High-Precision Machining by Measuring and Compensating the Error Motion of Spindle's Axis of Rotation in Radial Direction

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Abstract—This paper deals with cutting force monitoring for high precision machining. The authors have employed displacement sensors to monitor the cutting forces, as they are cheap and small enough to be built in the spindle structure. A monitoring method, which utilizes sensitive displacement sensors, is discussed. The sensors are installed in X Y directions near the front bearings of the spindle, to detect the small displacements of a spindle caused by cutting forces. Monitoring tests are carried out under end milling operations and the cutting forces are estimated from the displacement signals by the simple signal processing technique. However, as the displacement sensor measures the variation of the gap size between the sensor head and the target surface, it also records displacements due to error motion of a spindle's axis of rotation in radial direction and roundness errors of the target surface. By comparing the cutting force estimated from displacement sensors with the cutting force measured by using a dynamometer, the machine tool spindle error motions is investigated, and its compensation scheme is proposed. The test results show that the monitoring system is reliable for the adaptive control of machining accuracy for end milling process.

Index Terms—High Precision Machining, Cutting Force, Displacement Sensor, Spindle Error Motion

I. INTRODUCTION

The present global market competition has attracted the manufacturer's attention on automation and high precision machining via condition monitoring of machine tools and processes as a method of improving quality of products, eliminating inspection, and enhancing manufacturing productivity [1-6]. The cutting forces are the most important indicator for that as they could tell limits of cutting conditions, accuracy of the workpiece, tool wear, and other process information, which are indispensable for process feedback control [7-14]. Hence, reliable cutting force measurement systems are investigated. The most common method to measure cutting forces in machining operations is through table dynamometers. Although table dynamometers provide accurate and effective force measurement, they are more suitable for laboratory or experimental use rather than for practical application on production machines, due to the limitation of workpiece size, mounting constraints, high sensitivity to overload, and high costs [15-17]. Furthermore, the dynamic characteristics of table dynamometers are strongly dependent on the workpiece mass, which may change during machine operation. To overcome limitations of workpiece mass and size, a force sensor can be integrated to the spindle itself instead of installing it on the machine table, thus converting an ordinary spindle into a called monitoring spindle [18-20].

The authors have employed displacement sensors, as they are cheap and small enough to be built in the spindle structure. Displacement signals are translated into cutting force information by the calibration. However, the monitoring quality is a problem, because sensors also detect the displacement caused by machine tool spindle error motions in the radial direction [21-26]. In this research, we develop a spindle with displacement sensors in X and Y-axis directions near the front bearings of the spindle, to monitor the spindle displacement. Cutting forces are estimated from the displacement signals by the simple signal processing technique. Monitoring tests are carried out under end milling operations on cast iron workpieces. By comparing the estimate with the measured cutting force by using a dynamometer, the machine tool spindle error motions in sensor output is investigated, and its compensation scheme is proposed. With its compensation scheme implemented, the experimental result shows that the monitoring system is reliable for the adaptive control of machining accuracy for end milling process.

II. MEASUREMENT OF THE SPINDLE DISPLACEMENT TO INVESTIGATE THE SPINDLE'S AXIS ERROR MOTIONS

A. Experimental set-up

In order to measure the machine tool spindle displacement caused by cutting force during cutting to