

Paper:

# Design of Motion Accuracy Measurement Device for NC Machine Tools with Three Displacement Sensors

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**To measure motion accuracy, including that of the rotary axis of five-axis machining center that have been widely introduced into production sites recently, a device with three displacement sensors combined to measure the center position of the master ball was invented and will be added to the International Standard. Such measurement devices are not difficult to produce in principle, but the commercially available products are expensive. This study discusses a three-dimensional (3D) coordinate measurement device with multiple displacement sensors, discussing it in terms of the test standards of the machines to which the device has been applied and in relation to devices which have been studied, developed, and released. Our measurement device is then designed and produced, and its measurement accuracy is confirmed.**

**Keywords:** 5-axis machining center, measurement device, motion accuracy, displacement sensor

## 1. Introduction

A machining center, a machine which rotates and moves a cutting tool relative to a workpiece to cut it, is a predominant machine in production sites because it alone performs many types of process, such as drilling, boring, and milling. Standard machining centers move a cutting tool in three directions,  $X$ ,  $Y$  and  $Z$ , and some of them incline the orientation of the rotating cutting tool relative to the workpiece. Since full control of the orientation of the cutting tool requires two additional rotating axes for a total of five control axes, a machine that has this capability is referred to as a five-axis machining center. The use of the five-axis machining center will (1) machine workpieces with complicated shapes, (2) improve machining efficiency and accuracy because it processes at the optimal angle for the cutting tool, and (3) improve efficiency because the workpiece can be machined from various directions without requiring replacement of the workpiece. These three features are currently increasing the demand for five-axis machining centers.

According to some reputations, however, the five control axes complicate the machine configuration and make

the machines less accurate than three-axis machines. Possible reasons for this include the difficulty of testing their machining accuracy. Standardization of the tests will give clear results of their accuracy, thereby encouraging the manufacturers and the users to use the machine reliably and facilitating the maintenance of the accuracy of the machine.

One popular topic on the subject of accuracy tests for the five-axis machining center is a device which reads the center coordinates of the master ball using multiple displacement sensors. Such devices were released around the same time in Europe by a university and an NC manufacturer individually. However, the designs of the devices are significantly different. The measurement device configuration used for target machine accuracy tests is yet to be discussed.

This study first counts up previously released measurement devices of the same type. It then presents test standards of the currently produced five-axis machining centers and discusses necessary conditions for the device configuration. Finally, an actual measurement device is designed and an accuracy test of the machine is conducted.

## 2. Machine Accuracy Measurement Device with Multiple Displacement Sensors

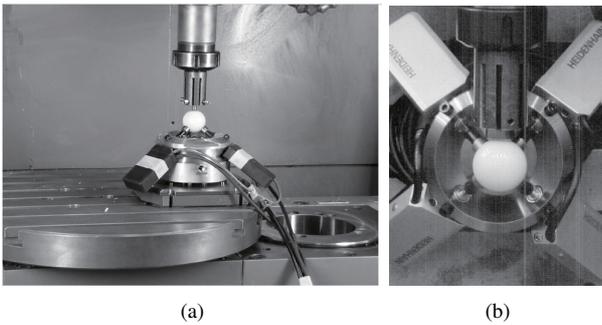
### 2.1. Cases Reported in 20<sup>th</sup> Century

The idea to use of two displacement sensors to measure two-dimensional (2D) coordinates and to use of three displacement sensors to measure 3D coordinates is not particularly new.

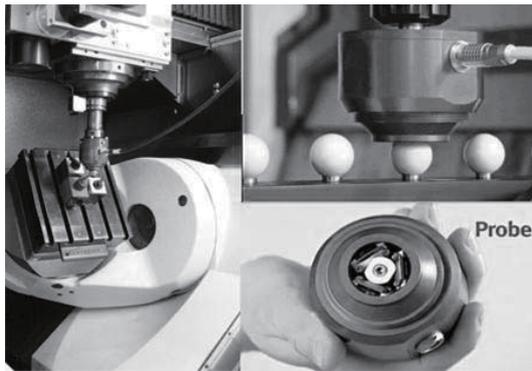
The standard for accuracy tests of industrial robots is ISO 9283, and the technical report for the standard is ISO / TR 13309 [1], in which multiple displacement sensors are disposed on a probe introduced there to measure the ball position and displacement.

Another device for accuracy tests of machine tools was also released, one in which two displacement sensors are used to measure the 2D position [2].

Both of those devices fix the displacement sensors. Another proposed device has rotary joints mounted to the front and back of the displacement sensors, which is a technology to which a so-called parallel mechanism is ap-



**Fig. 1.** R-test developed by ETH Zürich, (a) Device with three sensors, (b) Device with four sensors.



**Fig. 2.** Device sold by IBS Precision.

plied [3]. In its background, telescoping magnetic ball bar with a socket using a permanent magnet and a ball as a rotary joint has become popular for machine tool accuracy tests [4, 5]. There is a reported case of development of a device for 6-DOF machine tool accuracy tests to which the parallel mechanism is applied [6].

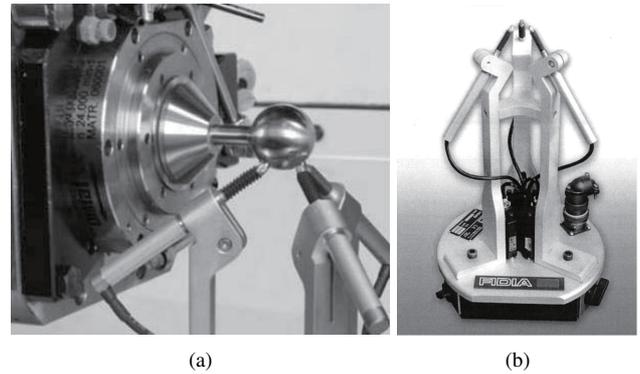
## 2.2. Recent Development Examples in Europe

The following two organizations proposed and released similar measurement devices at almost the same time.

### 2.2.1. R-Test

R-test was developed by ETH Zürich so that the coordinate (position) of artefacts such as a ball array would be acquired for a 3D coordinates measuring instrument in a short period of time with high accuracy. It later proved to be effective for accuracy checking five-axis machining centers and has thus been studied and reported on. There are also reports on the use of three sensors and use of four sensors for redundancy [7–9] (**Fig. 1**).

There is a commercially available product released by IBS Precision of the Netherlands [10] for acquiring the position of a ball array that is the original target. This is the only product available as a single device so far (**Fig. 2**). This product has problems in terms of the size of its range of measurement, which is as small as 1 mm in the three directions, and in its expensiveness.



**Fig. 3.** HMS by FIDIA, (a) Device in right angle, (b) Device in acuter angle.

### 2.2.2. Head Measuring System

Head Measuring System is a device proposed by FIDIA, an NC Device manufacturer in Italy, for the adjustment of the kinematic parameters of a five-axis machining center [11] (**Fig. 3**). This device is directly connected to the NC device of FIDIA to adjust the kinematic parameters by causing the machine to move in a predetermined way but it can not be used for other purposes. This device is not sold alone. FIDIA has filed a patent including a wide range of claims relating to this device.

## 3. International Standard for Five-Axis Machining Center Tests

### 3.1. Structure of Standard Described in ISO

A test code for accuracy tests for machine tools currently in the ISO standard is ISO 230, which is made up of multiple parts. Devices for measuring machine positioning accuracy and motion accuracy are described in ISO 230-1. As of 2011, ISO 230-1 is being revised. ISO / DIS 230-1 [12] has been added with a description of devices for measuring position accuracy with multiple sensors, the target of this study in anticipation of standardization of accuracy measurement of five-axis machining centers.

The standard for accuracy measurement of five-axis machining centers is ISO 10791, which also has multiple parts. All the parts of ISO 10791 are presented in **Table 1**. The current standard only describes a part of the measurement method for five-axis machining centers in part 6, so frequently used cone frustum cutting is currently being formally introduced into the standard. Methods other than cone frustum cutting are currently being discussed, and test items with the measurement device targeted by this study are likely to be described in parts 4 and 6.

### 3.2. Ball Bar and Multiple Sensor Method

A ball bar is a measurement device consisting of two balls and a bar with a built-in displacement sensor. The balls at the two ends work as a spherical joint, thereby measuring the distance between the balls at both ends with