A Topology Optimization Approach Considering Design for Additive Manufacturing

John Olsen, Graeme Sabiston and Il Yong Kim*

Department of Mechanical and Materials Engineering, Queen's University, Canada
E-mail: kimiy@queensu.ca

Abstract

As the aerospace industry continues to grow, it is imperative to reduce the environmental impact of all aircraft. Decreasing structural mass using design optimization methods can lead to improved fuel efficiency and a smaller environmental footprint. Topology optimization, a technique which determines the optimal layout of material in a given design space, has been identified as a leading design optimization tool. Integration of topology optimization into the mainstream design process, within the aerospace industry, has been hindered most notably by manufacturability. Additive manufacturing (AM) has significantly more design freedom than traditional manufacturing methods, providing opportunity for topology optimization implementation and further advancement into industry. Although, additive manufacturing provides more design freedom, there are a new set of design challenges, such as time and cost, and the presence of void regions. The most prominent factors associated with time and cost are support volume of the part. Complications arising from void regions within the part may include; inability to remove build material powder in powder bed fusion AM techniques and limited tool access for post-processing operations to remove support material. This paper presents an advanced DfAM (Design for Additive Manufacturing) method that minimizes cost and time associated with AM, while also restricting void regions. The methodology has been efficiently integrated into a three-dimensional framework, based on advanced topology optimization algorithms. The result is a robust design tool, producing designs free of void regions, that allows the user to vary optimization parameters based on the desired structural performance and the post-processing method used to clear support material. A three-dimensional DfAM problem, that inherently has void regions, is explored revealing the trade-off between important design parameters, as well as showing the effectiveness of the proposed methodology.

Keywords –
DfAM, topology optimization, additive manufacturing, void region, density gradient, PDVR

1 Introduction

Topology optimization (TO) is a mathematical framework that has the ability to determine the optimal layout of material in a given design space. In traditional TO, the objective function is formulated to minimize compliance (a measure of strain energy) subject to a volume fraction constraint. The results are light weight and high-performance designs, but the geometry tends to be difficult or expensive to manufacture. Recently, significant research has been aimed at integrating TO and additive manufacturing (AM), due to the significant increase in design freedom of AM versus traditional manufacturing methods.

The layer-wise nature of material deposition in AM allows for less constraints overall, but also presents a new set of design challenges, such as the requirement of support material. Support material is needed wherever an overhang angle in the part is above a threshold value – typically set at 45^o. The support material is a sacrificial structure that is removed after part completion and can significantly contribute to material cost and manufacturing time. Another challenge encountered in AM is having accessibility to remove support structures and any un-melted powder granules that may be enclosed in the manufacturing process. Both unwanted design features addressed above, are seen in Figure 1.

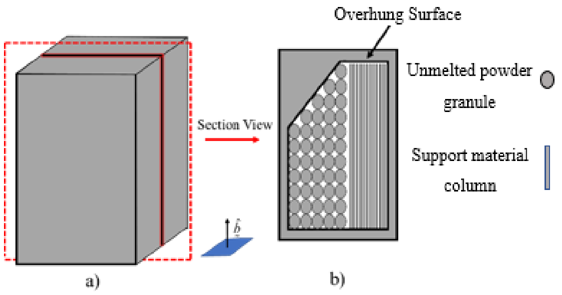


Figure 1: Hollow rectangular prism. (a) Iso-metric view, build vector shown in bottom right corner. (b) Section view of (a).

2 Methodology

2.1 Support Volume Calculation

A Helmholtz PDE filtering operation is used to filter the element densities [1]. As a result, the spatial gradient information is readily available, which allows the surface area of the part to be defined. A Heaviside projection scheme is then used to identify all supported surfaces. Finally, the support volume is calculated by integrating between the supported surfaces and either the build plate, or a supporting surface – part of the structure itself.

2.2 Particle Diffusion Void Restriction (PDVR)

The algorithm for void restriction is based off the PDVR methodology developed by Sabiston and Kim [2]. Particles are initialized within the design domain and are released at multiple different diffusion angles, corresponding with the principle axis. The time that it takes the particle to reach the boundary of the domain is recorded, with particles taking a longer time to travel through elements with higher density than elements with lower density. If the total summed diffusion time is above a specified diffusion time constraint, then the elements with higher diffusion time and low density are penalized to have solid density.

3 Numerical Results

A 3D torsional beam load case (Figure 2) was selected to convey the effectiveness of the methodology. All examples are solved with a 51x31x31 element mesh and a 30% volume fraction.

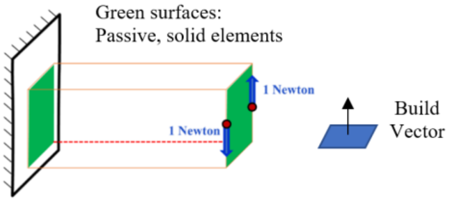
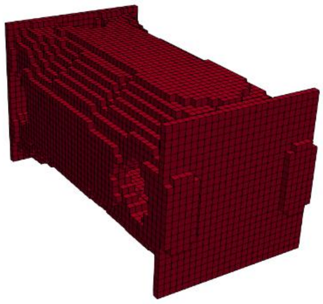


Figure 2: 3D Torsional beam load case.

To resist the loading in pure compliance minimization, all available material is pushed to the outward limits of the design domain, resulting in the formation of a void region in the interior of the part. The resulting topology is shown in Figure 3.

(a) Isometric view



(b) Sectioned-isometric view

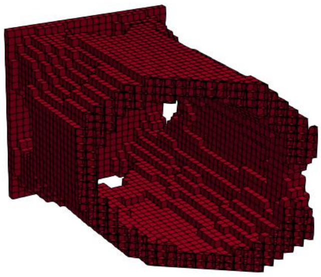
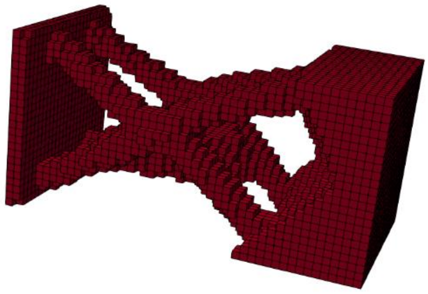


Fig 3. Compliance minimization. (a) Isometric view of projected topology. (b) Cut-away view of (a)

With the addition of the diffusion time constraint, the material is distributed in a truss-like structure as seen in Figure 4.

(a) Isometric view



(b) Sectioned-isometric view

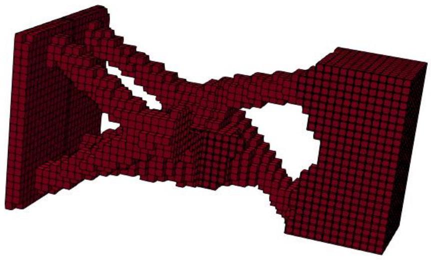
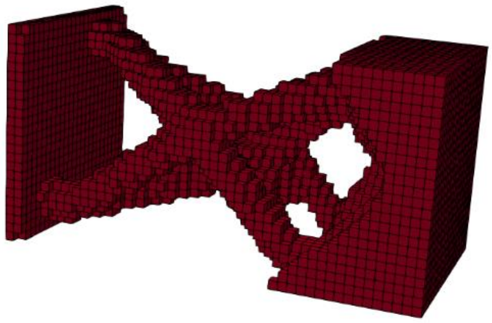


Fig 4. Optimal design with diffusion time constraint. (a) Isometric density view. (b) Cut-away view of (a).

All areas of the part are accessible for support structure and excess build powder removal; however an appreciable amount of support material is still required to manufacture the part. Figure 5 shows the resulting topology when the volume of the support structure is minimized, while still adhering to the diffusion time constraint.

(c) Isometric view



(d) Sectioned-isometric view

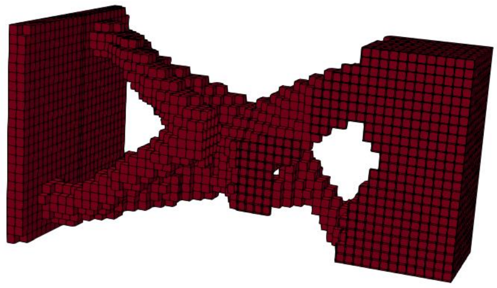


Fig 5. Optimal design with diffusion time constraint and support volume minimization. (a) Isometric density view. (b) Cut-away view of (a).

A similar truss structure is admitted, but with only two attachment points onto the support wall (left), versus four in Figure 4. For this case, the decrease in cross members results in a decrease in support volume. Table 1 depicts the tradeoffs in performance between pure compliance minimization, the inclusion of the void restriction constraint, and the former with the addition of support volume minimization.

Table 1: Performance summary.

Optimization	**Rel. Compliance**	**Rel. Support Volume**
Compliance Min	**1.00**	**2.12**
Compliance Min **+ Void Restriction**	**1.86**	**1.14**
Compliance Min **+ Void Restriction** **+ Min Support Volume**	**1.91**	**1.00**

As expected, an increase in design constraints results in a greater compliance. With the addition of support volume minimization, the amount of support volume decreased, while restricting void formation.

4 Conclusion

The numerical results show promise in two key areas of DfAM; cost and void region restriction. Although a large increase in compliance was reported in the academic test problem, the methodology admitted a manufacturable result from an otherwise infeasible design. Future parameter tuning and parallel solving techniques, to analyze a higher resolution mesh, will likely improve the optimality of the results.

References

[1] B. S. Lazarov and O. Sigmund, “Filters in Topology Optimization Based on Helmholtz-Type Differential Equations,” *Int. J. Numer. Methods Eng.*, 86(6), p. 765–781., 2011.

[2] G. Sabiston and I. Y. Kim, “Void Region Restriction for Additive Manufacturing via Diffusion Physics Approach,” 2019.