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Research Article

A proposal of feed rate setting for high-speed CNC milling machines by the vibration-based method

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ABSTRACT

High precision and product surface finish quality are the main characteristics of these precision machine tools. Machining with different tool paths at different feed rates is applied to increase productivity. Today, machine tools using high-speed machining methods have been developed to shorten machining times and increase production capacity. However, the vibration of high-speed machine tools is the main cause of product quality reduction. The effect of the machining speed on the vibration diagnostic process of the machine is to choose the appropriate machining mode. This paper describes the vibration analysis methods of machine tools based on simulated results to determine the natural frequencies of vibration and dynamic modeling of the ball-screw feed drive system. Analysis of structural simulation results shows that the higher the rigidity of the machine, the lower the vibration amplitude, and the greater the ability to absorb and suppress vibrations for the machine tool without using dampers. Meanwhile, the combination of the measurement analysis and dynamics modeling on machine tools is an effective method for optimizing speed and controlling machining vibrations. First, the finite element model (FEM) is applied to determine the stiffness analysis and the natural vibration frequency of the machine tool. The simulation results are analyzed and compared with experimental measurement results. The vibration frequency of the ball-screw drive system during machining at different feed rates is also modeled and verified by the measurement results. Finally, the results from the proposed methods are used to predict the vibration frequency of the system, especially the ball-screw through the feed drive or rotational speed. In addition, the purpose of the proposed method is to prevent resonance by way of the forced frequency away from the natural frequency in high-speed machining. This paper proposes a survey method that can be applied for high-speed machine tools with different structures to choose an appropriate feed rate in machining.

Key words: CNC milling machines, ball-screw feed drive system, Feed rate, Vibration frequency, finite element model (FEM)

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INTRODUCTION

Nowadays in Vietnam, the process of researching and developing CNC machine tools is mostly performed by university laboratories. Many studies on CNC machine tool design have been considered for processing and assembly to serve surveying and practical experiments. Through research on CNC milling machines [1], the research team at the Laboratory of Applied Mechanics (LAM) at Ho Chi Minh City University of Technology took the initiative step by step to build our own CNC milling machines. By using simulation tools to analyze the strength and stiffness of self-manufacture CNC milling machines [2,3], LAM has collected many databases for many different machine models. The long-term continuous vibration of the machining process is the main cause that directly affects the reduction of machine tool rigidity. High-speed CNC milling machines require a high spindle speed to meet fast feed rates and achieve high product machining efficiency. From the results of the study [4], high spindle speed was identified as a source of vibration and vibration propagation during machine tool operation. In addition, a high spindle speed can cause vibration propagation to the cutting tool, resulting in rapid wear and damage of the cutting tool [5].

The small-sized machine tool during machining combined with dynamic and static analysis are investigated. This study suggests a structural optimization solution to achieve higher stiffness along with lower vibration. Therefore, the most important factor in the development of high-speed machine tools is to minimize machine tool vibration. However, the result is based on investigating the machine tools that have been in service for a long time with accuracy and precision deterioration. The chatter of the machine is considered to be the cause affecting the spindle and machine tool [6]. Rotating parts in CNC milling machines are commonly used, especially in operations

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that convert rotary motion from the motor to translating motion through the ball-screw feed drive system. Due to the operation under high load, continuous high-intensity operating conditions, the ball-screw feed drive system cannot avoid fatigue and damage arising. Failure to diagnose and detect damage in time can cause machine damage and even serious damage. Therefore, early failure diagnoses and damage assessment to ensure the safe operation of machinery are very important.

The development of health monitoring systems for machine tools based on early failure diagnoses has become widespread. Many research results on early fault detection techniques have successfully applied diagnostic methods such as vibration-based methods and sound-based methods. In particular, the parts that need to be considered and regular monitoring in the ball-screw feed drive system are coupling or pulleys, bearings, and ball screws. In the field of rolling element bearings, vibration-based methods for failure identification are most popular because they are easy to measure, and measured data can be processed to extract useful information[7]. In addition, research in the field of early fault diagnosis by combining AI-based methods also successfully achieved[8]. The process of vibration leading to damage of the bearing takes place over a very long time. However, the influence of the bearing failure vibration on the system is negligible. In addition, the ball-screw is one of the important components in the system. The ball-screw in good condition responds accurately to position control and operates smoothly. Many studies on the accuracy of position show that the vibration effect is greatly increased when the ball screw is worn, leading to damage during long-term operation. The investigation with improving the accuracy of the ball-screw[9] and diagnosing early failures under specific conditions[10] was carried out and obtained satisfactory results. In addition, the research results using sound-based and vibration-based methods[11] are increasingly popular for building a health monitoring system for ball screws.

Even though the contributions of the health monitoring system are necessary, the minimized damage caused by long-term operation is also considered an effective solution. Normally, the cause of shaft failure, such as shaft wear due to long-term operation under axial loads, stiffness deterioration affecting the shaft's natural vibration frequency reduction, and resonance by the vibration frequency of the rotating shaft, coincides with the natural vibration frequency. The aim of this paper is to investigate the simulation results and analysis of vibration measurement signals obtained from machine tools combined with dynamic modeling of the feed drive system. Based on the analysis results, the authors proposed some recommendations, such as choosing the feed rate by ball-screw rotation speed and calculating the vibration frequency of the rotating shaft. For the high-speed CNC machines coming into operation with stable health, only a few of the above proposed can be applied. Research on the relationship between the shaft's rotation speed and the natural frequency of a high-speed CNC milling machine to avoid resonance is considered an effective solution in this paper.

MATERIALS AND METHODS

Preparation of the model and FEM analysis

Simulation analysis of the machine structure vibration is performed to investigate the static and dynamic characteristics of the system. The model of the high-speed CNC milling machine was described and modeled by using Solidworks software, as shown in Figure 1. Modal analysis was performed based on the finite element model (FEM) using ANSYS software. The simulation results are confirmed based on a comparison with the experiment

Structural configuration

The structure of the high-speed milling machine is designed and manufactured in the double column type, which can withstand good vibration and high rigidity. The high-speed CNC milling machine is divided into two systems. One is a translation system, which includes the translation X-axis and Z-axis. The other is a workpiece system that includes the translation Y axis and rotation axis A. The translation axes X, Y, Z of the CNC machine used a ball-screw feed drive system and the rotating axis through the gearbox reducer. The maximum travel range of the Z translating stage is 250 mm, and the maximum X-Y area is 800 mm $\times$ 500 mm. The CNC milling machine has a large travel range, and under high-speed operating conditions, a ball-screw feed drive system was chosen. Ball-screw feed drive systems have been widely used in high-precision machine tools. Recently, modern machines aimed at improving productivity need to operate at high speeds to shorten machining times. The ball-screw feed drive system for the machine tool needs to be strong enough to withstand vibrations during high-speed machining. The structure of the ball-screw feed drive system is shown in Figure 2. The specifications of the ball-screw feed drive system of the CNC milling machine tool are represented in Table 1.

Table 1: The specifications of the ball-screw feed drive systems

Stages	Travel (mm)	Accuracy (μm)	Maximum travel speed (mm/min)
X-Axis	800	2.5	2000
Y-Axis	500	2.5	2000
Z-Axis	250	2.5	2000

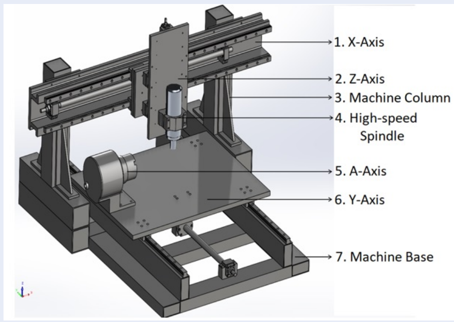

Figure 1: Model of the high-speed CNC milling machine.

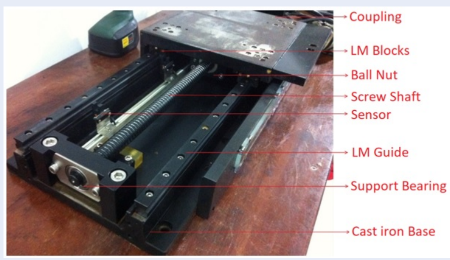

Figure 2: Structure of ball-screw feed drive systems

Modal analysis

In this paper, modal analysis is the basis of the dynamic problem based on the finite element method, which is used to analyze the natural frequencies of the machine structure. The natural vibration frequency depends on the characteristics of the machine structure and not on the external force. When the forced frequency of the load approaches the natural frequency of the machine, the amplitude of the vibration will gradually increase, which produces resonance. In addition, permanent constraints are located on the bottom face of the machine base. However, through the experimental vibration results, the forced frequency of the excitation in the machining process is quite low. Therefore, setting high mode shapes for modal analysis is unnecessary. The first six mode shapes and the corresponding total deformation need to be determined.

Vibration-based theoretical of ball-screw feed-drive system

Bearing vibration frequency

The equation to determine the vibration frequency of the bearing is used when a failure problem occurs on the bearing. These frequencies are calculated to predict the value of the vibration frequency that may occur. The calculated values can be verified by the results from the vibration frequency spectrum of the measured signal during operation. By analyzing the results from the amplitude spectrum, the amplitude peak values can indicate the failure frequency in the components. With the geometrical parameters of the bearing (Figure 3), the vibration frequency of the ball bearing [12] can be calculated according to the following formulas:

Fundamental train frequency (FTF):

$$FTF = \frac{f_s}{2}\left(1-\frac{d}{D}\cos\alpha\right) \tag{1}$$

Ball spin frequency (BSF):

$$BSF = \frac{Df_s}{2d}\left[1-\left(\frac{d}{D}\cos\alpha\right)^2\right] \tag{2}$$

BPFO is the ball pass frequency for the outer race (BPFO):

$$BPFO = N\frac{f_s}{2}\left(1-\frac{d}{D}\cos\alpha\right) = N\times FTF \tag{3}$$

BPFI is the ball pass frequency for inner race (BPFI):

$$BPFI = N\frac{f_S}{2}\left(1+\frac{d}{D}\cos\alpha\right) \tag{4}$$

To calculate the bearing vibration frequencies from these equations, it is necessary to determine the bearing geometry parameters (Table. 2).

According to Iñigo Bediaga et al. [12], the comparison of traditional feature extraction and detection methods includes fast Fourier transform (FFT) analysis, amplitude demodulation analysis and Hilbert transform techniques. Meanwhile, these frequencies will

Table 2: Bearing geometry parameters.

f_S	Shaft speed in [rev/sec]
d	Bearing ball diameter [mm]
D	Pitch diameter of the bearing [mm]
α	Ball contact angle
N	Number of rolling elements

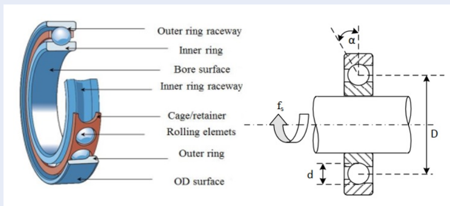

Figure 3: Geometrical parameters of the bearing [12].

depend on the shaft rotation speed and bearing geometry parameters. Based on the literature from the studies that have been done, when using equations (1) - (4), there are some limitations that need to be considered. The geometry and specifications of the bearings are usually provided in the manufacturer's technical manuals. However, for some types of bearings, these parameters will have to be determined by indirect calculations from empirical formulas. The above equation applies not only to angular contact ball bearings operating at low speeds but also to other types of bearings without different specifications. In addition, the actual vibration frequencies of the bearing depend on the degree of damage and the degree of vibration propagation of the components, leading to deviations from the calculated results.

Vibration frequency of ball-screw

In the ball-screw feed drive system, not only vibration from the ball bearing but also the ball-screw generates a vibration signal when they are operated. The measured vibration signals provide rich and varied information about the operating condition of the system. In particular, when the CNC milling machine runs continuously at high speed, the different frequency components of the vibration signal change continuously. Different from the vibration of a ball bearing, the vibration states of a ball screw are often very variable and depend on the operating condition as well as other mechanical properties. As shown in Figure 4, the structure of the ball-screw system consists of a ball nut, screw shaft, steel balls, ball return type, integral lead shift and wipe. The ball-screw system parameters are shown in Table 3.

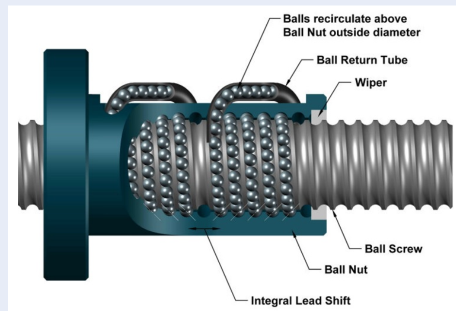

Figure 4: Ball-screw system [13].

Rolling motion steel balls between the nut and the screw help to convert the rotational motion from the drive motor to reciprocating motion along the screw. During operation, the external load causes a state of compression on the nut and screw shaft, while the friction force from the steel ball is generated and changes depending on the operating state. Usually, defects such as wear, fatigue and deformation leading to failure are mainly found in rolling friction components such as screw shafts and steel balls. In this study, the vibration frequency of the ball screw is calculated through formulas based on the vibration of the ball bearing. The frequencies are deduced considering the nut as an outer ring and the screw as an inner ring [12] as follows.

$$BPFS = \frac{1}{120} Zn \left(1 + \frac{D_w}{d_m} \cos\alpha\right) \quad (5)$$

$$BPFN = \frac{1}{120} Zn \left(1 + \frac{D_w}{d_m} \cos\alpha\right) \quad (6)$$

$$BFS = \frac{1}{120} n \frac{d_m}{D_w} \left(1 - \frac{D_w}{d_m} \cos\alpha\right) \left(1 + \frac{D_w}{d_m} \cos\alpha\right) \quad (7)$$

In this study, the primary purpose of calculating the vibration frequency of ball screws is not to detect defects. From the survey results, it is possible to predict

Table 3: Ball-screw system parameters.

BPFS	The ball pass frequencies of the shaft.
BPFN	The ball pass frequencies of the nut.
BSF	The ball spin frequencies.
α	Contact angle.
dm	The pitch diameter of balls.
DW	The diameter of each ball
n	The rotational speeds
z	The number of balls

the vibration frequency of the ball-screw with different rotational speeds of the shaft. For the speed of rotation, the rotational speeds of the nut as an outer ring do not have any speed ($n_e = 0$) but the rotational speeds of the screw shaft as an inner ring ($n_i = n$) followed by Figure 5.

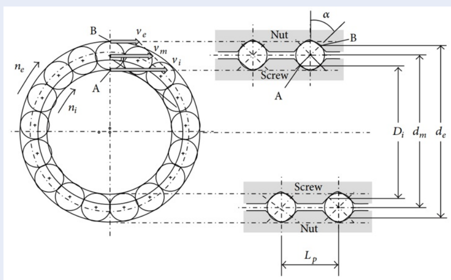

Figure 5: Modeling ball-screw based on rolling bearing[11].

However, the vibration frequencies follow by equations (5) - (7) are still not for ball-screw but rotational rolling bearings because of the difference between the pitch diameter of balls. The effective pitch diameter and number of balls of ball-screw must be newly derived into $d_m^{'}$ and z'. By using concept of Mahalanobis distance, the effective pitch diameter of ball-screw and number of balls described by Figure 6.

The effective pitch diameter $d_m^{'}$ and number of balls z' of ball-screw can be calculated by the following equation:

$$d_m^{'} = \sqrt{L_p^2 + (\pi D_b)^2} \tag{8}$$

$$z' = \frac{d_m^{'}}{D_w} \tag{9}$$

The effective ball pass frequencies of the shaft according to Won Gi Lee et al.[11] are collected from equations (5), (8) and (9):

$$BPFS' = \frac{1}{120} z' n \left(1 + \frac{D_w}{d_m^{'}} \cos\alpha\right) \tag{10}$$

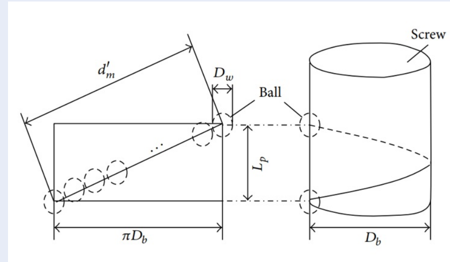

Figure 6: Effective pitch diameter and number of balls of ball-screw[11].

For some types of conventional ball screws, the parameters are announced by the manufacturer. However, other types are produced for some specific machines that will have to be determined by the experiment. Through experimental investigation, the above equations (5) - (10) can be applied precisely with angular contact of 15 - 45 degrees and rotating speeds from 0 - 3000 rounds per minute (rpm).

RESULTS AND DISCUSSION

Modal analysis results

The research focuses on determining the vibration capacity of the structure through simulation results of natural vibration frequencies. The design and machine structure of the high-speed milling machine is shown in Figure 1 with a double column-type structure with good vibration resistance. The initial survey criterion is that the relationship between vibrations depends on the types of materials that make up the machine parts with characteristics such as good specific stiffness, high damping capacity, small thermal expansion, etc. The CNC milling machine surveyed in this study has a steel frame structure, and cast aluminum has been used for some machine components to ensure good load-carrying capacity and vibration absorption. For modal analysis, the material properties were determined, and the contacts between the machine parts were established with the structure-ground contact area fixed. The model is automatically meshed for triangular or tetrahedral finite elements, and boundary conditions are set using the no separates function that provides translational and rotational motions. Through the evaluation criteria, the research chooses meshing on a high mesh level (smooth) with 224,375 nodes and 125,748 elements to create accuracy for the obtained results. In FEM, the materials used for structural components are made of steel with elastic modulus E_1 =210 GPa, Poisson's ratio m_1=0.3 and density r_1=7800 $^{kg/m3}$. The materials of the cast aluminum component have elastic modulus E_2 =70 GPa, Poisson's ratio m_2=0.33 and density r_2=2810 $^{kg/m3}$. The results from the FEM and the experimental results are compared. Through previous studies, we can conclude that the constructed finite element model shows that the accuracy of the results is acceptable.

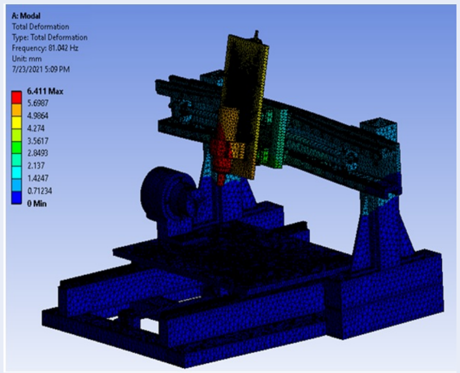

Figure 7: The first natural frequency of the CNC milling machine modal analysis result.

From modal analysis, the first natural frequency obtained is 81.042 Hz, with the tooltip being the position with the greatest total deformation, as shown in Figure 7. Based on these results, the excitation vibration frequency from the high-speed spindle should not equal 81.042 Hz. The natural vibrational frequencies of the second mode shape (Figure 8) and remaining mode shapes are also determined in a similar way to the first natural frequency determination method in the first mode shape.

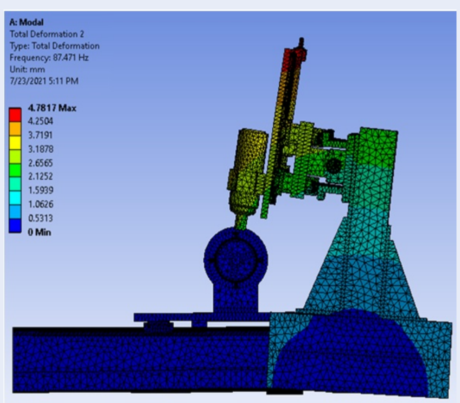

Figure 8: The second natural frequency of the CNC milling machine modal analysis result.

The results of Table. 4 show the natural vibration frequencies and the corresponding maximum total deformation position of the CNC milling machine. The deformation calculation will help designers with information on how the structure will deflect. Basically, the first mode in the modal frequencies is the most important mode and is mostly considered in designs because the total deformation is usually largest in the first mode. This is consistent with the vibration propagation process. The process of vibration propagation begins from the vibration source, which is the spindle, followed by the Z and X stages, and the workpiece stage, which is directly affected by the cutting force during the machining process. The column and the machine platform are the final stages. Figure 9 shows the column vibration results.

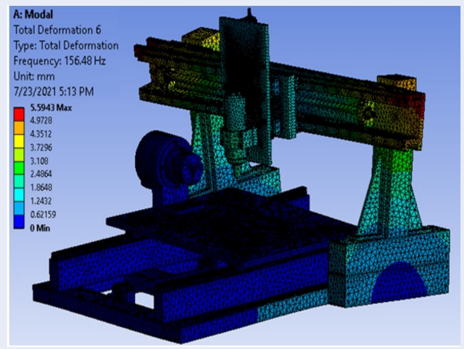

Figure 9: The sixth natural frequency of the CNC milling machine modal analysis result.

Vibration measurement setup and result.

Experimental measurement and analysis of the vibration signal were performed on the machine tool during the machining process to check the vibration parameters, such as vibration frequency, vibration amplitude, and power spectral density (PSD). Based on the results of the modal analysis in Table 4, the devices used for the vibration test mainly consisted of 5 accelerometers at 5 measurement locations. For each measuring position, the vibration signal is measured in three directions X Y Z. Therefore, a total of 15 vibration signals will be obtained after the measurement process. Based on the results in Table 4, the suggested vibration measurement locations are included (Figure 10).

Comparing the natural vibration frequency results from Table. 4 with the measurement results after analyzing the measured signal shows that there is a deviation. This can be explained because the experimental vibration frequency of the CNC milling machine depends on many factors, such as the material, the

Table 4: The modal analysis result.

Mode shapes	Simulation results		
	Frequency (Hz)	Total deformation (mm)	Stages (location)
1	81.042	6.4110	Z-Axis (tool tip)
2	87.471	4.7817	Z-Axis (motor mount)
3	96.58	3.9512	A-Axis
4	124.07	5.7324	A-Axis (Workpiece)
5	143.21	6.0625	Y-Axis (Table)
6	156.48	5.5943	X-stage (two ends of column)

structure of the machine, the state of the machine's strength, and the signal interference from the external environment. However, this deviation is not significant, so the results from modal analysis can be used in the absence of experimental measurement conditions.

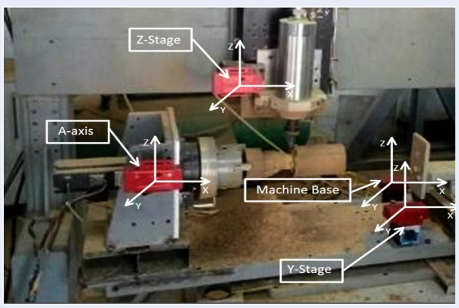

Figure 10: Set up vibration measurement locations.

Table 5: Set up experimental vibration of the CNC milling machine.

Spindle speed (rpm)	24000
Feed rate (mm/min)	600
Deep cut (mm)	1
Step over (mm)	1
Journal of X-axis (mm)	300
Journal of Y-axis (mm)	300
Journal of Z-axis (mm)	10

This paper determines the relationship between the feed rate and the vibration frequencies of a high-speed CNC milling machine during operation. The CNC milling machines were investigated under the condition of material processing with low hardness at constant cutting force and federate as shown in Table. 5.

The results obtained from the measured signal are shown in Figures 11, 12, 13, 14 and 15.

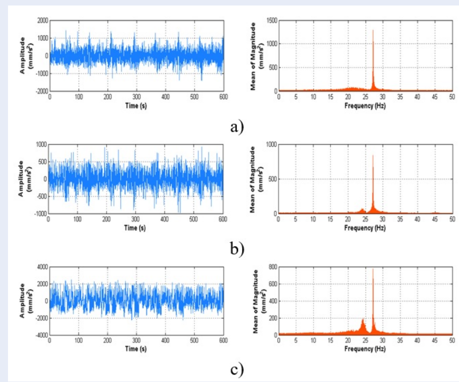

Figure 11: Vibration of the Z-stage with a spindle in 3 directions: (a) Ox, (b) Oy, and (c) Oz

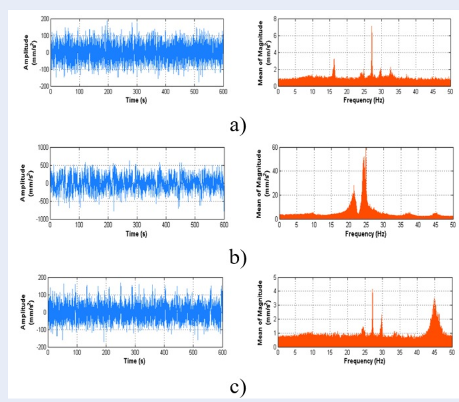

Figure 12: Vibration of the X-stage (two ends of column) in 3 directions: (a) Ox, (b) Oy, and (c) Oz

The results of the machine vibration measurements are shown in Table 6.

Table 6: The vibration frequency measurement results

Measure-ment position	Direction	Frequency 1 (Hz)	Freq-uency 2 (Hz)	Freq-uency 3 (Hz)
Z-stage with Spindle.	X	27	-	-
	Y	24.5	27	-
	Z	24.5	27	-
X-stage (two ends of column).	X	16	24.5	27
	Y	21.5	24.5	-
	Z	24.5	27	30
Rotary A-axis.	X	21.5	24.5	27
	Y	21.5	24.5	27
	Z	24.5	27	-
Y-stage.	X	24.5	-	-
	Y	21.5	24.5	27
	Z	24.5	-	-
Machine frame (Base)	X	24.5	27	-
	Y	24.5	-	-
	Z	24.5	-	-

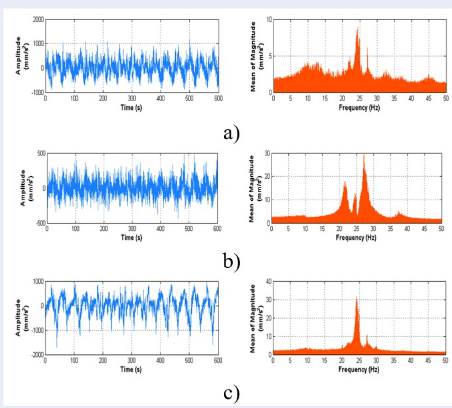

Figure 13: Vibration of the Rotary A-axis in 3 directions: (a) Ox, (b) Oy, and (c) Oz

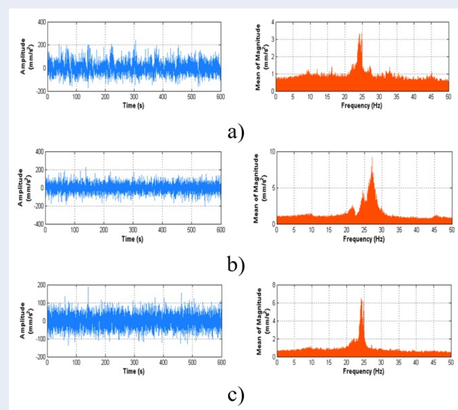

Figure 14: Vibration Y-stage in 3 directions: (a) Ox, (b) Oy, and (c) Oz

From the measurement results, the vibration of the CNC milling machine is very diverse, with many vibration frequencies. There are some notable vibration frequencies, such as 24.5 Hz and 27 Hz because they often occur at the same time at many measurement sites. Other vibration frequencies of 16 Hz and 30 Hz appear only once in the X-stage, and 21.5 Hz appears 4 times with 3 times in the Y direction. Therefore, it can be observed that the CNC milling machine vibrated in the frequency range from 24.5 Hz – 27 Hz with the constant feed rate of the stages. The difference of 2.5 Hz is quite small and acceptable because it is affected by the actual operation status of the stages.

The experimental feed rate and vibration frequency.

In the machining process, the most frustrating problem for CNC milling machine programming is the selection of the appropriate cutting speed and feed. This

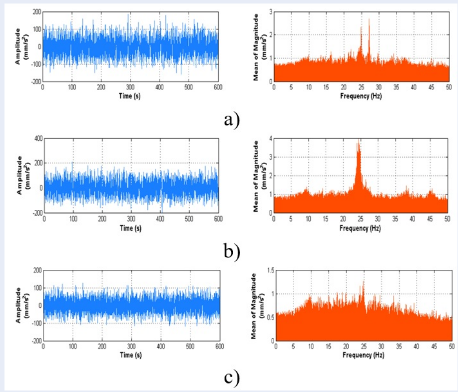

Figure 15: Vibration of the machine frame (base) in 3 directions: (a) Ox, (b) Oy, and (c) Oz

choice is actually more difficult considering that vibration during high-speed machining affects the entire machine. Through the vibration survey of the machine, combined with the equation of ball pass frequencies of the shaft, the vibration frequency can be predicted based on the rotation speed of the ball-screw shaft. The ball-screw feed drive system on the surveyed CNC milling machine has the following parameters in Table. 7.

Table 7: Specifications of ball-screw

Lead L_p	5 mm
Contact angle a	45^o
Diameter of ball centers D_b	25 mm
Diameter of ball D_w	3.175 mm
Circuit	1.5 turn

By applying the parameters from Table. 7 and equations (8) and (9), the ball pass frequencies of the shaft (10) become:

$$BPFS' = \frac{1}{120} Z' n \left(1 + \frac{D_w}{d'_m} \cos\alpha\right) = 0.21235n \quad (11)$$

The frequency is calculated in Hz according to the rotational speed of the ball-screw shaft n in rpm. Based on the feed rate, the shaft rotation speed can be calculated using the following formula:

$$Feed\left(\frac{mm}{min}\right) = n\,(rpm) \times LeadL_p\,(mm) \quad (12)$$

The measured results from Table 6 show the actual frequency of vibration caused when setting the constant feed rate at 600 mm/min. According to formula (12), the rotation speed of the ball-screw shaft n is 120 rpm. Based on the experimental rotational speed and vibration frequency, the experimental ball pass frequencies of the shaft ($BPFS^{exp}$) can be found as follows:

$$BPFS_1^{exp} = 0.20416n \quad (13)$$

$$BPFS_2^{exp} = 0.225n \quad (14)$$

Based on the experimental vibration measurement frequency, the rotational speed of the ball-screw shaft calculated by equation (11) is approximately 115 rpm and 127 rpm, which is different from the experimental rotation speed of 120 rpm. This insignificant deviation can be explained because we consider more experimental factors, such as the drive efficiency of ball-screw feed drive systems and knuckles and the friction generated between the nut and ball-screw shaft. In addition, the experimental frequencies are also dependent on the level of ball-screw wear and damage. Comparing the results from the calculation with the experimental measurements proved that the vibration of the ball-screw feed drive system and the CNC milling machine can be predicted through the feed rate as well as the rotation of the ball-screw shaft. Therefore, the authors can propose a range of feed rates to achieve the highest speed with predictable vibration and suitable for specific machining conditions.

Propose feed rate setting for high-speed CNC milling machines.

Vibration occurs in most types of machinery using rotating parts, leading to fatigue and failure of the structure or machine, reducing operational productivity. Vibration occurs in most types of machinery using rotating parts, leading to fatigue and failure of the structure or machine, reducing operational productivity. These unwanted vibrations caused by the impact of external forces are negligible and only occur in a short time. Therefore, it is considered a noise component. The vibrations caused by the operation of the ball-screw drive system related to the rotation speed and feed rate of ball-screw were studied in this paper. Combined with the simulation results of the modal analysis from Table 4, the authors can predict the rotational speeds of the ball-screw shaft and the feed rate causing the vibration frequency resonance (Table. 8).

However, through measurement experiments, it has been shown that only the ball-screw rotational speeds and feed rates calculated in Table. 8 are excluded, the generated vibration frequency can still approach the resonant frequency. Based on Figure 16, the vibration tuning range should be investigated.

Table 8: The feed rates causing the vibration frequency resonance.

Mode shape	Modal analysis Frequency (Hz)	$BPFS_1^{exp}$ (HZ)	Rotation speed n_1 (rpm)	Feed rate F_1 (mm/min)	$BPFS_2^{exp}$ (HZ)	Rotation speed n_2 (rpm)	Feed rate F_2 (mm/min)
1	81.042	81.05152	397	1985	81	360	1800
2	87.471	87.38048	428	2140	87.3	388	1940
3	96.58	96.46875	450	2350	96.525	429	2145
4	124.07	123.9087	578	3035	123.975	551	2755
5	143.21	143,2025	668	3505	143.1	636	3180
6	156.48	156,4937	730	3830	156.375	695	3475

Low tuning is achieved when the operational forcing frequency ω is at least twice the value of the natural frequency ω_n. High tuning is achieved when the operational forcing frequency is less than one-half the value of the natural frequency ω_n.

In many cases of modern machinery design required, there is already a relative stiffness foundation. In addition, a resonance separation of at least $\pm$ 20% should be obtained for the least favorable natural frequency. If the natural frequency is determined from measurements on the CNC milling machine, then the resonance separation should be at least $\pm$ 10%[14]. Therefore, based on the results in Table 8, the authors can propose a feed rate suitable for specific machining conditions.

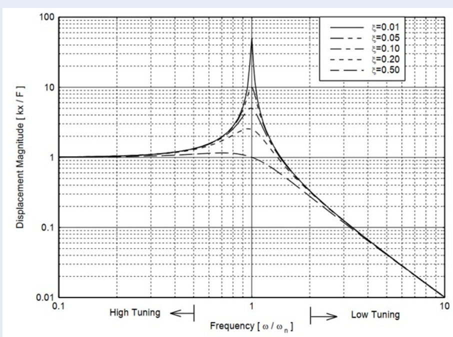

Figure 16: Steady-state Response of a Single-degree-of-freedom System Subjected to an Applied Sinusoidal Force[15].

CONCLUSION

In this paper, a vibration-based experimental investigation method on a high-speed milling machine structure was presented. This survey method has modeled the entire experimental machine structure, including ball-screw feed drive systems. Then, modal analysis by FEM was performed, including mode shapes, total deformation and natural frequencies. The investigation of the vibration caused by the operation of the ball-screw feed drive systems is carried out. During the operation of the high-speed CNC milling machine, the measured vibration frequencies are 24.5 Hz and 27 Hz, with a constant feed rate of 600 mm/min. Based on this study, the following conclusions can be made:

- The paper focuses on developing a method to determine the vibration of the high-speed CNC milling machine structure into operation. Then, the authors can accurately identify the natural frequencies and proposed vibration positions that need experimental measurement for CNC milling machines.
- Calculation and vibration measurement methods for determining shaft vibration frequency in ball-screw feed drive systems have been presented in this paper.
- In this paper, the authors also mentioned the resonance phenomenon that occurs by the coincidence of natural frequencies and the forced frequency. The FEM analysis has shown the natural frequencies with the corresponding mode shapes of the CNC milling machine structure.

The survey method presented in the article can also be applied to high-speed CNC milling machines with other structures. In the framework of studying the influence of the feed rate on the machine vibration frequency, the results of this study show the potential of vibration prediction for high-speed CNC milling machines. However, experimental factors such as working conditions and damage levels of the machine can cause interference and erroneous measurement results, reducing the accuracy of the method. Therefore, it is necessary to evaluate the health status and working conditions of CNC milling machines before applying the proposed research method.

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LIST OF ACRONYMS

CNC: Computer Numerical Control
FEM: Finite Element Model.
FTF: Fundamental train frequency.
BSF: Ball spin frequency.
BPFO: Ball pass frequency for outer race.
BPFI: Ball pass frequency for inner race.
BPFS: Ball pass frequencies of the shaft.
BPFN: Ball pass frequencies of the nut.

CONFLICT OF INTEREST

Nhi NGO-KIEU, Hung NGUYEN-QUOC, Toan PHAM-BAO, and Luan VUONG-CONG declare that they have no conflicts of interest.

CONTRIBUTORS

Nhi NGO-KIEU designed the research. Hung NGUYEN-QUOC, Toan PHAM-BAO, and Luan VUONG-CONG processed the corresponding data. Hung NGUYEN-QUOC wrote the first draft of the manuscript. Nhi NGO-KIEU helped to organize the manuscript. Toan PHAM-BAO revised and edited the final version.

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