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The Effect of Imbalance on Rotor Vibration in Electric Motors

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ABSTRACT

Mechanical system failures in electric motors are often caused by mass imbalance in the rotor. This imbalance occurs when the mass distribution is uneven relative to the axis of rotation, causing the center of mass to deviate from the rotational axis. Such conditions generate centrifugal forces that lead to excessive vibrations, accelerate component wear, reduce efficiency, and shorten the motor's lifespan. Mass imbalance in the rotor system is one of the main causes of excessive vibration in rotating machines, which can result in performance degradation, component wear, and even catastrophic failure. This study aims to analyze the vibration characteristics caused by unbalance in a single rotor and evaluate the effectiveness of the trial weight balancing method (three-test-mass method) in reducing the resulting vibrations. Experimental testing was conducted using a Digital Signal Analyzer (DSA), an accelerometer sensor, and a rotor test system with various unbalanced mass configurations installed on the rotor disk. Vibration data were analyzed in both time and frequency domains using the Fast Fourier Transform (FFT) to identify dominant frequencies due to unbalance. The results show that the highest vibration amplitude occurs at the fundamental frequency corresponding to the rotor's rotational speed. The three-test-mass balancing method proved effective in significantly reducing the vibration amplitude after mass correction. These findings indicate that identifying unbalance through vibration response and applying an appropriate balancing method can improve the stability and reliability of rotating rotor systems, including both three-phase induction motors and universal motors such as electric drills.

Keywords: unbalance, vibration, single rotor, DSA, FFT, three-test-mass balancing.

1.0 INTRODUCTION

Mechanical systems in industrial machinery, including electric motors, rely heavily on the dynamic balance of rotating components such as rotors. One of the main causes of failure in rotating systems is rotor mass imbalance, a condition where the mass distribution is not uniform relative to the axis of rotation. This imbalance generates centrifugal forces that trigger mechanical vibrations, which—if left unaddressed—can lead to bearing damage, increased wear, reduced efficiency, and ultimately, total system failure. In electric motor systems, vibrations caused by imbalance not only contribute to mechanical wear but also significantly reduce motor performance.

2.0 METHODOLOGY

Vibration in mechanical systems is a dynamic response caused by oscillating forces, whether from internal or external sources. In rotating machinery, vibrations typically arise from imbalance, misalignment, bearing faults, or resonance. These vibrations can be measured in terms of acceleration, velocity, or displacement over time. One important technique for identifying vibration sources is frequency domain analysis using the Fast Fourier Transform (FFT).

Rotor Imbalance : occurs when the center of mass does not coincide with the axis of rotation. This condition results in oscillating centrifugal forces that increase with rotational speed and cause higher vibration amplitudes. There are three main types of rotor imbalance:
Static Unbalance: The center of mass is offset from the rotational axis, even though the mass distribution is symmetrical along the shaft.
Couple Unbalance: Caused by asymmetric mass distribution on opposite sides of the rotor.
Dynamic Unbalance: A combination of static and couple unbalance, and the most common type in real-world rotors.

This study considers two types of electric motors: the three-phase induction motor, known for its durability and efficiency, and the universal motor, which is commonly used in portable tools. Due to their high rotational speed, universal motors are more susceptible to rotor imbalance issues. To detect imbalance, frequency analysis using FFT is applied to vibration signals. FFT converts time-domain data into the frequency domain, identifying dominant frequencies at multiples of the rotational speed (1X, 2X, 3X, etc.). The amplitude at these frequencies reflects the severity of the mass imbalance.

Three-Test-Mass Balancing Method

Rotor balancing can be experimentally performed using the three-test-mass method, which has proven to be efficient and accurate, especially for simple rotor systems. This method involves attaching three test weights at different angular positions on the rotor and measuring the resulting vibration amplitude. From the measured vibration data, the optimal weight and angular position for correction can be calculated. Suryadi and Vetrano (2018) demonstrated the success of this method in identifying imbalance in a single rotor using a Digital Signal Analyzer (DSA).

Related Studies

Several other studies also emphasize the importance of vibration analysis and balancing methods in rotating systems:
Santoso et al. (2019) analyzed vibrations in centrifugal pumps due to imbalance and successfully reduced the amplitude after balancing.
Rizki & Hidayat (2020) reported that variations in rotor mass distribution affect vibration amplitude, and FFT is a key tool for diagnostics.

This study builds upon those approaches by applying them to universal and three-phase induction motors, and comparing their sensitivity to mass imbalance.

3.0 RESULT

This research uses an experimental approach to analyze the effect of rotor mass imbalance on the vibration characteristics of two types of electric motors: a universal motor (electric drill) and a three-phase induction motor. The study involves vibration measurements with varying unbalanced masses and rotational speeds, as well as frequency spectrum analysis using FFT.

1. Tools and Materials:
2. Universal Motor (Electric Drill):
   Primary object for testing imbalance effects at high speeds.
3. Three-Phase Induction Motor:
   Used for comparison due to its different dynamic characteristics.
4. Three-Phase Inverter:
   Used to control the speed of the induction motor.
5. Vibration Sensor (Accelerometer):
   For measuring rotor vibration acceleration.

Data Acquisition System (DAQ) and FFT Software:
To record and analyze vibration signals in the frequency domain.

Test Weights (Balancing Weights):
Small metal masses (e.g., 1g, 2g, 3g) precisely mounted on the rotor.

Research Steps:

i. Preparation of the test system
ii. Baseline vibration measurement (without imbalance)
iii. Installation of unbalanced masses
iv. Vibration measurement
v. Application of the three-test-mass balancing method
vi. Comparison of results
vii. Test Parameters:
viii. Unbalanced Mass Variations: 1 gram, 2 grams, 3 grams
ix. Test Rotational Speeds: 1000 RPM, 2000 RPM, 3000 RPM (controlled via inverter or manually)
x. Measurements: Vibration amplitude (mm/s²), dominant frequency (Hz)

The vibration testing system, as shown in Figure 1, employs an electric motor to drive the rotor through a coupling. The rotor is mounted on a shaft supported by two bearings, with the entire assembly fixed onto a rigid frame to prevent deflection that could interfere with accurate vibration measurements by the Digital Signal Analyzer (DSA).

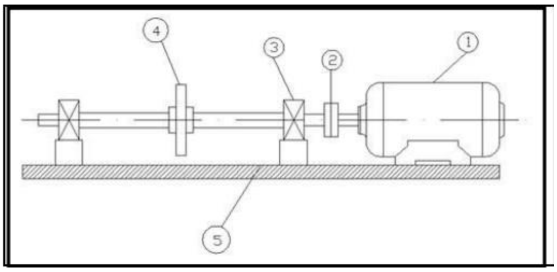

Figure 1: Component Layout of the Single Rotor Imbalance Testing System.

1. Electric Motor (Power Source)
2. Coupling (Motor-to-Rotor Connector)
3. Bearings (Rotor Support)
4. Rotor (Test Object)
5. Frame (System Support Structure)

Figure 2 shows the dimensions of the rotor used in the testing. From the figure, it can be seen that the rotor has a diameter of 120 mm, a width of 32 mm, and a shaft hole diameter of 20.9 mm.

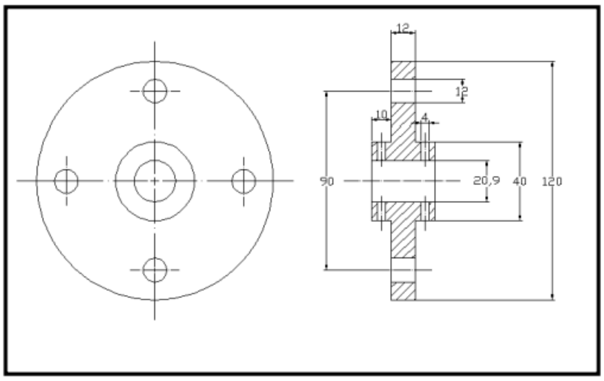

Figure 2: Illustrates the test rotor.

Vibration is generated by the centrifugal force resulting from the mass imbalance of the rotating rotor. The rotor's rotational speed is controlled using an electric motor and a slide regulator. The vibration is transmitted from the rotor to the bearings, and then detected by an accelerometer mounted on the bearing housing. The vibration signal is then sent to the Digital Signal Analyzer (DSA), which is integrated with a computer for data analysis (Figure 3).

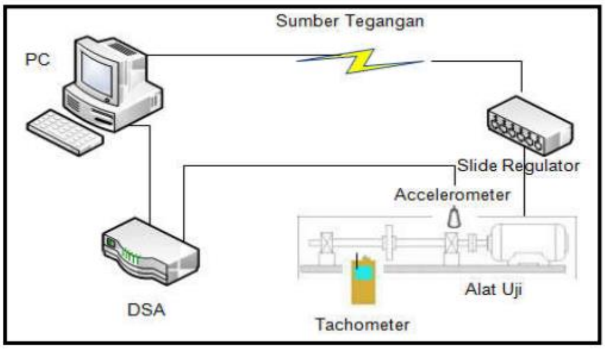

Figure 3: Balancing Test Equipment Setup

The testing procedure consists of two main stages: vibration response measurement due to imbalance and the balancing process. The first stage, vibration response measurement, is carried out by assembling the testing system (Figure 1), attaching unbalanced mass to the rotor, and connecting the electric motor (via slide regulator) to a 220 V power source. The accelerometer is mounted vertically on the bearing housing, and the Digital Signal Analyzer (DSA) is connected to the computer (Figure 4).

Figure 4: Transducer Installation Vibration Measurement Due to Imbalance

After assembling the testing system (Figure 1) and attaching the unbalance mass to the rotor, the following steps were carried out:

i. A tachometer was installed near the rotor shaft to monitor the rotational speed.
ii. The slide regulator was gradually turned until the rotor reached the desired rotational speed, as displayed on the tachometer's LCD screen.
iii. Once the rotor achieved a stable speed, vibration data were recorded using the Digital Signal Analyzer (DSA).
iv. Steps 1 to 3 were repeated for various rotational speeds, ranging from 200 rpm to 2500 rpm, with increments of 50 rpm.
v. The vibration data recorded by the DSA, including both time and frequency domains, were analyzed to determine the amplitude and frequency of the vibrations.

Balancing Process

Balancing was performed at a rotational speed of 1500 rpm using the three trial mass method. The procedure followed these steps:

1. Testing system was assembled (Figure 1) and the unbalanced mass was mounted on the rotor.
2. The electric motor was connected to a 220 V power supply via the slide regulator.
3. The DSA was connected to the computer, and the accelerometer was mounted vertically on the bearing (Figure 4).
4. The DSA channels were configured.
5. A tachometer was used to monitor the rotor's rotational speed.
6. The rotor was spun to 1500 rpm and stabilized.
7. Vibration measurements were recorded using the DSA. A trial mass of 17.9 grams was attached at Position A (Figure 5), the rotor was run at 1500 rpm, and the vibration amplitude was recorded.
8. Step 8 was repeated for Position B (Figure 6) and Position C (Figure 7), each located 120° apart.
9. Based on the amplitude data from steps 8 and 9, the optimal position and value of the correction mass were calculated.

The correction mass was installed, and vibration measurements were repeated to evaluate the effectiveness of the balancing process.

Figure 5: The test began by placing

The test began by placing the trial mass at Position A (Figure 5). After measuring the vibration amplitude, the trial mass was then moved to Position B. Position B was maintained at the same radial distance as Position A but rotated by 120° (Figure 6). At Position B, the vibration amplitude measurement was repeated at the same rotational speed as in Position A.

Figure 6: After completing the measurement

After completing the measurement at Position B (Figure 6), the trial mass was moved to Position C. Position C was kept at the same radial distance as Positions A and B but rotated 120° from Position B (Figure 7). At the same rotational speed as in the previous measurements, the vibration amplitude was then recorded.

Figure 7: After determining the optimal position

After determining the optimal position and weight of the correction mass (Figure 7),
the correction mass was installed as shown in Figure 8. Subsequent vibration measurements were conducted to analyze the system's response in both the time and frequency domains, which were expected to show a reduction in vibration amplitude.

Figure 8: Position of the Correction Mass

To evaluate the effectiveness of the three-trial-mass balancing method, the test was conducted at a rotational speed of 1500 rpm. The initial vibration data, which reflected the rotor's mass unbalance, showed a dominant frequency of 24.905 Hz, a magnitude of 0.0166 g, and an amplitude (Ro) of 0.150 g. For the balancing procedure, the trial mass was placed at three different positions separated by 120° (Figure 10), with a radial distance of 47 mm from the rotor center—equal to the distance of the initial unbalanced mass. The test was repeated three times for each trial mass position.

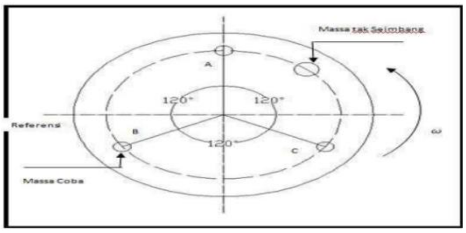

Figure 9: Position of test mass installation

Rotor Mass Unbalance Test Results

The testing was carried out by varying the rotor's rotational speed from 200 rpm to 2500 rpm in 50 rpm increments, resulting in a total of 47 speed variations. For each speed, the vibration response data in the time and frequency domains were recorded for 10 seconds using a Digital Signal Analyzer (DSA) and analyzed using the FFT method.

The FFT analysis results showed that as the rotor speed increased, both the dominant vibration frequency (active frequency) and its magnitude also increased.

3.1 Effect of angular phase unbalance on the performance use MATLAB simulation

This study also analyzed the effect of angular phase unbalance on the performance of a 100 HP / 75 kW three-phase induction motor during startup and steady-state conditions, using MATLAB simulation.

The induction motor is an asynchronous machine that converts electrical energy into mechanical energy through electromagnetic induction. This type of motor is available in various KVA ratings and operates by supplying alternating current (AC) directly to the stator, while the rotor is induced by a transformer-like effect from the stator.

Figure 10 illustrates the basic structure of an induction motor. A three-phase induction motor utilizes three identical stator windings, electrically separated by 120°, to produce a rotating magnetic field when supplied with a three-phase voltage.

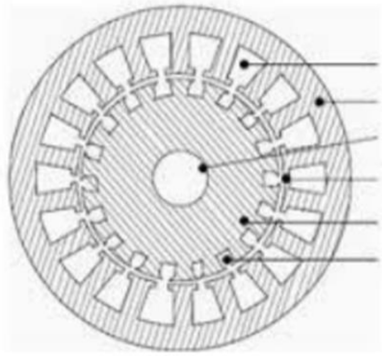

Figure 10: Basic Construction of a Simple Induction Motor

The speed of the synchronous magnetic field (*ns*) is determined by the equation:

$$ns = 120f/p$$

where f is the supply frequency,
and p is the number of pole pairs.

This rotating magnetic field induces an electromotive force (EMF) in the rotor. An unbalanced power system, as defined by the IEEE, refers to any variation in voltage magnitude or phase angle among the phases, which primarily affects polyphase systems, including three-phase systems. One of the methods to quantify this unbalance is the Line Voltage Unbalance Rate (LVUR), as defined by NEMA.

Figure 11 shows the simulation circuit of a three-phase induction motor built in MATLAB/Simulink to analyze the effect of voltage unbalance on motor performance. The induction motor model used has the following specifications: 100 HP, 75 kW, 400 V, 50 Hz, and synchronous speed of 1480 rpm.

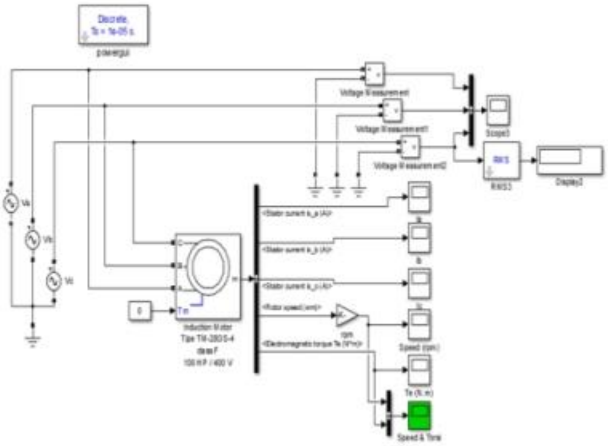

Figure 11: Simulation circuit of a three-phase induction

Table 1 presents the simulation results under no-load conditions, whereas Table 2 presents the results of the unbalanced phase angle simulation with load applied to a three-phase induction motor.

Table 1 : Simulation Results of Phase Angle Unbalance (No Load Condition)

	Rise time	Peak time	Settling time	Steady state
Stator A	0.00086 second	0.01 second	0.29 second	121 Ampere
Stator B	0.0040 second	0.12 second	0.30 second	121 Ampere
Stator C	0.0010 second	0.04 second	0.28 second	121 Ampere
Torque	0.0025 second	0.01 second	0.45 second	169 Nm
Rotation	0.085 second	0.22 second	0.35 second	1498 Rpm

Table 2: Results of Unbalanced Phase Angle Simulation with Load on 3 Phase Induction Motor

	Rise time	Peak time	Settling time	Steady state
Stator A	0.0050 second	0.12 second	0.30 second	146 Ampere
Stator B	0.0066 second	0.04 second	0.28 second	67 Ampere
Stator C	0.00051 second	0.01 second	0.29 second	208 Ampere
Torque	0.0039 second	0.04 second	0.40 second	660 Nm
Rotation	0.088 second	0.22 second	0.41 second	1501 Rpm

4.0 DISCUSSION

4.1 Rotor Mass Imbalance and Vibration Response

The experimental results confirmed that rotor mass imbalance generates significant vibration responses that increase with rotational speed. The FFT analysis demonstrated that the dominant vibration frequency corresponds to the rotor's rotational speed, which aligns with theoretical expectations of synchronous vibration behavior under unbalance conditions. This correlation validates that mass eccentricity is the primary source of the observed vibrations. The increase in both amplitude and frequency with higher rotational speeds indicates that even minor unbalances can become critical at elevated rpm levels, a phenomenon well-documented in rotor dynamics studies (Rao, 2019).

The application of the three-trial-mass balancing method effectively reduced vibration amplitudes at 1500 rpm. Before correction, the system exhibited a dominant frequency of 24.905 Hz with an amplitude of 0.150 g, while after correction, a significant reduction was observed. This highlights the efficiency of the balancing process in redistributing mass to counteract the initial eccentricity. The findings support the notion that trial mass balancing remains one of the most practical and reliable approaches for laboratory-scale unbalance correction (Muszynska, 2005).

4.2 Comparison Between Universal Motor and Induction Motor Characteristics

The universal motor (electric drill) and the three-phase induction motor demonstrated distinct dynamic behaviors due to differences in their structural design and operating principles. The universal motor, operating at higher speeds, was more sensitive to small unbalances, generating higher vibration amplitudes. In contrast, the induction motor showed more stable vibration responses, but unbalances still introduced notable increases in vibration amplitude as speed increased. This difference underlines the role of motor type in determining susceptibility to unbalance, echoing previous studies that found universal motors to be more vulnerable to instability under mass eccentricity (Chen et al., 2020).

4.3 Effectiveness of the Balancing Method

The three-trial-mass method proved effective in minimizing vibration at the target speed of 1500 rpm. The sequential placement of trial masses at 120° intervals allowed accurate determination of the corrective mass location and magnitude. Post-balancing results confirmed a significant reduction in vibration amplitude, both in time and frequency domains, indicating the restoration of rotor symmetry. This outcome aligns with literature that emphasizes the cost-effectiveness and simplicity of the three-point balancing approach compared to more complex balancing algorithms (ISO 1940/1, 2016).

4.4 Simulation Analysis of Phase Angle Unbalance in Induction Motor

The MATLAB simulation revealed that voltage phase angle unbalance significantly affects motor performance. Table 1 (no-load condition) showed relatively uniform current distribution across the three stators (121 A each) and stable torque (169 Nm). However, under load (Table 2), notable asymmetry emerged: Stator A current increased to 146 A, Stator B decreased sharply to 67 A, and Stator C rose to 208 A. This unbalanced current distribution indicates additional thermal and mechanical stresses on individual stator windings, which can accelerate insulation degradation and reduce motor lifespan (IEEE Std. 115, 2019).

Torque also increased substantially from 169 Nm under no load to 660 Nm with load, indicating that unbalance introduces higher mechanical stresses. Furthermore, the rise in steady-state rotational speed from 1498 rpm to 1501 rpm, though small, suggests efficiency fluctuations. These findings are consistent with prior studies reporting that unbalanced voltage conditions elevate power losses, reduce efficiency, and cause overheating in induction motors (NEMA MG1, 2016).

4.5 Practical Implications

The results underscore two critical implications. First, balancing rotors is essential to reducing vibration levels, improving machine reliability, and preventing premature bearing or shaft failures. Second, unbalanced phase angles in power supply system represent a serious operational risk for three-phase induction motors. Condition monitoring techniques such as vibration analysis and current signature analysis are indispensable for early detection of these issues. The combined use of experimental balancing techniques and simulation-based performance analysis provides a robust framework for improving both rotor health and motor reliability in industrial applications.

5.0 RESULT

Simulation using MATLAB / Simulink demonstrated that phase angle unbalance in a three-phase induction motor significantly affects both transient and steady-state characteristics.

1. Although the peak time remained relatively unaffected, phase angle unbalance significantly increased the rise time and settling time of the stator current and torque, particularly during motor startup. This indicates a considerable impact on the motor's dynamic response.
2. Under steady-state conditions, the phase angle unbalance led to an increase in stator current and torque, which can reduce motor efficiency and potentially cause damage to the motor.

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