Title:
Boss Recognition Algorithm and Application to Finite Element Analysis

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Introduction:
In finite element analysis (FEA), meshes are typically used to represent object geometry for simulation and analysis. Meshing is an essential FEA process that can affect the accuracy and computational efficiency of a solver considerably. Tetrahedral meshes are commonly used because they can be generated automatically, but they have low accuracy and a high number of meshes is required to describe a given object shape. In particular, tetrahedral meshes are unsuitable for representing thin or corner areas. By contrast, hexahedral and prism meshes are characterized by higher accuracy, convergence, and application specificity, rendering them more preferable to tetrahedral meshes. However, hexahedral and prism meshes are inherently more complex and difficult to generate.

Feature recognition has been studied since 1980 [6]. Nevertheless, most studies have been related to computer-aided design (CAD), computer-aided manufacturing (CAM), and computer-aided process planning (CAPP). Rib and hole recognition are two feature recognition algorithms from the literature that are relevant to this study. For rib recognition, Li et al. [3,4] proposed a seed face method called holistic attribute adjacency graph (HAAG). A seed face represents a key face of features, and this key face is the starting point of the feature recognition algorithm to search features. For hole recognition, Li et al. [5] proposed an inner-loop-based approach for recognizing small depression features. Loop data were obtained from a boundary representation (B-rep) data structure and were classified as convex, concave, and smooth.

Recently, several studies have outlined different approaches, such as refinement [7], decomposition [2], grid-based, and mapping, for generating hexahedral or other types of meshes. The mapping approach is usually integrated with the grid-based approach. Gregson et al. [1] developed a method for converting a regular hexahedron from a PolyCube to the input model. A PolyCube is a union of cubes transformed from an input model, but the meshing result depends on the model orientation. Moreover, transformation by the aforementioned method might lead to smoothing of sharp features.

The purpose of the present study was to propose an approach based on feature recognition for generating better quality of solid meshes for FEA applications. A boss is a complex feature, often comprising a hole, ribs, and a tube, in CAD models. Particularly, this study focused on the development of a boss recognition algorithm, the output of boss data for meshing, and the development of a process for automatic boss meshing. The proposed boss recognition emphasizes the recognition of all bosses on a CAD model and the computation of all corresponding data needed for automatic generation of solid meshes. The proposed process for boss recognition mainly contains three parts, preliminary functions, data base and boss recognition. The first two parts provide a general framework that can be used for other feature recognitions. The core algorithm of the boss recognition is the tube recognition, which mainly involves five steps of validations. The recognition data required for meshing is different from the past recognition method. The output data of a boss includes rib data, tube data and hole data, which record not only feature data, but also meshing data that can be used for automatic meshing. The meshing of a boss is primarily divided into rib meshing and tube meshing. Both hexahedral meshes and prism meshes are used on ribs and tube, depending on the regularity and orthogonality of the shape. Once a boss can be recognized and meshed appropriately, similar algorithms can be developed for other simpler features.

<u>Main Idea:</u>

The basic structure of a boss is depicted in Fig. 1, which primarily contains three components: a tube, a hole and ribs. The tube is the main component of the boss; it is composed of top face, bode face and base face. The base face is the face where the boss resides. The top face and body face determine the outer shape of the tube. A hole is located on the center of the tube; it is composed of a hole-face and a loop, where the loop denotes the boundary of the hole. Ribs are attached on the body face and base face. A rib is composed of end faces and shell faces, located on the side and top of the rib, respectively.

Boss structure	
A. Tube	A1. Top face
	A2. Body face
	A3. Base face
B. Rib	B1. End face
	B2. Shell face
C. Hole	C1. Hole face
	C2. Virtual loop

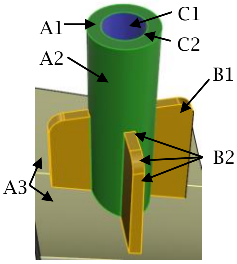

Fig. 1: Basic structure of boss in this study

Fig. 2 depicts the overall structure of the proposed feature recognition method for bosses. It is primarily divided into three parts: preliminary functions, data base and boss recognition. The preliminary functions are employed to deal with irrational geometry on the geometric data and to recognize fillets and loops. Three main functions in this stage are entity grouping, fillet recognition, and loop recognition. The entity grouping reorganizes irrational geometry by grouping the faces and edges with similar attributes. It can record those elements of similar attributes so that they can be processed simultaneously, without changing the geometric data. The entity grouping consists of plane grouping, edge grouping, and surface grouping. Fillets are recognized using a fillet recognition algorithm. When the diameter of a fillet is too small, it may be suppressed before the meshing. Loops are used to help the recognition of other features. A loop recognition algorithm is employed to recognize all types of loop. A loop may describe the boundary of a depression or protrusion feature, and hence can be employed for searching the target feature. The data base is established for boss recognition. It is primarily composed of edge AAG and face AAG. However, additional topological information of edges and faces are also recorded in accordance with the needs of the proposed algorithm.

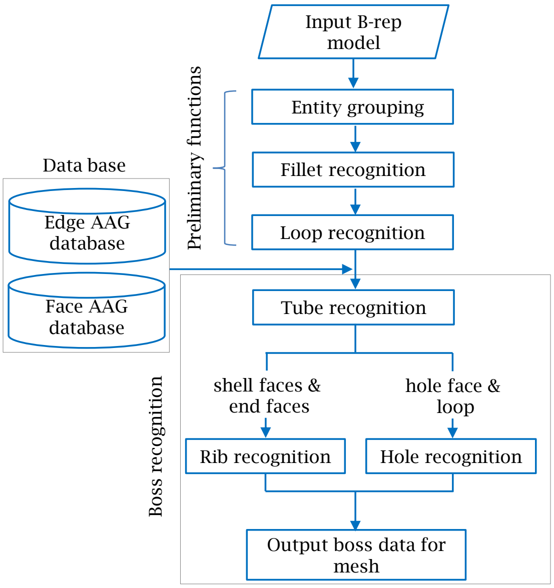

Fig. 2: Overall flowchart of the proposed method for boss recognition.

The proposed boss recognition process is composed of the following three steps: tube recognition, rib recognition, and hole recognition. First, the tube recognition records the relationships of ribs and hole, body, and base faces. It outputs shell and end faces for the searching of ribs, and a hole face and a loop for the searching of the hole. Rib recognition and hole recognition are then implemented separately to identify the desired features. After the previous steps, all features and data related to a boss are now available. After we employ hexahedral and prism elements for representing a boss, the boss data can finally be analyzed and saved for further use later.

<u>Boss Recognition:</u>

The boss recognition is performed loop by loop. For each loop, called tested loop hereafter, the tube recognition is performed first. The overall flowchart of the tube recognition is shown in Fig. 3. The tube recognition involves five steps for validating each of input loop data. If one of the five steps is not satisfied, no tube exists on the tested loop and the check shifts to the next loop. By contrast, if all five steps are satisfied, a tube exists on the tested loop, and the data corresponding to the tube are recorded. It will yield a set of shell faces and end faces for rib recognition. This procedure continues until all loops have been tested. The five tube recognition steps are described as follows:

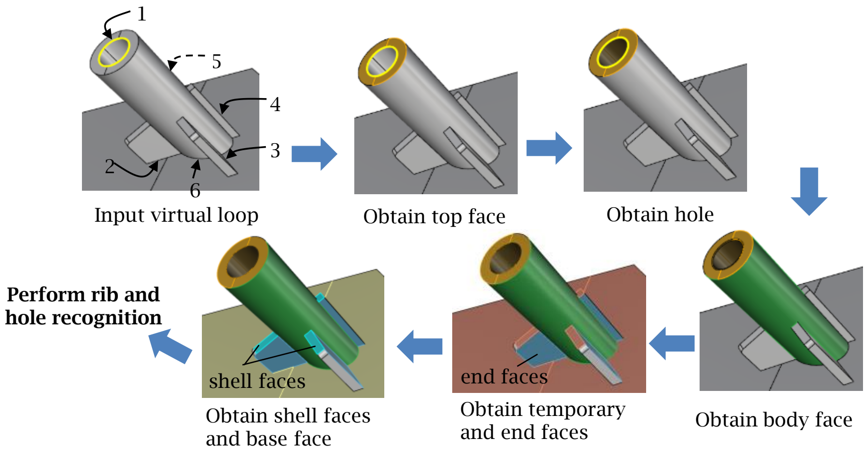

Fig. 3: Overall flowchart of the tube recognition algorithm.

(1) Find all convex edges: First, the algorithm finds the face belonging to the tested loop and records it as the top face (A1 in Fig. 1). Next, the edges related to the tested loop are inspected to ensure that they are convex to form a hole. If one of these edges is not convex, it does not satisfy the aforementioned condition, and all information recorded until that point is deleted. The process then moves to the next loop.

(2) Obtain a valid hole: Check whether a hole is available and determine parameters such as hole shape (circular or regular polygon) (C1 in Fig. 1), radius, and center point. All edges on the hole boundary are composed of lines or arcs. If all edges are arcs and can form a circle, the radius and hole faces are recorded. If the edges do not fit either of the two aforementioned conditions, all current information is deleted, and the process moves to the next loop.

(3) Obtain body faces: Body faces are found from among the faces neighboring the outer loop of the top face. The green faces in Fig. 1 are the top (A1) and the body (A2) faces. Subsequently, the radius and center point of the tube are recorded. The center points of the hole and the tube should be inspected to ensure that their distance is smaller than the desired tolerance.

(4) Obtain temporary and end faces: The algorithm searches for faces neighboring the body faces and classifies them into vertical- and horizontal-connecting faces. If the vertical-connecting faces are planar and connected to a concave edge, they are recorded as the end faces (B1 in Fig. 1). If the horizontal-connecting faces are connected to a concave edge, they are recorded as the temporary faces. If any convex edge is found, all recorded data are deleted, and the process moves to the next loop.

(5) Obtain shell and base faces: After the end faces are determined, the temporary faces can be classified into two types: shell faces and base faces. If a temporary face connects to an end face with a concave edge, it is recorded as a base face (A3 in Fig. 1). If a temporary face is a convex edge, it is recorded as a shell face (B2 in Fig. 1). The shell face can be different in accordance with the height of the ribs. If the height of a rib is lower than that of the tube, the shell face attached to the tube will be an independent face. By contrast, if the height of a rib is equal to that of the tube, the shell face

attached to the tube and the top face will be merged into one face.

Finally, all aforementioned data including meshing information are recorded. However, each recognition procedure can be independently performed or called from other recognition procedures. For example, rib and hole recognitions are called from the tube procedure, and rib, hole, and tube recognition procedures are called from the boss procedure.

Boss Meshing:

In meshing, a boss can primarily be decomposed into two parts, ribs and tube. If fillets exist on the surface boundaries, the meshing process would be more difficult, and the meshing data would be more complex too. Therefore, we only discuss the meshing algorithm for bosses with all fillets suppressed. The meshing algorithm with all fillets remained will be discussed elsewhere. For rib meshing, as depicted in Fig. 4, node seeding on one end face is performed first. If the end face is rectangular, it is meshed using rectangular meshes. By contrast, if the end face is non-rectangular, it is meshes using triangular meshes. A mapping process can finally be implemented along the second end face to generate the solid meshes for the rib.

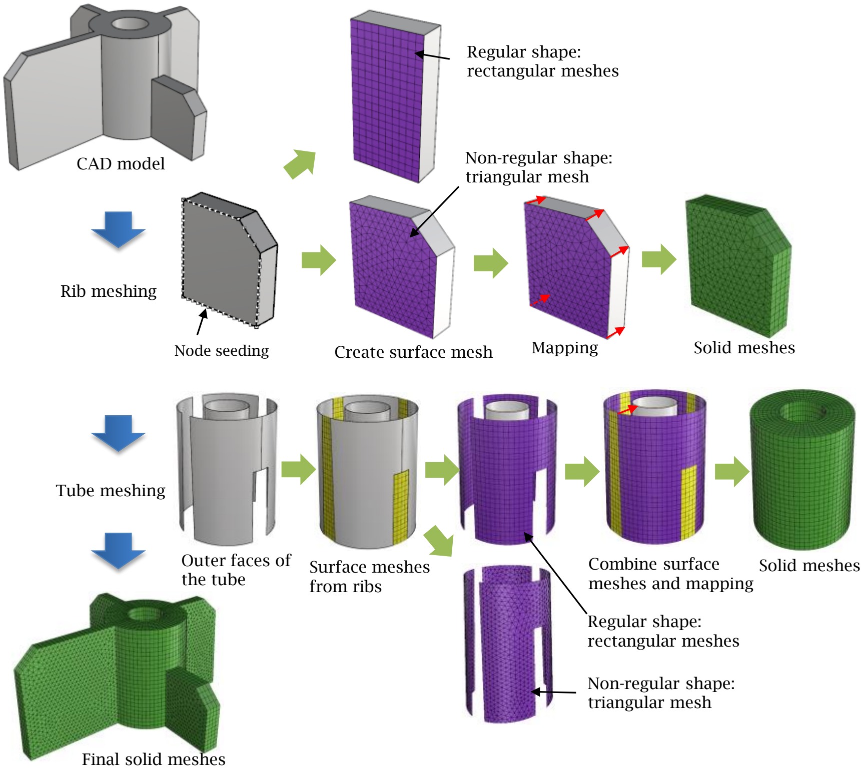

Fig. 4: Generation of solid meshes

For tube meshing, as depicted in Fig. 4, the outer faces of the tube are obtained first. It may be one or more than one faces. The surface meshes from the ribs and all their boundary edges are used to check the regularity of the surface meshes. If all surface meshes from the ribs intersect the tube orthogonally, the outer faces of the tube are meshed using rectangular meshes. Otherwise, the outer faces of the tube are meshed using triangular meshes. By combining the surface meshes from the ribs and the meshes from the outer faces of the tube, a mapping process can be implemented to generate solid meshes for the tube. If the ribs intersect the tube orthogonally, the tube can be meshes using all hexahedral meshes; while if the ribs do not intersect the tube orthogonally, the tube is meshes using both hexahedral and prism meshes.

Results and Discussion:

The boss recognition algorithm proposed herein was employed to test more than 30 models, and all bosses were recognized successfully. A program based on the proposed algorithm was written in C++ and based on the Rhino CAD platform and the openNURBS function. Figure 5(a) illustrates examples of boss recognition results obtained using the proposed algorithm. Tubes, ribs, and holes are shown in green, blue, and yellow, respectively. Shape complexity ranged from a simple individual boss to several interconnected. Bosses recognized successfully in this study include, for example, a boss located on several surfaces or nonregular faces and a boss with many virtual faces that are ribs and tube faces sharing the same face. In addition, Fig. 5(b) shows recognition results of three real examples that entailed combining rib, hole, and boss recognition. We compared all results with those obtained using CADdoctor™ under the same conditions such as radius, width, and height. The upper values in each plot indicate our result, whereas the lower values indicate the results obtained using CADdoctor™. The first and second values in each row indicate the number of bosses and ribs recognized, respectively. As indicated by the results, the definitions of boss in our study and CADdoctor™ are not completely identical. For example, the rib height can be the same as the tube height in the proposed algorithm; whereas it is not in CADdoctor™. This indicates that our boss recognition can recognize more than CADdoctor™. However, it still has limitations. For instance, the following cases cannot be recognized by the proposed algorithm: 1) when a boss has no base face, 2) when a hole is not located at the center of the tube, or 3) when the cross-sectional shape of a hole is not circular or regular polygonal.

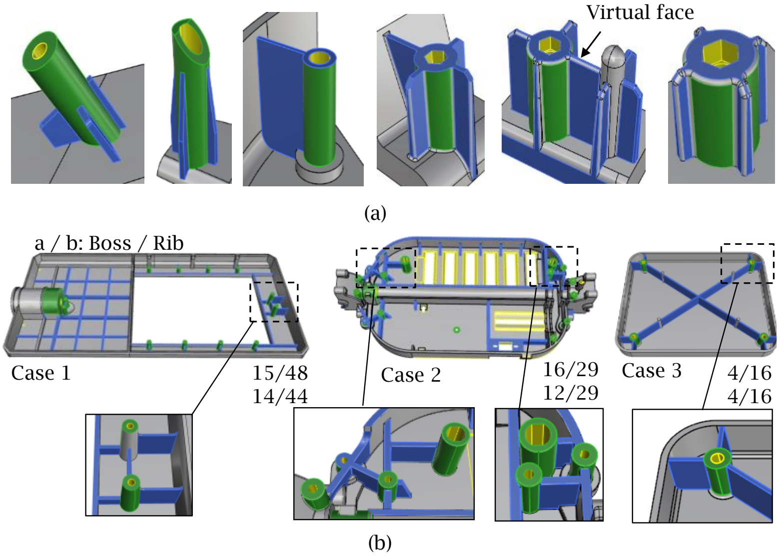

Fig. 5: Several boss recognition results, (a) boss examples, (b) real CAD models.

Regarding computational efficiency, the face number in the CAD model is the main factor affecting the computational time of the proposed algorithm, but the average computing time of each process is only a few seconds. Fig. 6 illustrates the meshing result of a case 4 involving the removal of all fillets. Figure 6(a) shows a boss mesh comprising pure tetrahedrons, and Fig. 6(b) shows the same boss mesh, comprising hexahedrons and prisms (hybrid). For these two solid meshes, the same node seeding size was employed and four layers were employed in each rib. Table 1 shows a comparison of the quality of the two solid meshes, comprising tetrahedrons and hybrid. Consider, for example, case 4; the average orthogonality with tetrahedral elements is 17.41, and the maximum orthogonality is 55.28. However, with hexahedral elements, the average orthogonality is 1.58, and the maximum orthogonality is 16.83, which represent a dramatic decrease. Other indices such as the mesh number, aspect ratio, and skewness improved considerably as well. Both the minimum aspect ratio and minimum skewness are also improved significantly. As mentioned, satisfactory solid meshes should satisfy the following criteria: requirement of fewer meshes; aspect ratio and skewness of 1; orthogonality of 0.

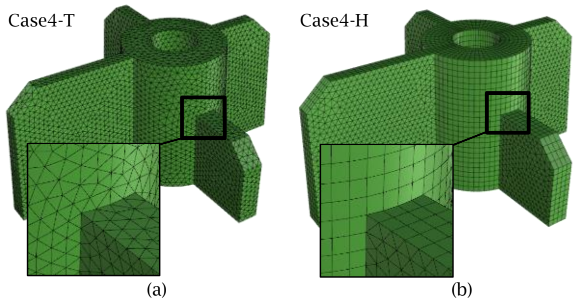

Fig. 6: Two kinds of solid mesh in a boss, (a) tetrahedron, (b) hexahedron.

Criteria / Case	Mesh number	Aspect ratio /Min	Orthogonality /Max	Skewness /Min
Case 4-T	79,654	0.82 / 0.40	17.41 / 55.28	0.89 / 0.63
Case 4-H	24,328	0.99 / 0.73	1.58 / 16.83	0.99 / 0.81
Range/Best	-	0 ~ 1 / 1	180 ~ 0 / 0	-∞ ~ 1 / 1

Tab. 1 Quality table of two boss solid meshes.

Conclusion:

This study focused on the development of a boss recognition algorithm for small and thin features, and verified the feasibility of the proposed algorithm by using several CAD models. A procedure for generating hexahedral and prism meshes for bosses was also presented. The main contribution of the proposed method is that we propose an approach based on feature recognition for generating better quality of solid meshes for FEA applications. An algorithm for the recognition of bosses was proposed. The output data of a boss for meshing was developed. The process for automatic meshing of bosses was also presented. The proposed method not only can be used for bosses, but also can be expanded to other common features. This method can reduce the necessity of manual operation, hence decreasing the overall operational time. Furthermore, the meshing results indicate that all quality indices of the meshes generated using the proposed method improved considerably. Notably, the proposed meshing algorithm was feasible only for recognized features, and small fillets on a CAD model should be removed first. In future studies, developing additional feature recognition and feature decomposition algorithms for converting most CAD model features into hexahedral meshes is imperative.

References:

[1] Gregson, J.; Sheffer, A.; Zhang, E.: All-hex mesh generation via volumetric PolyCube deformation, Computer Graphics Forum, 30(5), 2011, 1407-1416. http://dx.doi.org/10.1111/j.1467-8659.2011.02015.x

[2] Jüttler, B.; Kapl, M.; Nguyen, D.-M.; Pan, Q.; Pauley, M.: Isogeometric segmentation: The case of contractible solids without non-convex edges, Computer-Aided Design, 57, 2014, 74-90. http://dx.doi.org/10.1016/j.cad.2014.07.005

[3] Li, Y.; Wang, W.; Liu, X.; Ma, Y.: Definition and recognition of rib features in aircraft structural part, International Journal of Computer Integrated Manufacturing 27(1), 2014, 1-19. http://dx.doi.org/10.1080/0951192X.2013.799784

[4] Li, Y. G.; Ding, Y. F.; Mou, W. P.; Guo, H.: Feature recognition technology for aircraft structural parts based on a holistic attribute adjacency graph, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 224(2), 2010, 271-278. http://dx.doi.org/10.1243/09544054JEM1634

[5] Li, J.; Sun, L.; Peng, J.; Du, J.; Fan, L.: Automatic small depression feature recognition from solid B-rep models for meshing, 2011 International Conference on Electrical and Control Engineering (ICECE), 2011, 4386-4389. http://dx.doi.org/10.1109/ICECENG.2011.6057432

[6] Shah, J. J.; Anderson, D.; Kim, Y. S.; Joshi, S.: A discourse on geometric feature recognition from CAD models, Journal of Computing and Information Science in Engineering, 1(1), 2001, 41-51. http://dx.doi.org/10.1115/1.1345522

[7] Yamakawa, S.; Shimada, K.: HEXHOOP: Modular templates for converting a hex-dominant mesh to an ALL-Hex mesh, Engineering with Computers, 18(3), 2002, 211-228. http://dx.doi.org/10.1007/s003660200019