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High-Frequency Compensation of Dynamic Distortions in Micromachining Force Measurements

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Abstract

In this paper, we present a comprehensive technique to obtain accurate three-dimensional (3D) micromachining forces for frequency bandwidths up to 25 kHz. The capability to precisely measure cutting forces is central to gaining fundamental understanding on micromachining mechanics and dynamics. Multi-axis dynamometers are used to measure 3D machining forces. Forces experienced during micromachining involve very high frequencies due to the ultra-high spindle speeds used during the process. However, the specified bandwidths of the dynamometers do not meet high frequency requirements of micromachining forces; this limitation stems from the structural-dynamics response of the dynamometers. Therefore, it is important to develop approaches to compensate for the distortions arising from the dynamic effects of the dynamometer's structure in order to accurately measure micromachining forces. This paper presents a fully 3D compensation approach to enable accurate determination of 3D micromachining forces within a wide frequency range. The presented approach involves: (1) accurate identification of 3D force measurement characteristics of the dynamometer in the form of 3x3 force-to-force frequency response functions (F2F-FRFs) matrix within a 25 kHz bandwidth, (2) design of an optimal inverse filter for post-processing the measured force data to remove the influence of structural dynamics of the dynamometer; and (3) validation of the compensation approach through impact testing where the actual applied force data acquired by the reference force sensor is compared with the corrected dynamometer measurements. Subsequently, the presented approach is demonstrated by obtaining 3D micromachining forces during micromilling of a brass workpiece. It is concluded that the presented approach is effective in high-frequency correction of dynamometer measurements for accurate measurement of 3D micromachining forces within the 0-25 kHz frequency range.

Keywords: Micromachining, Multi-axis Dynamometers, High Frequency Force Measurement.

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1 Introduction

In the last two decades, the mechanical micromachining processes have seen important advances, and are now increasingly applied in industry [Ehmann et al., 2005; Dornfeld et al., 2006]. Mechanical micromachinig processes, such as micromilling, have recently emerged as a viable technique to manufacture three-dimensional (3D) micro-scale parts on a myriad of materials for a broad range of applications [Filiz et al., 2007; Filiz et al., 2008]. Mechanical micromachining processes use micro-scale cutting tools (as small as 10μm in diameter) within high precision machining systems. To attain effective material removal rates while using micro-scale tooling, ultra-high-speed (> 80,000 revolutions per minute) spindles are used during micromachining processes [Bediz et al., 2014].

Accurate measurement of 3D micromachining forces—that include very high frequencies arising from the ultra-high spindle speeds used during the process—is central to gaining fundamental understanding on process mechanics and dynamics [Liu et al., 2004; Chae et al., 2006] . Cutting forces include critical information on the quality and productivity of the processes [Chae et al., 2006]. Since the machining forces include components at the harmonics of (spindle and) tooth passing frequencies, the micromachining forces require a measurement capability in a relatively wider frequency range.

Dynamic cutting force measurement during machining processes is performed by using multi-axis dynamometers [Chae et al., 2006]. Although these dynamometers provide accurate measurement of machining forces, their frequency bandwidth is limited due to the dynamic effects arising from structural response of the dynamometers, especially for micromachining processes, which include forces with high frequency components [Girardin et al., 2010; Tounsi et al., 2000]. To precisely measure 3D machining forces within their workspace, the dynamometers include a number of high-stiffness preloaded tri-axial load cells within a mechanical assembly [Youssef et al., 2008]. Each load cell measures the strains ensuing directly from dynamic deflections of the dynamometer structure caused by the applied force. Hence, the bandwidth of dynamometers is correlated with the structural dynamics of their mechanical structure [Schmitz et al., 2009]. Actually, the structural response of the dynamometers, and thus, their bandwidth, also depend on other factors such as boundary conditions and the workpiece attached to the dynamometer [Korkmaz et al., 2014]. Intrinsically, the measured forces at frequencies above the dynamometer bandwidth become significantly different from the (actual) applied forces. Furthermore, structural response causes dynamic (frequency-dependent) cross-talk between different measurement directions, which induce further inaccuracies in force measurements [Korkmaz et al., 2014]. Therefore, the effects of structural response on the force measurement characteristics of dynamometers must be thoroughly analyzed within a broad range of frequencies and the issue of inadequate bandwidth of dynamometers must be addressed.

The research on high frequency measurement of micromachining forces has taken two major directions in the literature. A few researchers proposed the development of a new dynamometer to measure wide frequency bandwidth dynamic cutting forces [Totis et al., 2014; Transchel et.al, 2012]. However, there is still no commercially available dynamometer that can meet the high frequency requirements of the micromachining processes. Another approach implemented by researchers is to post-process the measured force data for removing the influence of the dynamic effects caused by the structural dynamics of the dynamometer [Castro et al., 2006; Altintas et al., 2004]. To this end, dynamic force measurement characteristics of the dynamometer are determined in the form of force-to-force frequency response functions (F2F-FRFs) by applying a known force to the dynamometer, and comparing the measured force and applied force in frequency domain. The obtained F2F-FRFs are then used to compensate the distortions of the micromachining forces at higher frequencies through applying a filter such as an inverse filter or a Kalman filter. It should be noted that since the compensation approach is created from F2F-FRFs, the accurate identification of F2F-FRFs within a broad range of frequencies is pivotal for the success of the compensation approach.

There have been several efforts in the literature to compensate the effects of structural response of the dynamometers on acquired force data for accurate determination of high frequency machining