The Effect of Shaft Whirling on Accuracy of Rotating Coil Magnetic Measurement System

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Abstract. The electromagnetic in the storage ring serve to focus the electron beam in vertical and horizontal axis along the beamline. Thus, precision of the electromagnetic field is a crucial step to considering for control the electron motion. The rotating coil is spread technique for measuring the electromagnetic field of magnet. However, the measurement uncertainties of the electromagnetic field are effect to controlled the electron motion before utilizing. This paper examines impact of the errors of the rotating coil magnetic measurement system. The whirling shape in each position along the length of the shaft is used for approximation uncertainty.

1. Introduction

The synchrotron light generator is used more electromagnetic in an electron storage ring. The inquiry on the condition of the electromagnetic field is important to consider. A rotating coil is an extensive approach to electromagnetic field measurement this method consists of the rotating coil speed control and voltage harmonic signal recording. The speed control of the rotating coil is effect to the nominal of the harmonic signal [1]. The PID controller is a conventional design technique, apply to speed control of the rotating coil [2]. The harmonic coil magnetic field measurement system and the measurement results for quadrupole magnets were detail [3]. In addition, the uncertainties of shaft diameter can be influenced by whirling of the shaft during rotation [4]. The characteristic of the harmonic signal which is measured from the search coil depends on the shaft whirling that can be investigated on misalignment in vertical and horizontal [5]. In order to minimize the whirling displacement considering on mass, length of shaft, radial and young’s modulus is essential [6]. Moreover, natural frequency analysis and vibration, shape by using the modal test technique is important to determine the optimal speed [7]. The unbalance, mechanical misalignment and looseness phenomena can be detected by rotating coil technique [8]. This paper presents the verifying on whirling shaft imprecise of the electromagnetic field using a rotating coil approach. The experiment includes three topics. First topic demonstrates the natural frequency via the impact test, second topic is whirling shaft measurement that performs the motor speed at 200, 400 and 600 RPM and last topic simulates rotating coil magnetic measurement. The results of whirling shape can be used to approximate the measurement error that increasing the electromagnetic field measurement accuracy.

2. Equation of motion

The structure of the rotating coil is a coil that is packed in a cylindrical shaft, which is a circular shaft and supported by bearing, moves in a magnetic field with electric motor in a manner that revolves around itself at a constant speed. The mathematical model of shaft with bearing can be divided into two cases. The bearing is flexible object and a shaft is rigid object as first case, as shown in figure 1. The second case, considered bearing as a rigid object and a shaft as a flexible object, as shown in figure 2. where $k_b$ is stiffness of the bearing, $E$ is Modulus of Elasticity, $L$ is the length of the shaft, $M$ is the mass of shaft and $I$ is the moment of inertia.
The several whirling problems cause of shaft movement due to mass. Moreover, mass effect to unbalance while moving which unbalance influence to vibration force. The model of unbalance vibration is shown in figure 3. Unbalance of rotation, where $k_{\text{eff}}$ is stiffness of shaft or bearing and $f(t)$ is a force from unbalancing

$$f(t) = m\omega^2 e \sin \omega t$$

(1)

where $m$ is the mass of shaft, $e$ is centrifugation of the shaft from the center, $\omega$ is the angular velocity and $me$ is the force that causes unbalance. Whirling of a shaft that caused by mass which the whirling causes the behaviour to move in various ways such as a circle or oval as shown in figure 4.

The analysis of shaft includes of whirling shaft and shaft torsional in this case the conserving on 2 DOF and constant speed at 200, 400 and 600 rpm was investigated. The equation of motion in horizontal and vertical is shown in Eq. (2)-(3) respectively.

$$m\ddot{x} + c\dot{x} + kx = m\omega^2 e \cos \omega t$$

(2)

$$m\ddot{y} + c\dot{y} + ky = m\omega^2 e \sin \omega t$$

(3)

The equation of motion that can expose the natural frequency of shaft from free vibration without damping analysis from shown in Eq. (4)

$$\omega_{1,2} = (k/m)^{1/2}$$

(4)

The amplitude of centrifugal force due to shaft unbalance is $m\omega^2 e$ and the amplitude is dependent on rotating speed as shown in Eq. (5)-(6)

$$x(t) = X \cos(\omega t - \phi)$$

(5)

$$y(t) = Y \cos(\omega t - (\phi + \frac{\pi}{2})) = Y \sin(\omega t - \phi)$$

(6)

where $X$ and $Y$ are amplitude in horizontal and vertical, $\omega$ is rotating speed and $\phi$ is phase of displacement. The rotating coil magnetic measurement system has a symmetrical whirling of both axes through the magnetic field as shown in figure 5.
The dipole magnetic flux can determine in Eq. (7).
\[ \phi(\theta) = A B_0 \cos(\theta) \]  
(7)

The arithmetic of area of a coil as shown in Eq. (8).
\[ A = NI (R_{ext} - R_{int}) \]  
(8)

The electromotive force can determine from the rotating of the coil as shown in Eq. (9).
\[ V = \frac{d\phi}{dt} = \omega A B_0 \cos(\theta) \]  
(9)

Where \( B_0 \) is a magnetic field, \( N \) is a number of turns of the coil, \( I \) is the effective length of the coil and \( R_{ext}, R_{int} \) is radial of rotation of the wires. From Eq. (9) The flux enclosed of rotating coil (\( \psi \)) to calculate as shown in Eq. (10)
\[ \psi(\theta) = NI \int_{R_{int}}^{R_{ext}} B_0 \cos(\theta) \]  
(10)

where \( \psi = volt \cdot sec = tesla \cdot m^2 = weber \)

3. Experimental and Simulation results

The topic of results is divided into two sections: Section 1 describes the experimental setup for the investigation of natural frequency by impact testing and measuring the whirling of shaft horizontal and vertical direction and dynamic responses of the rotating coil and simulation results of impact test. Section 2 demonstrates the whirling of shaft measurement.
3.1. Impact test setup
The impact test section consists of the impact force hummer 1000 lbf sensitivity 1 mV/lbf with Dewetron DEWE-2601 and ± 50g sensitivity 105 mV/g accelerometer with FRF by Dewesoft X3.

3.2. Measurement whirling of shaft setup
The setup consists of NI PXIe-1071, the eddy current probe with an amplifier with 4 mm measurement range. The speed control system includes 24 Volt 250-watt DC motor, MATLAB/Simulink® and microcontroller board as shown in figure 6.

3.3. Impact test
The investigation of the natural frequency used impact test by roving sensor technique. The first mode of natural frequency is 1831.08 RPM (30.518 Hz) and the second mode is 3002.4 RPM (50.049 Hz) as shown in figure 7.

3.4. Measurement whirling of shaft
The speed of a rotating coil magnetic measurement system is good for a range of 200 – 600 rpm, due to this speed is close to the actual speed that used in machine and far from the natural frequency. This section is measured at 200, 400 and 600 rpm in the vertical and horizontal direction and 5 measuring points in each speed as shown in figure 8. According to the experiment 1 to 3, it was found that the whirling shaft is a similarity. The amplitude in horizontal and vertical is increasingly dependent on rotating speed. The maximum amplitude of shaft whirling can be found at the 3rd measuring position and the first position shown the minimum amplitude in each speed. On the other hand, the bottom amplitude of shaft whirling in the vertical was indicate too high compared with the top. In addition, the amplitude at the third position illustrates in Table 1.
3.5. Correlation of rotating coil

The experimental results 1 - 3 will be taken at the third measurement point because of the highest centrifugal distances as shown in Table 1 to simulate the shaft orbits and study the effects of shaft centrifuge on magnetic field measurements. The two polar magnetic field simulations with different magnetic field paths will be simulated.

Determined \( oB_r = 1 \) and area A has radial change according to the distance of whirling in the experiment through the magnetic field type Skew dipole (for observing the effect in horizontal field) and Normal dipole (for observing the effect in vertical field). The results are shown in figure 11.

### Table 1. The value of shaft whirling

| Speed (RPM) | Horizontal(mm) | Vertical(mm) |
|-------------|----------------|--------------|
|             | Left           | Right        | Left           | Right          |
| 200         | -0.11648       | 0.13925      | -0.19735       | 0.17456        |
| 400         | -0.12049       | 0.14694      | -0.14851       | 0.18653        |
| 600         | -0.11632       | 0.14277      | -0.15046       | 0.19058        |

Figure 9. Whirling in horizontal and vertical of 600 RPM.

Figure 10. Whirling in radial of 600 RPM.

Figure 11. The harmonic of the magnetic flux when the rotating coil moving through skew dipole and normal dipole magnet at 600 RPM.
The comparison between the simulation results of the ideal magnetic field measurement and the magnetic field measurement with whirling shaft at the rotational speed of 600 rpm in horizontal and vertical axis is shown in figure 1. The effect of the centrifugal force from the shaft weight. Causes the size of the radius \( (R_{ext}, R_{int}) \) to change. When measuring the magnetic field, therefore causing measurement discrepancies. The size of the error increase according to the shaft rotation speed as shown in Table 2.

Table 2, shown an error value of a magnetic field that measures in 2 axes. The simulation results show the error of vertical field is higher than the error of horizontal field at all speeds. Because the vertical axis has an earth's gravitational force acting on the shaft, therefore the vertical radial \( (R) \) is higher than the horizontal axis. The experiment found that if the accuracy of magnetic field measurement was needed, it is necessary to control the speed round of use. In order that rotating coil has minimum whirling.

| Speed (RPM) | Error Horizontal (%) | Error Vertical (%) |
|-------------|-----------------------|--------------------|
| 200         | 0.2399                | 0.3002             |
| 400         | 0.3151                | 0.3545             |
| 600         | 0.3153                | 0.3667             |

4. Conclusion
This paper presents effect of the whirling of the shaft that caused by weight, length and rotation speed round. For measuring of magnetic field intensity with rotating coil technique, measuring distance of the whirling of the shaft at horizontal axis and vertical axis at each position through the length of the shaft will can estimate the error of the measurement with this technique. In order to compensate the error that happen with the tool of the magnetic field intensity measurement for higher measurement accuracy.

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