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 micromachining 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
forces. Castro et al., 2006 identified the frequency dependent force measurement characteristics of a dynamometer only along z axis, which is vertical to the measurement surface, to apply an inverse filter for correction of dynamometer measurements within 0-4 kHz frequency range. Since the presented approach was single directional, the dynamic cross-talk issues were not addressed. Tounsi et al., 2000 focused on the dynamic cross-talk issue up to 2 kHz and concluded that the effect of dynamic cross-talks is negligible within that frequency range. As a result, they also applied an inverse filter for removing the effects of structural response of a multi-axis dynamometer within a 2 kHz bandwidth. Chae et al., 2007 compensated the influence of structural dynamics of a multi-axis dynamometer up to 5 kHz through a post-processing technique based upon Kalman filtering, and did not take the effect of dynamic cross-talks into account since it is found to be less than 10% within that frequency range. Kalman filter was used to minimize the amplification of noise due to inverse filtering when the exact force measurement characteristics of the dynamometers are not known. However, for a fully 3D compensation, the proposed technique requires a tedious curve-fitting approach that should work for 3x3 F2F-FRF matrix within entire frequency range. Considering high-frequency nature of micromachining forces, it is very arduous to create such a curve-fitting method for a wide frequency range [Scippa et al. 2014]. Conversely, it is much simpler to implement an inverse filter when the system characteristics are obtained with good coherence values [Girardin et al., 2010]. As such, the compensation approaches in the literature were only accomplished up to 5 kHz, and dynamic cross-talk effects were neglected within this frequency range. Considering the high-frequency and 3D nature of micromachining forces, the aforementioned approaches should be significantly improved for accurate measurement of 3D micromachining forces since the micromachining forces require a wider frequency bandwidth. For instance, a four-fluted tool rotating at 150,000 rpm provides signals at its tooth-passing frequency of 10 kHz. Therefore, development of a new compensation approach is needed for accurate measurement of 3D micromachining forces within a relatively broader range of frequencies. Besides, since dynamic-cross-talks are significant at higher frequencies, the compensation approach should take their effects into account [Korkmaz et al., 2014].

In this paper, we present a fully 3D compensation approach for enabling accurate determination of 3D micromachining forces within a 25 kHz bandwidth. The presented approach involves: (1) accurate identification of 3D force measurement characteristics of the multi-axis dynamometers in the form of 3x3 F2F-FRF matrix, capturing both the direct and cross-talk components within the 0-25 kHz frequency range; (2) design of an optimal inverse filter based upon 3x3 F2F-FRFs matrix for post-processing the measured force data to remove the influence of the structural dynamics of the multi-axis dynamometers; 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 compensated dynamometer force measurements. Subsequently, the presented approach is demonstrated to obtain accurate 3D machining forces within 25 kHz bandwidth during ultra-high-speed micromilling. As such, the presented approach addresses all the aforementioned shortcomings of the existing compensation techniques, and thus, provides an effective means of accurate measurement of 3D micromachining forces within a broad range of frequency.

2 Dynamic Characterization of Multi-axis Dynamometers

The success of a compensation approach relies on the accurate identification of force measurement characteristics of the dynamometers. To this end, a comprehensive characterization technique was recently developed by the authors. This section summarizes the experimental technique originally presented in [Korkmaz et al., 2014] for accurate determination of 3D dynamic force measurement characteristics of multi-axis dynamometers within a 25 kHz bandwidth.
2.1 Experimental Setup

The experimental setup used for obtaining 3D force measurement characteristics of the multi-axis dynamometers is depicted in Figure 1. The dynamometer that will be characterized is attached to a support structure, which specifies the boundary condition. In Figure 1, a cast-iron block, which represents a rigid support, is shown as the support structure. A custom designed brass artifact (see Figure 1(a)) is mounted onto the dynamometer measurement surface to enable 3D characterization. A tailor-made impact excitation system (see Figure 1(b)) is used to apply impulsive excitation forces with a high frequency-bandwidth along three-directions.

In this study, a three-axis miniature piezoelectric dynamometer (Kistler-9256C1) with a noise threshold of 2 mN and a specified resonant frequency of 5 kHz is used [Korkmaz et al., 2014]. The dynamometer includes four preloaded, three-component force sensors incorporated between a titanium cover plate and two lateral plates. The charge signals generated from these force sensors of the dynamometer due to the applied dynamic forces are fed into a charge amplifier (Kistler 5080A). The charge amplifier is used to convert the charge signals into the voltages that are proportional to the applied forces through calibrated sensitivity values. To perform a 3D characterization of the dynamometer, a brass artifact that will facilitate the force application in three-directions is mounted onto the dynamometer surface. Also, a novel impact excitation system (IES) recently developed by the authors [Bediz et al., 2014] is utilized to provide known, repeatable, single-hit, and high frequency bandwidth (25 kHz) excitation to the dynamometer for the successful analysis of dynamic force measurement characteristics of the dynamometer.

2.2 Dynamic Characterization Tests

In this work, 3D dynamic force measurement characteristics of the dynamometer are captured by creating F2F-FRFs, where the input is the applied force to the dynamometer, and the output is the measured force. For each test, a 3 x 3 matrix of F2F-FRFs, capturing not only the high-frequency dynamic behavior, but also the dynamic cross-talk effects, is determined.

Figure 1 describes the procedure used for obtaining the 3 x 3 F2F-FRFs matrix. For a given pillar, the tailor-made IES is used to apply high frequency bandwidth impulsive forces in each of the three mutually orthogonal directions. For each impact excitation, the dynamic forces from the dynamometer in each of its three-axes are measured. For instance, for the excitation in the x direction, dynamometer measurements in each of the x, y, and z directions are obtained. The measured dynamic forces from the impact excitation system and the dynamometer are then processed to obtain F2F-FRFs.
After completing the tests for all three directions for a given pillar, the complex-valued 3 x 3 F2F-FRF matrix, \([H(j\omega)]\) and the corresponding coherence matrix, \([C(\omega)]\) are calculated. To minimize the effect of noise, rather than directly calculating the FRFs from the ratio of the input and output Fourier transforms, the auto and cross power-spectra of the input (excitation force) and the output (dynamometer measurement) signals are used in this work. This approach produces two F2F-FRFs as the lower and upper bounds of the exact F2F-FRF as

\[
[H_{ik}(j\omega)] = \frac{S_{R_kF_i}(j\omega)}{S_{R_kR_k}(j\omega)} \quad \text{and} \quad [H_{ik}(j\omega)] = \frac{\bar{S}_{F_kF_i}(j\omega)}{\bar{S}_{F_kF_k}(j\omega)}.
\]

Here, the subscripts \((k\) and \(i\) indicate the excitation force and measured force directions, respectively. \(H_{11}\) is the ratio of the averaged cross-power spectrum \(\bar{S}_{R_kF_i}\) to the averaged input auto-power spectrum. Similarly, \(H_{22}\) is the ratio of the averaged output auto-power spectrum \(\bar{S}_{F_iF_i}\) to the averaged backwards cross-power spectrum. The complex averaging, as indicated by the over bars, is used to minimize the effect of spectral noise: Each test is repeated ten times for this purpose. The F2F-FRF for the excitation force in the \(k\) direction and the measured force in the \(i\) direction is then calculated as the arithmetic mean of the two FRFs as

\[
[H_{ik}(j\omega)] = \frac{1}{2} \left( [H_{ik}(j\omega)] + [H_{ik}(j\omega)] \right).
\]

To describe frequency-dependent force measurement characteristics of the multi-axis dynamometer, the 3 x 3 F2F-FRFs matrix is then represented as

\[
[H(j\omega)] = \begin{bmatrix}
H_{xx}(j\omega) & H_{xy}(j\omega) & H_{xz}(j\omega) \\
H_{yx}(j\omega) & H_{yy}(j\omega) & H_{yz}(j\omega) \\
H_{zx}(j\omega) & H_{zy}(j\omega) & H_{zz}(j\omega)
\end{bmatrix}
\]

To evaluate the reliability and repeatability of the measurements [Ewins et al., 2000], corresponding coherence function values for each F2F-FRF is calculated as

\[
[C_{ik}(\omega)] = \frac{\left| \bar{S}_{R_kF_i}(j\omega) \right|^2}{\bar{S}_{F_kF_i}(j\omega)\bar{S}_{R_kR_k}(j\omega)}.
\]

It is noted here that \(C_{ik}(\omega)\) is real valued since the two cross-power spectra \(\bar{S}_{R_kF_i}(j\omega)\) and \(\bar{S}_{F_iF_k}(j\omega)\) are complex conjugates of one another. For the 3D response, a 3x3 coherence matrix is composed as

\[
[C(\omega)] = \begin{bmatrix}
C_{xx}(\omega) & C_{xy}(\omega) & C_{xz}(\omega) \\
C_{yx}(\omega) & C_{yy}(\omega) & C_{yz}(\omega) \\
C_{zx}(\omega) & C_{zy}(\omega) & C_{zz}(\omega)
\end{bmatrix}.
\]

The off-diagonal terms of this matrix indicates the repeatability and reliability of the obtained dynamic cross-talk characteristics.
3 Three-Dimensional Compensation Approach

The three-dimensional compensation approach enabling high frequency correction of the measured force data by removing the effects of structural response of the multi-axis dynamometers is outlined in Figure 2. In this study, high frequency correction of the measured force components is achieved in the discrete frequency domain and the time domain forces are then reconstructed. The correction is done on both the magnitude and phase of the measured force components since complex domain correction is inevitable to rebuild the accurate time domain signal. Furthermore, the off-diagonal (cross-talk) terms of force components since complex domain correction is inevitable to rebuild the accurate time domain

Accordingly, at higher frequencies, due to the complex-nature of [H(\omega)] and the corresponding coherence matrix, [C(\omega)] are determined. Since it is known that [H(\omega)] constitutes important descriptors of linear time-variant dynamical systems, the linear relationship between the applied force components, \{R(\omega)\} and the measured force components, \{F(\omega)\} is defined as

\[
\begin{bmatrix}
F_x(j\omega) \\
F_y(j\omega) \\
F_z(j\omega)
\end{bmatrix} =
\begin{bmatrix}
H_{xx}(j\omega) & H_{xy}(j\omega) & H_{xz}(j\omega) \\
H_{yx}(j\omega) & H_{yy}(j\omega) & H_{yz}(j\omega) \\
H_{zx}(j\omega) & H_{zy}(j\omega) & H_{zz}(j\omega)
\end{bmatrix}
\begin{bmatrix}
R_x(j\omega) \\
R_y(j\omega) \\
R_z(j\omega)
\end{bmatrix}.
\]

It should be noted that this relationship between applied and measured force components is valid only if the entire structure (dynamometer + workpiece + support structure) is a linear system. To satisfy this assumption, it is indispensable to compute the coherence matrix by varying the applied force amplitude, and to show that the coherence values for all terms of \([H(\omega)]\) are close to 1 within 25 kHz bandwidth [Korkmaz et al., 2014; Ewins et al., 2000].

Clearly, if \([H(\omega)]\) deviates from identity matrix, which is the case when the frequency bandwidth of the dynamometer is exceeded, the measured force components will be different from the applied force components. Accordingly, at higher frequencies, due to the complex-nature of \([H(\omega)]\), the measured forces will deviate significantly from the applied forces in magnitude, direction (due to the cross-talk effects) and phase. Considering the fact that the accurate measurement range of the dynamometers is very small with respect to high frequency requirement of micromachining forces [Korkmaz et al., 2014], high frequency correction of multi-axis dynamometer measurements through 3D compensation approach enabled by the accurate determination of \([H(\omega)]\) should be performed.

The objective of 3D compensation approach is to determine the unknown applied forces, \{R(\omega)\} by compensating the distortion of the measured forces. Therefore, the high frequency correction of the dynamometer measurements requires the optimal solution of a linear system of equations with the presence of the measured force components and precisely determined \([H(\omega)]\). Thus, as seen in Figure 3, the three-dimensional compensation approach includes multiplication of the measured force components, \{F(\omega)\} by the inverse of the 3 x 3 F2F-FRFs matrix, \([H(\omega)]^{-1}\) as

\[
\begin{bmatrix}
K_x(j\omega) \\
K_y(j\omega) \\
K_z(j\omega)
\end{bmatrix} =
\begin{bmatrix}
H_{xx}(j\omega) & H_{xy}(j\omega) & H_{xz}(j\omega) \\
H_{yx}(j\omega) & H_{yy}(j\omega) & H_{yz}(j\omega) \\
H_{zx}(j\omega) & H_{zy}(j\omega) & H_{zz}(j\omega)
\end{bmatrix}^{-1}
\begin{bmatrix}
F_x(j\omega) \\
F_y(j\omega) \\
F_z(j\omega)
\end{bmatrix},
\]

Figure 2: The 3D compensation approach.
to obtain the corrected force components \( \{K(j\omega)\} \) in 3D. Accordingly, the result of the compensation approach is a corrected force vector, \( \{R(j\omega)\} \) which is aimed to be identical with the applied force vector, \( \{F(j\omega)\} \). It should be noted that the measured force components are low-pass filtered (<30 kHz) before correction using a frequency domain zero phase-shift filtering approach. As such, the presented approach aims at compensating the high frequency distortions of micromachining forces to obtain accurate 3D micromachining forces.

4 Validation of the Compensation Approach

In this section, 3D compensation approach is validated. To this end, first, 3D force measurement characteristics of a miniature three-axis piezoelectric dynamometer (Kistler-9256C1) are determined. Next, IES is used to excite the dynamometer assembly with a broad bandwidth known force input. The actual applied forces acquired by high frequency force sensor of the IES are then compared with the corrected dynamometer forces obtained through applying the 3D compensation technique.

4.1 Dynamic Characterization of the Dynamometer

To identify 3D force measurement characteristics of the dynamometer, the dynamometer is fixed to the rigid cast iron block and the brass artifact is attached to the dynamometer measurement surface (see Figure 1). Subsequently, to populate complex-valued \( [H(j\omega)] \) and corresponding real-valued \( [C(\omega)] \) matrices, impact excitation forces are applied on three mutually orthogonal surfaces of the square pillar located at the center of the artifact (see Figure 2 for pillar 5). For each case, the applied force from the IES and the resulting forces from each of the three dynamometer channels are acquired, and the data is processed to obtain the 3 x 3 F2F-FRFs matrix \( [H(j\omega)] \) and the associated coherence matrix \( [C(\omega)] \).

![Figure 3](image)

**Figure 3:** System identification: (a) The F2F-FRFs matrix and (b) The corresponding coherence matrix.

The magnitude plots of the obtained F2F-FRFs are given in Figure 3(a). As seen in Figure 3(a), structural response of the dynamometer does not influence its force measurement characteristics at low frequencies since the diagonal terms have the magnitude of unity and cross-talk amplitudes are relatively small at those frequencies. However, at higher frequencies, the amplitudes of the diagonal terms vary significantly from unity and cross-talk amplitudes become relatively large. This indicates the deviation of the measured forces from the applied ones at high frequencies. In conclusion, it is
essential to compensate the dynamic effects arising from structural response of the dynamometer at high frequencies.

The coherence functions corresponding to the nine F2F-FRFs are shown in Figure 3(b), where the dashed lines indicate 90% coherence value. Except when the actual response is very small, including the anti-resonance regions and the low-frequency regions for the cross-talk terms, the coherence values are all above 90% within the range of 25 kHz. Thus, it was concluded that the force measurement characteristics can be determined reliably within a bandwidth of 25 kHz using our unique approach.

4.2 Impact Testing

After completing a thorough identification of the 3D force measurement characteristics of the dynamometer, the characterization setup is disassembled. Then, the dynamometer is fixed on the rigid cast iron block, and the artifact is mounted onto the dynamometer surface again. Subsequently, an input force (multiple-impact force shown in Figure 4) is provided by IES on pillar 5 along z direction as a separate test.

4.3 Post-processing the Measured Forces for High Frequency Correction

While acquiring the forces from the reference sensor of the IES, the output forces from the each of the three-axes of the dynamometer are also measured. The output forces resulting from multiple impact tests are shown Figure 5.

Subsequently, the dynamometer measurements are post-processed using 3D compensation approach described above to remove the effects arising from structural dynamics of the dynamometer. The 3D compensation results, where the actual input force acquired by the reference sensor of the IES is compared with the corrected forces are also given in Figure 5. As seen in Figure 5, the force measurements obtained using multi-axis dynamometers are significantly distorted due to the structural dynamics of the multi-axis dynamometers in 3D. In interpreting these results, the force is considered to be applied in z direction by using IES within a broad frequency range. Furthermore, the multiple-impact force induces an input force with very complex frequency domain behavior. As shown in 5 without compensation, the measured force components significantly deviate from the applied forces in magnitude, direction, (due to the cross-talk effects) and phase. Thus, it is clear that the effect of dynamometer dynamics and dynamic cross-talks cannot be neglected at high frequencies. Indeed, as seen in Figure 4, the frequency threshold above which dynamic distortions should be removed is fairly low (< 2 kHz), especially considering micromachining applications.

It can be concluded from Figure 5 that when the presented 3D approach is utilized to compensate all the effects arising from structural response of the dynamometer, the corrected force components are almost identical with the applied force components with small discrepancies in amplitude and phase.

As shown here, the high frequency correction of the multi-axis dynamometer in three dimensions both on amplitude and phase of the measured forces can be accomplished using the presented 3D compensation approach.
Demonstration of the Compensation Approach

To demonstrate the utilization of the presented compensation approach for accurate measurement of high frequency micromachining forces, micromilling experiments are performed while simultaneously acquiring micromachining forces in three-directions. Subsequently, the acquired forces are post-processed to remove the influence of structural dynamics of the dynamometer. In this study, a high precision miniature machine tool (mMT) shown in Figure 6(a) is used for micromilling experiments. The mMT is equipped with a three-axis Aerotech ASL130-XYZ slide with 10 nm positioning resolution, 250 mm/s maximum linear (feed) speed, 25 mm x 50 mm x 50 mm workspace, and 1 μm positioning accuracy, and an ultra-high-speed air-bearing, air turbine spindle with maximum 160,000 rpm rotational speed. The slides are controlled from a computer using G-code programming. A stereo microscope with 95X magnification is used to view the process and to indicate the workpiece surface.

Figure 5: Accurate measurement of high frequency forces: (a) Forces along x direction; (b) Forces along y direction; and (c) Forces along z direction.

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The Kistler dynamometer is attached to the mMT for measurement of micromachining forces as shown in Figure 6(a). Prior to micromilling experiments, 3D force measurement characteristics of the dynamometer are obtained since the boundary conditions are changed. To this end, a cube-shaped brass workpiece that will facilitate the force application in three-directions is mounted onto the dynamometer surface (see Figure 6(b)). The size of the workpiece is chosen to be sufficiently small (5 mm x 5 mm x 5mm) to eliminate the effect of force application position, which is shown to be significant in [Korkmaz et al., 2014]. The subsequent micromachining experiments are performed on the same workpiece. The micromilling forces are acquired in three directions during a full-immersion slot cutting with a 508 μm diameter two-fluted tungsten carbide micro end-mill when the axial depth of cut is 40 μm, the feed rate is 5 μm/flute, and the rotational speed of the spindle is at 150,000 rpm.

Next, the resulting forces are post-processed using the presented compensation approach for high frequency correction of the multi-axis dynamometer measurements in 3D. The measured force components (without compensation) and the corrected force components (with compensation) at the harmonics of (spindle and) tooth passing frequencies are given in Figure 7(a). As seen in Figure 7(a), the amplitudes of the measured force components are significantly different from those of the actual applied force components. Therefore, without compensation, the measured forces will be wrong and misleading for deducing information regarding process mechanics and dynamics. For instance, the fundamental frequency component corresponding to the rotational frequency of 2.5 kHz along z direction is attenuated due to the structural response of the dynamometer such that the difference between the actual and measured forces is greater than 100% (see Figure 7(a)). Therefore, without compensation, the measured forces would give wrong information about the axial run-out behavior of the spindle. The similar differences in the amplitudes of the peaks can also be observed at higher frequencies. It is also important to note that the dynamic effects arising from the structural response of the dynamometer may not only increase but also decrease the amplitude of the force components depending upon the corresponding F2F-FRF amplitudes. As seen in Figure 7(a), for example, the tooth passing frequency component along z direction at 5 kHz is amplified due to the effect of structural dynamics whereas the fundamental frequency component in the same direction is decreased.

![Figure 6](image_url): (a) The miniature machine tool used for machining experiments and (b) Dynamic characterization of the dynamometer when it is attached to the stages of mMT.

Although Figure 7(a) reveals the significance of the high frequency correction of the dynamometer measurements, it is necessary to reconstruct the corrected time domain force components since the compensation is done on both the magnitude and phase of the measured force components due to the complex nature of the $H(j\omega)$. Therefore, the corrected time domain force components are then reconstructed by performing inverse Fast Fourier Transformation (FFT) of $\{K(j\omega)\}$. The measured force components (without compensation) and the corrected force components (with compensation) in time domain are plotted in Figure 7(b). It is shown in Figure 7(b) that the dynamic effects arising from
structural dynamics of the dynamometer influence not only the amplitude but also the phase of the measured force components. The cutting force signature obtained by a multi-axis dynamometer during ultra-high-speed micromilling processes becomes significantly different from the actual cutting force signature. Therefore, it is critical to perform a three-dimensional compensation approach as presented in this study. Taken together, the 3D compensation approach presented in this study is successfully implemented to obtain accurate micromilling forces in 3D within a 25 kHz bandwidth.

Figure 7: Measured and corrected micromilling forces: (a) in the frequency domain and (b) in the time domain.

6 Summary and Conclusions

This paper presented a comprehensive method of accurate measurement of 3D micromachining forces within a broad range of frequencies. In this method, the force measurement characteristics of multi-axis dynamometers were obtained in the form of 3x3 force-to-force frequency response functions (F2F-FRFs) matrix within a 25 kHz bandwidth. These F2F-FRFs captured not only the high-frequency dynamic behavior, but also dynamic cross-talk effects, enabling a fully three-dimensional characterization of the multi-axis dynamometer. It was shown that the measured forces significantly deviate from the applied forces in magnitude, direction, (due to the cross-talk effects) and phase due to the effects arising from structural response of multi-axis dynamometers without compensation. Next, the fully 3D compensation approach and its validation were presented. As a result of compensation trials, it was concluded that this approach is effective in high frequency correction of multi-axis dynamometers for accurate measurement of 3D micromachining forces up to 25 kHz.
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