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Verification of Surrogate Modeling and Optimization Design of ECU Heat Radiation Structure by Using MBD

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In recent years, the automotive industry has undergone major technological transformation driven by carbon neutrality initiatives and the rapid adoption of New Energy Vehicles (NEVs). NEVs employ advanced systems such as electric powertrains and battery management systems absent in conventional internal combustion engine vehicles. As vehicle lineups diversify for global markets, development efficiency has become critical, requiring shorter development cycles, platform commonization, and standardization.

Similar challenges arise in the hardware development of Electronic Control Units (ECUs) that control electric and electromagnetic actuators. To support front-loaded development, Model-Based Development (MBD) is widely used. ECU design under MBD requires integrated consideration of control, electrical, mechanical, and thermal domains, as electronic components must operate reliably within temperature limits. Therefore, high-fidelity multi-domain simulation consistent with hardware behavior is essential.

In thermal analysis, discrepancies between simulations and hardware measurements mainly stem from inaccuracies in estimated component heat generation and insufficient reproducibility of heat transfer paths in structural components. To address these issues, a collaborative research project has been conducted within the Society of Automotive Engineers of Japan (JSAE), Electronics Equipment and Thermal Design Working Group.

A demonstrator ECU board for controlling a solenoid actuator was developed. Electrical circuit behavior, including transient phenomena, was reproduced by coupling circuit models with a one-dimensional mechanical solenoid model, enabling highly reproducible calculation of component heat generation. These results were applied to ECU thermal models to evaluate heat transfer reproducibility. Previous studies improved accuracy by refining thermal models, especially for Thermal Interface Material (TIM) structures, but at significantly higher computational cost.

To maintain accuracy while reducing computational burden, this study investigates a surrogate modeling approach. The proposed method replaces repeated three-dimensional thermal FEM analyses with a surrogate model combining machine learning and a one-dimensional thermal network, using thermal resistance parameters to represent heat transfer paths and enable rapid temperature estimation for design optimization.

To simplify model construction, training was performed using a single heat-generating component mounted on a printed circuit board. TIM position and size were treated as design variables, and component temperatures from thermal simulations formed the training data. Approximately 3,000 patterns were generated within 35 hours. This approach reduced complexity while assuming superposition of temperature contributions from multiple components.

The surrogate model shows excellent agreement with conventional thermal analysis for the single-component case, achieving a mean absolute error of 0.04 °C and a maximum absolute error of 0.31 °C.

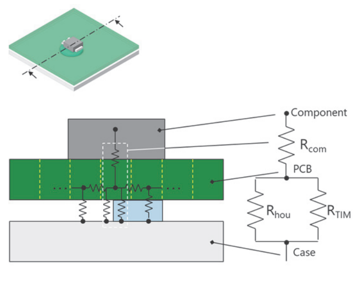

Fig.1 Thermal Network Method model

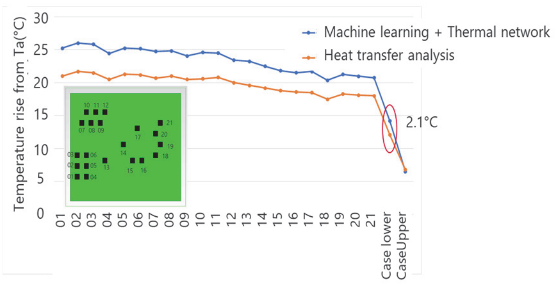

Fig.2 Temperature Prediction by Multi-Element Model