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Innovative Design and Machining Verification of a Dual-Axis Swivel Table for a Milling Machine

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ABSTRACT

This study was aimed to develop a dual-axis rotary table for small and medium-sized five-axis milling machines. The rotation and tilting axis of swivel table were respectively driven by servo motor with gear reducer to achieve low speed, high torque, high rigidity and high precision machining capability. Essentially, the dynamic interaction between the workpiece and the cutter in the cutting process is an important factor that affects the machining performance, which also implies that the structural characteristics of the rotary table with the tilting angle will affect the cutting performance of the five-axis machine. Therefore, at the design stage of a five-axis machine tool, it is a prerequisite to evaluate change of dynamic characteristics of the rotary module within the desired feeding range. To this purpose, this study employed the finite element method to analyze the dynamic characteristics of the rotary table under different configurations. In order to evaluate the application feasibility of the dual-axis module on a milling machine, ISO S-shaped machining tests were carried out. Meanwhile, considering the influence of machining vibration on the surface quality of the work piece, the vibration induced at spindle tool and rotary table were assessed for comparisons and used to evaluate their variations with the milling cycles. Based on various experimental results, it is confirmed that the proposed dual-axis rotary table has good structural dynamic characteristics with stable vibration features during a small batch production tests. Current results clearly demonstrate the potential and capability of the proposed dual-axis rotary table in practical application and commercialization.

Keywords: dual-axis rotary table, dynamic characteristics, five-axis milling machine, machining stability.

INTRODUCTION

Five-axis milling machines have been widely used to process complex-shaped parts, in which the dual-axis rotary table that controls multi-axis surface cutting is the most important primary module. In general, the driving mechanism of the dual-axis rotary table was constructed by servo motors and gear reduction mechanisms to increase the driving torque at lower speed. Gear reduction mechanisms usually could be the worm gear mechanism or roller gear cam mechanisms with speed reduction ratio of 30 to 60. For example, as shown in Figure 1(a), a dual axis rotary table with diameter of 250 mm was driven by roller gear cam mechanisms in rotation and titling axis, respectively, in which the tilting axis was rated with driving torque of 500 Nm and speed of 25 rpm and the rotation axis was rated at 50 rpm. This rotary table with mechanical transmission mechanism can achieve high transmission torque and torsion rigidity, but the surface wearing and backlash of the transmission components generated during long-term operation probably affects the dynamic response, motion accuracy and precision [1-2].

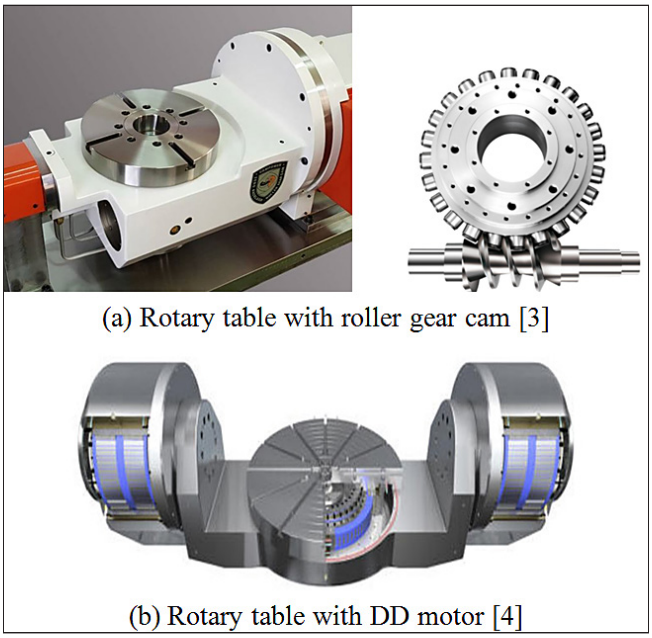


Fig. 1. Dual-axis rotary table, (a) driven with roller gear cam transmission mechanism, (b) driven with direct drive motor

The other kind of the dual-axis rotary table was directly driven by torque motors in rotation and tilting axis. The advantages of direct driven mechanism include high rotation speed, better motion accuracy, high dynamic response and no clearance. Therefore, they are often used in high-precision five-axis milling machines. For example, as shown in Figure 1(b), the rotary table with diameter of 600 mm was constructed with high driving torque of 2800 Nm at 80 rpm in swivel axis and the C-axis is rated at 105 rpm. In commercial application, the above mentioned dual-axis rotary table are designed for five axis milling machine rated at medium and heavy duty loading capacity and working space.

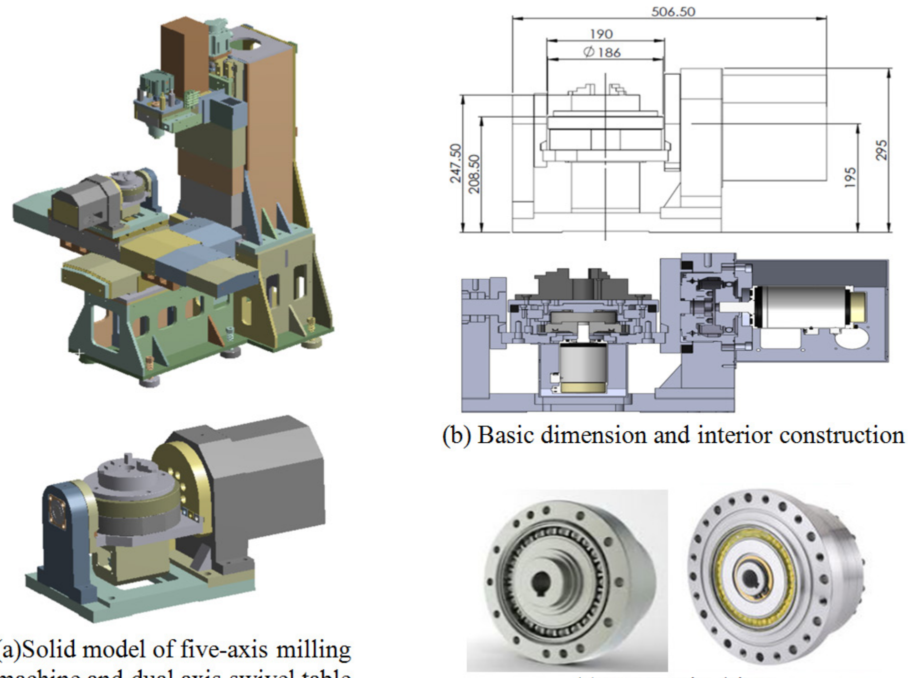
Recently, compact multi-task milling machines are highly demanded for manufacturing of the small components, which was designed with feeding strokes of around 350×250×300 mm in X, Y and Z axis, respectively. To meet multiple axes machining, small scaled titling rotary with compact size and required dynamic specification is a prerequisite for developing the compact multi-task milling machines. To this purpose, this study proposed an innovative design of dual-axis rotary table rated with high torque transmission, working capacity and dynamic performance. The rotation and tilting axis are driven by harmonic drivers and servo motors. The harmonic driver has been widely used as the joint actuator in robotic system, in which the contact mechanical characteristics of the flexible parts in harmonic gear reducer are shown to have great influence on the motion and vibration characteristics [5]. Therefore, in order to achieve development goals, designers must evaluate the structure characteristics and specifications of driving components within the desired spatial configuration of the rotary module [6, 7].

On the other hand, in five-axis machining, the engagement between the cutter and the workpiece will change with the feeding path, yielding the cutting force to change with the lead and tilt angles of the tool during the machining process. This further affects the machining stability of the tooling system [8-11]. For example, Ozturk and Budak [10] derived the analysis model for calculating the dynamic milling force and tool deformation of five-axis milling tool. Their results showed that the lead angle and tilt angle of milling tool have great influences on the stability of cutters. In addition, considering the dynamic interaction effects between the workpiece and the cutter in the machining process, Li et al. [12] proposed a general cutting dynamics model to investigate the forced vibration of the five-axis machine tool, which can be used to predict the vibration behavior of workpiece under different tooling configuration. Hung et al. [13] investigated the influence of the spindle orientation on tool point dynamics and machining stability for a milling machine with rotary head and showed that the changing of the spindle tooling axis orientation indeed alter the structural configuration of the spindle tooling system and hence the machining performance. This shows that the structure performance of the swivel head or rotary table, and the dynamic motion accuracy affect the cutting performance of the five-axis machine [7, 14]. Therefore, at the design stage of a five-axis machine tool, it is important to evaluate variation of dynamic characteristics of the rotary module within the feeding range according to the processing requirements. Basically, the static and dynamic characteristics of a rotary module are greatly affected by the torsional rigidity of the feeding drive mechanism [15]. Wei et al. [16] reported that the dynamics of tilting table driven by worm gear mechanism in the tilting direction are affected significantly by the stiffness of the transmission system, which was found to vary at different tilting angles. Du et al. [17] further proposed an integrated model by coupling the spindle-bearing module with the rotary-tilting spindle head structure. This model was employed to predict the tool point frequency response functions of the milling spindle at arbitrary posture. Essentially, above mentioned researches clearly indicate a strong dependence of machining stability on tooling orientation.

As known, compact milling machines offer advantages in terms of space efficiency and cost-effectiveness. Despite their smaller size, they are capable of delivering machining performance comparable to medium-sized machines. Currently, commercially available rotary table usually utilizes the direct drive motors or roller gear components as the main drive mechanisms. Typically, compact rotary tables featuring a table diameter ranging from approximately 170 to 210 mm are designed to operate with a swivel speed between 20 to 30 rpm and can deliver a maximum torque of around 300 to 400 Nm. The maximum installation dimensions for these tables are approximately 1000×700 mm in length and height [3, 4]. Despite its high driving torque, this module is not suitable for implementation on a milling machine with a worktable size of approximately 450×300 mm in length and width. Furthermore, considering manufacturing costs and the selection of key component specifications, customization of the rotary module for specific applications are not conducive. In response to market demands for manufacturers to upgrade existing three-axis small milling machines to five-axis machines, and taking into account working space and machining capacity, this study aims to develop a dual-axis rotary table suitable for mounting on machines with a worktable size of 450×300 mm. As a well-known fact, the combination of compact design, high torque density, precision, smooth motion, and reliability makes harmonic drives a favorable choice in various robotic applications, contributing to improved performance and efficiency in robotic systems. Therefore, harmonic drivers were employed as the driving mechanism for both the rotation and swivel axes of the rotary table. This design specification ensures that the workspace and load-carrying capacity are comparable to commercially available rotary modules. To guarantee that the mechanical performance aligns with the necessary processing capacity and cutting efficiency, modal and harmonic analyses were conducted during the design phase. This involves utilizing a finite element modeling approach to assess the structural dynamic performance of the rotary table and, consequently, to understand the impacts of the driving mechanism. Additionally, tapping tests were performed on the prototype to assess the dynamic behavior variations under different tilting configurations, serving as a validation for the finite element computations. Subsequently, several cutting tests were executed on the milling machine equipped with the rotary table to analyze the vibration responses of the spindle tool and the rotary table under the influence of cutting forces. The results of these tests were employed to demonstrate the practical applicability and effectiveness of the proposed dual-axis rotary table, enhancing the potential for future commercialization.

DESIGN OF DUAL-AXIS SWIVEL TABLE

Figure 2 shows the solid model of the two-axis swivel table designed for a three axes milling machine. The worktable has a diameter of 190 mm with load capacity of 90 kg. The main dimensions of the module is 475×250×275 mm in length, width and height, which can be well accommodated within the space of the vertical milling machine shown in Figure 2. The rotation axis (labeled C-axis) and tilting axis (labeled B-axis) was respectively driven by the gear reducers (harmonic driver) with servo motors. The harmonic driver of C-axis and B-axis has the same speed ratio of 80. The maximum speed of the tilting axis is 25 rpm with continuous and maximum torque of 206 and 520 Nm, respectively. The maximum speed of the rotation axis is 35 rpm with continuous and maximum torque of 101 and 304 Nm,



(a)Solid model of five-axis milling machine and dual axis swivel table

(b) Basic dimension and interior construction

(c) Harmonic driver

Fig. 2. Solid models of five-axis milling machine and dual-axis swivel table with main components and the milling machine

respectively. Due to the structural interference within working space, the tilting axis has a swiveling range from −15° to +105° about Y axis and the rotation table can be rotated infinitely about Z axis. The prototype of rotary table was made of medium carbon steel S45C, as shown in Figure 3.

ASSESSMENT OF VIBRATION CHARACTERISTICS OF SWIVEL TABLE

Impact tapping tests

In this section, tapping tests were conducted on the swivel table to extract the dynamic characteristics such as the frequency response functions and modal parameters. The experiment configuration of tapping test is shown in Figure 3, in which the prototype with dimension in length, width and height of 475×250×275 mm was placed on the granite platform.

Two accelerometers (PCB, 652A25) were mounted on fixture chuck to assess the vibration excited by impact hammer (PCB, 086D05) along the swivel direction and axial direction of the swivel axis, respectively. The impact hammer equipped with force transducer at the hit tip can measured the force imparted on the tested object. The time series dynamic response (in g/N) is obtained by dividing the measured acceleration signal, given in units of g, by the impact force in Newtons (N). Details of the testing procedure and

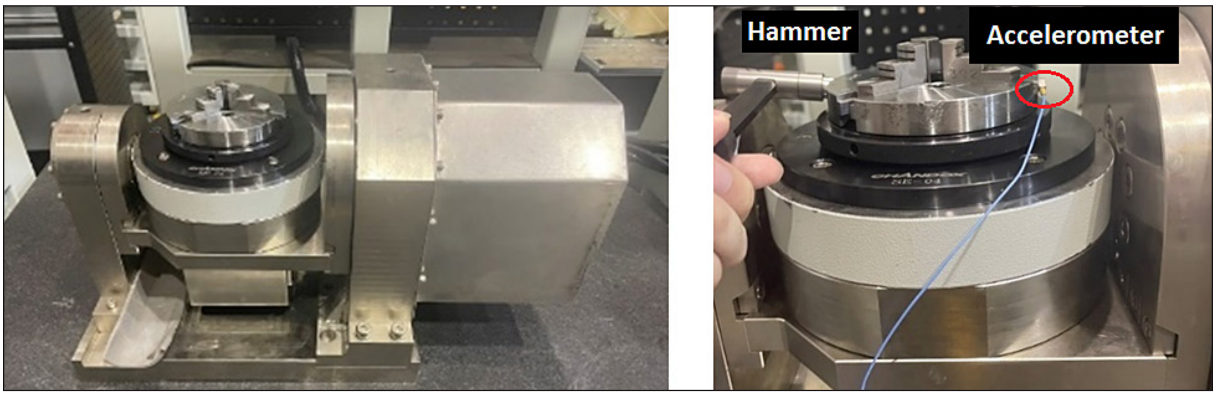
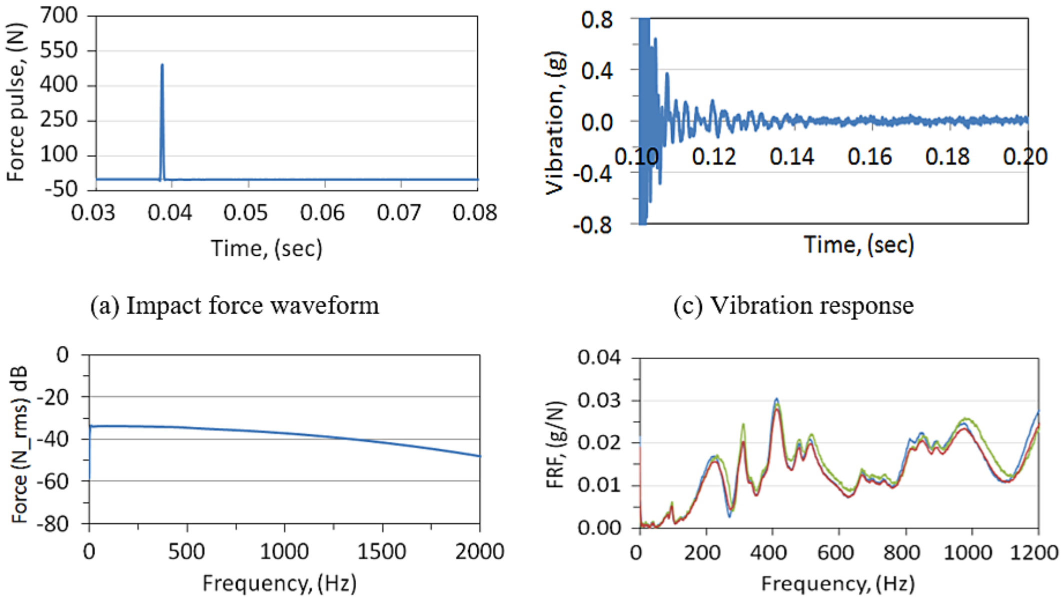


Fig. 3. Configuration of tapping test of swivel table placed on the granite platform



(a) Impact force waveform
(c) Vibration response
(b) Force frequency spectrum
(d) Frequency response function

Fig. 4. Signals involved in impact vibration test, (a) Impact force waveform, (b) Force frequency spectrum, (c) Vibration response, (d) Frequency response function

techniques are available in reference [18]. Typically, each measurement at specific point was repeated for at least three impacts. Each impact was conducted with single shock pulse without double hit. As shown in Figure 4, the impact force applied on the rotary table shows a clean pulse with peak about 490N. Its frequency spectrum ensures the force level across the frequency range of interest and hence the vibration response can be accurately triggered and assessed by sensor. Finally, the dynamic response was averaged from the results of three impacts, which was transformed into frequency response functions (FRFs) through Fast Fourier Transformation (FFT). Essentially the FRF is expressed in terms of vibration amplitude in acceleration (g) as a function of frequency (in Hertz, Hz), as shown in Figure 4 (d), illustrating the frequency responses from three measurements. The frequency response function can be used to characterize the dynamic compliance of the tested rotary module.

Frequency response functions

Figure 5 shows the frequency response functions assessed at the fixture of the worktable along the swivel direction and Y-axial direction, respectively. From figure, it is found that the rotary table shows some peak amplitudes at frequency around 101, 205, 368 and 437 Hz, respectively. The modal shapes of these fundamental modes can be clearly illustrated by finite element modal analysis presented in Section 3.3. In addition, as shown in Figure 5, the table fixture has significant amplitude around 0.13 μm/N at 205 Hz, which represents the maximum compliance, also the minimum dynamic stiffness, of the rotation table in the swivel direction. Besides, the compliance associated with this mode was found to change with the change of the tilting angle, as shown in Figure 6. The maximum compliance varies around 0.082–0.13 μm/N for table swiveling from horizontal (90°) to vertical direction (0°), as listed in Table 1. The lowest compliance of the fixture occurs at the vertical direction. The variation of the maximum compliance within the tilting range is about 37%.

Similarly, the frequency response function in Y axis shows the maximum compliance occurring at 100 Hz, and the next at 437 Hz. The maximum compliance was found to vary with the tilting angle. The maximum compliance changes from 0.132–0.384 μm/N for table swiveling from horizontal to vertical direction. The rotary table has lowest value of maximum compliance (0.132 μm/N) when it was positioned at horizontal state, but the compliance reaches highest value at tilting positions (60 and 90 degree), which can be the weaker position of the rotary table. Results of the taping tests clearly demonstrate that the dynamic compliance of the table can be affected to vary with the tilting angle due to the change of the structure configuration in swiveling motion.

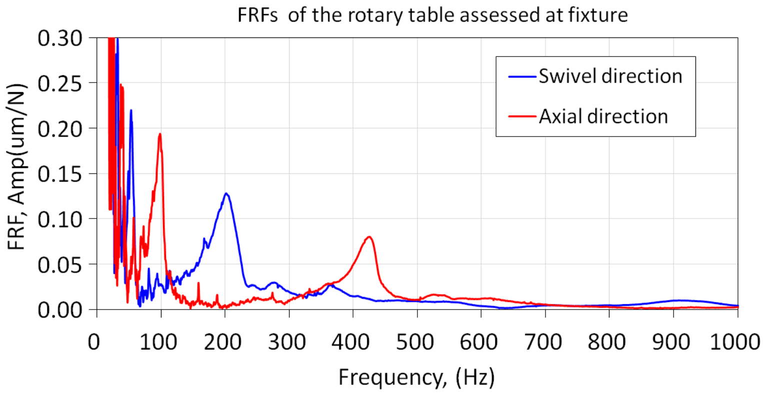


Fig. 5. Frequency response functions of the worktable along swivel direction and Y-axial direction

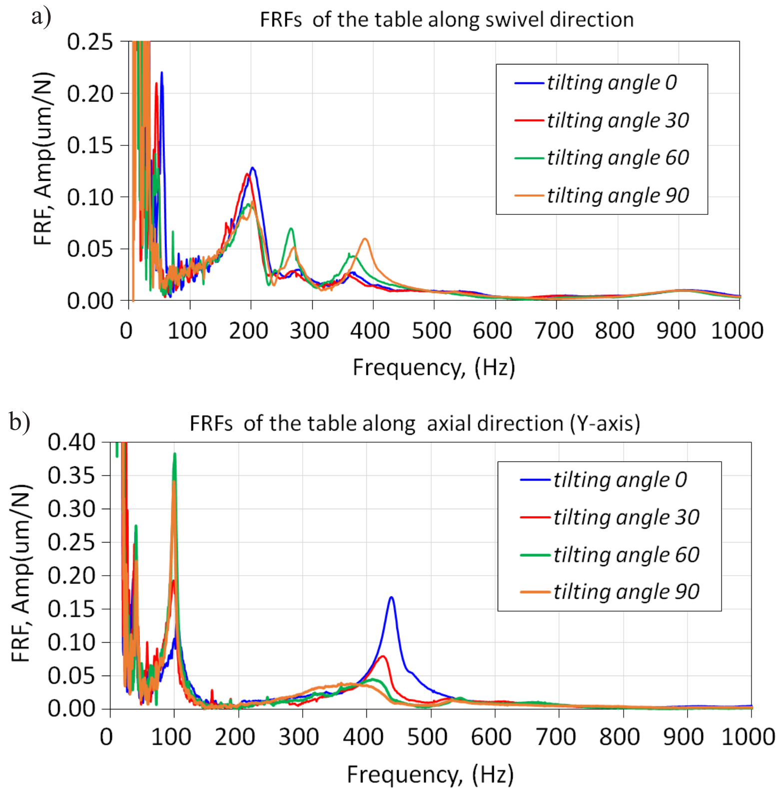


Fig. 6. Comparisons of frequency response functions of the rotary table at different tilting angle, (a) along swivel direction, (b) along Y-axial direction

Table 1. Variation of the modal compliance of rotary table with change of tilting angle

Swinging angle	Maximum compliance (μm/N)		Minimum stiffness (N/μm)	
	Y-axis direction	Swivel direction	Y-axis direction	Swivel direction
0°	0.132	0.130	7.569	7.702
30°	0.194	0.113	5.166	8.869
60°	0.384	0.090	2.606	11.131
90°	0.341	0.082	2.930	12.153

Finite element modeling

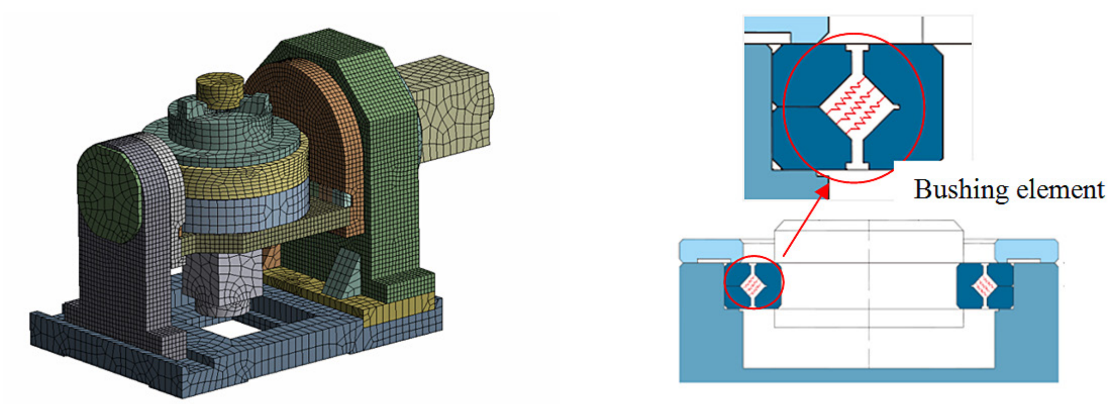
The dynamic characteristics of the dual-axis swivel table can also be analyzed by finite element method, apart from the tapping test. The result can help designer to determine the structure configuration and specification of components at design phase. Figure 7 shows the finite element model of the rotary table, which was meshed using eight-node hexahedral element with a total number of 48,642 elements and 171,942 nodes. Basically the non-rotating components and machine structures were assumed as fully bonded contact status. In harmonic drivers, the cross roller bearing and the flexspline gear with circular spline gear, which consist of the rolling/sliding interface in contact sites, are the main parts dominating the transmission performance and dynamic characteristics of the module [19] These components were appropriately simplified in geometry. The rolling interfaces were modeled by surface contact elements with adequate stiffness or rigidity [20]. The rigidity against moment loading of cross roller bearing is 99.45 kNm/rad in C-axis driver and 179.2 kNm/rad in B-axis driver respectively [21]. Besides, the torsion rigidity of the gear train in harmonic driver, which is defined as the ratio between the applied torque to the wave generator and the torsion angle at output gear, is rated at 7.55 kNm/rad for C-axis driver and 276 kNm/rad for B-axis driver, respectively [21]. These values were introduced in the rolling interfaces.

The materials used for structural components of swivel module are made of carbon steel with an elastic modulus E = 200 GPa, Poisson's ratio $\mu = 0.3$, and density $\rho = 7800$ kg/m^3. With this model, the vibration modal shapes and the frequency responses were predicted through the modal analysis and harmonic analysis. The boundary conditions are imposed on the bottom surface of machine bases with fully constrained state. The harmonic analysis was performed to measure the frequency response at the fixture of rotary table. In the finite element governing equation for harmonic analysis, the damping matrix was assumed to be proportional to the structural stiffness matrix [K] according to the relationship $[C] = \beta[K]$. The value β represents the structural damping constant, depending on the damping properties of the material. Here, the damping constant was assumed as 5.0% for the model.

Dynamic characteristics of of swivel table

According to the results of modal analysis, the fundamental vibration motions of the swivel table were illustrated in Figure 8. The vibration mode at around 197 Hz is associated with the swing motion of rotary table along the swivel direction of (B-axis). It is clear that this mode is dominated by the driven mechanism of tilting axis, especially the torsional rigidity of the harmonic driver. The swivel mode is comparable to the critical mode at 205 Hz, which induced significant vibration amplitude as observed in the frequency response function measured from prototype machine. The mode at 352 Hz is the yawing vibration of the whole structure of C-axis rotation table with B-axis cradle, but also coupled with the bending vibration of the rotation shaft of C-axis. The predicted modal frequency is close to measured value of 360 Hz. In some extent, it was affected by the bending stiffness of the bearing in B-axis and C-axis. The vibration mode at 118 Hz is the forward and backward movement of the cradle of rotation table along axial direction, also the Y-axis of the milling machine. The vibration mode at 418 Hz is the lateral bending vibration of the rotation shaft of C-axis, which is affected by the bending stiffness of bearing in C-axis harmonic driver.

Overall, the results of modal analysis reveal that the predicted modal frequencies are in good agreements with the measurements of the tapping



(a) Finite element model of the two axis swivel table

(b) Modeling of the cross roller bearing

Fig. 7. Finite element model of the two axis swivel table and modeling of the cross roller bearing

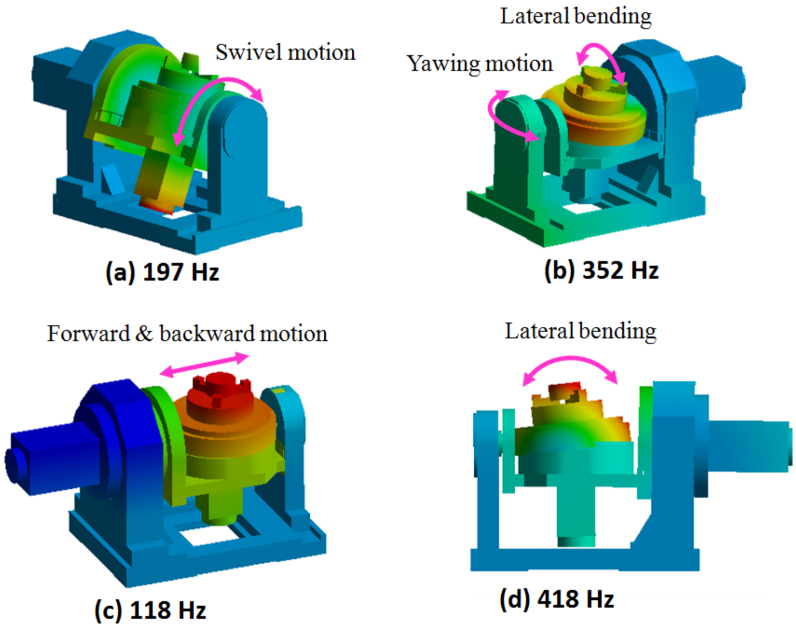


Fig. 8. Fundamental vibration modal shapes of dual-axis rotary table

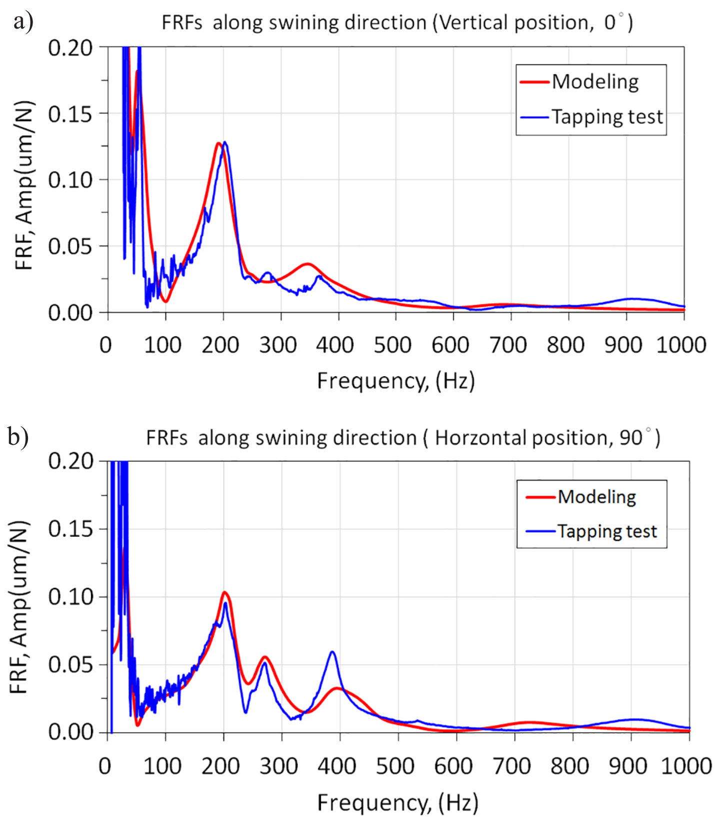


Fig. 9. Comparisons of predicted FRFs of rotary table with measurements

tests, with the difference about 4–10%. This indicates that proposed rotary model with the modeling of the interface characteristics of the driving components can accurately describe the vibration characteristics of the dual-axis rotary table.

The frequency response functions of the rotary table predicted by harmonic analysis were illustrated in Figure 9 for comparison with the measurements. As observed, the predicted FRFs of the rotary table at vertical and horizontal position agree well with the measured FRFs by tapping tests. The maximum compliances of the rotary table at vertical and horizontal position are accurately predicted. This clearly indicates that the

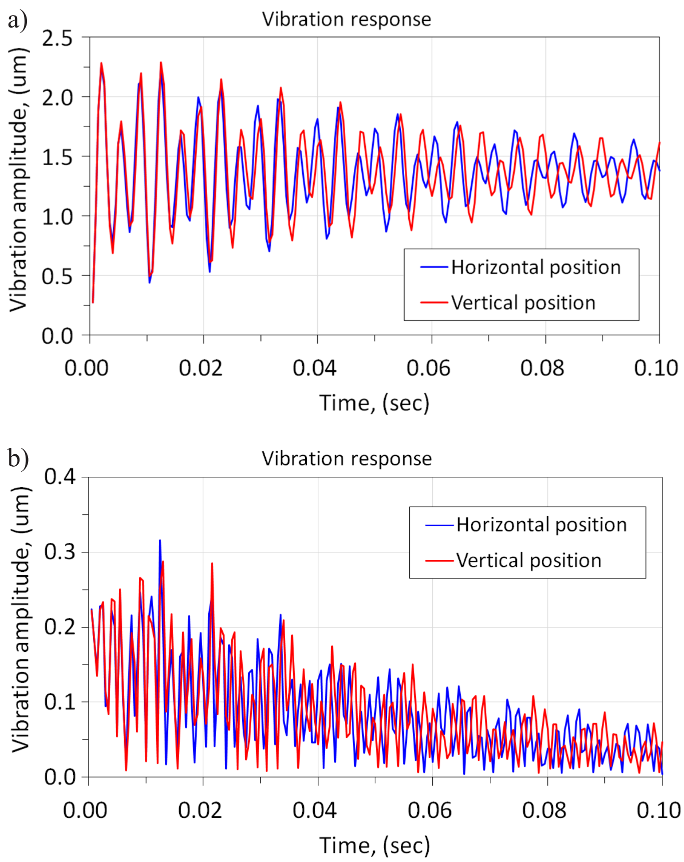


Fig. 10. Predicted vibration responses of rotary table at vertical and horizontal positions. a) vibration response (displacement); b) vibration response (acceleration)

finite element model of the dual-axis rotary table can show the dynamic behaviors as found from a physical prototype.

With this model, we can predict the vibration response of the rotary table when it subject to the shock loads from instant engagement of the cutting tool and workpiece. The results are depicted in Figure 10, which shows the amplitude of vibration response in unit of displacement (μm) and acceleration (g), respectively. In this analysis, shock load of unit newton was applied on the fixture chuck of the rotation table. It is found from Figure 10 that the transient vibration behavior of the rotary table at vertical position is similar to that at horizontal position, with slightly difference. This indicates the rotary table has consistent structure performance in responding to the external dynamic excitation, favorable to sustain the loading condition in machining process.

MACHINING VERIFICATION

To assess the feasibility and stability of the rotary table in withstanding cutting forces during machining, experiments were conducted on a five-axis milling machine. These tests was aimed to evaluate the vibration behaviors induced during the machining process, which are critical characteristics influencing machining quality and can serve as indicators of the structural performance of the rotary table. Two distinct machining tests were performed: slot milling along a circular cylindrical part and five-axis S-type milling. The machining configurations are illustrated in the following.

Circular slot milling

The configuration of the machining test is illustrated in Figure 11. An aluminum workpiece (Al 6061) with a diameter of 50 mm and a length of 30 mm was secured onto the fixture of rotary table. A high-speed steel (HSS) end miller with four flutes and a diameter of 10 mm was inserted in the spindle tool holder. The cutting process was conducted by full slot machining along the circumference of the part, which was driven by the C-axis to feed against the cutter. The spindle tool's rotational speed and C-axis of the rotary table were set at 7500 rpm and 30 rpm, respectively.

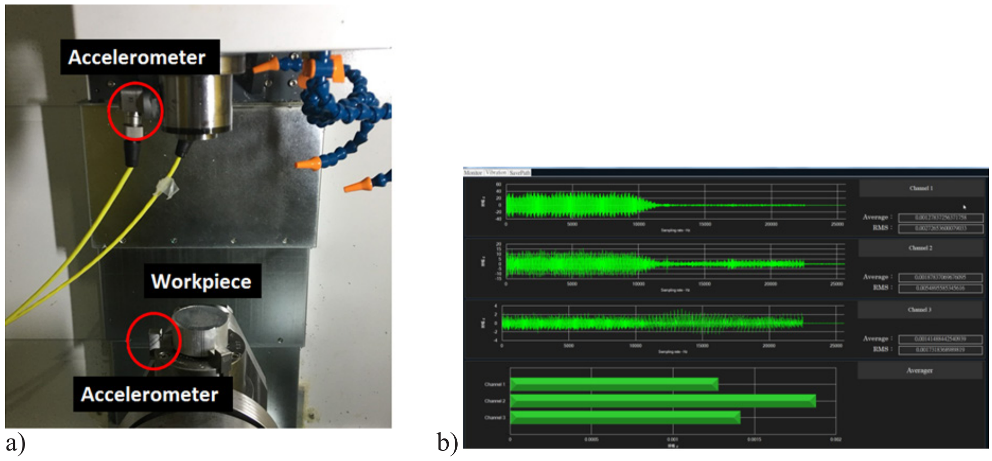


Fig. 11. Machining experimental conducted on five-axis milling machine and vibration monitoring system. a) machining test setup, b) vibration monitoring interface

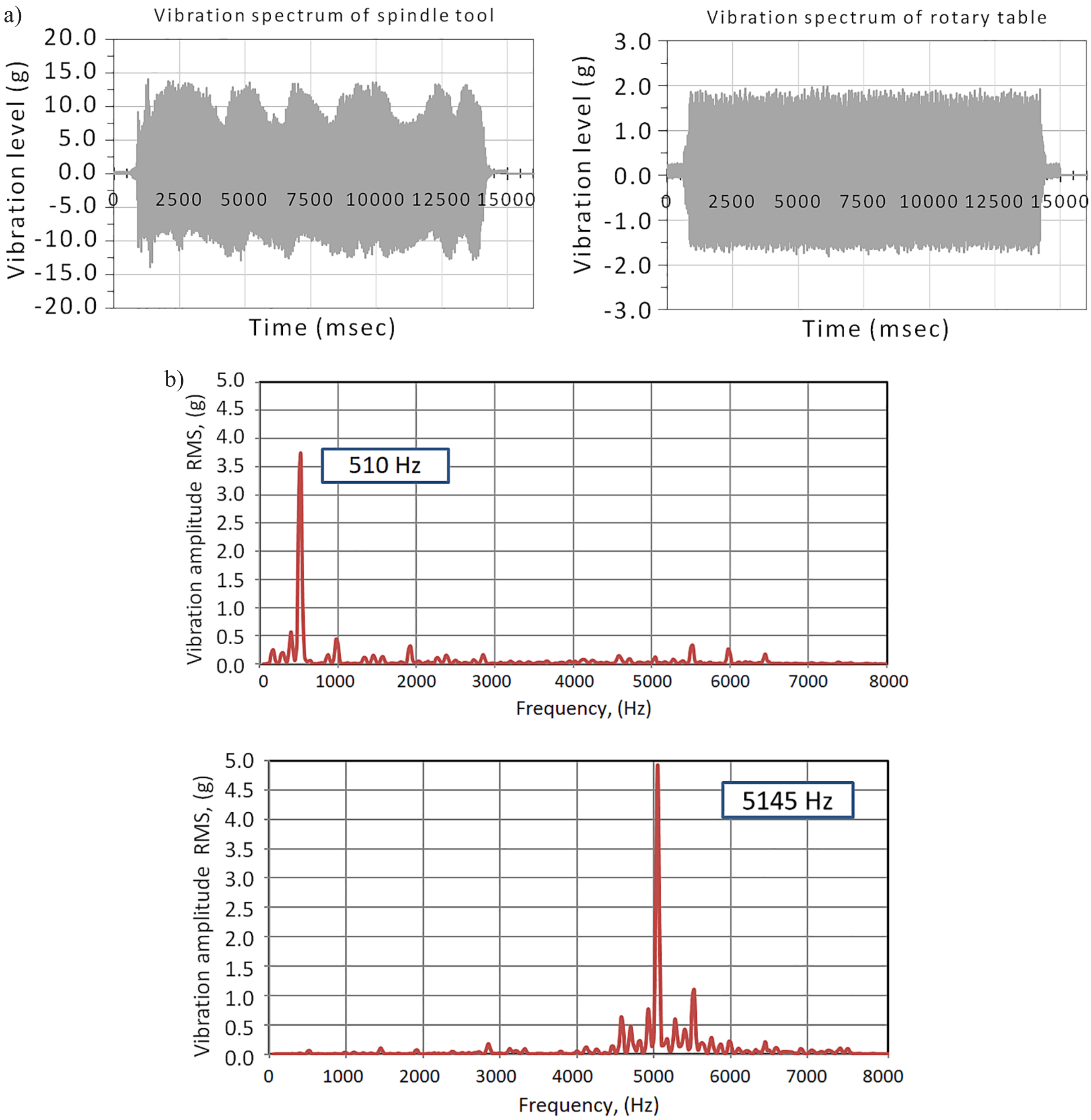


Fig. 12. Vibration spectrums (a) and frequency responses (b) of the spindle tool and rotary table

Cutting depths ranged from 1.0 mm to 2.0 mm, with increments of 0.1 mm. Two accelerometers were mounted on the spindle housing in the X and Y directions, and another accelerometer was mounted on the housing of the C-axis. Following each slot machining operation, the root mean square (RMS) value of the vibration signals during the milling period was computed based on the recorded vibration signals throughout the machining process.

Figure 12 shows the typical vibration spectrums of the spindle tool and rotary table. From the frequency responses of the table and spindle, it can be found that main excitation frequency of the rotary module is at 510 Hz, close to the tool passing frequency but distinct from the natural frequency observed in tapping tests. Furthermore, the vibration induced in the rotary table during machining was observed to be more stable compared to the spindle tool. Figure 13 shows the RMS values of the vibrations generated under different cutting depths, clearly illustrating that the vibration levels of both the spindle tool and rotary table increase with the cutting depth. However, the rotary table exhibits lower vibration levels than the spindle tool. This observation suggests that the rotary table demonstrates excellent structural performance in withstanding cutting loads, characterized by stable vibration behavior.

S-Type contour milling

In this experiment, cutting tests were conducted on curved surface S-shaped specimens under finish conditions to investigate the vibration behavior of the rotary table in a five-axis contouring process. As shown in Figure 14, the curved surface S-shaped specimens was a small scaled model of the ISO 10791-7 standard for five-axis machining test [22]. Before the finishing process, these specimens were initially milled from stock material to create the S-shaped workpieces through rough machining. A total of 15 specimens were prepared for the finishing machining operation. For the finishing process, a four-flute high-speed steel milling cutter with a diameter of 10 mm and a length of 80 mm was employed. The workpiece material A6061 had dimensions of 84×124×32 mm.

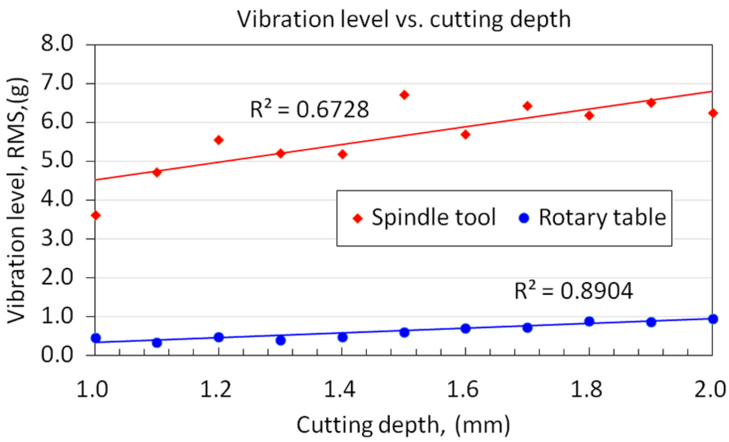


Fig. 13. Variation of vibration feature (RMS value) of spindle tool and rotary table under different cutting depth

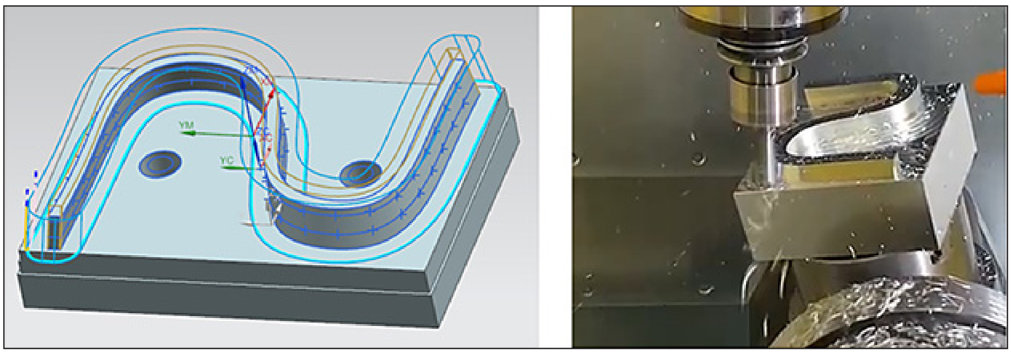


Fig. 14. Machining experiments conducted on S-shaped curve by five-axis milling machine.
(a) S-shaped curve model (b) Machining of S-shaped curve

The contouring experiments were conducted through flank milling under specific conditions, including a spindle speed of 7500 rpm, feed rate of 1000 mm/min, cutting depth of 12 mm, and radial cutting depth of 0.5 mm. Throughout the machining process, accelerometers with a sampling rate of 2 kHz were employed to assess the vibrations of both the spindle tool and rotary table. The root mean square (RMS) value was calculated based on 20,000 data points from vibration sensor reading per second through software implemented in the monitoring system. Consequently, the change of vibration RMS values with milling time throughout the whole machining process of each specimen can be recorded for subsequent comparison.

Figures 15 illustrates the variations of the vibration RMS values of the spindle tool and rotary table during contour milling cycles for specific specimens 1, 5, and 10, respectively. These figures clearly indicate that both the spindle tool and rotary table exhibit similar vibration responses throughout the one milling cycles. Obviously, for the milling process of a specific specimen, the vibration of the rotary table is consistently lower than that of the spindle tool. Moreover, based on the vibration responses observed in the experiments, it is evident that the majority of vibrations generated during the cutting process are stable. However, there are significant vibrations abruptly occurring at specific positions, such as the transition point of the cutting path along the inner arc surface, where deceleration and acceleration of the feeding motion are conducted, as observed in study of Sato et al. [23]. The other situation is the overcut occurring at the tool exit from the curved surface. Significant machine vibrations can be excited by the high jerk or unstable high cutting force generated under these cutting conditions.

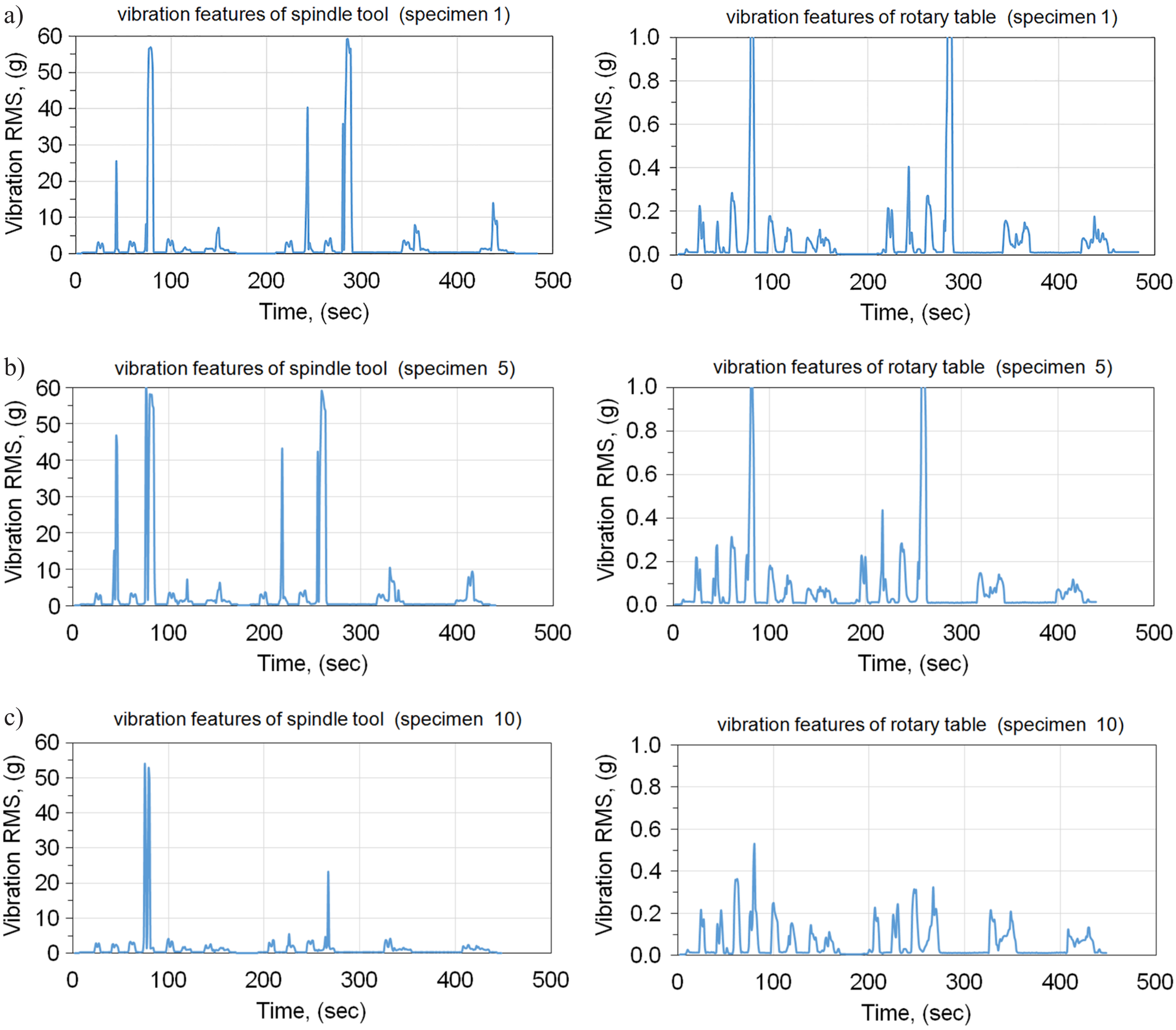


Fig. 15. Variations of the vibration RMS values of the spindle tool and rotary table during contour milling cycles, for specimens 1, 5, and 10, respectively

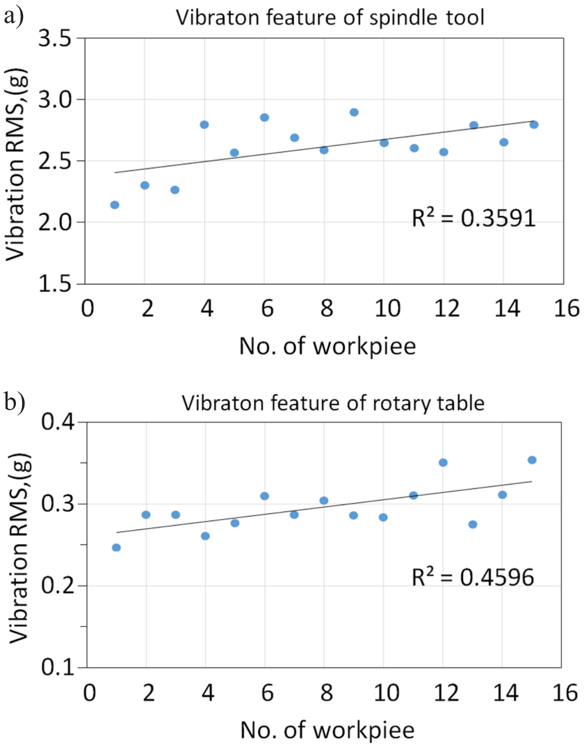


Fig. 16. Variations of the overall vibration level generated in machining from the first to the fifth specimen

Figure 16 illustrates the variations of the overall vibration level generated in machining from the first to the fifth specimens, which show a noticeable increasing trend in vibration with the progression of milling cycles. This observation is particularly noteworthy as these specimens are processed using the same cutter under identical cutting conditions. The rise in vibration levels over milling cycles could potentially be attributed to the progressive wear of the cutting edges. This phenomenon is worthy for further investigation in future studies. Comparisons of the vibration features collected from the milling tests obviously indicate that the rotary table exhibits robust structural performance in sustaining cutting loads, characterized by stable vibration characteristics.

CONCLUSIONS

This study primarily focuses on the development of a dual-axis rotary table designed for integration into a five-axis milling machine. Prior to prototyping, the dynamic characteristics of the rotary table were investigated using finite element modeling approach and subsequently validated through tapping tests. The results revealed that the modal frequency and compliance of the rotary table varied with the tilting of the swivel axis, ranging from 0.082 to 0.13 μm/N as the table swiveling from the horizontal (90°) to the vertical direction (0°), showing the variation of the dynamic characteristics with the change of tilting angle. Finally, the structural performance and feasibility of the rotary table for application in milling machines were confirmed through S-shaped machining tests. The collected vibration characteristics from the tests served as indicators for this evaluation. The milling tests demonstrated that the vibrations of the rotary table were lower than those of the spindle. Additionally, an increasing trend in vibration feature was observed with the progression of milling cycles. This obviously indicates that the rotary table exhibits robust structural performance in sustaining cutting loads, characterized by stable vibration characteristics.

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