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Dynamic characterization of multi-axis dynamometers

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ABSTRACT

In this paper, we present a comprehensive technique for accurate determination of three-dimensional (3D) dynamic force measurement characteristics of multi-axis dynamometers within a broad range of frequencies. Many research and development efforts in machining science and technology rely upon being able to make precise measurements of machining forces. In micromachining and high-speed machining, cutting forces include components at frequencies significantly higher than the bandwidth of force dynamometers. Further, the machining forces are three-dimensional in nature. This paper presents a new experimental technique to determine the three-dimensional force-measurement characteristics of multi-axis dynamometers. A custom-designed artifact is used to facilitate applying impulsive forces to the dynamometer at different positions in three dimensions. Repeatable and high-quality impulse excitations are provided from a novel impact excitation system with a bandwidth above 25 kHz. The force measurement characteristics are presented within 25 kHz bandwidth using 3×3 force-to-force frequency response functions (F2F-FRFs), which capture both direct and dynamic cross-talk components to enable fully three-dimensional characterization. The presented approach is used to characterize the dynamic behavior of a three-axis miniature dynamometer. The effects of force-application position, artifact geometry, and dynamometer-fixturing conditions are explored. Moreover, the relationship between the force-measurement characteristics and structural dynamics of the dynamometer assembly is analyzed. It is concluded that the presented technique is effective in determining the force-measurement characteristics of multi-axis dynamometers. The changes in dynamometer assembly that affect its structural dynamics, including artifact (workpiece) geometry and especially the fixturing conditions, were seen to have a significant effect on force-measurement characteristics. Furthermore, the force-measurement characteristics were seen to change substantially with the force-application position. The presented technique provides a foundation for future compensation efforts to enable measuring forces within a broad range of frequencies.

1. Introduction

Mechanical micromachining processes, such as micromilling, have been increasingly used to manufacture micro- and meso-scale features, parts, and devices on a variety of materials for a broad range of applications [1–6]. Enhancing the quality and productivity of micromachining processes requires gaining fundamental understanding on process mechanics and dynamics [7–9]. To this end, measurement of dynamic machining forces, which include important information about the process characteristics, is critical. However, accurate measurement of dynamic forces during micromachining poses important challenges due to their high frequency content and small magnitudes [4,10,11]. Micromachining is performed using micro-scale cutting tools that are rotated at ultra-high rotational speeds (>60,000 rpm). Since machining forces include components at the harmonics of (spindle and) tooth-passing frequencies, the micromachining forces contain frequency components well above the bandwidth of commercial dynamometers, especially when multi-tooth cutting tools are used. Furthermore, since the force magnitudes are smaller, obtaining accurate force measurements becomes more critical.

Dynamic machining forces are commonly measured by using multi-axis force dynamometers [11–13]. These dynamometers include a number of preloaded tri-axial load cells within a mechanical assembly to accurately measure forces in multiple directions within dynamometer's workspace [14,15]. Since the load cells measure the strains induced in the dynamometer structure by the machining forces, and since the strain distribution varies with not only the static but also the dynamic deflections, the force measurement characteristics of multi-axis dynamometers are correlated with the structural dynamics of their mechanical structure [15–17]. Generally, the usable bandwidth of a dynamometer is considered to be below the first (dominant) resonant frequency of the dynamometer [15,16]. Actually, the bandwidth also depends on

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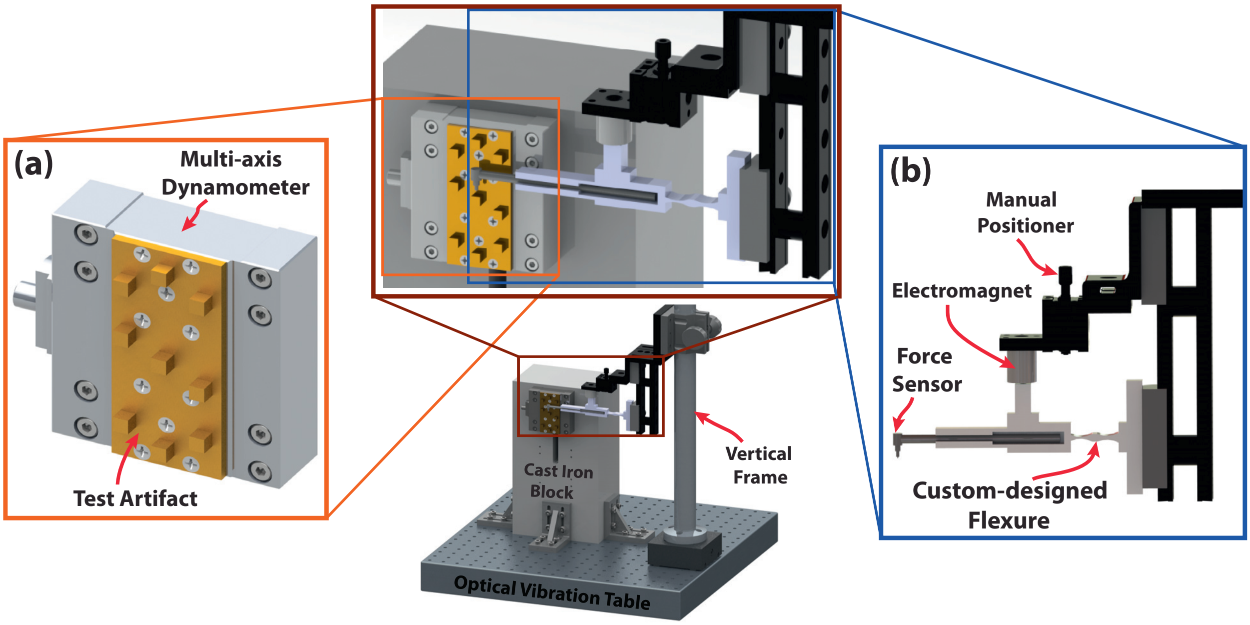

Fig. 1. The testbed for determination of 3D dynamic force measurement characteristics of multi-axis dynamometers: (a) the dynamometer with the attached test artifact; and (b) the impact excitation system to provide repeatable excitations within a broad range of frequencies.

other factors, since the structural response arises from not only the dynamometer's structure, but also the boundary conditions (i.e., where and how the dynamometer is fixed) and the workpiece (or the tool) attached to the dynamometer [15–17]. As a result of structural response, the measured forces at frequencies near and above the first resonant frequency become significantly different from the applied forces [18–20]. Furthermore, the structural response causes dynamic (frequency-dependent) cross-talk between different measurement directions, thereby inducing further inaccuracies in force measurements. Therefore, gaining a thorough understanding of the dynamic force measurement characteristics of multi-axis dynamometers is crucial to improve their usable frequency ranges and to achieve accurate measurement of high frequency forces during micromachining processes [8,9,16].

One way to address the issue of limited bandwidth without re-designing dynamometer structure is to post-process the measured data to compensate for the effects of structural dynamics, e.g., [8,18–20]. This is commonly done by performing experimental identification of the frequency-dependent measurement characteristics in the form of frequency response functions (FRFs) between the applied and measured forces [21]. For this purpose, a known force is applied to the dynamometer, and the measured force and applied force are compared in the frequency domain. Commonly, the excitation force is a transient force from an instrumented impact hammer [8,9] or a steady-state force from a dynamic shaker [20]. The compensation is then applied by creating a filter, such as a Kalman filter [18], from the force-to-force frequency response functions [18], and by post-processing the measured data using the filter [18,22,23]. Hence, the success of a compensation approach relies heavily on accurate identification of dynamic force-measurement characteristics of dynamometers.

A number of approaches have been presented in the literature for obtaining force measurement characteristics of multi-axis dynamometers within the context of developing compensation algorithms [8,18–20]. However, considering the high-frequency and multi-dimensional nature of micromachining forces, those approaches cannot be directly applied to characterize dynamometer dynamics for measurement of micromachining forces: *First*, most of the works involved a one-dimensional analysis, where the characterization was conducted only along a single force-application direction—generally, vertical to the measurement dynamometer surface [21,24]. However, considering the three-dimensional nature of the machining forces, a multi-axis identification approach is required. *Second*, due to the limitations of the dynamic testing approaches utilized in the literature, the reliable frequency range of the identification methods was commonly limited to 5 kHz [8,25]. *Third*, as the presented approaches were single-directional in nature, the dynamic cross-talk issues were not addressed. *Fourth*, the effect of workpiece and/or the boundary conditions that alter the structural dynamic response, and thus, the force measurement characteristics, was not captured. And *fifth*, the effect of force application position that could alter the strain distribution was not considered.

Only few works in the literature addressed some of the aforementioned issues. Jun et al. [26] considered the response in three-dimensions, and also included the effect of dynamic cross-talks in their identification approach. Yet, their approach was limited to a frequency of 500 Hz. Tounsi and Otho [22] considered the dynamic cross-talk up to 2 kHz, and concluded that the effect of dynamic cross-talk was negligible for that frequency range. More recently, Girardin et al. [20] presented a shaker-based approach that included three-dimensional identification of dynamometer dynamics up to 16 kHz. However, they concluded that the identification data is not usable at frequencies higher than 2 kHz, above which low coherence values were observed.

In this paper, we present a comprehensive technique for accurate determination of three-dimensional (3D) dynamic force measurement characteristics of multi-axis dynamometers within a broad range of frequencies. The technique uses an experimental approach, including (1) a custom designed test artifact that enables providing dynamic excitations in three dimensions and at different force-application positions; and (2) a novel impact excitation system that provides repeatable excitations up to 25 kHz. The testing approach results in obtaining three-dimensional (3×3) force-to-force FRFs. As such, the presented approach addresses all the aforementioned shortcomings of the existing techniques, and thus, provides an effective means of 3D dynamic characterization of dynamometers within a broad frequency range. The