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Article

Bridging Diagnostic Condition Monitoring and NVH Tonal Excitation Through Frequency-Domain Structural Mapping

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Featured Application

The mapping methodology presented in this manuscript can aid in the vibration-based assessment of tonal excitation growth in powertrain systems, providing a structural link between diagnostic monitoring and NVH assessment practices.

Abstract

In general, condition monitoring (CM) and noise, vibration and harshness (NVH) are often treated as separate disciplines, despite the fact that both rely on vibration measurements. CM relies on broadband statistical metrics such as RMS, kurtosis, and envelope analysis to detect faults. Meanwhile, NVH investigates tonal excitation mechanisms related to gear mesh frequency (GMF) and its modulation components. In this study, we investigate whether a numerical relationship can be established between classical CM indicators and physically based tonal excitation indicators derived from frequency-domain analysis. Using a controlled gearbox degradation dataset, Spearman correlation analysis was performed between broadband metrics and GMF-related tonal features, including GMF-band energy and absolute sideband energy. Results show moderate but statistically significant correlations between RMS, envelope peak amplitude, and tonal indicators, whereas kurtosis exhibits no meaningful association. Additionally, tonal amplification due to degradation is shown to be structurally localized rather than uniformly distributed across sensor locations. These findings demonstrate that broadband CM indicators partially encode tonal excitation growth, establishing a reproducible data-driven bridge between diagnostic condition monitoring and NVH excitation analysis.

Keywords: condition monitoring; gear mesh frequency; tonal excitation; vibration analysis; NVH; spectral analysis; degradation mapping

1. Introduction

Condition monitoring (CM) and noise, vibration, and harshness (NVH) engineering are traditionally treated as distinct domains within rotating machinery analysis, despite their shared reliance on vibration measurements.

Condition monitoring primarily aims at early fault detection and health assessment using broadband statistical indicators such as root mean square (RMS), kurtosis, crest factor, and envelope analysis. These descriptors have been widely validated in bearing and gear diagnostics, particularly for detecting localized defects and impulsive signatures [1-3]. RMS is commonly interpreted as a global vibration energy metric, while kurtosis and envelope analysis enhance sensitivity to impulsive fault-related components.

While RMS is usually treated as an indicator of total vibration energy, kurtosis and envelope analysis are much more sensitive to detect fault-related components.

In contrast, NVH engineering focuses on tonal excitation mechanisms, structural transfer paths, and radiated noise characteristics. In geared systems, the vibration profile is primarily driven by the gear mesh frequency (GMF) and its sidebands. These sidebands are caused by transmission errors and varying mesh stiffness [4,5]. These components are related to perceived tonal noise and structural reinforcement. This makes frequency domain excitation analysis central to NVH assessment.

Although both CM and NVH work on the same vibration data. Their analysis targets are quite different. The targets of CM are usually interpreted as broadband health indicators without any specific structural reference [1]. While the targets of NVH are closely related to physically identified excitation sources and transfer characteristics [6]. Therefore, the tonal part related to GMF is usually implicitly included in broadband CM indicators rather than being explicitly interpreted as excitation sources.

This conceptual divide gives rise to a methodological divide between diagnostic monitoring and acoustic performance evaluation. Although the progression of gear damage has been shown to affect the amplitude and sideband patterns of the GMF [2, 3], it is not clear to what extent classical broadband CM descriptors capture tonal excitation mechanism dynamics in the context of NVH.

The present study addresses this gap by investigating whether commonly used CM features can be quantitatively mapped to physically defined tonal excitation proxies derived from frequency-domain analysis. Using a controlled gearbox degradation dataset, correlations are evaluated between broadband statistical indicators and GMF-related tonal metrics. The objective is not classification performance, but structural interpretation: to determine whether widely used CM indicators implicitly track excitation mechanisms directly relevant to tonal noise generation. By explicitly linking diagnostic vibration features to tonal excitation proxies, this work proposes a reproducible mapping framework that structurally connects condition monitoring practice with NVH excitation analysis.

2. Materials and Methods

The overall processing and mapping strategy is illustrated in Figure 1. Following pre-processing, feature extraction is performed in parallel in the frequency and time domains. Tonal excitation proxies are computed from Welch power spectral density estimates, while classical condition monitoring indicators are derived from time-domain and envelope-processed signals. The two feature groups are subsequently linked through non-parametric correlation analysis.

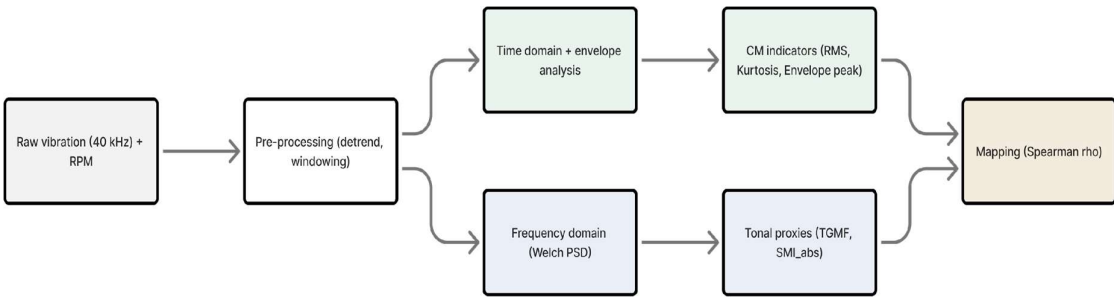


Figure 1. Reproducible CM–NVH mapping workflow with parallel feature extraction.

2.1. Dataset and Operating Conditions

The analysis is based on a publicly available gearbox vibration benchmarking dataset developed for controlled degradation studies. The vibration data used in this investigation were obtained from the publicly available NREL Wind Turbine Gearbox Benchmark dataset [7], recorded at the NREL Dynamometer Test Facility. Measurements were conducted on a 750-kW wind turbine drivetrain featuring a dual-speed generator.

The gearbox under study is a three-stage system composed of a planetary stage and two parallel-shaft stages, resulting in a transmission ratio of 1:81.49. The measurement campaign aimed to establish a controlled experimental baseline for condition monitoring research.

The dataset contains ten healthy (H1–H10) and ten damaged (D1–D10) one-minute recordings obtained under dynamometer conditions.

Vibration signals were sampled at 40 kHz from multiple accelerometer locations positioned on the gearbox housing. The high-speed shaft rotational speed was recorded simultaneously. The high-speed pinion tooth count is 22, resulting in a nominal gear mesh frequency of approximately 660 Hz at 1800 rpm operating speed.

Documented damage includes high-speed gear scuffing and bearing degradation, making the GMF region physically relevant for tonal excitation analysis.

Only radial accelerometer channels associated with the high-speed and intermediate shaft regions were considered for tonal mapping.

2.2. Signal Processing

Each one-minute recording was processed independently. Signals were segmented into fixed-length windows to reduce spectral variance. Power spectral density (PSD) estimates were computed using Welch's method with a constant window length and overlap across all files to ensure comparability.

Prior to spectral estimation, signals were detrended to remove the DC offset. No additional filtering was applied beyond down-sampling, where computational efficiency required it.

All feature extraction procedures were applied identically across healthy and damaged datasets to avoid bias.

2.3. Definition of Tonal Excitation Proxies

Two physically motivated tonal proxies were defined near the gear mesh frequency.

GMF-Band Energy (TGMF)

The primary tonal proxy was defined as the integrated spectral energy within $\pm 10\%$ of the GMF [2]:

$$TGMF = \int_{f_{GMF}(1-\alpha)}^{f_{GMF}(1+\alpha)} PSD(f)df, \quad (1)$$

where $\alpha=0.10$.

This metric captures the strength of the dominant tonal excitation component associated with gear meshing.

Absolute Sideband Energy (SMI_abs)

Amplitude modulation of the GMF produces sidebands at frequencies [1]:

$$f_{GMF} \pm kf_{1x}, \quad (2)$$

Absolute modulation energy was defined as the sum of spectral energy around the first-order sidebands:

$$SMI_{abs} = E_{GMF-1x} + E_{GMF+1x} \quad (3)$$

Unlike normalized sideband ratios, this formulation preserves modulation growth even when GMF amplitude increases disproportionately.

2.4. Classical Condition Monitoring Indicators

These indicators represent broadband energy, impulsiveness, and modulation-related characteristics, which are typically used in diagnostic practice.

For each channel and file, classical broadband diagnostic indicators were computed:

- Root mean square (RMS)

- Kurtosis
- Envelope peak amplitude

These indicators represent global vibration energy and impulsive characteristics commonly used in diagnostic condition monitoring practice.

The GMF-band energy (TGMF) and absolute sideband energy (SMI_abs) were treated separately as physically defined tonal excitation proxies (Section 2.3), rather than classical broadband CM indicators.

2.5. Statistical Mapping

The relationship between classical CM indicators and tonal excitation proxies was evaluated using Spearman's rank correlation analysis [8].

Spearman's method was selected due to its robustness to non-normal distributions and monotonic but non-linear relationships.

Correlation coefficients (ρ) and corresponding p-values were computed across the damaged dataset to evaluate whether broadband CM features track tonal excitation growth.

The objective was not predictive modeling, but structural association assessment.

3. Results

3.1. Tonal Amplification from Early to Advanced Damage

Figure 2 presents the GMF-band energy for early (D1) and advanced (D10) damaged states across selected channels. A consistent increase in GMF-band energy is observed in most high-speed-related sensor locations. The most pronounced amplification occurs at channel AN9, which is located near the high-speed downwind bearing. Moderate increases are observed at AN6 and AN4, while certain channels show only minor variation.

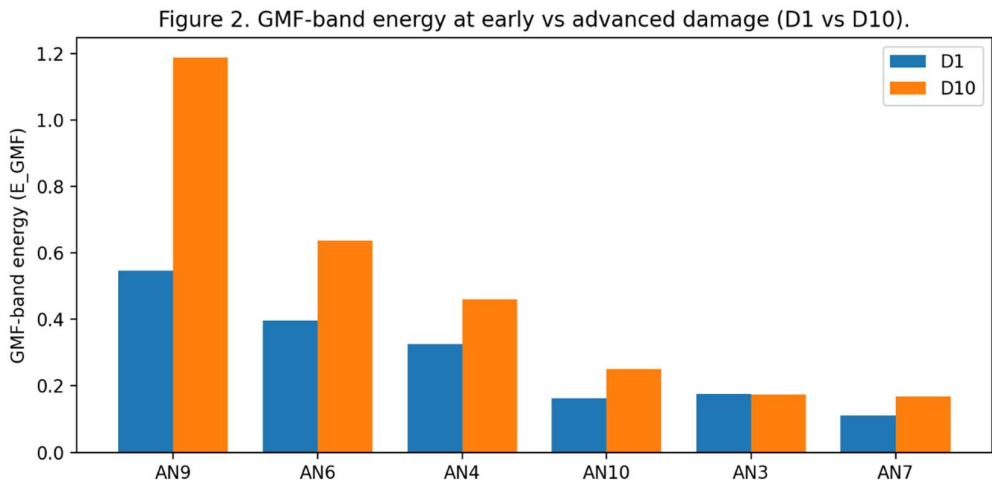


Figure 2. GMF-band energy at early and advanced damage states (D1 vs D10).

This non-uniform amplification suggests localized excitation growth rather than global broadband vibration increase.

Figure 3 shows the evolution of absolute $\pm 1\times$ sideband energy (SMI_abs). Sideband energy increases alongside GMF-band energy in most high-speed-related channels. This confirms that the tonal growth is accompanied by modulation enhancement rather than being limited to a single spectral peak.

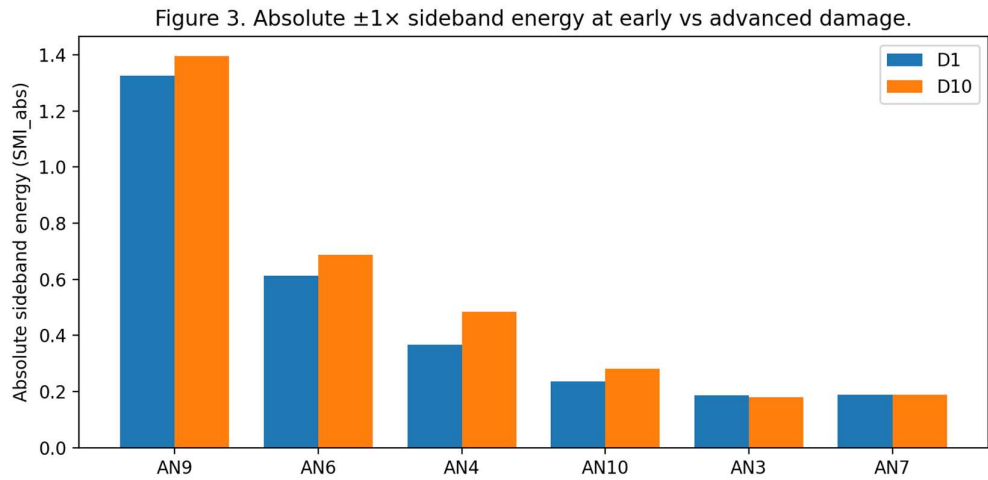


Figure 3. Absolute $\pm 1\times$ sideband energy at early and advanced damage stages.

Together, these observations indicate that damage progression alters excitation characteristics in a structurally meaningful manner.

3.2. Progression Behavior Across the Damage Sequence

Figure 4 illustrates the GMF-band energy progression for selected channels (AN9, AN6, AN4). While the overall trend from D1 to D10 indicates amplification, the growth is not strictly monotonic.

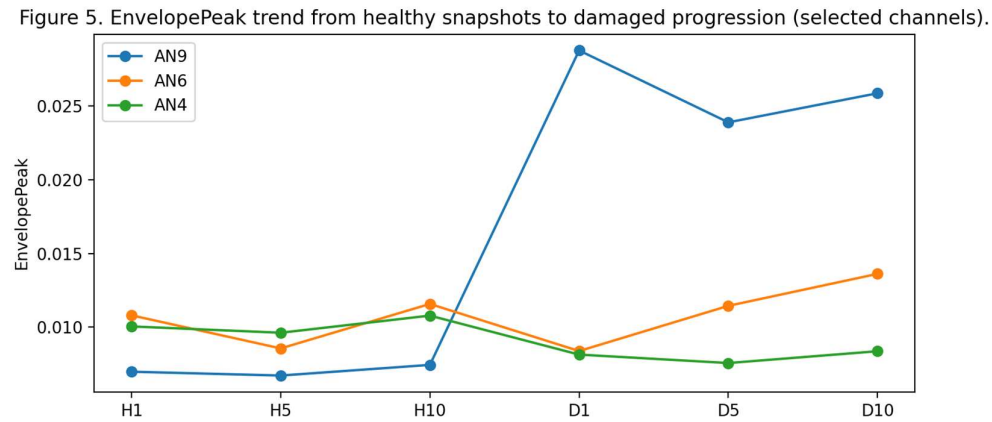


Figure 4. GMF-band energy progression across damage sequence (selected channels).

Channel AN9 exhibits the strongest tonal increase across the sequence. AN6 and AN4 demonstrate moderate growth, suggesting excitation transmission through intermediate structural components. The absence of uniform scaling across all channels supports the interpretation of localized excitation mechanisms rather than global system stiffening or uniform noise increase.

This behavior aligns with the documented high-speed gear and bearing damage.

3.3. Mapping CM Indicators to Tonal Proxies

The relationship between classical CM indicators and tonal excitation proxies was evaluated using Spearman's rank correlation analysis (Figure 5).

Figure 4. Spearman correlation between CM indicators and tonal proxies (damaged set).

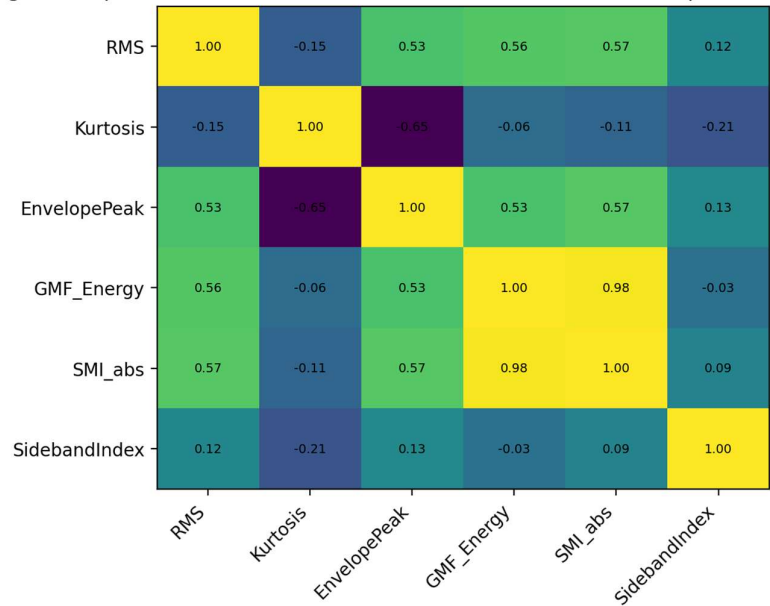


Figure 5. Spearman correlation between CM indicators and tonal proxies (damaged set).

A strong correlation was observed between GMF-band energy and absolute sideband energy ($\rho = 0.98$, $p < 10^{-11}$). This result is expected, as both proxies are derived from spectral components located in the vicinity of the gear mesh frequency. The high correlation confirms internal consistency of the tonal excitation framework rather than providing independent information.

Moderate but statistically significant correlations were found between RMS and GMF-band energy ($\rho = 0.56$, $p = 0.015$), as well as between RMS and SMI_abs ($\rho = 0.57$, $p = 0.013$). Envelope peak amplitude exhibited similar correlation levels with tonal proxies ($\rho \approx 0.53\text{--}0.57$, $p < 0.05$).

In contrast, kurtosis showed a weak, statistically insignificant association with tonal metrics, suggesting that impulsive broadband indicators do not directly track tonal excitation growth in this dataset.

These results demonstrate that commonly used broadband CM features partially encode tonal excitation behavior, even when not explicitly designed for NVH-oriented interpretation.

3.4. Healthy-to-Damaged Transition Behavior

Figures 6 and 7 show the evolution of RMS and envelope peak amplitude across healthy and damaged states. Both indicators exhibit a clear separation between healthy and damaged conditions, with damaged states consistently exhibiting elevated levels.

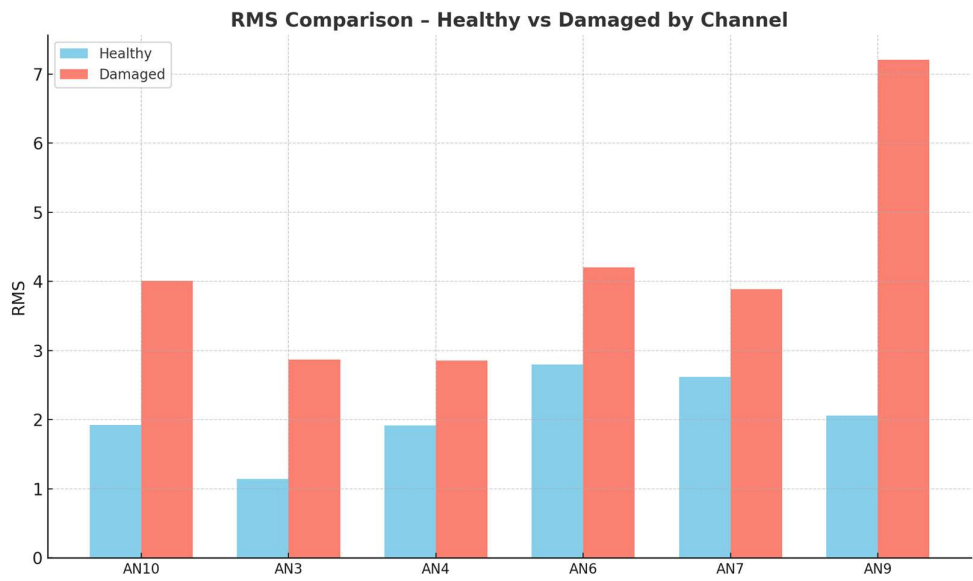


Figure 6. RMS progression from healthy snapshots to advanced damage (selected channels).

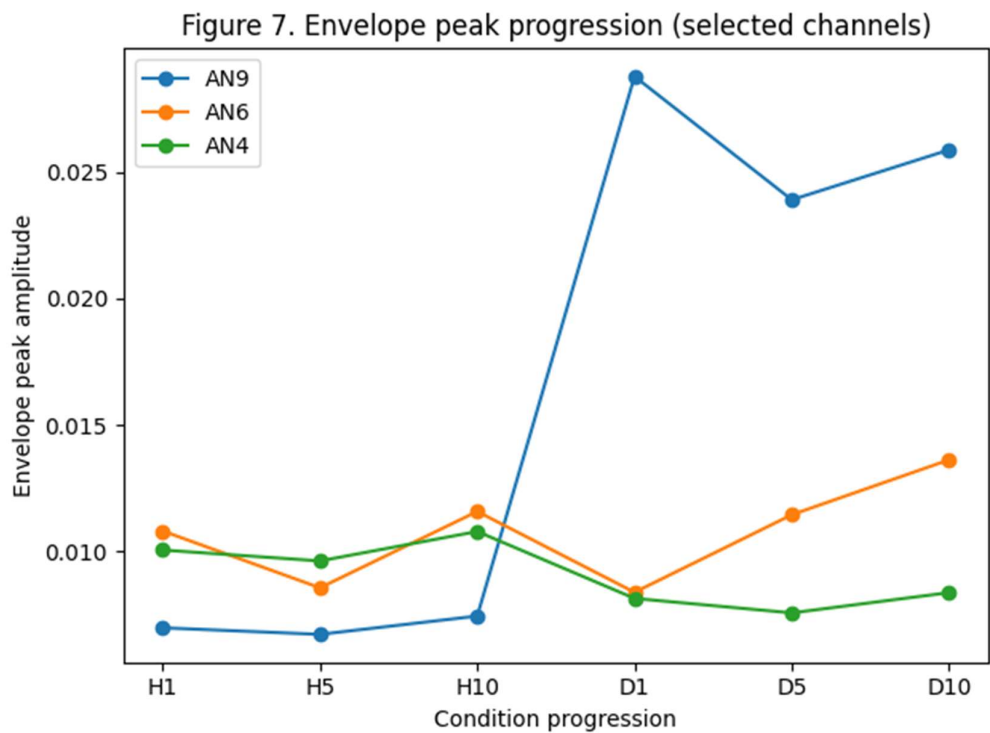


Figure 7. Envelope peak progression from healthy to damaged states (selected channels).

However, the progression within the damaged set is less pronounced than the healthy-to-damaged transition. This suggests that classical CM indicators are highly effective for state separation but less sensitive to fine-grained degradation tracking.

The results reinforce the view that broadband vibration metrics reflect changes in structural excitation, but do not necessarily provide a linear degradation index.

4. Discussion

4.1. From Diagnostic Indicators to Excitation

The results indicate that classical vibration-based CM indicators do not operate independently of tonal excitation mechanisms. Moderate but statistically significant correlations between RMS and GMF-band energy suggest that broadband vibration growth partially reflects the amplification of structurally dominant tonal components.

This observation is important from a methodological perspective. In practical diagnostics, RMS is often interpreted as a general energy metric without explicit reference to excitation structure. However, the present findings show that, at least under controlled operating conditions, increases in RMS are not purely broadband phenomena but are strongly influenced by the growth of GMF-related tonal components.

It is important to note that the near-unity correlation observed between GMF-band energy and absolute sideband energy does not imply redundancy, but reflects their shared physical origin in gear mesh excitation. While GMF-band energy captures the dominant tonal component, the sideband metric represents amplitude modulation effects associated with transmission error and time-varying mesh stiffness. Their strong correlation therefore indicates coherent excitation growth rather than duplication of identical features.

The same holds for envelope peak amplitude, which showed a consistent correlation with both GMF-band and sideband energy. While envelope analysis is traditionally associated with bearing fault detection and impulsive behavior, the observed relationships suggest that modulation-based tonal growth also contributes to envelope-based indicators.

Reframing broadband CM indicators as excitation descriptors rather than purely diagnostic metrics may enable earlier integration between monitoring and acoustic risk assessment workflows.

In contrast, kurtosis did not demonstrate a meaningful association with tonal metrics. This indicates that impulsive broadband descriptors are not necessarily sensitive to tonal amplification mechanisms, reinforcing the need to distinguish between impact-driven and tone-driven degradation signatures.

4.2 Localized Excitation Growth and Structural Sensitivity

The channel-dependent amplification patterns observed in the GMF progression analysis provide additional insight. Tonal growth was not uniformly distributed across all sensor locations. Instead, specific channels associated with the high-speed shaft region exhibited dominant amplification.

This non-uniform behavior suggests that degradation-induced excitation growth is structurally localized and transferred through defined load paths. Such behavior aligns with physical expectations in gear-bearing systems, where damage does not instantaneously translate into a uniform increase in housing vibration.

From an NVH perspective, this finding supports the idea that tonal noise amplification originates from localized excitation mechanisms and is subsequently shaped by structural transfer characteristics. Condition monitoring indicators, when interpreted through tonal proxies, can therefore provide indirect information about excitation localization.

4.3. Implications for Bridging CM and NVH Domains

The primary contribution of this study is not the identification of damage, but the establishment of a structural link between diagnostic features and tonal excitation behavior.

In industrial practice, CM and NVH workflows are often separated: diagnostic systems aim to detect faults, while NVH engineering evaluates tonal noise risk. The present results demonstrate that both domains rely on overlapping spectral structures, particularly around gear mesh frequencies.

By explicitly defining tonal proxies and statistically mapping them to CM indicators, it becomes possible to reinterpret diagnostic vibration metrics as excitation descriptors. This creates a

methodological bridge that could enable early integration of degradation monitoring into NVH risk assessment frameworks.

Such integration may be particularly relevant in electrified drivetrains, where tonal components are perceptually more dominant due to the absence of combustion noise masking.

4.4. Limitations and Scope

Several limitations should be acknowledged. First, the dataset represents controlled laboratory measurements at a fixed operating condition. Variable load and speed effects were not investigated. Second, the study evaluates structure-borne vibration rather than airborne acoustic response. The tonal proxies, therefore, reflect excitation potential rather than radiated noise levels. Third, the sample size is limited, and the degradation progression is predefined within the benchmarking dataset. Finally, while strong state separation was observed in aggregated indices, progression tracking within the damaged set was less distinct.

The absence of operational variability limits extrapolation to real-world industrial scenarios. These constraints limit direct industrial generalization. However, they do not invalidate the structural mapping framework demonstrated here.

5. Conclusions

This study examined whether classical vibration-based condition monitoring indicators can be quantitatively mapped to tonal excitation behavior in a geared drivetrain system.

Two physically defined tonal proxies—GMF-band energy and absolute sideband energy—were introduced and evaluated across a controlled degradation dataset. Tonal amplification was observed in high-speed-related channels, with non-uniform structural sensitivity.

Spearman correlation analysis revealed moderate but statistically significant associations between broadband CM indicators (RMS, envelope peak) and tonal excitation metrics. In contrast, kurtosis exhibited a weak association, indicating limited sensitivity to tone-driven degradation mechanisms.

These findings demonstrate that classical CM indicators partially encode tonal excitation growth, even when not explicitly designed for NVH interpretation. The proposed mapping framework provides a reproducible approach for linking diagnostic vibration features to excitation mechanisms relevant for tonal noise assessment.

Future work should extend the methodology to variable operating conditions and integrate airborne acoustic measurements to further validate the CM–NVH bridge under industrial scenarios.

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Data Availability Statement: The derived vibration feature dataset and analysis scripts supporting the findings of this study are publicly available in the Zenodo repository at: <https://doi.org/10.5281/zenodo.18835352>. The original raw vibration data were obtained from the publicly available NREL Wind Turbine Gearbox Vibration Condition Monitoring Benchmark Dataset (Sheng, 2014; <https://doi.org/10.25984/1844194>). The original dataset is not redistributed in this repository and should be accessed directly from the NREL source.

Conflicts of Interest: The authors declare no conflict of interest.

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