

# On the Development of Lofts for Doubly Curved Sheet Metal Components

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## Abstract

*Practical automated flat pattern generation with inbuilt production features for doubly curved sheet metal components (SMCs) is addressed here utilizing a new and unique Point Transformation Algorithm (PTA). This is the third in the series of papers on practical Flat Pattern Development (FPD) [8] and Production Loft Generation Systems (PLGS) [9] complementing the pioneering work [6,7]. In the first two publications, automated loft generation programs have addressed sheet metal components having a Principal Flat Surface (PFS) only. The flat pattern development of 3-D components that do not have the flat surface (termed as Non-PFS components) having complex features of double curvature in addition to cutouts and nibbled holes typical of aircraft components were so far not addressed due to lack of relevant published algorithms. This paper traces the evolution of developments and provides the record of fully illustrated, automated loft generation scheme for aircraft SMCs including the Non-PFS components which underwent validation through production tests by sponsors. Details of some of the unique features of the system like simplified surface model generation, termed as topological model and powerful algorithms deployed with potential for CAD/CAM applications are included.*

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**Key Words:** FPD, SMC Loft Generation, Point Transformation Algorithm, Topological Model

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## 1. Introduction

Loft is a planar drawing (obtained through the development of SMCs) which incorporate production and inspection features suited to manufacturing, transfer to astrofoil sheets, released for production. In sheet metal components with PFS, the direction of strain during forming is well defined, whereas in non-PFS components this is not the case. Mathematically, doubly curved surfaces are non-developable [3]. Approximate Flat Patterns (FP) within specified tolerances are accepted in practice. Hence, the method of generating FP for a doubly curved surface depends on the material characteristics of the component. Therefore, different methods have to be used to obtain FP for diverse fields such as clothing, shoe manufacturing, aircraft, automotive and naval industries.

Further, a brief survey of literature pertinent to development of 3D doubly curved surfaces complementing the earlier reported survey for 2D surfaces [8,9] revealed very interesting developments. For example, surface curvatures in terms of mathematical models of splines and patches as well as mapping techniques were utilized by Hinds et al [4] for FPD which after trimming (to get rid of excess material) and stitching (to take care of cuts) were needed for cloth industry. Parida and Mudur [5] addressed planar development of complex surfaces using geometric features (binomial patches) as inputs subdivided into triangular grids and obtained flat pattern without considering material or thickness characteristics. The resulting FP had cuts and overlaps which they minimized and

deployed for tape layouts in composites (utilized by the sponsorer, Aeronautical Development Agency (ADA) for composite manufacturing concurrently with authors' SMC developments [6] also for ADA ). Among the grid techniques, even finite element techniques were also utilized. Azariadis and Aspragathos [1] have shown greater appreciation for the need of multitude of industry specific technological developments to suit variety of fields like aircraft, ship, cloth and shoe industry and presented an approximate design of FP for 3D surfaces. The refinements (based on surface geometry or generalized inverses) of their FP have reduced gaps and overlaps to suit development of upper 3D surfaces of shoe. Azariadis et al. [2] also presented a genetic algorithmic approach to solve global minimization problem under constraints to refine the FP. In summary, both the geometrical constituent manipulation techniques as well as discretization techniques involving elemental grids in deriving FP in conjunction with optimization techniques for incorporating constraints and minimization processes have no doubt reduced cuts, gaps and even overlaps. Yet, they have fallen short of the demands of the sheet metal loft development requirements of aircraft SMCs, which needed integration of material characteristics and bi-directional flow of metal besides incorporation of geometrical features. Thus, making a case for evolution of aircraft SMC application specific practical loft generation procedures.

Research and development of automated Sheet Metal Flat Pattern Development is sponsored by ADA for over a decade. These developments are authenticated through appropriate validation tests, incorporating essential production features facilitating loft generation for a restricted class of components (having a *Principal Flat Surface* termed as PFS SMCs). These, as well as the procedures in vogue at the industrial lofting group, and in commercial systems together with a modest indigenous three dimensional application activity have already been published [8,9]. Where, aircraft SMCs have been classified into two major groups: (a) Principal Flat Surface (PFS) (which possess at least one PFS) category and (b) Non-PFS category. The latter, have no reference PFS and possess curvature in more than one direction. Such components (referred as set III in that classification), constitute approximately 20% of aircraft components, have a part of Numerical Master Geometry (NMG). All these technologies were utilized in the prototype development of Light Combat Aircraft due to Aeronautical Development Agency (ADA) in India in conjunction with production tests carried out at Hindustan Aeronautics Limited (HAL) and their utilitarian summary since inception in 1990 till date is also due to appear shortly [10]. Based on these, it is evident that Non-PFS category of aircraft components are the most complex for which reliable techniques of FPD are unavailable. In what follows we shall address the evolution of unique omni potent technique which paved the way for loft generation of not only the earlier addressed components but also the components with bi-directional curvatures with production features.

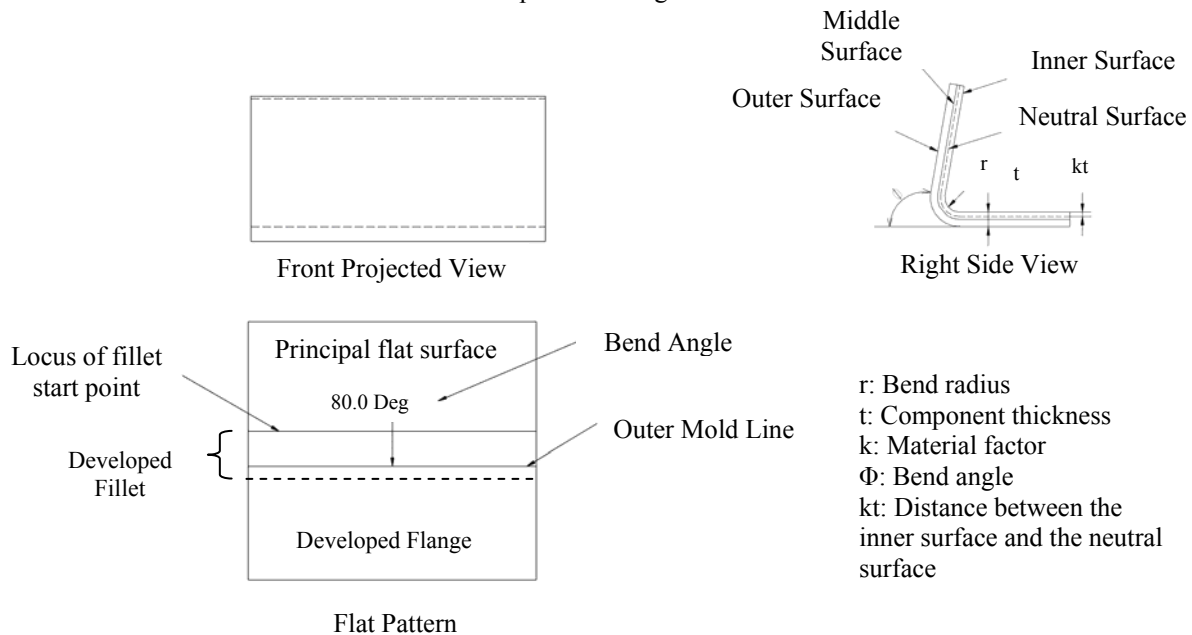
For these components, the *Point Transformation Algorithm* (PTA) is exclusively developed for the first time and is illustrated here. To generate the points on the component geometry, different component geometry specific methods deploying radial, parallel, ortho normal and hybrid sectioning have been systematically experimented with. It also utilizes a unique highly simplified SMC CAD model, termed as the *Topological Model* (TM) consisting of the component geometry defined through a portion of NMG delineated by 3D surface curves bounding the basic component surface (does not include projections like nibbled holes) While importing faces (patches derived from parent surface using boundary curves) appearing in a sheet metal surface model or a solid model - from one CAD system to another, there is a possibility of data loss, as all translators do not support these entities. Also, as most CAD systems have translators for importing and exporting points, curves and surfaces, the TM is found to be accurate, reliable and extremely simple to import. It serves to substitute the FPD methods based on the surface model (even for the components which were successfully addressed earlier) without the need for generating the complete SMC surface model. This technique utilizes the PTA and the computational efforts are reduced employing well known recursive procedure, the adaptation of which in the present context is termed as *Recursive Division Algorithm* (RDA).

The PTA transforms a point on the defining contour of a three-dimensional surface on to the FP. This transformation also embeds the Prasad's Bend Correction (BC) algorithm [6,9] (at every discretization step) which facilitates accurate determination of SMCs blank's dimensions incorporating direction dependent plastic flow. It is now adapted to the 3D surfaces with double curvature utilizing the vectors of contour curves.

Various design and production features such as open and closed cutouts, nibbled holes, reference axis mapping etc. have been accounted for in the present work. Local radius of curvature and convex/concave profile of the component geometry for bend correction are adapted and successfully implemented on PC taking care of the multidimensional nature of curvature.

## 1.1 Nomenclature

ANGLE OF BEND	The angle included between inward normals of bent and unbent surfaces.
BC	Bend Correction, the correction needed to be applied to true length of the cross-section of SMC surface model, in order to obtain the bend corrected length of the corresponding plane unbent sheet.
CONTOUR	Boundary curves of a part of drawing or component
CUTOUTS	These are holes, with a variety of shapes and sizes, made in the SMC. In general, these cutouts, no matter what their geometrical form may be, are not permitted to have sharp corners and invariably all the cutout shapes have filleted corners to ensure smooth flow of loads around these corners, there by avoiding the stress singularities.
DIRECTION OF BEND	This term is used to facilitate the computation of direction dependent bend correction
ENTITY	A drawing unit (like line, arc, surface, B-spline, point etc.).
FILLET	An operation creating a smooth arc in lieu of a sharp corner joining entities.
FLANGE	Flange is a (plane/curved) surface, which is attached to an edge of the PFS with a fillet connecting them. It is a part of the SMC, which is produced by bending (in the plane of bending) along the edge contour. The flanges addressed should have upper end contours, which are not reentrant and would be with monotonically varying flange heights along the contour where they are attached to PFS.
FLANGE SEGMENT	Flange segments are divisions of flange attached to corresponding PFS segments and are discriminable by their layers / colours in CAD model.
FP	Flat Pattern: It is the planar drawing of the blank required to form the desired sheet metal component
FPD	Flat Pattern Development: It is the process of determining flat pattern for a sheet metal component corresponding to it's neutral surface. The neutral surface is the surface within the sheet that is parallel to the inner and outer surfaces and on which the net stress of the sheet is zero. This is explained in Fig. 1.

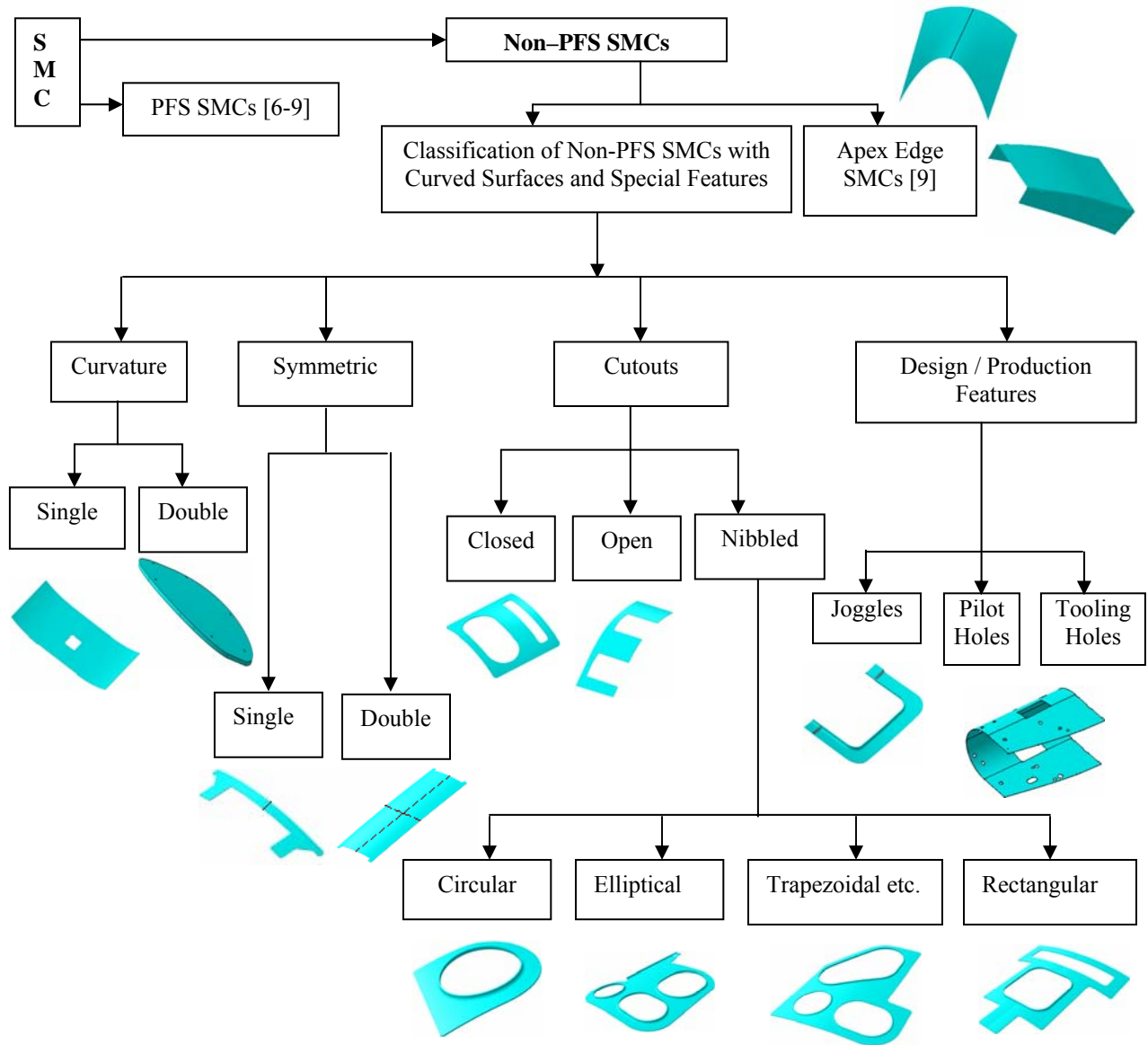


**Fig. 1.** Flat pattern development of a simple sheet metal

Focal Point (FPt)	The point which all section planes pass through in radial sectioning method
GITA	Graphical Interactive Three-dimensional Application (an indigenously developed PC based CAD) software of Aeronautical Development Agency (ADA)
JOGGLE	Unique geometry shape incorporated in sheet metal components to enable the adjacent parts to overlap/butt each other.
NMG	Numerical Master Geometry: This is a CAD model of surface geometry, completely defining the aerodynamic shape of an aircraft or such other objects like automobiles etc.
OFFSET	This is the parameter specifying the normal displacement of the FP contour in the contour augmentation process. This is an operation for increasing the sheet metal blank area
PFS	Principal Flat Surface is a plane ( $Z=0$ ) and this is the part of SMC surface which is held intact during the forming process. The existence of this PFS in the SMC is a pre-requisite for accurate FPD of SMCs manufactured through bend forming. However, SMCs exist without this also (e.g. stretch formed SMCs).
REFERENCE LINES	A pair of local axes defined for the production loft generation. These axes are defined with respect to the aircraft.
TM	Topological Model: it is a CAD model represented through NMG surface and component boundary curves in 3D space. In contrast, a full-fledged surface model is basically made of faces (patches derived from parent surface using component boundary curves). While importing faces appearing in a sheet metal surface or solid model - from one CAD system to another, there is a possibility of data loss, as all translators do not support these entities.

## 2. Overview of SMCs

An overview of the aircraft Non PFS sheet metal components with relevant illustrative features is presented in Fig. 2. The sections that follow, deal with the details of such component models and various aspects of the development of their production loft



**Fig** Fig. 2. Overview of Non-PFS Components

### 3. An Insight into Surface Model Domain

The PFS category of SMC models represent most of the SMCs used in different industries while the Non PFS category of SMC models are unique to vehicle shell manufacturing. These are further sub-divided into two categories (a) Apex edge components (with angle type of sections) and (b) the general class. This paper primarily addresses FPD of the latter class of the most general complex Non-PFS SMCs. These components have curvatures in one or more directions simultaneously. The design features of SMCs addressed in this system are open cutouts, closed cutouts, nibbled holes etc. The SMC surface model belonging to this category comprises NMG surface, boundary curves and reference planes. Further, the SMC surface model chosen for this purpose can be categorized as the inner, middle or outer surface model depending upon the choice exercised in creating the surface model.

### 4. The Non PFS SMC Flat Pattern Development

The generic approach to FPD of non-PFS component involves creation or importing of a CAD model from other CAD systems together with the reference axes and various features of SMC on to a PC based CAD software (GITA), with ease. Its validation and verification precedes the evolution of the technique for the FPD. If we define model standards, which would be met during the preprocessing stage, the FPD becomes a smooth sail if the models meeting the standards only are supplied to the system. The steps involved in the generic approach are given below.

1. Creation or importing of CAD model through translators
2. Verification and preprocessing of CAD model
  - a) Reference axis definition
  - b) Identification and auto tagging of the boundary curves
  - c) Identification of nibbled holes and auto layering
3. Sectioning
4. Point Transformation Algorithm
  - a) Generating an array of 3D points on Non-PFS boundaries
5. Bend correction algorithm for Non PFS components to get accurate flat pattern

#### 4.1 Creation or importing of CAD model through translators

The surface model is either made directly in the PC CAD system or imported through IGES route from other CAD systems. Since the surface model is complex, having aircraft geometry, surfaces with boundary curves defining the components, it is found convenient to choose a model comprising boundary curves in 3D space which lie on the NMG of the 3D object (say aircraft). We shall term this model as the *Topological Model*, TM . In fact, it is too simple to believe as viewing this model, without super posing grid or blended NMG, is impossible as the model consists of hollow curves only. It is chosen because it is simple to create on a PC based system without referring to the cumbersome process of surface patch assembly. Such models can be easily imported through IGES route.

#### 4.2 Verification and preprocessing of CAD model

The model created on a PC based system could be a full-fledged surface model or it can be the TM comprising base surface geometry (portion of NMG), with the component definition completed through bounding space curves. Alternatively, such models can also be imported onto a PC from other platforms through IGES route. In either case it is essential to verify the integrity of such models to ensure that their boundary curves do not have gaps and overlaps. Hence filling gaps and avoiding overlaps of the boundary curves constitutes verification of the CAD model. This process of validation becomes a prerequisite for FPD. These aspects have become part of the model standards.

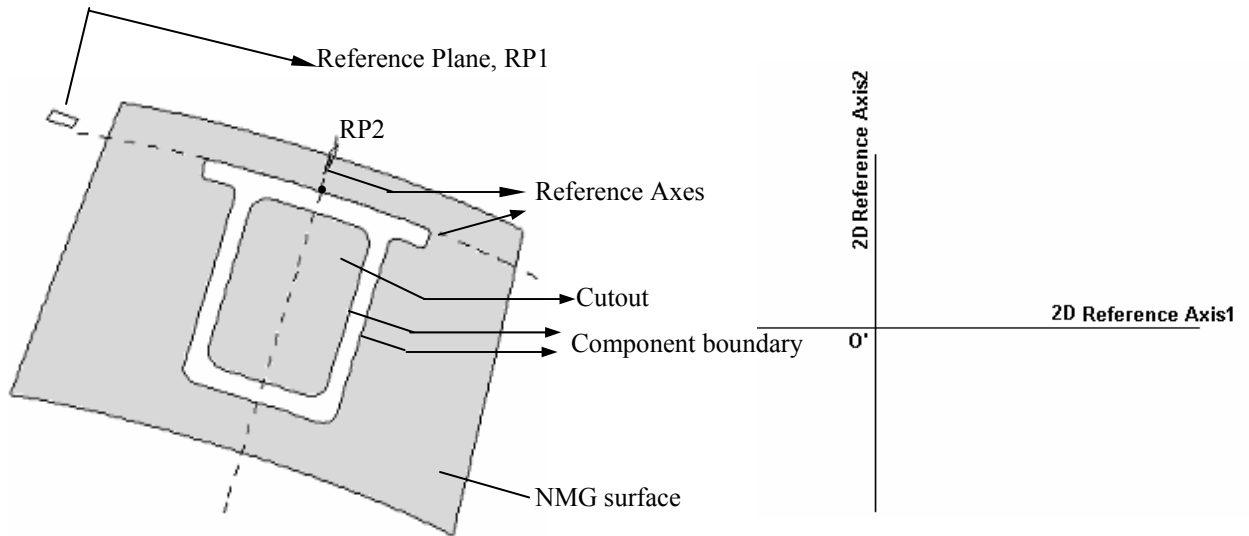
The standard TM is made available on PC together with the reference planes with tag names RP1, RP2 and NMG surface with tag names 1,2,...,n respectively.

#### 4.2.1 Reference axis definition

Reference axis is one of the production features required for components manufacture. The CAD models are made with reference to a global coordinate system (e.g. aircraft coordinate system). Definition of local coordinate system to enable for manufacturing is referred as 'reference axis definition'. Reference planes are created to realize the 'reference axis definition' and these planes are either parallel to X,Y, Z axes or inclined at an angle to the global (e.g. aircraft) coordinate system. These reference planes correspond to aircraft center line, fuselage reference line etc. and the same are tagged as RP1 and RP2. The following Fig. 3 shows a typical SMC model with reference planes and curves.

#### 4.2.2 Identification and auto tagging of the boundary curves

The Non PFS SMC boundary geometries are B-spline curves. The open cutout is converted into a closed one by generating an edge curve in this open region of the component. All the boundary curves are read, sorted, and stored in an array. The model check system is designed to check the correctness and availability of pre-defined identifier in the CAD model. System performs continuity checks and tags the segments sequentially ( $CC_1, \dots, CC_n$ ).



**Fig. 3.** A topological model with NMG surface and reference axes

#### 4.2.3 Identification of nibbled holes and auto layering

SMCs with closed profiles may contain fillet and flange surfaces attached to it termed as 'Nibbled Hole'. Automatic extraction of data (involving parsing of input data and geometric reasoning) from a given model is carried out for all geometric entities as detailed in [9]. In order to identify the complex geometric features of the components and perform flat pattern development of the projections, which are protruding out of the NMG surface, the data corresponding to each of such features are organized in different layers. The algorithm of the process involved is as follows

**Step1:** Store the sequence number of all CCVs (Composite Curves  $CC_1, \dots, CC_n$  bounding the domain of the model) in an array (viz. `ccv_array[ ]`)

**Step2:** Store the sequence number of NMG surfaces in layer 0 in another dynamic array with variable size (viz. `surf array [xxx ]`), where xxx has to be filled based on the number of surfaces present.

**Step3:** Get the list of curves for each of the CCVs (ie.  $CC_1, \dots, CC_n$ )

**Step4:** Locate the corner points of surfaces and compare them with end points of CCVs.

**Step5:** Compare the cutout contour with corner points of the surface to find fillet surfaces attached to it.

**Step6:** If fillet surfaces are found, identify the flange surfaces attached to these.

**Step7:** Put all the untagged surfaces obtained through above mentioned steps and attached to CCVs sequentially in layers '1' to 'n' respectively.

Layer Management is an automated process for organizing various parts of the model in different layers during preprocessing. It is designed for the ease of identification and processing of different CAD model geometry features utilizing the layering characteristics of CAD.

Layers 0 and 252 are reserved for TM together with NMG surface and FPD output with essential production features respectively whereas layers 1 through 251 sequentially stores the fillet and flange surfaces attached to curves  $CC_1, \dots, CC_n$ .

### 4.3 Evolution of various techniques for FPD

A sheet metal component has significant thickness. As can be seen from equation (1), (refer section 4.5.3) the material factor 'k' and the component thickness are important parameters in determining the bend corrected length and hence the flat pattern.

Since there is no unique way of developing FP for SMCs with Non-PFS geometry, different methods are conceived and researched to evolve suitable techniques. Hence, some candidate methods, which suit the task are conceived, designed, developed, tested and evaluated before zeroing onto a reliable technique. One such method is adopted from earlier success with Normal Cross Section Development (NCSD) for PFS components; namely sectioning the CAD model and decomposing it into an equivalent 2D problem to derive solution. Thus, different candidate sectioning methods were designed and experimented with to meet the accuracy demand of a given geometry to evolve feasible techniques. Some of these techniques are summarized in the following sections.

### 4.4 Sectioning methods

These are basically transitional adaptations of sectioning techniques [8,9], which were successfully utilized for FPD of PFS class of SMCs. All length computations in these methods for segments of the curve contained within the model interior only need be bend corrected.

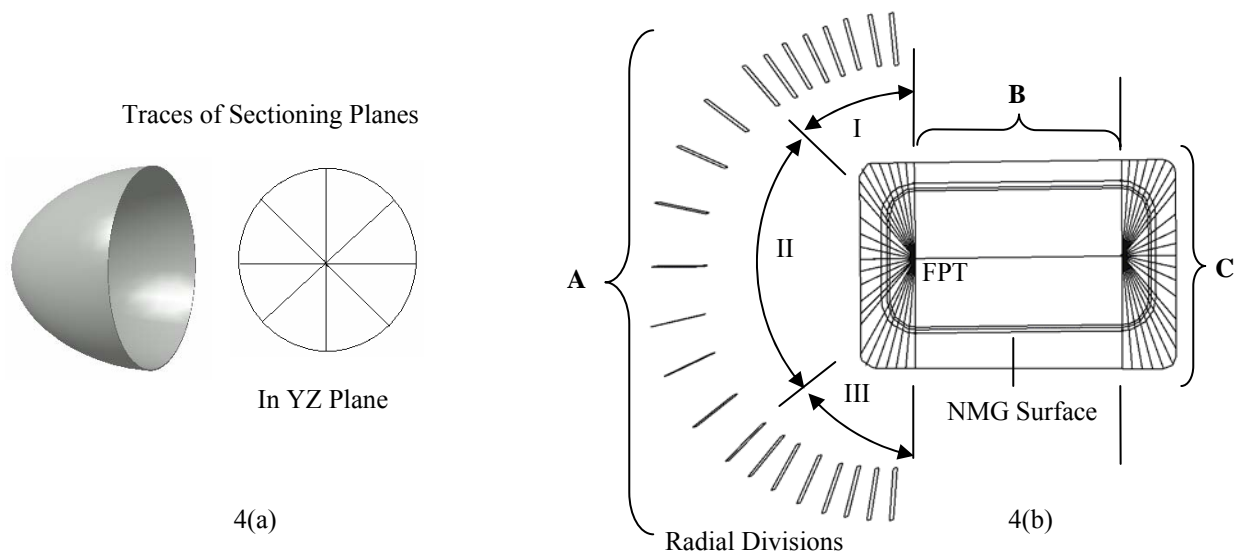
#### 4.4.1 Radial sectioning

Radial sectioning is a method of making angular divisions on a surface. This is most suitable for fully curved SMCs with low radius of curvature bounding curves as well as for axi-symmetric components. Appropriate number of divisions is made based on geometry of the surface. The sectioning method is explained below.

Though this method is ideally suited for ellipsoidal shells, its limitations (listed below) are dominant for majority of components such as those shown in Fig. 4(b). Actually the shell shown is a very special case (axi-symmetric). It can in fact be developed considering a single generator curve. The resulting FP is a circle whose dimension is the bend corrected length of the generator curve.

Where as, more complex components such as those shown in Fig. 4(b), one has to adopt a combination of techniques. In the example problem, one can divide the component into three regions A,B and C. The middle region B can be addressed by the normal sectioning procedure detailed in [8,9]. For the regions A and C, radial sectioning procedure can be adopted as detailed in the following steps.





**Fig. 4.** Radial sectioning method

- Step1: Identify the Focal Point (FPt) shown in Fig. 4(b).
- Step2: Generate the boundary curves for NMG surface.
- Step3: Divide regions containing bends (viz., A and C) into 3 segments designated as I, II and III. Their extent can vary depending on the curvature.
- Step4: Create different set of angular planes at focal point in all the three segments depending on the geometry. For example, Fig. 4 (b) shows more planes (angular divisions) in region 'I' and 'III' (corresponding to curved regions).
- Step5: Section surface with these planes and store the bend corrected 3D lengths and angles in a two dimensional array.
- Step6: Transfer the focal point on to a 2D plane.
- Step7: Map the angular lengths with reference to the focal point on the 2D plane.
- Step8: Fit a smooth curve passing through the end points of angular lines.

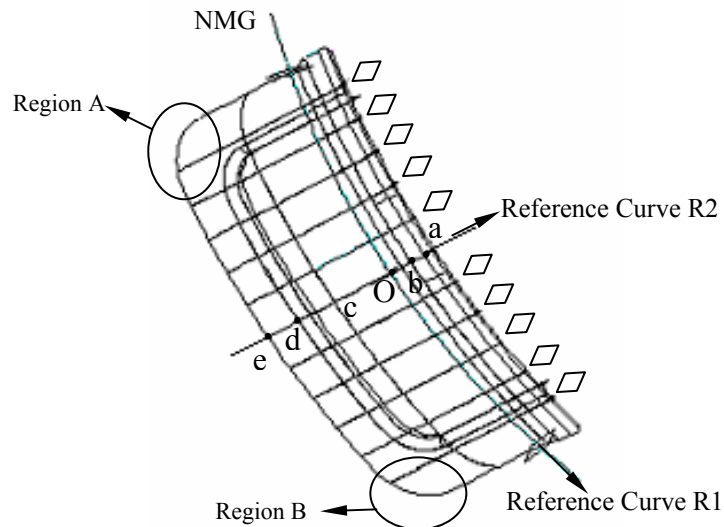
### **Limitations**

- (i) The user should identify the focal point in the CAD model interactively.
- (ii) Surfaces should be independent and discrete entities to apply radial sections.
- (iii) To plot angular lines, reference planes are required.

(iv) Determination of sub regional ranges (a,b,c) and divisions are difficult as these are component dependent. Thus, radial sectioning can not be used as an independent technique due to its limitation in its applicability.

#### 4.4.2 Parallel sectioning

Parallel sectioning technique is another method of FPD process. The procedure is an adaptation of the CSD (Cross Section Development) method [8].



**Fig. 5.** Parallel sectioning method

**Step1:** Identify the reference curve and origin 'O' (the intersection point of the curves).

**Step2:** Create parallel planes normal to a reference curve.

**Step3:** Section the NMG surfaces with these planes as shown in Fig. 5

**Step4:** Measure the section curve lengths from the reference curve R1 starting with the first curve (R2). For e.g., store the lengths oa, ob, oc, od and oe (effecting bend correction where relevant).

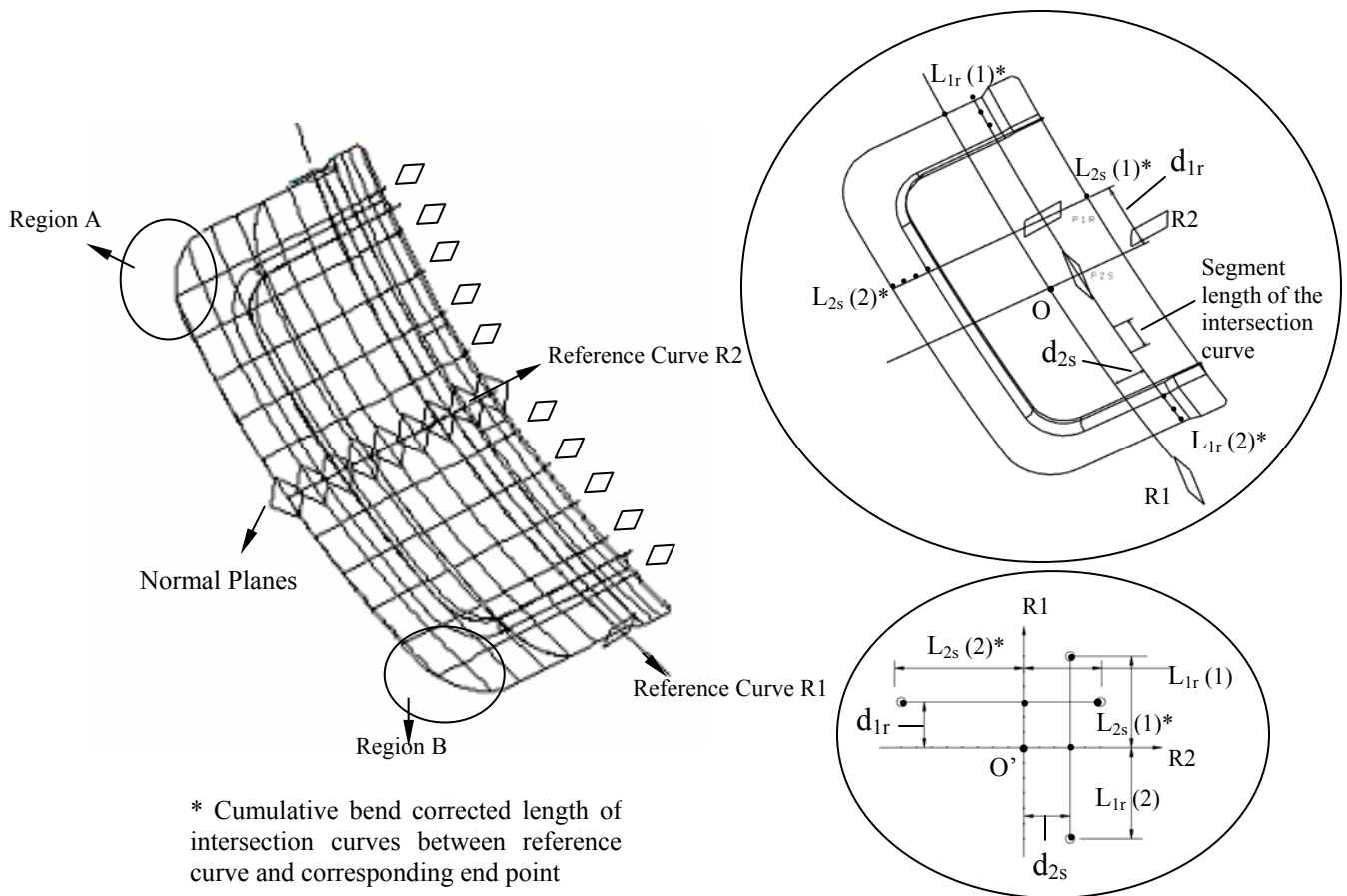
**Step5:** Plot the curve lengths in a FP plane and store the end points.

**Step6:** Generate smooth B-spline curves passing through the end points corresponding to component model boundary to obtain FP contour.

Here the limitation of this technique lies in choosing the number of sections in regions such as A and B which need very high number of sections, yet with no guarantee for accurate FP determination.

#### 4.4.3 Ortho-normal sectioning

This is another method of FP development wherein the given component is sectioned by sets of parallel planes normal to both reference axes respectively. This is a simple adaptation of cross sectional development for a pair of orthogonal directions. This procedure of FP development is explained below.



●: Points on boundary of FP

**Fig. 6.** Ortho normal sectioning method

Step1: Identify two reference curves (R1, R2) and the origin.

Step2: Create planes (such as  $(P_{11}, \dots, P_{1r}, \dots; \text{ and } P_{12}, \dots, P_{2s}, \dots)$ ) on both the reference curves and store the distances from the origin of these planes (viz.,  $d_{1r}$  and  $d_{2s}$  measured along the reference lines R1 and R2) respectively in two different arrays applying bend correction where relevant.

Step3: Intersect the surfaces with these planes and obtain and mark the lines normal to the reference curves

Step4: Calculate cumulative segmental section curve lengths corresponding to each of the sectioning plane and store it (e.g.  $L_{1r(1)}$  and  $L_{1r(2)}$  are the lengths corresponding to a typical sectioning plane  $P_{1r}$  parallel to R1 and  $L_{2s(1)}$  and  $L_{2s(2)}$  and the lengths corresponding to a typical sectioning plane  $P_{2s}$  parallel to R2 as shown in the inset.

Step5: Transfer the 3D distances of the sectioning planes from the origin (such as  $d_{1r}$  and  $d_{2s}$ ) along the reference curves R1 and R2 on to a 2D plane and mark them.

(Note.: All the cumulative distances are obtained by summing up segmental lengths bend corrected where relevant).

Step6: Mark the end points of the 3 dimensional sectioning lines corresponding to sectioning planes  $P_{1r}$  and  $P_{2s}$  (viz.,  $L_{1s(1)}, L_{1s(2)}; L_{2r(1)}, L_{2r(2)}$ ).

Step9: Fit smooth B-spline passing through all the end points of the normal lines.

This is ideally suited for rectangular type of components; however, its limitations for general components are significant.

## Limitations

- (i) Region A and B shown in Fig. 6. require more sections.
- (ii) In these regions, interpolations would be needed as it might not be possible to obtain required intersections without unduly increasing the divisions.
- (iii) Sorting of these intersection points is tedious, time consuming and hence inefficient.

Thus, the above methods are found to be efficient for a specific set of components while the same are highly inefficient for the rest. Thus, these developments could not result in a unique, reliable and efficient technique suitable for all the categories of general Non-PFS SMCs. Hence a need arose to look beyond the sectioning techniques that became the integral part of FPD system developments since 1989 till date. In what follows we shall go down from line entities to point entities and try to evolve techniques, which would be able to transform each point on the boundary of the TM of SMC on to a plane facilitating creation of FP. Hence, the task consists of an accurately transforming each point on the TM to a corresponding point on the FP. This proposition looks tall and infinitely time consuming at first glance. However, systematic research has yielded selection of points, which would permit accurate determination of FPs with reliability and economy consistent with specified accuracy limits.

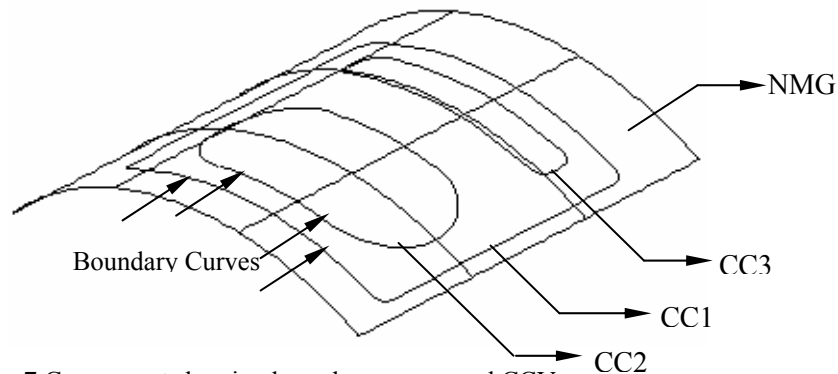
## 4.5 The Point Transformation Technique

This new technique applied for SMC flat pattern development of a wide range of components including the components with bi-directional curvature comprises the following steps.

- a) Creation of topological model as detailed in (Fig. 7) section 4.5.1.
  - b) Finding a suitable method of dividing each of the CCVs of TM for obtaining 3D set of points needed to uniquely define these curves to facilitate FPD. Fig. 8 and section 4.5.2 describe the method of generating an array of 3D points on component boundaries of NMG needed for efficient processing.
  - c) The process of obtaining FP corresponding to topological model together with associated nomenclature (vide Fig. 9), termed as the *Point Transformation Algorithm PTA* are given in section 4.5.3
  - d) Nibbled holes etc are then processed as offsets to this basic part of FP as illustrated in Fig 10 and described in section 4.5.4.
- Thus the above four steps constitute the Point Transformation Technique.

### 4.5.1 Algorithm for point generation on TM

The TM with face boundary curves is discretized during pre processing of FPD. Features such as open cutout, closed cutout and nibbled holes etc. are recognized as boundary curves on NMG. These features are identified, tagged and layered automatically. The Fig 8. shows three closed curves with corresponding tag names, in which, the first defines the component and the others define the cutouts.

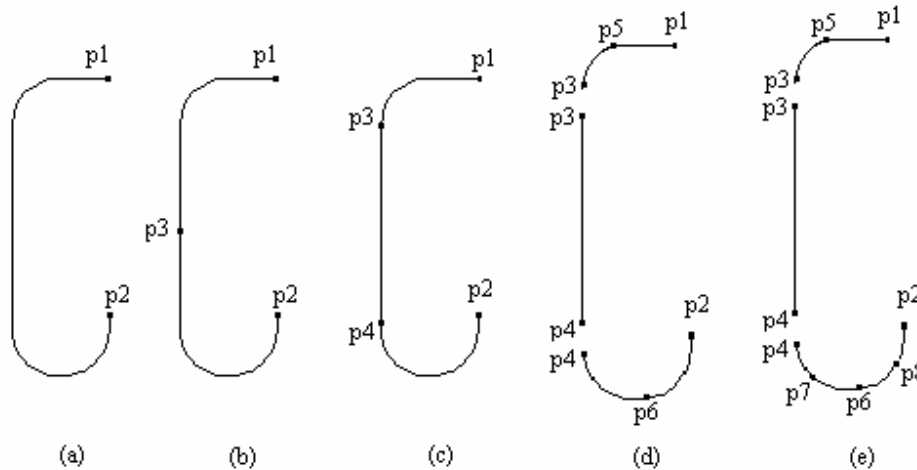


**Fig. 7** Component showing boundary curves and CCVs

#### 4.5.2 Generating an array of 3D points on non-PFS boundaries

Dividing the TM boundary and identifying essential number of boundary points is a task linked to the efficiency of this process. Number of options such as divisions based on a number of criteria like equi-divisions, divisions linked to geometric parameters of the curves etc. are tried resulting in the evolution of a reliable and foolproof algorithm. Since the objective of this task is - minimal effort and maximum efficiency consistent within the required accuracy, the division process is linked to minimal error. The quantum of difference between curve and arc lengths is utilized for optimizing the division control.

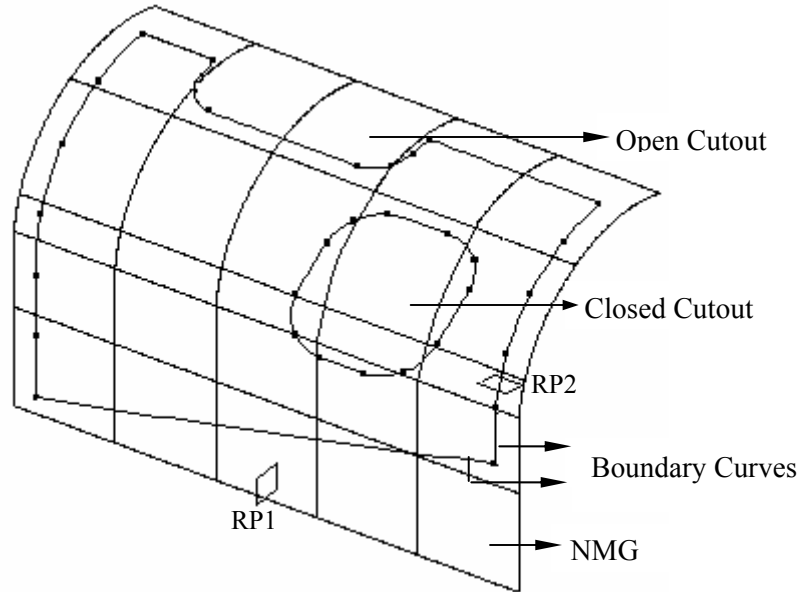
Points are generated on the boundary curves such that the curve length between any pair of adjacent points and the corresponding chord length are varying within a predefined tolerance limit  $\Delta$ . This  $\Delta$  is the factor that controls number of points and hence the elapsed time and efficiency.



**Fig. 8** Illustration of sequence of point division

1. Consider a typical boundary curve shown in Fig. 8(a) to fit minimum number of points on it.
2. Measure the curve length and chord length between the end points p1p2 shown in Fig. 8(a). Check if the difference between these lengths ( $\Delta_d$ ) is within the prescribed tolerance  $\Delta$ .
3. If  $\Delta_d$  is more, divide the curve into two equal segments with the point p3 at the middle of the curve as shown in Fig. 8(b). Find  $\Delta_{d1}$  corresponding to p1p3 and p3p2.
4. Repeat the process of division until difference  $\Delta_{d1}$  is within the tolerance limit. Fig. 8(c) shows the curve divided into three segments p1p3, p3p4 and p4p2. Find  $\Delta_d$  for each of these curves. At this stage, it is found that curve p3p4 has attained the tolerance  $\Delta$ . Now the process of division is required only for p1p3 and p4p2.
5. The process is repeated till all segments of division attain the tolerance limit. (the current example required 7 divisions and 8 points)

The following diagram (Fig. 9) illustrates minimum number of points generated on boundary curves of a typical Non-PFS component.

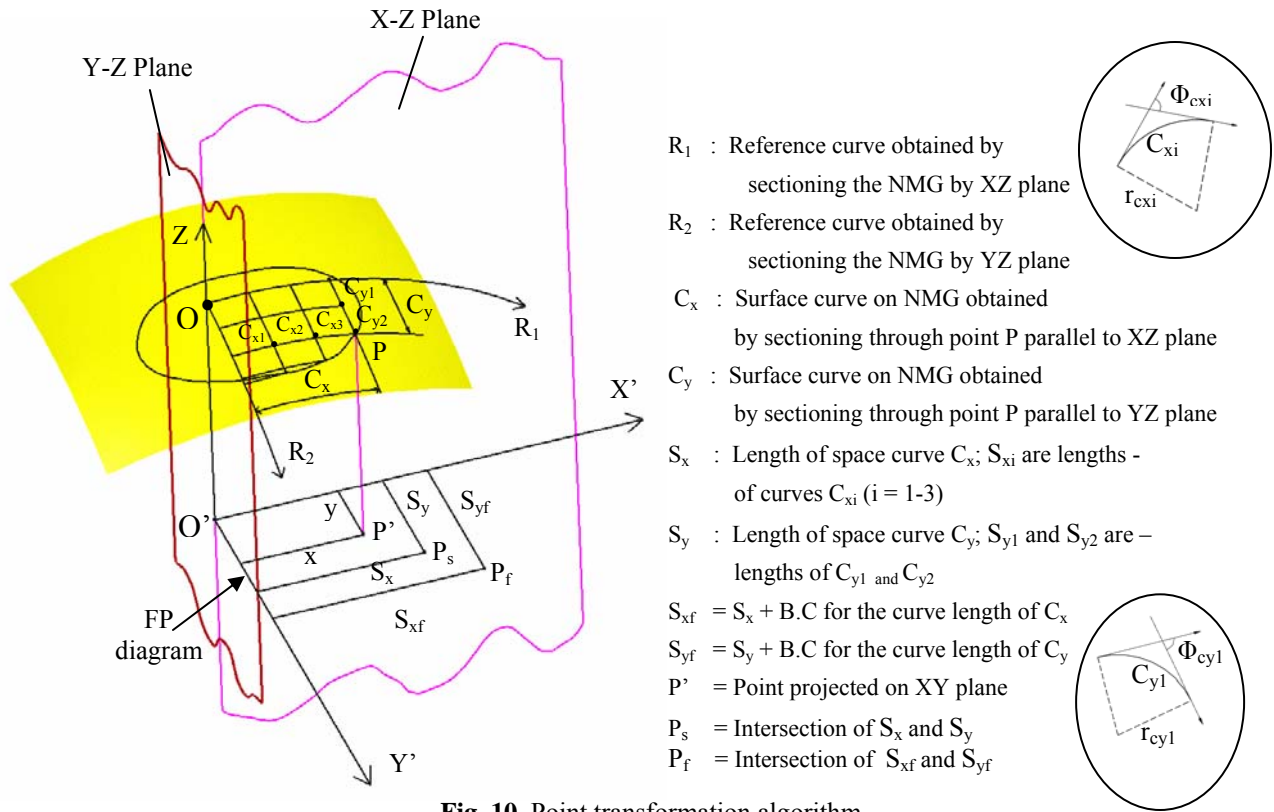


**Fig. 9** Points generated on boundary curves

#### 4.5.3 Bend correction algorithm for non PFS components

This algorithm utilizes the topological model together with NMG and reference axes. The geometrical constructional details, which are needed to explain the algorithm, are first detailed in Fig. 10. Since the nomenclatures are all relevant to this algorithm only, they are given in this figure itself. The detailed steps of the algorithm and the sequence they are performed are then explained using this diagram.

- Step1: Utilizing the reference planes (i.e. XZ and YZ), a pair of sections is made on SMC. These are termed as principal reference curves ( $R_1$  and  $R_2$ ).
- Step2: The point of intersection of these curves 'O' is termed as the origin of the PTA and is located on the NMG.
- Step3: A pair of normal lines corresponding to these curves is plotted on the FP (parallel to reference planes). Their intersection point O' (Point corresponding to the origin above) serves as the origin for FP diagram. Pair of normal lines are termed as axes of FPD, viz. O'X and O'Y (corresponding to the reference curves  $R_1$  and  $R_2$ ).
- Step4: The curves and surfaces (fillets and flanges) attached to boundaries are identified and shifted to another layer.
- Step5: Generate minimum number of points (say  $P_1$  to  $P_n$ ) on the boundary curve such that the resultant curve maintains sufficient accuracy .
- Step6: At each point of the boundary curve (say at P), a characteristic pair of orthogonal set of 'sectioning planes' is created parallel to reference planes (section curves  $C_x$  and  $C_y$  corresponding to it).
- Step7: Obtain curve lengths as curvilinear coordinates ( $S_x$  and  $S_y$ ) of points with respect to reference planes by sectioning NMG surface with these sectioning planes. Apply BC to these curve lengths to get accurate lengths at each of the chosen boundary points ( $P_1$  to  $P_n$ ) to obtain  $S_{xf}$  and  $S_{yf}$  as defined in the diagram.
- Step8: Transfer the lengths onto the reference axes in FP drawing.
- Step9: Repeat this for all the boundary points of the curve ( $P_1$  to  $P_n$ ). Generate a smooth B-spline curve, which corresponds to the face boundary curve on the NMG.



**Fig. 10.** Point transformation algorithm

$$\text{Bend correction} = (k t \phi) - \frac{1}{2} t \phi - \frac{1}{2} (t \phi) s1 s2 \dots (1)$$

Though this algorithm and the utility was earlier presented in references [6,9], it is being explained now for the completeness and to clarify its application to doubly curved 3D surfaces while the choice options of creating ‘inner’, ‘middle’ and ‘outer’ surface models are exercised.

Here:  $k$  is a material factor which quantifies the fraction of the distance of neutral axis location relative to the inner surface in terms of the sheet metal thickness ( $t$ ). This is obtained for different materials at different hardness levels basing on practical test data and is stored in the data base of the software system for ready retrieval during the process of FPD

$t$ : Component thickness

$\phi$ : Angle of bend

$s1$ : sign convention for SMC surface model (-1 for inner surface, 0 for middle surface and +1 for outer surface),

$s2$ : sign convention for direction of bend (+1 for clockwise bend and -1 for counter-clockwise bend)

The clockwise bend refers to the direction of angle which the normal of the bend surface makes with the unbent reference surface at each location.

As the process of bend correction is truly complex for components with bi-directional curvature (as they utilized local vector manipulations), this is best illustrated through the example of bend segments described in PTA into which this correction process is integrated.

Illustration (Refer Fig. 10)

Section Curve  $C_x$  is divided into minimum number of arcs, say into three arcs  $C_{x1}$ ,  $C_{x2}$  and  $C_{x3}$  as shown in the example given in Fig. 10. Determine the radius ‘ $r$ ’ of any segment of 3 dimensional section curve and the angular bend ‘ $\Phi$ ’ between the end normals of the segments and calculate the bend corrected length as under.

In the illustrative example the curves  $C_x$  and  $C_y$  are divided into two segments each and their curve lengths  $S_{x1}, S_{x2}, S_{x3}, S_{y1}, S_{y2}$ ; and the radii of their bends  $r_{x1}, r_{x2}, r_{x3}; r_{y1}, r_{y2}$  as well as the angles of the bend  $\Phi_{x1}, \Phi_{x2}, \Phi_{x3}; \Phi_{y1}, \Phi_{y2}$  are determined for each of these four segments. The insets given in Fig. 10 clearly explain how these parameters are determined from the geometric entities of segmental curves. Hence the final the bend corrected segment lengths  $S_{xf}$  and  $S_{yf}$  are obtained as under:

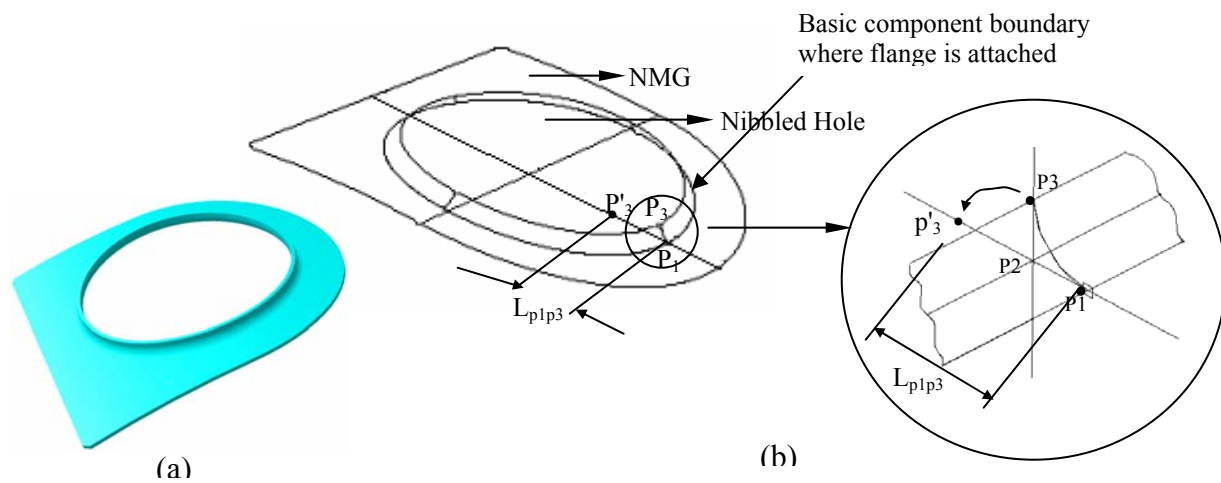
$$S_{xf} = S_{x1} + S_{x2} + S_{x3} + (\text{BC for } C_{x1}, C_{x2} \text{ and } C_{x3}) \dots \dots \dots (2)$$

$$\text{Similarly } S_{yf} = S_{y1} + S_{y2} + (\text{BC for } C_{y1} \text{ and } C_{y2}) \dots \dots \dots (3)$$

Note : each bend correction formula corresponding to the four segments use the segment specific parameters which are identified through the suffice utilized for specifying each of them. The angles between the normals as well as between the tangents are identical.

#### 4.5.4 Nibbled Hole Processing using offset method

Open and closed cutout boundary having fillet and flange surfaces attached to it is called nibbled hole. Fig. 11(a). illustrates a nibbled hole attached to a closed cutout boundary on Non-PFS 3D surface.



**Fig. 11** Nibbled hole development process

Following algorithm illustrates the development of nibbled hole

1. The fillet and flange surfaces attached to the boundaries of the holes are appropriately placed in different layers.
2. Mark a point P1 on the boundary curve corresponding to the nibbled hole as shown in Fig11(b)
3. Insert a plane normal to the NMG as well as to the basic component boundary at point P1 and section the projection to obtain the cross section P1P3 as shown in the inset.
4. In these normal planes, vectors normal to the edge curves at P1 and P3 would become tangents to the sectional curve P1P3 intersecting at point P2. A vector joining P1P2 gives the direction of unfolding.
5. Measure the bend corrected length of the section  $L_{p1p3}$  of the flange at the location of the attachment of the flange (viz. P1) to the basic component boundary.

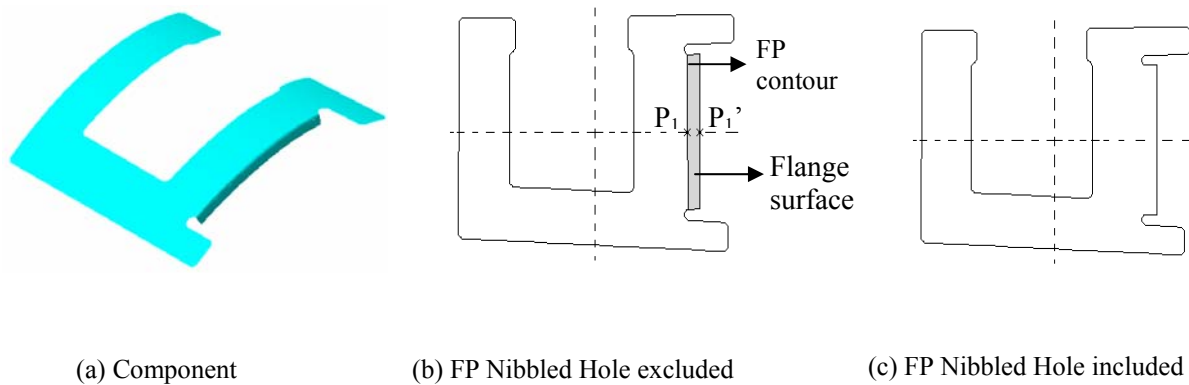
Details of the processing of a nibbled hole portion:

6. Transfer the coordinate point P1 to P1'(onto FP plane) using PTA.

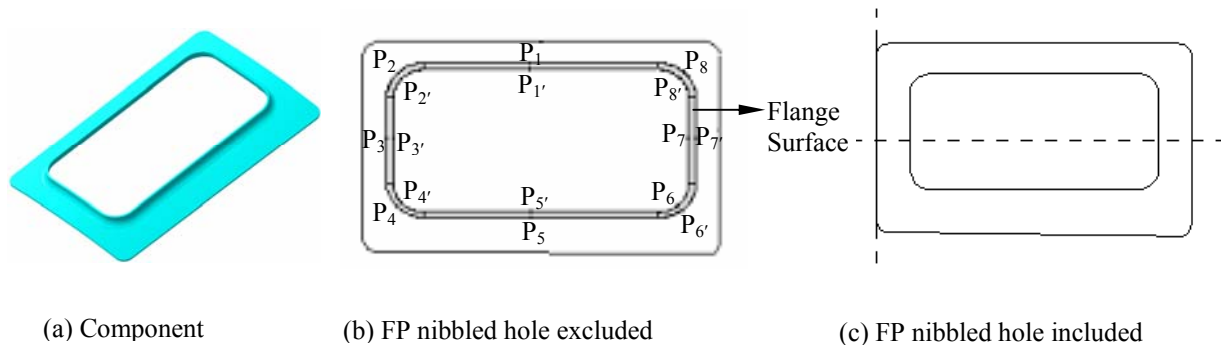


7. Mark the FP point corresponding to P1 by offsetting the contour curve in the direction of trace of P2 by a distance equal to bend corrected length of 'F<sub>Lp1p3</sub>' (ie., P1'P3').
8. Repeat the process for all the boundary curves of the hole. Fill the gaps by appropriately extending the curve contours and trimming the curves in case of overlapping contours.

The following Fig. 12. illustrates the Nibbled hole processing in case of fillet surface attached to an open cutout. The offset curve and the direction of offset  $p_1'$  is also marked in the figure, whereas Fig. 13 shows the process in case of closed cutouts.



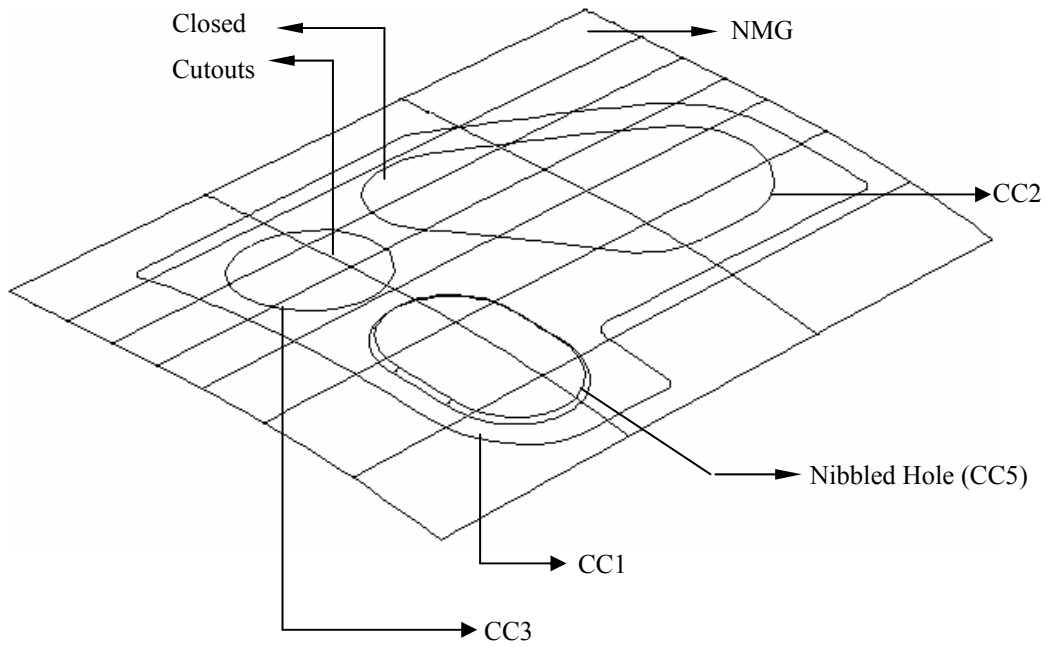
**Fig. 12** Two stage processing of nibbled hole of open cutout components



**Fig. 13** Two stage processing of nibbled hole of closed cutout components

#### 4.5.5 FPD automation using point transforming technique PTA

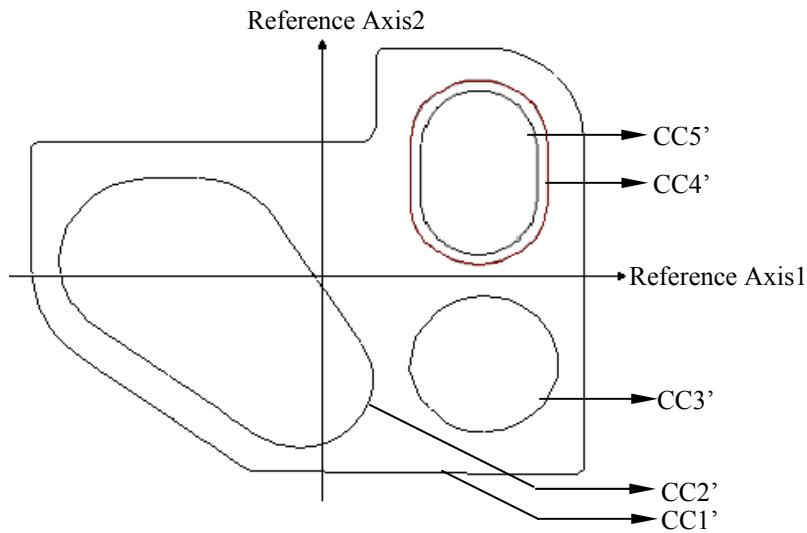
Automation of FP development utilizing point transforming technique which actually transfers a point on NMG to a corresponding point on FP PTA is a generic approach to the development process. It has been designed for components ranging from simple sheet metal geometry to complex doubly curved surface. Various features of SMCs addressed in this automatic process are open cutouts, closed cutouts and nibbled holes etc. In order to develop the FP of this class of SMCs, a two-stage process is utilized. Fig. 15 illustrates one such actual component.



**Fig. 14** Component with closed cutouts and nibble hole

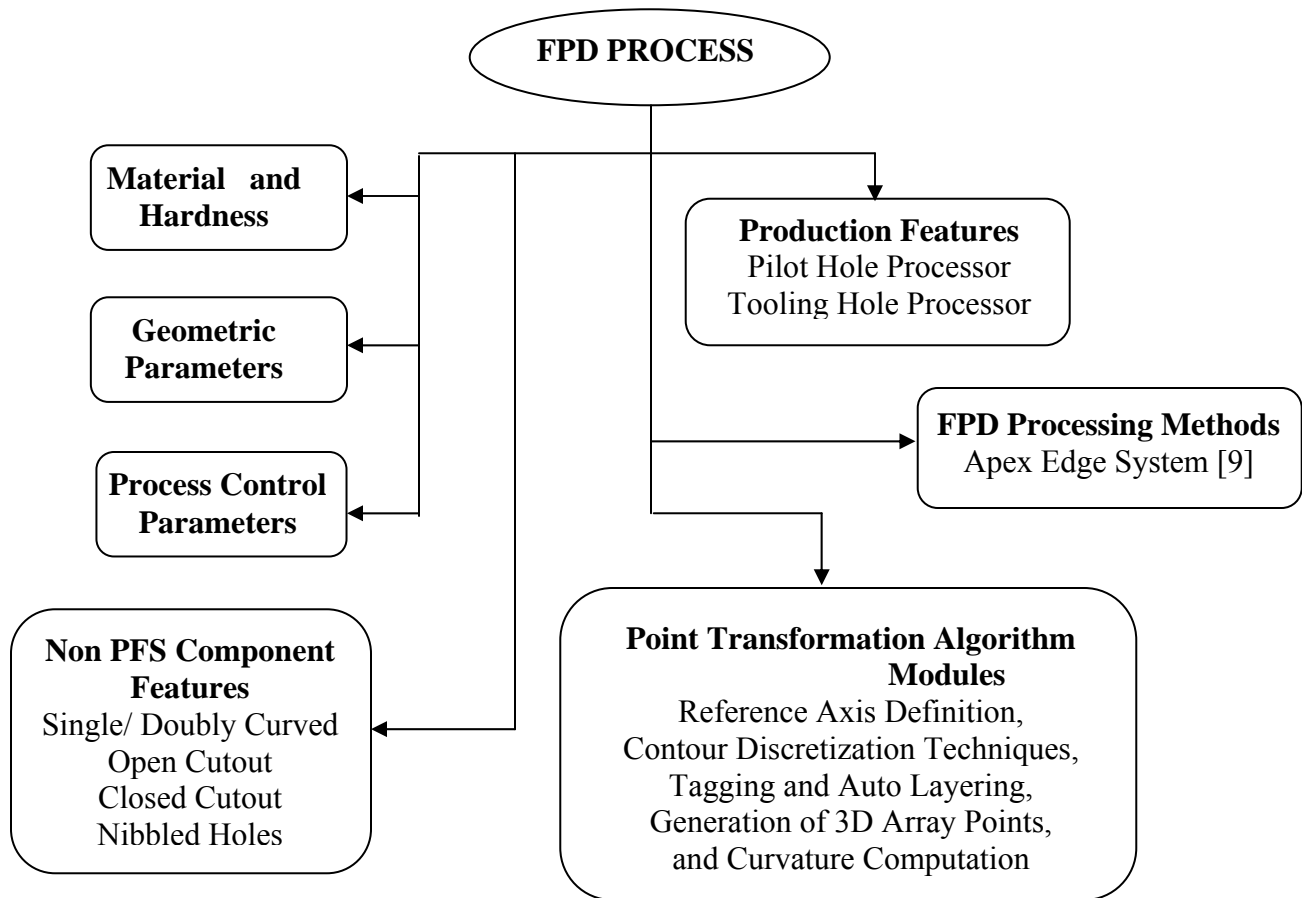
Stage I: The TM corresponding to the boundary curves lying on the NMG is first transferred to FP drawing plane.  $CC1'$ ,  $CC2'$ ,  $CC3'$  and  $CC4'$  are the basic FP contour.

Stage II: The features of SMCs, which are appendages, are addressed by reconstructing or modifying the basic FP contour shown in Fig. 15. Finally,  $CC1'$ ,  $CC2'$ ,  $CC3'$  and  $CC5'$  only represent FP, while  $CC4'$  which was an intermediate stage gets merged into the interior of FP.



**Fig. 15.** FP output after processing nibbled hole

The block diagram for illustrating the input and the corresponding FP output processing details are shown in Fig. 16. the nomenclatures that are used in this flow chart pertain to the PLGS [9].



**Fig. 16** Block diagram for input and output process of non- PFS SMCs

## 5. Conclusion

This paper has brought out unique, platform independent, well-defined algorithms for FPD of Non-PFS SMCs utilizing *the PTA*. Any production loft generation system could utilize this technique to cater to various design features such as cutouts, nibbled holes and production features common to aircraft SMCs including transfer of reference axis to FPD. Even as a technique, this PTA for FPD is new and is also integrated into a full-fledged FPD system. The resulting software is termed as GITA Flat Pattern Development -II (GFPD-II) as it utilizes GITA CAD platform of ADA.

The software including the new algorithms is proven with testing and validation on actual aircraft SMCs (some of these are illustrated in this paper), in collaboration with an aircraft factory (Hindustan Aeronautics Limited - HAL), engaged in the concurrent production of new aircrafts for ADA. It is developed using 'C' language and SDK (Software Development Kit) tools on VC++ 6.0 platform and works in WINDOWS environment. This is now extensively used for loft generation of production series of Light Combat Aircrafts by HAL.

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