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Thermo-structural Coupled Optimization of a High-Power-Density DC Power Supply Chassis

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Abstract: High-power-density DC power supply enclosures, operating within confined spaces, are simultaneously subjected to high heat flux density and complex mechanical loads. Consequently, thermo-structural coupling has emerged as a critical bottleneck constraining their reliability. This paper takes such an enclosure as a case study, systematically analyzing the characteristics of heat source distribution and the features of the structural loading. A thermo-structural coupled finite element analysis (FEA) model is established to elucidate the interaction mechanism between the temperature and stress fields. Building on this, a synergistic design strategy is proposed, integrating heat dissipation topology optimization with structural lightweighting. Through measures such as optimizing the fin layout, reconfiguring the air duct, and adjusting the mounting position, a comprehensive enhancement of both thermal performance and structural strength is achieved. The study demonstrates that the optimized enclosure exhibits significant improvements in its maximum temperature, maximum equivalent stress, and first-order natural frequency, providing effective support for the integrated design of high-power-density power supply enclosures.

Keywords: High Power Density; DC Power Supply; Chassis; Thermostructural Coupling; Topology Optimization; Finite Element Analysis

1. Introduction

The power specifications of high-power-density DC power supplies are continuously escalating, posing significant challenges to the structural design of their enclosures. Power losses, dissipated as heat from the power devices, create high heat flux densities within a confined volume, necessitating efficient thermal pathways to transfer this heat to the exterior. Concurrently, the enclosure must withstand mechanical loads such as vibration, shock, and acceleration, meaning the requirements for structural strength and stiffness cannot be compromised. A fundamental conflict exists between thermal and structural design, particularly in terms of spatial layout and material selection: effective heat dissipation requires materials with high thermal conductivity and unobstructed airflow paths, whereas structural load-bearing capacity demands a sufficient cross-section and high joint stiffness. These two sets of requirements compete for the limited internal space. This paper establishes a thermo-structural coupled finite element model to analyze the interaction between the temperature and stress fields. A multi-objective co-

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optimization is then performed to achieve a balanced integration of heat dissipation capability and structural strength.

2. Chassis Structure and Thermal-Mechanical Load Characteristics

2.1 Typical Chassis Structure and Functional Layout

The subject of this study is a modular DC power supply chassis for a spacecraft platform, with overall dimensions of 280 mm × 220 mm × 110 mm, a volume of approximately 6.8 L, a rated power of 3.2 kW, and a power density of approximately 0.47 kW/L. The chassis is constructed from 6061-T6 aluminum alloy, selected for its excellent thermal conductivity and machinability. Internally, the chassis is functionally zoned: the power conversion section, located in the center, houses the IGBT modules and a high-frequency transformer, constituting the area of highest heat concentration; the filtering and energy storage section, situated on either side, is equipped with electrolytic capacitors and filter inductors, generating the second-highest level of heat; and the control and drive section, positioned at the front, contains the control and driver boards, which produce a relatively low amount of heat. Power devices are mounted on the baseplate via thermally conductive and electrically insulating gaskets; heat is conducted through the baseplate to the cooling fins and subsequently dissipated via convection. The top cover and side walls provide sealing and electromagnetic shielding, while also serving as an auxiliary structural load path.

2.2 Heat Source Distribution and Heat Dissipation Path

The primary heat sources within the chassis include conduction and switching losses from power switching devices, core and copper losses from the transformer, winding losses from the filter inductor, and the equivalent series resistance (ESR) losses from the bus capacitor. Among these, the heat generated by the power switching devices accounts for 55%–65% of the total losses, making it the central focus of the thermal design; the high-frequency transformer accounts for approximately 20%–25%, while the filter inductor and capacitor collectively account for about 15%–20%. These major heat sources are concentrated, with the heat flux density in the power device mounting area reaching 15–25 W/cm², which falls into the high-flux-density category. The thermal path is as follows: heat is conducted from the device junction to the package, transferred to the baseplate via a thermally conductive insulating washer, and then conducted from the base of the fins to their tips, ultimately being dissipated into the ambient environment by forced air cooling or natural convection [1]. Under high-power operating conditions, high thermal resistance in any part of this path will lead to an excessive junction temperature; therefore, thermal management optimization should focus on reducing the overall thermal resistance of the entire path.

2.3 Mechanical Loading Conditions and Structurally Weak Areas

In aerospace applications, power supply enclosures are subjected to a severe mechanical environment during the launch phase. In accordance with the GJB 1027A and NASA-STD-7001 standards, the enclosure must withstand a peak acceleration of 12.5g (5–100Hz) for sinusoidal vibration, a total RMS acceleration of 8.2g (20–2000Hz) for random vibration, and a peak acceleration of 40g from an impulse response spectrum. During the in-orbit operational phase, the enclosure must also withstand static loads resulting from its own weight and from thermal deformation at mounting boundaries. Under these loads, the vulnerable areas are typically the corners where the base plate joins the side walls, the root of the mounting studs for power devices, and the central region of the top cover plate. The corners, due to abrupt changes in cross-section, create stress concentrations, making them prone to the initiation of fatigue cracks under vibration. The substantial mass of the power devices exerts a significant shear force on the mounting studs under acceleration loads, making these a critical area for strength verification.

3. Thermo-structural Coupled Finite Element Analysis

3.1 Theoretical Basis of Coupled Analysis

The fundamental principle of thermo-structural coupling analysis is that changes in the temperature field induce thermal expansion in a material. This expansion, when constrained by the structure, generates thermal stress. In turn, this thermal stress can alter the contact thermal resistance and structural stiffness, which subsequently affects the temperature distribution.

According to the theory of thermoelasticity, the total strain in a structure is composed of two components: the mechanical strain induced by mechanical stress and the free thermal strain induced by temperature changes. The thermal stress arising from temperature gradients within the chassis structure is a central concern in thermo-structural coupling. When this thermal stress exceeds the material's yield strength, it will cause plastic deformation. Furthermore, under long-term, cyclic thermal loads, it can also lead to low-cycle fatigue failure. Therefore, the accuracy of the thermo-structural coupling analysis directly impacts the assessment of the chassis's reliability.

3.2 Finite Element Model Development

A thermo-structural coupled finite element model is established on the ANSYS Workbench platform. The model incorporates the primary components, including the chassis enclosure, power devices, transformer, inductor, PCB, and mounting hardware. Small-scale features that do not affect the thermal and structural transfer characteristics are reasonably simplified. A hexahedral-dominant hybrid mesh strategy is employed: a refined mesh with an element size of 0.5–1 mm is applied to the power devices and critical connection areas, while a coarser mesh with an element size of 3–5 mm is used for non-critical regions, such as the chassis enclosure. The total number of elements is approximately 780,000, and the number of nodes is approximately 350,000. Regarding the material properties, the thermal conductivity of the 6061-T6 aluminum alloy is set to 167 W/(m•K), the coefficient of linear thermal expansion to 23.6×10^{-6}/K, the elastic modulus to 68.9 GPa, and Poisson's ratio to 0.33. The thermal conductivity of the equivalent packaging material for the power devices is set to 3.2 W/(m•K), with a density of 2.3 g/cm³.

The boundary conditions are defined as follows: for the thermal analysis, a volumetric heat source is applied to the power device based on its measured power loss, and the ambient temperature is set to 45°C (a typical temperature inside a spacecraft cabin). The convective heat transfer coefficient between the chassis's outer surface and the ambient air is set to 15–25 W/(m²•K) under forced air-cooling conditions. For the structural analysis, a fixed constraint is applied to the bottom surface of the chassis mounting feet, and bonded contact is defined between the various components. Subsequently, the nodal temperatures obtained from the thermal analysis are applied to the structural model as a body load, and an indirect coupling method is employed to solve for the thermal stress distribution.

3.3 Initial Design Thermal-Structural Response

A thermo-structural coupled analysis was performed on the initial design. The thermal analysis results indicated that the maximum temperature of the chassis, 127.3°C, was located at the junction of the power IGBT module. This exceeds the recommended maximum operating junction temperature of 125°C for silicon-based devices, representing an unacceptable thermal condition. The average temperature of the power device mounting plate was 86.5°C. A localized high-temperature zone, with a temperature gradient of approximately 18°C/cm, was observed at the junction between the mounting plate and the side wall, caused by the uneven distribution of ribs. The structural analysis results showed that under the combined thermal and mechanical loads, the maximum equivalent stress in the chassis was 187.6 MPa, located on the inner side of the junction between the mounting plate and the side wall. This value, which is 78% of the yield strength (241 MPa) of the 6061-T6 aluminum alloy, indicates a low safety margin. The maximum displacement was 0.38 mm, occurring in the central region of the top cover plate; the stiffness is sufficient to meet general requirements. The first-order modal analysis revealed a natural frequency of 118 Hz, which is close to the launch vehicle's excitation frequency (approx. 110 Hz), posing a risk of resonance and necessitating urgent structural modifications [2].

4. Thermostructural Co-optimization Design

4.1 Optimization Strategy and Design Variables

To address the initial design problem, an optimization strategy was established, prioritizing temperature control, while also considering structural strength and dynamic frequency avoidance. The temperature control objective is to reduce the maximum junction temperature to below 115°C; the strength objective is to limit the maximum equivalent stress to below 150 MPa and increase the safety factor to above 1.6; and the dynamic objective is to raise the first-order natural frequency to above 135 Hz. The design variables selected are: rib height (initial: 25 mm, range: 15–45

mm), rib spacing (initial: 8 mm, range: 5–12 mm), base plate thickness (initial: 6 mm, range: 4–10 mm), and the positional offset of the power device installation (±15 mm). The rib parameters influence the heat dissipation area and flow resistance; the base plate thickness simultaneously affects thermal diffusion capability and structural stiffness; and the installation position affects the heat source distribution and the load transfer path. The comprehensive optimization of these four variables necessitates a balance between thermal and structural performance.

4.2 Topology Optimization of the Heat Sink Structure

Topology optimization of the heat sink layout was performed using the SIMP interpolation model (with a penalty factor of 3 and a filter radius of 2 mm), aiming to minimize the maximum temperature while being constrained by the volume fraction. The process converged after 80 iterations. The results indicated that the optimal configuration exhibits a fin distribution characteristic of being 'dense at the root and sparse at the tip.' The fin density directly beneath the power device is significantly higher than in other regions, suggesting that heat should be extracted along the shortest path from the source. Accordingly, the fin layout was reconstructed: the power device area features dense, short fins (spacing: 6 mm, height: 32 mm), while the area farther from the heat source employs sparse, long fins (spacing: 10 mm, height: 40 mm), with the total mass remaining essentially unchanged. Compared to a uniform layout, the variable-density layout shortens the lateral thermal diffusion path on the baseplate, resulting in a significant improvement in heat dissipation efficiency [3].

4.3 Multi-objective Optimization of Structural Parameters

Building upon the optimized thermal design, a multi-objective optimization was conducted, targeting the maximum temperature, maximum equivalent stress, and the first-order natural frequency. A surrogate model was constructed using the Response Surface Methodology (RSM), with 25 experimental points generated via a Central Composite Design (CCD) to fit a second-order polynomial response surface. The NSGA-II genetic algorithm (with a population size of 100 and 200 generations) was employed to solve for the Pareto front. The optimal trade-off solution is as follows: a base plate thickness of 9 mm, a rib root height of 38 mm and a tip height of 28 mm (a variable-height design), and a forward offset of the power device by 12 mm along its length. The thickened base plate enhances thermal diffusion capacity and bending stiffness; the variable-height ribs strike a balance between the heat dissipation area and unobstructed flow channels; and the offset of the power device reduces the peak shear stress on the mounting studs. Collectively, these three adjustments improve both the thermal and structural performance.

5. Optimization Results and Discussion

5.1 Verification of the Optimized Scheme's Thermal Performance

A thermo-structural coupled analysis was conducted to validate the optimized design. The thermal analysis results indicate that the maximum junction temperature of the power IGBT module was reduced from an initial 127.3°C to 111.8°C, a decrease of 15.5°C, which is below the design target of 115°C. The average temperature of the power device mounting base plate decreased from 86.5°C to 74.2°C, and the maximum temperature difference across the base plate was reduced from 18.5°C to 9.3°C, resulting in a significant improvement in temperature uniformity. The heat sink's efficiency increased from an initial 0.58 to 0.73, indicating that the fin surface area is being more fully utilized. Under the same ambient temperature and cooling conditions, the maximum allowable long-term operating ambient temperature for the optimized design increased from an initial 38°C to 49°C, significantly enhancing the power supply's environmental adaptability.

5.2 Verification of Mechanical Properties of the Optimized Scheme

The results of the thermo-structural coupled stress analysis indicate that, under the combined action of thermal and mechanical loads, the maximum equivalent stress of the chassis is reduced from an initial 187.6 MPa to 138.2 MPa, a decrease of 26.3%. Consequently, the factor of safety increases from 1.28 to 1.74, satisfying the aerospace application requirement for a factor of safety of no less than 1.5. The region of stress concentration remains at the junction between the base plate and the side wall, but the extent of the peak stress area is significantly reduced. The shear stress at the root of the power device mounting stud is reduced

from an initial 89.4 MPa to 62.7 MPa, resulting in a substantial increase in the safety margin. The maximum displacement of the top cover plate is reduced from 0.38 mm to 0.22 mm, and the structural stiffness is slightly improved. The modal analysis indicates that the first-order natural frequency increases from 118 Hz to 142 Hz, successfully avoiding the launch vehicle excitation frequency band (approx. 110 Hz), thereby eliminating the risk of resonance.

5.3 Optimization Mechanisms and Future Applications

Analyzing the underlying mechanisms that drive the effectiveness of the optimization: the variable-density layout of the fins, denser at the root and sparser at the tip, shortens the conduction path from the heat source to the fin root, thereby reducing the thermal spreading resistance; the thickened base plate enhances in-plane thermal diffusion, allowing heat from hotspots to be more rapidly distributed across the entire base area; adjusting the position of the power device shifts the mass distribution, which effectively improves the load-bearing path and reduces stress concentration at the mounting points [4]. The key to the simultaneous enhancement of thermal and structural performance lies in the directional consistency between the optimization of the heat dissipation path and that of the load-bearing path—both require an efficient, low-impedance connection between the heat source and the support. This insight offers a valuable reference for the integrated design of high-power-density electronic enclosures.

6. Conclusion

This paper addresses the dual challenges of high heat flux dissipation and complex mechanical load-bearing within the confined space of high-power-density DC power supply enclosures. A thermo-structural coupled finite element analysis (FEA) model is established to reveal the distribution patterns and interaction characteristics of the temperature and stress fields. With the maximum temperature, maximum equivalent stress, and first-order natural frequency as optimization objectives, a synergistic enhancement of both thermal performance and structural strength is achieved through the multi-objective optimization of the heat sink's topology and key dimensions. The methodology presented herein can serve as a valuable reference for the integrated structural-thermal design of high-power-density electronic equipment, such as those for aerospace and communication applications. Future research will further investigate the coupled effects of transient thermal loads and fatigue life.

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