

Topology Optimization of Missile and Aviation Components for AM Fabrication

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Abstract: *Components within missile systems are vulnerable to performance degradation as a result of heat and vibrations generated by neighboring components. Conventional methods to alleviate this degradation include installing passive vibration-damping materials, adding material to shift resonance frequencies and adding heat sinks to removed unwanted heat. All of these approaches add parasitic weight to the system. Topology optimization methods are well established analysis tools that are used to determine an optimal material distribution of a design space, subject to a performance constraint, for a given set of loads and boundary conditions; making them ideal for tailoring the thermal and frequency response of missile components and associated structures without adding parasitic weight. Generally, topology optimization results in complex geometries that have been difficult to realize with conventional manufacturing methods. However, given the recent advances in additive manufacturing (AM) technologies, the full potential of topology optimization as a design tool can be realized. Materials Sciences Corporation (MSC) and the U.S. Army Aviation & Missile Research Development & Engineering Center (AMRDEC) have focused on linking ABAQUS and TOSCA with in-house codes to develop a design, fabrication and verification process that enables additive manufacturing of components generated using multi-physics topology optimization techniques. MSC will present several examples of optimized designs for missile and aviation applications that were developed using the multi-physics topology optimization capabilities, i.e., statically determined stress, frequency, temperature, etc., within TOSCA.*

Keywords: *Topology Optimization, Additive Manufacturing, Multiphysics, Thermal Management*

1. Introduction

Additive manufacturing (AM), or more commonly termed “3-D printing”, offers the potential to fabricate complex geometries that cannot be realized using conventional subtractive methods. To take advantage of the full potential of AM for structural applications, the U.S. Army Aviation and Missile Research, Engineering and Design Center (AMRDEC) and Materials Sciences Corporation (MSC) have identified topology optimization (TO) methods as a promising design tool. Topology optimized AM structures have the ability to eliminate traditional inverse material property relationships to produce a lightweight, high strength/stiffness, and multifunctional e.g., damage tolerance, thermal, and electrical performance. The AMRDEC/MSC team is currently

investigating multi-physics TO tools for the developing mounts and chassis for equipment housed in aviation and missile systems. As part of this effort the AMRDEC/MSD team evaluated the use of the sequential couple thermo-mechanical optimization capability in Tosca on an example problem that is representative of an equipment chassis relevant to missile and aviation applications. The objective was to develop a concept that integrates heat sinks and equipment mounts in a single AM structure with minimal attachment points to the housing structure.

2. Optimization Workflow and Implementation

The present iterative optimization design process scheme is based upon the density topology optimization approach “[Bendsøe, 2003]”, see Figure 2-1. For each automate design iteration the CAE modeling “[Abaqus]” determines the design responses of the model by solving the equilibriums of the various modeling disciplines. The implementation “[Abaqus, TOSCA]” then calculates the adjoint sensitivities with respect to the design variables for the design responses “[Tortorelli, 1994][Van Keulen,2005]” of the various modeling disciplines. A design response defines a response of the current analysis model for a given optimization iteration. Thereby, a design response extracts one scalar value which can be a direct measure from the CAE model (e.g., mass, center of gravity, etc.) or is determined by the results of the primal solutions for the equilibriums of the model (e.g. stiffness, stresses, nodal displacements, nodal reaction forces, modal eigenfrequencies, nodal temperatures, nodal thermal fluxes etc.). The design responses are then applied for defining an optimization problem consisting of constraints which have to be fulfilled and an objective function which is either minimized or maximized according to the choice of the user. Alternatively, a so-called bound formulation can also be applied as objective which for example can be used for maximizing the gaps between adjacent natural modal eigenfrequencies. The optimization problem is solved using mathematical programming. The mathematical programming is strictly based upon the values of the user defined design targets and the sensitivities of the design responses.

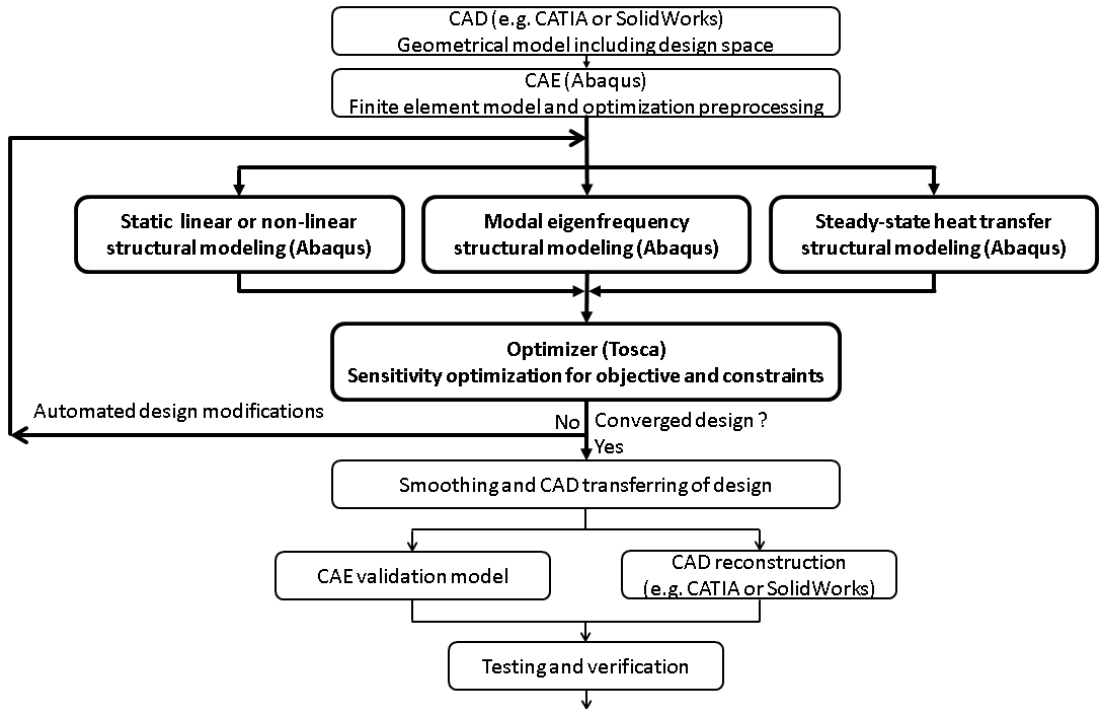


Figure 2-1. Workflow of Topological Design using Dassault Systèmes Software Solutions.

The topology optimization for static structural has the constitutive modeling as design variable whereas the modal eigenfrequency has the constitutive modeling and physical density as design variable for determining the optimized structural layout. The topology optimization for the steady-state heat transfer modeling has the conductive and the convection as design variables. The convection is modified during the optimization iterations since the surface is changing when topology is redesigned [Mingdong,2016].

Note, that design requirements are single analyzing discipliners (no coupled analysis between structural and thermal is supported) but the optimization will be multi-physics as both structural, modal eigenfrequencies and thermal design responses are simultaneously being considered in the optimization, see Figure 2-1. However, an often applied workflow is to apply a temperature field and loading in the structural static modeling causing a deformation due to the thermal expansion. Then again, the temperature field for the structural static modeling has to be design independent and thereby, the same in each optimization iteration.

3. Concept Development

The multi-physics topology optimization capability in Tosca for ABAQUS was utilized to develop a preliminary design for an AM chassis. The analysis model used for optimization consists of the chassis and a composite housing. This model was used to develop two separate analysis steps, consisting of heat transfer and linear, static analyses, cf. Figure 3-1. For the heat transfer analysis, a film coefficient was applied to the outer surfaces of the housing and the lid that is representative of a free convective surface. With the exception of the lower surface where the housing interfaces with the airframe; a film coefficient representative of a conductive interface was applied to this surface. At the internal surfaces where electronics components are mounted a heat flux is applied. A perfectly conducting interface is assumed between the chassis and housing.

For the static analysis, the housing is fixed at the surface that corresponds to the interface with the airframe. This portion of the analysis contains 6 sub-steps that correspond to static g-loads in the positive and negative directions of the principal axes of the model, i.e., X, Y, and Z; Figure 3-1 shows the +Y load case. The static g-loads are an idealization of the dynamic loading requirement that chassis must meet. It must be noted that a static g-load approximation of a dynamic impact event is not ideal. It can be shown [Scavuzzo, 2007], that even for a simple structure; analysis using static g-load can be misleading and result in the design of a structure that may decrease structural integrity. However, to the best of MSC's knowledge there are no commercially available optimization tools that are capable of meaningfully conducting topology optimization based on a dynamic simulation using an explicit FE solver. The interface between the chassis and housing is modeled using a tied constraint; this enables the optimization to remove material as necessary such that it should determine optimal attachment locations for chassis rigidity.

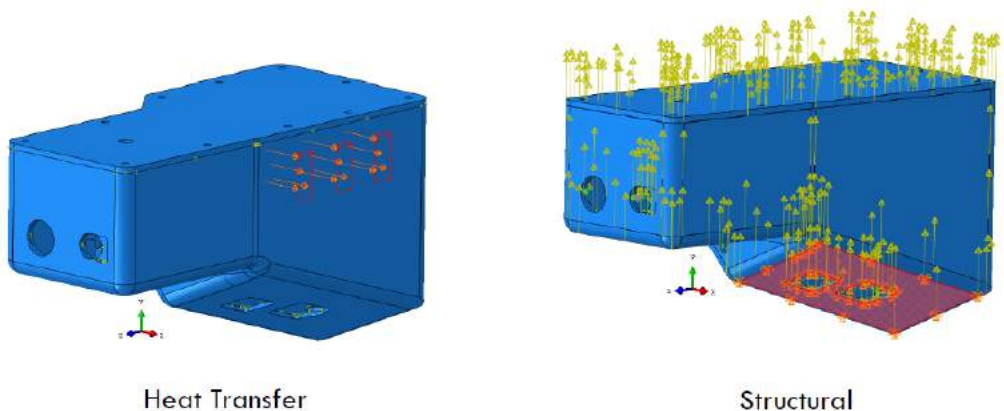


Figure 3-1. Schematic of the Loads and Boundary Conditions for Preliminary Multi-Physics Optimization.

A topology optimization analysis was performed to maximize the stiffness of the chassis under the constraints of an 80% reduction in the design space weight and that the temperature on nodes at corners of regions that are representative of the electronics components are less than their maximum operational temperature, cf. Figure 3-1. An 80% volume reduction was used to ensure a

meaningful material distribution could be obtained. It must be noted that regions of the design space required to mount the components housed within the chassis were frozen, viz., could not be removed by the optimization. This mesh resolution was selected based on several analysis iterations on a modern Linux workstation. Analyses with higher resolution meshes required runtimes that were not practical for design purposes, e.g., days. However, with the current mesh resolution imposing a higher volume reduction would not result in a meaningful distribution of material for concept development. Nevertheless, the current result, cf. Figure 3-2, is indicative of the complexity that is anticipated in future iterations and was pursued to establish the feasibility of fabrication in parallel with the pursuit of higher resolution optimizations. Using the optimized material distribution as a suggested design a concept was developed, cf. Figure 3-3. A significant amount of time was required to convert the mesh based optimization result into a conventional CAD representation. However, this is insignificant compared to reduction in time the TO based design process offers compared to conventional, iterative design processes. Although the optimized design by definition meets design requirements, and the volume constraint was selected in part to provide a concept that is equivalent in weight to the multiple conventionally machined brackets currently used to mount equipment, a single component chassis should provided increased system rigidity and reduce the number of mounting points in the housing.

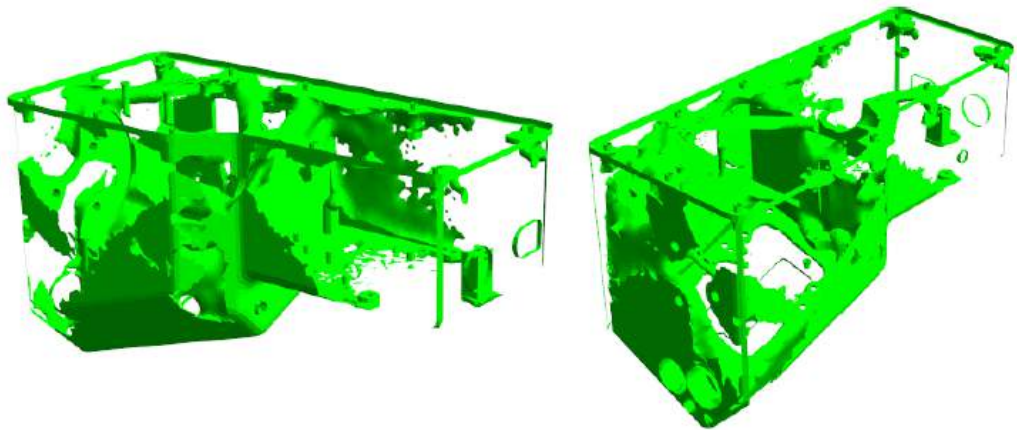


Figure 3-2. Preliminary Optimized Material Distribution.

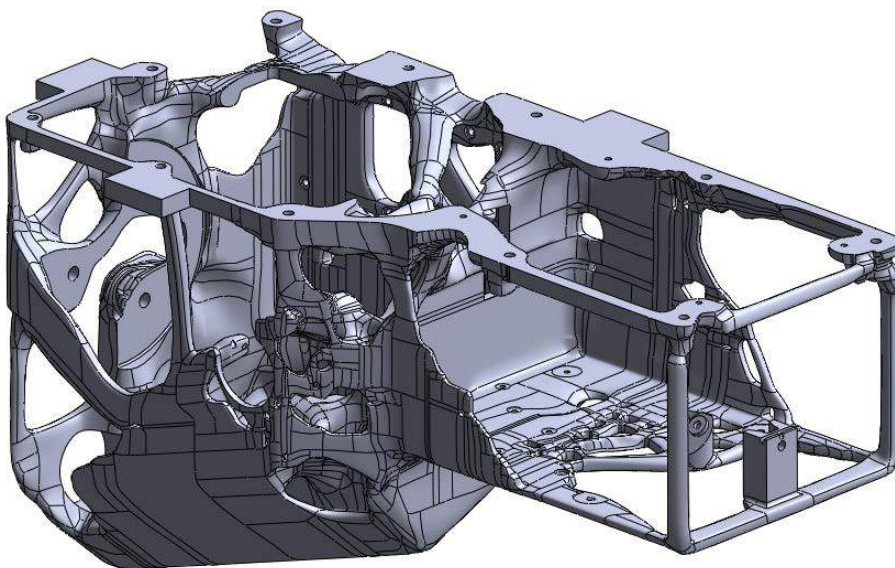


Figure 3-3. Preliminary FTL Chassis Concept for Casting.

4. AM Fabrication Trail

Given the size of the chassis concept, MSC is pursuing an AM enabled casting method of fabrication, cf. Figure 4-1. It is believed that the technical maturity of this fabrication technique will enable MSC to rely on the knowledge base of industry experts to mitigate fabrication issues. Additionally, initial data indicates the potential for a significant reduction in cost per unit for this method of fabrication relative to direct build AM methods, e.g., DMLS and EBM. Pursuant to this objective, the AMRDEC/MSR has engaged the Metal Casting Center and the Additive Manufacturing Center at University of Northern Iowa in conjunction with Eck Industries, Inc for preliminary fabrication of FTL Chassis concepts. At the time of this manuscript fabrication trials are still being conducted; an example of a casting trial is shown in Figure 4-2.

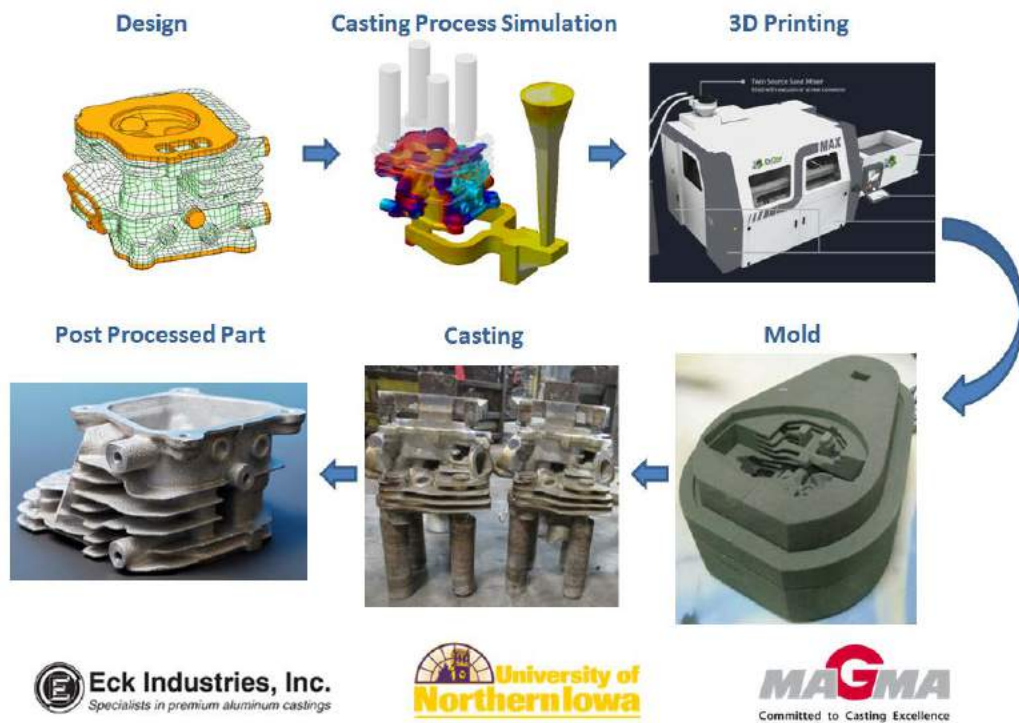


Figure 4-1. AM Enabled Casting Process.

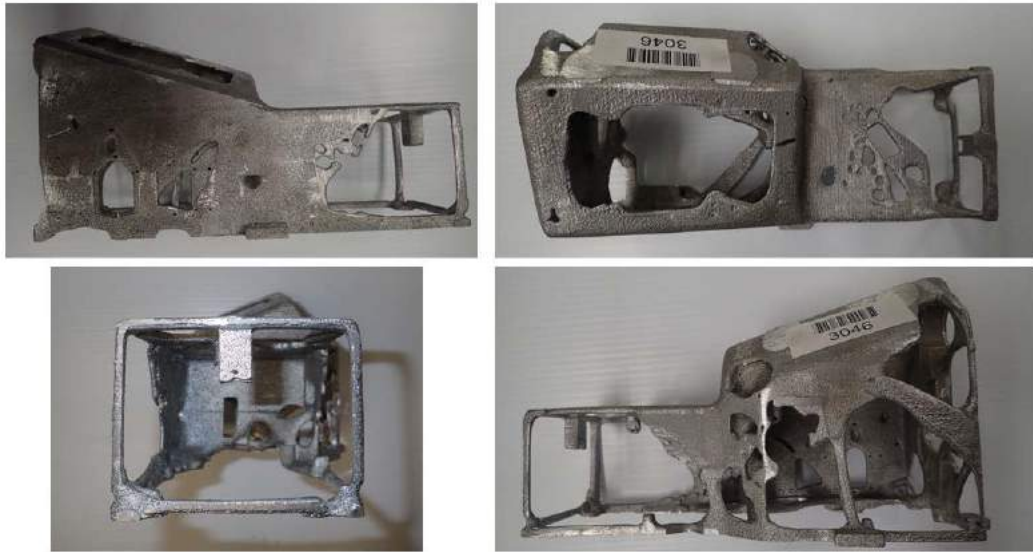


Figure 4-2. AM Enabled Casting Trial Part.

5. Remarks

This section lists a summary of the findings and recommendations as a result of the research detailed in this manuscript:

- The MSC/AMRDEC team has demonstrated that the multi-physics optimization capability in Tosca can be used to determine optimal material distributions for structures with thermo-mechanical loads.
- AM enabled casting is believed to be a technically mature fabrication technique that will enable MSC/AMRDEC to rely on the knowledge base of industry experts to mitigate fabrication issues. Additionally, initial data indicates the potential for a significant reduction in cost per unit for this method of fabrication relative to direct build AM methods, e.g., DMLS and EBM.
- Approximating dynamic impact events with static g loads can result in stress distributions that are not accurate for design purposes. A topology optimization tool that is capable of meaningfully conducting an optimization based on a dynamic simulation using an explicit FE solver is needed.
- Topology optimization models with a large design domain and a high weight reduction constraint are limited by practical mesh resolutions for typical workstations. Adaptive meshing techniques and/or topology optimization tools designed for parallel computing are needed.

- Geometry refinement, viz., conversion of geometry from design, i.e., CAD, to an analysis, i.e., mesh, based representation, is the limiting factor in the utility and efficiency of topology optimization based design methodologies. Although significant progress has been made to integrate and improve reconstruction tools, analysis tools that work with a native CAD representation of the geometry are desired to eliminate the refinement step from the design process.

6. References

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