

Multi performance parametric optimization for motor using machine learning models and robust validation

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Electric vehicle traction motors are required to satisfy various performance requirements, including high output, high efficiency, low noise, and high quality. In particular, as motor output and power density continue to increase, electromagnetic excitation forces tend to become larger, making motor noise reduction an important design challenge. However, reducing motor noise often conflicts with other performance requirements, such as torque and efficiency. Therefore, motor design must consider multiple performance targets, including NV performance, simultaneously.

Conventional specification exploration for balancing motor noise and other performance metrics often relies on designers' experience and trial-and-error processes. As a result, it is difficult to efficiently derive an optimal specification that balances multiple performance requirements. In addition, motor noise evaluation requires both electromagnetic field analysis and structural analysis. Evaluating many design candidates directly by finite element analysis requires significant computational time. Furthermore, electromagnetic excitation force is affected by current harmonics and manufacturing variations. Therefore, robustness under manufacturing variations and current-harmonic conditions must also be considered in the design process.

To address these challenges, a machine learning surrogate model capable of rapid prediction was constructed using electromagnetic field analysis results and applied to multi-performance motor optimization and robustness evaluation considering variability factors. For multi-performance optimization, approximately 10,000 electromagnetic field analysis cases generated by Latin hypercube sampling were used as training data. The surrogate model was developed to predict maximum torque, WLTC efficiency, reliability-related indicators, and electromagnetic excitation force. A comparison with electromagnetic field analysis results confirmed that the model achieved sufficient prediction accuracy for specification exploration.

Active learning was also applied to improve the efficiency of model construction. By preferentially selecting additional training data in regions with high prediction uncertainty and near constraint boundaries, the number of training data points was reduced by approximately 50% compared with conventional manual sampling while maintaining the prediction accuracy required for optimization.

The constructed surrogate model was then incorporated into an optimization framework. A specification search was conducted with the objectives of maximizing efficiency and minimizing electromagnetic excitation force while satisfying constraints related to performance, reliability, manufacturability, and structural strength. As a result, a candidate specification was obtained that improved maximum torque by 2.71 N·m and WLTC efficiency by 0.18%, while reducing the sixth-order radial excitation force by 1.26 dB compared with the baseline specification. In addition, the exploration time was reduced by approximately 90% compared with directly evaluating the same number of candidate geometries by finite element analysis.

For robust validation, fault tree analysis was performed to identify factors that affect electromagnetic excitation force. In addition to eccentricity and roundness, which had conventionally been recognized through empirical evaluation as factors affecting motor noise, a total of 29 variability factors were extracted, including dimensional variations, magnet characteristics, current amplitude, harmonic amplitude, harmonic phase, and temperature. A surrogate model for robust validation was constructed using approximately 4,000 analysis cases with these factors as input variables. The constructed surrogate model was then applied to a comprehensive validation of 100,000 variation conditions.

Figure 1 shows a comparison between the conventional validation condition, which considers only roundness and eccentricity, and the validation result considering all 29 variability factors. The results showed that combinations of current amplitude, air gap, harmonic amplitude, and harmonic phase could lead to excitation-force deterioration exceeding the conventional worst-case condition. In addition, the analysis focusing on harmonic current conditions demonstrated that the proposed method can be used to search for conditions that reduce electromagnetic excitation force.

Future work will include experimental validation of the extracted variability factors and harmonic current phase conditions. In addition, the design scope will be expanded to include control and structural domains.

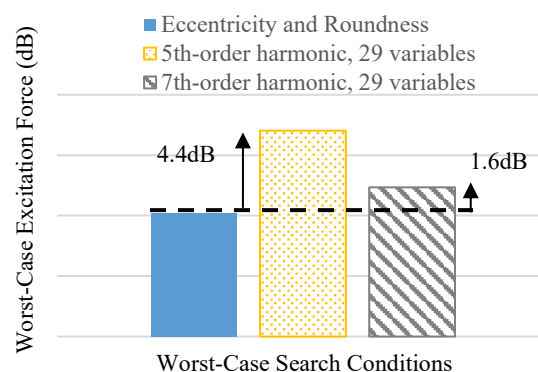


Fig.1 Comparison of Excitation Forces Under Worst-Case Conditions