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Electromagnetic vibration and noise analysis of PMSM by coupling electromagnetic field and structure

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This study aims to predict vibration and noise of a permanent magnet synchronous motor (PMSM) during vehicle operation by developing an integrated analysis method that couples electromagnetic field analysis with structural analysis. Although high levels of quietness are required for electrified vehicles, vibration and noise caused by electromagnetic excitation forces in motors are difficult to predict using conventional isolated analyses, because electromagnetic forces, structural resonances, and transmission characteristics interact with each other in a complex manner.

In this study, the fundamental and harmonic components of the current were synthesized analytically to elucidate the influence of current harmonics on electromagnetic excitation forces and vibration noise. Furthermore, by focusing on the velocity dependence of both current and electromagnetic excitation forces, an efficient analysis process is proposed in which analysis points are limited to operating conditions where current ripple changes significantly. This approach reduces the number of required analyses by 99.6% while maintaining strong correlation with experimental results.

In the electromagnetic field analysis, time–space frequency analysis is conducted, and the relationship between magnetic flux density and electromagnetic excitation force is theoretically formulated based on Maxwell stress equations. The results show that the fundamental magnetic flux density generates electromagnetic excitation forces of temporal 0th/spatial 0th order and temporal 12th/spatial 12th order. In addition, interaction between the 5th- and 7th-order current harmonics is shown to generate a 6th-order electromagnetic excitation force component (36th order in mechanical angle).

In the structural analysis, particular attention is paid to the annular 0th mode and the circumferential torsional vibration mode of the stator. A method is proposed in which spatial modes of electromagnetic excitation forces are reflected in structural analysis through phase-controlled force inputs. This approach quantitatively reproduces resonance phenomena and the resulting increase in vibration noise when the spatial modes of excitation forces coincide with structural natural modes. The experimental results for stator vibration and drive-unit acoustic power were compared with the analysis results, showing that the torsional vibration peak of the stator agreed within 0.1 dB, while the annular 0th-mode peak matched within an accuracy of 1.9 dB.

Furthermore, parametric analyses with reduced current harmonic components demonstrate that decreasing the 5th-order current component effectively reduces the 6th-order electromagnetic excitation force and the radiated acoustic power of the drive unit.(Fig.1,2) However, the results also reveal that even with ideal current waveforms, noise peaks caused by spatial harmonics and structural resonance remain, indicating the necessity of combining control-based and structural countermeasures.

Through this study, vibration and noise analysis is extended from conventional component-level evaluation to system-level prediction of the entire drive unit. The proposed method provides a fundamental technology supporting model-based and prototype-less development, contributing to the design of low-vibration and low-noise electric vehicles.

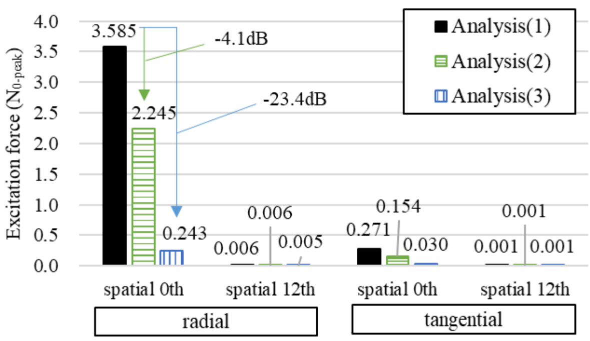

Fig.1 electromagnetic excitation force at 36th order(elec.6th)

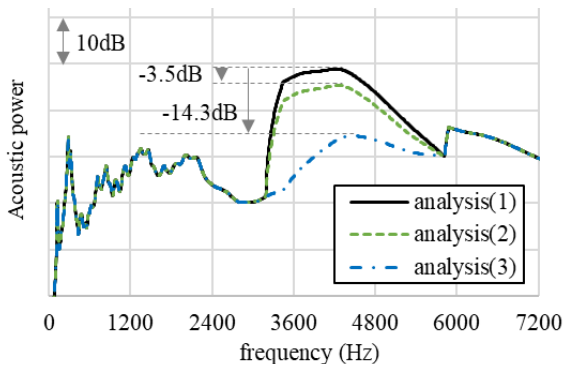

Fig.2 acoustic power of drive unit at 36th order(elec.6th)