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Increasing milling stability predictions accuracy considering speed dependent spindle behavior with an automated measurement device

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ABSTRACT

Manufacturers seek to enhance productivity by investing in high-speed machine tools. However, at elevated spindle speeds, dynamic characteristics of spindles may change due to thermal loads on bearings, complicating the task of finding optimal spindle speeds. To address this issue, an automated measurement system was developed to evaluate dynamic characteristics of tooling assemblies under rotating conditions. The system employs a solenoid actuator for excitation and capacitance probes for response measurement. Dynamic measurements and milling tests were conducted on a 5-axis milling machine tool and benefits of the system in improving accuracy of stability prediction are presented.

1. Introduction

High-speed machining (HSM) is attractive to manufacturers, as it can reduce cycle times and maximize productivity due to higher spindle speeds and feed rates. It is especially popular for aluminum machining. However, spindles can exhibit dynamic variations at high spindle speeds. The main culprit for these changes is usually the bearings, which experience thermal deformations, bearing load relaxation and preload changes at high spindle speeds as presented by Matsubara et al. [1], Rabréau et al. [2] and Ozturk et al. [3], respectively.

Efforts in predicting variations in dynamics due to spindle speeds often focus on rotor dynamics and structural dynamics studies requiring precise modeling of spindle systems as detailed by Abele et al. [4]. Effect of real manufacturing environment variations such as spindle manufacturing tolerances, wear and tear during production cannot be simulated accurately hence predictions of theoretical models may not be helpful in production. In addition, manufacturing engineers in the industry cannot measure variations of dynamic characteristics of milling tool assemblies and they generally conduct iterative cutting tests on machine tools to identify optimum cutting conditions. These tests result in additional lead time and waste for manufacturers.

The solution to this problem requires development of a measurement system that can automatically measure dynamic characteristics of tooling assemblies on machine tools. Various research groups have developed systems to acquire frequency response functions (FRFs) of spindles at rotating conditions. The most frequently applied design to excite tools uses magnetic excitation with electrical coil magnets. Rantatalo et al. [5] used finite element method, magnetic excitation, and inductive displacement measurements to analyze lateral vibrations in a milling spindle. The study found that bearing stiffness decreases at high speeds, which affects milling stability predictions. Similarly, Archenti [6] developed a system with an array of non-contact magnetic actuator pads around tools. This system can excite cutting tools modified with a metallic collar and collect vibration data using multiple non-contact displacement sensors. Takasugi et al. [7] proposed a novel non-contact spindle measurement method that uses the concept of an eddy current brake. Most recently, Yamato et al. [8] developed a magnetic coil actuated system that utilizes a special magnetic holder assembly (dummy tool) to capture natural frequency changes due to varying bearing preload at high speeds. Because excitation force can not be measured directly with magnetic excitation, it was predicted through magnetic field analysis. However, magnetic excitation methods often suffer inaccuracies in estimating excitation force. More importantly, the inability to measure actual cutting tools without alterations to enable magnetic excitation limits their use in obtaining precise frequency response functions for machining stability predictions for milling tools in production.

There have also been attempts to measure FRF at rotary conditions using manual methods. For example, Cheng et al. [9] performed measurements on rotating spindles by exciting them with an impact hammer manually. However, health and safety requirements within a production environment do not let such manual measurements take place in practice. Manual excitation can potentially be replaced with a commercially available automated hammer in such scenarios [10]. However, it still requires response measurement for calculation of FRFs.

This paper proposes an automated measurement system that can excite milling tools directly on production machines at a wide range of spindle speeds, overcoming the challenges of previously developed systems. The main challenge it solves is measuring actual milling tool FRFs without any modification on them. The following section details the design specifications and elements of this new system. Section 3 presents measurement results for a production tooling assembly.

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Section 4 presents milling test results for the tooling assembly, demonstrating the benefit of the new system in predicting the stability of the milling process accurately. The paper concludes with a discussion of results and future work.

2. Automated measurement system

2.1. Design requirements

Design requirements for the measurement device are listed below:

- It must be compact and lightweight so that it can be moved between machine tools easily and fits various fixture configurations,
- It must measure actual milling tools mounted in production machine tools with diameter between 10 mm to 25 mm
- It must excite the tools with a short-pulse single impacts with less than20 ms contact time to ensure acceptable frequency excitation range while generating an impact force exceeding 100 N,
- The actuation force and impact duration must be measured and adjusted depending on flexibilities of milling tools,
- Due to rotation of milling tools, response of the system must be measured without contact.

2.2. Developed system

Fig. 1 demonstrates the automated measurement system which is composed of a solenoid actuator, a force cell, two capacitive displacement sensors and a base plate that keeps all the elements together. Sensors and the actuation system require dedicated drivers and amplifiers. The system connection diagram is presented in Fig. 2.

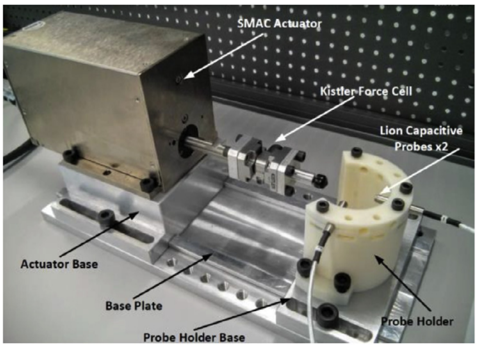

Fig. 1. Automated tap testing system.

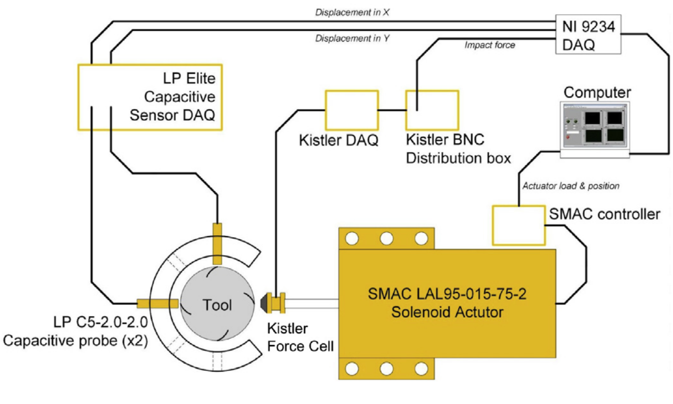

Fig. 2. System schematic and components.

The system weighs 4.5 kg and it is adaptable to both horizontal and vertical table clamping.

2.2.1. Actuator side

Considering the design requirements, the SMAC LAL95 moving coil actuator system was selected from numerous actuation options, including piezo-electric exciters and pneumatic actuators. On the actuator, a preloaded tri-axial Kistler 9317C force cell was mounted to measure the impact force accurately.

The programmable PID controller of the SMAC's actuator has been tuned using the actuator's programmable logic controller to ensure the shortest impact duration while maintaining the highest impact force value without double or multiple impacts. To ensure consistent impact force, the actuator power was automatically cut at a calibrated distance from the tool shank. A soft-touch routine was used to calibrate the required travel distance. For example, for the representative 12 mm diameter ball-end mill, a 0.5 mm free-travel distance delivered a 150 N impact force with 350 mm/s velocity and 1.2 ms impact duration. Calibration and controller tuning achieved ±4% peak force variation and ±1% impact duration difference, ensuring high repeatability for consecutive hits.

2.2.2. Response side

To acquire vibration displacement data at high rotating speeds, non-contact capacitive sensors were chosen. As maximum vibration amplitudes are generally in the order of 10 µm with a fast decay rate, the capacitive sensors provided the best and compact solution among the other sensors including laser displacement sensor and laser vibrometer. The chosen sensor (Lion Precision C5–2.0–2.0) has 50 nm measurement resolution with a measurement range of ±125 μm and a bandwidth of 15,000 Hz which gives the required amplitude and frequency measurement range for a wide range of milling tools. The system has been designed to host two identical displacement sensors in orthogonal configuration which can measure both direct and cross-FRFs. For most practical applications, one capacitive sensor inline with the actuator will be sufficient.

2.4. FRF calculation

A software application has been developed to automate impact testing with multiple excitations in series and to compute the FRFs from the captured force and displacement measurements FFTs (Fast Fourier Transforms). The peaks of force measurements were automatically detected by the software and the average of the multiple impacts are obtained. The frequency response function (FRF) was calculated as the function of FFT $X(j\omega)$ of the captured free vibration displacement $X(t)$ and FFT $F(j\omega)$ of the force impulse $F(t)$. Hence, the FRF calculation can be simply defined as the ratio of cross-power spectrum, $S_{xF}(j\omega)$ and the autospectrum of the force signal, $S_{FF}(j\omega)$ (Eq. (1)) [11].

$$\Phi = \overline{S_{xF}(j\omega)}\,\overline{S_{FF}(j\omega)} = \frac{\frac{1}{N_m}\sum_{n=1}^{N_m}[X(j\omega)\cdot F(j\omega)]}{\frac{1}{N_m}\sum_{n=1}^{N_m}[F(j\omega)\cdot F(j\omega)]} \tag{1}$$

The accuracy of measurements was checked by calculating the coherence using (Eq. (2)) where $\overline{S_{xF}(j\omega)}$ and $\overline{S_{FF}(j\omega)}$ are the average cross-power spectrum and autospectrum of N_m impacts, respectively.

$$\gamma_{xF}^2 = \frac{\left|\overline{S_{xF}(j\omega)}\right|^2}{\overline{S_{FF}(j\omega)}\cdot\overline{S_{xx}(j\omega)}} \tag{2}$$

2.5. Special considerations

It is worth noting that the measurements with the system at rotating conditions have to be made on shanks of milling tools rather than tool tip due to flutes of milling tools. As a solution, an indirect measurement method was utilized. The relation between the measurements at the shank and at the tooltip were measured by manual tap testing for a given tool at static conditions which is represented as G21 measurement in Fig. 3. This involves exciting tool tip (point 1) with an impact hammer manually and measuring the response of the tool in the shank (point 2) via an accelerometer. Then, at rotating conditions, measurement was done at the shank as G22 measurement where the actuator automatically excites the shank (point 2) and the capacitive sensor measures the response of the tool on the

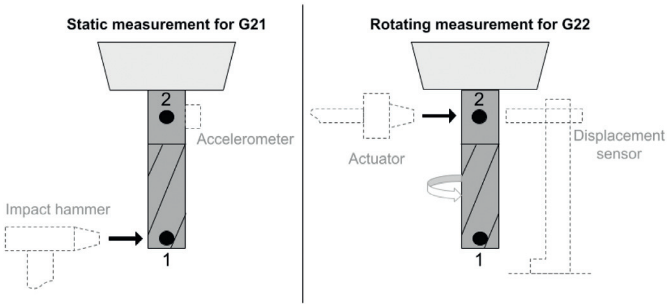

Fig. 3. (a) G21 using manual tap test, (b) G22 measurement at rotating conditions.

shank (point 2). Using these two measurements, namely G_{21} and G_{22}, the tool tip frequency response function G_{11} was calculated using the Eq. (3) for each spindle speed. This formulation assumes that G_{21} measurement is not influenced by spindle speed and G_{12} and G_{21} measurements are equal to each other [11].

$$G_{11} = \frac{G_{21} \cdot G_{12}}{G_{22}} = \frac{G_{21}^2}{G_{22}} \tag{3}$$

In the future, by integrating an additional displacement sensor in the system at a higher position along the tool axis , G_{21} can also be measured with the setup automatically rather than the manual tap test. The tool will need to move to a higher position for making the G_{21} measurement after G_{22} measurement is completed.

3. Dynamic measurement results

The experimental setup utilized a 5-axis Starrag Ecospeed machine tool equipped with a 30,000 rpm spindle. The measurement system was fixed to the machine's vertical tombstone using a vice clamp. A 12 mm diameter solid carbide ball end mill with two flutes (Sandvik R216.42–12,030-AK22A H10F) clamped to a shrink fit tool holder (Bilz ThermoGrip T1200–120/HSKA63) was selected and measured.

In this test setup, the G_{22} was measured on the shank, 45 mm above the tool tip which corresponds to the 2nd point while the 1st point indicates the tool tip as shown in Fig. 3.

Firstly, a benchmark test was conducted to compare measurements from the automated system and manual impact testing. This was done while the system was stationary and G_{22} measurements were collected with both setups. As shown in Fig. 4(a), the results are close to each other up to 3000 Hz. The coherence calculated for the automated system is also acceptable up to 3000 Hz. The most dominant mode is measured as 1340 Hz in both manual and automated measurements.

After the G_{22} measurement, G_{21} and G_{11} were measured using the manual method and presented in Fig. 4(b) and (c) respectively. Finally G_{11} is computed using Eq. (3). This is benchmarked with the measurement of G_{11} obtained with the manual tap test in Fig. 4(c). The results are close to each other up to 3000 Hz. The method with the automated system slightly overestimates the magnitude of the mode at 3500 Hz and the automated system misses the mode at 4500 Hz which was captured by the manual test. However, it can be concluded that the method with the automated system gives reliable results up to 3000 Hz for the given tooling assembly and captures the dominant tool natural frequencies accurately.

The automated impact test system was used to measure the dynamics response at every 1000 rpm starting from static condition up to 30,000 rpm. The computed direct tool tip FRFs, G_{11}, for each spindle speed is presented in Fig. 5. The analysis indicated that the magnitude of the frequency response function at the most dominant mode at 1340 Hz increased considerably (50%+) after 8000 rpm while the natural frequency of the same mode decreased slightly (2–3%) compared to the static measurement. Such changes will cause considerable variations on the stability limits. Decreasing natural frequency shifts the optimum spindle speeds to lower values while increased magnitude of FRF means more instability in the milling tests at higher speeds.. The G_{11} is also computed for the y direction (G_{yy}) from dedicated y-axis G_{22} measurements using the system. For completeness,

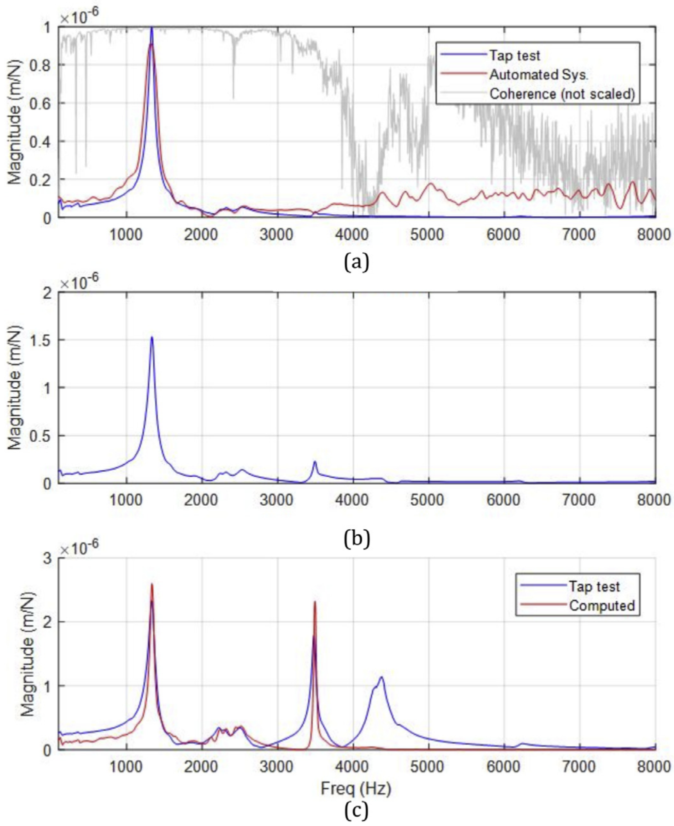

Fig. 4. Measurement at static conditions in X direction of the machine tool a) G_{22} b) G_{21} c) G_{11}.

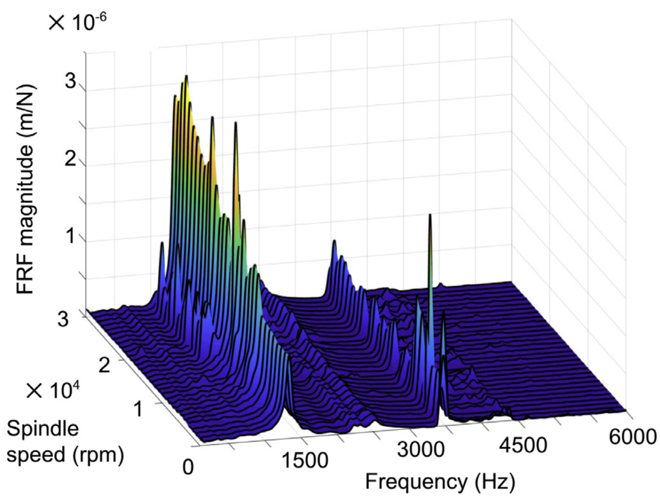

Fig. 5. Magnitude of FRF between 0–30,000 rpm.

the cross-FRF (G_{xy}) is also captured using the second displacement sensor. It was observed that the magnitude of the cross-FRF was an order of magnitude lower compared to the direct measurement.

In order to demonstrate robustness of the measurement solution, the automated measurement system was installed on three different machine tools including Hermle C52, Cincinnati FTV5 and Starrag X40 in addition to Starrag Ecospeed. Former two of these machines had horizontal tables while the latter two had vertical tables. The method worked well in all four scenarios. Moreover, in addition to the 12 mm ball end mill, two other flat end tools which were 16 mm and 20 mm in diameter were also tested with the system. These tests were conducted with the same setup without any modification aside from the gap adjustment for the non-contact displacement sensors for different diameter tools.

Although not observed in the provided 12 mm diameter tool example, in the case of the 16 mm diameter tool, a frequency shift of 9% has been observed for the dominant natural frequency (2682 Hz at static condition, 2910 Hz at 30,000 rpm). In cases where natural frequency shift is more than around 5% of the static measurement, the methods presented in Eq. (3) were observed to provide overestimated FRFs due to the frequency response phase mismatch.

To circumvent the overestimation, an alternative modal parameter correlation based method was proposed where the mode shape relation between the G_{22} and G_{21} measurements was utilized. The procedure begins by measuring G_{21} and G_{22}. After extracting the modal parameters from these measurements, the mode shapes were inferred and the ratio of modal stiffness (r_k), denoted $r_k = k_{G22}/k_{G21}$ is determined for each mode from the static measurements of G_{21} and G_{22}. Once the G_{22} is measured at rotating conditions, r_k is applied to estimate the corresponding tool tip response, G_{11} FRF while retaining the extracted damping ratios and natural frequencies from the G_{22} measurement.

4. Experimental cutting tests

A milling test was designed where the 12 mm ball end mill tool machined the edge of an Al7075-T6 workpiece without engaging the tip of the tool with the workpiece. Force measurements were done to calculate the specific cutting force coefficients (CFCs) using a Kistler 9139AA dynamometer. The CFCs were identified to be $[K_{rc}, K_{tc}, K_{ac}] = [453, 956, 235]$ MPa.

The step over into the workpiece was 4 mm and depth of cut was 5.4 mm in an up milling scenario. As the tool moved along the tool path, lead and tilt angles changed continuously where lead angle varied between 0° and 20°, and tilt angle varied between −10° and 10° The variation of lead and tilt angles caused variation in the tool workpiece engagement throughout the cut and resulted in a varying stability behavior along the tool path.

Milling tests at 26 different spindle speeds between 9300–12,300 rpm were performed. Each test was demonstrated with a straight line in Fig. 6 where X axis represents length of the toolpath path and Y axis represents spindle speed. If the process experienced chatter during tests, the conditions where chatter was observed was marked with markers *. For example, at 12,300 rpm, the process chattered initially hence there are * markers in the beginning, then the process got stable for a while and it chattered again in most of the second half of the toolpath as indicated by * markers. In another example, at 11,300 rpm, no chatter was observed throughout the cut; hence, it is a straight line throughout the cut without any * markers in Fig. 6.

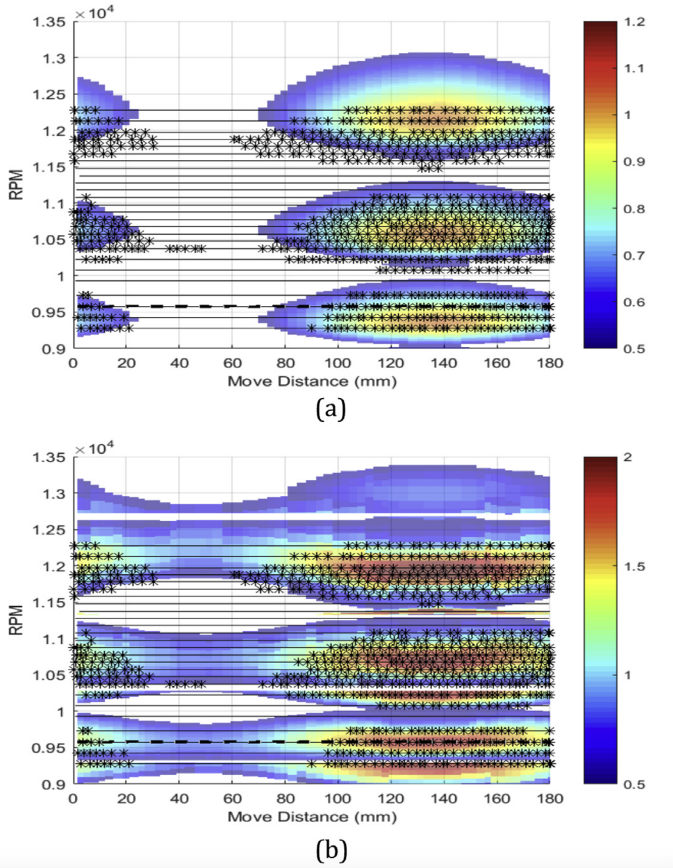

Fig. 6. Experimental results with stability roadmap, *markers represent regions with chatter. Stability map (a) using static FRFs (b) using rotating FRFs.

These experimental results were compared with the predicted stability map. Stability map formulation uses the zeroth order frequency domain formulation by Ozturk and Budak [12], however it calculates the maximum value of the eigenvalues rather than stable depths of cut at each point on the tool path. If the eigenvalue is below 0.5, then the process is stable. If it is above 0.5, the process is unstable and the magnitude of the eigenvalue is plotted as a heatmap in Fig. 6 for two cases. Higher the magnitude of the eigenvalue, higher the severity of chatter vibrations predicted.

In Fig. 6(a), static FRF measured by the automated system was used for plotting the heatmap. In Fig. 6(b), the measurements obtained at rotating conditions were used. Blue regions show low severity chatter vibrations areas while red regions show high severity chatter areas. It is clear from the results that predictions with the static FRF results overestimate the stability in certain areas. However, rotating FRF measurements in Fig. 5 demonstrated that magnitude of the FRF increased after 8000 rpm and there was a slight shift of natural frequencies at higher speeds. The effects of these are visible in the stability map in Fig. 6(b). Using rotating FRFs in the stability predictions increased the accuracy of the stability predictions significantly. For example, the stability map with static FRF results failed to predict the chattering cases between 10,000–10,500 rpm and between 11,500–12,000 rpm while the stability map based on the rotating FRFs at Fig. 6(b) successfully predicted those chattering cases.

5. Conclusion

This paper presents the design, development and application of an automated measurement system for assessing nonlinear dynamic behavior of milling tool assemblies at high rotating speeds. The proposed system overcomes the limitations of existing methods by enabling direct excitation and measurement of actual milling tools in production without requiring modifications to milling tools. Using a solenoid actuator for controlled excitation and non-contact capacitive sensors for response measurement, the system demonstrated repeatable measurement of FRFs of tooling assemblies under both static and rotating conditions automatically.

The experimental results validated the accuracy of the automated system when compared with manual impact testing at static conditions. Measurements up to 30,000 rpm revealed significant increases in magnitude of the dominant mode and slight reduction of natural frequencies in the presented case. In different tools and machine tools, larger changes in the dominant frequencies were observed. Milling test results confirmed that the use of FRFs obtained under rotating conditions improved the accuracy of machining stability predictions compared to static FRFs, thereby reducing the risk of chatter during high-speed machining.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

O. Ozkirimli: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **E. Ozturk:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

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References

[1] Matsubara A, Asano K, Muraki T (2015) Contactless dynamic tests for analyzing effects of speed and temperature on the natural frequency of a machine tool spindle. *High Speed Machining* 1(1):18–26.

[2] Rabréau C, Ritou M, Le Loch S, Furet B (2017) Investigation of the evolution of modal behavior of HSM spindle at high speed. *Procedia CIRP* 58:405–410.

[3] Ozturk E, Kumar U, Turner S, Schmitz T (2012) Investigation of spindle bearing preload on dynamics and stability limit in milling. *CIRP Annals* 61(1):343–346.

[4] Abele E, Altintas Y, Brecher C (2010) Machine tool spindle units. *CIRP Annals* 59 (2):781–802.

[5] Rantatalo M, Aidanpää J-O, Göransson B, Norman P (2007) Milling machine spindle analysis using FEM and non-contact spindle excitation and response measurement. *International Journal of Machine Tools and Manufacture* 47(7–8):1034–1045.

[6] Archenti, A., 2011. A Computational Framework for control of machining system capability: from formulation to implementation. PhD thesis, KTH Royal Institute of Technology, Stockholm, Swenden.

[7] Takasugi K, Sakai H, Ooshima M, Noda D, Asakawa N (2022) Development of contactless dynamic spindle testing using an eddy current brake. *Precision Engineering* 74:396–402.

[8] Yamato S, Yokohara Kazuma, Nara Y, Matsubara A (2025) Static and dynamic measurements of spindle system during rotation by noncontact electromagnetic loading system. *International Journal of Automation Technology* 19(1):24–40.

[9] Cheng C-H, Schmitz TL, Scott Duncan G (2007) Rotating tool point frequency response prediction using Rcsa. *Machining Science and Technology* 11(3):433–446.

[10] Automatic modal hammers | vImpact | MAUL-THEET, 2024, December 16). MAUL-THEET. https://www.maul-theet.com/products/measuring-equipment/automatic-modal-hammers/#technical-data. Accessec January 4, 2025.

[11] Altintas Y (2012) *Manufacturing automation: metal cutting mechanics, machine tool vibrations, and CNC design*, Cambridge university pressCambridge, United Kingdom.

[12] Ozturk E, Budak E (2010) Dynamics and stability of five-axis ball-end milling. *Journal of Manufacturing Science and Engineering* 132(2):021003.

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