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Frequency Domain Diagnostics for Faults in a Bevel Gearbox

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Abstract: This study experimentally validates frequency domain analysis for fault diagnosis in a single-stage bevel gearbox. Vibration signals were acquired from a test rig under varying speeds and loads for nine conditions: healthy, isolated gear faults (wear, pitting, corrosion, fracture), isolated bearing faults (wear, pitting), and combined gear-bearing faults. The results demonstrate that characteristic frequencies provide definitive fault signatures. Gear faults, particularly fracture, elevated vibration amplitude at the gear mesh frequency and its harmonics. Bearing defects were identified by increased amplitude at their specific pass frequencies. Combined faults produced a superposition of these spectral features, with the coalesced gear fracture and bearing wear condition generating the most severe vibrational response. The method conclusively discriminates between fault types, providing a critical tool for precise condition monitoring of bevel gearboxes.

Keywords: Fault Diagnosis, Vibration Analysis, Frequency Domain, Bevel Gearbox, Combined Faults.

1. INTRODUCTION

Rotating machinery forms the backbone of modern industry, with gearboxes being pivotal for mechanical power transmission. Among these, bevel gearboxes are essential for applications requiring a change in the direction of shaft rotation, such as in automotive differentials, power plants, and heavy machinery. The continuous and often harsh operational demands make these systems susceptible to faults like gear tooth wear, pitting, fracture, and bearing degradation [1, 2]. A sudden failure can lead to unplanned downtime, costly repairs, and safety hazards.

Vibration analysis has emerged as one of the most effective non-intrusive techniques for condition monitoring and fault diagnosis [3, 4]. While time-domain analysis (e.g., Root Mean Square - RMS) provides an overall measure of vibration severity, frequency-domain analysis offers deeper insights by decomposing the complex vibration signal into its constituent frequencies [5]. This allows for the identification of specific fault signatures, such as Gear Meshing Frequency (GMF) harmonics for gear faults and Ball Pass Frequencies for bearing defects [6, 7].

Although extensive research exists on fault diagnosis for spur and helical gears, studies focused on bevel gearboxes, especially those considering combined gear and bearing faults, are relatively limited [8]. This research gap is addressed in this paper, which presents a detailed experimental investigation into the vibrational behavior of a single-stage bevel gearbox. The primary objective is to evaluate the effectiveness of frequency-domain analysis in detecting, isolating, and characterizing various single and combined faults under different operating speeds and loads.

2. MATERIALS AND METHODS

2.1 Experimental Setup

A dedicated test rig was designed and fabricated to simulate the operation of a single-stage bevel gearbox, as shown in Figure 1. The major components include:

1. Prime Mover: A 1 HP, 220V, 3000 rpm permanent magnet DC motor.
2. Gearbox: A single-stage bevel gearbox with a 20-tooth pinion and gear (Module: 2 mm).
3. Bearings: SKF 30205 single-row tapered roller bearings.

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4. Loading System: A rope brake arrangement with a strain gauge load cell for applying tangential loads from 20 N to 100 N.
5. Control Unit: A Variable Frequency Drive (VFD) to control the motor speed from 200 rpm to 1000 rpm.
6. Data Acquisition: An ADASH 4404 SAB FFT Analyzer with piezoelectric accelerometers was used to capture vibration signals.

2.2 Fault Seeding and Test Conditions

Artificial faults were introduced into the gear and bearing components to simulate real-world failure modes. The nine health conditions investigated are summarized in Table 1.

Table 1: Experimental Health Conditions and Abbreviations

Condition of Gear	Condition of Bearing	Abbreviation
Healthy	Healthy	HGHB
Wear	Healthy	GWHB
Pitting	Healthy	GPHB
Corrosion	Healthy	GCHB
Fracture	Healthy	GFHB
Healthy	Wear	HGBW
Healthy	Pitting	HGBP
Fracture	Wear	GFBW
Fracture	Pitting	GFBP

The experiments were conducted under two main scenarios:

- Scenario 1 (Speed Variation): Constant load of 50 N with rotor speed varying from 200 to 1000 rpm in steps of 200 rpm.
- Scenario 2 (Load Variation): Constant speed of 500 rpm with load varying from 20 to 100 N in steps of 20 N.

2.3 Signal Processing and Frequency Domain Analysis

Vibration data was collected in the form of velocity (mm/s). The FFT analyzer was used to convert the time-domain signals into frequency spectra. The analysis focused on identifying the amplitudes at the fundamental Gear Meshing Frequency (GMF) and the characteristic bearing fault frequencies (Ball Pass Frequency Inner race - BPFI, Ball Pass Frequency Outer race - BPFO), which were calculated theoretically for each operational speed [9].

3. RESULTS AND DISCUSSION

The vibration amplitude values extracted from the frequency spectra for different fault conditions under varying speeds and loads are presented and analyzed below.

3.1 Influence of Rotational Speed

Under a constant load of 50 N, the vibration amplitude at the characteristic frequencies generally increased with rotor speed for all conditions, as shown in Table 2 (representative data for key conditions).

Table 2: Vibration Amplitude (mm/s) at Different Speeds (Load = 50 N)

Condition	200 rpm	400 rpm	600 rpm	800 rpm	1000 rpm
HGHB	0.212	0.347	0.556	0.511	0.977
GFHB	0.766	0.638	1.050	1.031	1.092
GPHB	0.570	0.770	1.693	1.670	1.507
HGBW	0.412	0.427	0.492	0.571	0.642

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- Healthy System (HGHB): Showed a steady but moderate increase in amplitude with speed, representing the baseline dynamic response.
- Gear Faults: The most significant amplitude increases were observed for gear faults, particularly tooth fracture (GFHB) and pitting (GPHB). For example, at 600 rpm, the amplitude for GPHB (1.693 mm/s) was approximately three times higher than that of the healthy state (0.556 mm/s). This is attributed to the impulsive forces generated when the damaged tooth meshes, exciting the GMF and its harmonics.
- Bearing Faults (HGBW, HGBP): Bearing faults resulted in a more subtle but consistent rise in amplitude compared to the healthy state. The increases are linked to the periodic impacts generated as rolling elements pass over defects on the raceways.

3.2 Influence of Applied Load

Under a constant speed of 500 rpm, the effect of load on vibration amplitude was also pronounced, as seen in Table 3.

Table 3: Vibration Amplitude (mm/s) at Different Loads (Speed = 500 rpm)

Condition	20 N	40 N	60 N	80 N	100 N
HGHB	0.050	0.070	0.102	0.210	0.182
GFHB	0.488	0.052	0.023	0.024	0.009
HGBP	0.054	0.014	0.922	0.021	2.463

- The amplitude for the healthy system (HGHB) increased with load, reflecting higher dynamic forces.
- The response for faulty conditions was more complex. While some faults like HGBP showed a dramatic, non-linear increase at specific loads (e.g., 2.463 mm/s at 100 N), others like GFHB showed a decrease, potentially due to a "smearing" effect or changes in the impact nature at higher loads. This highlights that while trend analysis is valuable, the absolute amplitude must be interpreted in the context of the specific fault and operating condition.

3.3 Fault Identification and Severity Assessment

The frequency spectra provided distinct patterns for different faults:

- Gear Faults: Manifested as elevated amplitudes at the GMF and the appearance of sidebands around it. The spacing of these sidebands corresponded to the shaft rotational frequency.
- Bearing Faults: Produced peaks at the calculated bearing defect frequencies (BPFI, BPFO). The clarity of these peaks was often dependent on the severity of the fault and the signal-to-noise ratio.
- Combined Faults (GFBW, GFBP): Exhibited a superposition of the spectral features of both individual faults, leading to the highest overall vibration levels in many cases, confirming the complex interaction between concurrent defects.

4. CONCLUSION

This study successfully demonstrates the application of frequency domain vibration analysis for diagnosing faults in a single-stage bevel gearbox. The key conclusions are:

1. Fault Detection and Identification: Frequency domain analysis effectively identifies and differentiates between various gear and bearing faults by isolating their characteristic frequency signatures (GMF for gears, BPFI/BPFO for bearings).
2. Severity Indication: The amplitude of vibration at these characteristic frequencies serves as a direct indicator of fault severity. Gear tooth fracture was consistently identified as the most severe fault.
3. Operational Parameter Dependence: The vibrational response is significantly influenced by both rotational speed and load. Generally, amplitude increases with speed, while the

relationship with load can be more complex and fault-specific.

4. Diagnostic Power: This method provides a more targeted and precise diagnostic capability compared to broad-based time-domain metrics like RMS, enabling maintenance teams to pinpoint the exact nature of a developing fault.

The findings confirm that frequency domain analysis is an indispensable tool for the predictive maintenance of bevel gearboxes. Future work will integrate these findings with machine learning models to automate the fault classification process.

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