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# Development and testing of an integrated smart tool holder for four-component cutting force measurement

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Cutting force measurement is a significant requirement for monitoring and controlling the machining processes. Hence, various methods of measuring the cutting force have been proposed by many researchers. In this study, an innovative integrated smart tool holder system based on capacitive sensors is designed, constructed and tested, which is capable of measuring triaxial cutting force and a torque simultaneously in a wireless environment system. A standard commercial tool holder is modified to make itself be the force sensing element that has advantages of simple structure and easy machining. Deformable beams are created in the tool holder, and the tiny deformations of which used to calculate the four-component cutting force are detected by six high precision capacitive sensors. All the sensors and other electronics, like data acquisition and transmitting unit, and wireless power unit, are incorporated into the tool holder as a whole system. The device is intended to be used in a rotating spindle such as in milling and drilling processes. Eventually, the static and dynamic characteristics of the smart tool holder have been determined by a series of tests. Cutting tests have also been carried out and the results show it is stable and practical to measure the cutting force in milling and drilling processes.



## 1. Introduction

Nowadays, manufacturing enterprises face the growing demands of increased product quality, reduced cost and higher processing efficiency, so cutting process monitoring becomes particularly important [1,2]. As one of the most significant machining process variables, the information of cutting force generated in metal cutting can be used to understand the principle of chip formation [3], optimize cutting parameter [4], design tool geometry [5], monitor tool wear or failure [6,7], and detect and suppress chatter vibration [8]. Thus, various methods to measure cutting force in turning, milling and drilling have been proposed by researchers.

Commonly, table dynamometers are the most generally used equipments in machining operations, since they can provide highly accurate and effective cutting force measurement, and are easy to design and manufacture. Many types of table dynamometers are developed based on strain gauge sensor [9–11], especially piezoelectric sensor [12,13]. However, when used, the dynamometer is clamped onto the machine table and a workpiece is mounted on top of the dynamometer, which undoubtedly limits the geometry and dimension of the workpiece. Besides, considering table dynamometers' complicated installation and high cost, they are more suitable for laboratory or experimental use rather than for practical application on production machines.

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Due to the limitations of current commercial sensor systems and the significant challenges for flexibility and reconfigurability, sensor integration techniques are being accepted. Byrne [14] proposed an integrated force sensor solution for drilling operations by integrating two piezoelectric force sensing rings into a direct driven motor spindle. Similarly to Jun et al. [15], who integrated a force ring to the spindle housing to measure triaxial cutting force, and finished the evaluation work on the sensor performance. Totis et al. [16] developed a rotating dynamometer for milling process by installing commercial piezoelectric triaxial force sensors between the modular cartridge and the cutter body. Also, Ma et al. presented several sensor-integrated methods for measuring the feed and transverse forces [17] and the torque [18] in milling process, a thin film polyvinylidene fluoride (PVDF) piezoelectric strain sensor was mounted to the shank of a cutting tool, and all the electronics and batteries were located in a metal housing that was mechanically attached to the tool holder.

There are already some kinds of commercial piezoelectric rotating dynamometers developed by several companies, like Kistler Instrument Corporation [19], and some of these products can measure four-component cutting force simultaneously with good dynamic performance. However, these products are mostly very expensive. Thus, some other kinds of sensors are adopted for cutting force measurement. Albrecht et al. [20] presented a method of measuring just radial cutting force by integrating capacitive sensors into the spindle to measure the static and dynamic variations of the gap between the sensor head and the rotating spindle shaft. Rizal et al. [21] developed a force sensing element on which strain gauges were mounted, and then integrated it on a tool holder to measure three cutting forces in milling. Similar work was done by Suprock [22] and Nichols [23], who designed a strain gauge-based tool holder for torque measurement, which was defined as smart tool holder in their studies. All the rotating dynamometers developed by these researchers were tested and confirmed to have good performance for cutting force measurement. Nevertheless, to authors' best knowledge, the most present devices based on capacitive sensors or strain gauges can only measure two or three-axis cutting force, or torque. Too many strain gauges are needed if they are used to measure more axises forces, just like the dynamometer developed by Rizal et al. [21], in which three full Wheatstone bridge circuits were designed and 24 strain gauges in total were integrated, which doubtless increases the system complexity and reduces the reliability.

This present study makes a further contribution in addressing the issues, dealing with the design and construction of an integrated smart tool holder system, which is capable of measuring triaxial cutting force and torque simultaneously in milling and drilling operations. A standard commercial tool holder is modified to form deformable beams and make itself be the force sensing element. Six capacitive sensors are used and integrated to the force sensing tool holder to detect the beams' deformations, and then calculate the four-component cutting force. The rotating dynamometer is designed to measure forces not higher than 1000 N of cutting and 100 N·m of torque with up to 3000 rpm of spindle speed when using a two-inserts tool. Moreover, the device has advantages of simple structure and low cost, which make it easy to manufacture and suitable for industrial use. A series of tests have been carried out, and the results show it is stable and practical to measure the cutting force in milling and drilling processes.

## 2. Force component in milling operation

When the cutters cut the workpiece material, the cutting force acts on the milling cutters directly, and then transmits to the tool holder. The force on each cutter which consists of main cutting force, thrust force and perpendicular cutting force is complicated and time-varying. However, to facilitate detection and analysis, the cutting force can be decomposed into three-dimensional orthogonal forces and a torque at a certain time as illustrated in Fig. 1. A standard right-handed Cartesian coordinate is established. The axis of rotation is set as *Z*-axis with the positive direction towards machine spindle. Thus, this work is to design and construct an integrated smart tool holder system as a rotating dynamometer for measuring these four component cutting forces that are an axial force ($F_z$), two mutually perpendicular radial forces ($F_x$ and $F_y$), and a torque ($T$, same as $M_z$). By assembling different types of cutter arbors and cutters, the smart tool holder can be applied in not only milling but drilling operations.

## 3. Design and construction

### 3.1. Design and model of force sensing tool holder

The smart tool holder for cutting force measurement is regarded as an integrated rotating dynamometer. The structure form and dimensions of the force sensing element have great influence on the dynamometer's stiffness, sensitivity and accuracy of measurement, and hence they were taken into consideration to ensure the performance. Fig. 2 illustrates the geometrical structure of the force sensing tool holder. The prototype of the tool holder used in this paper is BT50SLN32-150 (Harbin Measuring & Cutting Tool Group Co. Ltd.) with inner diameter ($d$) 32 mm, outer diameter ($D$) 70 mm and height of cylindrical part ($H$) 113 mm. And the material is 40Cr. Four horizontal deformable beams and four vertical deformable beams which can make deformation concentrated are created by machining grooves along the radius on the tool holder. The deformations in the proper positions of the beams can be detected by high precision capacitive sensors, and then the cutting forces and torque can be calculated by these deformations. A previous similar prototype, which was studied by the authors in a preliminary work [24], was proven to fulfill the force-measuring needs. Compared to the previous structure, the grooves were made along a line parallel to the diameter in this paper instead of along the radial direction to make the structure much