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A Machine Learning Approach to Estimate Tire Blocked Force Spectrum for Road Noise Simulation

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Accurate prediction of tire block force (TBF) spectra is essential for efficient NVH performance evaluation in vehicle development. Conventional frequency-by-frequency prediction approaches require high-dimensional outputs and long training times, limiting their applicability in early design stages. This study proposes a data-driven TBF spectrum prediction framework that combines PCA-based dimensionality reduction with a Gradient Boosting regression model. By predicting low-dimensional latent representations instead of full spectra, the proposed method significantly improves training efficiency while maintaining high prediction accuracy.

TBF spectra in the 20–500 Hz range are high-dimensional and contain complex frequency-dependent characteristics. Direct 1 Hz resolution prediction models require independent models for each frequency, leading to increased computational cost, long training time, and accumulated prediction errors such as peak shift and level mismatch. To address these limitations, this study introduces a latent-space-based prediction approach that reduces output dimensionality while preserving key spectral features.

The proposed framework consists of four main steps. First, the TBF spectrum in the 20–500 Hz range (480 frequency bins) is compressed using Principal Component Analysis (PCA), reducing the output dimension from 480 to 60 while retaining the dominant spectral characteristics. Second, a Gradient Boosting regression model is trained to predict the PCA latent representation from tire design parameters. Third, the predicted latent variables are mapped back to the original frequency domain through inverse PCA transformation. Finally, the reconstructed spectrum is evaluated using FRAC and HIF metrics. Data preprocessing includes removal of duplicate samples, handling of missing values, and exclusion of the noise-dominant 1–20 Hz range.

The proposed method achieves an average FRAC and HIF score of 0.98 or higher on the test dataset. Major peak frequencies and overall spectral shapes are accurately reproduced. Compared to direct 1 Hz prediction models, the proposed approach demonstrates comparable prediction accuracy with significantly improved training efficiency due to a 66.7% reduction in output dimension. Some discrepancies are observed in the 160–300 Hz range, which are attributed to missing wheel resonance information in the input features rather than limitations of the prediction model itself.

The results confirm that PCA latent representations effectively capture the dominant characteristics of TBF spectra. Prediction accuracy is high for major PCA components, while lower-order components show reduced predictability, consistent with their lower energy contribution. The framework also reduces sensitivity to noise by focusing on key spectral features rather than point-wise frequency prediction.

Compared to conventional FE simulations, the proposed framework enables significant reduction in prediction time, allowing rapid road noise evaluation in early tire design stages. Furthermore, the reconstructed TBF spectra can be directly integrated into existing FBS-based NVH processes, making the approach practical for real vehicle development workflows.

This study demonstrates that predicting low-dimensional latent representations of TBF spectra is an effective and efficient alternative to direct frequency-by-frequency prediction. The proposed PCA–Gradient Boosting framework achieves high accuracy, improved training efficiency, and strong compatibility with existing NVH analysis pipelines, making it well-suited for early-stage tire NVH development.

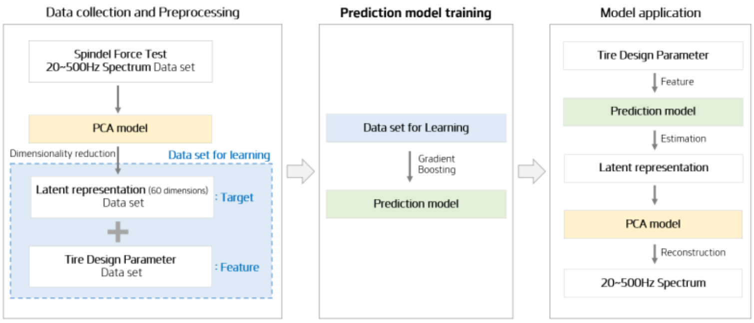

Fig1. Overall System Architecture