A Methodology For The Aero-thermal Optimization Of Hybrid And Electric Propulsion Systems

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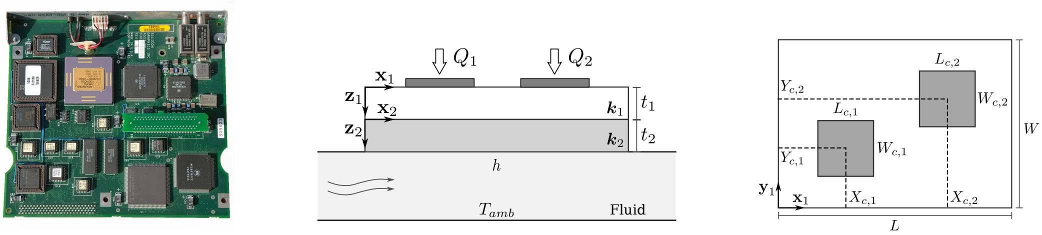
Abstract

Thermal management for electric motors is important as the automotive and aerospace industries continue their transition to hybrid or fully electric propulsion. The objective of this work is to present an advanced methodology for aero-thermal optimization of power electronics cooling systems to limit heating in hybrid and electric motors. The printed circuit board itself (solid domain) is modeled as a composite layered substrate with discrete heat sources, where the temperature distribution is obtained by solving Laplace's steady state heat equation and then transforming it into a closed form using Fourier series. The prediction of the temperature distribution and heat transfer across the fluid-solid interface is used as a boundary condition for a continuous thermal adjoint solver to optimize the flow topology of the cooling system (fluid domain). An adjoint-based shape optimization method for improving heat transfer in Conjugate Heat Transfer (CHT) problems is formulated. In the topology optimization scheme, extended heat transfer surfaces with constant wall temperature in the fluid domain are generated based on variational information of a cost function obtained from temperature distribution and adjoint velocity fields. The gradient of the multi-objective function, which takes into account both the pressure losses and the recoverable thermal power through the boundaries is calculated by solving the adjoint equations and used in a built-in implementation of the Method of Moving Asymptotes for design optimization. A case study of this application is discussed in detail.

Introduction

The importance of electronics in a range of industrial applications is growing exponentially as electronic components form the core of complex systems in hybrid and electric ground vehicles, aerospace aircraft and drones, among others. To limit the environmental impact of these technological developments, it is essential that these systems are highly efficient and minimize energy consumption. One way to achieve this goal is to optimize the cooling systems associated with various electronic components. This is achieved by improving the heat transfer processes that dissipate the high amount of heat produced. The scenario investigated in this study is shown in Fig.1. A multiple stacked printed circuit board (PCB) consists of multiple layers of substrate material and heat spreaders placed on top to reduce the thermal stress on the electronic components. The electronic PCB is cooled by forced liquid convection at the bottom to ensure the optimum operating temperature ranges of the electronic components. The optimal design of such a system usually involves two main steps, namely the design of the layout of the substrate and the cooling system.



(a) PCB (b) simplified scheme: side view (c) simplified scheme: top view

Figure 1. Design of multi-source compound printed circuit board (PCB) cooled by forced liquid convection.

Over the years, several numerical strategies have been developed for the characterization of the solid compound board. The Finite Difference (FD) Method and Finite Element Analysis (FEA) are reliable in solving heat transfer problems in these domains [1], but require a particularly high computational effort; therefore, their use for a fast optimization procedure is discouraged. On the other hand, analytical solutions based on Fourier expansion series reduce computational time while guaranteeing accurate results [6]. Assuming externally applied sources resembling the heat generated by various electrical components, solutions for multilayer isotropic substrates [6] and multicomponent arrays [5] are available in the literature. The best configuration under a variety of scenarios is quickly extracted using this approach, along with the temperature distribution at the boundary between the substrate and the cooling channel. The optimal design of the cooling system is achieved using a Finite Volume (FV) thermal adjoint solver, which simultaneously considers the minimization of pressure losses and the maximization of recoverable thermal power. Among the various adjoint optimization approaches available in the literature, the topology optimization strategy (TO) was chosen in this work. While the use of an adjoint method for fluid mechanics dates back to the seventies [8], TO has been used more recently by Borrval and Petersson [2] to optimize the dissipated power in a Stokes flow and extended to conjugate heat transfer (CHT) problems by Dede [3] and Yoon [11]. The solution of the TO problem using an adjoint formulation implies independence of the gradient computation with respect to the number of control variables. This makes the approach particularly suitable for problems with a large number of degrees of freedom, such as those encountered in fluid mechanics [4, 7].
In this work, a *multi-variable optimizer* for the solid region is combined with a *thermal adjoint solver* for the fluid domain to achieve the overall optimization of both the electronic system and the cooling system. The multivariable optimizer provides an initial electronic arrangement and heat flux at the fluid-solid interface. Subsequently, the *thermal adjoint solver* is applied for the optimal design of the cooling system. The optimization of the overall system is achieved by an iterative procedure. The software and methodology presented in this study are is developed in a in-house C++ library developed by the authors using the OpenFOAM framework.

Methodology

The multi-step procedure presented in this section includes two main steps: a) the implementation of a multivariable optimization procedure for the design of the upper solid layers and the component arrangement and b) the development of a thermal adjoint solver for the optimization of the cooling system. A description is provided in the following two subsections.

Multi-variable optimization of the solid multi-layer substrate

The temperature distribution in an upper solid region consisting of N isotropic layers (Fig. 1) is described by the steady-state heat conduction equation:

$$\nabla^2\theta = \frac{\partial^2\theta}{\partial x^2} + \frac{\partial^2\theta}{\partial y^2} + \frac{\partial^2\theta}{\partial z^2} = 0 \tag{1}$$

where $\theta(x, y, z) = T - T_{amb}$ is the temperature excess with respect to an ambient reference condition. The topside boundary conditions are based on the presence of N_c electronic components. Each component generates a thermal power $Q = q\,A_c$ through its contact area A_c, from which follows:

$$\left.\frac{\partial\theta_1}{\partial z}\right|_{z_1=0} = 0 \qquad (x, y) \in (A_{base} - A_c) \tag{2}$$

$$-k_1 \left.\frac{\partial\theta_1}{\partial z}\right|_{z_1=0} = q \qquad (x, y) \in A_c \tag{3}$$

For the N-th layer, at the fluid-solid wall, it holds:

$$-k_N\, \left.\frac{\partial\theta_N}{\partial z}\right|_{z_N=t_N} = h(x, y)\,\theta_N(x, y, t_N) \tag{4}$$

The sidewalls are adiabatic. Under these boundary conditions and using variable separation,the temperature distribution written in terms of Fourier expansion series is:

$$\begin{aligned}\theta =& A_{00} + B_0 z + \sum_{m=1}^{\infty}\cos(\lambda_m x)\,[A_m\, \cosh(\lambda_m z) + B_m\, \sinh(\lambda_m z)] + \sum_{n=1}^{\infty}\cos(\delta_n y)\,[A_n\, \cosh(\delta_n z) + B_n\, \sinh(\delta_n z)] \\ &+ \sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\cos(\lambda_m x)\cos(\delta_n y)\,[A_{mn}\, \cosh(\beta_{mn} z) + B_{mn}\, \sinh(\beta_{mn} z)]\end{aligned} \tag{5}$$

where $\lambda_m = \dfrac{m\pi}{L}$, $\delta_n = \dfrac{n\pi}{W}$ and $\beta_{mn} = \sqrt{\lambda_m^2 + \delta_n^2}$. The A_i and B_i Fourier coefficients are calculated via the closure equation, considering either perfect adhesion between the solid layers or the presence of a finite conductance. Eq. 5 provides the bi-dimensional temperature distribution at the fluid-solid wall and is necessary for calculating the total resistance of the system. In fact, the total resistance R_t for single-source scenarios is the sum of a 1D contribution R_{1D} and the spreading resistance R_{sp}:

$$R_t = R_{1D} + R_{sp} = \frac{\max(\theta_1)}{Q}. \tag{6}$$

For multi-component configurations, Influence Coefficient Method is used because it accounts for the interaction effects among sources:

$$\theta_s = \sum_{i=1}^{N_c} \theta_i(X_{c,s}, Y_{c,s}, 0) = \sum_{i=1}^{N_c} Q_i f_{i,s} \qquad \rightarrow \qquad R_{t,s} = \frac{\theta_s}{Q_s} = \sum_{i=1}^{N_c} \frac{Q_i}{Q_s} f_{i,s} \tag{7}$$

where the power Q of the i-th source is multiplied by an influence coefficient $f_{i,s}$. The total resistance is used as the objective function in the multivariable optimization method for the solid domain, which exploits the iterative Limited-Memory BFGS algorithm considering constraints (L-BFGS-B). Constraints are: a) the maximum solid encumbrance; b) the production capability for the minimum solid layer thickness; c) the minimum and maximum in-plane dimensions; d) the components must lay within the top surface. The optimization of the solid layers provides the updated interfacial temperature distribution, which becomes a boundary condition for the *thermal adjoint solver*.

Topology optimization of the fluid region via thermal adjoint method

Topology optimization in the fluid domain is performed using a density-based approach, such that the material distribution is given by a variable $0 \leq \eta \leq 1$; $\eta = 1$ for the fluid, and $\eta = 0$ for the solid. Given the objective function J, the minimization problem becomes:

$$\text{minimize } J(\boldsymbol{u}, p, T, \eta) \tag{8}$$

subjected to:

$$R^p = \nabla \cdot \boldsymbol{u} = 0 \tag{9}$$

$$\boldsymbol{R^u} = (\boldsymbol{u} \cdot \nabla)\boldsymbol{u} + \nabla p - \nabla \cdot (\nu \nabla \boldsymbol{u}) + \alpha(\eta)\boldsymbol{u} = 0 \tag{10}$$

$$R^T = (\boldsymbol{u} \cdot \nabla)T - \nabla \cdot (D(\eta)\nabla T) = 0 \tag{11}$$

where the steady-state, incompressible Navier-Stokes equations R^p-$\boldsymbol{R^u}$ are used together with the temperature transport-diffusion equation R^T to model the physics of the fluid domain. The momentum balance is augmented with the Brinkman penalization term $\alpha(\eta)\boldsymbol{u}$ so that if the value of the inverse permeability α is high, $\boldsymbol{u} \rightarrow 0$, and Eq. 11 assumes a solid state form being dominated by diffusion. When $\alpha \rightarrow 0$ the fluid equations are recovered. The material properties are interpolated from the value of the pseudodensity η by the Random Approximation of Material Properties (RAMP) model. The constraint represented by the flow equations is enforced by optimizing an augmented objective function L:

$$L = J + \int_\Omega \boldsymbol{\lambda} \cdot \boldsymbol{R} \, d\boldsymbol{\Omega} \tag{12}$$

where Ω represents the domain where the TO is performed, $\boldsymbol{\lambda}$ is the vector of Lagrange multipliers (called *adjoint variables*) and $\boldsymbol{R}$ contains the continuity, momentum and temperature transport-diffusion equations. The sensitivity of the cost function, representing its gradient with respect to the design variables, is written as:

$$\frac{\delta L}{\delta \boldsymbol{b}} = \frac{\delta J}{\delta \boldsymbol{b}} + \frac{\delta}{\delta \boldsymbol{b}} \int_\Omega \boldsymbol{\lambda} \cdot \boldsymbol{R} \, d\boldsymbol{\Omega} \tag{13}$$

where $\delta/\delta\boldsymbol{b}$ is the total derivative, including contributions from domain deformation. Eq. 13 is rearranged to obtain the continuous adjoint equations:

$$R^q = \nabla \cdot \boldsymbol{v} + \frac{\partial J_\Omega}{\partial p} = 0 \tag{14}$$

$$\boldsymbol{R^v} = -(\boldsymbol{u} \cdot \nabla)\boldsymbol{v} - (\nabla \boldsymbol{v})\boldsymbol{u} - \nabla \cdot (2\nu\varepsilon(\boldsymbol{v})) + \alpha\boldsymbol{v} + \nabla q - T\nabla\phi + \frac{\partial J_\Omega}{\partial \boldsymbol{u}} = 0 \tag{15}$$

$$R^\phi = -\boldsymbol{u} \cdot \nabla\phi - \nabla(D\nabla\phi) + \frac{\partial J_\Omega}{\partial T} = 0 \tag{16}$$

which are completed by the corresponding boundary conditions [9]. Once the adjoint equations are solved, it is possible to obtain the value of the sensitivity and update the design variables. This was done using the Method of Moving Asymptotes (MMA), implemented directly in OpenFOAM. The procedure described so far is valid regardless of the objective function. Herein, J is a linear combination of two functions J_1 and J_2 representing respectively the power dissipated by the fluid, to be minimized, and the net thermal power recoverable from the domain, to be maximized:

$$J_1 = -\int_{\partial\Omega} \Big(p + \frac{1}{2}\boldsymbol{u}^2\Big)\boldsymbol{u} \cdot \boldsymbol{n} \, d\partial\boldsymbol{\Omega} \;, \; J_2 = \int_{\partial\Omega} (\rho C_p T)\boldsymbol{u} \cdot \boldsymbol{n} \, d\partial\boldsymbol{\Omega}. \tag{17}$$

The bi-dimensional distribution of the heat transfer coefficient, together with the updated temperature field at the interface, can be used as input to perform a new *multivariable optimization* step.

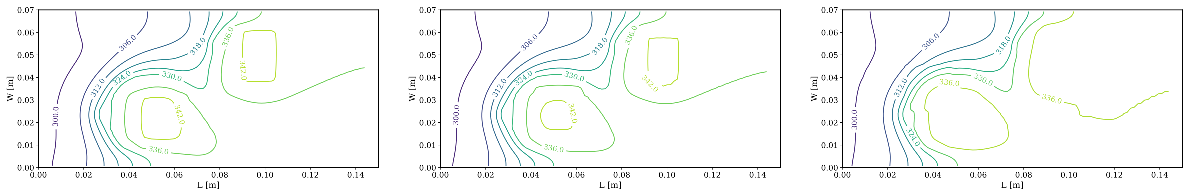
Results

A simplified case is presented to show the applicability of the proposed approach. In particular, a *multivariable* and a *thermal adjoint* optimization are iteratively performed to investigate their coupling. A solid compound substrate is mounted on an initially empty channel allowing the forced flow of a coolant (Fig. 1b and 1c) from left to right. The substrate and component properties are shown in Tab. 1. The *multi-variable optimization* (MVO) optimizes the substrate and relocates the components to minimize the thermal stress. A validation procedure of the MVO results was performed by comparing the solutions with finite-volume multi-region CHT simulations. As shown in Fig. 2, the thermal stress on the components is rapidly reduced after a few iterations.

Components						**Layers**					
N_c	L_c	W_c	$X_{c,i}$	$Y_{c,i}$	Q_i	N	L	W	k_j	t_j	T_{amb}
2	[20; 15]	[20; 23]	[55; 97.5]	[22; 49.5]	8	2	150	70	[4; 200]	[1; 3]	298.15

Table 1. Substrate characteristics: lengths are in mm, ambient temperature is in K.

Most of the properties of the solid pack can be varied by imposing external constraints. In particular, the total thickness can be apportioned among the solid sheets, provided that it satisfies the encumbrance limitations. Similarly, source relocation is essential to reduce cross-interactions and thus the overall resistance of each component. Reducing the thickness of low conductive solid plates has great benefits for heat dissipation. The opposite is true for highly conductive materials (see Fig. 2 and Tab. 3).



(a) MVO Iter: 1 (b) MVO Iter: 7 (c) MVO Iter: 12

Figure 2. emperature distribution at the top of the PCB at different iterations of the multivariable optimizer (MVO).

At the end of the multivariable optimization loop, the substrate properties are updated (Tab. 2). The results, which are shown in Tab. 3 show a relative reduction of peak temperature in excess $\Delta\theta$ of 17%. The total component resistance is reduced by $\approx$ 38%.

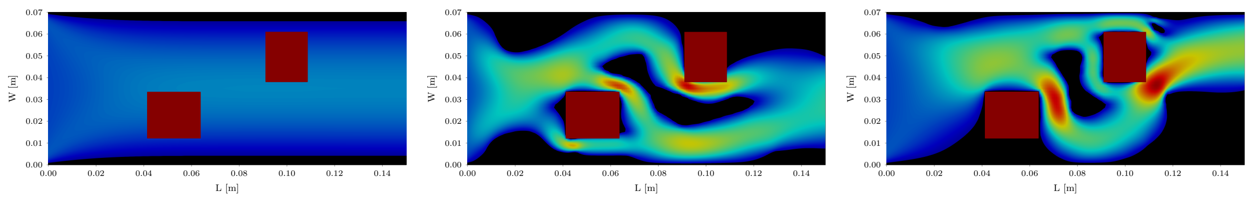
Components		**Layers**
$X_{c,i}$	$Y_{c,i}$	t_j
[38.2; 112.8]	[34.3; 47.5]	[0.5; 5]

Table 2. Optimized substrate

	Temperature peak		**Total resistance**	
	Source 1	Source 2	Source 1	Source 2
Initial Config.	343.16	344.96	1.17	1.31
Final Config.	335.44	336.98	0.73	0.80

Table 3. Optimized substrate results: temperature in K, resistance in K/W

The temperature distribution at the interface, obtained from Eq. 5 for the optimal arrangement designed by the MVO, is used as boundary condition to shape the cooling duct through topology optimization. A mass flow rate of $\dot{m} =$ 0.43 kg/s is prescribed at the inlet. Brown rectangles mark the location of the electrical components in Fig. 3.



(a) Adjoint Iter: 1 (b) Adjoint Iter: 50 (c) Adjoint Iter: 250

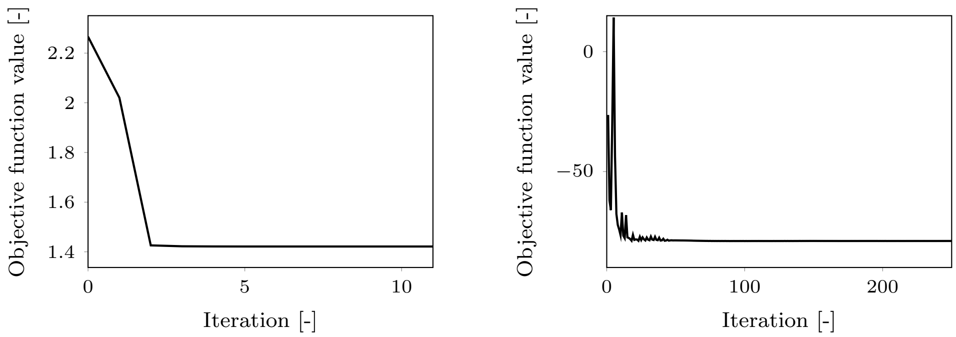
Figure 3. Velocity magnitude at different iteration of the topology optimization.

Fig. 3 shows the evolution of the adjoint optimization cycle: the topology is modified by adding solid material (aluminium) to the domain to enhance the heat dissipation and the system performance (Fig. 3b and 3c). The velocity magnitude is highlighted in Fig. 3 for different *thermal adjoint solver* iterations, to show how the solid material is distributed: the solid region is marked in black, where velocity is zero. The difference of the objective functions with respect to the reference configuration (Fig. 3a) are displayed in Tab. 4. Both values of dissipated power and recovered thermal power increase during the optimization cycle, but the thermal increment is eight order of magnitude higher than the one of pressure losses. A modest net increase of dissipated power corresponds to a clear gain of recoverable thermal power: the growth of J is $\approx 200\%$ for both iteration 50 and 250.

Iteration	ΔJ_1 $[W]$	ΔJ_2 $[W]$	ΔJ $(\%)$ $[-]$
50	$2.2 \cdot 10^{-10}$	$1.2 \cdot 10^{-2}$	199%
250	$2.1 \cdot 10^{-10}$	$1.2 \cdot 10^{-2}$	200%

Table 4. Performance comparison with respect to non-optimized solution at different iterations of TO cycle.

The evolution of the objective function for both the MVO and TO is reported in Fig. 4: both descent are steep at the first iterations, showing rapid converge to a final value. The decrement of the objective function of the thermal adjoint optimizer is not monotone in agreement with other results reported in the literature [10].



(a) multi-variable optimizer

(b) thermal adjoint solver

Figure 4. Trend of objective functions during optimization cycle for MVO and TO.

Conclusion

A multistep methodology has been proposed for the simultaneous optimization of an electronic compound printed circuit board and its associated cooling system. The thermal stress in the PCB, the weighted sum of pressure losses and recoverable thermal power in the cooling duct have been minimized in a fully automatic fashion, proving the good performances of the presented approach. The study of improved iterative multi step optimizer to be applied to industrial configurations is currently under investigation.

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