Incremental Feature Generation and Modification during Design Evolution

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The concept of feature was introduced because of need to integrate the design and the manufacturing activities. Therefore, the generation of features usually occurs after design completion. However, in recent product development approaches such as concurrent engineering (CE), features need to be generated during design evolution. This paper presents an incremental feature generation (IFG) and feature modification (FM) approach applicable during design evolution, defined by constructive solid geometry (CSG) and boundary representation (B-rep). In IFG, a classified boundary component, obtained from boundary evaluation, is defined as a protrusion or depression (P/D) according to Boolean operation and convexity analysis. The existing features are then updated in accordance with feature interactions in the FM. The FM involves feature existence analysis and modification procedures. The modification procedures are ; 1) decide whether the remaining part of an existing feature is valid for a feature definition, 2) update it as a new feature and 3) define the feature relationship. In the IFG approach, the geometry of the current design step is automatically isolated by Boolean operation and defined as a protrusion or depression (P/D) without convexity calculation of topological entities such as edges or face sets. The above procedures are performed through tracing Boolean operations and convexity checking of an intersection edge loop generated during design evolution.

Key Words : Feature Interaction, Feature Modification, Concurrent Engineering

1. Introduction

The concept of feature was introduced because of need to integrate the design and the manufacturing activities. Therefore, the generation of features usually occurs after design completion. However, in recent product development approach such as concurrent engineering (CE), features need to be generated during design evolution. Previous research for generating features falls broadly into three basic approaches : automatic feature extraction (FEX), feature based design (FBD) and manual feature identification (FID). Automatic feature extraction (FEX) systems (Choi, 1982 ; Hende, 1984 ; Joshi, 1988 ; Flori, 1989) searches complete part information for predefined template patterns, using several schemes such as graph matching, pattern matching and the logic approach. In the feature based design (FBD) approach (Dixon, 1985 ; Ostro, 1987 ; Cutro, 1988 ; Shah, 1991), a user adds predefined features and monitors the interaction of the added features. In the manual feature identification (FID) (Chang, 1982 ; Chen, 1982 ; Humme, 1986), a user manually defines the features and their interaction relationships. As discussed, the previous works emphasized generating features either before or after a design. It requires a new scheme to generate the features as the design evolves. In addition, the feature interaction is a fundamental problem in the feature generation during design evolution. However, the above three basic approaches are not capable of resolving the feature interaction.

The FEX systems are only appropriate for

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defining the basic features because of the use of templates. Even if they can handle certain simple kinds of feature interactions, none of them are capable of handling arbitrary interactions. Because the user adds individual features according to functional requirements while the interaction arises in the detailed topological or geometrical information, a scheme to monitor and update the interaction automatically is necessary in a FBD approach. In the FID, a user needs to define the interacting features and their relationships. Most of the above cases have limitaions in handling the feature interactions automatically. Thus several methods have been proposed to solve the feature interaction problems. In Rossignac's work (1988), the feature interaction relationship is traced as a new feature is added; however the existing feature is not automatically redefined or modified. Vandenbrande (1990) proposed a method to recognize interacting features and to decompose them into simple features. His method uses a blend of artificial intelligence techniques and computational geometry techniques to decompose the delta volume into machining features. Thus, his method which requires defining a stock volume has limitation for general applications. Chen (1992) also proposed the method of spatial reasoning on form feature interaction. Chen's method supports the analysis of feature interactions, but it is limited to feature-based design using solid primitive features.

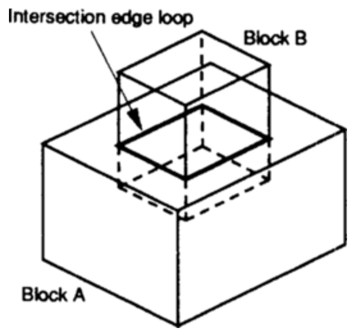
As discussed, even these approaches proposed specifically for interaction problems are limited to certain applications. Thus, this paper presents a scheme for incremental feature generation and feature modification, generating a feature as the design evolves and automatically redefining the interacting feature. The features in this paper are protrusion or depression (P/D) as defined by Kyprianou (1980):

Protrusion feature: a convex face set closed by a concave boundary loop
Depression feature: a concave face set closed by a convex boundary loop

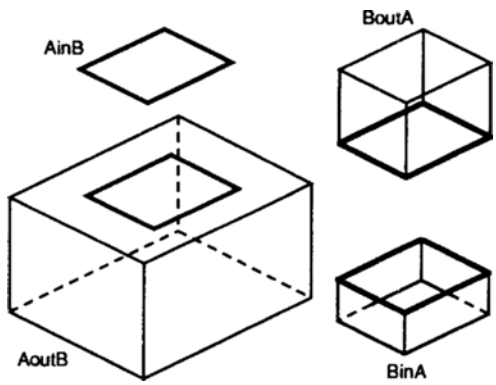
In the following sections, an incremental feature generation scheme is introduced and the feature interaction is briefly discussed. Then the feature existence analysis and feature modification procedure are discussed in detail. Finally, the proposed scheme is applied to an example for illustration.

2. Incremental Feature Generation

In incremental feature generation (IFG), as a designer represents his design intent by creating local geometry on a part, shape features resulting rom the local geometry are automatically generated. In this paper, the evolving part geometry is defined by constructive solid geometry (CSG) and boundary representation (B-rep). The part geometry is constructed with a primitive and a Boolean operation at each design step. The boundary information of an evolving part geometry at each design step is obtained by boundary evaluation. As a new primitive coimbines with an existing solid, a new feature is generated. The feature generation procedure continues until the design is



(a) Intersection of two blocks



(b) Classified components (B-comp)

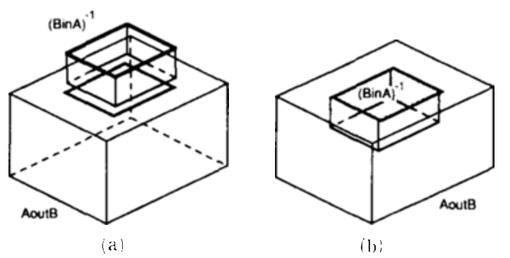
Fig. 1 Boundary classification

completed. In the new feature generation, a classified boundary component, obtained from a boundary evaluation procedure (Manty, 1988), representing the geometry of the current design step, is defined as a protrusion or a depression (P/D) according to its convexity properties of its topological entities such as a face set and its boundary loop.

In IFG, a boundary evaluation procedure from CSG to B-rep is necessary to generate boundary information of evolving design. It uses set-membership classification (Manty 1988). Figure 1(a) shows interaction of two blocks by a Boolean operation. First, the boundary evaluation procedure generates an intersection edge loop(I-loop) between boundaries of the two blocks as shown by the heavy lines in Fig. 1(a). The intersection edge loop(I-loop) splits each boundary of the solid into two parts, AinB and AoutB and BoutA and BinA respectively as shown in Fig. 1(b). They are obtained by 4-way classification (Manty, 1988) and named "classified boundary components (B-comp)" in this paper. From the components of the 4-way classification, the results of Boolean operations can be computed as follows:

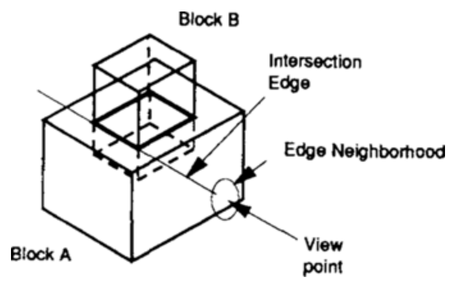
$$\begin{aligned} A\cup B &= A\mathrm{out}B \otimes B\mathrm{out}A \\ A\cap B &= A\mathrm{in}B \otimes B\mathrm{in}A \\ A-B &= A\mathrm{out}B \otimes (B\mathrm{in}A)^{-1} \end{aligned} \qquad (1)$$

where $\otimes$ denotes the gluing operation, and $(B\mathrm{in}A)^{-1}$ denotes the "complement" of $B\mathrm{in}A$, ie, $B\mathrm{in}A$ with the orientation of all faces reversed. Fig. 2 shows a new solid obtained by gluing $(B\mathrm{in}A)^{-1}$ on $A\mathrm{out}B$ according to the difference ($-$) Boolean operation. The B-comp, $(B\mathrm{in}A)^{-1}$, forms a depression because $(B\mathrm{in}A)^{-1}$ is a concave face set with an I-loop being a convex boundary loop. This is shown by convexity analysis of the I-loop and a face set of $(B\mathrm{in}A)^{-1}$. For the convexity analysis, edge neighborhood model (Morte, 1985) is adopted and convexity of boundary surface is introduced. If two plane boundary surfaces of solids intersect with each other, the intersection edge (Fig. 3(a)) is either convex or concave according to the Boolean operation. A difference operation ($-$) generates a "convex intersection edge," and a union operation ($\cup$) generates a "concave intersection edge" (Fig. 3(b)). On the other hand, when the primitives A and B are convex solids, the face set of a boundary surface of the primitives always form a convex

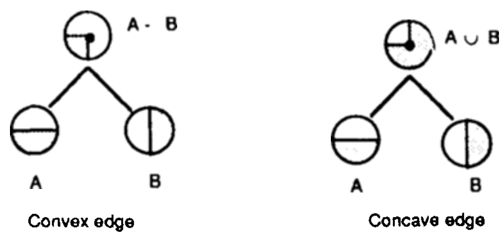


(a) $A-B = \mathrm{AoutB} \otimes (\mathrm{BinA})^{-1}$ $\otimes$: gluing
(b) $(\mathrm{BinA})^{-1}$ = Depression

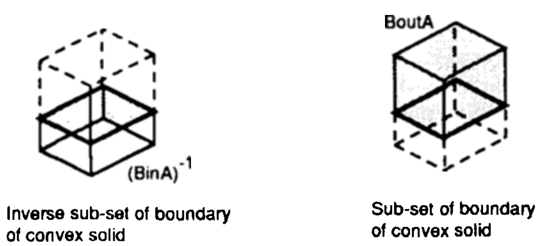
Fig. 2 New solid by gluing and recognized depression



(a) Intersection of two solids



(b) Edge neighborhood model for I-loop



(c) Convexity properties of classified components

Fig. 3 Convexity analysis of B-comp

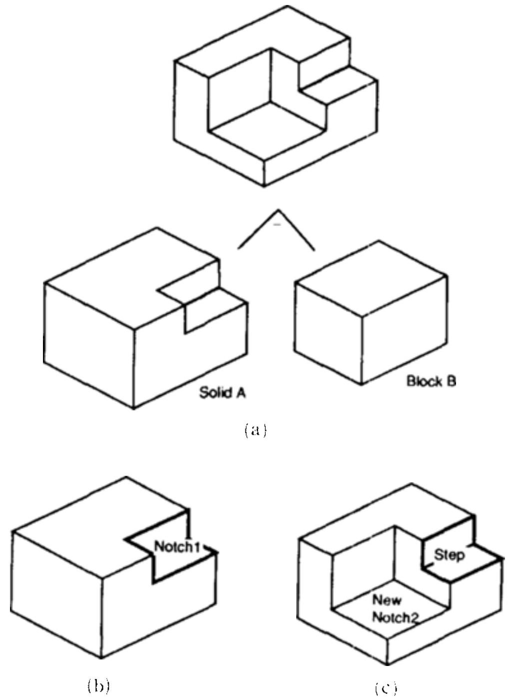
face set and the edges on a boundary surface are always convex edges. $B\text{in}A$ is a subset of boundary of the convex solid Block B, and the $(B\text{in}A)^{-1}$ represents "complement" of $B\text{in}A$ which changes convexity of a face set so that $(B\text{in}A)^{-1}$ is a concave face set (Fig. 3(c)). According to the above analysis, I-loop of $(B\text{in}A)^{-1}$ is a convex edge loop and a face set of $(B\text{in}A)^{-1}$ is a concave face set so that $(B\text{in}A)^{-1}$ in Fig. 2 forms a depression relative to $A\text{out}B$, which is defined as P/D. Similary, if a Boolean operation is union ($\cup$), the $B\text{out}A$ of the classified components forms a protrusion relative to $A\text{out}B$. Thus, whenever a new convex primitive (B) is operated on an existing solid (A) with generating a closed intersection edge loop, a classified boundary surface of the solid B, $(B\text{in}A)^{-1}$ or $B\text{out}A$, is defined as a depression or a protrusion as follows:

$$
\begin{aligned}
&A \cup B = A\text{out}B \otimes B\text{out}A \\
&B\text{out}A \rightarrow \text{Protrusion} \\
&A - B = A\text{out}B \otimes (B\text{in}A)^{-1} \\
&(B\text{in}A)^{-1} \rightarrow \text{Depression} \qquad (2)
\end{aligned}
$$

The intersection operation is not included because it does not generate a protrusion or a depression. If the intersection edge loop is not closed, $(B\text{in}A)^{-1}$ or $B\text{out}A$ can not be simply defined as P or D according to Boolean operation. This case occurs when features interact each other and it will be discussed in the following sections. For implementation of this IFG approach, a module to check Boolean operators and a closed I-loop is required to be embedded into a conventional CAD system.

3. Feature Interaction

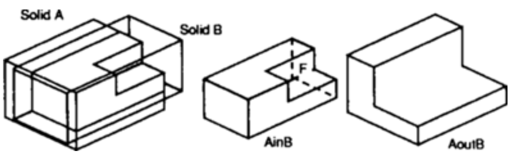
The feature interaction is fundamental in IFG. As a design evolves by Boolean operations with primitives, previously defined features interact with a new primitive. This interaction changes existing features according to the interaction relationships. Figure 4 illustrates this by an example. When a Block B is subtracted from a Solid A (Fig. 4(a)), the existing feature, Notch 1 (Fig. 4(b)), is changed to a Step feature, while a new



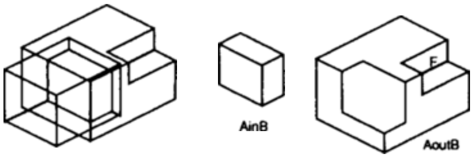
(a) Design evolution by Boolean operation
(b) Feature at design step i : Notch
(c) Feature at design step i+1 : Step

Fig. 4 Necessity of feature modification

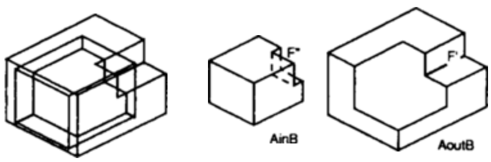
feature Notch 2 is generated by the Block B (Fig. 4(c)). Thus, as the design evolves, the existing features need to be updated according to the interaction relationships. First of all, the interaction between existing features and a new primitive needs to be defined. The cases for modification then need to be specified. Finally, the procedures for each case need to be developed. The interaction is defined by 4-way, 8-way and generalized 4-way classification (Manty, 1988) in this approach. The interaction cases are shown in Fig. 5 : an existing feature (F) is removed from a new primitive (Fig. 5(a)) ; an existing feature remains without interaction with a new primitive (Fig. 5(b)) ; and an existing feature is modified by a new primitive (Fig. 5(c)). Thus, the last case needs modification procedures to redefine the existing feature. This last case can be further classified into three cases : a part of a feature face set including its boundary edges is removed ; a part of a feature face set excluding its boundary



(a) $F \subset AinB \rightarrow F \not\subset \partial S$



(b) $F \subset AoutB \rightarrow F \subset \partial S$



(c) $F \subset AinB$ and $AoutB \rightarrow F' \subset \partial S$

Fig. 5 Feaure existence by 4-way classification

edges is removed; and the convexity of feature boundary edges is changed. For each of these cases, modification procedures need to be developed. The details of interaction analysis and modification procedures for each case are discussed in the following sections.

4. Feature Existence Analysis

As a design evolves, the previously defined feature face set interacts with the boundary of a new primitive. Feature faces are then removed or modified according to interaction relationships. Thus, the existence of an existing feature for interaction relationship needs to be analyzed. The previously defined features are assumed always to exist on a solid A when a Boolean operation, $A < OP > B$, is performed and a solid B is always a primitive. The existing feature (F) is contained in one of, or a combination of, the following classified components of the boundary of solid A (∂A):

$$F \subset \partial A \rightarrow F \subset \varnothing(C1, C2, \cdots, Cn)$$

where $\varnothing$(.) represents a union of subsets of(.), and Ci represents a classified boundary component. (3)

The combinations in Eq. (3) can be characterized according to the 4-way or 8-way classifications (Manty, 1988). The feature existence analysis by 8-way classification can be simplified to a generalized 4-way classification, which is used for generalized feature existence analysis in this research.

Existence by 4-way Classification: Using 4-way classification, surface contact between boundary surfaces of two solids A and B is not allowed. When the two solids intersect each other, the boundary of Solid $A(\partial A)$ is classified into two components as follows:

$$\partial A \rightarrow A\text{out}B,\ A\text{in}B \tag{4}$$

Thus, an existing feature (F) is contained in A out$B$, Ain$B$, or both of them as follows:

$$\begin{aligned} & F \subset \partial A \\ \rightarrow\ & F \subset \varnothing(A\text{out}B,\ A\text{in}B) \\ \rightarrow\ & F \subset A\text{in}B \\ & F \subset A\text{out}B \\ & F \subset A\text{out}B \text{ and } A\text{in}B \end{aligned} \tag{5}$$

Figure 5 illustrates the feature existence of Eq. (5) by the 4-way classification. Consider a new solid formed by a Boolean operation; the solids which are formed by union or difference operation are as follows:

$$\begin{aligned} A \cup B &= A\text{out}B \otimes B\text{out}A \\ A - B &= A\text{out}B \otimes (B\text{in}A)^{-1} \end{aligned} \tag{6}$$

where $\otimes$ represents gluing operation of two boundary components, and $(B\text{in}A)^{-1}$ represents a complement boundary component of Bin$A$, which has an inverse face normal to Bin$A$. Thus, the effects of Boolean operation, either union or difference, on a feature F on a solid A are:

(a) If F is contained in Ain$B$ (Fig. 5(a)), F is removed from the boundary of the new solid because Ain$B$ does not exist in the boundary of the new solid according to Eq. (6);

(b) If F is contained in Aout$B$ (Fig. 5(b)), then F remains in the new solid without interaction with a new boundary component because A out$B$ exists unchanged in the boundary of the new solid;

(c) If F is contained in both Ain$B$ and Aout B (Fig. 5(c)), the part of F in Aout$B$ (F')

remains in a boundary of a new solid and the other part of F in $A\text{in}B$ (F'') is removed according to Eq. (6). In this case, F' needs to be redefined as a new feature because it is different from the original F. Thus, a face set of a feature F results in a new solid (S) as follows:

$$\begin{array}{lll} \text{when } F \subset A\text{in}B & F \not\subset \partial S & \\ \text{when } F \subset A\text{out}B & F \subset \partial S & \\ \text{when } F \subset A\text{in}B \text{ and } A\text{out}B & F' \subset \partial S & (7) \end{array}$$

According to the Eq. (7) and examples in Fig. 5, when $F \subset A\text{in}B$ and $A\text{out}B$, the feature F needs to be modified for a valid protrusion or depression feature.

Existence by 8-way Classification: If the boundary surfaces of two solids are allowed to touch each other, the boundary of a solid $A(\partial A)$ is classified into four components as follows by 8-way classification:

$$\partial A \rightarrow A\text{out}B,\ A\text{on}B+,\ A\text{on}B-,\ A\text{in}B$$

where $+(-)$ represents touching in the same (different) face normal (8)

Thus, an existing feature (F) is contained in a subset of the four components as follows:

$$F \subset \partial A \rightarrow F \subset \varnothing(A\text{out}B,\ A\text{on}B+,\ A\text{on}B-,\ A\text{in}B)$$

where $\varnothing(.)$ represents a union of a subset of(.) (9)

Existence by Generalized 4-way Classification: If the reclassification rules (Manty, 1988) are applied to the classified boundary components by 8-way classification, they are simplified as follows:

$$\partial A \rightarrow \langle A\text{out}B \rangle,\ \langle A\text{in}B \rangle$$

where, when $A \cup B$,

$$\text{then } \langle A\text{out}B \rangle = A\text{out}B \otimes A\text{on}B+,$$
$$\langle A\text{in}B \rangle = A\text{in}B \otimes A\text{on}B-$$

when $A - B$,

$$\text{then } \langle A\text{out}B \rangle = A\text{out}B \otimes A\text{on}B-,$$
$$\langle A\text{in}B \rangle = A\text{in}B \otimes A\text{on}B+ \qquad (10)$$

Thus, a feature existence similar to Eq. (5) is as follows:

$$\begin{array}{ll} F \subset \partial A & \\ \quad \rightarrow F \subset \varnothing(\langle A\text{out}B \rangle,\ \langle A\text{in}B \rangle) & \\ \quad \rightarrow F \subset \langle A\text{in}B \rangle & \\ \quad F \subset \langle A\text{out}B \rangle & \\ \quad F \subset \langle A\text{out}B \rangle \text{ and } \langle A\text{in}B \rangle & (11) \end{array}$$

Similar to Eq. (6), new solids are obtained as follows:

$$\begin{array}{ll} A \cup B = \langle A\text{out}B \rangle \otimes B\text{out}A & \\ A - B = \langle A\text{out}B \rangle \otimes (B\text{in}A)^{-1} & (12) \end{array}$$

In this case, the feature existence depends on Boolean operations. If a feature exists only in either $A\text{out}B$ or $A\text{in}B$, the existence is not affected by Boolean operations because $A\text{out}B$ always is $\langle A\text{out}B \rangle$ and $A\text{in}B$ is always $\langle A\text{in}B \rangle$ according to Eq. (10). However, if any part of the existing feature is contained in $A\text{on}B+$, $A\text{on}B-$ or both, features existence is affected by Boolean operations through Eq. (11). For example, a feature existing in $A\text{in}B$ and $A\text{on}B-$ exists in $\langle A\text{in}B \rangle$ for $A \cup B$, and it is removed from the resultant solid. On the other hand, a feature existing in $A\text{in}B$ and $A\text{on}B-$ exists in $\langle A\text{out}B \rangle$ and $\langle A\text{in}B \rangle$ for A−B, and a part of F, $F' \subset \langle A\text{out}B \rangle$ remains at a new solid, and the other part of F, $F'' \subset \langle A\text{in}B \rangle$, is removed. Thus, feature existence in Eq. (7) can be used when surface contact are allowed by replacing boundary components in Eq. (7) with $\langle$boundary component$\rangle$ as follows;

$$\begin{array}{lll} \text{when } F \subset \langle A\text{in}B \rangle & F \not\subset \partial S & (13a) \\ \text{when } F \subset \langle A\text{out}B \rangle & F \subset \partial S & (13b) \\ \text{when } F \subset \langle A\text{in}B \rangle \text{ and } \langle A\text{out}B \rangle & & \\ \quad F' \subset \partial S & & (13c) \end{array}$$

Feature Existence Cases: Among the three cases in Eq. (13), Eq. (13c) is a typical case requiring modification. In Eq. (13c), F is divided into two portions:

$$\begin{array}{ll} F \subset \langle A\text{out}B \rangle \text{ and } \langle A\text{in}B \rangle & \\ \rightarrow F' \langle A\text{out}B \rangle \text{ and } F'' \subset \langle A\text{in}B \rangle & (14) \end{array}$$

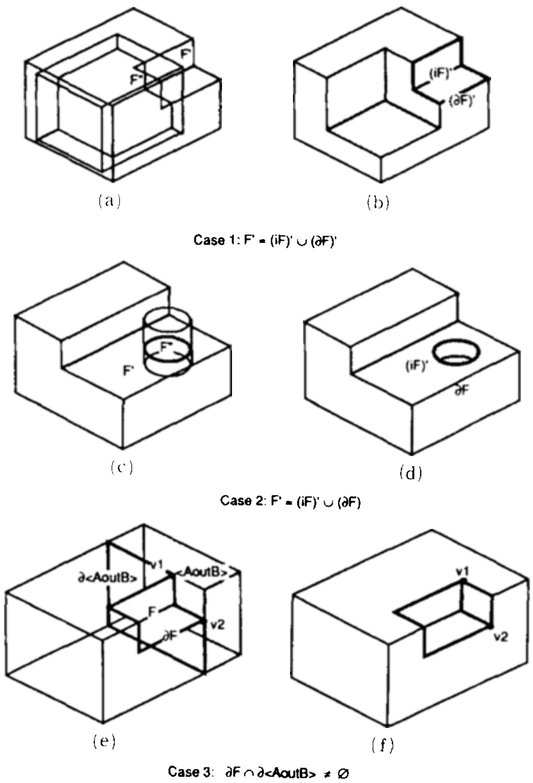
In the above, $F' \subset \langle A\text{out}B \rangle$ remains in a new solid while $F'' \subset \langle A\text{in}B \rangle$ is removed. Therefore, the modification algorithm is necessary for F', which can be defined as a union of two sets as follows:

$$F' = (iF)' \cup (\partial F)' \qquad (15a)$$
$$F' = (iF)' \cup (\partial F) \qquad (15b)$$
$$F' = (iF) \cup (\partial F)' \qquad (15c)$$

In Eq. (15), iF and ∂F represent the interior of F and the boundary of F respectively, and $(iF)'$ represents a part of iF, and $(\partial F)'$ represents a part of ∂F. Among the three cases in Eq. (15), case (c) is not valid because F' is defined as a part of a face set, not all of a face set of F (interior F).

Figure 6 shows an example of the case in Eq. (15). The feature F is divided into F′ and F'', where F' is made of $(iF)'$ and $(\partial F)'$ in Fig. (6(b)), and F′ is made of $(iF)'$ and (∂F) in Fig. (6(d)). On the other hand, Eq. (13b) has two cases as follows:

$$F \subset \langle A\text{out}B \rangle$$
$$\rightarrow F \subset \langle A\text{out}B \rangle$$



(a) Intersection with new primitive
(b) Resultant feature
(c) Intersection with new primitive
(d) Resultant feature
(e) Common edge path
(f) New feature in resultant solid

Fig. 6 Two cases for F⊂⟨AoutB⟩ and ⟨AinB⟩

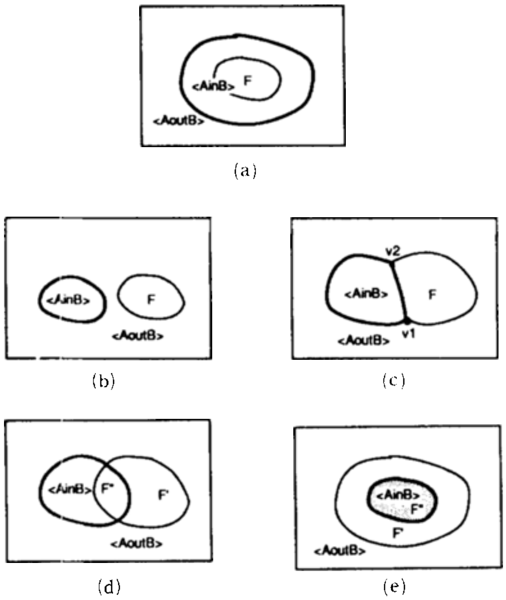
$$\text{with } \partial F \cap \partial\langle A\text{out}B \rangle = \varnothing \quad (16a)$$
$$\rightarrow F \subset \langle A\text{out}B \rangle$$
$$\text{with } \partial F \cap \partial\langle A\text{out}B \rangle \neq \varnothing \quad (16b)$$

In Eq. (16a), a new boundary component, glued with $\langle A\text{out}B \rangle$, has no effect on the existing feature F. However, in Eq. (16b), a new boundary component has an effect on the existing feature F because the intersection edge of $\langle A\text{out}B \rangle$ and a new boundary component may change the convexity of boundary edges of F. Figures 6(e) and (f) show an example of case (b) in Eq. (13). In Fig. 6(e), the path from $v1$ to $v2$ is the common edge shared by ∂F and $\partial\langle A\text{out}B \rangle$, and while originally convex as a boundary edge loop of depression F, it is changed to concave in the new solid in Fig. 6(f). Therefore, case b) in Eq. (13) needs to be considered as a case which needs modification. Considering Eqs. (13)~(16), the feature existence can be generalized as follows:

$$F \subset \langle A\text{in}B \rangle \quad (17a)$$
$$F \subset \langle A\text{out}B \rangle$$
$$\text{with } \partial F \cap \partial\langle A\text{out}B \rangle = \varnothing \quad (17b)$$
$$F \subset \langle A\text{out}B \rangle$$
$$\text{with } \partial F \cap \partial\langle A\text{out}B \rangle \neq \varnothing \quad (17c)$$
$$F \subset \langle A\text{out}B \rangle \text{ and } \langle A\text{in}B \rangle$$
$$(iF)' \subset \langle A\text{out}B \rangle \text{ and } (iF)'' \subset \langle A\text{in}B \rangle$$
$$(\partial F)' \subset \langle A\text{out}B \rangle \text{ and } (\partial F)'' \subset \langle A\text{in}B \rangle \quad (17d)$$
$$F \subset \langle A\text{out}B \rangle \text{ and } \langle A\text{in}B \rangle$$
$$(iF)' \subset \langle A\text{out}B \rangle \text{ and } (iF)'' \subset \langle A\text{in}B \rangle$$
$$(\partial F) \subset \langle A\text{out}B \rangle \quad (17e)$$

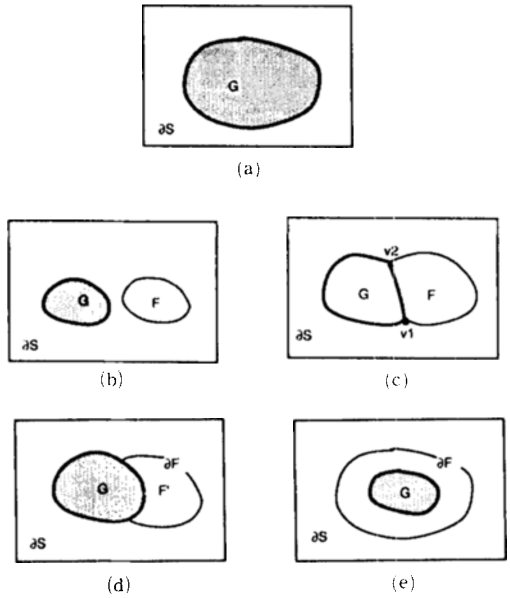
Figure 7 shows the plane models (Manty, 1988) of the above cases in Eq. (17). It displays the feature existence on an old solid. On the other hand Fig. 8 displays the existence on a new solid. In Eq. (17a) (Fig. 8(a)), F does not exist in a new solid, so that F is removed from a feature data base. The feature in Eqs. (17b) (Fig. 8(b)) remains without any interaction. On the other hand, F in Eqs. (17c), (17d), (17e), (Figs. 8(c), (d), (e)) require modification procedures.

In case of Fig. 8(c), only the boundary edges of feature F interact with the new boundary edges of G. This requires a modification algorithm to update F because a protrusion or depression definition of F may change due to the convexity



(a) $F\subset\langle AinB\rangle$
(b) $F\subset\langle AoutB\rangle$ and $\partial F\cap\partial\langle AoutB\rangle=\emptyset$
(c) $F\subset\langle AoutB\rangle$ and $\partial F\cap\partial\langle AoutB\rangle\neq\emptyset$
(d) $F\subset\langle AinB\rangle$ and $\langle AoutB\rangle$ and $F'=(iF)'\cup(\partial F)'$
(e) $F\subset\langle AinB\rangle$ and $\langle AoutB\rangle$ and $F'=(iF)'\cup(\partial F)$

Fig. 7 Plane models of feature existence of old solid



(a) $F\not\subset\partial S$
(b) $F\subset\partial S$ and $\partial F\cap\partial G=\emptyset$
(c) $F\subset\partial S$ and $\partial F\cap\partial G\neq\emptyset$
(d) $F'\subset\partial S$ and $F''\not\subset\partial S$ and $(\partial F)'\subset\partial S$
(e) $F'\subset\partial S$ and $F''\not\subset\partial S$ and $(\partial F)\subset\partial S$

Fig. 8 Plane models of feature existence of new solid

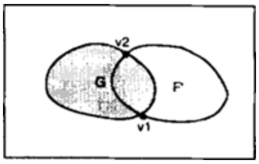
change of the boundary edges of F. In Fig. 8(d), a part of a boundary edge loop, $(\partial F)''$ and a part of a face set F, $(iF)''$, is removed, and the other part of F, $(\partial F)'$ and $(iF)'$, remains. Therefore, the remaining part needs to be defined as a new protrusion or depression. In the case of Fig. 8(e), only a part of the face set of F is removed, and a new face set G from a new primitive replaces it so that a feature definition of F may change according to a new face set. They are summarized as the following three cases :

Both iF and ∂F are removed	(18a)
Only iF is removed	(18b)
Only ∂F is affected	(18c)

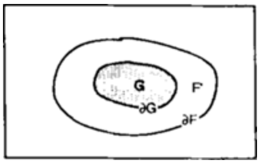
These three cases are referred to as Case A, Case B and Case C for modification procedures in what follows. When a modeling is based on the local operation (Chiyo, 1988), a user defines a new feature boundary loop (FBL) on the surface of a solid and creates a protrusion or a depression inside the FBL. The FBL is the same as the I-loop and the user-defined-feature is the same as a new face set G in case of using Boolean operation. Then the rest of the modification procedure is the same as the Case A, B and C.

5. Feature Modification Procedure

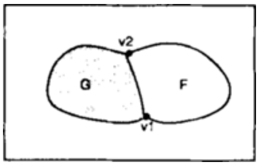
Modification procedures are developed for the three cases of Eq. (18), in which solids have plane or cylindrical surfaces, and the solid angle is either 90° or 270°. It is assumed that : in Case A, there are only two intersection points, $v1$ and $v2$, between a boundary loop of $F(\partial F)$ and a boundary loop of $G(\partial G)$, as shown in Fig. 9 (a) ; in Case B, ∂G inside iF does not interact with ∂F (Fig. 9(b)) ; in Case C, common edges of ∂F and ∂G are a continuous edge path which has only one starting point ($v1$) and one end point ($v2$). Moreover, the interaction is limited to only the two-feature interaction in the above three cases. The modification procedures for each case decide



(a) Case A : Both iF and ∂F are removed

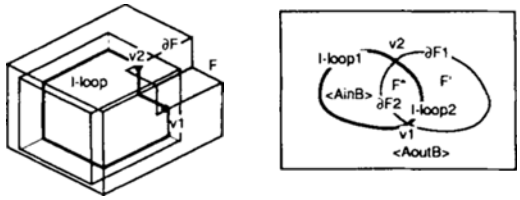


(b) Case B : Only iF is removed

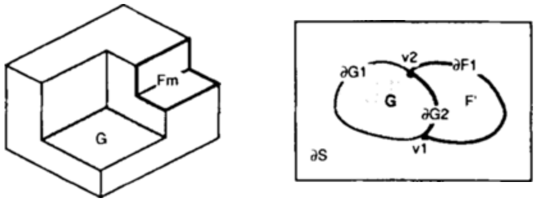


(c) Case C : Only ∂F is effected

Fig. 9 Three feature interaction cases for modification



(a) (b)



(c) (d)

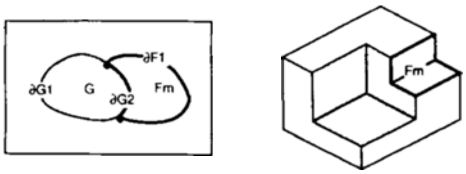
(a) An old solid and I-loop
(b) A plane model of (a)
(c) A new solid with a modified feature
(d) A plane model of (c)

Fig. 10 A feature modification example

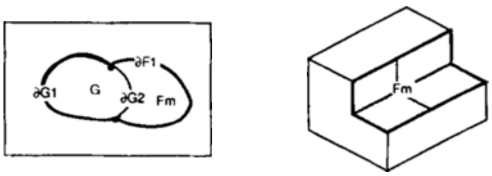
whether the remaining part of the existing feature F, (F' in Case A and Case B and F in Case C) in Fig. 9, it is valid for a new protrusion or depression feature.

5.1 Case A

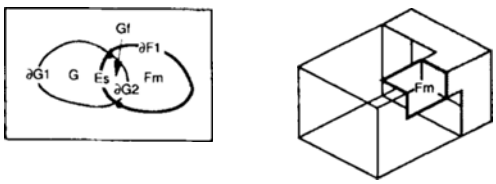
Figure 10 shows a typical case of the modification procedure with its plane model. The new intersection loop (I-loop) divides F into $F' \subset \langle A\ \mathrm{out} B\rangle$ and $F'' \subset \langle A \mathrm{in} B\rangle$, generating the intersection points, $v1$ and $v2$, with ∂F. The ∂F and I-loop are divided into two parts such as $\partial F1$ and $\partial F2$, and I-loop1 and I-loop2. In the new solid (Fig. 10(c)), I-loop is a boundary loop of a new boundary component G. The existing feature F remains after losing a face set F'' so it is no longer valid for protrusion or depression (P/D) definition. Therefore, F' needs to be redefined as a new P/D feature. There are three possible cases for redefining F' as a new P/D with additional topological entities. The cases shown in Figs. 11(a), (b) and (c) are referred to as Case A. 1, Case A. 2 and Case A. 3 respectively. First of all, F' is redefined as a new feature without any additional topological entities (Case A. 1). Secondly, F' is redefined as a new feature with



(a) Case A.1 : F and G by same Boolean OP (∂G2 is a set of edges)



(b) Case A.2 : F and G by same Boolean OP (∂G2 is no edge)



(c) Case A.3 : F and G by different Boolean OP.

Fig. 11 Feature modification and examples : Case A

Table 1 Feature modification procedure for case A

Case	Existing feature	Boolean operation for F	Boolean operation for G	Edges in $\partial G1$	Edges in $\partial G2$	Result feature	New feature(Fm)
Case A.1	D(P)	$-(\cup)$	$-(\cup)$		not broken	D(P)	• Fm = F′ • ∂Fm = ∂F1 ⊕ ∂G2
Case A.2	D(P)	$-(\cup)$	$-(\cup)$	not broken	totally broken	D(P)	• Fm = F′⊗G • ∂Fm = ∂F1 ⊕ ∂G1
Case A.3	D(P)	$-(\cup)$	$\cup(-)$			D(P)	• Fm = F′⊗Gf • ∂Fm = ∂F1 ⊕ Es

⊗:gluing two boundary surfaces ⊕:gluing two boundary edge paths
D(P):Depression(or Protrusion)

additional topological entities, which has two cases; one including all of G(Case A. 2) and the other including a part of G(Case A.3).

Case A.1 : When F and G are obtained by the same Boolean operation, and a new boundary segment ($\partial G2$) is an actual edge path, only F' is redefined as the same P or D as F. The new boundary loop of a new feature Fm is a connected loop with $\partial F1$ and $\partial G2$.

Case A.2 : On the other hand, when F and G are obtained by th same Boolean operation, and the new boundary segment ($\partial G2$) is not an actual edge path, the whole of G needs to be with F' in a new feature because its new boundary loop ($\partial F1 \oplus \partial G2$) is not an actual edge loop enclosing F'. In addition, the $\partial G2$ should be a dummy edge loop because any edge path in both G and F' has convexity different from $\partial F1$. The $\partial G1$ also should be an actual edge path to be a boundary edge loop for a new feature. The face set of the new feature is a connected face set consisting of G and F' and its boundary edge loop is $\partial F1 \cup \partial G1$.

Case A.3 : When the Boolean operations generating G and F are different, F' requires a part of $G(Gf)$. ∂G has different convexity from $\partial F1$ so that $\partial G1$ or $\partial G2$ cannot be a part of new boundary loop with $\partial F1$. On the other hand, any edge path inside G has the same convexity as $\partial F1$. However, the face set Gf should not have any edge path because any edge path inside G has convexity different from that in F' which results in Gf having face convexity different from that of F'. In consequence, a part of $G(Gf)$ needs to be included in a new feature. Therefore, the new feature is a connected face set of F' and Gf, and its new boundary is Es and $\partial F1$.

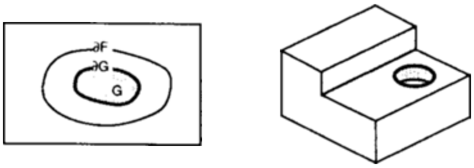
The above three modification procedures are summarized in Table 1. According to the protrusion/depression definition in the section 1, the Fm and F' are two-dimensional face sets (2-manifold), and ∂Fm, $\partial F1$, $\partial G1$, $\partial G2$ and Es are one-dimensional edge paths in the Table 1.

5.2 Case B

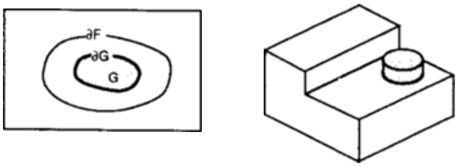
In Case B, a new boundary component G exists inside of F as shown in Fig. 9 (b) so that F can be modified according to the convexity of ∂G or iG. For the modification procedure, the three cases for Case B are defined as shown in Fig. 12.

Case B.1 : If G is defined to have the same P/D as F (Fig. 12 (a)), ∂G can be another boundary loop of F' because the edge loop of ∂G has the same convexity as ∂F. F' is then defined as a new feature Fm because it is enclosed by ∂F and ∂G. Fig. 12(a) shows an example of this case. The previous feature was a depression (Step). At the next design step, another depression (Blind-hole) is created inside of the Step feature. However, the Step feature which lost part of its face still satisfies the depression definition. Thus, it is updated as depression Step 1, one of a family of Step features.

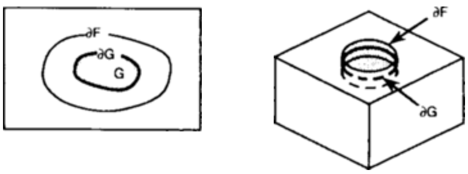
Case B.2 : If G is defined to have a different P/



(a) Case B.1 : F and G by Same Boolean operation (∂G is a set of edges)



(b) Case B.2 : F and G by different Boolean operation (∂G is a set of edges)



(c) Case B.3 : F and G by Same Boolean operation (∂G is no edge)

Fig. 12 Feature modification and examples : Case B

D from F, F' cannot be defined as another P/D. The new edge loop ∂G on F' has convexity different from that of ∂F. On the other hand, G cannot be combined with F' as a new feature because G has convexity different from that of a face set of F'. Thus, in this case, the existing feature needs to be manually defined as a compound depression or protrusion (Dc/Pc) including G. Therefore, the new feature is a compound face set consisting of F' and G, and its new boundary loop is ∂F. Fig. 12(b) shows an example where a previous depression (Step) feature violates the depression definition for Step feature and is redefined as a Dc, Step-with-Boss.

Case B.3 : If G is obtained by the same Boolean operation as F, and ∂G does not have an actual edge (Fig. 12(c)), F and G are combined as a new feature because both face sets in iF and iG have the same convexity. ∂F is then a new boundary of Fm. Fig. 12(c) shows an example of this case, where a cylinder is subtracted from a Block to make Blind-hole with a greater depth.

The procedures for each of the above cases are summarized in Table 2.

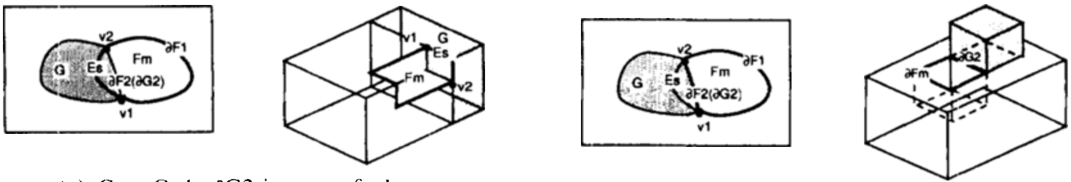
5.3 Case C

Case C is similar to the case A.3. $\partial F2$ has lost its original convexity and $\partial G2$ cannot become boundary edges of a modified feature without additional assumptions. This case occurs when F is a depression and G is obtained by the union ($\cup$) operation, or F is a protrusion and G is obtained by the difference ($-$) operation. The modification procedure is similar to the Case A. 3, but is requires two cases such that $\partial G2$ is a set of edges and $\partial G2$ is no edges.

Case C.1 : When $\partial G2$ is a set of edges and the convexity of $\partial F2$ is changed, the new edge path from $v2$ to $v1$ is necessary for a new P/D definition. The new edge path is only obtained from edges inside of G because the edges have the same convexity as ∂F by a Boolean operation. Shown in Fig. 13(a), a depression (Notch) feature is changed to another depression (Blind-step) feature.

Table 2 Feature modification procedure for case B

Case	Existing feature	Boolean operation for F	Boolean operation for G	Edges in ∂G	Result feature	New feature
Case B.1	D(P)	−(∪)	−(∪)	not broken	D(P)	• $Fm = F'$ • $\partial Fm = \partial F \oplus \partial G$
Case B.2	D(P)	−(∪)	∪(−)	not broken	Dc(Pc)	• $Fm = F'(G)$ • $\partial Fm = \partial F \oplus \partial G$
Case B.3	D(P)	−(∪)	−(∪)	totally broken	D(P)	• $Fm = F' \otimes G$ • $\partial Fm = \partial F$



(a) Case C. 1 : $\partial G2$ is a set of edges

(b) Case C. 2 : $\partial G2$ is no edge

Fig. 13 Feature modification and example : Case C

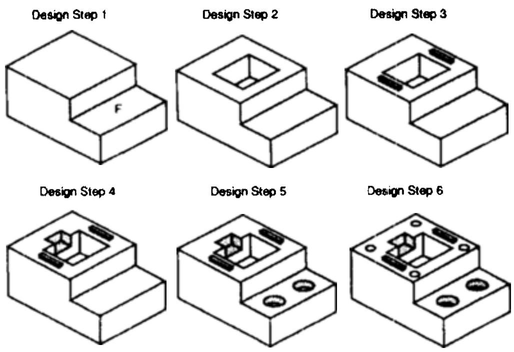
Table 3 Feature modification procedure for case C

Case	Existing feature	Boolean operation for F	Boolean operation for G	Edges in $\partial G1$	Edges in $\partial G2$	Result feature	New feature(Fm)
Case C.1	D(P)	$-(\cup)$	$\cup(-)$		not broken	D(P)	• $Fm = F' \otimes Gf$ • $\partial Fm = \partial F1 \oplus Es$
Case C.2	D(P)	$-(\cup)$	$\cup(-)$	not broken	totally broken	D(P) $G \rightarrow P(D)$	• $Fm = F$ • $\partial Fm = \partial F$

Case C.2 : When $\partial G2$ is no edges, a modified feature still needs to have Es as boundary edges to satisfy the P/D definition. However, as shown in Fig. 13(b), a practical depression is the one before modification. In addition, G cannot be defined as a protrusion even though it is a practical protrusion. To solve this problem such that P and D exist interacting each other, this Case C.2 is defined as shown in Table 3.

6. Example

The IFG and FM procedure, developed in this research, can be explained further by means of step-by-step application to a sample part. Fig. 14 shows the features generated by IFG and FM at each design step. At each design step, a user performs a Boolean operation and the IFG generates an appropriate protrusion or depression and the FM updates the existing protrusion or depression. At design step 1, a new boundary surface (F) is defined as a depression according to the scheme because F is a concave face set with a convex boundary loop. In step 2, a depression 2 (Pocket) feature is generated and the depression 1 (Step) feature generated in step 1 remains unchanged. The depression 1 (Step) feature does not interact with the new boundary defined as the Pocket feature at step 2. Two protrusions (Boss) are generated at design step 3. At step 4, the Pocket feature interacts with a new feature Notch



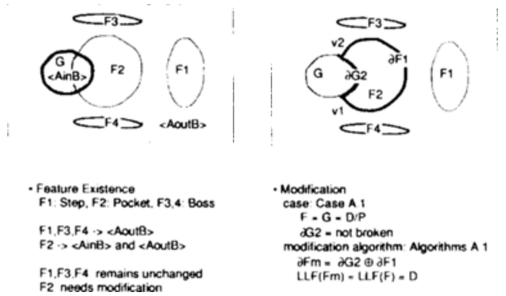
(a) Design evolution

	Design Step1	Design Step2	Design Step3
IFG	#1: Depression: Step	#2: Depression Pocket	#3,4:Protrusion: Boss

Approach	Design step 4	Design Step5	Design Step 6
IFG	#5: Depression: Notch #2: Pocket -> Pocket1	#6,7: Depression: Blind hole #1: Step -> Step1	#8,9,10,11: Depression Blind_hole

(b) Generated features at each design step

Fig. 14 Dynamic feature generation



(a) Feature existence (b) Modification

Fig. 15 Plane model of sample part feature interaction

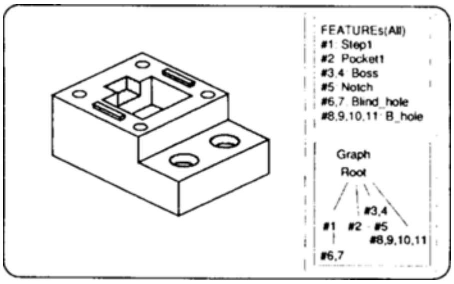


Fig. 16 Features of sample part

while the Step and Boss features do not interact with the Notch because Step and Boss belong to $\langle A\mathrm{out}B\rangle$ and a depression Pocket belongs to $\langle A\,\mathrm{in}B\rangle$ and $\langle A\mathrm{out}B\rangle$, as shown in Fig. 15(a). Thus, the Pocket is modified with new boundary edges ($\partial G2$ in Fig. 15(b)), and it is defined as a new depression feature Pocket 1, a family of Pocket features (Case A.1). The interaction relationship is defined in a feature database. At design step 5, two depressions (Blind-holes) are generated inside of the Step feature, which requires modification. Because both the Blind-hole and the Step are depressions, the Step feature keeps the depression definition. It is defined as Step 1, a family of Step features by feature modification (Case B. 1). All of the features generated during design evolution of a sample part and their mutual relationships are shown in Fig. 16. The relationship is represented by a graph, and can be used in feature-based process planning, in which such relationships are generally used to determine the process sequence.

7. Conclusion

This paper presents an approach for incremental feature generation and modification with interacting features. Such an approach enables us to evaluate the design with reference to downstream activities and to analyze interaction cases and to update interacting features as a design evolves. The approach involves boundary evaluation procedure and feature existence analysis and modification procedures. Boundary evaluation procedures generate classified boundary components, and define them as P/D according to convexity analysis. The existence analysis classifies the existing features into three groups by 4-way boundary classification. It further classifies one group into three interaction cases. The modification procedures determine the interacting feature as a valid single feature according to the convexity of a topological entity. In this approach, convexity calculation of topological entities, which is required in other feature recognition algorithms, is not necessary because of the convexity analysis of intersection edge loops (I-loop) and boundary components by Boolean operations. This approach can also be used for checking the geometrical validity of the feature-based design (FBD) approach. To enhance and generalize the current IFG and FM procedure, additional research is needed. The procedures required to cover general operations with other primitives, and interaction cases having more than two features need to be developed. An efficient procedure for feature existence analysis is necessary to reduce the number of analysis iterations on the same features. Algorithms based on general modeling schemes other than Boolean operation should be developed. An integrated data structure for both geometry and feature handling should be developed. It should provide the capability to allow a user to define ambiguous features and to edit feature attributes interactively. An investigation of the relationship between design evolution procedure and application process sequence is required for proper on-line evaluation.

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