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Development and testing of an integrated rotating dynamometer on tool holder for milling process

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ABSTRACT

The cutting force provides significant information to help understand the machining process, optimization, tool condition monitoring, tool design and others. Hence, various methods of measuring the cutting force have been proposed by many researchers. In this work, an innovative integrated rotating dynamometer and tool holder is designed, constructed and tested that can fulfil the requirement to measure the cutting force in a wireless environment system. The device consists of a strain gauge based sensor that is mounted on a newly designed force sensing element which is then placed in the rotating tool holder. The force sensing element is designed in the form of a symmetrical cross beam type with four arms, shaped as a rectangular parallelepiped. This device is intended to be used in a rotating spindle such as in milling and drilling processes. A conditioning system and an inductive telemetry transmitter unit are incorporated into a modified tool holder in order to collect and transmit the cutting force signal to the data acquisition system. The rotating dynamometer has been subjected to a series of tests to determine its static and dynamic characteristics. Thus, it is tested experimentally by conducting cutting tests up to cutting speed 550 m/min with a single-tool insert. The results show it is suitable and reliable to measure the cutting force in milling processes.

1. Introduction

The cutting force measurement is an essential requirement in the machining process. One of the most important machining process variables related to the cutting performance is the cutting force that is generated by the cutting tool as it cuts and shears the workpiece. It is also used as an important indicator in designing a machine tool, and for cutting process optimization [1], investigation of the fundamental study of cutting tools performance [2], prediction of surface roughness [3], tool wear monitoring [4], prediction of chattering [5] and others.

Commonly, table dynamometers are used to measure cutting force in the milling and drilling process, where a workpiece is mounted on top of the dynamometer which is clamped to a machine tool table. The principle of the commercial dynamometer is pressure detection using piezoelectric materials that are used in dynamometer construction as the main element and are converted to a proportional electric charge. A table dynamometer based on a strain gauge has also been

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developed by Korkut [6]. He developed a three-force component analogue dynamometer which consists of four elastic octagonal rings, on which strain gauges were mounted, clamped between the upper and lower plates, forming a platform. There were differences from the table dynamometer designed by Yaldiz et al. [7], who developed a table dynamometer to measure three perpendicular cutting force components and torque. The system combined the strain gauge and piezoelectric accelerometer to measure static and dynamic cutting forces.

Nowadays, flexibility and reconfigurability are the most significant challenges for the machining process. In this regard, the application of the sensors system must have a sufficiently broad operating range to allow for various cutting tool sizes and workpiece configurations. Therefore, there has been interest in developing a rotating force-sensing system built into the machine tool structure in order to allow for efficient reconfigurability. A spindle-integrated force sensor using a piezoelectric ring has been proposed for milling and drilling processes by Scheer et al. [8], Park et al. [9] and Byrne and O'Donnell [10]. They placed a flange piezoelectric force ring into the spindle flange and the spindle suspension, and data were transmitted from the rotating part of the sensor to a stator via telemetry. Also, Totis et al. [11] proposed a rotating dynamometer using 3D piezoelectric for measuring triaxial cutting force components in face milling. The sensors were clamped between the modular cartridge and the cutter body by means of a preloading screw.

However, commercial table dynamometers based on piezoelectric are commonly used for fundamentals study since they provide highly accurate measurement of cutting forces. However, they have a limited use in laboratory settings due to limited workpiece geometry and dimensions, and it is also difficult to use piezoelectric sensors to measure static forces over a long period without drift since their dynamic response is influenced by the mass and geometry of the workpiece. They are also not suitable instruments for industrial use due to their lack of overload protection and their high costs [12]. Alternatively, forces can be estimated from the elastic deformation that can be measured by a strain gauge. This is a sensor which produces an output voltage proportional to the elastic deformation and is also small in size and mass, low in cost, easily attached, and highly sensitive to strain. In the past, not much work has been reported on rotating dynamometers using a strain gauge as a transducer. There are several uses of a strain gauge on a rotating spindle, such as those reported by Adolfsson and Stahl [13], who have built equipment for measuring cutting force components at each cutting edge for face milling, similarly to Smith [14], and Suprock [15], who proposed a sensor-integrated spindle for torque measurement.

This present study makes a further contribution in addressing the issues, dealing with the design and construction of an integrated rotating dynamometer and tool holder. The force sensing element used in this system is strain gauge-based and of a cross beam type, with a data transmitter using inductive telemetry. It is capable of measuring the main cutting force, F_c, the thrust force, F_t and the perpendicular cutting force, F_{cN}, in milling and also in drilling operations. The advantage of this rotating dynamometer is its flexibility as it can be assembled with a variety of cutting tools size and geometries.

2. Force component in milling operation

Fig. 1 shows the cutting force generated when the milling cutter cuts the workpiece material. The direction of the active force (F_a) changes with the entry angle φ. The components of the active force have two directions inclusive of direction of cutting speed (v_c) and feed rate (v_f). The components cutting force (F_c) and perpendicular cutting force (F_{cN}) are related to a co-rotating system of coordinates, with their directions parallel to the cutting speed and toward the centre of the spindle. The components feed force (F_f) and perpendicular feed force (F_{fN}) are related to a fixed system of coordinates. The forces that have a relationship with tool-specific components are cutting force and perpendicular cutting force. The thrust force (F_t) also has a direct relationship with the tool system because the workpiece is against the cutting tool and its direction is always in the vertical axis. For converting the active force from the fixed system of coordinates into a co-rotating system, the following equations apply [16].

$$F_c = F_f \cos\varphi + F_{fN} \sin\varphi \tag{1}$$

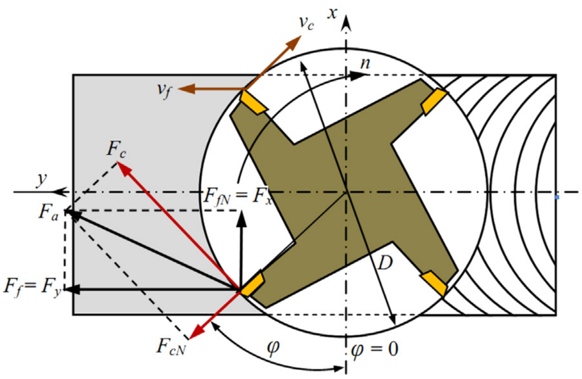

Fig. 1. Components of the cutting force in face milling.