

EFFICIENT ROBUST TOPOLOGY OPTIMIZATION FOR LARGE-SCALE 3D STRUCTURES

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Abstract

Robust topology optimization has been widely adopted to mitigate the sensitivity of optimized designs to manufacturing variations, modeling errors, and other sources of uncertainty. However, extending robust formulations to large-scale three-dimensional problems remains challenging due to the substantial computational cost associated with uncertainty modeling. Classical robust approaches typically rely on multiple deterministic analyses corresponding to geometric perturbations or adopt probabilistic formulations such as Monte Carlo methods. While the former evaluates only a small number of deterministic perturbations, the latter provides a more comprehensive description of uncertainty effects but requires repeated analyses over many stochastic realizations, which can become prohibitive for large-scale 3D systems. In this work, we propose a computational framework for robust topology optimization aimed at large-scale three-dimensional problems, achieved through improvements in both the robustness formulation and the solving strategy. First, a robust optimization formulation is developed within a standard robust design framework based on Monte Carlo sampling, incorporating stochastic gradient techniques to significantly reduce the computational burden associated with uncertainty evaluation. Second, an efficient solution strategy based on a highly optimized matrix-free geometric multigrid conjugate gradient (mfGMGCG) solver is proposed. The solver is combined with a parallel task scheduling strategy that efficiently distributes multiple perturbed systems arising in robust topology optimization across available CPU cores, enabling efficient utilization of modern multi-core computing resources over a wide range of problem scales. The proposed approach is demonstrated on several large-scale problems, including compliance minimization and compliant mechanism design. The results show that the framework enables robust design of complex 3D structures while maintaining competitive computational performance.