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Research paper

Smooth geometry extraction from SIMP topology optimization: Signed distance function approach with volume preservation

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ABSTRACT

This paper presents a novel post-processing methodology for extracting high-quality geometries from density-based topology optimization results. Current post-processing approaches often struggle to simultaneously achieve smooth boundaries, preserve volume fraction, and maintain topological features. We propose a robust method based on a signed distance function (SDF) that addresses these challenges through a two-stage process: first, an SDF representation of density isocontours is constructed, which is followed by geometry refinement using radial basis functions (RBFs). The method generates smooth boundary representations that appear to originate from much finer discretization, while maintaining the computational efficiency of coarse mesh optimization. Our approach can reduce maximum equivalent stress values compared to conventional methods. This reduction is achieved through continuous geometric transitions at boundaries. The resulting implicit boundary representation facilitates seamless export to standard manufacturing formats without intermediate reconstruction steps, providing a robust foundation for practical engineering applications where high-quality geometric representations are essential.

1. Introduction

With the increasing availability of additive manufacturing and other modern manufacturing methods, topology optimization (TO) has become an invaluable tool for structural design, enabling engineers to discover novel geometries. This approach to computational design determines the optimal material distribution within a design space to achieve specified performance objectives while satisfying given constraints [1,2]. The field has rapidly evolved from academic research into practical engineering applications across aerospace [3], automotive [4], and biomedical industries [5]. Among various TO methods, density-based approaches like the Solid Isotropic Material with Penalization (SIMP) method have become predominant due to their mathematical simplicity and robust convergence properties [6,7]. Simultaneously, boundary-based approaches such as parameterized level set methods have gained attention for their ability to maintain sharp boundaries throughout the optimization process and handle complex geometric evolution [8–10], though they present computational challenges such as slower convergence and sensitivity to initial design [11]. Consequently, density-based approaches remain the industry standard due to their computational efficiency and robust implementation. Still, the density based methods exhibit two significant limitations: jagged boundaries due to the underlying finite element discretization and regions of intermediate density values that do not represent physically meaningful material states [11,12].

These limitations present significant challenges in translating optimized designs into practical applications. Consequently, the development of effective post-processing methods has become a critical area of research [12]. Several key factors must be considered in the development of such methods:

1. **Geometric fidelity**: The post-processed geometry must preserve the fundamental structural features and topological characteristics of the optimized solution while eliminating artificial artifacts.
2. **Volume preservation**: The specified material volume fraction from the original optimization must be maintained to ensure design feasibility and performance requirements remain satisfied.

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