An approach to systematically reduce the extent of the design space in topology optimization for heat transfer problems

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In this paper, we present an approach how to reduce the spatial extent of the design space in topology optimization in order to reduce computational costs. We consider heat transfer problems of complex systems with cooling through natural convection. The proposed approach consists of two steps, which shift the compromise between computational cost and model quality to either side, respectively. The combination results in a smaller design space and therefore reduced computational cost. We apply the method to the optimization of an electro hydrostatic actuator. The proposed approach can help the product developer in finding optimal solutions for the thermal optimization of complex systems.

Nomenclature

CHT	=	Conjugate Heat Transfer
EHA	=	Electrohydrostatic Actuator
V_{pre}	=	Preliminary volume fraction
V_{sec}	=	Secondary volume fraction
V_{fin}	=	Final volume fraction

I.Introduction

The method of topology optimization is a suitable tool to find objectively optimal or optimized solutions to complex problems. Its origins are in structural mechanics[1] but it has since then been applied to other domains such as heat transfer as well[2]. However, it is often applied to small, specific problems such as heat sinks,[3] or exemplary problem formulations such as a heated cavity[4].

To ensure a suitable spatial resolution of the optimized geometry, the design space needs to be finely discretized. When applying topology optimization to physically large problems or in general problems with a large design space, this results in a large number of mesh cells. This in turn increases the computational time to solve the simulation model and the optimization problem. This is especially relevant for large scale problems or whole systems. For the application to industrial problems, high computational times should be avoided. Keeping the need for computational resources and time low helps to bring the method of topology optimization further into industrial product development. Chen et al. presented in Ref. 5 two approaches for determining an optimized design space for topology optimization. One is based on the Taguchi method,[6] and the other on a genetic algorithm. However, both approaches come with the downside of needing many evaluations of the objective function. When applied to (conjugate-) heat transfer problems, this comes at a high computational cost.

Therefore, our aim in this paper is to present an approach to reduce the extent of the design space in topology optimization for heat transfer problems without the need of many objective function evaluations.

II.Proposed approach

When dealing with simulations, an engineer always has to find a compromise between model quality and computational cost of the simulation model. This compromise depends on many factors, including development phase, intended use of the simulation model, available computational resources, and many more. Although very important, finding the optimal balance for a given case is often not trivial. This is especially true, when the simulation model is used in the context of automatic optimization. Because of the iterative nature of automatic optimization methods, the computational cost is scaled by the number of iterations, and if the model quality of the underlying simulation model is not sufficient, the optimization results cannot be trusted.

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In the proposed approach, we divide this problem of finding the optimal balance between model quality and computational cost up into two separate parts. In the first part, the preliminary optimization, we shift the balance towards a low computational cost. In the second part, the secondary optimization, we shift the balance towards a high model quality. First, we decrease the computational cost and model quality for an initial estimate of the optimization result, which in the second part gets refined in an optimization, where we prioritize the model quality.

The proposed approach to systematically reduce the design space consists of four key steps, each of which will be described in the following.

1. *Setting up the underlying CHT simulation model*

The base for automatic optimizations of all kinds are simulation models. In our case, we focus on optimization of heat transfer problems, so the underlying simulation model is a CHT simulation model of the system under investigation. The CHT simulation model should include all necessary geometries and boundary conditions to accurately predict the temperature within the system under a specified load case.

2. *Simplification of the CHT simulation model and definition of the initial design space*

In the second step, the goal is to simplify the underling CHT simulation model to decrease the computational cost to solve it. This is achieved by omitting geometric details that have a negligible effect on the temperature distribution within the system under investigation. Besides changes in the geometry, the physical models also pose options to lessen the computational cost. For example disabling thermal radiation in cases where it has a diminishing effect on the temperature distribution within the system.

Additionally, we place a design space for the preliminary topology optimization. This design space should be relatively large to avoid restricting the optimization algorithm. The idea is to give the optimization algorithm a lot of space to work with to create an optimal design.

3. *Setting up and conducting the preliminary topology optimization*

After the design space was set up in step 2, we define the objective function and constraints for the preliminary topology optimization. The objective function should be the same in the preliminary topology optimization as well as in the following secondary topology optimization. The volume constraint V_{pre} for the preliminary topology optimization needs to be weakened compared to the total volume constraint V_{fin} to allow for an additional volume constraint in the secondary topology optimization.

After all inputs for the preliminary optimization are defined, the optimization is executed until an appropriate stopping criterion is met.

4. *Transfer of the optimization result as the design space into the detailed CHT simulation model*

In the final step of the proposed approach, the optimization result from step 3 serves as the design space for the secondary topology optimization. This secondary optimization is conducted on the detailed CHT simulation model from step 1. The inputs for the optimization problem are the same as for the preliminary optimization in step 3, except the volume constraint V_{sec}, which must be chosen such that it satisfies Eq. (1).

$$V_{pre} * V_{sec} = V_{fin} \tag{1}$$

Here, V_{fin} is the final desired volume constraint for the whole optimization process. V_{pre} and V_{sec} are the volume constraints for the preliminary and secondary optimization, respectively.

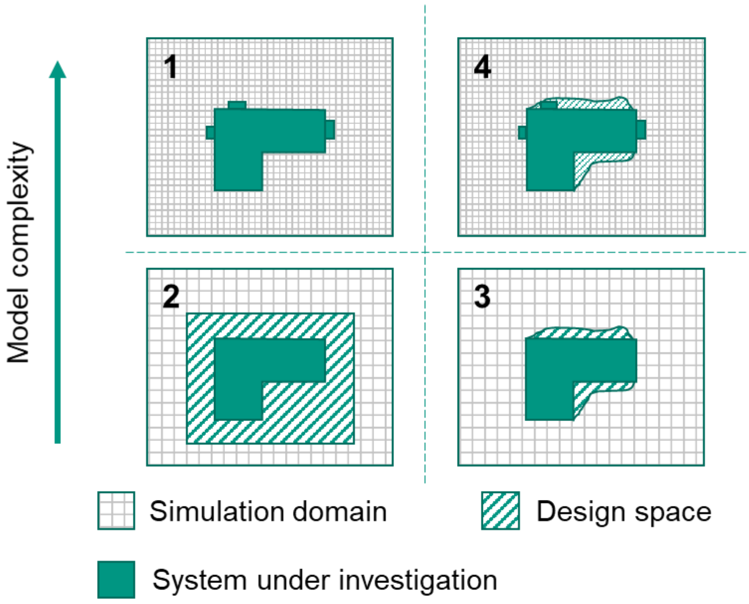

Figure 1. Graphical representation of the four steps of the proposed approach. *Note the missing geometric details in step 2 and 3. A coarser pattern of the simulation domain and design space in step 2 and 3 depict a coarser discretization.*

After completing the above-mentioned steps, a spatially reduced design space for a topology optimization on the system level is achieved. By returning to the detailed CHT simulation model in step 4, all geometric details and physical models of the underlying simulation model are considered in the secondary topology optimization.

By using this approach to reduce the extent of the design space, the computational cost to solve the optimization problem reduces as well, since the necessary fine discretization of the design space is limited to a smaller volume. This effect is stronger, the larger the problem size is. The proposed approach potentially enables the method of topology optimization to be applied to larger problems in the product development of structures for heat transfer while keeping the development cost low.

III.Application to an industrial case

A. Problem description

Within modern aircraft development, a trend towards thinner wings can be seen.[7] On the one hand, this is a result of improvements in manufacturing techniques and material research. On the other hand, this is because thinner wings result in less aerodynamic drag, which in turn increases the aircrafts efficiency. Although beneficial for the operation of the aircraft, thinner wings decrease the installation space for systems within the wings, such as hydraulic and mechanical actuators to drive the control surfaces.

Another trend in aircraft development is the so-called *more electric aircraft*.[8] This development has the goal of eliminating centralized hydraulic and/or pneumatic distribution systems, and replace them with an electrical grid, which distributes the power between involved subsystems. In places where hydraulic power is necessary, it is generated locally in a separate closed hydraulic loop. For actuators of control surfaces, this resulted in the development of an *electro hydrostatic actuator* (EHA).[9] Figure 2 shows an EHA and a conventional hydraulic actuator of the Airbus A380.

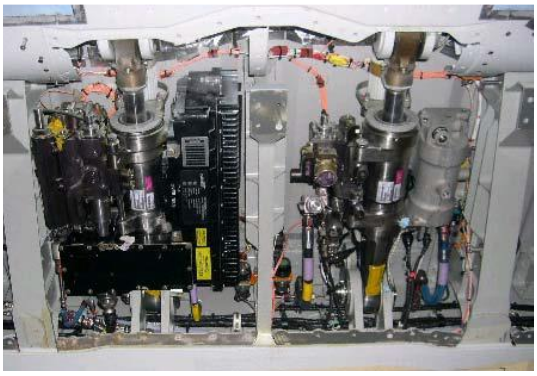

Figure 2. Airbus A380 aileron EHA (left) and conventional hydraulic actuator (right).[10] *Notice the dense packaging of the EHA due to involved additional subsystems.*

An EHA converts electrical power to hydraulic power to drive an actuator, which can then drive a control surface. It is therefore placed within the aircraft's wings. An EHA consists of a power electronic unit which drives a motor-pump unit. The generated hydraulic power is then converted into mechanical power through a cylinder and piston.

The combination of the high power density of the EHA and the reduced installation space due to thin wings results in the necessity of a thorough thermal investigation of the EHA. Since it is a highly compact system, it is not sufficient to analyze and optimize each involved subsystem individually. All subsystems are mechanically and therefore thermally coupled, which makes a thermal investigation of the whole system inevitable.

Within this research, we are investigating an industrial EHA. The developed methods however can be applied similarly to an aerospace EHA. In the following, we describe the simulation and optimization of the industrial EHA.

B. CHT simulation model

The simulation and optimization were carried out in Siemens Simcenter Star-CCM+ 2021.2.1 (16.04.12-R8). The geometry of the CHT simulation model of the industrial EHA can be seen in Figure 3. Heat enters the system through volumetric heat sources in the motor, consisting of a separate rotor and stator, and in the pumps internal volume. The heat losses were estimated through a Matlab-Simulink simulation model of the system.[11] The considered load case was a sine movement of the piston with a frequency of 1 Hz, an amplitude of 1.5 mm and a constant force of 6 kN acting on the piston. Since the timescales of the heat transfer are much larger than the movement of the piston, we neglected any movement and assumed the system to be stationary. The system gets cooled through natural convection. The simulation model was validated through test bench measurements where thermal probes were placed onto the system and compared against simulation results.

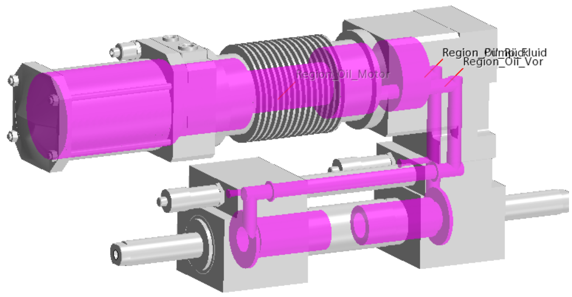

Figure 3. Geometry (grey) and internal hydraulics (pink) of the industrial EHA in the detailed CHT simulation model.

C. Optimization

The aim of this optimization was to reduce the surface temperature of the EHA. Therefore, the objective function was to minimize the average surface temperature on the EHA's outer surface. The final volume should be around 10 % of the initial design space. In the following we describe the steps taken from the proposed approach.

1. Setting up the underlying CHT simulation model

The existing simulation model of the EHA was taken as the base for the optimization. No adjustments had to be taken to use it for the optimization.

2. Simplification of the CHT simulation model and definition of the initial design space

The simulation model was drastically simplified by remodeling the geometry just by using cuboids and cylinders. The simplified geometry can be seen in Figure 4. The internal hydraulic geometry was omitted. The heat sources within the motor and the pump were kept as separate internal volumes serving as volumetric heat sources.

The initial design space for the preliminary topology optimization was placed as a box around the EHA. It encompassed the whole system with around 1.15 times the size in each direction.

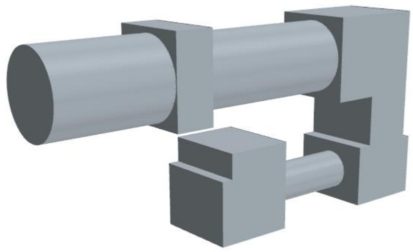

Figure 4. Simplified geometry of the industrial EHA for the preliminary topology optimization.

3. Setting up and conducting the preliminary topology optimization

The objective function was adapted to ensure the average temperature was calculated on the surface of the simplified geometry. The volume constraint was defined as $0.45 < V_{pre} < 0.55$ to enable a further volume reduction in the secondary optimization. We ran the optimization for 100 iterations, which turned out to yield a converging optimization result.

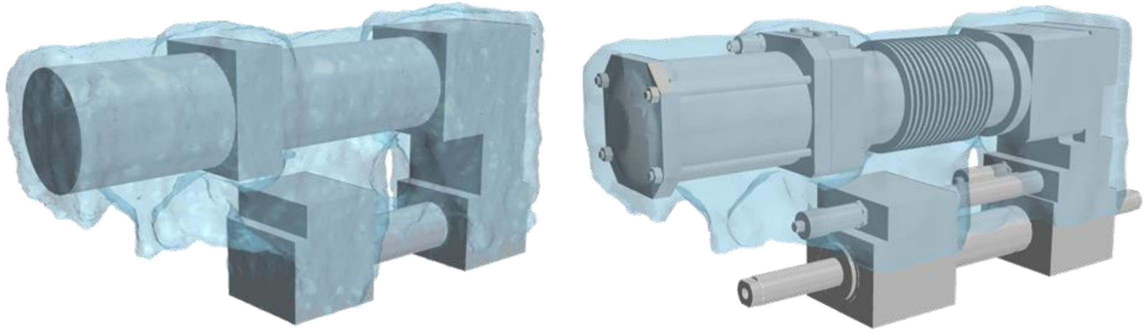

Figure 5. Optimization result of the preliminary optimization (left) and remeshed optimization result transferred to the detailed simulation model (right).

4. *Transfer of the optimization result as the design space into the detailed CHT simulation model*

We extracted the optimization result as the isosurface of the material indicator at a value of 0.5, which corresponds to a value of the level-set function of zero. The optimization result can be seen in Figure 5 on the left. It is visible, that the optimization algorithm created a new thermal bridge between the motor and pump housing on the upper half of the EHA and the cylinder and piston on the lower half. This helps distributing the heat within the system.

We remeshed the exported isosurface in an external software to smoothen it and to get rid of sharp angles that would cause problems during meshing of the design space in the secondary optimization. During this step, we also got rid of small artifacts at the bottom of the EHA that also posed problems during meshing of the secondary design space.

After conducting these four steps, we had a design space for a topology optimization on our initial detailed CHT simulation model, which we could then use to conduct the secondary topology optimization.

D. Results

The secondary optimization was carried out with the same boundary conditions and objective function as the preliminary optimization. The only difference was the adjusted design space, resulting from the preliminary optimization and the increased level of geometric detail. The volume constraint was defined as $0.2 < V_{sec} < 0.25$ resulting in a final volume constraint of $0.09 < V_{fin} < 0.1375$ with respect to the original cubical design space.

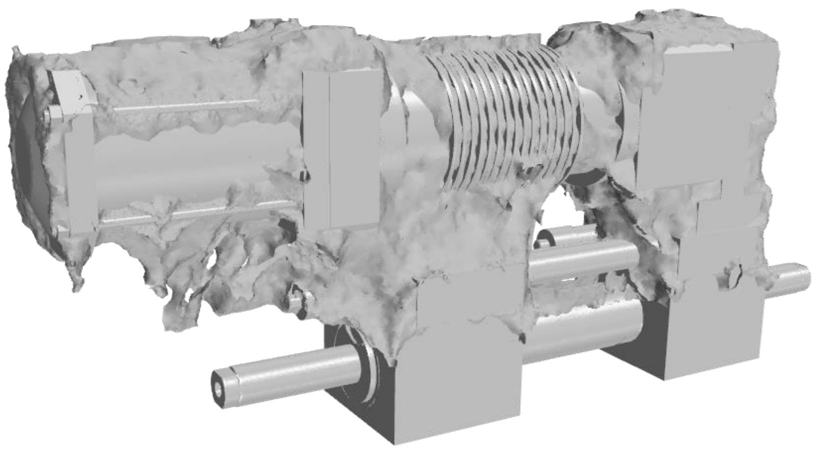

Figure 6. Final geometry of the optimization after both the preliminary and the secondary optimization are carried out.

The final resulting geometry after both steps of the proposed approach can be seen in Figure 6. It is clearly visible, that the shape is similar to the one obtained from the preliminary optimization. Design features such as the thermal bridge between the motor housing on the top and the cylinder and piston on the bottom are maintained between the preliminary and secondary optimization. However, a lot of the additional material that was placed in the preliminary optimization around the hot components got removed. Some vertical extensions above the cylindrical parts are still present, presumably to reduce recirculation regions resulting from the free convection.

One would expect to see some kind of fins or ribs protruding from the EHAs surface. However, these features are not present in our optimization result. The reason for this could be an error in the optimization problem formulation or deficiencies in the mesh.

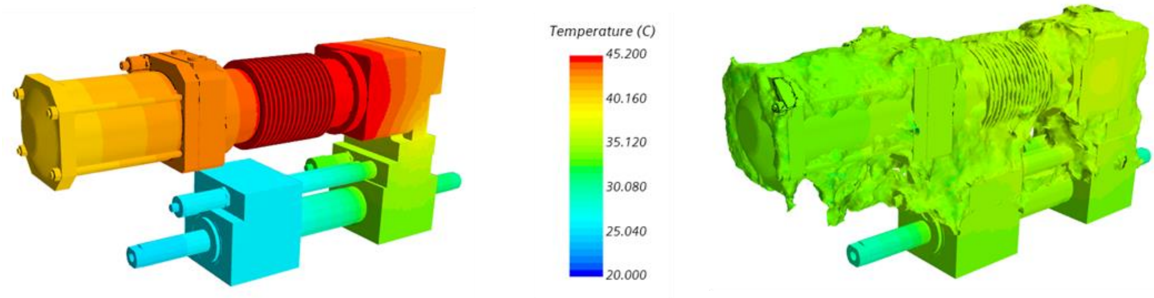

Figure 7. Final geometry of the optimization after both the preliminary and the secondary optimization are carried out.

Figure 7 shows a comparison between the temperature distribution throughout the system of the original non-optimized geometry and the geometry resulting from the presented approach. Immediately visible is the more homogenous distribution of temperature on the surface of the optimized geometry. The average surface temperature was lowered by 3.4 K.

Comparing our optimization with a regular optimization where the original cubical design space is used, we reduced the cell count within the design space by 36%. This is obviously counterbalanced by the increased cell count outside of the design space. Since we can employ a coarser discretization outside of the design space, the overall cell count can still be reduced. In our case, this reduction of the whole simulation's cell count was 8%. The effectiveness of implementing the presented approach increases with the problem size, as well as the inverse of the cell size in the design space. When using a very fine discretization for the design space, small reductions in the extent of the design space already lead to a relatively high reduction in the cell count.

IV.Conclusion and Outlook

By using two chained optimizations with different levels of detail, we can systematically reduce the extent of the design space in TO for heat transfer problems. This on the one hand helps in choosing a suitable design space and on the other hand can potentially reduce the computational cost when applied to large scale problems.

Even though the resulting geometry shows a decrease in the average surface temperature, which satisfies the optimization objective, the lack of fin-like structures in the resulting geometry calls for adjustments in the optimization setup. Further investigation into the formulation of the optimization problem is necessary to ensure a fully optimized geometry. This includes, but is not limited to, the objective function, boundary conditions and meshing parameters. Furthermore, a complete automatization of the whole process is desirable. Without the need of manually exporting the isosurface, remeshing and repairing it and reimporting it back into the detailed simulation model, the method of topology optimization gets more attractive to use for product developers.

In future works we want to apply the proposed approach to the design of different products where thermal effects are relevant. Especially in early phases of product development where the geometric shape is not yet fully specified, topology optimization can generate initial design proposals. These design proposals can then serve as a foundation or a guideline for shaping the product's geometry.

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