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An Approach to the Automatic Recognition of Boolean Decomposition Loops for Swept Volume Decomposition

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Abstract

Hexahedral meshing needs performing volume decomposition that decomposes a complex shape into simple hex meshable sub-domains, which is a very time-consuming and experience needed work. It is necessary to research and develop intelligent swept volume decomposition approaches. The fundamental work of the volume decomposition approaches based on reconstruction of swept features is to recognize the decomposition loops from the complex edge traces. In this paper, an intelligent approach to the automatic recognition of Boolean decomposition loops is presented. This approach first constructs feature vertex adjacent graphs of the part model to be decomposed, and then implements searching for the nodes of decomposition loops. In the searching processes, the initial node selection, the node growth, the searching evaluation, and feedback operations are employed. This work lays the foundation for the subsequent swept volume decomposition.

Keywords: swept volume; volume decomposition; hexahedral meshing; feature recognition; decomposition loops

1. Introduction

In the finite element analysis (FEA) process, meshing to discretize geometry for the FEA model is a fundamental work. Hex meshes have been widely used because they have many desirable properties and provide more accurate results than tetrahedral meshes [1]. However, due to the limitations of current hexahedral meshing algorithms, there is no general method that can automatically generate high quality hexahedral meshes for a complex solid model. It is

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usually required to perform volumetric decomposition in order to reduce the complex shape into hex meshable sub-domains. Nevertheless, up to now, fully automatic decomposition of B-rep models is still a challenging problem [2]. The users usually have to manually decompose a complex part model into a set of simple geometries, which is a very time-consuming and experience needed work. It is necessary to research and develop intelligent volumetric decomposition approaches.

Over the last decades, the automatic volume decomposition has been extensively researched [2-9]. Many approaches on automatic volume decomposition have been proposed, including the half space based approaches [4], the sequential iterative volume decomposition approach [5], swept feature recognition based approaches [6-8]. As the swept volume can easily generate high quality hexahedral meshes, the swept volume decomposition has attracted considerable attraction in the FEA field. Meanwhile, as the swept feature modeling is the main geometric modeling method to build a solid model, the swept volume decomposition based on feature recognition should be a promising research direction. Liu and Gadh [6] presented a recursive volume decomposition method which automatically decomposes complex shaped objects into simple sub-objects for automatic hexahedral mesh generation. Edge loops are used to construct the cutting surface for decomposition of basic simple objects. Lu et al. [7, 8] also proposed the feature-based work on shape recognition and volume decomposition, which can automatically decompose a CAD model into swept volumes. Their approaches use a type of edge loops called CLoops to form the cutting surface. The feature determination procedure is based on the CLoop recognition algorithm. However, there are two issues in their approaches. One is the presented recognition approach doesn't well consider the multiple feature's intersection. A complex part model is usually modeled by many interacting volume features and the interacting edges are intertwined with each other. In addition, due to the merging and splitting of surfaces resulting from Boolean operations, some interacting edges may be lost. It is difficult to identify which edges can form a CLoop that can segment a valid swept volume. The other weakness is unable to recognize depression features. Without depression features it is difficult or impossible to completely decompose all types of complex solid models into a set of swept volumes.

Based on the analysis of the shape evolution in the feature modeling process, we have realized an intelligent approach to the automatic decomposition of B-rep models based on virtual reconstruction of swept features. The approach mainly includes four steps: 1) automatic recognition of Boolean decomposition loops, 2) collection of face shells based on Boolean decomposition loops, 3) automatic reconstruction of swept volume by fitting non-manifold face shells based on the medial axis principle, and 4) reconstruction of CSG tree of swept features based on the dependent relationships among the reconstructed swept features. In the above four steps, the automatic recognition and construction of Boolean decomposition loops is crucial and the foundation for subsequent works. This paper mainly introduces the approach to the automatic recognition of Boolean decomposition loops.

The presented approach first constructs a feature vertex adjacent graph (FVAG) of the part model to be decomposed, and then implements searching for the nodes of decomposition loops. In the searching process, the initial node selection, the node growth, the evaluation for node searching, and feedback operations are employed.

2. Boolean decomposition loops

It can be easily found that as long as a swept feature still exists in a B-rep model, it must leave some traces on the model boundary. One of the most common traces is a set of edges resulting from Boolean operations. In general, protrusion features produce concave edges and depression features produce convex edges on the model boundary, respectively. If a single swept feature intersects with a B-rep model, the intersecting edges may form a closed single edge loop. However, in an actual part model, most volume features are intertwined each other. In addition, due to merging and splitting of surfaces resulting from Boolean operations, a part of intersecting edges may be lost, which brings the difficulty of recognizing intersecting edge loops. In order to decompose swept volume features, we give the following definitions on Boolean decomposition loops:

Definition 1. Let loop $L = \{e_1, e_2, \ldots, e_n\}$ be a closed edge loop consisting of a set of sequentially connected boundary edges or missing edges with the same convexity. The direction of the edge linking vertex v_i to v_{i+1} (i=1, …, n-1) is defined as the direction of L. If L can divide the boundary of a solid model into two different face shells along the L direction, L is defined as a decomposition loop.

Definition 2. If all edges of a decomposition loop are concave edges, the decomposition loop is defined as a concave loop. If all edges of a decomposition loop are convex edges, the decomposition loop is defined as a convex loop. Concave loops and convex loops are uniformly defined as the Boolean decomposition loops.

When two intersecting bodies are performed a Boolean union operation, concave edges may be produced between two intersecting surfaces. Hence, a concave loop can separate a protrusion feature from the part model along its one side. When two intersecting bodies are performed a Boolean subtract operation, convex edges will be produced between two intersecting surfaces.

A convex loop is the trace left by a Boolean subtraction operation between a tool body and the target boundary model. Along a convex loop, its right side is the face of the target body model and its left side is the face of the tool body model. If a tool body penetrates a target body, two convex loops will be formed; otherwise, a convex loop will be formed. Fig. 1 illustrates some concave loops and convex loops defined according to above definitions.

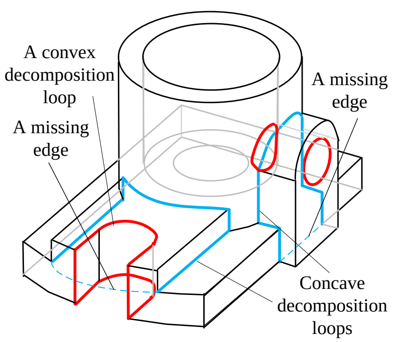

Fig. 1. Illustration of Boolean decomposition loops

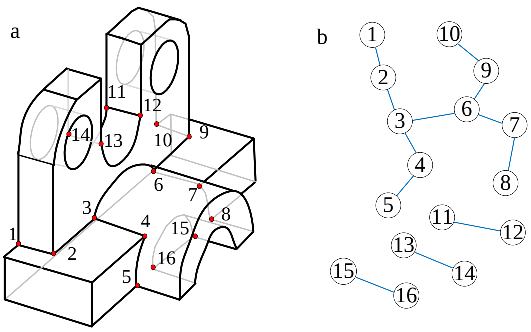

Fig. 2. (a) feature vertices; (b) feature vertex adjacent graphs

3. Recognition of Boolean decomposition loops

3.1. Feature vertex adjacent graph

The feature vertex adjacent graph is a formal geometric description for the traces of swept features. The following gives its definition:

Definition 3. The vertex on all concave faces is defined as the feature vertex. A simple undirected graph formed by feature vertices and their connecting edges is defined as the feature vertex adjacent graph (FVAG).

In a FVAG, each node corresponds to a feature vertex of the B-rep model and each arc corresponds to a boundary edge or a missing edge connecting two feature vertices. Hence, a FVAG can be represented as a tuple $G = <V, E>$, where V denotes the collection of feature vertex nodes, $V = \{v_1, v_2, \ldots., v_m\}$, and E denotes the collection of edges connecting two nodes, $E = \{e_1, e_2, \ldots, e_{m-1}\}$. m must be greater than 1. Fig. 2 shows an example of FVAGs of a part model. According to the characteristic of an undirected graph, the FVAG data structure is designed as follows:

struct *CNode* {int *VertexId*; bool *bSelected*; int *numAdjacentNode*; *CNode* pAdjacentNode*;}

In the above data structure, *VertexId* denotes the ID value of a geometric vertex associated by a node, by which the geometric information of the feature vertex can be accessed.

3.2. Decomposition loop search

The decomposition loops can be searched from the FVAGs of the part model. A decomposition loop includes a root node, a leaf node, and a set of intermediate nodes. If the leaf node of a decomposition loop grows to coincide with its root node, the decomposition loop will be closed. In this paper, we propose an intelligent approach to searching a decomposition loop, which includes the following four steps:

(1) Initial node selection

In general, an unselected node that has minimum number of edge links is selected as the initial node. In the subsequent search processes, the initial node is the root node of a decomposition loop. Starting from a root node, a decomposition loop starts growth.

(2) Decomposition loop growth

If the leaf node of a decomposition loop is not a terminal node, it is required to select a new adjacent node to make the decomposition loop growth. The search space to select a growing node is limited in the processed FVAG. In this paper, we propose a selection rule based on the minimum distance, namely if an adjacent and unselected node's vertex is nearest to the face where the leaf node's vertex is located on, the node is selected as the growing node. The minimum distance rule can ensure that the adjacent faces of a decomposition loop can form a continuous face shell.

(3) Search evaluation

When a decomposition loop grows to its terminal node, there are usually two cases: 1) The adjacent node is same to the initial node (root node), namely the decomposition loop will be closed; 2) There is no new adjacent node to be connected. Hence, it is required to make a decision to judge whether the currently searched loop is a valid decomposition loop.

For the first case, it is necessary to check whether the collected adjacent faces along a decomposition loop can meet the minimal face shell requirements to form a swept volume. For the second case, it is required to find a missing edge that can connect the terminal node to another disconnected adjacent node. It is very crucial to find such an adjacent node. We have summarized three kinds of terminal vertex modes as shown in Fig. 3.

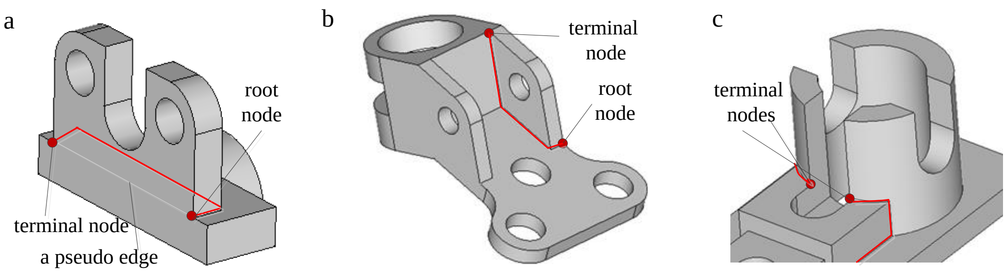

Fig. 3. (a) surface fusion mode; (b) corner adjacent mode; (c) surface segmentation mode

(4) Back propagation.

If the evaluation result is not satisfied with the requirements, such as failure to find a missing edge to make the loop closed, it is required to roll the leaf node back to the previous node having unselected child nodes; and to select a new growth node and continue above search. If the rolling back operation reaches to the root node, then it is required to change the separation direction and continue to search.

4. Case study

To demonstrate the feasibility and effectiveness of the proposed approach, and for the sake of brevity, we take a part model as shown in Fig. 4(a) as a case of recognizing Boolean decomposition loops. The following gives the specific steps of the automatic recognition and a part of recognized results.

(1) Input the part's B-rep model and implement some geometric pretreatments.

(2) Eight inner loops of four through holes are first identified from the part B-rep model: c1-c2, c3-c4, c5-c6, and c7-c8. Then, construct the FVAGs of the part model, as shown in Fig. 4 (b).

(4) Search for decomposition loops from the constructed concave FVAGs. The searching results are six decomposition loops as follows:

T1{3, 13, 29, 30, 31, 32, 15, 17, 20, 21, 22, 6, 5, 4, 3}, T2{7, 23, 24, 25, 26, 10, 9, 8, 7}, T3{35, 36, 35}, T4{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12}, T5{14, 13, 29, 30, 31, 32, 15, 16}, T6{19, 18, 17, 20, 21, 22, 23, 24, 25, 26, 27, 28}

(5) Construct convex decomposition loops. In the decomposed FVAG sub-graphs, G1{37, 38}and G2{40, 41} cannot be used to construct concave loops. Hence, we construct the convex FVAGs for these regions and obtain a convex decomposition loop: c9{38, 41, 53, 52, 40, 37, 50, 51}.

(6) After completing above operations, total nine convex decomposition loops (from c1-c9) and six concave decomposition loops (from T1 to T6) can be created.

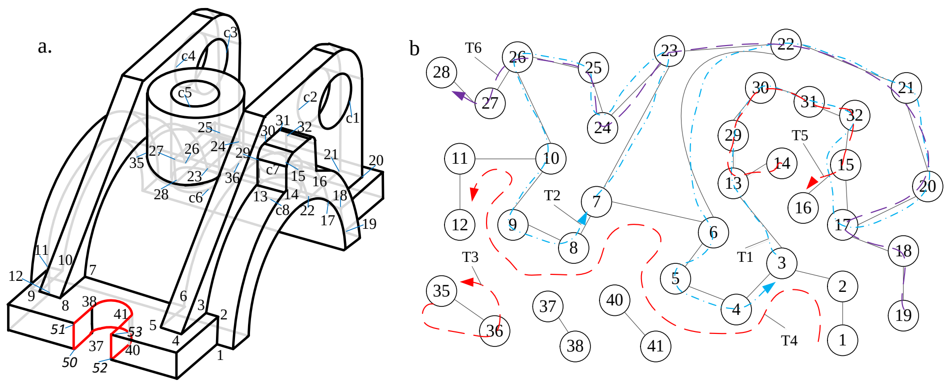

Fig. 4. (a) the case model and its feature vertices; (b) FVAGs and recognized decomposition loops

5. Conclusion

The decomposition approach based on reconstruction of swept features needs to identify their boundary. The edge loops are the important traces of the swept feature existence. Due to the intersection of swept features, the boundary edges of features are usually intertwined. In this paper, an intelligent approach to the automatic recognition of Boolean decomposition loops is proposed. This approach first constructs FVAGs of the part model to decomposed, and then searches decomposition loop nodes from the constructed FVAGs. The algorithm analysis and case study demonstrate the presented approach is effective for medium complex models.

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