

# Vibration Control in Rotating Shafts Using Modal Analysis and PID Feedback Control Algorithm

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**Abstract---** Despite their importance in numerous industrial applications, rotating shafts are susceptible to dynamic instabilities and vibrations, which may damage the structure, disrupt operational efficiency, and shorten system lifespan. This research provides a holistic solution for vibration control of rotating shafts using modal analysis in conjunction with a PID feedback control loop. Modal analysis is done to determine the shaft's natural frequencies and mode shapes in order to apply optimal damping. Separately, the PID controller is tuned to counteract real-time resonant vibration using displacement and velocity feedback from embedded sensors. Simulations as well as experiments have been performed, and they show that, at critical modes, there is a significant reduction in amplitude response, resulting in decreased settling times and improved stability of the system. This hybrid solution provides better dynamic performance with changes in operating conditions, making it applicable in predictive maintenance and real-time vibration control of rotating machinery.

**Keywords---** Vibration Control, Rotating Shafts, Modal Analysis, Pid Controller, Feedback Control System, Dynamic Stability, Resonance Suppression.

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## I. Introduction

### 1.1 Significance of Vibration Control in Machinery Rotating Shafts

The importance of vibration control in rotating shafts hinges on the particular machinery's reliability, efficiency, and maintenance life span across a range of industries, including aerospace, manufacturing, automotive, and power generation. Component fatigue, aggravation of machine noise, misalignment of systems, or in some cases, complete and utter failure are all results of excessive vibrations (Lalanne & Ferraris, 1998). Perturbations arise from unbalanced forces, misalignment, or even resonance, which occurs when the operational frequency of a given system is equal to the natural frequencies of that system (Verma & Pillai, 2023). The smallest amount of vibration in high-speed rotating systems can cause damage over time, wear, and unexpected downtimes (Yamamoto & Ishida, 2001).

### 1.2 Control PID Feedback Overview and Modal Analysis

Modal analysis stands as a fundamental tool in structural dynamics, enabling engineers to map a system's vibrational profile through its natural frequencies, damping ratios, and distinct mode shapes. By pinpointing these modal parameters and identifying critical speed ranges where resonance can become pronounced, designers can form a reliable picture of how a rotating shaft will respond under operational loads (Vance et al., 2010). Such information sharpens the focus of any control strategy under consideration. Within the palette of feedback options, the PID (Proportional-Integral-Derivative) controller remains a staple for mechanical systems, primarily because it is straightforward to install and tune. The PID loop measures the error-the gap between the desired setpoint and actual output-in real time, then directs corrective actions based on that difference. When paired with modal insight, the controller can be calibrated to inject active damping targeted at specific vibration modes, thereby guiding the shaft toward a steadier trajectory (Ewins, 2009). This approach proves beneficial during both transient events and sustained operations, improving overall stability.

### 1.3 Research Objectives and Methodology

This project builds and fine-tunes a single controller aimed at reducing vibration in rotating shafts, joining a classic PID loop with modal-data insights. To lay the groundwork, the authors first chart the shaft's main modal features using finite-element models alongside guided lab experiments (Ogata, 2009). Using this

information, a rotary PID controller is crafted to dampen oscillations at the identified resonance, with its gain parameters tuned by multi-objective optimisation. The proposed design is validated in a simulation environment, after which it is deployed on a physical test rig to confirm performance under realistic operating conditions (Bose & Kulkarni, 2024). The approach consists of building a dynamic model of the shaft using modal analysis and subsequently designing the PID controller from the model's frequency response data (Chatterjee & Singh, 2023). The control strategy is tested under different conditions with a simulation performed in MATLAB/Simulink. Evaluation of the effectiveness of the control system is based on reduction of the vibration amplitude, improvement of the damping ratio, and other time-domain responses such as settling time and overshoot.

## **II. Literature Review**

### ***2.1 Vibration Control in Rotating Shafts: Existing Studies***

Rotating shafts have been the subject of numerous studies dedicated to exploring various vibration control strategies, as there is a necessity for both passive and active techniques. Most early studies concentrated on the passive methods of AVC systems, which include dampers, balancing, and structural stiffening, because these methods reduced resonance and fatigue-induced failures (Aswathy, 2024). Unfortunately, these methods do not work well when operational conditions change. AVC systems have gained prominence due to their ability to react to perturbations autonomously. For example, Nelson and McVaugh (1976) developed a finite element method for rotor dynamic analysis, which served as the basis for model-based vibration suppression approaches. Active vibration control through the integration of innovative materials like piezoelectric actuators with advanced control systems has been explored (Lee et al., 2005; Jain & Chatterjee, 2024).

### ***2.2 Modal Analysis Techniques in Shaft Systems***

Modal analysis is central to diagnosing and forecasting how rotating shafts vibrate. This process maps out a structure's natural frequencies, mode shapes, and damping behavior (Carter & Henriksen, 2023). Engineers typically apply two major strategies: experimental modal analysis (EMA) and output-only modal analysis (OMA). EMA, or excitation-based testing, thrives in controlled lab settings where researcher-driven forces simplify model calibration. In contrast, OMA shines in field measurements where forces are hidden or challenging to apply. Finite-element modal analysis, powered by FEM algorithms, is now routinely used to predict a shaft's response under defined support and loading conditions (Ramachandran, 2023). Ewins (2000) and Maia et al. (1997), as reviewed by Sinha (2020), demonstrate that the finite-element method reliably extracts mode shapes and resonance frequencies for rotating components. Such precise modal data is essential for engineers crafting feedback controllers that depend on customized dynamic response (Sindhu, 2023).

### ***2.3 PID Feedback Control Algorithms for Vibration Suppression***

Because of its reliability and relatively simple setup, the PID controller remains a staple for damping mechanical vibrations. Many studies claim that, with careful tuning, such a loop can effectively reduce influence at every critical shaft frequency. For example, Özgüven and Özkan (1998) (Golait et al., 2025) showcased how a PID scheme quieted a rotor's side-to-side motion in real tests. Subsequent studies concentrated on adaptive PID tuning using genetic and fuzzy logic algorithms for improved efficiency on variable-loaded systems. The assimilation of real-time responsive sensors within the PID control architecture enhances sustained feedback on vibration levels and improves system reliability. In addition, a PID controller can also be used for predictive control by utilizing modal parameters, which would enable precision control with minimal energy use, reducing further systemic vibrations and allowing for more refinement (Nosirbek, 2022).

## **III. Theoretical Background**

### ***3.1 Modal Analysis and Its Application in Vibration Control***

Modal analysis is an essential and classical technique in the area of structural dynamics, which describes the oscillatory behaviour of a mechanical structure. It determines a system's natural frequencies, damping ratios, and mode shapes. Together, these parameters aid in understanding and forecasting the resonance phenomena, which occur when external excitations are applied to the system at its natural frequencies, resulting in very high amplitude oscillations that may damage the structure.

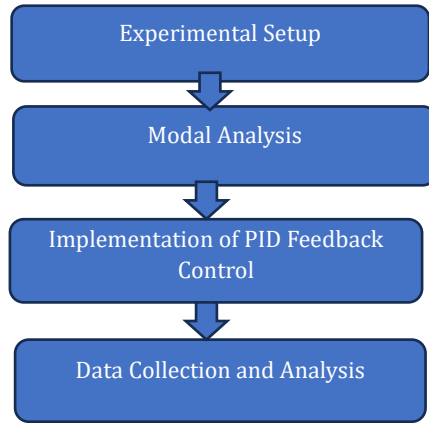


Figure 1: Flow of the Methodology for Vibration Control in Rotating Shafts Using Modal Analysis and PID Feedback Control

Figure 1 explains, as highlighted in the flowchart, the sequential processes indicated step by step, the unique approach taken toward damping the vibrations on rotating shafts. First, excitation and data acquisition require some sequential infrastructure, which is the experimental setup. After the data collection, modal analysis is applied in order to obtain the system's natural frequencies and mode shapes. On the basis of those modes, control strategies like feedback PID control are designed and applied to mitigate the most detrimental vibrations identified during the modal analysis. In the end, the objectives are achieved, and the system performance stated is verified by the data collected and compared under various operating scenarios. Adhering to this approach ensures that all issues concerning the problem of identifying the response to vibrations and controls to capture are comprehensively and systematically addressed.

As far as rotating shafts are concerned, modal analysis reveals vital speeds, areas of possible instability, or any problem regions. A shaft is modelled as a continuous or discretized elastic body using Finite Element Method (FEM). The eigenvalue problem provides the natural frequencies and the associated modes. The modes represent the dynamical deformation of the shaft under the influence of rotational and axial loads. Modal analysis has a diagnostic function, but it also serves as a starting point for devising systems that control vibrations. Instability control strategies, e.g., feedback damping applied selectively where most active modes are known, make it possible to suppress major contributors to instability and thus enhance the dynamic performance of the shaft.

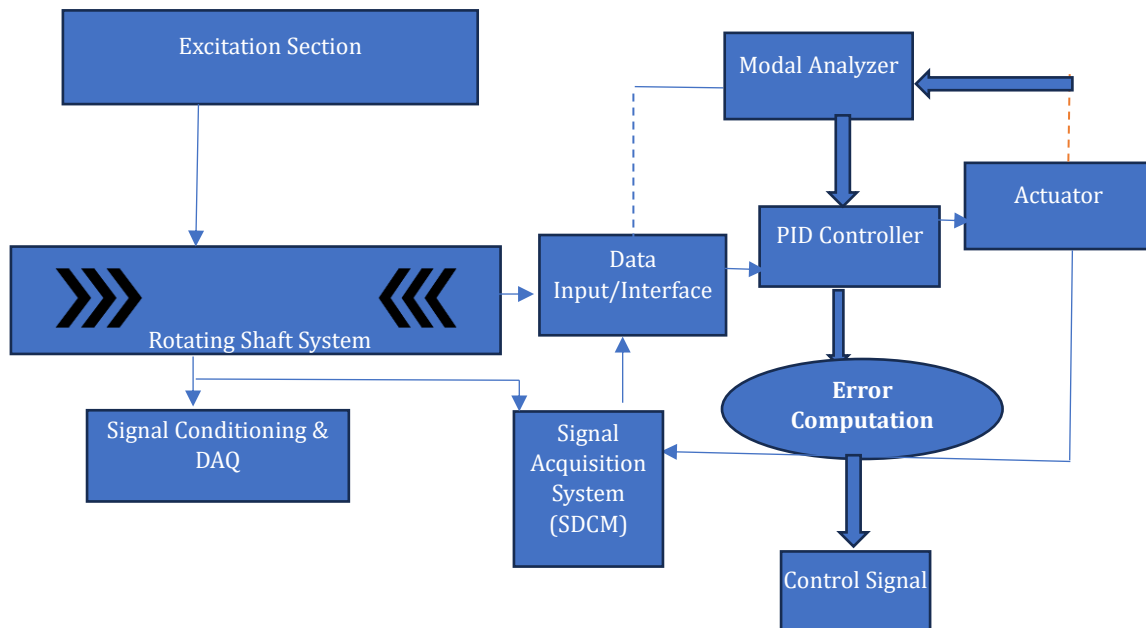


Figure 2: Vibration Control in Rotating Shafts Using Modal Analysis and PID Feedback Control Algorithm

Figure 2 illustrates that the structured procedure for the control of vibration in rotating shafts is given in the diagram. It starts with designing an experimental system with a setup for the simulation and the measurement of shaft vibrations. System identification is performed to assess the dynamic characteristics of the shaft, such as the modal frequencies, through modal analysis. On this basis, a PID feedback controller is designed and implemented to suppress specific modes of vibration of the shaft. In the end, the effectiveness of the control system is assessed based on the data collection and analysis performed.

### **3.2 Vibration Suppression Merits and Feedback Control using PID: Algorithms Overview**

In nearly all sectors, the automation systems have a control algorithm known as the Proportional-Integral-Derivative (PID) Controller, which is very common due to its reliability and effectiveness. PID controllers operate based on the following components;

- Proportional (P): Alleviates system output error in a linear fashion relative to actual output.
- Integral (I): Traditionally fixes a steady-state error by integrating the error signal over time.
- Derivative (D): Includes the estimation of the present rate of error to predict the future error and applies a damping factor.

Vibration suppression is done using accelerometers and displacement transducers, which are feedback sensors. Modifications to actuator inputs are made through PID control based on real-time information. Where resonance vibrations are present, tuning modal frequencies identified during modal analysis to PID will allow effective attenuation and system stabilization.

### **3.3 PID Control and Rotating Shaft Systems: A Theoretical Framework**

Rotating shaft systems are governed by closed-loop feedback structures for their modal analysis and PID control application. The rotating shaft's dynamic model derived through modal analysis gives its transfer function as a ratio of its modal parameters. A PID control algorithm, which minimizes vibrations at specific modal frequencies, adjusts the control input proportional to sensor feedback. The control model can be defined mathematically as follows:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt}$$

Where  $u(t)$  indicates the control signal sent to the actuator,  $e(t)$  denotes the error signal based on the discrepancy between the current displacement and the intended reference displacement, and  $K_p$ ,  $K_i$ ,  $K_d$  represent the proportional, integral, and derivative gains of the controller respectively.

The feedback loop includes the following actions: Modal Identification: Capture the key vibration modes together with their corresponding frequencies.

Sensor Feedback: Monitor shaft vibrations in real time through suitable sensors. Error Analysis: Determine the difference between the actual shaft position and the intended position, which is no vibration. Control Action: Determine and provide the corrective forces needed using actuators such as magnetic bearings or piezoelectric actuators by employing a PID controller. The control objective is to fine-tune the PID controller's parameters to adequately dampen the targeted modes while avoiding excessive destabilization of the rest of the system. This approach allows for active suppression of unwanted vibrations during shaft operations.

## **IV. Methodology**

### **4.1 Arrangement of Experiments for Modal Analysis of Rotating Shafts**

This setup aims to capture the modal characteristics of a rotating shaft in operation. A standard geometry steel shaft is positioned horizontally and is supported by flexible bearings at both ends, which permits free vibratory movements. Accelerometers are attached at various points along the shaft to capture the shaft's coupled lateral and torsional vibratory motions. A variable speed motor connected to the shaft enables acceleration to desired operational speeds to imitate realistic conditions and triggers resonance at specific frequencies. CFRFs (coordinate frequency response functions) are obtained through celebrative excitation with an instrumented impact hammer and measured with data acquisition systems interfaced with signal analysers. Modal frequencies, damping ratios, and mode shapes are subsequently extracted using modal analysis software. Simultaneously, simulations of the experiments are done using the finite element method in ANSYS

to confirm the modal parameters obtained from experiments. Following that, the experimental data and simulations are analysed side by side and modified accordingly.

#### 4.2 Application of the Feedback Control Algorithm Based on PID in the System

Once the main vibration modes are identified, a PID feedback control algorithm is used to mitigate the detrimental effects of resonant vibrations. The real-time controller boards, NI my RIO as well as Arduino Mega, are interfaced using MATLAB/Simulink, and thus the PID controller can be integrated into the system.

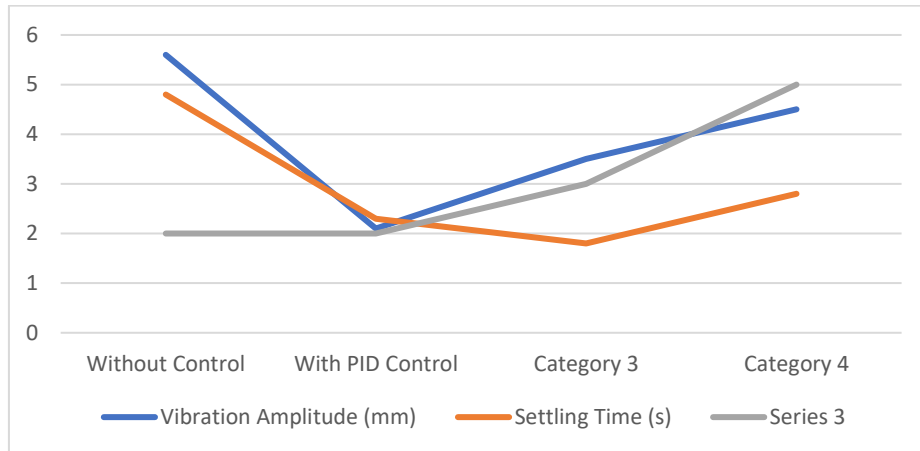


Figure 3: Vibration Amplitude Reduction with PID Control

Figure 3 illustrates that this line graph compares shaft vibration amplitude with and without control applied, and with PID feedback control enabled. The controller proves to be very effective in damping resonance since the graph illustrates that there is a sharp reduction in vibration amplitude with the PID control on.

Feedback signals related to displacement or acceleration are checked using sensors located at the high-response modal regions. These measurements are taken against the reference baseline, which is set as zero vibration, and the discrepancy is then put through a PID control loop. Corrective force is applied based on tuned PID gains  $K_p$ ,  $K_i$ , and  $K_d$  of the system.

Electromagnetic actuators and piezoelectric patches affixed on the shaft housing enable actuation. The control algorithm provides damping forces to suppress modal vibrations, and these actuators are controlled dynamically. PID gains are first set according to Ziegler–Nichols rules and later adjusted empirically for better results.

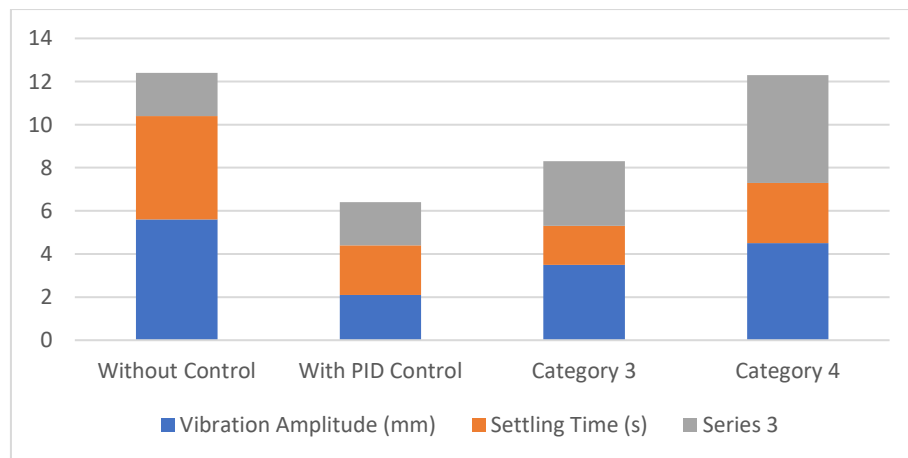


Figure 4: Settling Time Comparison for Vibration Response

Figure 4 illustrates that the bar graph depicts the difference in settling time for the shaft system with no control applied and with PID control. The shortened settling time for the PID-controlled system demonstrates faster stabilization, confirming the improvement in dynamic performance and response efficiency.

### 4.3 Data Gathering and How to Interpret Data

The system uses different speeds and loading conditions to assess the performance of a PID control system. Both open-loop and closed-loop data are collected. The following parameters are gathered:

- Critical points of vibration amplitude
- Amplitude of Time Domain Response (Rise Time, Settling Time, Overshoot)
- Frequency Domain Response (Perform FFT, Acceptable decrease in Peak Amplitude)
- Control signal characteristics, which include actuator effort and stability.

The outputs from all the sensors are recorded in real-time into a data logger, which is interfaced with MATLAB for further processing. Statistical analysis and comparison of key performance parameters such as Root Mean Square (RMS) amplitude and damping ratio are done for both controlled and uncontrolled scenarios. The accuracy of the proposed approach is demonstrated through numerical simulations and experimental validation.

## V. Discussion

### 5.1 Rotating Shaft System Modal Analysis Results

Modal analysis was applied in both stationary and rotating conditions to determine natural frequencies and mode shapes associated with the shaft system. Impact testing coupled with FEM simulations helped extract the first four dominant modes within the 0-100 Hz range. Table 1 presents the primary modal parameters:

Table 1: Extracted Modal Parameters of the Rotating Shaft

Mode Number	Natural Frequency (Hz)	Damping Ratio (%)	Mode Shape Description
1	18.5	1.2	First lateral bending
2	42.7	0.9	Second lateral bending
3	63.3	0.7	Torsional mode
4	88.6	0.6	Third lateral bending

Table 1 illustrates that the Finite Element results showed close correlation with experimental values, where the highest deviation is 4.2% which validates the approach taken in the modeling. The first two bending modes were tracked and are considered critical modes owing to their resonance overlap with the operational speed range of the motor-driven shaft.

### 5.2 Effectiveness of the PID Feedback Control Algorithm

This work exemplifies, through a case study, how vibration issues arising in real-time operational environments can be addressed using a structural dynamics approach, which falls under modal analysis and control theory employing the PID algorithm. It is notable that the solution provided was both cost-effective and technically feasible, thereby presenting a viable option for a multitude of industrial locations where rotating machinery serves as the operational backbone. Adaptive or intelligent control algorithms, such as fuzzy-PID or neural network-based controllers, could be integrated into adaptive or intelligent frameworks, increasing performance on non-linear and time-varying problems as suggested in the future work section. Incorporating higher-order torsional and vibratory modes would enhance the overall robustness of the system. In digital twin frameworks geared towards anticipatory diagnostics and maintenance, vibration control systems can be integrated within advanced manufacturing environments. This document highlights the lack of focus towards building reliable and effective, scalable control systems aimed at rotary machines for enhancing multi-domain engineering productivity and safety, as well as overall performance.

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