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Stress-based Topology Optimization of Thermal Structures

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Abstract

In the design of modern day thermal structures, scenarios are often encountered in which thermal expansion due to an elevated temperature environment cannot be accommodated to reduce or prevent damaging thermal stresses. This is especially true for aerospace applications including engine exhaust-washed structures for low observable aircraft and integrated thermal protection panels for hypersonic vehicles. In these cases, the need for specific platform-level capabilities overrules conventional structural design practices. This presents a challenging design scenario whereby the trade-space between the need for structural stiffening material to maintain acceptable stress levels must be balanced with the additional thermal load created by that material. This occurs due to the fundamental design dependency of the loading that results due to restrained thermal expansion of structural components. In fact, past research has demonstrated that due to this design dependency improper material placement that was originally meant to decrease stresses may actually result in an increase in stresses and potentially damaging increases in loading transferred to surrounding structures.

Recent studies have indicated that structural topology optimization may be a suitable tool for design of these thermal structures due to its unique ability to determine optimal material orientation based on a given set of geometric and loading conditions. However, the basic minimum compliance, mass constrained topology optimization problem is questionable for this application due to numerical difficulties that arise from the participation of a design dependent load, including gravity, pressure, or thermal effects, in the compliance objective. In addition, a minimum compliance structure is generally a maximum stiffness structure, which is typically undesirable in a thermal environment. Thus we seek a solution that more directly addresses the stresses generated in the structural domain and propose the direct inclusion of stress-based criteria in the topology optimization problem with thermal loads.

To date a stress-based topology optimization methodology has been developed and demonstrated on mechanically loaded structures. The framework is capable of both (i) minimum stress, mass constrained and (ii) minimum mass, stress constrained topology optimization. It is based on the use of aggregation functions for stress, to reduce the computational burden of sensitivity analysis, and block-aggregation, to retain sufficient local control in the aggregated stress constraints. In addition, an interpolation scheme is utilized to relax the stress values obtained at intermediate material densities. Prior work also includes extensive investigation into the performance of the general minimum compliance problem and other alternatives and provides the impetus for investigation of stress criteria.

In this work we will present the application of the framework and underlying stress-based design criteria to topology optimization problems containing mechanical loads, thermal loads, and combinations of both. To the authors' best knowledge, this has yet to be demonstrated in the literature. The paper will highlight the application technique and challenges for stress-based topology optimization with design dependent thermal loads. Discussion will also include the merits and drawbacks of this problem formulation compared to more common compliance or energy-based topology optimization for this class of problems.