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Dynamics of ultra-high-speed (UHS) spindles used for micromachining

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ABSTRACT

Micromachining dynamics commonly dictate the attainable accuracy and throughput that can be obtained from micromachining operations. The dynamic behavior of miniature ultra-high-speed (UHS) spindles used in micromachining critically affects micromachining dynamics. As such, there is a strong need for effective techniques to characterize the dynamic behavior of miniature UHS spindles. This paper presents a systematic experimental approach to obtain the speed-dependent two-dimensional dynamics of miniature UHS spindles through experimental modal analysis. A miniature cylindrical artifact with 5 mm overhang is attached to (and rotating with) the spindle to enable providing the dynamic excitations to and measuring the resulting motions of the spindle. A custom-made impact excitation system is used to reproducibly excite the spindle dynamics up to 20 kHz while controlling the impact force. The resulting radial motions of the spindle are measured in two mutually perpendicular directions using two independent fiber-optic laser Doppler vibrometers (LDVs). To ensure the mutual orthogonality of the measurements, the two lasers are aligned precisely using an optical procedure. A frequency-domain filtering approach is used to remove the unwanted spindle motion data from the measurements, thereby isolating the dynamic response. The spindle dynamics is then represented in the form of frequency response functions (FRFs). A global curve-fitting technique is applied to identify natural frequencies and damping ratios. The developed approach is demonstrated on a miniature UHS spindle with aerodynamic bearings, and dynamic characteristics are analyzed at different spindle speeds and collet pressures. The spindle speed is shown to have a significant effect on dynamic response, especially at higher spindle speeds, while the collet pressure is observed not to have any significant effect on the spindle dynamics. It is concluded that the presented approach can be used to characterize the dynamics of miniature UHS spindles effectively.

1. Introduction

In the past few decades, there has been an increasing demand for micro-scale products from various industries such as medical equipment manufacturing, aerospace, and consumer products. Mechanical micromachining is one of the emerging techniques for fabricating three-dimensional (3D) complex micro-scale features on a broad range of materials [1,2], including metals (e.g., [3]) and polymers (e.g., [4,5]). In order to attain high material removal rates while using micro-scale cutting tools (as small as 25 μm in diameter), miniature ultra-high-speed (UHS) spindles that can rotate at speeds above 60,000 rpm[1] are used in mechanical micromachining [1].

Unwanted vibrations during micromachining bring important limitations to satisfying accuracy and material removal rate requirements. As such, the dynamic behavior of the spindle-holder/collet-tool system at the cutting edge—commonly referred as the tool tip dynamics—must be well-characterized. Dynamics of the UHS spindles critically affect the tool-tip dynamics and, thus, the vibrations generated during the micromachining operations [6–8]. Therefore, the quality and the throughput of the micromachining processes are strongly correlated with the dynamic behavior of the miniature UHS spindles.

The dynamics of the conventional and high-speed spindles that are used in macro-scale machining operations have been well-studied in the literature. Some works have attempted to model the spindle dynamics analytically, e.g., [9,10]. Although analytical models provided promising results, accurately capturing spindle dynamics using analytical techniques has been challenging due to the large level of uncertainties arising from the spindle characteristics (e.g., bearings) and the lack of accurate models for damping behavior. For these reasons, *experimental modal analysis* is generally considered as the prevailing approach for modeling spindle dynamics. In this experimental modeling approach, either a tool [11] or a cylindrical artifact [12,8] is attached to the spindle. An excitation force is then applied to the tool/artifact, commonly using an instrumented impact hammer, and the ensuing dynamic

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[1] UHS spindles with speeds reaching above 400,000 rpm have become commercially available.

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response is measured using a motion sensor (e.g., an accelerometer). If desired, the dynamics of the cylindrical artifact can be removed from the overall response to determine only the spindle dynamics [13]. The dynamic behavior is then represented in the frequency domain in the form of frequency response functions (FRFs). Curve fitting techniques can then be used to identify the dynamic (modal) parameters from the FRFs. In general, the impact tests are performed on a non-rotating spindle [12,14,15]. However, it has been shown that the dynamic behavior of spindles may change significantly with the spindle speed [16–19]. In addition, spindle dynamics may vary with collet pressure and/or with the tool overhang length [20,8,21].

Applying traditional modal testing techniques to modeling the dynamics of miniature UHS spindles poses significant challenges: *First*, non-contact measurement techniques, such as Laser Doppler Vibrometry (LDV), are required since the contact-based measurement methods cannot be applied due to the relatively large size and weight of the transducers (e.g., accelerometers) and the associated adverse effects to dynamic behavior of the spindle [22,23]. Further complications arise in using contact-based sensors when the spindle is rotating at ultra-high speeds. *Second*, the frequency bandwidth of the excitation and measurement methods must cover the bandwidth of micromachining forces, which can reach up to 20 kHz [3]. Current dynamic excitation methods are commonly limited to a 10 kHz bandwidth. This necessitates development and use of techniques that provide dynamic excitations with a broad frequency bandwidth. *Third*, the excitation force exerted to the miniature spindle system should not exceed limiting force for the bearings (preferably ≤ 20 N) to prevent damage. Even with miniature hammer systems, impact force amplitudes can be as high as 200 N during a manual impact, and can cause significant damage to the bearings of miniature spindles. *Fourth*, obtaining highly repeatable excitations and measurements (i.e., with high coherence) becomes especially difficult when testing miniature spindles, which necessitates excitations on and measurements from small artifacts (e.g., a 3 mm diameter cylindrical artifact). And *fifth*, since the measurements need to be performed on a rotating spindle to capture the rotational effects, the *unwanted spindle motions*, which arise from the tool-spindle centering errors and spindle error motions, are also measured together with the dynamic response. Thus, an effective approach for removal of unwanted spindle motion data from the measurements is needed to isolate the dynamic response to the provided excitation.

To date, only a few works investigated the dynamics of miniature UHS spindles. For instance, Park and Rahnama [24] determined the dynamics of a *non-rotating* miniature spindle through modal testing within a 10 kHz bandwidth. A short cylindrical artifact attached to the spindle was instrumented with an accelerometer, and the excitations were provided manually using an impact hammer. The repeatability of the obtained FRFs and the associated uncertainties have not been discussed in the paper since no coherence data was provided. Later, Aran and Budak [25] obtained the tool-tip dynamics from a miniature endmill attached to a *non-rotating* UHS spindle using modal testing. Due to the manual impact excitations, the bandwidth of the excitations was limited to 10 kHz, and low coherence values were observed above 10 kHz and below 3 kHz. More recently, Jin and Altintas [26] used a piezoelectric actuator to excite the micro-endmill attached to a non-rotating high-speed spindle to obtain the tool tip dynamics. The dynamic motions were measured using an LDV system. Although this method enabled obtaining the dynamic behavior at high frequencies, it cannot be applied for modal testing from a rotating spindle due to the contact-based excitation approach.

In the aforementioned studies on UHS spindle dynamics, the experiments were all performed on non-rotating spindles and only along one direction and, thus, the gyroscopic effects that have strong effect at ultra-high rotational speeds and the effect of cross FRFs have not been captured. Furthermore, UHS spindles that use aerodynamic bearings do not allow performing modal tests from non-rotating spindles, as the bearings cannot carry any load when not being rotated at high speeds. Therefore, the modal tests need to be performed at operational speeds to accurately identify the speed-dependent dynamics of the spindle.

In this paper, an experimental modal analysis approach to obtain the speed-dependent two-dimensional dynamics of miniature UHS spindles is presented. This approach addresses all the aforementioned challenges and enables testing and modeling spindle dynamics when the UHS spindle is rotating at its operational speeds. A miniature cylindrical artifact with 5 mm overhang is attached to (and rotating with) the spindle to enable providing the dynamic excitations to and measuring the resulting motions of the spindle. The approach involves (1) application of a non-contact measurement approach based on the use of two LDV systems that are aligned in a mutually orthogonal configuration to enable two-dimensional measurements, (2) providing reproducible dynamic excitations within the 20 kHz bandwidth through the use of a custom-made impact excitation system; and (3) removing the unwanted spindle motion data from the measurements by using a frequency-domain filtering approach in order to isolate the dynamic response. The developed technique is demonstrated on an UHS air-bearing spindle: modal tests are performed at a spindle speed from 50,000 rpm to 170,000 rpm and at two collet pressures, and the modal characteristics (natural frequencies and damping ratios) are extracted from the obtained FRFs using a global curve-fitting approach.

2. Experimental setup

Fig. 1 shows the testbed constructed to perform experimental modal analysis of miniature UHS spindles. The miniature UHS spindle under examination is placed on a cast iron platform. An aluminum frame is constructed around the spindle to allow attaching the fiber-optic measurement lasers and associated optics. The entire experimental setup is placed on a vibration isolation table (Newport RS 4000 with tuned damping) to eliminate potential external effects from noise.

2.1. Dynamic excitations

To provide dynamic excitations to the spindle in two mutually orthogonal (horizontal and vertical) directions, a custom-designed impact excitation system (IES) is used [27]. In designing the IES, the excitation bandwidth, the amplitude of the impact force, and the repeatability of the impacts are the main considerations. The bandwidth of the impact excitations is required to capture the dynamic excitations (up to 20 kHz) from forces experienced during micromachining. Also, the impact force magnitudes should be small (preferably ≤ 20 N) so that no physical damage is imparted on the miniature UHS spindle. Lastly, the excitations should be repeatable in terms of bandwidth, force magnitude, and impact location—especially considering increased sensitivity to uncertainties due to the miniature size of the spindles and the artifacts.

To address the aforementioned challenges, an IES was designed and constructed to deliver repeatable, high bandwidth impacts with controlled impact force amplitudes [27]. The IES includes a small instrumented impact load cell (PCB-086E80) attached to a tailor-made flexure-based body (fabricated from acrylonitrile butadiene styrene, ABS), an automated electromagnetic release mechanism, and precision positioners (see Fig. 2). The system functions by releasing the flexure-based body from a specified