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Minimization of Discrepancy Between Measurement and Thermal Fluid Analysis for ECUs Using Inverse Analysis

Minoru Shibutani [1)] Ryuta Yoshida [2)] Haruki Takei [3)] Masanari Ueda [4)] Yoshiko Ikeda [5)]
Osamu Seya [2)] Kazunari Hashimoto [6)] Keita Inoue [6)] Takuya Shinoda [6)]

1) Kozo Keikaku Engineering Inc., 38-13 Honcho 4-chome, Nakano-ku, Tokyo, 164-0012, Japan
2) Institute of Science Tokyo, 2-12-1 Ookayama, Meguro-ku, Tokyo, 152-8550, Japan
3) Siemens K.K., Shinyokohama Square Bldg. 16F, 2-3-12 Shinyokohama, Kohoku-ku, Yokohama, Kanagawa, 220-0033, Japan
4) Siemens EDA Japan K.K., 4-7-35 Kitashinagawa, Shinagawa-ku, Tokyo, 140-0001, Japan
5) Toshiba Electronic Devices & Storage Corporation, 1 Komukai-Toshiba-cho, Saiwai-ku, Kawasaki, Kanagawa, 212-8583, Japan
6) DENSO CORPORATION, 1-1 Showa-cho, Kariya, Aichi, 448-8661, Japan

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1. Introduction

With the advancement of electrification and Advanced Driver Assistance Systems (ADAS) in automobiles, the integration and power density of Electronic Control Units (ECU) are accelerating. Thermal management is critical for product reliability. Consequently, front-loading through Model-Based Development (MBD) is urgently required to shorten development periods and improve quality. To enhance the effectiveness of MBD, improving the prediction accuracy of thermal fluid analysis is essential.

However, discrepancies between measurements and simulations persist. While accurately estimating component heat generation and geometric modeling are primary challenges, the uncertainty regarding the thermophysical properties of the printed circuit board (PCB) specifically the anisotropic thermal conductivity caused by the orientation of glass fibers in insulation layers such as FR-4, is also one of the key factors influencing simulation accuracy.

To address this, this study aims to establish a methodology that minimizes the discrepancy between measurement and simulation by combining highly accurate circuit models with an inverse analysis utilizing an optimization tool to accurately identify the PCB's thermal properties.

2. Proposed Approach and Experimental Setup

Applying inverse analysis directly to a fully assembled PCB to identify its properties often causes a "confounding effect" between the internal thermal resistance of the component packages and the PCB's thermal conductivity. To completely eliminate this confounding factor, we propose an approach that uses an unpopulated bare PCB with a simple heat source to independently identify the true thermal properties (in-plane and out-of-plane equivalent thermal conductivities) of the board.

To avoid insufficient temperature gradients typical in large, low-thermal-conductivity boards, a segmented 50 mm square model with the same wiring pattern as the target ECU was used. A 15 mm square ceramic heater (4 W heat generation) was placed at the center of the board. To minimize contact thermal resistance, a thermally conductive adhesive was applied as a thin film.

To perfectly match the boundary conditions in CFD, a rigorous experimental setup was implemented:

- Known Emissivity: A blackbody spray was applied to both sides of the board and the heater surface to achieve a uniform emissivity (ε =0.95).
- Elimination of Thermal Bridges: Conduction heat loss was blocked by a point-contact support stand, and measurements were taken in a windproof acrylic case to ensure a natural convection environment. Furthermore, to minimize heat dissipation errors due to the fin effect of the thermocouples, isothermal routing was performed based on JEITA guidelines (EDR-7338).

3. Inverse Analysis using an Optimization Tool

In the CFD model, conjugate heat transfer conditions including natural convection and radiation, identical to the experiment, were constructed. The optimization tool was used to perform an inverse analysis with the in-plane (kx, ky) and out-of-plane (kz) thermal conductivities of FR-4 as variables. To cancel out noise from minor environmental temperature fluctuations, the temperature rise (ΔT) relative to the ambient temperature was used for evaluation. To guide the search algorithm to the correct physical solution, the Root Mean Square Error (RMSE) of the temperatures at multiple points radiating from the heater was adopted as the objective function to be minimized. This methodology completely eliminates heuristic parameter tuning. Future work includes evaluating the simulation accuracy using the identified thermal conductivity. Following this, microscopic validation of these parameters will be conducted by comparing them with theoretical solutions based on the rule of mixtures, considering glass cloth orientation and copper foil residual rates.

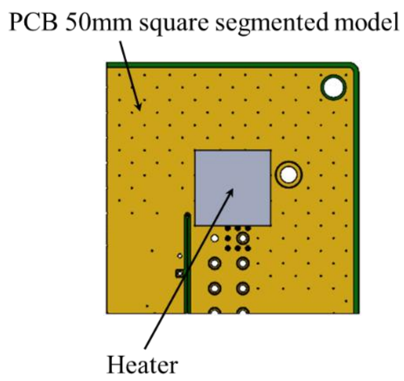

Fig.1 CFD Model