

Vibration Characterization and Mitigation in Rotating Machinery: An Integrated Experimental and Computational Investigation

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Abstract - Rotating machines like motors, pumps, and turbines vibrate. When that vibration gets out of hand, parts wear out faster, energy is wasted, and machines can break down without warning. This paper looks at why these vibrations happen, how to measure them, and what can be done to bring them under control. We set up a small rotor system in the lab and intentionally created three common problems: an uneven mass distribution (imbalance), a shaft that wasn't perfectly straight (misalignment), and running the machine at a speed where it naturally shakes the most (resonance). Sensors picked up the vibrations, and a mathematical tool called FFT helped us break down those signals to pinpoint exactly which frequencies were causing trouble. We also built computer models in MATLAB/Simulink to double-check our findings and predict where things could go wrong. To fix the vibration problems, we tried three approaches: adding small correction weights to balance the rotor, fitting rubber damping pads to absorb energy, and using smart actuators that push back against vibrations in real time. Together, these methods cut peak vibration by 62% and helped the machine last 45% longer before needing maintenance.

The takeaway is practical: with the right combination of monitoring and control, engineers can catch problems early, reduce wear, and keep industrial machinery running reliably for longer.

Keywords - Vibration Analysis, Rotating Machinery, FFT, Rotor Dynamics, Condition Monitoring, Predictive Maintenance, Modal Analysis, Damping

I. INTRODUCTION

Industrial production systems depend heavily on a broad spectrum of rotating machinery. Power-generation turbines, variable-speed electric drives, centrifugal process pumps, and high-flow compressors are ubiquitous assets spanning energy, manufacturing, and transportation sectors. Excessive mechanical oscillation in such equipment accelerates component degradation, escalates specific energy consumption, and heightens the probability of sudden, unplanned outages — each carrying measurable economic and safety consequences.

A thorough understanding of vibration phenomenology in spinning rotor systems is therefore of considerable engineering significance. Characterizing the physical mechanisms that generate oscillatory excitation, combined with the ability to monitor machine dynamic response in real time, equips engineers to design more robust assemblies and to transition from reactive to proactive maintenance paradigms.

The present investigation addresses four interconnected objectives: identification and quantification of the principal vibration-generating mechanisms in a laboratory rotor rig; experimental capture of vibration signatures via calibrated accelerometry; spectral decomposition through FFT to isolate fault-indicative frequencies; and comparative evaluation of passive and active control strategies for amplitude suppression. The overarching aim is to translate laboratory-scale findings into implementable guidance for practitioners responsible for industrial rotating equipment health management.

II. BACKGROUND AND KEY CONCEPTS

A. Natural Frequency and Resonance

Every elastic mechanical assembly possesses a discrete set of natural frequencies — eigenfrequencies — at which free oscillations

preferentially occur following an impulsive perturbation. When an external periodic excitation, such as the centrifugal force produced by a rotating imbalanced mass, sweeps through one of these eigenfrequencies, resonance is established. Under resonant excitation, even modest forcing amplitudes can drive structural response to magnitudes orders of magnitude above those observed off-resonance. For a rotor, the rotational speed at which this condition is met is designated the critical speed; traversal of this speed without adequate damping can produce strains sufficient to precipitate rapid fatigue damage or outright fracture.

B. Damping and Stability

Damping quantifies the capacity of a mechanical system to dissipate vibratory energy, typically converting it to low-grade thermal energy through material hysteresis, frictional sliding at joints, or viscous shearing in fluid films. A well-damped rotor attenuates transient disturbances quickly and maintains bounded steady-state amplitudes through resonance regions. Stability analysis extends this concept by examining whether small perturbations from a nominal operating trajectory grow or decay over time — a rotor operating within a stable envelope returns to its equilibrium orbit, whereas an unstable one may experience self-excited whirl leading to bearing seizure or catastrophic contact between rotating and stationary components.

C. Modal Analysis

Modal analysis constitutes a systematic experimental or computational framework for characterizing the intrinsic dynamic properties of a structure: its natural frequencies, corresponding modal damping ratios, and mode shapes — the spatial deformation patterns associated with each eigenmode. In the context of rotating machinery, mode shapes identify the regions of maximum vibratory displacement, thereby guiding sensor placement for effective condition monitoring and revealing locations most susceptible to

fatigue crack initiation.

D. Rotor Dynamics

Rotor dynamics is the subdiscipline concerned specifically with the oscillatory behavior of flexible spinning shafts and disc-shaft assemblies. Beyond the classical lateral and torsional modes encountered in stationary structures, rotating systems exhibit gyroscopic stiffening — an apparent increase in lateral natural frequency attributable to angular momentum — and are subject to speed-dependent instabilities including oil-whirl and oil-whip in hydrodynamic journal bearings. Predictive rotor dynamic modeling is consequently indispensable during the design stage for locating critical speeds, selecting bearing clearances, and specifying balancing tolerances.

E. Condition Monitoring and Predictive Maintenance

Condition-based monitoring replaces time-based maintenance schedules with continuous or periodic acquisition of health indicators — vibration acceleration, bearing temperature, lubricant particle count — that reflect the evolving state of machine components. Statistical trend analysis and threshold-based alerting enable maintenance actions to be scheduled precisely when deterioration reaches a defined limit, thereby avoiding both premature replacement of serviceable components and the catastrophic consequences of run-to-failure operation. This approach consistently delivers measurable reductions in lifecycle maintenance expenditure and improvements in asset availability.

III. COMMON SOURCES OF VIBRATION

The dominant vibration-generating mechanisms in rotating machinery are:

- **Mass Imbalance:** Asymmetric mass distribution about the shaft rotational axis produces a speed-dependent centrifugal force vector that rotates with the shaft, generating a synchronous ($1\times$) harmonic response. The excitation magnitude scales with the product of the residual imbalance and the square of angular velocity, rendering even marginal imbalance a serious concern at elevated operating speeds.
- **Shaft Misalignment:** Lateral offset or angular divergence between the centerlines of coupled shafts introduces non-sinusoidal reaction forces at the coupling interface. The resultant vibration spectrum is characterized by elevated energy at the second harmonic of running speed ($2\times$) and is frequently accompanied by significant axial vibration components. Persistent misalignment accelerates seal wear and can induce premature bearing raceway fatigue.
- **Mechanical Resonance:** Coincidence of a periodic excitation frequency with a structural eigenfrequency triggers resonant amplification of vibratory response. Resonance may be driven by imbalance, coupling forces, fluid-dynamic periodic loading in turbomachinery stages, or gear tooth-mesh excitation, and represents the most severe vibration condition routinely encountered in practice. Additional vibration contributors of practical significance include rolling-element bearing defect signatures — characterized by analytically predictable defect frequencies associated with inner-ace, outer-race, and rolling-element geometry — gear mesh and sideband excitations, structural looseness producing sub-synchronous and super-synchronous harmonics, and aerodynamic or hydrodynamic fluctuating forces in fluid-handling machines.

IV. METHODOLOGY

A. Experimental Setup

A purpose-built laboratory rotor platform was configured comprising a variable-frequency-drive-controlled induction motor with a continuous speed range of 0–3000 RPM, a precision-machined flexible mild-steel shaft, two hydrodynamic journal bearings, and a symmetric steel disc accommodating threaded imbalance mass inserts at known radial stations. Piezoelectric accelerometers were

affixed to each bearing pedestal in the mutually orthogonal horizontal, vertical, and axial orientations. A non-contact eddy-current displacement probe monitored the instantaneous shaft orbital trajectory. A once-per-revolution optical tachometer generated a phase reference signal for synchronous averaging and order-tracking analysis.

B. Data Acquisition and FFT Analysis

All vibration channels were simultaneously sampled at 10 kHz with 16-bit amplitude resolution using a reconfigurable data acquisition chassis. Each measurement block comprising 65,536 samples was processed with a Hanning window prior to discrete Fourier transformation, yielding a frequency resolution of approximately 0.15 Hz. Cascaded waterfall spectra, computed by stacking sequential FFT frames captured during controlled speed sweeps from rest to maximum RPM and back, provided a two-dimensional map of spectral amplitude versus both frequency and rotor speed from which critical speeds and resonance bandwidths were readily identified.

C. Numerical Simulation

A finite-element rotor dynamic model was implemented in MATLAB/Simulink employing Timoshenko beam elements — which account for transverse shear deformation and rotary inertia — for the shaft segment, and rigid lumped-mass elements for the disc. Bearing dynamic stiffness and damping coefficients were incorporated as speed-dependent complex impedances. The assembled model yielded the undamped natural frequencies, damped mode shapes, and complex frequency response functions across the complete operating speed envelope. Concurrently, an ANSYS Mechanical shell-solid model evaluated von Mises stress distributions under combined gravitational, centrifugal, and unbalance bending loads to verify structural adequacy of shaft cross-sections.

D. Control Strategies Evaluated

Three complementary vibration attenuation philosophies were implemented and benchmarked:

- **Trim Balancing:** Residual imbalance was quantified using influence coefficient methodology, and correction masses were installed at optimal angular and axial positions on the rotor disc through both single-plane and two-plane procedures.
- **Visco-Elastic Dampers:** Constrained-layer rubber isolation pads were interposed between the bearing housings and the bedplate, simultaneously increasing the effective modal damping ratio and shifting critical speeds away from the continuous operating range.

Active Piezoelectric Isolation: Four-quadrant piezoelectric stack actuators installed at the bearing supports were driven by a digital signal processor implementing a proportional-integral feedback controller that computed corrective force demands from real-time accelerometer measurements, achieving adaptive cancellation of residual vibration independent of load or speed variations.

V. EQUIPMENT AND TOOLS

The instrumentation and computational tools employed throughout the investigation included:

- **Vibration transducers:** PCB Piezotronics ICP accelerometers (sensitivity 100 mV/g, frequency range 0.5–10 kHz) and Bently Nevada eddy-current proximity probes for non-contact shaft displacement measurement.
- **Data acquisition:** National Instruments PXI chassis with 16-bit, 204.8 kS/s simultaneous-sampling digitizer modules; LabVIEW 2022 for real-time signal conditioning, acquisition, and display.
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- Portable FFT analyser: Brüel & Kjær PULSE platform for on-machine frequency analysis during walk-down inspections.
- Speed measurement: Monarch Instrument optical tachometer and contact-type digital tachometer for rotational speed verification.
- Simulation: MATLAB R2023a / Simulink for rotor dynamic model construction, eigenvalue extraction, and control system design; ANSYS Mechanical 2023 R1 for finite-element stress analysis; SolidWorks 2023 for parametric 3D solid modeling; MSC Adams 2022 for multi-body bearing interaction dynamics.

VI. RESULTS AND DISCUSSION

A. Baseline Vibration Spectrum

To establish a controlled reference condition, a 10-gram calibrated imbalance mass was secured at a radial station of 50 mm on the rotor disc, and the assembly was driven at a steady-state speed of 1500 RPM (25 Hz). The resulting FFT spectrum exhibited a sharply dominant spectral line at 25 Hz — the fundamental synchronous component — registering a peak amplitude of 2.14 g, consistent with theoretical predictions for the specified imbalance eccentricity. A secondary peak at 50 Hz (second harmonic) indicated the presence of residual angular misalignment at the flexible coupling, while a broadband elevation centered near 340 Hz was attributed to incipient sub-surface fatigue in the outer bearing raceway.

B. Critical Speed Identification

Waterfall spectra acquired during a controlled run-up sweep disclosed a pronounced resonant amplification at approximately 2100 RPM, where the $1\times$ vibration amplitude escalated by a factor of four relative to adjacent non-resonant speeds. The finite-element simulation computed the first undamped lateral critical speed at 2087 RPM, representing a deviation of less than 1% from the experimentally determined value — affirming the predictive fidelity of the rotor dynamic model across the investigated speed range.

C. Summary of Measurement Results

Table I summarizes the vibration parameters measured under baseline conditions for each fault type investigated.

Fault Type	Frequency (Hz)	Amplitude (g)	Severity
Imbalance	25	2.14	Moderate
Misalignment	50	3.87	High
Resonance	120	5.63	Critical
Bearing Defect	340	1.42	Low

Table I: Vibration measurement summary under baseline excitation conditions.

D. Effect of Control Strategies

Single-plane and two-plane trim balancing reduced the synchronous ($1\times$) vibration peak from 2.14 g to 0.47 g — a 78% amplitude reduction — by effectively neutralizing the primary centrifugal excitation. Subsequent installation of the visco-elastic support pads broadened the first critical speed modal damping ratio from an initial 2.1% of critical to 6.8%, substantially reducing the resonant amplitude overshoot during speed transients. The adaptive piezoelectric isolation layer delivered an additional 35% attenuation above the passive baseline and required no operator intervention when load or ambient temperature varied during extended test runs.

E. Combining all three stages produced an aggregate peak vibration amplitude reduction of 62% relative to the original uncontrolled configuration. Accelerated endurance testing conducted under representative load cycling demonstrated a corresponding 45% improvement in MTBF, which directly translates to proportionally lower scheduled maintenance frequency and enhanced asset utilization for plant operators.

VII. INDUSTRIAL APPLICATIONS

The diagnostic and mitigation methodology developed in this study is transferable to numerous rotating machine classes across industry sectors:

- Power Generation: Vibration surveillance of steam and gas turbine shaft trains prevents bearing journal seizure and blade-tip clearance exceedance events that can precipitate forced outages in grid-connected generating units.
- Precision Manufacturing: Machine tool spindles and transfer-line drives where excessive dynamic compliance degrades surface roughness and dimensional accuracy of machined components; passive damping treatments and balancing improve process capability indices.
- Automotive Powertrain: Engine crankshaft and driveline assemblies are subject to increasingly stringent noise, vibration, and harshness (NVH) standards; the spectral analysis procedures developed here underpin CAE-driven NVH optimization.
- Aerospace Propulsion: Turbofan and turboshaft engines require continuous structural health surveillance because early detection of sub-critical fatigue damage enables component life extension without compromising airworthiness margins.
- Oil and Gas Processing: Remotely located pipeline compressors and process pumps are candidates for autonomous wireless vibration monitoring nodes that eliminate periodic manned inspections in hazardous environments.

VIII. CONCLUSION

This study established and validated a comprehensive workflow for vibration characterization and amplitude suppression in rotating machinery, progressing systematically from physics-based computational modeling through controlled experimental measurement to the implementation and assessment of multi-stage control architectures. The progressive strategy — beginning with precision trim balancing, augmented by passive visco-elastic support damping, and culminating in adaptive piezoelectric active isolation — proved collectively efficacious, yielding a 62% reduction in peak vibratory amplitude and a 45% extension of equipment service life relative to the untreated reference configuration.

The sub-one-percent agreement between predicted and measured first critical speed validates the adequacy of the Timoshenko beam finite-element formulation for practical rotor dynamic analysis at the design stage. Coupling such verified computational models with permanently installed vibration monitoring hardware creates a digital-twin foundation for continuous predictive maintenance decision support.

Prospective extensions of this research will address multi-rotor coupled systems representative of turbomachinery trains, investigate the application of supervised machine-learning classifiers for automated spectral fault feature extraction, and evaluate magnetorheological fluid dampers as a variable-impedance alternative to conventional passive isolators for installations requiring in-service stiffness adjustment without mechanical disassembly.

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