Dynamic Characterization of a Miniature Ultra-High-Speed (UHS) Spindle through Experimental Modal Analysis

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Abstract

In this study, we present a new systematic approach for obtaining dynamic characteristics of a miniature ultra-high-speed (UHS) air-bearing air-turbine spindle through experimental modal analysis. To enable high bandwidth excitation, a custom designed impact apparatus is used. The response of the system is measured simultaneously using two laser Doppler vibrometers (LDV) in mutually orthogonal directions. The experiments are conducted on a rotating artifact showed that the spindle speed has a significant effect on dynamic response of UHS spindles.

1 Introduction

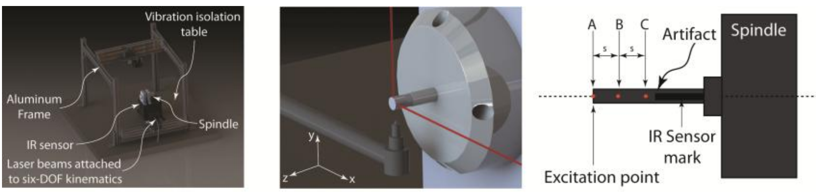
Micromachining is one of the emerging techniques for creating three-dimensional complex micro-scale geometries on a broad range of material [1]. In micromachining, miniature UHS spindles are used to enable obtaining high material removal rates when using micro-scale tools. Dynamic behaviour of the spindle-collet-tool systems, as reflected at the tool tip, determines the achievable process efficiency and quality that can be obtained during machining. Spindle dynamics have an important effect on this dynamic behaviour [2,3].

Modal testing is commonly used to obtain the dynamic models of macro-scale spindles [4]. However, there are significant challenges in applying conventional modal testing techniques to miniature UHS spindles. First, due to the high spindle speeds, the dynamic excitations occur in a wide range of frequencies (up to 15 kHz) [5,6]. Thus, both the excitation and the measurement techniques are required to be reproducible in a broad frequency bandwidth. Second, due to the small size, the excitation force should be sufficiently low to prevent damage to the fragile spindle bearings. And third, considering the potentially strong effect of spindle speed on the dynamic behaviour, the experiments must be conducted at different spindle speeds.

This paper presents a systematic approach to obtain dynamic characteristics of a miniature UHS air-bearing air-turbine spindle. The dynamic excitation is provided using a tailor-made miniature impact hammer apparatus to provide broadband excitation-frequency and small forces in a repeatable manner. The vibration response is measured in a non-contact manner using two fiber optic LDVs arranged in mutually orthogonal orientations. The non-ideal radial motions of the spindle are removed from the vibration measurements to isolate the dynamic response. The dynamics of the spindle is acquired at different spindle speeds in the form of frequency response functions (FRFs) using the excitation force and vibration response.

2 Experimental Facility and Test Procedure

The entire experimental setup (see Figure 1(a)) is placed on a vibration isolation table. An impact hammer system utilizing a miniature impact hammer is designed to excite the system in the *y* (vertical) direction. The response of the system in the *x* and *y* directions are measured using two LDVs. The *x* and *y* lasers are configured in a mutual perpendicular fashion [7]. An infrared (IR) sensor is used to provide a reference for the angular position of the artifact to enable removing non-ideal radial motions of the spindle.



(a) (b) (c)

Figure 1: (a) Experimental Setup (b-c) Experimental procedure (CAD model and schematic diagram)

Simultaneous measurements in *x* and *y* directions are performed at three different locations of the artifact (Figure 1(b)-(c)). The system is excited by the miniature impact hammer at one location and the responses are measured on different locations of the artifact (10 mm, 7.5 mm, and 5 mm away from the collet). From these measurements, direct and cross receptances are obtained and are used to obtain rotational FRFs at the tip [3]. The experiments are conducted at different spindle speeds (60 krpm - 150 krpm) while the air bearing pressure, collet torque, and tool overhang are kept constant as 0.5 MPa, 1.5 Nm, and 10 mm, respectively.

3 Data Acquisition and Subtraction of Error Motion

Due to the eccentricity arising from attachment errors of the artifact, and the axis of rotation errors, UHS spindles exhibit non-ideal radial motions [7]. A time domain algorithm is used to subtract the error motion from the measured data (see Figure 2). The pulses in the IR sensor data are used to mark the beginning of each rotation cycle of the artifact. The error motion value at every angular position of each cycle in the second region is determined and averaged. The averaged values are then subtracted from the measured displacements at the same angular positions of the cycles at the first region, leaving out only the transient vibrations.

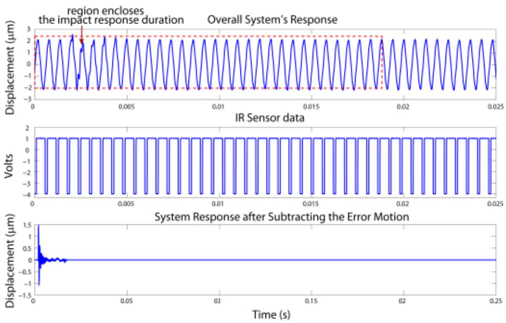


Figure 2: Steps of time domain filtering example of a sample data

4 Results and Discussion

For FRF measurements, ten averages are taken for each test. It is observed that the excitation bandwidth up to 16 kHz can be obtained. Figure 3(a) shows the artifact tip direct receptances obtained for different spindle speeds. Figure 3(b) shows the rotational tip point FRFs for 60 krpm spindle speed. Preliminary results show that the damping characteristic of the spindle is highly affected by the spindle speed. Yet, a more comprehensive quantitative study should be performed to understand the effect of different parameters on spindle dynamics. The obtained FRF information at the artifact tip can be used together with the analytically obtained tool models to predict the tool tip dynamics.

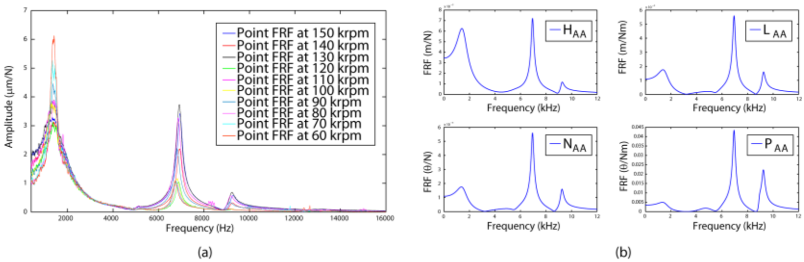


Figure 3: (a) Point FRFs measured from the artifact, (b) Translational and rotational FRFs of Point A (at spindle speed of 60 krpm)

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