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Frame Field Guided Topological Improvement for Hex Mesh using Sheet Operations

Rui Wang, Shuming Gao*, Zhihao Zheng, Jinming Chen

State Key Lab of CAD&CG, Zhejiang University, Hangzhou 310058, PR China

Abstract

High-quality hex meshes are crucial for finite element analysis. However, the quality of a hex mesh improved by geometric smoothing cannot guarantee to satisfy the requirement of finite element analysis. To this end, this paper puts forward an approach to topological optimization of hex mesh based on frame field and sheet operations, which improves the quality of the worst elements of the hex mesh by optimizing its topological structure. The approach first builds an initial frame field on the input hex mesh and optimizes it to obtain a high-quality frame field. Then, the problematic sheet that leads to the poor quality of the hex mesh is determined according to the initial and optimized frame fields. Finally, the structure of the problematic sheet is adjusted based on the high-quality frame field and sheet operations. Experimental results demonstrate that our topological optimization approach can effectively improve the minimal Scaled Jacobian value of the hex mesh.

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Keywords: hex mesh; mesh optimization; topological optimization; frame field; sheet operations.

1. Introduction

In finite element analysis, the quality of a hex mesh directly determines the precision and efficiency of simulation [1]. A poor quality element, such as a element with minimal Scaled Jacobian value less than 0.2, could make the mesh unusable for simulation. However, high-quality hex meshing is still an open problem, and mesh editing can easily lead to a degradation of the mesh quality, so to adequately support the subsequent numerical analysis, mesh optimization becomes essential.

Hex mesh improvement algorithms can be classified into two categories: geometric smoothing and topological optimization. Geometric smoothing [2], the most popular hex mesh improvement method, improves the overall quality of the hex mesh by optimizing the locations of mesh nodes. However, since geometric smoothing cannot change the topological connections between mesh nodes, the qualities of some hex meshes improved by geometric smoothing do not satisfy the analysis requirement.

* Corresponding author. Tel.: +86 571 88206681 ; fax: +86 571 88206680.
E-mail address: smgao@cad.zju.edu.cn

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Unlike geometric smoothing, topological optimization allows to change the connections of mesh nodes during the optimization process, which can further improve the mesh quality after geometric smoothing. However, due to the global layered structure of hex mesh, efficient topological optimization of hex mesh becomes very difficult. Moreover, to date there are only several related works about hex mesh topological optimization [3,8–14].

In theory, there are three types of hex mesh topological modification operations [3]: flipping operation, atomic operation and sheet operation. Similar to the well-known flipping operations in tet meshes, Bern et al. [4] presented flipping operations for hex mesh, which translated several hexahedra into other hexahedra with the same boundary via several proposed patterns, and realized the localization of hex mesh modification. Tautges et al. [5] put forward a set of atomic operations that are irreducible by considering the mesh face as the object. Since the global structure of the hex mesh is not taken into account, these two kinds of topological modification operations are difficult to be applied to improve the mesh quality of hex mesh, so they are rarely used in hex mesh optimization. Sheet operations [6] regard the layered structure of a hex mesh (which is called sheet, or Spatial Twist Continuum [7]) as an operand. These operations change the topology of the hex mesh by the insertion and extraction of sheets, as well as adjusting the extension direction of sheets, and they are considered as the straightforward topological modification operation.

Sheet operation based hex mesh topological optimization can be divided into two categories, according to different optimization objectives: density optimization [8–10] and valence optimization [11–14]. The density optimization of hex mesh is carried out by means of adding or deleting elements to ensure the element densities are in line with requirements of the density function. Woodbury et al. [8] extracted the sheets locally by adding supplementary sheets to be able to coarsen the local region. Harris et al. [9] presented corresponding refinement templates for single and double sheet insertions, which could freely control the direction and region of mesh refinement. For the problem of uneven density of hex mesh after mesh editing, Zhu et al. [10] proposed the sheet operation based coarsening and refinement strategies to optimize the density of hex mesh. In addition, sheet operations can also be applied to optimize the valences of mesh edges to improve the mesh quality. Mitchell et al. [11] eliminated the doublet elements of hex mesh through Pillowing operation. Shepherd [12] and Qian et al. [13] used the Pillowing operation on the whole boundary of hex mesh generated by grid-based method to improve the mesh quality of the boundary elements. Ledoux et al. [14] converted a hex mesh into fundamental mesh by sheet operations, which improved not only the quality of boundary elements, but also the mesh elements associated to geometric surfaces or curves. On the whole, existing topological optimization algorithms can improve the mesh quality of hex mesh to different extents, but there lacks a targeted approach to improving the quality of the worst elements of the hex mesh.

Considering that the mesh elements with worst quality are the main reason for not being able to use the hex mesh for simulation, in this paper we present an approach of frame field guided topological improvement for hex mesh using sheet operations. Our focus is on improving the mesh quality of the worst elements in a hex mesh. The approach presented in this paper has the following main contributions:

1). We optimize the hex mesh under the guidance of a high-quality frame field, making its structure conform to the orientations ofc the frame field as far as possible, so as to improve its topological structure;
2). We regard the determined problematic sheet as the primary object of topological optimization, which can naturally reflect the relationships between topological structure of the hex mesh and the frame field and can guarantee the validity of the resultant mesh;
3). We present the approach of building a high-quality frame field on the hex mesh, which is able to guide the topological optimization for the hex mesh.

2. Basic Concepts and Approach Overview

Before describing the optimization approach, we introduce some basic concepts of dual structure of hex mesh and frame field. Due to a limited space, we omit some familiar concepts related to hex mesh, which are described elsewhere [15].