Industrial Engineering & Management
Butdee and Kullawong, Ind Eng Manage 2015, 4:5
DOI: 10.4172/2169-0316.1000180
Case Report
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# Life Prediction of a Spindle CNC Machining Centre Using Natural Frequency Method of Vibration

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**Abstract**

In the performance of a spindle CNC system, its bearings play an important role. Many problems arising in a spindle CNC operation are linked to bearing faults. In this project, the accuracy of the instruments and devices used to monitor and control the motor system is highly dependent on the dynamic performance of its bearings. Thus, fault diagnosis of a motor system is inseparably related to the diagnosis of the bearing assembly. In this paper, bearing vibration frequency features are discussed for spindle CNC of bearing fault diagnosis. This paper then presents an approach for life prediction of spindle CNC rolling bearing using nonlinear regression analysis. Vibration data are used to assist in the design for controlling and rolling bearing fault diagnosis strategies. Then our results obtained indicate that controlling and rolling bearing fault diagnosis can be effective agents in life prediction and diagnosis.

**Keywords:** Spindle CNC; Bearing vibration; Fault diagnosis

## Introduction

Computer Numerical Control (CNC) is one in which the functions and motions of a machine tool are controlled by means of a prepared program containing coded alphanumeric data. CNC is an important technology increasing productivity and reducing production costs. The benefits of CNC are (1) high accuracy in manufacturing, (2) short production time, (3) greater manufacturing flexibility, (4) simpler fixturing, (5) contour machining (2 to 5-axis machining), (6) reduced human error. The drawbacks include high cost, maintenance, and the requirement of skilled part programmer.

CNC Spindle is the most important mechanical component in removing metal during machining operations. CNC Spindle is a rotating axis of the machine, which frequently used has a shaft at its heart. The shaft itself is called spindle, it is including three bearing in the front and two bearings in the rear of the spindle. Machine tool spindles lead to unstable chatter vibrations, cutting forces and uneven tensions in the belt and pulleys. This project presents the analysis of natural frequencies and vibration of CNC Spindle by considering no load. This method can be applied to help businesses gain a competitive edge [1]. In this time of expanding global markets, it has become essential for manufacturers to improve process efficiencies, maintain stricter part tolerances, and enhance part quality. Furthermore, the motivation for using analytical tools for process optimization, rather than costly trial and error, has perhaps never been greater. The application of natural frequencies and vibration is used widely in various machines [2].

## Literature Review

Vibration can be described as the mechanical oscillation about an equilibrium point [3]. In case that you are measuring vibration from the bearing of a machine, you are measuring the response of the bearing housing to the forces generated inside the machine [4]. Those forces relate to all of the rotating elements: the shaft, the balls in the bearing, and the blades on the fan, plus the vibration coming from the process and surrounding machines. The vibration tells us about the forces inside the machine [5]. To take advantage of this information a sensor (also called transducer) is needed to convert the vibration into an electrical signal that we can process and store. Collection good data is the most important part of the vibration analysis. The user should use the right sensor (mounted correctly as last time) and at the same time the test should be perform the same way every time, this means that the machine is running the same way as last time (previous vibration test). Depending on the machine speed or bearing type the user should select between displacement sensor, velocity sensor and acceleration sensors [6]. Annual calibration for this sensor is highly recommended by manufacturers [7]. Bearing faults are among the most common causes of failure in rotating machines [1,2]. The root cause of such failures includes pitting, spalling, electroerosion, and wear. Most commonly, faults occur as surface damage on the bearings' raceways or on the rolling elements.

A review is described of the development of all analytical and finite element (FE) models available in the literature for predicting the vibration response of rolling element bearings with localised and extended defects [8]. Low- and high-frequency vibration signals are generated at the entry and exit of the rolling elements into and out of a bearing defect, respectively [9]. Undesirable vibrations in rolling element bearings can be caused by faulty installation, poor maintenance and handling practices [10] or surface fatigue [11], which eventually leads to the formation of various types of defects [12], often referred to as spalls, within rolling element bearings. It is well-known that when a defective (spalled) component, either a rolling element, an outer raceway or an inner raceway, within an operating bearing interacts with its corresponding mating components, either defective or non-defective, abrupt changes in the contact stresses occur [13].

A theoretical model to predict the effect of localized defect on vibrations associated with ball bearing presented that the model yields both the frequency and the acceleration of vibration components of the bearing [14]; So, the effect of the defect size and its location had been investigated. In addition, the method about analysis of bearing stiffness

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**Received** September 08, 2015; **Accepted** November 10, 2015; **Published** November 12, 2015

**Citation:** Butdee S, Kullawong T (2015) Life Prediction of a Spindle CNC Machining Centre Using Natural Frequency Method of Vibration. Ind Eng Manage 4: 180. doi:10.4172/2169-0316.1000180

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variations, contact forces and vibrations in radially loaded double row rolling element bearings with raceway defects is applied to ball bearings on gearbox and fan test rigs seeded with line or extended outer raceway defects [15].

Moreover, a vibration-based health monitoring approach for cooling fans is proposed using a wavelet filter for early detection of faults in fan bearings and for the assessment of fault severity, and the results of show that the proposed method can effectively detect incipient defects and can better capture the degradation trend of fan bearings than traditional time-domain indices in vibration analysis [16]. Besides, the diagnosis of distributed bearing faults employing vibration analysis is modelled by incorporating the geometrical imperfections of the bearing components; so, it is shown experimentally that features extracted from vibrations in fault-free, localized and distributed fault conditions form clearly separable clusters, thus enabling diagnosis [17].

## Overview on Bearing Vibration Frequency Features of Bearing Spindle CNC

In the bearing fault diagnosis process of Spindle CNC, as shown in Figure 1, the sensors collect time domain vibration signals. The fast Fourier transform (FFT) technique is then employed to convert the time-domain signals into frequency-domain signals, which can provide salient features for the diagnosis of the bearing condition. The designed fault diagnosis system can use both time-domain and frequency-domain signals to perform motor bearing fault diagnosis [5,6].

Since most bearing vibrations are periodical movements, it is easy to extract vibration features from the frequency domain using the powerful and popular FFT technique. Many publications have studied the frequency features of rolling bearing vibration [18,19] Generally, rolling bearings consist of two concentric rings, called the inner raceway and outer raceway, with a set of rolling elements running in their tracks. Standard shapes of rolling elements include the ball, cylindrical roller, tapered roller, needle roller, and symmetrical and unsymmetrical barrel roller [20]. Typically, the rolling elements in a bearing are guided in a cage that ensures uniform spacing and prevents mutual contact.

There are five basic motions that are used to describe the dynamics of bearing elements, with each movement having a corresponding frequency [21,22]. These five frequencies are denoted as the shaft rotational frequency ($F_S$), the fundamental cage frequency ($F_C$), the ball pass inner raceway frequency ($F_{BPI}$), the ball pass outer raceway frequency ($F_{BPO}$), and the ball rotational frequency ($F_B$). These frequencies are illustrated in Figure 2.

Figure 3 describes several important variables that will be used

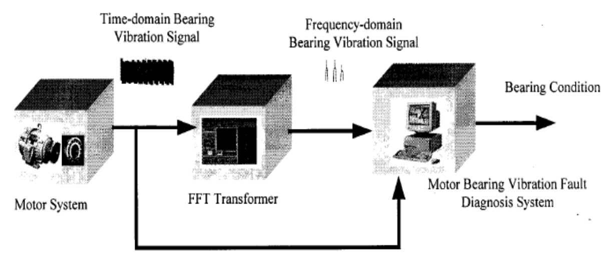


**Figure 1:** General flow of signals in a typical motor bearing fault detection process.

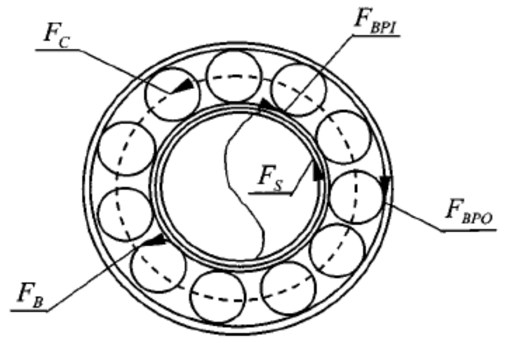


**Figure 2:** Basic frequencies in a bearing.

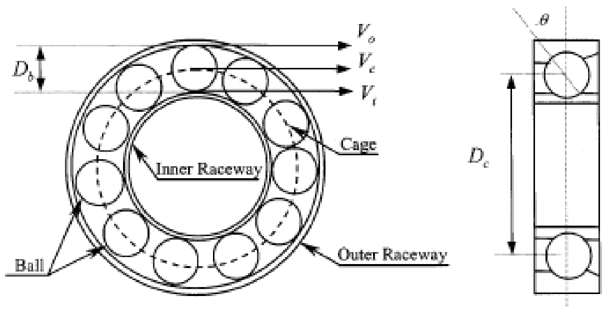


**Figure 3:** Structure of a ball bearing and the definition of each variable.

in later sections. $V_i$, $V_c$ and $V_o$ represent the linear velocities of the inner raceway, ball center, and outer raceway, respectively. $D_b$ is the ball diameter, $D_c$ is the bearing cage diameter measured from one ball center to the opposite ball center, and θ is the contact angle of the bearing.

1. Shaft Rotational Frequency ($F_S$), as bearings are often used to form a bearing–rotor system, the speed of the rotor (or shaft) $F_S$ is very important to the movements of bearings. All other frequencies are a function of this frequency.

2. Fundamental Cage Frequency ($F_C$), the fundamental cage frequency $F_C$ is related to the motion of the cage $V_c$. It can be derived from the linear velocity of a point on the cage , which is the mean of the linear velocities of the inner raceway $V_c$, and the outer raceway $V_c$, i.e., $V_c = (V_i + V_0)/2$. When $V_c$ is divided by the radius of the cage $r_c = (D_c/2)$, we can get the fundamental cage frequency $F_C$. Thus, $F_C$ can be written [5,6] as Equation (1).

$$F_C = \frac{V_c}{r_c} = \frac{V_i + V_o}{D_c} \tag{1}$$

Sometimes, it is more convenient to represent the linear velocities $V_i$ and $V_o$ as their respective rotational frequencies $F_i$ and $F_o$ multiplied by their corresponding radii $r_i = r_c - (D_b \cos\theta / 2)$ and $r_o = r_c + (D_b \cos\theta / 2)$. Thus, $F_C$ can be further expressed as Equation (2).

$$F_C = \frac{V_i + V_o}{D_c} = \frac{F_i r_i + F_o r_o}{D_c}$$

$$=\frac{1}{D_c}\left(F_i\frac{D_c-D_b\cos\theta}{2}+F_o\frac{D_c+D_b\cos\theta}{2}\right) \quad (2)$$

3. Ball Pass Inner Raceway Frequency ($F_{BPI}$), the ball pass inner raceway frequency indicates the rate at which the balls pass a point on the track of the inner raceway. The value of $F_{BPI}$ is equal to the number of bearing balls $N_B$ multiplied by the difference between the fundamental cage frequency $F_C$ and the inner raceway frequency $F_i$ [5,6] as Equation (3).

$$F_{BPI}=N_B\left|F_C-F_i\right|$$

$$=N_B\left|\frac{F_ir_i+F_or_o}{D_c}-F_i\right|$$

$$=N_B\left|\frac{F_i\left(r_c-\frac{D_b\cos\theta}{2}\right)+F_o\left(r_c+\frac{D_b\cos\theta}{2}\right)}{D_c}-F_i\right|$$

$$=\frac{N_B}{2}\left|\left(F_i-F_o\right)\left(1-\frac{D_b\cos\theta}{D_c}\right)\right| \quad (3)$$

4. Ball Pass Outer Raceway Frequency ($F_{BPO}$), similar to the ball pass inner raceway frequency $F_{BPI}$, the ball pass outer raceway frequency $F_{BPO}$ is defined as the rate at which the balls pass a point on the track of the outer raceway. The value of $F_{BPO}$ is a function of the number of bearing balls $N_B$ and the difference between the outer raceway frequency $F_O$ and the fundamental cage frequency $F_C$ [5,6] as Equation (4).

$$F_{BPO}=N_B\left|F_C-F_o\right|$$

$$=N_B\left|\frac{F_ir_i+F_or_o}{D_c}-F_o\right|$$

$$=N_B\left|\frac{F_i\left(r_c-\frac{D_b\cos\theta}{2}\right)+F_o\left(r_c+\frac{D_b\cos\theta}{2}\right)}{D_c}-F_o\right|$$

$$=\frac{N_B}{2}\left|\left(F_i-F_o\right)\left(1-\frac{D_b\cos\theta}{D_c}\right)\right| \quad (4)$$

5. Ball Rotational Frequency ($F_B$), the ball rotational frequency $F_B$ is the rate of rotation of a ball about its own axis in a bearing. This frequency $F_{BPO}$ can be calculated from either the ball pass inner raceway frequency or ball pass outer raceway frequency $F_{BPO}$. Both situations will give the same result [5,7,18,19] as Equation (5).

$$F_B=\left|\left(F_i-F_C\right)\frac{r_i}{r_b}\right|=\left|\left(F_o-F_C\right)\frac{r_o}{r_b}\right|$$

$$=\frac{D_c}{2D_b}\left|\left(F_i-F_o\right)\left(1-\frac{D_b^2\cos^2\theta}{D_c^2}\right)\right| \quad (5)$$

Where $r_b$ is the radius of the ball.

In a motor system, the outer raceway can be assumed stationary, since it is generally locked in place by an external casing, while the inner raceway is rotating at the speed of the shaft, i.e., $F_o = 0$ and $F_i = F_S$. Therefore, in a motor system, as Equation (2) to (5) can be summarily rewritten as Equation (6) to (9).

$$F_C=\frac{1}{2}F_S\left(1-\frac{D_b\cos\theta}{D_c}\right) \quad (6)$$

$$F_{BPO}=\frac{N_B}{2}F_S\left(1-\frac{D_b\cos\theta}{D_c}\right) \quad (7)$$

$$F_{BPI}=\frac{N_B}{2}F_S\left(1+\frac{D_b\cos\theta}{D_c}\right) \quad (8)$$

$$F_B=\frac{D_c}{2D_b}F_S\left(1-\frac{D_b^2\cos^2\theta}{D_c^2}\right) \quad (9)$$

## Nonlinear Regression

The basic idea of nonlinear regression is the same as that of linear regression, namely to relate a response Y to a vector of predictor variables $X=\left(x_1,\ldots,x_k\right)^T$. Nonlinear regression is characterized by the fact that the prediction equation depends nonlinearly on one or more unknown parameters [23]. Whereas linear regression is often used for building a purely empirical model, nonlinear regression usually arises when there are physical reasons for believing that the relationship between the response and the predictors follows a particular functional form. A nonlinear regression model has the form [24]:

$$Y_i=f\left(X_i,\theta\right)+\varepsilon_i\ ,i=1,\ldots,n \quad (10)$$

Where, the $Y_i$ are responses, $f$ is a known function of the covariate vector $X_i=\left(x_{i1},\ldots,x_{ik}\right)^T$ and the parameter vector $\theta=\left(\theta_1,\ldots,\theta_p\right)^T$ and $\varepsilon_i$ are random errors. The $\varepsilon_i$ are usually assumed to be uncorrelated with mean zero and constant variance.

The definition of nonlinearity relates to the unknown parameters and not to the relationship between the covariates and the response [25]. For example the quadratic regression model is considered to be linear rather than nonlinear because the regression function is linear in the parameters $\beta_j$ and the model can be estimated by using classical linear regression methods [23].

$$Y=\beta_0+\beta_1x+\beta_2x^2+\varepsilon \quad (11)$$

Practical introductions to nonlinear regression including many data examples are given by Smyth [26] and by Stromberg and Ruppert [27]. A more extensive treatment of nonlinear regression methodology is given by Bates and Watts [23] Stromberg and Ruppert [27] have considered high-breakdown nonlinear regression. Wei [24] gives an extensive treatment of generalized nonlinear regression models with exponential family responses. In particular, Wei [24] extends curvature measures of nonlinearity to this more general context and uses them for second-order asymptotics.

## Methodology

The Case Study of CNC Spindle Bearing, CNC of Bridgeport VMC 600 Specification: Year: 1998; Heidenhain 410 control system; Rapid feed rate: X, Y and Z: 40/40/20 m/min; Strokes: X, Y and Z: 600/410 /520 mm; 22 tool BT40 taper tool change; Spindle speed: 10,000 rpm; Table size: 840 × 420 mm in Figure 4 and Drawing of CNC Spindle of VMC 600 (Figure 5).

In this project, we used Bearing Vibration Signal of CNC Spindle Bearing of VMC 600 to create 3 main objectives in Figure 8.

1. To avoid when setting matches the natural frequencies of CNC Spindle Bearing, we determined the natural frequencies of CNC Spindle Bearing on respectively steps.


**Figure 4:** Our Case Study of CNC Spindle of VMC 600.

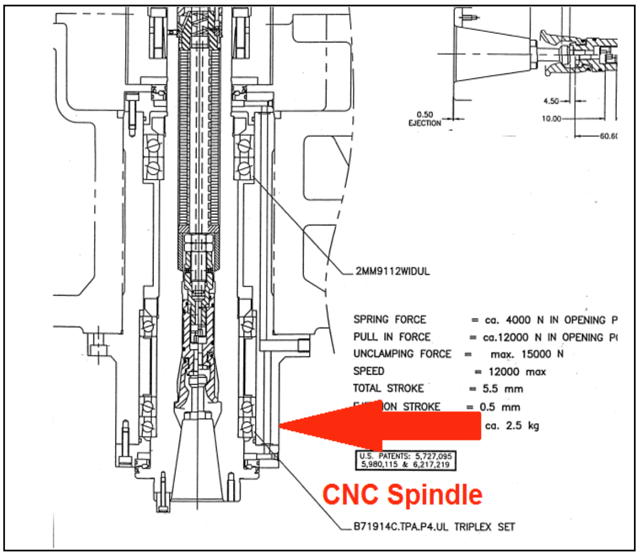


**Figure 5:** Drawing of CNC Spindle of VMC 600.

**Figure 6:** Fieldpaq II.

1.1 The equipment in Figure 6 used in the testing consisted of (1) Vibration Measurement of Fieldpad II (2) Probe Tip on Accelerometer: 100 mV/G (3) Hammer force sensor: 10 mV/lb.

1.2 We applied CH 1 Sensor Select in the Force, force window, Triggle Size setup CH1 about 10 mV, Slope positive, Delay 0%, and CH2 Sensor Select in Accelerometer, 10-2000 Hz, LOR 1600, Average 5, Rectangular window to install Probe Tip at CNC Spindle and to knock at the head of CNC Spindle with Hammer force in Figure 7.

2. To monitor Vibration for Health and to plan Preventive Maintenance in CNC Spindle Bearing, we calculated Reliability in Overall Vibration on each speed of different levels of no load on each working time (hours), and analysed Non Linear Regression on Working Times (hours) and Reliability. Our data for this objective were developed from measuring the vibration of CNC Spindle Bearing to collect the data of Overall Vibration on each speed of different levels of no load on each working time (hours), and to analyse Non Linear Regression on Working Times (hours) and Reliability [28-32].

3. To support information to diagnose the fault of CNC Spindle Bearing by applying Bearing Vibration frequency features, we analysed Non Linear Regression on Working Times (hours) and Vibration to forecast vibration cause damage of CNC Spindle Bearing. Our data for

**Figure 7:** Measurement Procedures to determine the natural frequencies of CNC Spindle.

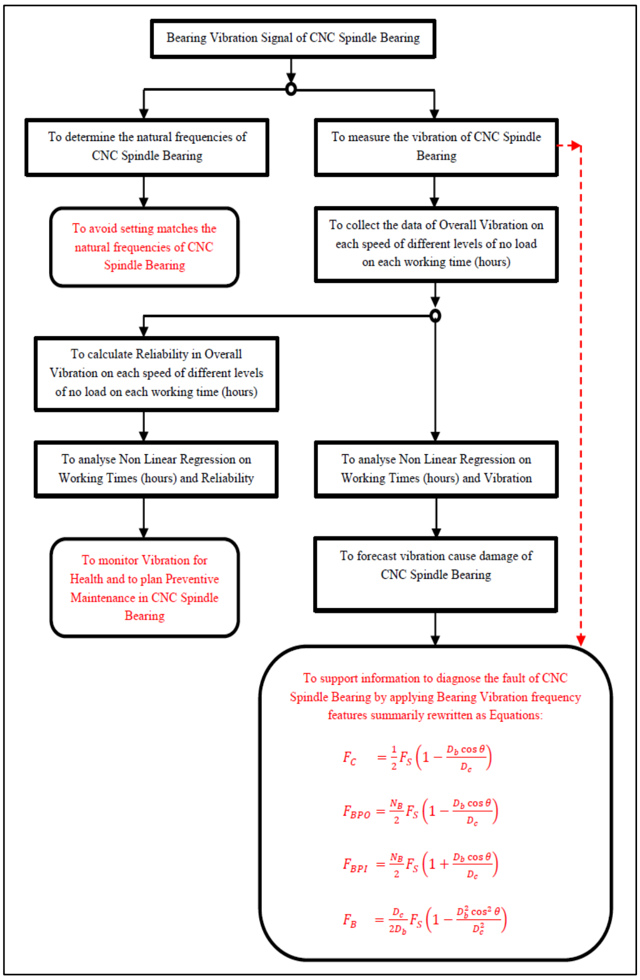


**Figure 8:** Schematic of Using Bearing Vibration Signal of CNC Spindle Bearing of VMC 600to create 3 mainobjectives.

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this objective were used by 2 parts:

(1) Measuring the vibration of CNC Spindle Bearing to collect the data of Overall Vibration on each speed of different levels of no load on each working time (hours) to analyse Non Linear Regression on Working Times (hours) and Vibration on respectively steps

(2) Measuring the vibration of CNC Spindle Bearing on times of CNC Spindle Bearing fault.

3.1 We measured the vibration of CNC Spindle Bearing with our methods used in this test in Figure 9 consisted of (1) FFT parameter settings following the H Frequency 10-1000 Hz, LOR 1600, Average 5, Hanning window (2) To measure Vibration of CNC Spindle on each speed at different levels of no load such as 500 rpm, 1,000 rpm, 1,500 rpm and 2,000 rpm.

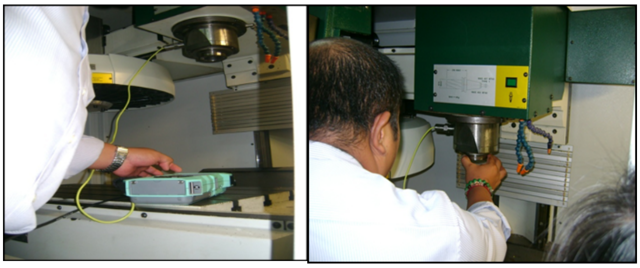


**Figure 9:** To measure the vibration of CNC Spindle.

| Natural Frequency (Hz) | Coherence |
|---|---|
| 173.44 | 0.559 |
| 1012.50 | 0.996 |
| 2139.05 | 1.000 |

**Table 1:** Natural Frequency at Spindle of CNC Spindle of Bridgeport VMC 600.

| Spindle Speed, RPM (Hz) | Vibrations (mm/sec, rms) |
|---|---|
| 500 (8.33) | 0.21 |
| 1,000 (16.67) | 0.22 |
| 1,500 (25.00) | 0.25 |
| 2,000 (33.33) | 0.19 |

**Table 2:** Overall Vibration on each speed of different levels of no load (VMC 600 Spindle) at 6,000 hours Spindle Speed, RPM (Hz) Vibrations (mm/sec, rms).

3.2 Because now our case study of CNC Spindle doesn't have the problem data of bearing fault. So, we try to calculate Equation 6 to 9 to support effective information for managing our bearing fault diagnosis on next time.

## Results

Natural Frequency at Spindle of CNC Spindle of Bridgeport VMC 600 in Table 1 and Graph of Frequency Response Function (FRF), g/lb and Coherence of Spindle: VMC 600 in Figure 10.

Overall Vibration on each speed of different levels of no load such as 500 rpm, 1,000 rpm, 1,500 rpm and 2,000 rpm at Spindle of CNC Spindle of Bridgeport VMC 600 at 6,000 hours in Table 2 and Graph of Auto Spectrum at 6,000 hours in Figure 11.

Our data analysis displayed about Overall Vibration on each speed of different levels of no load (VMC 600 Spindle) on each working time (hours) shown in Table 3; Reliability in Overall Vibration on each speed of different levels of no load (VMC 600 Spindle) on each working time (hours) shown in Table 4; Data and Graphs on Overall Vibration and Reliability in Overall Vibration on each speed of different levels shown in Table 5; Summary on Non Linear Regression: (X: Order); (Y: Vibrations) of VMC 600 Spindle shown in Table 6; Summary on Non Linear Regression: (X: Order); (Y: Reliability) of VMC 600 Spindle in Table 7.

## Discussion

1. We utilised that the manual of VMC 600 Spindle CNC about Bearing Fault with Vibration in Acceleration (mm/s$^2$) guided us to monitor the bearing health condition with the acceleration levels happened in each moment shown in Table 8.

1.1 We converted Velocity of beginning working time to General Acceleration with Equation (12) from Overall Vibration on each speed of different levels of no load of VMC 600 Spindle on 2,000 hours of working time shown in Table 9.

$$A = 2\pi fV \qquad (12)$$

$$V = A / 2\pi f \qquad (13)$$

(by A: Acceleration; V: Velocity; f: frequency)

1.2 We applied Bearing Health Condition with Levels of

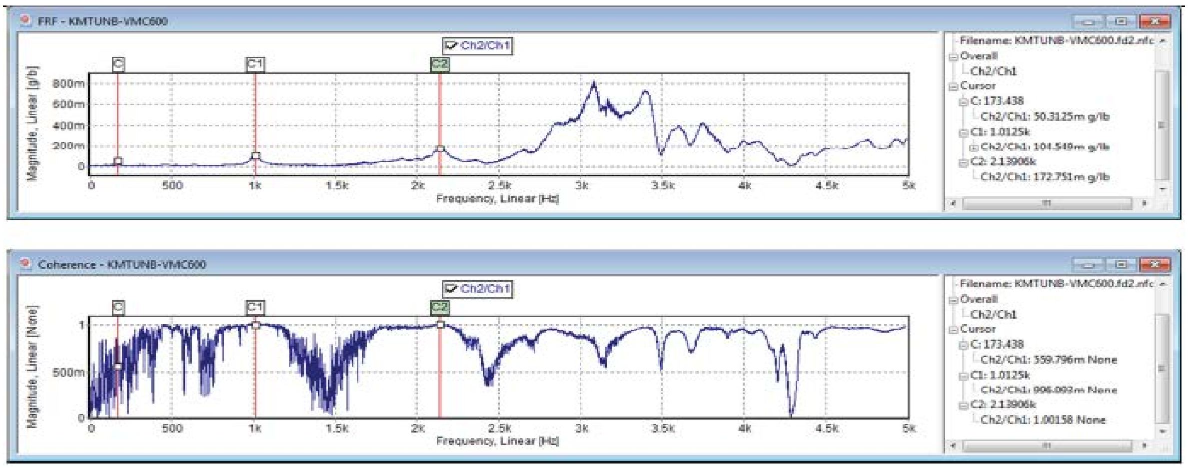



**Figure 10:** Graph of Frequency Response Function (FRF), g/lb and Coherence of Spindle: VMC 600.

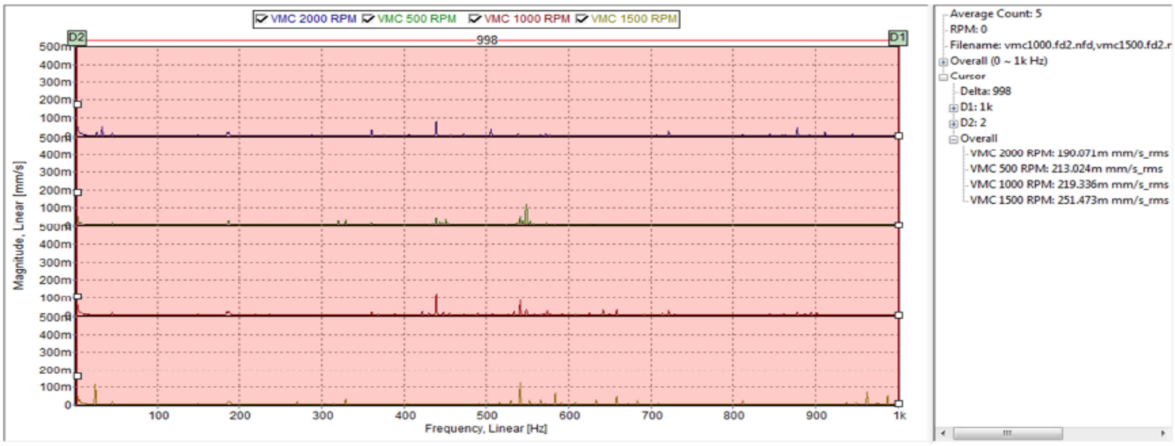



**Figure 11:** Graph of Auto Spectrum on each speed of different levels of no load (VMC 600 Spindle) at 6,000 hours.

| Spindle Speed, RPM (Hz) | Vibrations (mm/sec, rms) on each working time (hours); (VMC 600 Spindle) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2,000 hours | 2,500 hours | 3,000 hours | 3,500 hours | 4,000 hours | 4,500 hours | 5,000 hours | 5,500 hours | 6,000 hours |
| **500 (8.33)** | 0.165 | 0.165 | 0.166 | 0.167 | 0.169 | 0.173 | 0.183 | 0.197 | 0.210 |
| **1,000 (16.67)** | 0.169 | 0.169 | 0.169 | 0.171 | 0.175 | 0.181 | 0.185 | 0.200 | 0.220 |
| **1,500 (25.00)** | 0.183 | 0.183 | 0.184 | 0.187 | 0.189 | 0.190 | 0.227 | 0.250 | 0.250 |
| **2,000 (33.33)** | 0.158 | 0.163 | 0.166 | 0.167 | 0.169 | 0.173 | 0.183 | 0.187 | 0.190 |

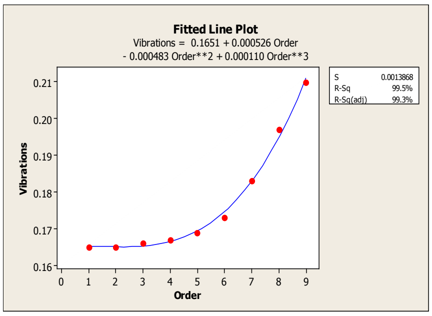
**Table 3:** Overall Vibration on each speed of different levels of no load (VMC 600 Spindle) on each working time (hours).

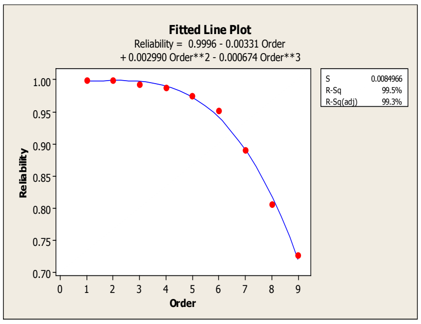
| Spindle Speed, RPM (Hz) | Reliability in Overall Vibration on each speed*; (VMC 600 Spindle) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2,000 hours | 2,500 hours | 3,000 hours | 3,500 hours | 4,000 hours | 4,500 hours | 5,000 hours | 5,500 hours | 6,000 hours |
| **500 (8.33)** | 1.000 | 1.000 | 0.994 | 0.988 | 0.976 | 0.952 | 0.891 | 0.806 | 0.727 |
| **1,000 (16.67)** | 1.000 | 1.000 | 1.000 | 0.988 | 0.964 | 0.929 | 0.905 | 0.817 | 0.698 |
| **1,500 (25.00)** | 1.000 | 1.000 | 0.995 | 0.978 | 0.967 | 0.962 | 0.760 | 0.634 | 0.634 |
| **2,000 (33.33)** | 1.000 | 0.968 | 0.949 | 0.943 | 0.930 | 0.905 | 0.842 | 0.816 | 0.797 |

$$^{*}Reliability\ in\ Overall\ Vibration\ on\ each\ speed = 1 - \frac{Vibrations\ (at\ begining\ working\ time:\ 2{,}000\ hours)}{Vibrations\ (on\ each\ working\ time)}$$

**Table 4:** Reliability in Overall Vibration on each speed* of different levels of no load (VMC 600 Spindle) on each working time (hours).

| Spindle Speed, RPM (Hz): 500(8.33); (VMC 600Spindle) | | | |
|---|---|---|---|
| **Order** | **Vibrations (mm/sec, rms) on each working time (hours)** | **Vibrations (mm/sec, rms)** | **Reliability in Overall Vibration** |
| **1** | 2,000 hours | 0.165 | 1.000 |
| **2** | 2,500 hours | 0.165 | 1.000 |
| **3** | 3,000 hours | 0.166 | 0.994 |
| **4** | 3,500 hours | 0.167 | 0.988 |
| **5** | 4,000 hours | 0.169 | 0.976 |
| **6** | 4,500 hours | 0.173 | 0.952 |
| **7** | 5,000 hours | 0.183 | 0.891 |
| **8** | 5,500 hours | 0.197 | 0.806 |
| **9** | 6,000 hours | 0.210 | 0.727 |



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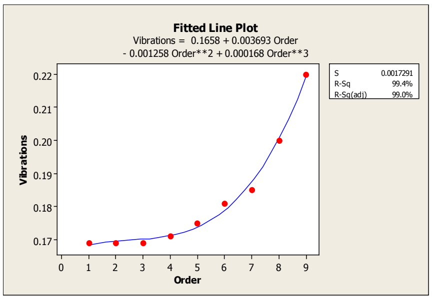
| Spindle Speed, RPM (Hz): 500(8.33); (VMC 600Spindle) | | | |
|---|---|---|---|
| **Order** | **Vibrations (mm/sec, rms) on each working time (hours)** | **Vibrations (mm/sec, rms)** | **Reliability in Overall Vibration** |
| **1** | 2,000 hours | 0.169 | 1.000 |
| **2** | 2,500 hours | 0.169 | 1.000 |
| **3** | 3,000 hours | 0.169 | 1.000 |
| **4** | 3,500 hours | 0.171 | 0.988 |
| **5** | 4,000 hours | 0.175 | 0.964 |
| **6** | 4,500 hours | 0.181 | 0.929 |
| **7** | 5,000 hours | 0.185 | 0.905 |
| **8** | 5,500 hours | 0.200 | 0.817 |
| **9** | 6,000 hours | 0.220 | 0.698 |



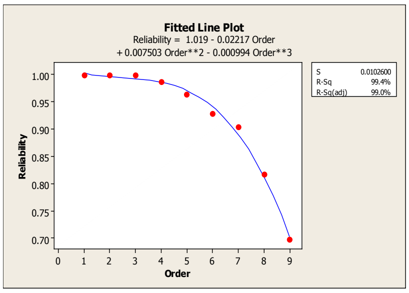




**Table 5:** Sample on Data and Graphs of Non Linear Regression on Overall Vibration and Reliability in Overall Vibration on Spindle Speeds, RPM (Hz): 500 (8.33) and 1,000 (16.67).

| No. | Spindle Speed, RPM (Hz) | Non Linear Regression: (X:Order); (Y: Vibrations ) of VMC 600 Spindle | | | Coefficient of Determination: | |
|---|---|---|---|---|---|---|
| | | **Durations (hours)** | **Orders** | **Equations** | **R-Sq** | **R-Sq (adj)** |
| 1 | 500 (8.33) | 2,000 to 6,000 | 1 to 9 | $Y = 0.1651 + 0.000526 X – 0.000483 X^2 + 0.00011 X^3$ | 99.5% | 99.3% |
| 2 | 1,000 (16.67) | 2,000 to 6,000 | 1 to 9 | $Y = 0.1658 + 0.003693 X – 0.001258 X^2 + 0.000168 X^3$ | 99.4% | 99.0% |
| 3 | 1,500 (25.00) | 2,000 to 6,000 | 1 to 9 | $Y = 0.1916 – 0.00886 X + 0.001816 X^2$ | 92.0% | 89.3% |
| 4 | 2,000 (33.33) | 2,000 to 6,000 | 1 to 9 | $Y = 0.1577 + 0.001381 X + 0.000262 X^2$ | 97.1% | 96.1% |

**Table 6:** Summary on Non Linear Regression: (X: Order); (Y: Vibrations ) of VMC 600 Spindle.

| No. | Spindle Speed, RPM (Hz) | Non Linear Regression: (X:Order); (Y: Reliability ) of VMC 600 Spindle | | | Coefficient of Determination: | |
|---|---|---|---|---|---|---|
| | | **Durations (hours)** | **Orders** | **Equations** | **R-Sq** | **R-Sq (adj)** |
| 1 | 500 (8.33) | 2,000 to 6,000 | 1 to 9 | $Y = 0.9996 – 0.00331 X + 0.00299 X^2 – 0.000674 X^3$ | 99.5% | 99.3% |
| 2 | 1,000 (16.67) | 2,000 to 6,000 | 1 to 9 | $Y = 1.019 – 0.02217 X + 0.007503 X^2 – 0.000994 X^3$ | 99.4% | 99.0% |
| 3 | 1,500 (25.00) | 2,000 to 6,000 | 1 to 9 | $Y = 0.9532 + 0.04844 X – 0.009924 X^2$ | 92.0% | 89.3% |
| 4 | 2,000 (33.33) | 2,000 to 6,000 | 1 to 9 | $Y = 1.002 – 0.008667 X – 0.001667 X^2$ | 97.1% | 96.1% |

**Table 7:** Summary on Non Linear Regression: (X: Order); (Y: Reliability) of VMC 600 Spindle.

| Levels of Acceleration | Bearing Health Condition |
|---|---|
| A < (2 GA) | Normal |
| (2 GA) < A < (6 GA) | Cautious |
| A > (6 GA) | Unusual |
| To define Acceleration: A; General Acceleration: GA | |

**Table 8:** Bearing Health Condition with Levels of Acceleration.

| Levels of Acceleration | Bearing Health Condition |
|---|---|
| A < (2)(8.64) | Normal |
| (2)(8.64) < A < (6)(8.64) | Cautious |
| A > (6)(8.64) | Unusual |
| To define Acceleration: A ($mm/sec^2$) | |

**Table 10:** Sample on Levels of Acceleration for Bearing Health Condition with our data in VMC 600 Spindle CNC on Speed: 500 RPM.

| Spindle Speed, RPM (Hz) | Velocity (at 2,000 hours) | General Acceleration |
|---|---|---|
| 500 (8.33) | 0.165 | 8.64 |
| 1,000 (16.67) | 0.169 | 17.70 |
| 1,500 (25.00) | 0.183 | 28.75 |
| 2,000 (33.33) | 0.158 | 33.09 |

**Table 9:** Converting Velocity of beginning working time to General Acceleration on each speed of different levels of no load of VMC 600 Spindle (at 2,000 hours).

| Levels of Velocity | Bearing Health Condition |
|---|---|
| V < (2)(0.165) | Normal |
| (2)(0.165) < V < (6)(0.165) | Cautious |
| V > (6)(0.165) | Unusual |
| To define Velocity: V (mm/sec) | |

**Table 11:** Sample on Levels of Velocity for Bearing Health Condition with our data in VMC 600 Spindle CNC on Speed: 500 RPM.

| S.No. | X | $X^2$ | $X^3$ | 0.000526(X) | 0.000483 ($X^2$) | 0.00011($X^3$) | Y | T = X (500) |
|---|---|---|---|---|---|---|---|---|
| 1 | 10 | 100 | 1000 | 0.00526 | 0.0483 | 0.11 | 0.23206 | 5000 |
| 2 | 11 | 121 | 1331 | 0.005786 | 0.058443 | 0.14641 | 0.258853 | 5500 |
| 3 | 12 | 144 | 1728 | 0.006312 | 0.069552 | 0.19008 | 0.29194 | 6000 |
| 4 | 13 | 169 | 2197 | 0.006838 | 0.081627 | 0.24167 | 0.331981 | 6500 |
| 5 | 14 | 196 | 2744 | 0.007364 | 0.094668 | 0.30184 | 0.379636 | 7000 |
| 6 | 15 | 225 | 3375 | 0.00789 | 0.108675 | 0.37125 | 0.435565 | 7500 |
| 7 | 16 | 256 | 4096 | 0.008416 | 0.123648 | 0.45056 | 0.500428 | 8000 |
| 8 | 17 | 289 | 4913 | 0.008942 | 0.139587 | 0.54043 | 0.574885 | 8500 |
| 9 | 18 | 324 | 5832 | 0.009468 | 0.156492 | 0.64152 | 0.659596 | 9000 |
| 10 | 19 | 361 | 6859 | 0.009994 | 0.174363 | 0.75449 | 0.755221 | 9500 |
| 11 | 20 | 400 | 800 | 0.01052 | 0.1932 | 0.88 | 0.86242 | 10000 |
| 12 | 21 | 441 | 9261 | 0.011046 | 0.213003 | 1.01871 | 0.981853 | 10500 |
| 13 | 22 | 484 | 10648 | 0.011572 | 0.233772 | 1.17128 | 1.11418 | 11000 |
| 14 | 23 | 529 | 12167 | 0.012098 | 0.255507 | 1.33837 | 1.260061 | 11500 |

**Table 12:** Sample on Excel Simulation to calculate Times form the equation of Non Linear Regression: Y = 0.1651 + 0.000526 X – 0.000483 X2 + 0.00011 X3.

| (Y) Levels of Velocity: V | Bearing Health Condition | (X = T/500) Times: T |
|---|---|---|
| V < 0.33 | Normal | T < 6,500 |
| 0.33 < V < 0.99 | Cautious | 6,500 < T < 10,500 |
| V > 0.99 | Unusual | T > 10,500 |
| To define Velocity: V (mm/sec) ; Times: T (hours) | | |

**Table 13:** Sample on Forecasting Times happened in Bearing Health Conditions in VMC 600 Spindle CNC on Speed: 500 RPM (by the equation of Non Linear Regression: $Y = 0.1651 + 0.000526 X – 0.000483 X^2 + 0.00011 X^3$).

| The bearing fault diagnosis (Hz) | | | |
|---|---|---|---|
| $F_C$ | $F_{BPO}$ | $F_{BPI}$ | $F_B$ |
| 3.716 | 106.207 | 85.460 | 36.748 |

**Table 14:** The bearing fault diagnosis of VMC 600 Spindle.

Acceleration for our data in VMC 600 Spindle CNC shown in Table 10.

1.3 Because our data of Vibration are Velocity (mm/sec), we must convert Levels of Acceleration into Velocity for Bearing Health Condition with Equation (13) shown in Table 11.

1.4 After that, we applied our equations of Non Linear Regression (Times and Vibration on Velocity) of VMC 600 Spindle to forecast Times happened in 3 Bearing Health Conditions such as Normal Times, Cautious Times, and Unusual Times by our created Excel Simulation to calculate Times form our equations of Non Linear Regression shown in Table 12.

1.5 We are able to summarise Forecasting Times happened in Bearing Health Conditions in VMC 600 Spindle CNC in Table 13.

2. We applied the equation (6) to (9) to calculate the bearing fault diagnosis of VMC 600 Spindle CNC (B71914-C-T-P4S; Dia. Shaft: 70 mm; No. Ball: 23; 8.33 Hz); therefore, the results shown in Table 14 to enhance proficient diagnosis when bearing fault will happen the symptom in Bearing Health Condition of Unusual.

## Conclusion

This paper has discussed 3 main parts. To begin with, we try to determine the natural frequencies of CNC Spindle to avoid setting that matches the natural frequency of the machine parts. In addition, we collected the vibration data used to assist in the design for controlling, predicting reliability in overall vibration on each speed in each working time by using non-linear regression. Moreover, in the bearing fault diagnosis process of CNC Spindle, we analysed rolling bearing fault diagnosis strategies in both time-domain and frequency-domain signals to perform motor bearing fault diagnosis. The results show that our model can be effectively used in the diagnosis of bearing faults of CNC Spindle through appropriate measurement and life prediction of CNC Spindle.

### Acknowledgement

We wish to express our thanks to the staff members of King Mongkut's University of Technology North Bangkok, Bliss Services (Thailand) Co., Ltd., and SCG Group (Map Ta Phut, Thailand) for their support during carrying out this research.

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