configuration of the integrated prediction model

The integrated prediction model is consisted of three subsystems: structural dynamics including spindle dynamics, feed drive dynamics, and cutting dynamics as shown in Fig. 1 [1]. The proposed model can describe well real cutting phenomena by reflecting the interactions, which are generated between the machine tool and the cutting process. The errors by spindle tool run-out, structural vibration, feed vibration, and servo bandwidth limit are considered at the same time. Therefore, it is possible to predict the achievable workpiece accuracy and surface quality without manufacturing the prototype.

The modeling techniques applied to each subsystem are introduced to accurately predict dynamic behaviors and the machining quality of high-speed machine tools. The prediction of performance is not easy in concept design stage due to the complexity of machine tools. The rigid multi-body approach can be utilized quickly to determine the optimum sizes of structures and to optimize the kinematic chain mechanism of the feed drive system by the simplified modeling method. This technique allows machine tool designers to easily evaluate the layout in conceptual design stage. However, the flexible multi-body approach reflecting the elastic structure is required to optimize the design parameters for machine structures, feed drives and spindle system in detailed design stage [1,2,8,14,20].

In this paper, structural dynamics including spindle dynamics and feed drive mechanisms are modeled by the FE method using commercial software, ABAQUS. Spindle dynamics was modeled by the methods proposed by Altintas and Cao [15–17]. Thus, it does not describe about the spindle modeling method, additionally. We used a 3-axis vertical machining center (Doosan DNM400) in order to implement and evaluate the proposed model as shown in Fig. 2. The main parameters for the flexible multi-body model are listed in Table 1, and most of them can be obtained from the design specification.

2.1. Flexible multi-body dynamics model

It is important to analyze the mechanical structure reflecting on its inertia and compliance in design stage. The FE method is used as the most appropriate analysis tool in design stage. Generally, FE models of machine tools contain hundreds of thousands degrees of freedom (DOF) at least in order to consider the behavior of the actual system, which especially results in an increase in the

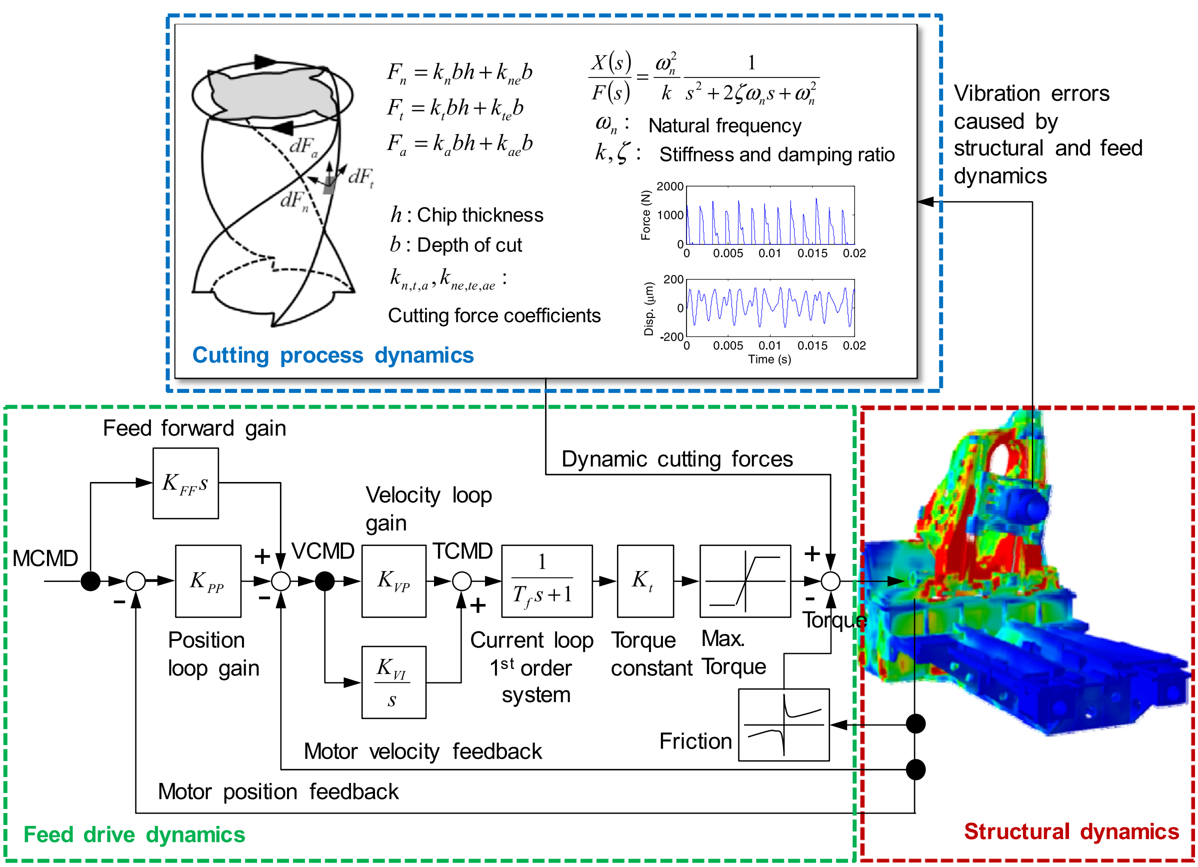

Fig. 1. Concept of integrated prediction model including the cutting process [1].