

DIGITAL TWIN BASED CONDITION MONITORING OF ROTATING MACHINERY USING STRESS AND VIBRATION ANALYSIS

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ABSTRACT: Modern industries increasingly rely on predictive maintenance techniques to ensure reliability and reduce unexpected failures in mechanical systems. By creating a virtual version of a physical asset, digital twin technology makes it possible to continuously monitor and analyse its operating behaviour. In this study, a digital twin-based approach is proposed for monitoring the condition of rotating machinery using stress and vibration analysis. A shaft supported by a deep groove ball bearing (6206 series) is considered as the mechanical system for investigation. Finite element simulations are carried out using ANSYS to perform static structural analysis, modal analysis, and harmonic response analysis. These simulations help in evaluating the stress distribution and vibration characteristics of the system under operating conditions. The obtained results are processed using Python to extract maximum and minimum parameter values, which are used to represent the digital twin model of the equipment. In a practical implementation, sensor data from the physical system can be integrated with the simulation model to continuously monitor equipment health. The proposed framework demonstrates how digital twin technology can support condition monitoring and predictive maintenance of rotating machinery by identifying abnormal stress and vibration behaviour at an early stage.

IndexTerms: Digital Twin, Predictive Maintenance, Rotating Machinery, Stress Analysis, Vibration Analysis, ANSYS Simulation

1. Introduction

Rotating machinery plays a crucial role in industrial systems like pumps, compressors, turbines and electric motors. These machines work under mechanical loads and environmental conditions which can slowly cause wear, fatigue and eventually failure of parts. When rotating equipment fails it can cause production downtime increase maintenance costs and create safety hazards. So checking the health of parts has become a key part of modern industrial maintenance strategies.

Traditional maintenance methods include fixing things after they break and doing maintenance. Fixing things after they break's done after a failure happens while regular maintenance is done at set times no matter the actual condition of the equipment. Regular maintenance reduces failures but it can still lead to replacing parts that are still good.

With Industry 4.0 technologies predictive maintenance has become an efficient way to manage equipment. Predictive maintenance focuses on monitoring the operating condition of machinery and predicting potential failures before they happen. This allows maintenance activities to be scheduled when necessary, reducing operational costs and improving system reliability.

Digital twin technology has become popular in years as a powerful tool for predictive maintenance. A digital twin is a copy of a physical system that continuously gets data from sensors on the real equipment. By combining real-time data with simulation models the digital twin can analyze the behavior of the system and detect abnormal conditions.

Stress and vibration analysis are two techniques used for monitoring the condition of rotating machinery. Stress analysis helps determine the distribution of stresses and deformation within components when subjected to external loads. Excessive stress levels may indicate a risk of structural failure. On the hand vibration analysis provides information about the dynamic behavior of the system and helps identify mechanical faults such, as imbalance, misalignment or bearing defects.

In this study a digital twin framework is developed for monitoring the condition of a rotating shaft supported by a deep groove ball bearing. Finite element simulations are performed using ANSYS to analyze distribution and vibration characteristics. The results obtained from the simulation are processed using Python to extract parameters that represent the operational state of the system. This approach demonstrates how digital twin technology can be used to support maintenance of rotating machinery.

2. Literature Review

Recent developments in smart manufacturing have highlighted the importance of digital twin technology for improving monitoring, control, and maintenance of industrial systems. Digital twin models enable the creation of a virtual representation of physical equipment, allowing engineers to analyse system behaviour, monitor operational conditions, and predict potential failures.

The concept of digital twins was initially introduced to establish a strong connection between physical systems and their virtual counterparts. By continuously exchanging data between the physical asset and its digital model, the system can simulate real-time behaviour and support intelligent decision-making. Research has shown that digital twins play a significant role in improving the efficiency, transparency, and flexibility of modern manufacturing environments [1].

In recent years, researchers have explored the application of digital twins for real-time monitoring and dynamic interaction in manufacturing systems. For example, Yu et al. proposed a digital twin workshop framework that enables continuous monitoring and synchronization between physical production systems and their virtual models. Their work emphasized the importance of integrating real-time data, virtual simulation models, and intelligent decision-making tools to improve production efficiency and system management [1]. According to this study, digital twin systems can provide better visualization of workshop operations and support remote monitoring of manufacturing equipment.

Another important area of research focuses on predictive maintenance using digital twin technology. Several studies highlight that digital twins can combine simulation models with real operational data to detect abnormal behaviour in machines and estimate future performance degradation. By analysing parameters such as stress, vibration, and temperature, it becomes possible to identify early signs of component failure and schedule maintenance activities before serious damage occurs [2].

Researchers have also investigated the integration of simulation tools with digital twin frameworks. Finite element analysis methods, such as structural analysis and vibration analysis, are frequently used to evaluate the mechanical behaviour of rotating machinery. These simulations provide valuable insights into stress distribution, natural frequencies, and dynamic responses of mechanical components. When simulation results are integrated with real-time operational data, the digital twin model can provide more accurate predictions of equipment condition [3].

Another line of research has focused on the use of data analytics and machine learning techniques in digital twin systems. In these approaches, sensor data collected from machines are processed using computational models to identify patterns and detect anomalies. Such systems can automatically analyse large volumes of operational data and support intelligent fault diagnosis and maintenance planning [4].

Despite significant advancements in digital twin research, several challenges still remain in practical industrial implementation. Many existing studies focus on monitoring individual machines rather than integrating multiple analytical techniques for comprehensive equipment health assessment. Additionally, the integration of simulation-based analysis with real-time sensor data for predictive maintenance requires further investigation.

Therefore, this study aims to develop a digital twin-based monitoring framework for rotating machinery by integrating stress analysis and vibration analysis. Finite element simulations are performed using ANSYS to evaluate the structural and dynamic behaviour of a shaft supported by a deep groove ball bearing. The simulation results are further processed using Python to extract critical parameters such as maximum and minimum stress and vibration values. These parameters form the basis for the digital twin model, which can be used to monitor equipment condition and support predictive maintenance.

3. Methodology

This study proposes a digital twin-based framework for monitoring the condition of rotating machinery using stress and vibration analysis. The methodology integrates finite element simulation, data processing, and digital twin implementation to evaluate the health condition of a shaft-bearing system. The overall process includes system modelling, simulation analysis using ANSYS, extraction of key parameters through Python, and implementation of a digital twin model for condition monitoring.

The workflow adopted in this research consists of the following major steps:

1. Development of the shaft-bearing system model
2. Finite element analysis using ANSYS
3. Extraction and processing of simulation results using Python
4. Implementation of a digital twin model
5. Condition monitoring and predictive maintenance framework

3.1 System Description

The mechanical system considered in this study consists of a rotating shaft supported by a deep groove ball bearing. The bearing selected for the analysis is a 6206 series deep groove ball bearing. The bearing has a bore diameter of 30 mm, an outer diameter of 65 mm, and a width of 16 mm. The bearing material is assumed to be chrome stainless steel, which provides high strength and wear resistance.

The shaft connected to the bearing is made of plain carbon steel with a length of 110 mm and a diameter of 30 mm. The shaft transmits rotational motion and is subjected to mechanical loading during operation. The shaft-bearing system is modelled to analyse the mechanical behaviour and vibration characteristics of the rotating component.

3.2 Geometry Modelling

The geometric model of the shaft-bearing system which is shown in figure 1 was developed using **SolidWorks**, a computer-aided design (CAD) software widely used for mechanical component modelling. In this stage, the individual components of the rotating system were created to represent the physical configuration of the shaft supported by a deep groove ball bearing. The modelling process involved creating the shaft geometry and the bearing components using standard sketching and extrusion operations available in SolidWorks.

After generating the individual parts, the shaft and bearing were assembled using appropriate assembly constraints to ensure proper alignment between the components. This assembly represents the actual arrangement of the shaft supported by the bearing in rotating machinery. The completed model was then exported from SolidWorks and imported into **ANSYS** for further finite element analysis, including structural and vibration studies. Accurate geometry modelling is essential because it forms the foundation for obtaining reliable simulation results in subsequent analysis stages.



Figure 1 : SolidWorks model of shaft and bearing assembly

3.3 Finite Element Meshing

After generating the geometry, the model is discretized using the finite element meshing process. Meshing divides the entire geometry into a large number of small elements that allow numerical computation of structural behaviour.

A suitable mesh size is selected to maintain a balance between computational efficiency and accuracy. A finer mesh is applied in critical regions of the shaft where stress concentration is expected. Proper mesh quality helps improve the accuracy and convergence of simulation results.

3.4 Static Structural Analysis

Static structural analysis is performed to evaluate the stress distribution and deformation of the shaft-bearing system under applied loading conditions. This analysis determines the equivalent **von Mises stress**, which is widely used to predict yielding or failure in ductile materials.

The applied loads simulate the operating forces acting on the shaft during rotation. The resulting stress distribution helps identify regions where maximum stress occurs. These regions are considered potential locations for structural failure if the stress exceeds the allowable material limits.

The results obtained from the structural analysis shown in the below figure 2 provides valuable information about the mechanical integrity of the rotating shaft.

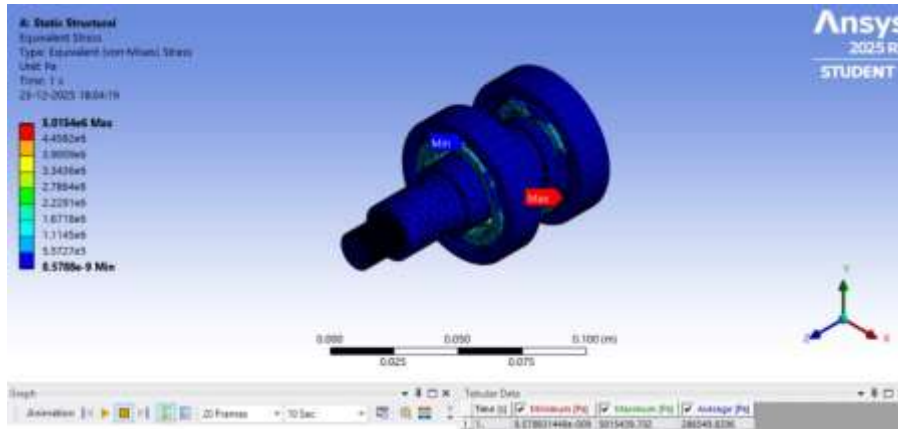


Figure 2: Equivalent von Mises stress distribution obtained from ANSYS static structural analysis

3.5 Modal Analysis

Modal analysis is conducted to determine the **natural frequencies and mode shapes** of the shaft-bearing system. Natural frequencies represent the frequencies at which the system tends to vibrate when excited.

Identifying the natural frequencies is important because operating machinery near its natural frequency may lead to resonance conditions. Resonance can significantly increase vibration amplitude and may result in mechanical damage or structural failure.

The mode shapes obtained from modal analysis illustrated in figure 3 below shows the vibration patterns of the shaft during dynamic excitation.

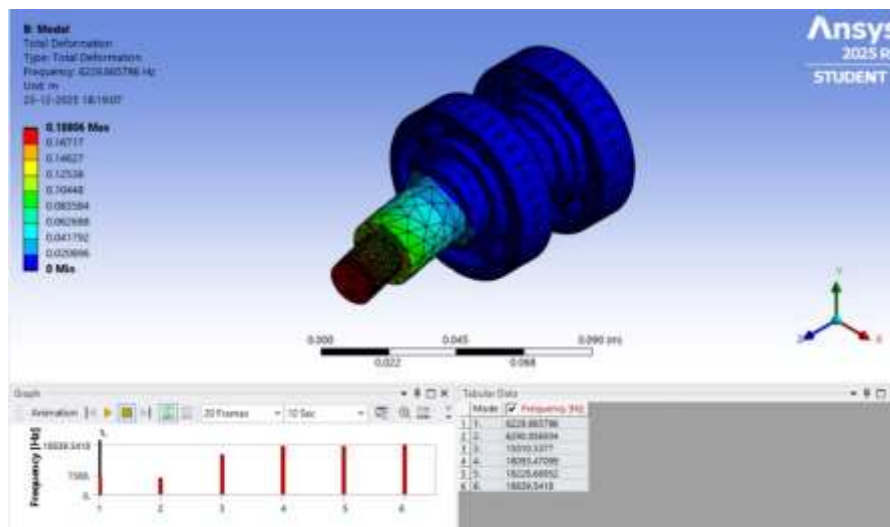


Figure 3: Mode shape obtained from modal analysis

3.6 Harmonic Response Analysis

Harmonic response analysis is performed to study the vibration behaviour of the shaft under periodic excitation. In this analysis, sinusoidal loads are applied to the system to simulate real operating conditions.

The analysis calculates the vibration amplitude of the shaft at different excitation frequencies. Peaks in the response curve as shown in the figure 4 indicate frequencies where the system experiences significant vibration.

The harmonic response results help identify vibration characteristics of the shaft and evaluate the dynamic stability of the rotating system.

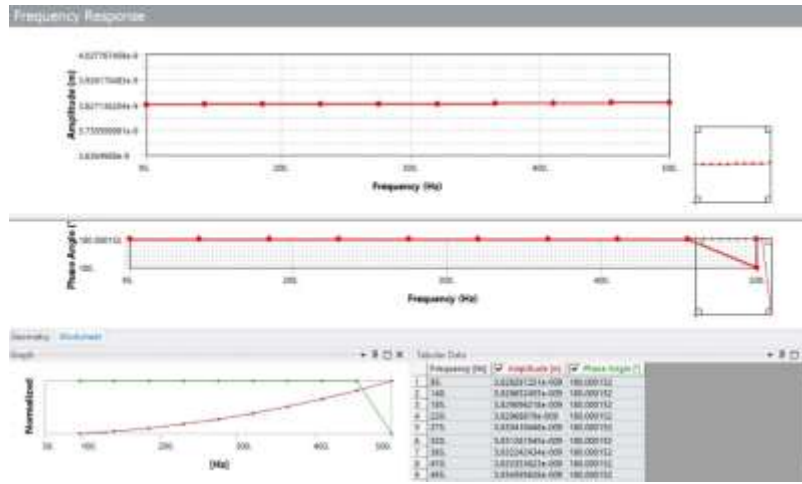


Figure 4: frequency response chart from harmonic response

3.7 Data Extraction Using Python

After completing the simulations in ANSYS, the obtained results were exported for further processing. These results include parameters such as stress values, deformation values, and vibration amplitudes. To analyse this data efficiently, Python programming was used.

The simulation data files were imported into Python using appropriate libraries. The program reads the ANSYS output files and processes the data to determine important parameters such as maximum stress and vibration values. These values provide useful information about the behaviour of the shaft–bearing system.

Python was also used to generate plots that help visualize the distribution of stress and frequency response characteristics. This step makes it easier to analyse the simulation results and interpret the behaviour of the mechanical system.

3.8 Digital Twin Implementation

The concept of a digital twin involves creating a virtual representation of a physical system that can continuously monitor its behaviour. In this study, the results obtained from ANSYS simulations and Python data processing are used to represent the digital model of the shaft–bearing system.

The digital twin model stores important parameters such as stress levels and vibration characteristics obtained from the simulation. In a real industrial environment, sensors installed on machinery can continuously measure parameters such as vibration, temperature, or load conditions. These sensor values can then be compared with the values obtained from the digital twin model.

If the measured values deviate from the expected range predicted by the digital twin, it may indicate abnormal operating conditions. In such cases, the system can alert the user so that maintenance actions can be taken before serious failure occurs. Thus, the digital twin helps in monitoring equipment health and improving reliability of rotating machinery.

Physical System → Sensors → Data Processing (Python) → Digital Twin Model → Condition Monitoring

3.9 Predictive Maintenance Framework

Predictive maintenance focuses on identifying potential failures before they occur by continuously monitoring the condition of machinery. In this study, predictive maintenance is achieved by analysing the stress and vibration behaviour of the shaft–bearing system.

The digital twin model created using simulation results provides a reference for normal operating conditions of the system. During operation, sensor data collected from the physical equipment can be compared with the predicted values obtained from the digital twin. If abnormal stress levels or unusual vibration patterns are detected, it may indicate the possibility of component damage or wear.

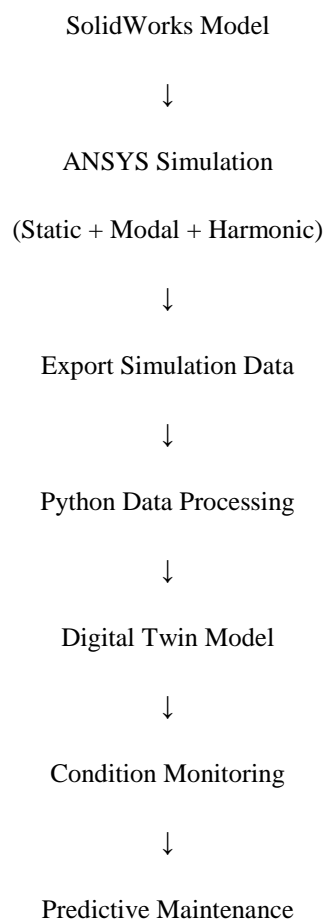
By detecting such conditions at an early stage, maintenance can be scheduled in advance, preventing unexpected machine breakdowns. This approach reduces downtime and improves the efficiency of industrial operations. Therefore, the integration of simulation analysis, Python data processing, and digital twin modelling provides an effective framework for implementing predictive maintenance in rotating machinery.

3.10 Methodology Workflow Summary

Based on the above methodology, the overall process of this study involves modelling the shaft–bearing system, performing simulation analysis, processing the obtained data, and implementing a digital twin framework for monitoring equipment condition. Initially, the geometry of the shaft and bearing assembly was created in SolidWorks and imported into ANSYS for simulation analysis. Static structural, modal, and harmonic response analyses were then performed to understand the stress distribution and vibration behaviour of the system.

The simulation results were exported and processed using Python to extract important parameters such as maximum stress and vibration values. These parameters were used as reference values for the digital twin model. In practical applications, real-time sensor data from the physical system can be compared with the digital twin model to detect abnormal conditions. Flow chart 1 explains the overall workflow followed in this research helps in monitoring the behaviour of rotating machinery and supports predictive maintenance strategies.

Flowchart-1: Overall Methodology



4. Results and Discussion

In this study, the shaft–bearing system was analysed using different simulation techniques in ANSYS to evaluate its structural and vibration behaviour. Static structural analysis, modal analysis, and harmonic response analysis were carried out. The results obtained from ANSYS were further processed using Python to understand the behaviour of the system and to evaluate the overall health condition for digital twin implementation.

4.1 Static Structural Analysis Results

Static structural analysis was performed to determine the stress distribution and deformation in the shaft when subjected to loading conditions. The results obtained from the analysis indicate that the maximum equivalent stress developed in the system is approximately $5.015 \times 10^6 \text{ Pa}$, while the deformation value obtained is 0.000184 mm .

From the stress distribution plot, it can be observed that the stress values vary across different regions of the shaft. Certain nodes experience higher stress compared to others, which usually occurs near the contact regions between the shaft and bearing components. However, the obtained stress value remains within the safe operating limits of the material.

These results of equivalent stress distribution as shown in figure 5 indicate that the shaft structure is capable of sustaining the applied loads without undergoing structural failure. Therefore, under the considered loading conditions, the system remains mechanically stable.

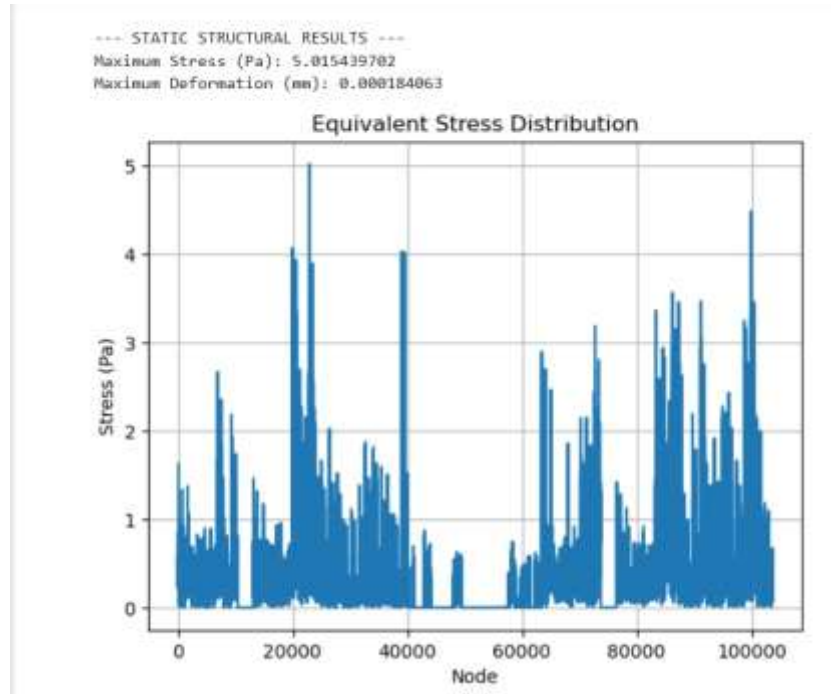


Figure 5: equivalent stress distribution results

4.2 Modal Analysis Results

Modal analysis was conducted to determine the natural frequencies of the shaft–bearing system. Natural frequencies represent the frequencies at which the system tends to vibrate when it is subjected to external disturbances.

The analysis generated several vibration modes. The first two natural frequencies were found to be approximately **6229 Hz** and **6290 Hz**, while higher modes appeared at frequencies such as **15010 Hz**, **18093 Hz**, **18228 Hz**, and **18839 Hz**.

These frequencies indicate the vibration characteristics of the rotating system. It is important that the operating frequency of the machinery does not coincide with these natural frequencies, because such a condition may lead to resonance. Resonance can cause excessive vibration and may damage mechanical components.

By identifying these natural frequencies that are represented in figure 6 allows us to know whether the system is being operated in a safe frequency range to avoid unwanted vibration problems.

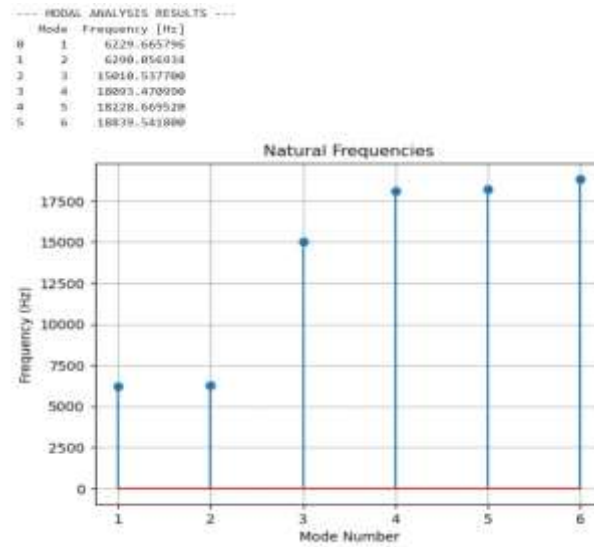


Figure 6: natural frequency results

4.3 Harmonic Response Analysis Results

Harmonic response analysis was performed to study how the system behaves when it is subjected to periodic excitation. The analysis shows the variation of vibration amplitude with respect to excitation frequency.

From the obtained results, the maximum vibration amplitude is approximately 3.835×10^{-6} mm, and the resonance frequency is observed around **500 Hz**. The frequency response curve shows a gradual increase in vibration amplitude as the excitation frequency increases.

Although the vibration amplitude increases slightly with frequency which can be seen in figure 7, the obtained values remain very small. This indicates that the shaft–bearing system is dynamically stable under the considered operating conditions.

Understanding this frequency response behaviour is important because excessive vibration may lead to fatigue and reduce the lifespan of rotating components.

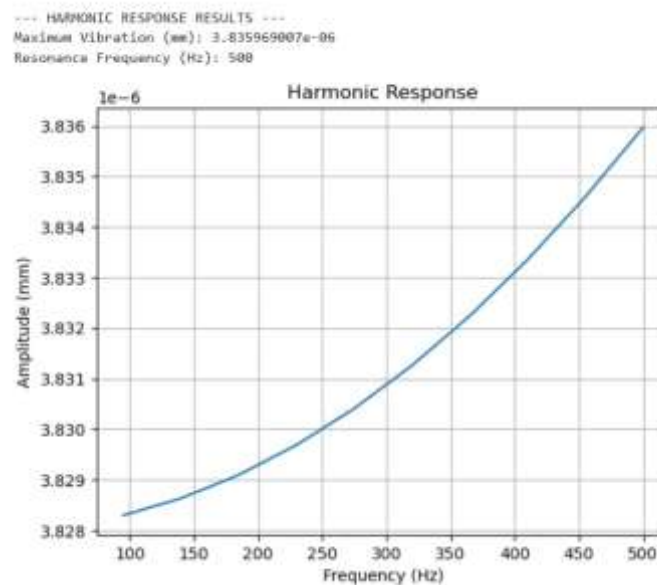


Figure 7: frequency vs amplitude chart

4.4 Python-Based Data Processing and Digital Twin Monitoring

The simulation results obtained from ANSYS were exported and analysed using Python. The Python program reads the output files and extracts important parameters such as maximum stress, deformation values, vibration amplitude, and resonance frequency.

Based on the processed data, the system health condition was evaluated and the results are shown as in the below f. The digital twin model compares the obtained parameters with predefined safety limits. From the analysis, both stress and vibration values were found to be within acceptable limits.

Therefore, the digital twin monitoring system indicates that the shaft–bearing assembly is operating under safe conditions. In real industrial applications, real-time sensor data can be integrated with the digital twin model to continuously monitor machine behaviour and detect abnormal conditions at an early stage.

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--- DIGITAL TWIN HEALTH STATUS ---  
✔ Stress within safe limits  
✔ Vibration within safe limits
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Figure 8: digital twin health status

6. CONCLUSION

This study presented a digital twin-based approach for monitoring the condition of a shaft–bearing system using simulation analysis and data processing techniques. The geometry of the shaft and bearing assembly was first created using SolidWorks and then analysed using ANSYS.

Static structural analysis was used to evaluate the stress distribution in the shaft. The obtained results showed that the stress values were within safe limits and the deformation was minimal. Modal analysis was performed to determine the natural frequencies of the system, which helps in understanding the vibration characteristics and avoiding resonance conditions.

Harmonic response analysis was conducted to study the behaviour of the system under periodic excitation. The vibration amplitude obtained from the analysis was relatively small, indicating that the system remains dynamically stable.

The simulation results were further processed using Python to extract important parameters and evaluate the overall system condition. The digital twin model used these parameters to determine the health status of the system. Based on the results, both stress and vibration levels were found to be within safe operating limits.

The proposed approach demonstrates how simulation tools, data analysis, and digital twin technology can be combined to monitor rotating machinery and support predictive maintenance. This method can help reduce unexpected failures and improve the reliability of industrial equipment.

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