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High frequency bandwidth measurements of micro cutting forces

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Abstract

The miniaturization of machine components is perceived by many as a core requirement for the future technological development of a broad spectrum of products. One of the challenges in micro engineering is the development of economical micro systems that are flexible, functional and made of appropriate engineering materials. The mechanical removal of materials using miniature tools, known as a micro machining process, has unique advantages in creating 3D components using a variety of engineering materials, when compared with photolithographic processes. Since the diameter of miniature tools is very small, excessive forces and vibrations will significantly affect the overall part and tool quality. In order to improve the part and tool quality, accurate measurement of micro cutting forces is imperative. In this paper, we focus on the development of an ultra precision micro milling system and the measurement of micro cutting forces using a three-axis miniature force sensor and accelerometers. Since the inherent dynamics of the workpiece and overall machine tool affects the frequency bandwidth, we employ the Kalman filter approach to fuse the sensor signals and compensate for unwanted dynamics, in order to increase the bandwidth of the force measurement system. Based on accurate cutting force measurement, we can come up with the optimal process parameters to maintain desired tolerances and also monitor the process to prevent failures.

Keywords: Micro machining; Kalman filter; Cutting force; Sensor fusion

1. Introduction

The miniaturization of components, in order to accommodate the demand for shrinking component size with high accuracy, is becoming increasingly important for various modern industries. Miniature systems can provide portability, lower power consumption, lower sample requirements, higher heat transfer, and laminar flow characteristics. Several researchers [1,2] have reached the consensus that 3D structures of high aspect ratio and complex geometry, utilizing a variety of materials, are very important. This stems, in part, from the advent of miniaturized systems for biomedical applications. The 3D ultra precision micro machining is a viable technology to fabricate small devices in the micro/meso range [3]. The principles of micro machining are similar to those of conventional machining, with the surface of the workpiece mechanically removed using micro tools. Micro components can be produced cost effectively, because there is no need for expensive photolithographic masks. The flexibility and efficiency of micro machining processes using miniature cutting tools allow for the economical fabrication of smaller batch sizes compared with other processes [4].

There are several critical issues associated with micro machining and machine tools: these come mainly from the miniaturization of the components, tools and processes. Very tiny vibrations and excessive forces can be detrimental to the longevity of tools and part tolerances due to the miniature size of end mills; and, it is also very difficult to detect damage to cutting edges or even broken shafts. Furthermore, conventional macro cutting force models, such as Merchant and Oxley's sharp edge theorems, cannot be applied in the prediction of micro cutting forces, because the chip thickness in micro machining applications can be comparable in size to the edge radius of the tool [5], resulting in large negative rake angles and elastic–plastic deformations of the workpiece materials. When the

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depth of cut is less than the critical chip thickness, the chips may not form and the cutting process becomes nonlinear [5–7].

Significant research has been conducted to monitor macro machining processes using various sensors, such as: spindle motor current and power [8,9]; a feed drive measurement [10] used to emulate force signals; vibration signatures [11]; acoustic emissions [12]; and, cutting forces [13,14]. Among these sensing methods, accurate measurement of cutting forces provides the most effective method for monitoring tool conditions, since it yields higher signal-to-noise ratios and best represents the state of machine tools and machining operations [14]. The common method of measuring cutting force in machining operations is by employing table dynamometers or piezoelectric load cells. However, the accurate measurement of very small cutting forces is challenging, because even a small amount of sensor noise can give an inaccurate cutting force signal. Moreover, the frequency bandwidth of commercial force sensors is inadequate for the majority of micro machining, due to very high rotational speeds used for micro milling processes. When the milling operations are performed beyond the frequency bandwidth of the force sensor, the force signals are distorted due to the inherent structural dynamics. Despite years of research in this area, reliable, versatile and practical sensors are not yet available for the monitoring and controlling of high-speed machining processes, especially for micro machining operations [15].

To overcome the limitations posed by commercial force sensors in micro machining, we utilize multiple sensors to fuse signals and compensate for unwanted dynamics in order to increase the frequency bandwidth. The fusion of signals increases the accuracy of the measurement and compensates for the incomplete data of each sensor. The sensor fusion techniques have been used in many applications. In this paper, the bandwidth of the force measurement mechanism is increased by compensating for the force sensor dynamics. The compensation method, based on the expanded Kalman filter (KF) developed by Park and Altintas [16], is enhanced by using the force sensor and accelerometer signals to reconstruct high frequency bandwidth cutting forces from the distorted cutting force measurements. The experimental cutting tests are performed using the micro machining centre platform developed in the Micro Engineering, Dynamics and Automation Laboratory (MEDAL) at the University of Calgary.

The article is organized in the following manner. First, this paper presents the development of the micro machining centre platform, where the characteristics and specifications of the machining centre are introduced with various controls and calibrations of sensors. Second, the enhanced KF methodology is examined to fuse the two different signals and compensate for unwanted dynamics. Then, the experimental results are examined with the reference signals. Discussion and future work are presented. The paper concludes with the contributions and effectiveness of this approach.

2. Development of micro machining centre

2.1. Micro machine tool

The majority of micro machine tools are based on conventional ultra precision machines with very high rigidity and a temperature-controlled environment. There has been strong interest from various research groups to build small scale machine tools to fabricate micro sizes [17–19]. There are several benefits of miniaturization of micro machines, such as portability and reduction in energy, space, materials and costs.

The design of the micro CNC machining centre platform was based on conventional column-and-knee-type machines, due to their simplicity and inherent rigidity. The micro CNC machine is constructed as a three-axis vertical milling machine, as shown in Fig. 1(a). The micro machining centre consists of a spindle, stages, frames and a control system. It has been specified to meet functional requirements for travel, minimum resolution, velocity, accuracy and load capacity. The machining centre requires a high-speed spindle, in order to increase the volumetric material removal rate (MRR) of the micro cutting tool. A 300 W electric motor spindle (NSK Astro 800E), which is capable of rotational speeds up to 80,000 rpm, is used for this machine tool to achieve adequate torque requirements, in order to machine various materials including steel, aluminium and other alloys. The three linear tables, which are equipped with cross-roller linear bearings (Parker Daedal 10600, 402LN, ζ Drive) and stepper motors, are used to actuate the X-, Y- and Z-axes where the position accuracy of the xy stage is $\pm 1.3\,\mu m$. The control of the stages and spindle is achieved through an open-architecture control system (National Instrument PXI7240 and PXI1250), which provides the control and data acquisition of the machining centre.

The interpretation from CAD/CAM designs are obtained by NI Motion-Assistant^{TM} algorithms. The overall micro machining centre is mounted on top of a vibration isolation table (Ealing 10×4) to prevent adverse ground vibrations. The micro tools used in this study are tungsten carbide (WC) micro end mills with micro grains (i.e. < 600 nm), due to their high hardness and strength [20] and their ability to machine steel. In this study, we utilized 200 μm diameter micro-end mills, as shown in Fig. 1(b).

The rigidity of the machine structure at the shank of the miniature tool was found to be 5.16E7 N/m by experimental modal analysis, using the impact hammer and the laser displacement (Keyence LK-G32) sensor. With the open-architecture system, the machine is controlled, and a variety of sensor signals is captured. The developed micro CNC machine is capable of fabricating 3D structures with various engineering materials.

2.2. Calibration and modal analysis of sensors

In this study, we utilized a commercial miniature piezoelectric force sensor and an accelerometer to measure