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SOLID DEFLATION APPROACH TO TRANSFORM SOLID INTO MID-SURFACE

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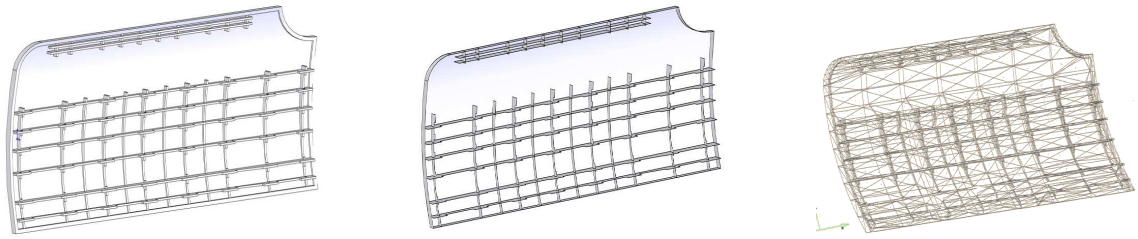
ABSTRACT

A simplified geometric model with lower dimensionality such as a mid-surface model is often preferred to a detailed solid model for the analysis process if the analysis result is not seriously impacted. In order to derive a mid-surface model, several methods such as medial axis transformation (MAT) and mid-surface abstraction have been proposed. In the former, although the algorithm can be applied for any complicated solid model, additional processing to trim and extend some parts of the result must be performed to obtain a practically useful CAE model. In contrast, the latter provides a more practical and usable output than the MAT approach. However, this method is not sufficiently robust for some complicated cases and it is very difficult to generalize the patch-joining algorithm due to the numerous special cases that arise unexpectedly. In order to solve these problems, in this paper, we propose a novel mid-surface generation approach called the solid deflation method. In this method, a solid is assumed to be created by inflating the air within the shell enclosing the solid. Thus, the solid itself can be converted into a zero-thickness model. Before deflation, the model is simplified by the removal of any detailed features whose absence will not alter the topological relationships.

KEYWORDS

Dimension reduction, solid deflation, simplification, mid-surface, geometry replacement



(a) (b) (c)

Figure 1 Conversion of a solid model into a mid-surface model for engineering analysis: (a) a solid model, (b) a mid-surface model, and (c) a mesh model generated on the mid-surface model

1. INTRODUCTION

Recently, three-dimensional (3D) CAD systems have been widely used for product design and simultaneously, engineering analysis has been conducted as an integral part of product design for purposes such as the evaluation of material or physical properties, determination of feasibility for manufacture, and assessment of suitability as part of a product. Finite element analysis (FEA) is one of the most popular engineering analysis methods; this method requires a finite element mesh as a geometric input. This mesh can be generated directly from a solid model for the detailed part model designed in a 3D CAD system. However, such a detailed solid model is often too complex to analyze efficiently, and excessive computation time is required. Therefore, an appropriate idealization process including detail removal and dimension reduction is indispensable for FEA mesh models (Lee, 2005, CAD).

As shown in Figure 1, the mid-surface model of a thin-walled part is widely used for the simulation of the injection molding process for plastic parts or car crash tests for an auto-body comprising sheet metal and plastic parts. The mid-surface model is derived from a solid model of the part through the idealization process. As shown in Figure 2, this process comprises two stages: detail removal and dimension reduction. In the detail removal stage, the system extracts and removes small features such as fillets, bosses, and holes that do not affect the analysis result significantly. In the dimension reduction stage, the solid is converted to a mid-surface model. However, creating the mid-surface is not an easy procedure to automate because of the shape varieties of the target model; in fact, it involves tedious manual work. Therefore, this issue has been a major challenge in this field.

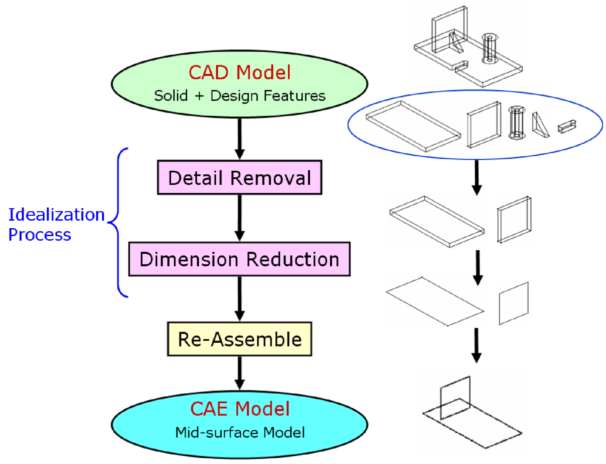


Figure 2 Transformation process from CAD to CAE models

A variety of mid-surface transformation methods have been proposed thus far. Medial axis transformation (MAT) and mid-surface abstraction are two representative approaches among these. These two methods are shown in Figure 3. In the MAT method, a medial surface is described by a locus of the center of the maximal inscribed sphere moving within a solid model. Although this algorithm can be applied for any complicated solid model, tiny branches that are not useful for analysis are created and its resultant surfaces are smaller relative to the outer faces of the original model. Therefore, the additional processes of trimming and extension of the result surface must be performed to obtain a practically useful CAE model. In contrast, the mid-surface abstraction method provides a more practical and usable output than the MAT approach. However, this method is not sufficiently robust for some complicated cases and it is very difficult to generalize the patch-joining algorithm due to the numerous special cases.

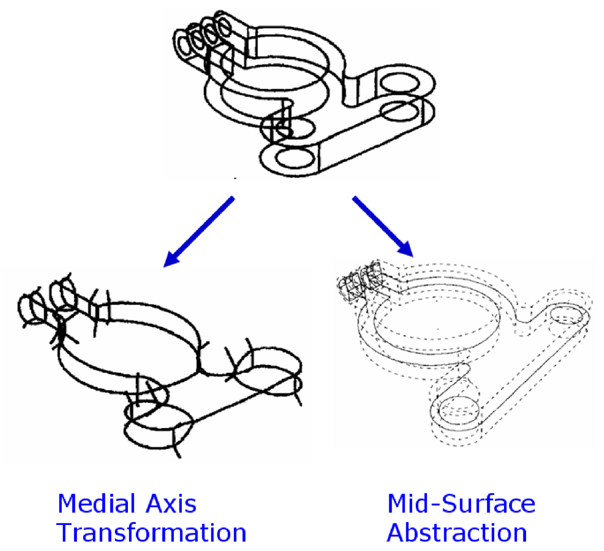


Figure 3 Medial surfaces created by the medial axis transformation and mid-surface abstraction methods

In order to solve these problems, in this paper, we propose a novel mid-surface generation approach called the solid deflation method. In this method, a solid is assumed to be created by inflating the air within the shell enclosing the solid. Thus, the solid itself can be converted into a zero-thickness model by deflating the air. A mid-surface model is extracted from the deflated solid. Before mid-surface generation, the model is simplified by the removal of any detailed features whose absence will not affect the analysis accuracy or alter the topological relationships in the solid model during solid deflation.

The remainder of this paper is organized as follows. Section 2 surveys the related work. Section 3 briefly describes the main concept and overall process of our approach. Section 4 introduces the development environment of our research. Sections 5 to 7 describe the detailed algorithms of our method that comprises solid simplification, deflation, and transformation into mid-surface. Section 8 presents a case study. Section 9 discusses some research issues and limitations of our approach. Section 10 presents some conclusions and suggestions for future work.

2. RELATED WORK

2.1. Detail removal

In order to ignore or suppress small geometric details in a 2D or 3D model, various detail removal techniques have been suggested. Gregory et al. (1987) introduced expert systems to extract form features from CAD models, and then selectively suppress the ignorable features for the generation of analysis models. Lee et al. (1998) introduced Fourier transformations for the suppression of geometric details. Sheffer (2001) reported that clustering methods are suitable for the simplification of CAD models in preparation for meshing. Li et al. (2002) developed a new metric system based on filleting to rate the LOD of boundary entities and they used this method to decompose a solid into detail features. Bianconi et al. (2003) suggested feature recognition methods for small features which are need using LOD by perceiving feature patterns.

Zhu et al. (2002) suggested an algorithm to identify and remove fillets or rounds in order to simplify the target model. Koo et al. (2002) proposed the "smooth-out" method that identifies small features that are negligible in the analysis and removes them from the part model. Chong et al. (2004) suggested a simplification method based on solid decomposition and reduction. Lee et al. (2005) proposed a small feature suppression or unsuppression system for preparing B-rep models for analysis. By using this system, analysts can generate analysis models with different levels of detail without having to repeat the simplification process from the original CAD geometry. Lee (2005, TOG) introduced a multi-resolution modeling technique to provide simplified solid models at various levels of detail using the concept of effective feature volume and the non-manifold topological framework.

2.2. Mid-surface generation

A variety of methods have been developed for the purpose of mid-surface generation from a solid. The well-known methods include MAT and mid-surface abstraction.

The concept of medial axis, first proposed by Blum (1967, 1973), has been applied in geometry transformation, and it is widely used for the creation of mesh models for analysis. MAT has the unique property of preserving the geometry information through the transformation process. It creates medial surfaces using the maximal inscribed sphere moving within a 3D solid model. When a locus of the center of the sphere is found, it is used to describe the medial surface of a model, as shown in Figure 4. MAT can be adjusted to any type of model with diverse shapes even if the target model has a complicated geometry.

Because of these excellent properties, this approach

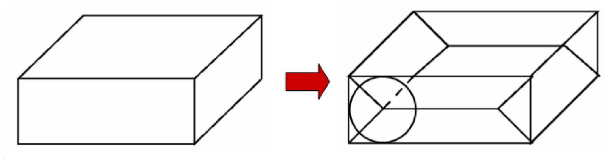


Figure 4 Medial axis transformation for a solid model

is a fine solution to generate mesh models for analysis (Ang et al., 2002; Armstrong, 1994; Cursoy et al., 1992; Patrikalakis et al., 1990) and it can be applied for the decomposition of a solid model as well (Lee et al., 1997; Sherbrooke et al., 1996). However, it requires the additional processes of extending or trimming of medial surfaces because the process creates tiny branches (shown in Figure 4) that are not useful for the analysis and its resultant surfaces are relatively smaller as compared to the outer faces of the target model.

Mid-surface abstraction was suggested by Rezayat (1996) as another method to create an analysis-friendly abstracted model from a part model. This method uses a ray cast from an arbitrary face along the direction of thickness to identify a face pair, and an adjacency graph is drawn by the iteration of pair detection. Mid-surfaces are generated by 2D Boolean operations and geometric interpolation from the pairs, and they are sewn according to the adjacency graph. This concept was recently applied to feature identification by Lockett et al. (2005) and to the development of a mid-surface model by Lee at al (2007) in a similar fashion. The method has the advantage of being a practical and fast solution to the development of a dimensionally reduced model. However, it has a weakness in dealing with complicated models. Mid-surface abstraction forces additional processing to extend the created mid-surfaces because each surface is created from the outer face independently. However, fewer additional operations may be required than those in the case of MAT.

2.3. Transformation of sheet into solid

Lee et al. (1995) suggested a conversion method from a sheet model to a solid model for the efficient solid modeling of thin-walled plastic or sheet metal parts. This approach is opposite to the dimension reduction of a solid. As illustrated in Figure 5, this method uses predefined topological operations to create a 2D model using pairs of faces, zero-length loops, and zero-length edges, and then converts it into a 3D model without changing the shape or topological information of the model. The zero-length loops and the zero-length edges adjacent to the face pairs are transformed into thickness faces of a solid model. This method shows a great potential for degenerate solids in the representation of thin-walled parts. However, because this method adopts solid boundary representation, it is difficult to represent the exact adjacency relations between topological entities in a sheet model, and to describe a mixture of wireframe and sheet objects that appear in the intermediate steps of sheet modeling operations.

In order to overcome these problems, Lee et al. (2001) introduced a non-manifold boundary representation as a topological framework and proposed a sheet thickening algorithm by presenting variations to a general non-manifold offset algorithm that is based on the mathematical definition of offsets. In addition, to facilitate sheet-modeling operations, they provided a set of generalized Euler operators for non-manifold models as well as sheet modeling capabilities including adding, bending, and punching functions with two-dimensional curve editors.

3. SOLID DEFLATION APPROACH

In this paper, we propose a novel method called the *solid deflation approach* for mid-surface generation. In this method, it is assumed that a solid model can be made by inflating air into a shell that encloses the solid while its thickness increases from zero; that is similar to the approach of Figure 5. Therefore, the solid can be converted into a deflated zero-thickness model with air pumped out and vice versa. Then, a mid-surface model is extracted from the deflated solid by selecting the faces on one side of the solid. This approach is the opposite of the sheet thickening method proposed by Lee et al. (1995). Note that the connectivity between the topological entities of the solid is preserved during the deflation process. In contrast to both the MAT and mid-surface abstraction methods, this approach does not require additional processes such as the trimming or extension of the mid-surfaces because of the constant topology.

As shown in Figure 6, the mid-surface generation process based on the solid deflation approach comprises the following three main steps.

(Step 1) Solid simplification: A CAD design model contains several detailed features such as rounds, holes, bosses, and snap shots for structural support or assembly functions. Such detailed features are detected and suppressed for a more efficient analysis as well as for successful solid deflation in which no

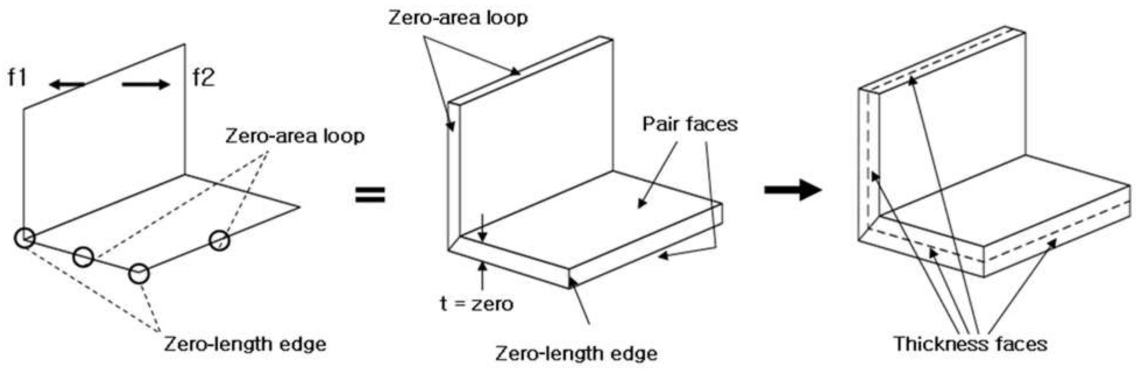


Figure 5 Transforming a sheet of solid topology into a thin-walled solid by face geometry replacement

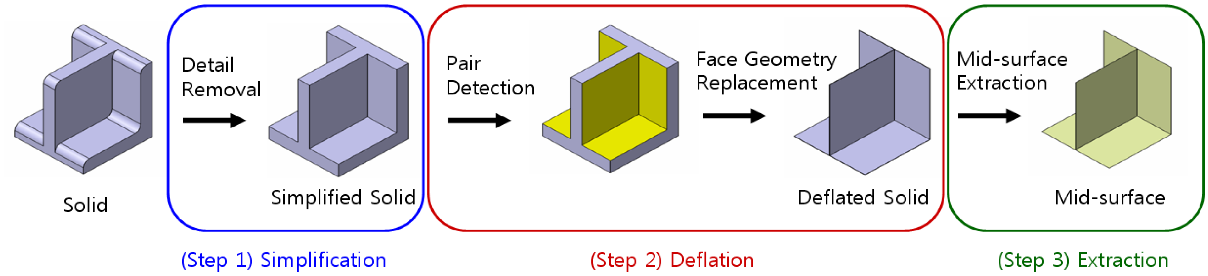


Figure 6 Solid deflation approach for mid-surface generation

change of topological relationships should be guaranteed. The suppression of detailed features is first performed automatically by the system using feature tree information. If there remain some detailed features that are not recognized due to feature interaction, they are eliminated manually by the user.

(Step 2) Solid deflation: The simplified solid model is shrunken to a degenerate solid with zero-thickness. As shown in Figure 6, this step includes two minor steps: face pair detection and face geometry replacement. First, face pairs are found to determine the faces to be changed. Then, for each face pair, a new medial surface is created and the surfaces of two faces are replaced with this surface. This process is essentially the opposite of the sheet thickening process in which the face pairs are moved out from a sheet to a solid (Lee et al., 1995). Theoretically, the solid should be converted to a degenerate solid with zero-thickness. However, current solid modelers often fail to manage edges with zero-length or faces with zero-area. Fortunately, they usually allow the user to change the tolerances for the same real numbers. Therefore, we adopt a more practical strategy where the solid is shrunken to a very thin solid and then the faces on one side of the solid are extracted. If necessary, they are stitched into a single sheet model by changing the tolerances appropriately.

(Step 3) Mid-surface extraction: When Step 2 is completed, the deflated model has near-zero-thickness, with the same topology as the simplified model before deflation. Only the faces contributing to the mid-surface model are extracted and sent to an FEA package where meshes are generated. If necessary, they are stitched into a single sheet model. However, in many cases, FEA packages are able to create shell meshes from a collection of mid-surfaces that do not have topological connectivity. In this paper, we omit the stitching task.

Our approach has been implemented using CAA, an API of CATIA V5. The following section introduces the development environment, and then the succeeding sections describe the three main steps of our method in greater detail.

4. DEVELOPMENT ENVIRONMENT

We select CATIA V5 as the implementation platform for our research because it is one of the most widely used CAD system in industries, especially in automotive industries.

There are three different ways to customize CATIA V5; these are collectively called the CATIA Openness Tools. They are Knowledgeware, Automation API, and Component Application Architecture (CAA). Figure 7 illustrates their properties and abilities.

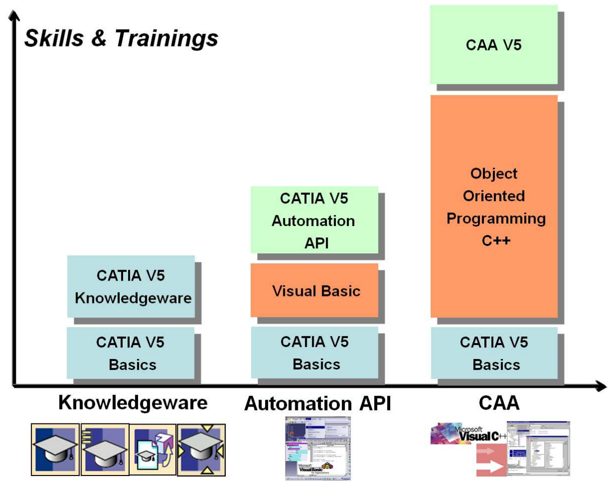


Figure 7 CATIA V5 customization tools (Dassault Systemes, 2002)

The user can capture and reuse the design intent using Knowledgeware, which provides a simple optimization toolkit for developers. The validation and certification processes for the design are also performed in this manner. However, Knowledgeware is a type of predefined function set provided by CATIA and thus it has some limitations in terms of user controllability.

The Automation API uses macros written in a standard interpreted language such as Microsoft Visual Basic. It provides an obvious mapping between the objects seen by the end user and the automation API. By using the journaling functionality of the Automation API, interactive programming can be implemented. However, since not all CATIA functions can be recorded by the Automation API, it is impossible to create new features or new components using this mechanism.

In contrast, the CAA provides good controllability to deal with feature models. Further, it is possible to create new user-defined features or components using CAA. CAA supports the management of the lowest levels of the modeler system such as the topology of a model or the operating structure of the modeler. It can be implemented using Microsoft Visual C++ and Java as the programming language environments, which are applied under the Component Object Model (COM) concept.

Our algorithms are implemented under the CATIA V5 CAA environment using Microsoft Visual C++ 6 because CAA allows wide accessibility to the topological and geometric information of the model as well as the feature information.

5. SOLID SIMPLIFICATION

In this step, detailed subsidiary features such as rounds, holes, bosses, and snap shots are detected and suppressed for the purposes of more efficient analysis and successful solid deflation in which topological relationships should not be changed. In this paper, the detailed subsidiary features to be removed are called “small features” hereafter.

Small features can be found by two methods. One uses the feature information of the model created by the feature-based CAD system, and the other uses the geometrical and topological information of the B-rep solid model for feature recognition. Although the latter feature recognition method can be applied to any model regardless of the availability of feature information, its limitations of supported feature types and domain dependency have been reported in literature (Shah et al., 1995). Currently, most CAD systems provide feature-based modeling capabilities, and product design is conducted using these capabilities. Thus, the former method using feature information is advantageous in the retrieval and removal of features although it cannot detect all the small features.

Therefore, in this work, we adopt a practical approach in which the suppression of detailed features is first performed automatically using feature information by the system and then, if any small features remain, they are eliminated manually by the user. Like other solid modeling kernels, CATIA CAA offers proper and efficient functions dealing with the feature information for modifying a feature-based solid model. The design specification of a feature can be retrieved by using these functions and therefore small features can be identified easily.

The flow of the simplification process is shown in Figure 8. First, the feature tree of the solid model should be retrieved. In CATIA V5, the feature tree contains lots of information about the model such as definition parameters, type of features, references, relationship with other objects, and so on. Further, the feature tree contains useful information about the modeling procedure. While retrieving the feature tree, the simplification module uses the defined type of the feature to make a list of the small features to be removed.

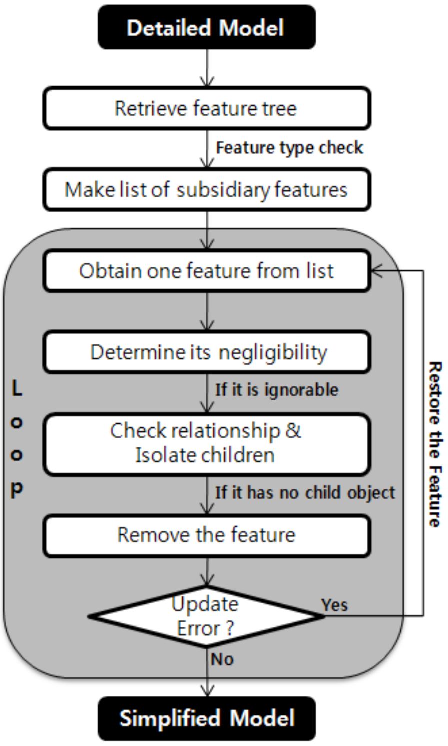


Figure 8 Flowchart of solid simplification

When a small feature is found, it is added to the list. This task is executed recursively from the top feature of the tree to the lowest feature by retrieving the child list. After the creation of the list is completed, a series of operations are performed for each feature in the list. The module determines whether or not the features can be ignored for the analysis. The negligibility of a feature is decided based on certain design parameters such as its radius, thickness, and volume. For example, the fillet feature should be reserved if the radius of the fillet is so large that it cannot be ignored in the analysis. Similarly, a boss feature that has a relatively large volume cannot be ignored. The limitation value of each parameter is usually set by the user's input.

The next step is to check the dependency relationship of the feature. If feature B is created after feature A and feature A is referred to by feature B, feature A cannot be removed independently because its deletion would affect the creation information of the original model, feature B. This situation occurs when a feature has another feature as an element of its design definition. In CATIA V5, the dependency relationship among features is defined as a "parent/child" relationship. This relationship can be cut by an isolation operation, as shown in Figure 9. Therefore, the relationship check of a feature and the isolation of children should be performed before the deletion process.

After the relationship check has been completed, the small features can be eliminated if they have no child features. In this step, the impact of a delete operation should be considered for maintaining the stability of the process. Sometimes, the deletion of some feature causes an error although isolation is performed properly. Such errors block the construction of the geometry and make the part model invalid. Thus, such a feature must not be removed even if it is a small fillet or a tiny hole, and thus, it is restored immediately to retain the validity of the part model.

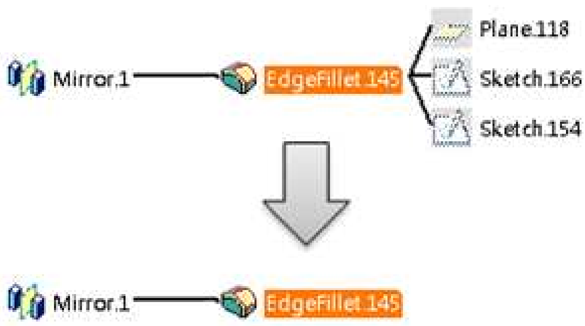


Figure 9 Isolation of children features

If all the unnecessary small features are removed, the simplification process is completed. However, a small feature that cannot be specified or removed using the feature tree information may exist, as shown in Figure 10. In most cases, the fillet feature can be easily identified by its type because a native type for fillet features exists in CATIA. By contrast, a feature such as a boss is not identified only by its type because it does not have its own type. Its type may vary depending on the manner in which the feature was originally created during the design process. Sometimes, such an object is formed by the combination of different types such as a pad, pocket, shaft, rib, hole, and shell in the modeler. Therefore, in this case, the user determines whether it is a small feature or not by considering other information such as the volume ratio, area ratio, and B-Rep information. If it is a small feature, the user deletes it manually in the general shape modeling (GSM) mode in CATIA V5.

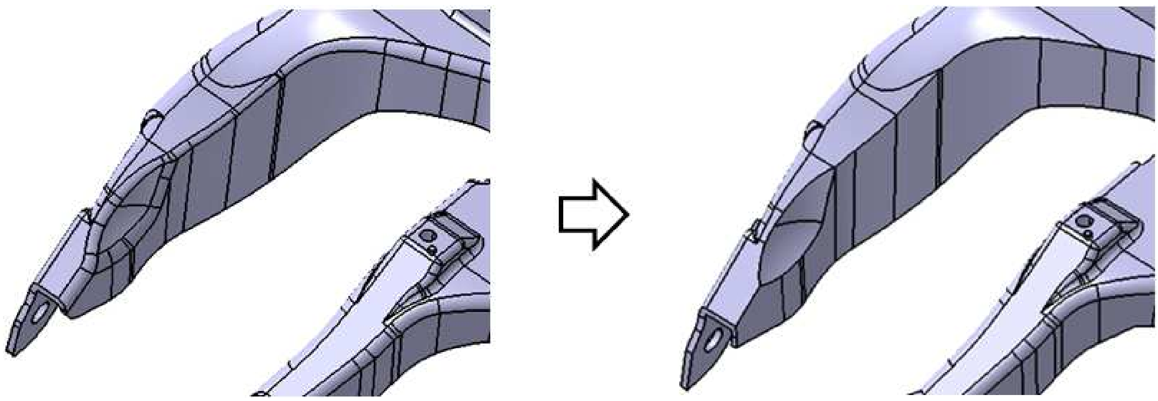


Figure 10 Removing fillets on a solid model using feature information. The small undeleted features are marked by the circle.

6. SOLID DEFLATION

After obtaining a simplified model from a detailed solid model by the process explained above, the solid deflation process will be executed. The process of solid deflation comprises the following two minor stages.

(Step 1) Face pair detection: This step involves finding and detecting face pairs that can be referenced to deflate a solid model later. Here, two faces will be compared and checked in a few steps, and they are considered to be a face pair if they pass some test steps. The face pairs are used to create mid-surfaces by offsetting in the next step.

(Step 2) Face geometry replacement: In order to deflate a solid model, we use a specific function of CATIA CAA that replaces a face with another face without changing the topological information of a model. An offset mid-surface for each face is required for the deflation operation, and it is usually created by offsetting a face of a pair that is to be replaced. The generation narrows the thickness to a near-zero value to reduce the dimensionality of a solid model. Then, the face of a pair from which an offset surface is generated is replaced by the newly created offset surface by using a native modeling function provided in CATIA CAA.

The procedure is conducted for a single face of a pair and is repeated for the all face pairs. During the deflation operation, a solid model is compressed to a near-zero-thickness solid model, which is similar to a sheet model. During the operation, the topology of a model usually remains the same when it is deflated with a small distance, while abstraction to a zero-thickness model makes the topological information of the model change in the CATIA environment. The ideal resultant model is a model with exact zero-thickness; however, some modelers including CATIA have a topological limit on zero-thickness. Therefore, the resultant model is acquired not as a sheet model but as a solid model with a narrow thickness clearance between the two faces of a pair.

6.1. Face pair detection

In order to deflate a solid model using the face replacement function of CATIA, three input parameters are required. They are the object face to be changed, the target face, and the direction of replacement. These parameters can be gathered from the face pairs. The maximum thickness (t_{max}) and the maximum draft angle (Θ_{max}) of the part model are required as user inputs to determine the pair. By face pair detection, the module identifies the faces that are to be changed to a mid-surface and the faces that will not be changed. Currently, planar and quadratic surfaces are considered in this work. The inclusion of freeform surfaces remains as future work.

In the case of planar faces, basically, two faces with collinear normal direction in a small distance can be considered as candidates for a face pair. The conditions for a face pair are as follows:

(Condition 1) Normal direction angle

(Condition 1.1) Parallel: In the case of normal extrusion faces, the directions of the normal vectors (N_1, N_2) of two faces (F_1, F_2) should be opposite, that is, they should be parallel, as shown in Figure 11 (a).

$$N_1 \cdot N_2 = -1 \tag{1}$$

(Condition 1.2) Draft angle: In the case of draft faces, the angle between two faces is smaller than the doubled maximum draft angle, as shown in Figure 11 (b).

$$180^o - Angle(N_1, N_2) < \Theta_{max} \tag{2}$$

These conditions can be extended in order to apply them to quadratic surfaces. If two conic faces have the same axis and the draft angles satisfy Equation (2), they can constitute a face pair. For spherical faces, the same origins and Equation (1) are sufficient conditions.

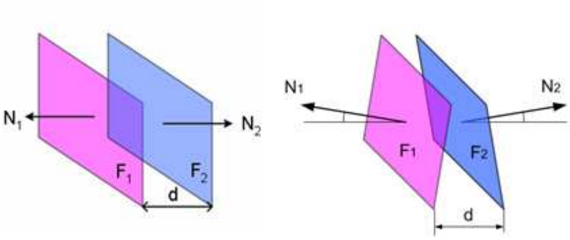


Figure 11 Comparison of normal directions: (a) exact parallel pair and (b) draft angle pair

(Condition 2) Distance
The distance between two faces is smaller than the maximal thickness.

$$d < t_{max} \tag{3}$$

(Condition 3) Overlap
When one face is projected to the other, they should be overlapped.

The face pair detection module narrows down the pair candidates under the three pair conditions above; parallel check, distance check, overlap test, and pair decision.

Parallel check

In this algorithm, the relation between two faces will be checked to determine whether they are parallel or not. In this paper, the parallelism of two faces includes exact parallel, called as “exact parallel pair” (Condition 1.1), and close to parallel, where two faces face each other at a small angle (Condition 1.2), called “draft pair.”

All the faces in a part model are examined and faces satisfying only Conditions 1.1 or 1.2 are selected as candidates for pairs. Figure 12 (a) shows the faces that cannot constitute a face pair because they are neither parallel nor close to parallel. In order to check this parallel criterion, a dot product is calculated with the normals of two faces, as given by Equation (1).

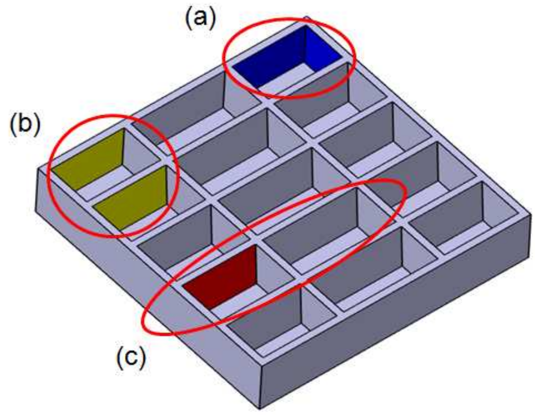


Figure 12 Conditions to detect face pairs

In addition, if there are some conic faces in the model, the program retrieves the axis system of that face and calculates the dot product for the first, second, and third directions of the axis systems. If the results of all dot products indicate parallelism, the two conic faces will be selected as candidates for pairs.

Distance check

In order to form a face pair, the distance between two faces should be smaller than the maximal thickness specified by the user (Condition 2). After checking the parallelism of two faces, the distance between the pair candidate faces is calculated to check if they satisfy this condition. During the parallel check step, all faces in the part model are checked. Two parallel faces located far away from each other, as shown in the Figure 12 (b), may be included in the result of the previous step. Of course, these faces should be eliminated from the face pair list because they cannot be compressed properly. When examining the distance between two faces, the distance should be measured along the normal direction of a face. For this purpose, a point of a face will be projected to the unbounded support surface of another face, which is drawn with dashed lines in Figure 13.

Overlap test

If a face has several parallel faces within the maximal thickness, as shown in Figure 12 (c), the overlap test is executed by the projection of one face to the other in order to determine a pair. If the projected face is overlapped to the other face in a certain area, they are determined to be overlapped. Let us introduce some CATIA-specific issues on this test.

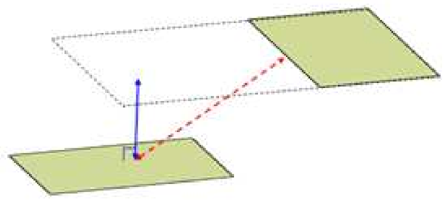


Figure 13 Distance of two faces: (a) distance between face surfaces along the normal direction and (b) shortest distance between two faces

In our implementation using CATIA CAA, a boundary curve of a face is projected to another face for this test. If the two faces are not overlapped at all, the result of the projection cannot be created in CATIA. On the other hand, even if the two faces overlap only at a point, the projection result can be created. However, the faces that overlap only on a point or on an edge cannot be paired because the offset face cannot be created. In this case, only the edge or point can be created between the two faces. Therefore, in this process, we find a 2D cell (faces) on the projection result and the face is considered to be an overlap face if the result has a certain area that is shared by two faces. This principle is shown in Figure 14.

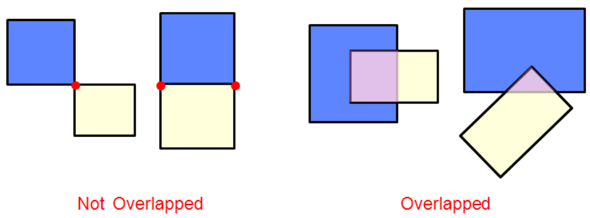


Figure 14 Overlap conditions in CATIA V5

Pair decision

If the two compared faces satisfy all the three steps described above, they are deemed to be a pair and are stored in the pair list. During the process of collecting face pairs, the program also retrieves non-pair faces or useless faces for deflation. The pair faces will be used for offsetting while non-pair faces are changed to near-zero-thickness elements or they are diminished.

6.2. Face geometry replacement

A solid model is now ready for shrinkage to a near-zero-thickness solid. The basic concept of deflation is based on an assumption that a solid is an inflatable 3D object. The geometry of a solid is obviously changed after deflating a solid relative to its geometry before deflating. However, it has a static topology regardless of whether the shape of a solid is varied.

The process of face geometry replacement is shown in Figure 15. An offset mid-surface is generated from the face of a pair. The geometry of the object face is replaced by the offset mid-surface, and then the section where the replacement occurs is partially deflated. This process is repeated until all the face pairs are replaced by their offset mid-surfaces.

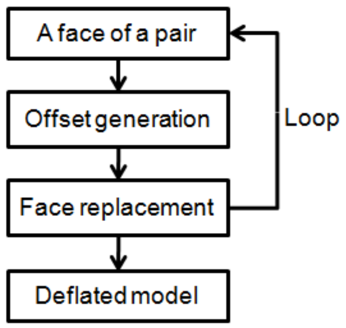


Figure 15 Face geometry replacement process

Offset mid-surface generation

CATIA V5 provides a useful modeling function for the deflation operation: a face replacement function that requires three input parameters, namely, an object face, a target face, and the direction of replacement for executing the function.

For deflation, the large and dominant faces that compose and define the geometry of a solid should be determined to retain their properties even after the deflation operation. In this manner, the other small faces such as thickness faces are diminished or eliminated from the solid model. Meanwhile, the dominant face is preserved so that it can be an object face to be replaced by another face. Further, the target face to be replaced by an object face is required as well. In order to create the target face, we must offset or transform the object face to the direction of the median of a solid in a manner similar to the mid-surface of the pair.

The target face is the offset mid-surface; this is not an exact mid-surface because it has a clearance from the mid-surface. There is a systemic reason for not creating an exact mid-surface for this operation. If an exact mid-surface is used as the target face for replacement, the resultant model has a zero-thickness, implying that the result is likely to be a sheet model rather than a solid. This implies that the topological property of the original model is altered by the operation. However, when using the offset surface with a clearance from the mid-surface, the deflated model has a very small distance between the replaced faces so that it has the same topology as the original model. In other words, the deflated model with a near-zero-thickness usually has the same topology as the original solid model, while the topology of the zero-thickness model is sometimes changed during the process. Further, some modelers such as CATIA do not support the zero-length edge and zero-area loop that are essential for generating a zero-thickness solid model. Because of these conditions in the environment, it is reasonable to use the offset having a clearance as the target face to conserve as much topological information as possible.

When creating the offset surfaces, each face pair is offset alone because the areas of the faces within a pair are usually different. In fact, CATIA cannot define the replacement operation when the target face is smaller than the area of a cross section where the target face is located and included because the topology of the model becomes invalid due to the imperfectly defined geometry of a new face.

If the two faces are positioned exactly parallel where Condition 1.1 is satisfied, the target face is generated by simply offsetting the object face. As shown in Figure 16 (a), the target face can be generated by offsetting a face by half the distance of two faces. The direction will be toward the inside. In order to preserve the topological information, the offset distance is made a little smaller than the half distance. Therefore, the offset distance is determined such that the resultant deflated model shall have a thickness of a tolerance in the CATIA modeler.

In the case of a draft pair satisfying Condition 1.2, the offset surface generation process will become a little complicated, as shown in Figure 16 (b), because the face cannot be offset directly. In the case of a planar face pair, first, the points on the corners of each object face in a pair are retrieved and then the mid-points of paired points are created. Three mid-points now define the mid-plane, and the target face of an object face is created by projecting the object face to its mid-plane. The target faces are created one by one in a loop, as shown in Figure 16. When the second face of a pair creates its target face, the information of the mid-plane that is generated in the previous loop is used. The distance of the offset is also determined such that the deflated model shall have a thickness of a tolerance as in the parallel pair case.

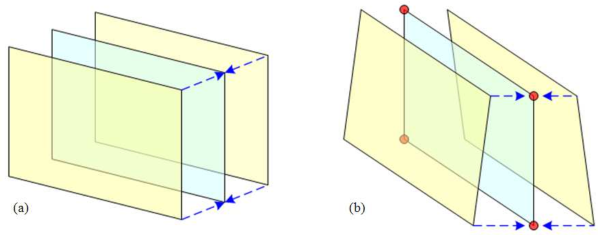


Figure 16 Mid-surface generation: (a) mid-surface for exact parallel pair and (b) mid-surface for draft angle pair

Face replacement

The face replacement operation preserves the topological information of a solid model while it is executed. Therefore, a thick solid may be reduced to a very thin model if the definition of the replacement is valid within the topological property of a model. When an offset mid-surface is generated from the face of a pair, as explained in the previous section, the object face is to be replaced by the offset mid-surface.

For face replacement, it is necessary to investigate the areas of the target face and the cross-sectional area where the target face is located after the object face and the target face are determined. If the target face is smaller than the cross section where the target face is located, as shown in Figure 17, the replacement operation cannot be defined in CATIA CAA because of topological incompleteness. In this case, the target face is expanded by scaling up so that the area becomes larger than the cross-sectional area for the replacement process. When the object and target faces satisfy the condition, face replacement is executed by substituting the object face with the target face along the direction of the normal target face.

Implementation issues in CATIA

The deflation operation should proceed with each face one after the other after face pair detection is completed, as shown in Figure 15. This process is likely to be more complicated than applying the procedure to the entire model at once. However, the reason why generating the offset surface and replacing the object to the target face are processed sequentially on each face is because of the real-time changes to the model during deflation.

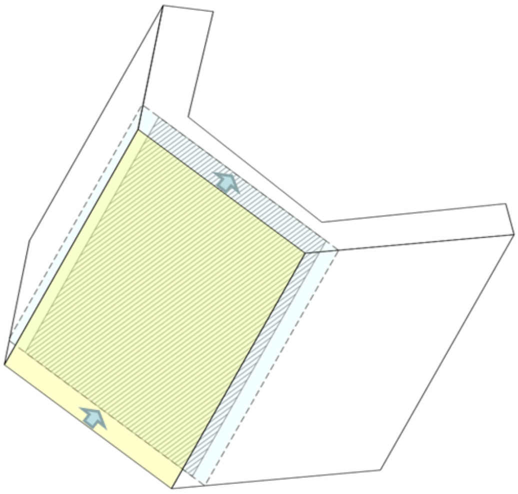


Figure 17 A smaller target face than the cross section area (dashed boundary line)

Generally, it would be better if all the offset surfaces of the face pairs are generated at once from the outer faces of a simplified solid. Then, it is possible to execute deflation on one or more pairs of faces. However, when it is applied within CATIA, the deflation process is not valid for the face pairs that are adjacent to the already processed faces because the offset surfaces defined in advance are not suitable for the operation; the geometry of the outer faces that are to be replaced are already changed when the adjacent faces are replaced. In short, the geometries of faces on the solid model change during the face replacement operation in real time. This implies that the offset surfaces that are retrieved at once before the replacement operation are not valid for the latter process. In order to overcome this problem, we repeat the flow of offsetting and replacing on a single face. This loop is repeated until all the face pairs are replaced by the operation.

In CATIA V5, a model should always be updated when an operation is performed within CAA in order to view the result of the operation. However, whenever the geometry or topology of a solid is changed by a CAA function, the identification information of the topological entities of a solid such as the tags and names of the faces, edges, or vertices may be changed. The face list stored in a solid is varied when this operation is executed as well. Therefore, irrespective of when a face is processed, it needs to retrieve the internal information for data management for the deflation process. Figure 18 shows the algorithm for managing the updated internal information in a solid.

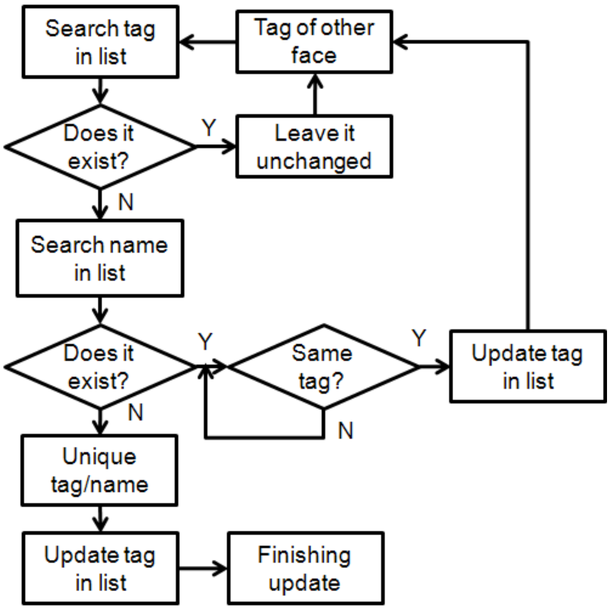


Figure 18 Algorithm for managing updated internal information of a solid

7. MID-SURFACE EXTRACTION

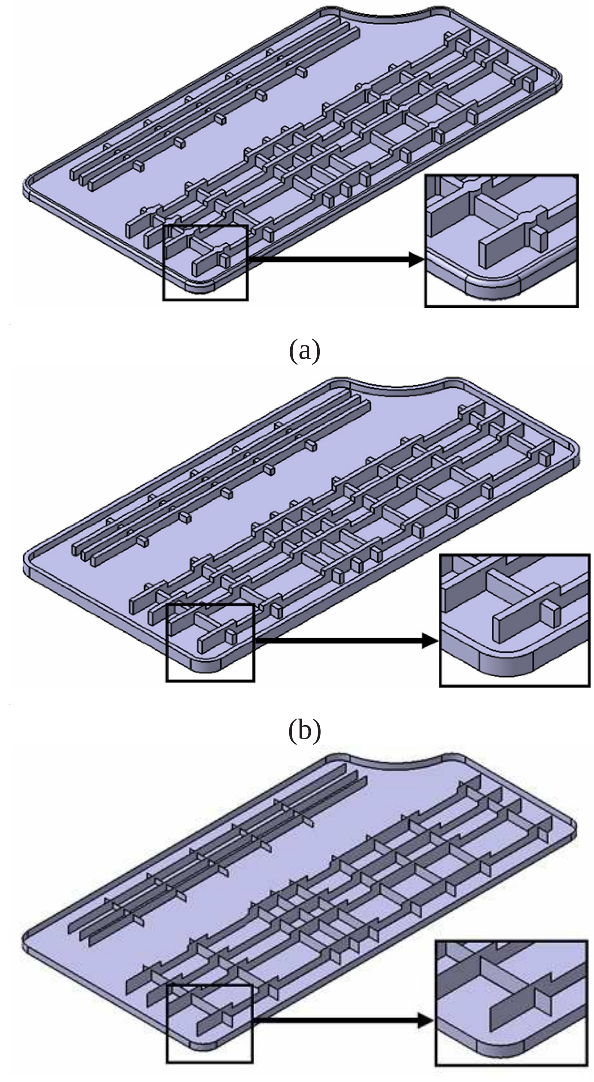
When the deflation operation is completed, one face of a pair is selected from each face pair and it is extracted to complete a mid-surface model for the analysis process. The result of the deflation process appears similar to a sheet model; in reality, it is a very thin solid model whose thickness is near zero. This resultant solid model itself can be used for the analysis process because it is similar to a sheet model.

A surface extraction process is performed to create a mid-surface model. The face pair information of the model is still available for the topology of the model; therefore, one face of a pair can be selected to be extracted for a mid-surface model. Only the selected faces that are dominant components of a solid construct a new mid-surface model.

In fact, the mid-surface model has clearances between the faces so that they exist separately without being connected to each other. However, the clearance can be within the adjustable tolerance so that they can be connected by the merging function provided in the analysis package tools. For instance, a HyperMesh can process a group of surface models with clearance.

8. CASE STUDY

In order to demonstrate these techniques, we selected two typical thin-walled plastic parts used in the automotive or electronics industries. They were modeled

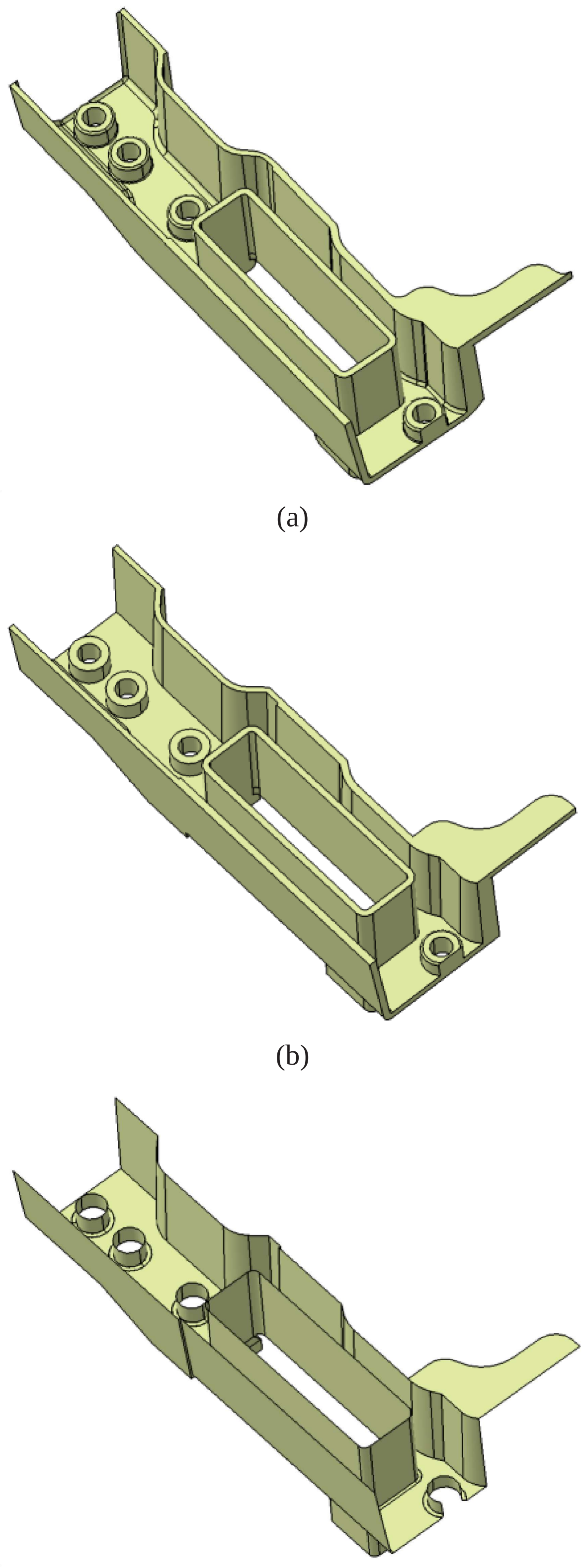


(a)

(b)

(c)

Figure 19 Mid-surface generation process for a cover part with ribs: (a) an original solid model, (b) a simplified model, and (c) a mid-surface model



(a)

(b)

(c)

Figure 20 Mid-surface generation process for a part of an automotive plastic part: (a) an original solid model, (b) a simplified model, and (c) a mid-surface model

in CATIA V5 and then converted to a mid-surface model using our system. Figures 19 (a), (b), and (c) show the original solid model for a cover part with ribs, its simplified model, and its mid-surface model, respectively. All small rounds or fillets were suppressed in the simplified model, as shown in Figure 19 (b). Figures 20 (a), (b), and (c) also show the same sequence of mid-surface generation steps. Since the implementation of our approach has not been completed yet, all processes were not performed automatically by the system. In such cases, the user intervened in the process and handled the model manually.

9. DISCUSSIONS

9.1. Zero-thickness model in CATIA

CATIA V5 supports non-manifold topological models represented by Selective Geometric Complexes (SGC) and provides a face replacement function that replaces the surface of a face with that of a given face. Therefore, if all the surfaces of the face pairs are replaced with their mid-surfaces, the solid may be converted to a mid-surface model. However, in practice, a solid is converted to a sheet model with some strange topologies. Table 1 shows the results of solid deflation for simple example models in CATIA. When a drafted T-rib and a rounded box with 10-mm thickness are deflated to zero-thickness solid models by the face replacement function, their topological information is changed, while the information is not changed when the solids are deflated to a near-zero-thickness model with 0.01-mm thickness. Thus, we utilize the offset surface with a tiny distance to the mid-surface in our deflation process to preserve the solid topology.

9.2. Feature-based simplification

This paper proposes a simplification for the purpose of reducing time-consuming deflation processes by removing small features that are not important in a part model. The main objective of the simplification process is to increase the efficiency of generating a mid-surface model. Because the simplified model is created by removing small features that can be ignored in the analysis process, it guarantees the accuracy of the analysis result even if it is different from the original detailed model. It decreases the computational load and time by reducing the level of complexity of a part model.

However, there are some limitations in this process. Since the module uses information from the feature tree, the part model must contain the feature tree. This implies that only a solid part model with feature information can be used with this algorithm. For implementation in CATIA CAA, several types of small features cannot be identified because some features do not have their own type. Therefore, extra approaches such as recognizing the geometric patterns of small features or using B-Rep information are considered, in addition to the feature type, to determine the small features to be removed.

9.3. Surface types

The algorithm is limited in its ability to detect diverse shapes of face pairs; it can find only planar and quadratic paired faces. As the pair detection method was developed only for planar and quadratic surface models in this paper, the face replacement function is also limited to such types of faces. However, part models of a product designed in the field comprise several curves and curved surfaces paired with other surfaces. Therefore, extended surface types should be considered.

9.4. Tangentially connected faces

When adjacent faces are connected with C^1-continuity and one of these faces is replaced by its new surface separately, this may break down the validity of a solid because the topology of the solid is destroyed, as shown in Figure 21. Thus, the tangentially connected faces should be detected and grouped together to replace the face geometry completely. This issue is essential for the deflation of curved surfaces.

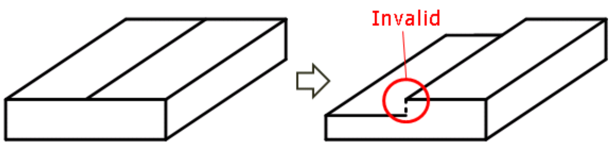
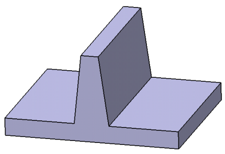
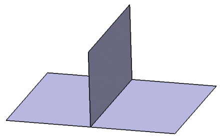
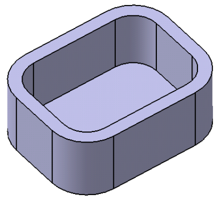
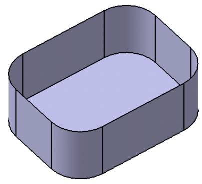


Figure 21 Topology invalidity that may arise within C_1-continuity case

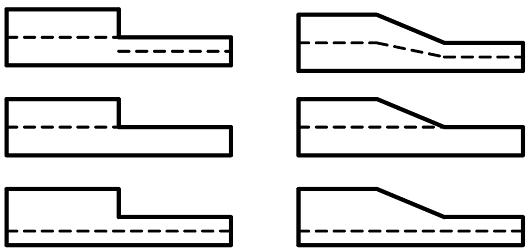
9.5. Ambiguity on mid-surface selection

There are several considerations to determine a mid-surface within a solid model. One case may have several alternatives to determine the mid-surface according to different viewpoints. The cross sections of models at the top of Figure 22 show different mid-surfaces (dashed lines) as decided under the different conditions. The models shown in Figures 22 (a) and (b) have ambiguities when determining the appropriate mid-surfaces for analysis because there are several choices. Some may select the top examples in Figure 22 as the ideal mid-surface; however, this creates a crack between the faces, which can perturb the analysis result. Any of the alternatives cannot be the ideal or the perfect answer for selecting the mid-surface. For our approach, face pairs are determined from faces separated by a pre-specified small distance; therefore, the differences in thickness are

Table 1 Comparison of topological information between a zero-thickness model and a near-zero-thickness model

Process	Before	After		Before	After	
Model						
Thickness	10 mm	0 mm	0.01 mm	10 mm	0 mm	0.01 mm
Vertex	16	12	16	32	24	32
Edge	24	15	24	48	40	48
Face	10	5	10	19	18	19

not the main issue for face pairing, and thus, the third examples shown in Figure 22 can be considered to be the mid-surface of each model. However, other alternatives may be selected according to the analysis conditions.



(a) (b)

Figure 22 Ambiguity in mid-surface selection

10. CONCLUSIONS

In this paper, we propose a new approach called the solid deflation method to convert a solid to a mid-surface. In this method, a solid is assumed to be a balloon filled with air. Thus, the solid itself can be converted into a zero-thickness model by deflating the air. In fact, in the algorithms, the detailed model is first simplified and then shrunken into a very thin solid; finally, one side of the solid is selected to extract a mid-surface model.

By introducing this method, a more practical and usable mid-surface model can be generated from a solid very efficiently and robustly because it can circumvent not only the tedious trimming and extension processes of the MAT method but also the time-consuming patch joining process of the mid-surface abstraction approach. In addition, our approach is implemented in CATIA V5 and thus it can be readily applied to engineering analysis in various industries.

However, our algorithms presented in this paper are currently applicable only to limited types of models: simple models comprising planar and quadratic surfaces with feature information. For future work, the surface types to be dealt with should be expanded to enlarge its capability for deflating a solid model. In addition, the feature recognition method needs to be considered to make our approach more robust and independent from feature information.

ACKNOWLEDGMENTS

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