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Development of Multi-Degrees of Freedom Optical Table Dynamometer

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Abstract
Accurate measurements of cutting forces are critical in machining operations for maximizing production, detecting tool wear and failure, adaptive control and monitoring. Traditionally, cutting forces are measured using piezoelectric quartz force sensors or strain gauges. These types of sensors have limitations in that they are unable to measure static force signals. The quartz crystals of a piezoelectric force sensor generate an electric charge only when force is applied to or removed from them. Strain gauges suffer drifts over a long period time. In order to overcome the challenges, a novel table dynamometer is developed based upon laser optics to measure planar forces and moments in both the static and dynamic range. The developed table dynamometer allows the measurement of both the in plane linear movements and the in-plane rotations. In order to achieve high sensitivity, a monolithic, flexure-based mechanical amplifier is adopted into the proposed table dynamometer. A prototype of the developed system is fabricated and the sensitivity and frequency bandwidth of the system are experimentally investigated. The results showed good agreement between the optical force sensor and a reference force transducer. The proposed dynamometer is tested for use in the measurement of cutting forces and compared with a conventional piezoelectric dynamometer.

Keywords: Force Sensor, Dynamometer, Laser, Optics, Mechanical Amplifier

1 Introduction

The measurement of forces is essential in many areas of science and engineering. In the field of manufacturing industry, measurement of forces during material removal operations can result in the indirect measurement of other important machining process parameters. It can be utilized to understand the machinability of the workpiece material by correlating the amount of removed material and measured forces. Understanding the amount of forces involved in the machining processes combined with the dynamic characteristics of the machine tool has led to the prediction of finished surface quality (Thiele, et al., 1999) and chatter stability (Budak, et al., 1998). In addition, force measurements may also be the indicator of the tool wear as the thrust component of the cutting force increases as the flank wear of the tool becomes excessive (Kline, et al., 1982). Also the tool breakage

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could be identified by monitoring force measurements as the cutting force magnitudes abruptly change when one of the milling cutter teeth chips or breaks (Altintas, 1994). With a wide range of phenomena that may be detected through force measurement, the use of reliable force sensing methods to monitor machine tools has the potential to increase the useful machining time of a given machine tool from 10 to 65 percent (Tonshoff, et al., 1988). Furthermore, the adaptive control of machining processes, which is most effective when cutting force data is used as the feedback parameter, can significantly boost overall productivity, prevent excessive deflection of tools and prolong the longevity of tools. The recent emergence of the concept of Smart Factory, or the 4^{th} generation manufacturing industry (Industrie 4.0), has raised the importance of monitoring the forces even further (Lucke, et al., 2008). In this concept, individual modules of the system monitor the manufacturing process and communicate the measured data between each part of the machine as well as the operator in real time, and optimize the process automatically based upon the measured data and the simulation algorithm. Measurement of forces is the fundamental source of information to create the cyber-physical systems in the machining processes.

The accurate measurement of forces, however, has been a challenging task due to a number of reasons. With regards to micromachining specifically, the frequency bandwidth of commercially available force sensors is inadequate for the majority of micro-machining cutting-force frequency regimes due to the very high rotational speeds used for micro-milling processes. Also any force sensing system that is remote to the cutting tool has a limited frequency bandwidth caused by dynamics of the mechanical elements located between the cutting point and sensors (Albrecht, et al., 2005). In terms of conventional piezoelectric force sensors, a significant limitation is their inability to measure static forces. The quartz crystals of a piezoelectric force sensor generate an electrostatic charge only when force is applied to or removed from them. Even though the insulating electrical resistance of the sensor, cables and amplifier is quite large, the electrostatic charge will eventually leak to zero through the lowest resistance path, causing the signal drift. The inability to accurately measure the static component of forces often results in force measurements matching the expected forces in qualitative analysis of the machining processes, but not in the quantitative terms.

Force sensors for static and slower dynamic force measurements are based on strain gauges. They are used because of their ease of application, and comparatively low cost to piezo transducers. The most widely used characteristic that varies in proportion to strain is electrical resistance. Although capacitance and inductance-based strain gages have been constructed, these devices' sensitivity to vibration, their mounting requirements, and circuit complexity have limited their application. Unfortunately even resistive stain gauges have limitations. They suffer from stability problems. In calibrated strain gauges, the passage of time always causes some drift and loss of calibration. Hysteresis and creeping caused by imperfect bonding is one of the fundamental causes of instability (Omega 1995). Strain gauges are also sensitive to temperature, vibration, acceleration and shock; they require proper protection as exposing a strain gauge transducer to conditions outside its operating limits can degrade performance. These limitations are all in addition to the frequency limitations as mentioned previously.

The overarching goal of this study is to develop a cost-effective platform to accurately measure forces in multiple degrees-of-freedom (MDOF), with high sensitivity and sufficient frequency bandwidth to be applicable in micro machining processes with small forces and high spindle speeds. A novel laser-optics based dynamometer design is proposed. In order to achieve the MDOF measurements capability, an optical model is developed to decouple translational and rotational effects from the measured signals. Also a flexure-based mechanical amplifier is adopted to increase the sensitivity and the precision of measurements.

In the following section of this manuscript, the overall design of the proposed system and how the measurement is made in the system is described. The development of the optical model and the mechanical amplifier is described in detail, followed by the experimental processes and their results to evaluate the developed system. It is summarized with a discussion of possible future studies.