Chapter 2
Digitized Modeling Technology of Turbine Blade

The digitized modeling technology of turbine blade is the input data of turbine blade casting mold. Due to the complexity of the turbine blade structure, it is much difficult to model the 3D parametric directly as a whole structure. The digitized modeling technology of turbine blade is input data of turbine blade casting mold. Due to the complexity of the turbine blade structure, it is much difficult to model the 3D parametric directly as a whole structure. The problem can be simplified by adopting structure decomposition, building, respectively, corresponding features of the decomposing structures and combining them with Boolean operations. The classification of blade structural features and the parametric modeling of structural features are introduced in this chapter.

2.1 Structural Features Classification of Turbine Blade

2.1.1 Structural Elements Classification of Turbine Blade

1. Necessity of the structural elements classification

The structure of an aero-engine's turbine blade has been introduced in Sect. 1.1.2. It is very difficult to model a solid 3D model for a turbine blade considered as a whole structure. There are some reasons as follows:

(1) Currently, the CAD (Computer-Aided Design) system is based on regularized modeling technique, which supports free-form surface modeling. However, only the topological relation between surface boundary and solid bodies has been considered in this regard, while modification of geometric parameters does little to the free-formed surface.

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(2) The present version of CAD system fully takes advantage of geometrical relationship. For example, the relationships between bore (or "Boss" feature) and its reference plane form a set of interconnected characteristics. Once a feature parameter is modified, the associated features will also be changed synchronously, which is viewed as the basis of parametric features. However, it is very difficult to establish association for all structural features. This is because, on the one hand, instead of relying on the relation of the geometric positioning, the positioning parameters of the features are based on different requirements of engine positioning coordinate system. For example, the aerodynamic data of turbine blade surface cannot be associated with other geometry information. On the other hand, the goal of establishing a direct connection between surfaces of different blade parts and the existing entities is tough to achieve. Though employing parameterized auxiliary planes (Datum Plane in UGNX), it is very complex to building parameterized auxiliary planes [1].

(3) Update failure appears in the current CAD system. Once this happens, the existing 3D models cannot be used anymore. In the meantime, the existing model of turbine blade needs to be rebuilt, which causes low efficiency of modeling.

In order to overcome the above difficulties, the method should be adopted, where features of different elements are constructed on the basis of structural decomposition, and those features are combined with Boolean operation. In other words, splitting the integral structure of blade into plentiful features that are in weak correlations to each other. Each feature is related with the others. For example, the parameters size of each structure is not completely associated whit the existing geometry as an input object. Using methods mentioned above, not only the difficulties of overall modeling would be overcome, but also the efficiency of designing and modification would be improved. Changes of structure only affect individual elements, and then synthetize again after modification, to solve the problem of updating failure of overall characteristic parameters modifications.

2. Classification of structural elements

The integral structure of turbine blade could be split into structural elements with simple shapes. Every structural element could be defined as a structural feature, which constitutes the whole structure. Therefore, classification of the structural elements should be completed first. The principle of classifying is the foundation of functions and modeling features as much as possible. Classification results are shown in Table 2.1.

Table 2.1 Classification of structural elements

Name of structural elements	Modeling characteristics	Relationships with existing geometric	Modifiability	Geometry types of surface
External profile of blade	Free-form surface built according to aerodynamic data	Associated with aerodynamic data	Modifying the aerodynamic data and the outside surface of blade changes	Free-form surface
Internal profile of blade	Constructing interpolation free-form surface associated with the outside surface	Associated with external profile of blade	Modifying external profile of blade and the thickness between external and internal profile of blade. Internal profile of blade changes	Free-form surface
Internal profile of fir tree root	Simple rectangular shape	Relatively independent		
External profile of fir tree root	Inputting joint type and parameters according to requirements of strength	Associated with internal profile of fir tree root	Parametric modifying	Sketch and tensile feature
Platform	Parameter determined by flow data	Associated with flow data	Parametric modifying	Sketch and extrude feature
Root extending segment (Shank)	Interpolation to construct free-form surface according to fir tree root and blade body constrained by data	Associated with internal profile of fir tree root and blade	Changing with the modifying of fir tree root and blade	Free-form surface
Longitudinal rib	Size of longitudinal rib determined by the requirement of cooling	Relatively independent	Modifying parameters	Sketch and text rude feature
Transverse rib	Given height size	Associated with internal profile of blade	Changing when modifying internal profile of blade or the depth and width of transverse rib change	Free-form surface
Pin fin	Associated with *X*-axis angle	Relatively independent	Changing when modifying angle and diameter, number	Ruled feature

(continued)

Table 2.1 (continued)

Name of structural elements	Modeling characteristics	Relationships with existing geometric	Modifiability	Geometry types of surface
Shroud	Given configurations	Associated with external profile of blade	Changing when external profile of blade changes	Ruled feature
Covering plat	Given configurations	Associated with external profile of blade	Changing when external profile of blade changes	Ruled feature
Trailing edge slot	Given configurations	Associated with the aerodynamic data of external profile of blade		Ruled feature
Cooling hole	Confirming the direction and location of the hole to avoid interference with transverse rib	Associated with the external profile of blade, longitudinal rib and transverse rib	Changing when blade and transverse rib changes	Ruled feature

2.1.2 Feature Modeling

1. Feature

Product model is the carrier of product information, where the structure and size information is the most important that could be expressed by different forms. Engineering drawing is employed mainly to describe the above information. In the 80s, it developed into 3D solid model building and feature modeling, which basically meets the needs of CAD parts after around 50 years improving. However, this solid model is only a geometry model, instead of product model, which lacks manufacturing information that product model needs. It is inconvenient for engineers due to the dominating geometrical description but lacking of engineering semantics. The function without parametric feature leads insufficiency of convenient modification function, which results in a low design efficiency. In the late 80s, feature modeling technology promotes product design from underlying to practical semantic level. Part features have become information carrier of product model under the integrated environment [2].

In 1978, feature first appeared as a technical term in a bachelor's thesis, *based on the Characteristics of the Parts in CAD*, which is directed by MIT (Massachusetts Institute of Technology) professor Gossard. Though it has been for decades, there is still not a strict and unified definition to feature since the uses of CAD/CAPP/CAM integrated system in all areas focus differently, which leads to the definition and understanding of features are different. The draft of criterion for Standard the Exchange of Product Model Data (STEP) published by ISO (International Organization for Standardization) which sets standards for shape, tolerances, materials and other features as basic elements of product definition. From then on, feature has obtained a legal status internationally. After decades of development, the feature of shape is still the most mature and practical type.

2. Feature modeling

Feature modeling is a 3D modeling method with semantics for product. While not having a unified definition, feature modeling is still applied into engineering, which is based on solid modeling. In CAD system, feature can be considered as local area of parts with certain shapes and features. Shape is the carrier of tolerance, craft, material and other non-geometric properties, which can be called shape features. By using feature modeling CAD system, product designing confronts no longer voxel of the pure geometric meaning, or low-level geometric elements such as point, curve, surface, etc. The Functional elements of product are used in design process, such as location hole, key slot, chamfer, etc., which directly reflect the design intents.

The process of feature modeling is detailed in the following. First, user cites parametric base feature, and then call interactive modeling operations (such as punch, grooving, chamfering, etc.) to assign location parameter value to the cited feature setting parameters and relative base feature. When positioning among features, axis, symmetry planes, etc., should be used as much as possible, and to determine by interactive pointing operation. In fact, modeling operations implicitly corresponds to some Boolean operators: incorporate/differential, which are automatically converted internally by the system. Product model built by feature modeling is commonly called feature model, which contains non-geometric attributes that are generally input interactively by users. Geometric attribute of feature model is generally expressed by boundary representation, which is still a 3D solid model.

The current CAD system provides various methods to feature modeling, which can be easily implemented to build a common structure, such as holes, slots, chamfers, etc., and still in progress. It also provides sketch-based 3D modeling approach, supplementing various shape features modeling capabilities that are not included in the common feature.

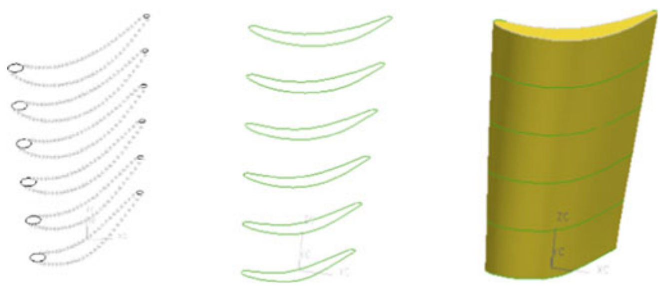
For aero-engine turbine blade, the structural elements in Sect. 2.1.1 can be expressed in the form of feature from the perspective of functioning, so terminology of feature can be used to package these structural elements, which contains the definition of shape features, parameter definition, operational definition, etc., forming a unique collection that includes all features of aero-engine turbine blade.

2.1.3 Feature Definitions of Turbine Blade Structure

The turbine blade's overall structure is decomposed in Table 2.1. Beginning with shape feature, each structural element will be defined as a feature. The definitions of features contain the ID of feature, function description, shape description, size relationships, position relationship, features operation, input data, and output feature.

Taking external profile, platform, fir tree root as examples, method of defining features is demonstrated as follows:

1. External profile
   Blade ID::=<ID_1>
   Functional Description::=<pneumatic external profile, having an effect on aero-engine turbine performance>
   Basic Shape Description::=<multilayer sectional closed curve of along the stacking axis vertical distribution>
   Dimension Definition::=<no geometric parameters, by the data points to generate free curve>
   Position Relation::=<the axis of aero-engine as basis reference>
   Input::=<data points of aerodynamic, radius and center of leading edge, radius and center of trail edge><data points of aerodynamic data>
   Output::=<3D features>
   Features Operation::=<establish spline><through curves feature>
   3D features of external profile are shown in Fig. 2.1.
2. Platform
   Platform ID::=<ID_3>
   Function Description::=<with simple structures, used for fastening blades and sometime joining blades and the cartridge receiver to make easily assembly, applied to blades connection>
   Basic Shape Description::=<the defined shape of sketch cross-sections>
   Dimension Definition::=<the defined dimension related to the aero-engine axis><the defined dimension of geometry>
   Position Relevance::=<using aero-engine axis as the reference datum>
   Input::=<dialog boxdata-in>
   Output::=<3D feature>
   Feature Operation::=<sketch construction><feature revolving>;
   3D model feature of platform is shown in Fig. 2.2.



Aerodynamic data Sectional data 3D features

Fig. 2.1 3D feature of external profile

Fig. 2.2 The platform

Fig. 2.3 The external form of fir tree root

3. External form of fir tree root
   The External form of Fir tree root ID::=<ID_5>
   Function Description::=<used for fitting blades and the disk parts together to make easily assembly, applied to blades connection>
   Basic Shape Description::=<the defined shape of sketch cross-sections>
   Dimension Definition:=<the defined dimension of geometry>
   Position Relevance::=<user-defined coordinate system>
   Input::=<dialog boxdata-in>
   Output::=<3D feature>
   Feature Operation::=<sketch construction><feature stretch>;
   3D model feature of the external form of fir tree root is shown in Fig. 2.3.

2.2 Parametric Modeling of Structural Features

2.2.1 Design Process of Turbine Blade

The turbine blade is designed as a hollow internal structure due to the high-temperature working environment, which can be embodied in a concave–convex ceramic core. The modeling process of turbine blades can be divided into the external profile modeling and the internal profile modeling, of which's structure is finally acquired through Boolean operations [3]. Furthermore, the turbine blades design is a process that involved designers from multidisciplinary background, which results in the regular patterns shown as follows:

Step 1 Turbine blade design begins with designing the blade structure, which emphasizes the schemes relevant to aerodynamic parameters and structures.

- Aerodynamic parameters concern: The thermography of flow channel must be provided, which includes the axial and radial dimensions of the blade entrance and exit, the divergence angle of top and bottom flow channel, and the blade axial dimensions along height direction. Besides, the aerodynamic parameters of turbines at different levels, which are in the different aero-engine status, are also necessary.
- Structure concerns: Discuss the necessity on blades gas cooling, position relation between internal profile and straining beam, the attachment type of disk parts and the existence of shroud or other features.
- Based on the concerns mentioned above, the cross-section data can be calculated by professional softwares, which concluding the data on points of concave and convex curves, center and radius of leading and trail edges.

Step 2 Model the external profile according to the cross-section data.
Step 3 Model the internal profile according to the external profile and offset wall thickness (normally unequally).
Step 4 Select styles of fir tree root and platform according to the attachment type not only between blades and disk parts, but also among blades.
Step 5 Design the exterior and interior of root extension.
Step 6 Design the gas cooling structure of internal profile according to the cooling methods.
Step 7 Acquire the preliminary blade body model by Boolean operation of all other structures, smooth the external minutiae and verify the hollow blade body.
Step 8 Model the minutiae of blades including blind flanges, bosses, film cooling holes, etc.

As shown in the Fig. 2.4, the aforementioned procedures completely contain the general steps of turbine blades modeling while they are not accurate. Repeated verification by designers from multidisciplinary background is required.

2.2.2 Basic Principle of Parametric Modeling

Parametric technology is to achieve the modification of design driven by parametric dimensions through creating geometric constraint sets by predefined method then

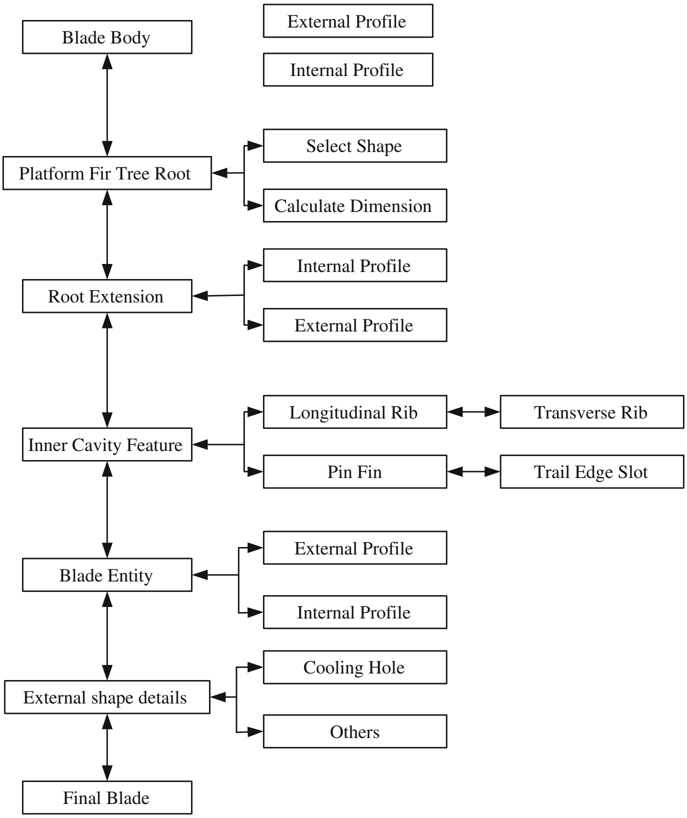


Fig. 2.4 Turbine blade design process

specifying one set of constraints as parameters to associate with those constraints, finally modifying the specified parameters by human–computer interaction. In the process of parametric design, design parameters have a clear correlation which has global relevance with the control dimension of designed object. Parametric design is different from design based on transfer, for it stores the whole process of design, and has the ability to design a series of products rather than a single product, which have similarity in their shapes and functions. At present, majority of commercial CAD systems are using feature-based parametric modeling which applies parametric idea to feature-based modeling. It defines and modifies a geometrical model by constraints and parameters. Constraints contain dimension constraints, topology constraints and engineering constraints. When a constraint or a parameter changes, the system would modify the model automatically. Features are also driven by constraints and parameters in feature-based parametric modeling. The conditions of constraints are appended on geometrical topology, and indicate the topology between geometrical elements. The shapes of feature and its sub-feature would change when its parameters and constraints changes [4]. Compared with traditional feature-based solid modeling, the characteristics of feature-based parametric modeling are listed as follows:

(1) Solid model strengthens the ability of describing models, but it is ineffective and inconvenient in modeling and using process. Feature-based modeling describes product design at a higher level because designers can use familiar terminology to express their intention, hence their design objects are no long original curves, or bodies, but the function elements of products shape.
(2) In order to build integrated information of products, feature-based modeling can express fuller technologies and manufacture management information of products than solid modeling. It contains engineering semantic information which can be mutual understood by CAD/CAPP/CAM system in their integration process, thus allows product design, analysis, process and manufacture to work concurrent, also design intention can be carried out thoroughly throughout following process.
(3) By parametric technology, users are agile to modify design plan to improve the usability and friendliness of the modeling system.

According to classification and structural characteristics of blade, it is equipped with complicated structures for both external profile and internal profile, which are relevant to other structure and contain lots of free-form surfaces. Therefore, the modeling process is very complex. When applying feature-based parametric modeling to modeling turbine blade, the following questions should be considered:

- How to decompose the intricate relation between different features?
- How to induce and detect parameters for features and position while build expression between parameters?
- How to model free-form surfaces?

It is difficult to apply the overall feature-based parametric modeling to turbine blades due to the complex structures of the turbine blades. Many structures and shapes rely on the result of aerodynamic design that showing free-form surfaces. And intricate relation between different design parts have strong coupling. However, the turbine blades can be considered as a combination of different functional features, which are combined by interrelated sub-features. Upon that it can be split into different sub-features by its function, in order to analyze parametric modeling of each of them. By analyzing geometric correlation between sub-features, parametric presentation between internal features and sub-features can be established via parametric expressions and so on. Then parameterizing the complex overall turbine blades can be transferred into parameterizing sub-features. Taking turbine rotor blades as an example, parametric modeling process of turbine blades is described in this chapter.

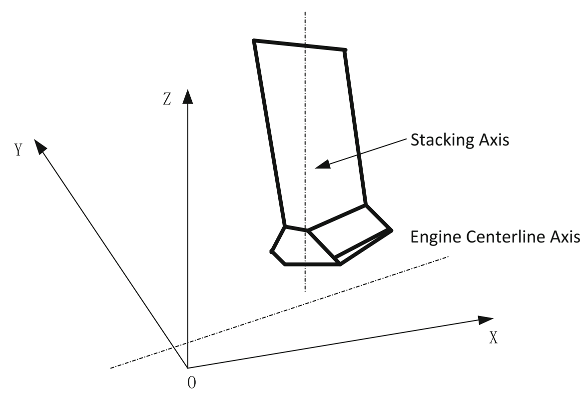
Modeling process of turbine rotor blade is divided into modeling of blade external shape and modeling of blade internal shape. Blade external shape consists of cover plate, internal profile of blade, extension root, extension tenon, etc. Blade internal shape consists of internal profile of blade, longitudinal rib, Transverse ribs, pin fin, inter root, inter tenon, etc. The turbine rotor blade model with cavity is obtained by using the Boolean operations between the blade internal solid and the blade external solid [5].

2.2.3 Datum Feature of Turbine Blade Modeling

Datum feature refers to the coordinates for modeling turbine blades that determines the location of each structure. Turbine blade modeling needs an orthogonal coordinate system. A horizontal plane that passes through the engine axis is defined as the *XOY* plane. *Z*-axis, whose direction following the length increase of the engine radius, is perpendicular to the engine centerline, but not necessarily intersects with it. *X*-axis generally parallels to mean chord, taking the front edge to the rear edge as its forward direction. Direction of *Y*-axis is determined by $Z \times X$. Generally, the stacking axis is coincided with *Z*-axis. If it is not coincided, the coordinate position of stacking axis is needed to specify. As shown in Fig. 2.5.

Three planes datum system is a datum plane system which constructed by three mutually perpendicular planes that can be used to locate the structure position of turbine blade. Radial plane *A* is a specified plane which is parallel to *XOY* plane. It is used to determine radial position of blade body. Plane *A* is a radial positioning surface of the blade on the engine. Angular plane *B*, which passes through *Z*-axis, is parallel to the plane of stacking axis. The angle between *X*-axis and it determines its direction. *X*-axis and its angle θ determines its direction. Plane *B* can be established by tenon node plane, plane that center line of platform lies, and plane across a point on platform. In order to facilitate design, angle θ is generally taken as zero degrees. Axial datum plane *C* that is vertical to datum plane *A* and *B*, determines the axial

Fig. 2.5 Turbine blade design datum system



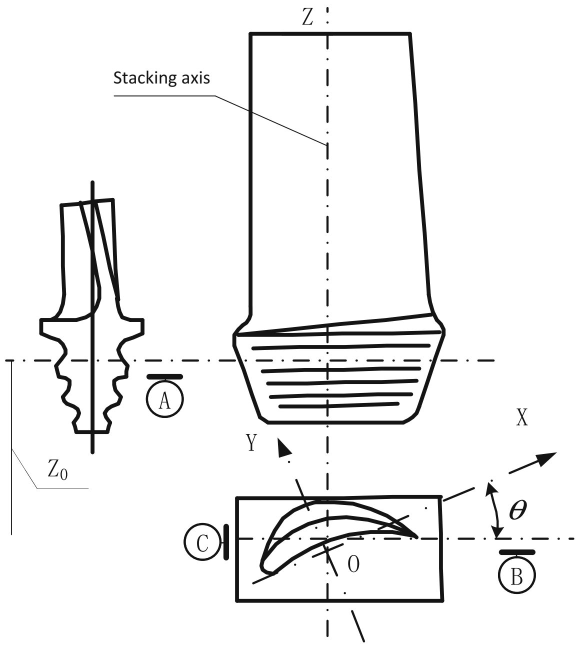


Fig. 2.6 Three Datum Cartesian coordinate system

position of datum system. It is usually established by the plane of end face on tenon. As shown in Fig. 2.6.

Three planes datum system is the foundation to choose mechanical processes datum and to convert process datum, which is necessary to detect blade size after machining, to ensure that all the deviation of size and shape are within the design range.

2.2.4 Surface Modeling of Turbine Blade

1. External profile of the blade

The modeling of blade's external profiles based on cross-section's aerodynamic data points of the blade, are calculated by pneumatic. Aerodynamic data points from the blade's external profile can be summarized as a set of data from different height cross-section along stacking axis direction. Each cross-section ha four parts, including suction surface curve, pressure surface curve, leading edge data and trail edge data. The aerodynamic data of suction surface and pressure surface are data points of suction surface curve and pressure surface curve. The data of leading edge and trailing edge are arc, whose form is center and radius of the arc in leading edge and trailing edge. As shown in Fig. 2.7.

The modeling of external profile should meet the following requirements [6]:

- The modeling of external profile should be based on aerodynamic data provided by turbine aerodynamics' calculation, to ensure the aerodynamic performance of blade as much as possible.
- Each cross-section is constituted by four curves, which are suction surface curve, pressure surface curve, leading edge arc and trail edge arc, whose join points should satisfy the first-order geometric continuity.
- Curves of leading edge and trail edge should be arc.
- External profile should be stacked as a set of data from different height cross-section along stacking axis direction.

For a set of data from cross-section of external profile, the points of suction surface and pressure surface fit suction surface curve *S*1 and pressure surface curve *S*2. The center and radius of leading edge and trail edge generate circle *O*1 and *O*2. Joining will be needed between suction, pressure surface and leading, trail edge since the endpoints of *S*1 and *S*2 cannot be guaranteed on circle *O*1 and *O*2, and a smooth connection between them cannot be guaranteed, either. Joining of cross-section curves should satisfy the following conditions:

(1) Section curve is closed curve, which consists of suction surface curve *S*1, pressure surface curve *S*2, leading edge curve *S*3 and trail edge curve *S*4;
(2) *S*1 and *S*2 must be free curve passing through pneumatic points as far as possible;

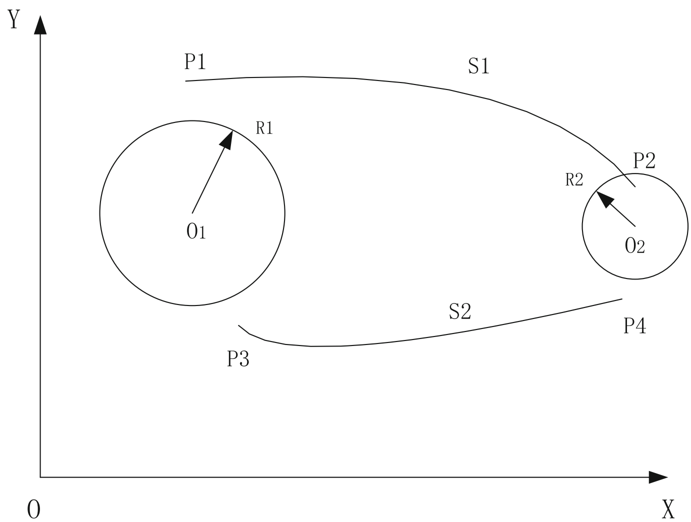


Fig. 2.7 Results of aerodynamic design

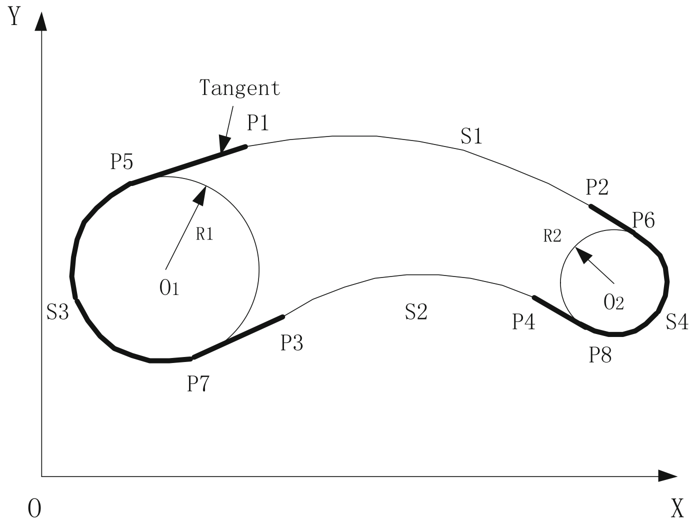


Fig. 2.8 Fitting external profile's cross-section

(3) $S3$ and $S4$ must be arc and its center and radius must comply with a given center and radius of the leading edge and trailing edge;
(4) The continuous in internal of $S1$ and $S2$ should at least geometric order G^2. And the continuous at the junction points should at least geometric order G^1;
(5) The central angle that corresponding to the arc of $S3$ and $S4$ should be no more than 180°.

Leading edge and trailing edge will be generated from $P1$ to $P2$, the endpoints of $S1$, and $P3$ and $P4$, the endpoints of $S2$. $P5$, $P6$, $P7$, $P8$ are the tangent points of leading edge and trailing edge, respectively, which are considered as the endpoints of two arcs. The circle where leading edge and trailing edge located is divided into two arcs by $P5$, $P6$, $P7$, and $P8$. An arc is taken as $S3$ and $S4$, with which a center angle is less than 180° $S3$ and $S4$. As shown in Fig. 2.8.

For the following three cases, tangent points from the endpoints of $S1$ and $S2$ are unable to meet conditions 1 and 3 for connecting, shown in Fig. 2.9. Free curve of suction surface curve or pressure surface curve is represented by S. P is the

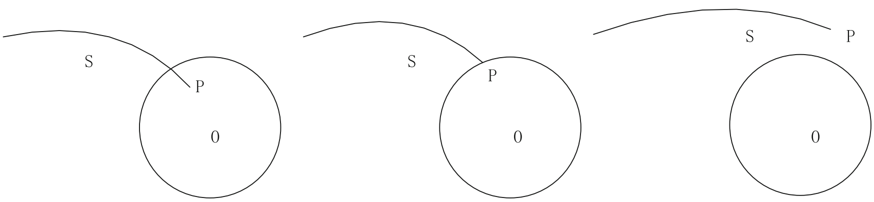


Fig. 2.9 The case of removing points

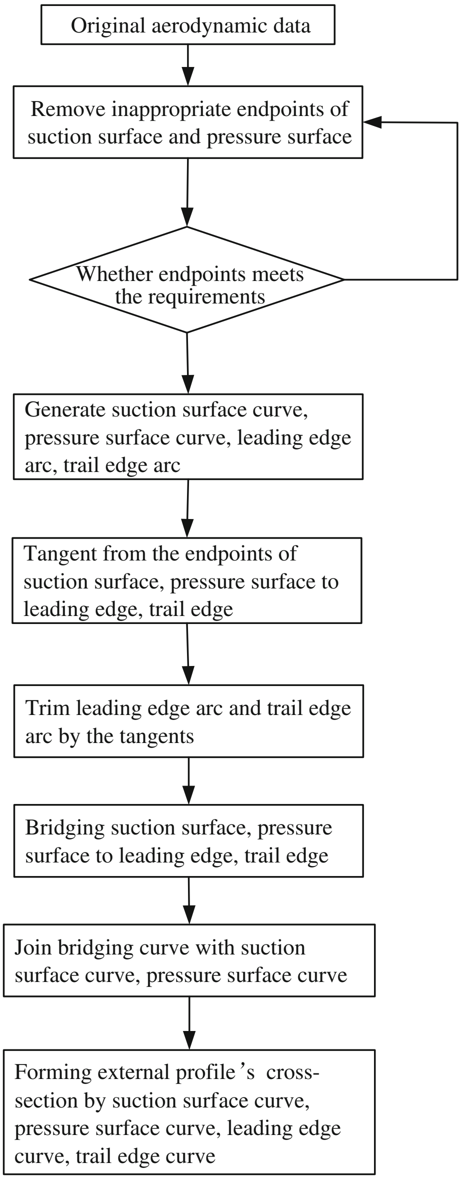


Fig. 2.10 The modeling process of external profile

endpoint of S. O is a circle where leading edge and trailing edge are located, and its radius is marked as R:

(1) The endpoint P of S locates in the circle O: $\overline{OP} < R$.

(2) The endpoint P of S is on or close to the circle O: $\overline{OP} < R + \Delta$, Δ represents a given minimum value.
(3) The endpoint P of S is outside the circle O: $X_p > X_o$, $Y_p > Y_o$, in which X_o and Y_o are X and Y coordinates of the center O, and X_p and Y_p are X and Y coordinates of P.

Data points in $S1$ and $S2$ that meet all conditions mentioned above are necessary to be removed. And then free curve $S1$ and $S2$ are reconstructed by all data points which meeting the requirements. At last, $S3$ and $S4$ are generated by constructing curve with leading edge and trail edge.

After structuring $S1$, $S2$, $S3$, $S4$, procedure of joining for cross-section of external profile is good to set about. The process of head edge bridging is shown in Fig. 2.9. The purpose of bridging is that using a spline curve connects the endpoints of two nearby curves to ensure the continuity of geometric order ($G1$) at the junction. After bridging, cross-section curve has been smooth and closed. Lastly, join the bridged curve with the original curves of suction surface and pressure surface, to form a new one, and to ensure the cross-section curve is composed by four curves, including suction surface, pressure surface, leading edge and trail edge.

The modeling process of external profile is shown in Fig. 2.10.

Schematic views of joining and the cross-section after joining are shown in Fig. 2.11.

The range of surface is given by a rectangular area of UV parameter plane. For the external profile surface, the U parameter is determined by the data of the blade cross-section curves; The V parameter direction is the stacking axis, ranging as $Z_1 \leq v \leq Z_n$, which Z_1 is the height of the first cross-section of the blade in the direction of the stacking axis, and Z_n is the height of the nth cross-section of the blade. In the overall modeling method of the cross-section curve, the U curve is structured in clockwise direction (suction surface → trail edge → pressure surface → leading edge) along the cross-section line. The V curve direction is consistent with the stacking axis, which can be constructed in the direction of the stacking axis by aligning the dispersion on different section curves. Points' alignment is the optimal method of the blade body-surface modeling which can ensure

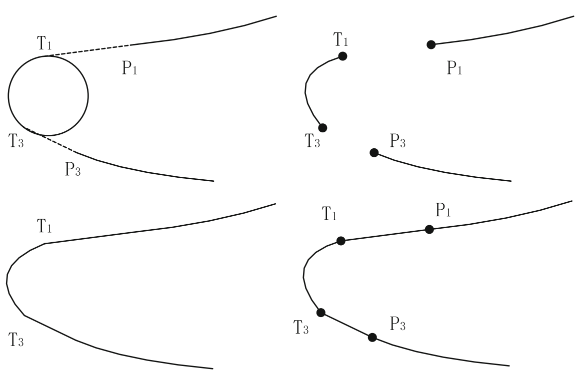


Fig. 2.11 Cross-section curves after joining

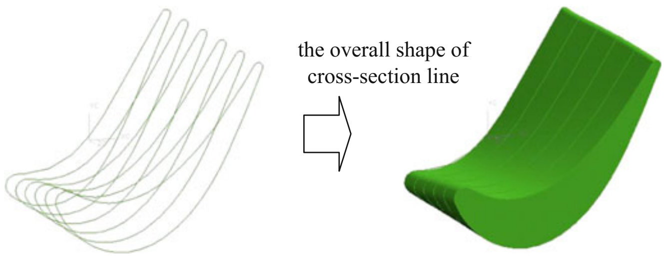


Fig. 2.12 The process of overall shape of cross-section curve

that the endpoints of the suction, pressure surface, leading and trailing edges are aligned with all cross sections, without distorting in the process of constructing the *V* curve. When using point alignment method, the system prompts users to select the alignment points, which must be in order and also accordance with each cross section, and then a group of identical figures will be displayed by the system according to your selection, which would be automatically aligned when configuring the entity. The alignment method can use zero tolerance that shows precise alignment between points that should be selected in the same direction and order. All section curves require corresponding alignment points. However, starting points and ending points cannot be used as alignment points, which need not be selected since each cross-section curve has a starting point and an ending point (the same point) itself. As shown in Fig. 2.12.

Sharp corner should be protected by point alignment if it is contained in cross-section curve. By the time system will produce a separate surface whose common edges are sharp edges produced by the sharp corner. At the mean time the best value of the tolerances should be set as 0, so that the accurate interpolation is produced, which is convenient to subsequent operations [7].

2. Internal profile of the blade

The internal profile of the blade is similar with the external profile, which is also a free-form surfaces generated by passing through the cross-section curve. Data in cross-section curve of internal profile are obtained from offsetting the corresponding cross-section curve of external profile. And the cross-section curve of internal profile is obtained from varying the wall thickness of the cross-section curve of external profile.

Assuming that the external profile of blade is composed by n cross-sections, according to the order of Z coordinates from small to large order they are recorded as: jm_1, jm_2…, jm_n. Taking any one of the cross-sections jm_i ($1 \leq i \leq n$), the control points of the section is expressed with symbol A_{i1}, A_{i2}, A_{i3}, A_{i4}, A_{i5}, and A_{i6} respectively. Symbol h_{i1}, h_{i2}, h_{i3}, h_{i4}, h_{i5}, and h_{i6} indicate the wall thickness of the corresponding control points, as shown in Fig. 2.13.

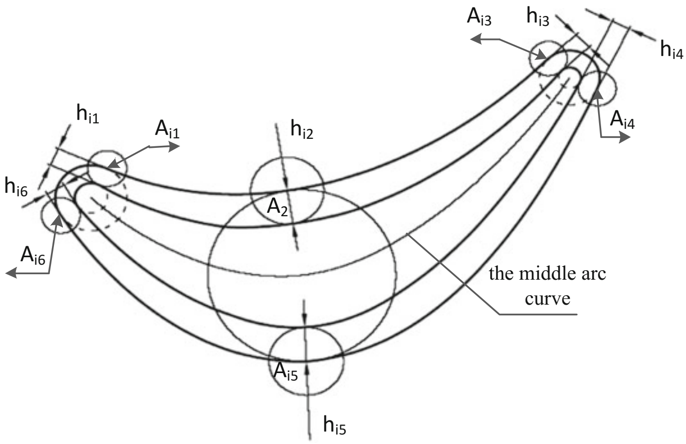


Fig. 2.13 The wall thickness of internal and external profile of the blade

Steps of the varying wall thickness are as follows:

(1) Select the root-section (jm_1) and inter-section (jm_n) of external profile as a design plane;
(2) According to the internal profile design rules, designer determines the thickness ($h_{11} \sim h_{16}$) of control point jm_1, the thickness ($h_{n1} \sim h_{n6}$) of control point jm_n, the number of interpolations between control points of leaf basin $N1$ (between A_{i1} and A_{i2} room) and $N2$ (between A_{i2} and A_{i3} Room), and the interpolation points number between control points of dorsal $N3$ (between A_{i5} and A_{i6}) and $N4$ (between A_{i4} and A_{i5});
(3) Enter the wall thickness between control points in jm_1 and jm_n by:

- Calculating the coordinates of $N_1 + N_2$ interpolation points between the control points by equivalent parameters on the suction curve $S1$ of external profile, and calculating the coordinates of $N_3 + N_4$ interpolation points on pressure surface curve $S2$;
- Calculating the wall thickness of interpolation point on $S1$ and $S2$:
  The wall thickness h'_{1j} ($1 \leq j \leq N_1$) between A_{11} and A_{12} is an arithmetic transition of h_{11} to h_{12};
  The wall thickness h'_{1j} ($N_1 + 1 \leq j \leq N_1 + N_2$) between A_{12} and A_{13} is an arithmetic transition of h_{12} to h_{13};
  The wall thickness h'_{1j} ($N_1 + N_2 + 1 \leq j \leq N_1 + N_2 + N_3$) between A_{15} and A_{16} is an arithmetic transition of h_{15} to h_{16};
  The wall thickness h'_{1j} ($N_1 + N_2 + N_3 + 1 \leq j \leq N_1 + N_2 + N_3 + N_4$) between A_{14} and A_{15} is an arithmetic transition of h_{12} to h_{13};
  The interpolation method between jm_1 and jm_n are;

(4) Interpolate the wall thickness of $jm_2 \sim jm_{n-1}$ by:

- Calculating the coordinates of $N_1 + N_2$ interpolation points by equivalent parameters on the curve S1 of $jm_2 \sim jm_{n-1}$, and the coordinates of $N_3 + N_4$ interpolation points on the curve $S2$ of $jm_2 \sim jm_{n-1}$.
- Processing linear interpolation to the wall thickness of the interpolating points and controlling points of $jm_2 \sim jm_{n-1}$ at the height of cross-section according to the wall thickness of jm_1 and jm_n.

  Enter the wall thickness of control points $hi1 \sim hi6$ $(2 \leq i \leq n-1)$ at the height Zi $(2 \leq i \leq n-1)$ of cross-section, enter the wall thickness $h11 \sim h16$ of control points jm_1 and the wall thickness $hn1 \sim hn6$ of control points jm_n by linear interpolation;

  Enter the wall thickness h'_{ij} $(2 \leq i \leq n-1,\ 1 \leq j \leq N_1 + N_2 + N_3 + N_4)$ of interpolation points $hi1 \sim hi6$ $(2 \leq i \leq n-1)$ at the height $Zi(2 \leq i \leq n-1)$, enter the wall thickness h'_{1j} $(1 \leq j \leq N_1 + N_2 + N_3 + N_4)$ of interpolation points jm_1 and the wall thickness h'_{nj} $(1 \leq j \leq N_1 + N_2 + N_3 + N_4)$ of interpolation points jm_n by linear interpolation;

(5) According to the wall thickness, calculate the coordinates of the internal profile points that corresponding to all interpolation points and control points of $jm_1 \sim jm_n$. The coordinates of the internal points are obtained by moving forward the wall thickness of the coordinates of external profile points (including control points and interpolation points) along the normal vector of the curve S_1 and S_2. Normal vector is from the external appearance of the cross-section curve to its interior;
(6) Construct basin curve $S'1$ and dorsal curve $S'2$ of internal profile by data points, the construction method is consistent with the external profile curve $S1$, $S2$.
(7) Construct the leading edge of internal profile $S'3$ and the arc of trail edge $S'4$

- Calculating the radius of leading edge and trail edge:

  Radius of leading edge: $R'_{i1} = R_{i1} - (h_{i1} + h_{i6})/2$, among them R_{i1} is the radius of leading edge;

  Radius of trail edge: $R'_{i2} = R_{i2} - (h_{i3} + h_{i4})/2$, among them R_{i2} is the radial of trail edge.

  For internal profile, the center of leading edge and trail edge can be directly determined by the blend of basin and dorsal curve, radius of the blend is the radius of leading edge and trail edge.

  Internal profile of body is one part of internal profile of blade, which is connected with the extension root. It has complex air-cooling structures such as longitudinal ribs, transverse ribs, pin fins, and so on. The solid of internal profile actually represents the cavity portion of the turbine blade. The solid of the blade cavity can be obtained by Boolean operation between the solid of internal profile and external profile blade.

3. Extension root modeling

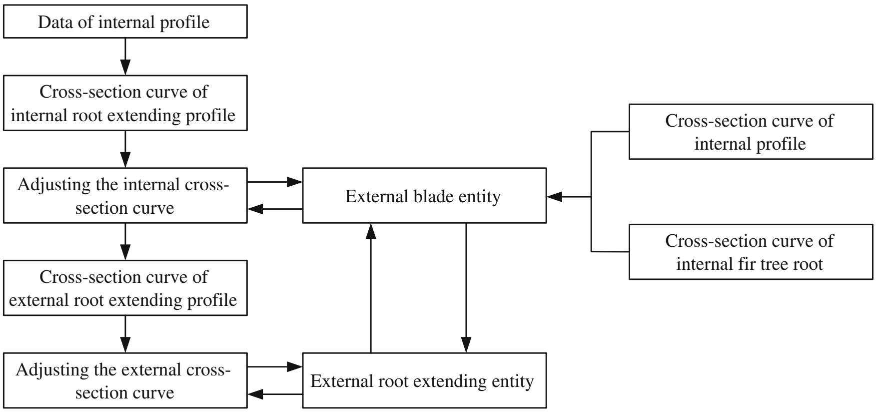


Fig. 2.14 Flow of generating root extension

Extension root is the transition part that connecting blade body and blade tenon. The extension root also has a cavity that can be divided into internal and external solid modeling, since the turbine blades are air-cooled hollow structured. The internal and external shape of the extension root should be transited smoothly and achieve the design strength. No more specific design requirements. Method of internal modeling first and then external modeling is adopted to extension root, which is shown in Fig. 2.14.

Similar to the internal profile modeling, the modeling of internal extension root is also based on a series of cross-section curves, and then the solid is obtained by lofting along the direction of stacking axis. The cross-section is the premise of generating the internal root extending profile. However, the structure of internal extension root profile does not affect the aerodynamic performance causing that designers are blind when designing the structure, which often "trial and try" the data relying on experience. The author gives an experiential method that can generate the cross-section of internal extension root profile, in order to meet the parametric design requirements [8].

Internal extension root connects the internal profile of blade body and fir tree root. Therefore, internal extension root can be seen as a structure that obtained by transiting from internal profile of blade body to internal profile of fir tree root in certain way that is being obtained by interpolation between the root-cross-section curve of blade body and the cross-section curve of fir tree root. In order to ensure the smoothness of final generated internal profile, the cross-section curve of extension root should include four structures that are similar to the cross-section of blade body. Method of acquiring the top cross-section is shown as follows:

(1) Intersect the plane which is H distant from the datum plane A with the internal profile, then form a closed curve S;

(2) Obtain n points on the curve S by the method of equal arc, and denote them as the set $P = \{P_1, P_2, \ldots, P_n\}$;
(3) Read three adjacent points P_{i-1}, P_i, P_{i+1} ($i = 1, 2\ldots n-2$) sequentially, then calculate the radius that includes these points and denote the radius as R_i. If the difference between R_i and R_{i+1} is less than the specified error value, it could say that these points are on the same arc. By this way several groups of point set can be found out and then denoted as PG_i in turn, and the points in every set are located on the same circle.
(4) Find the set that includes the minimum radius in PG_i, which are the radius of leading edge and trail edge. And the two groups of points are the points on the leading edge and trail edge, while the remaining points are on pressure spline and suction spline. Thus, the curve is separated into four parts including leading edge, trail edge, pressure spline, and suction spline.

The root-cross-section curve of internal extension root is the top-cross-section curve of internal fir tree root. As shown in Fig. 2.15, the top-cross-section and root-cross-section of extension root are connected by ruled surface. The method works as follows:

(1) Generate four ruled surfaces by the group of curves (C_{q1}, C_{q2}), (C_{p1}, C_{p2}), (C_{b1}, C_{b2}), (C_{h1}, C_{h2}) as shown in Fig. 2.15.
(2) Obtain specified height curve by intersecting the plane and surface.
(3) Edit the endpoints of the intersection curve to reach $G1$ continuity.
(4) Repeat step 2 and 3 to obtain several groups of middle section curve.

When designing the cross-section curves of external root extending profile, considering several factors such as the ventilation of cavity, strength, structure, and weight is an iterative process. In order to obtain the cross-section curves of internal profile, designers need to offset the cross-section curves of external profile according to a certain requirement. When the curves are offset, three thickness values on the key position should be given: tangent point of leading edge, tangent point of trailing edge and the point on the maximum thickness. The tangent point of leading and trailing edge are easy to obtain, while the maximum thickness should be obtained by the following steps, which is also shown in Fig. 2.16:

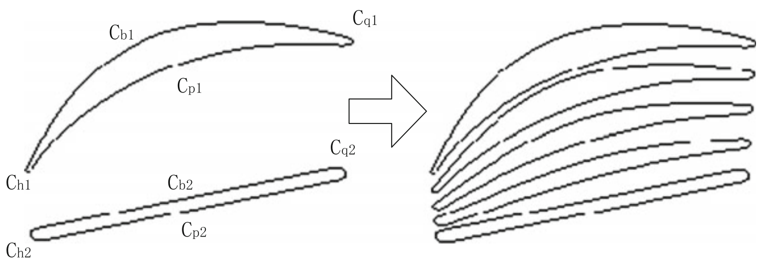


Fig. 2.15 Generating cross-section curve of internal root extending profile

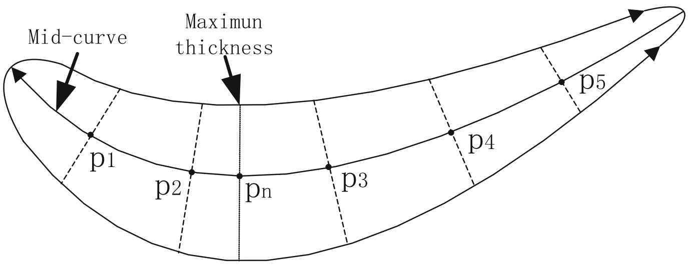


Fig. 2.16 Method of obtaining the maximum thickness

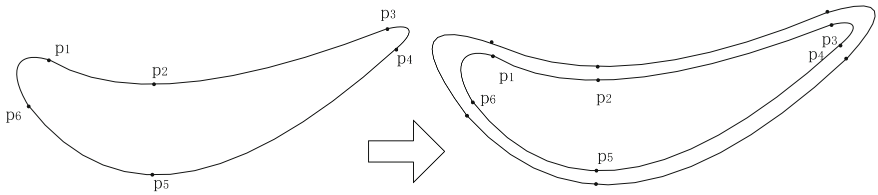


Fig. 2.17 Obtaining external root extension by key points

(1) Obtain the mid-face of internal blade entity, then intersect the plane with the mid-face to get the mid-curve of the certain cross-section, and mark it as *ML*.
(2) Obtain n points ($n > 3$) on the mid-curve by the method of equal arc, and denote them as the set $p = \{p_1, p_2, \ldots, p_n\}$.
(3) Calculate the thickness values at these points, and denote them as the set $H = \{h_1, h_2, \ldots, h_n\}$.
(4) Compare the value of every element in the set H, then calculate the maximum value h_i and the corresponding point p_i.
(5) Regard the mid-curve between p_{i-1} and p_{i+1} as a new mid-curve and then repeat step 1 to 4 till the length of arc between p_{i-1} and p_{i+1} is less than a certain value ε. And denote the calculated thickness value h_i as the maximum $h_{\max}$. Thus, the corresponding point p_i is the maximum point $p_{\max}$. Intersection between the normal vector of $p_{\max}$ and pressure spline and suction spline of the internal extension root is denoted as the maximum thickness point.

After obtaining the maximum thickness of blade body, varying thickness values can be interpolated to get the initial cross-section of external extension root. As shown in Fig. 2.17, designer defines 6 points that control the thickness at the cross-section curve of internal root extension. If these points are offset outwardly, the external cross-section of extension root can be formed.

Similar with generating the internal and external profile of blade body, solid can be obtained by passing through the cross-section curves of internal and external extension root, and the geometric entity of extension root can be obtained by Boolean operation.

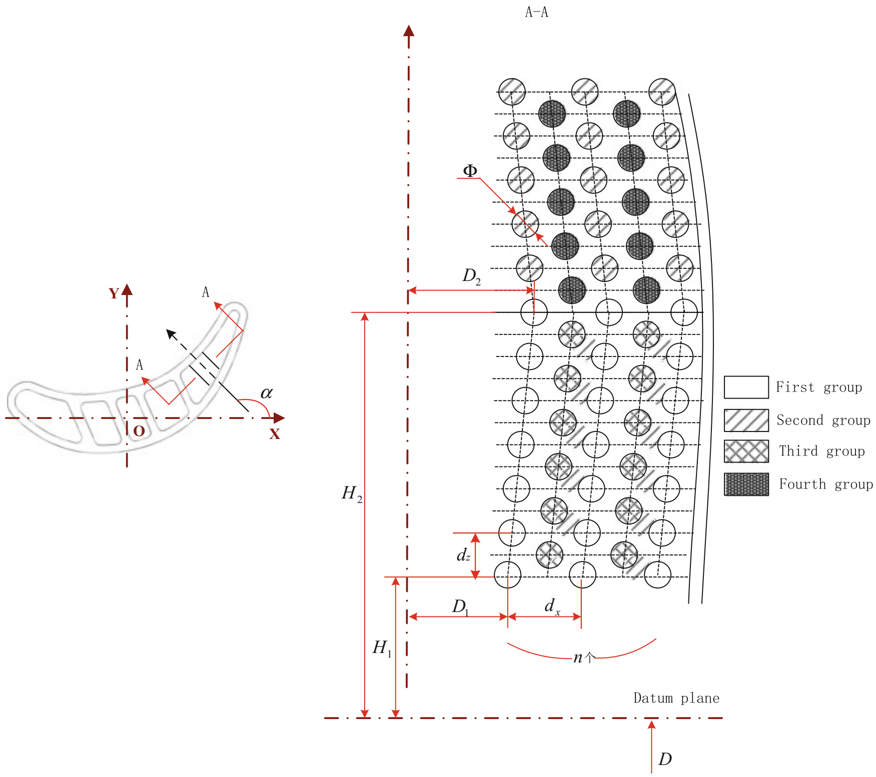
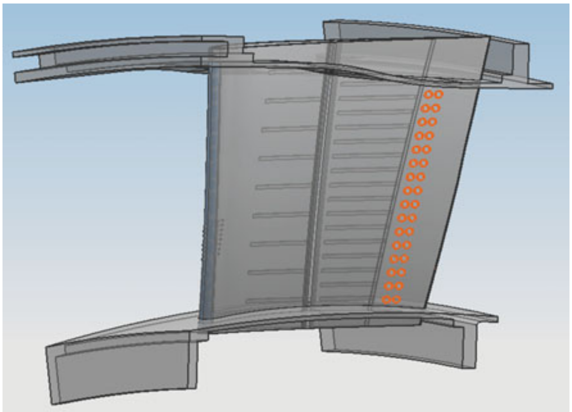


Fig. 2.18 Groups of pin fin

Fig. 2.19 Modeling of generating pin fin



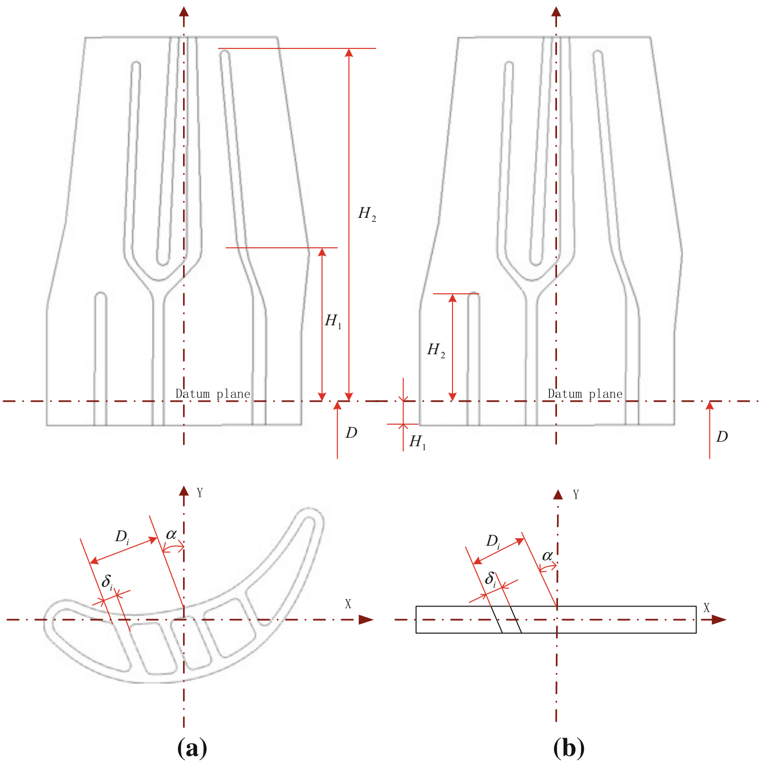


Fig. 2.20 Longitudinal rib

2.2.5 Internal Profile Feature Modeling of Turbine Blade

1. Modeling of pin fin

Turbine blade works under the high temperature, so complex cooling structures are included in the blade cavity, such as pin fin, longitudinal rib, transverse rib, cooling hole, and the split seam of trailing edge. Pin fin is generally located near the trailing edge and distributed in a complex array, as shown in Fig. 2.18.

It can be summarized that pin fin is a multiple array that is in accordance with certain rules of distribution. Every group of array includes these parameters: initial height H_1 of the pin fin, final height H_2 of the pin fin, the distance D_1 between the initial point of pin fin and stacking axis, the distance D_2 between the final point of pin fin and stacking axis, the distance D between datum plane and the center of engine, the distribution pitch dz in the Z-direction of pin fin, the distribution pitch dx in the X-direction of pin fin, the numbers n of pin fin in the X-direction, the diameter Φ of pin fin, and the angle α between the plane that pin fin located and X-axis. A set of regular pin fin is shown in Fig. 2.19

2. The modeling of longitudinal rib

Longitudinal ribs can be seen as a set of stretching features. Ribs of different blade structures are distinctive, such as rib 3 and rib 5. The structure of rib 5 is shown in Fig. 2.20.

As shown in Fig. 2.20, the geometry of each longitudinal rib is not identical, and it can be roughly divided into three conditions: only existing in fir tree root, only existing in internal profile part, and penetrating internal profile, inner root extending segment and fir tree root. The most complicated situation is the last one. This is because the ribs in internal profile and fir tree root have different torsion angles, which cannot be modeled with only one extrude. In order to solve the problem that the structures of longitudinal ribs and the definitions of parameters rarely diverse, longitudinal ribs can be classified into three groups: internal profile, inner root extending segment, and fir tree root, among which the parameters of the internal profile and fir tree root are the same, shown in the figure above shown in (a) and (b), including: longitudinal rib starting altitude H_1, terminal height H_2, angle α of rib tensile direction and the Y-axis, distance from the lower section of rib to tensile axis D_1, distance from the upper section of rib to tensile axis D_2 (both represented by parameters D_I in the above Fig. 2.20), thickness of low section of ribs δ_1, thickness of upper section of ribs δ_2 (both represented by parameters δ_i in the Fig. 2.20), and the datum from the engine center distance D. So that only a different parameter value is given, the longitudinal ribs of the vane segments and the tenon segments can be constructed, after generating longitudinal ribs of internal profile and fir tree root, the middle inner root extending segment can be generated with straight grain surface interpolation methods.

After classifying and simplifying the longitudinal ribs, the ribs of internal profile and the ribs of fir tree root both turn into the same tensile feature [9]. When modeling, a cross-sectional shape can be defined on the sketch first, and then extrude out the solids of ribs, and lastly operate Boolean with the internal profile. Among all, the definition of the sketch is the key. First of all, the normal vector of

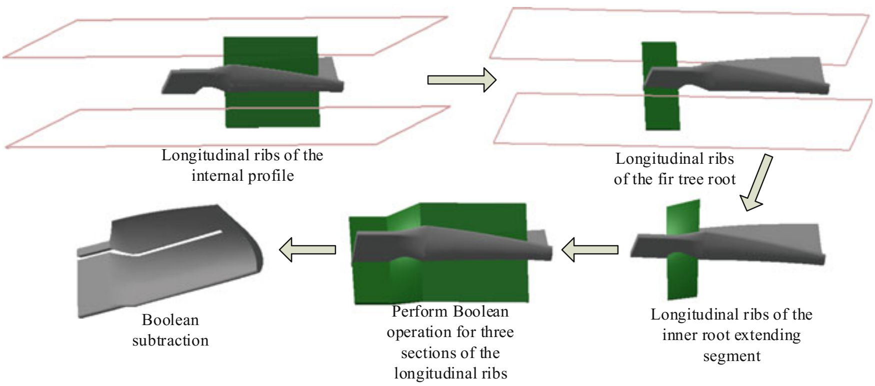


Fig. 2.21 The generation process of longitudinal ribs

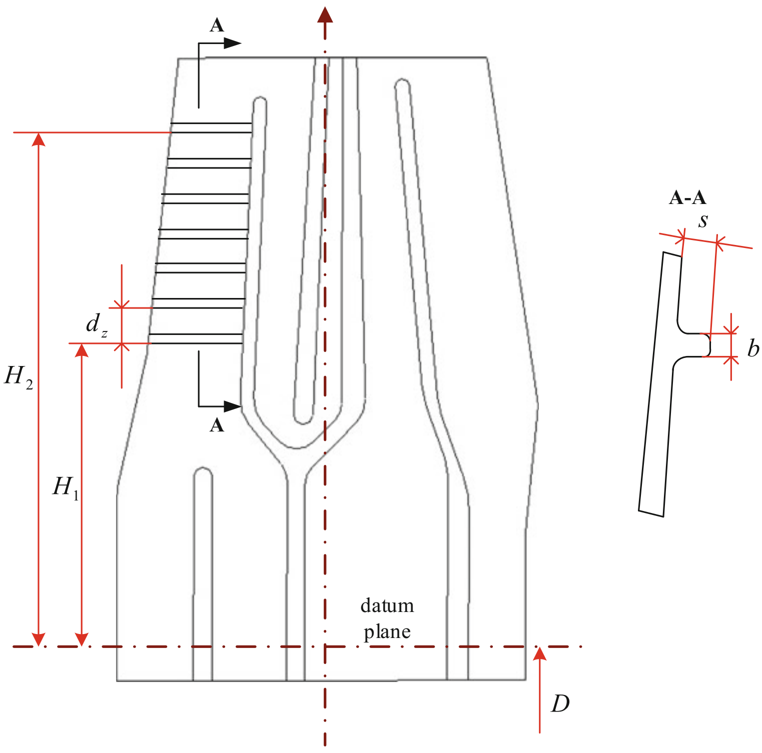


Fig. 2.22 The distribution of the transverse ribs

sketch plane is the same to the ribs tensile direction, that is to say, an angle α with the *Y*-axis is needed; second, in order to guarantee the extruded ribs are able to carry Boolean operation with internal profile, ribs must be completely passing through the internal profile, in this way, the enough extrude thickness is needed. In addition, there are two ideas to ensure the position of sketch. One is locating sketch near the mid-face of the blade, and then operating drawing on both sides of the blade; another is locating it on one side of the blade, then extruding to the other side.

The extending segment ribs of inner root cannot adopt the method that establish a sketch first and then extruding, since ribs of internal profile and fir tree root possess different torsion (different from angle α of *Y*-axis, fir tree root angle generally takes as 0°), which can only be generated in manner of straight grain surface interpolation. The general process of longitudinal ribs modeling is shown in Fig. 2.21.

3. Transverse ribs modeling

Transverse ribs are a series of small ribs, distributing among longitudinal ribs, which equidistant surface is its bump surface and internal profile surface. The main function of transverse ribs is *s* to enhance the heat effect of cooling gas. Along the

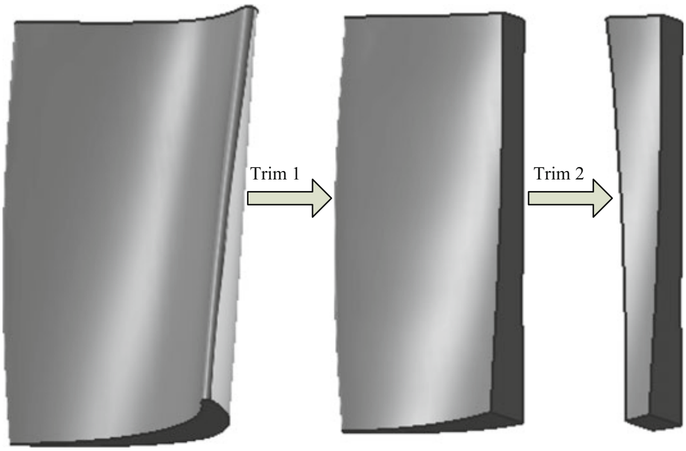
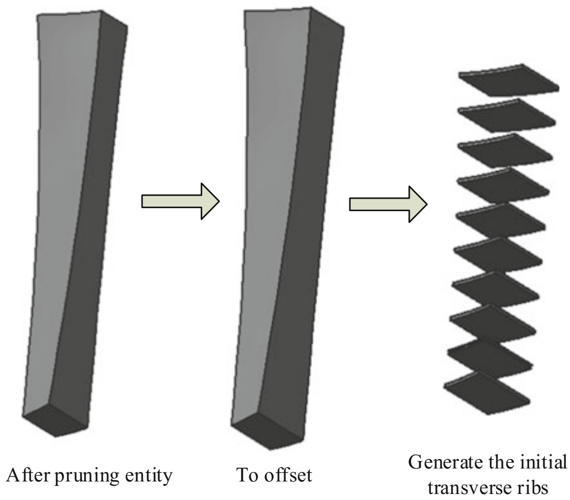


Fig. 2.23 Trim internal profile of blade

mid-face of blade, the transverse ribs can be divided into two parts, transverse ribs of pressure surface and transverse ribs of suction surface, which are separated by longitudinal ribs into multiple groups. As shown in Fig. 2.22.

A grouping modeling for transverse ribs are processed according to the distribution characteristics. As shown in the Fig. 2.22, each set of parameters include transverse ribs starting altitude H_1, transverse ribs terminate high H_2, the distance dz of transverse ribs along Z, transverse ribs depth S, transverse ribs thickness b, and datum plane from the center of the engine distance D. In addition to these parameters, in the actual system development, the location of transverse ribs is also taken into account, which two questions would be asked: first, is that ribs of pressure surface or suction surface; second, which two longitudinal ribs segment the

Fig. 2.24 Generate the initial transverse ribs



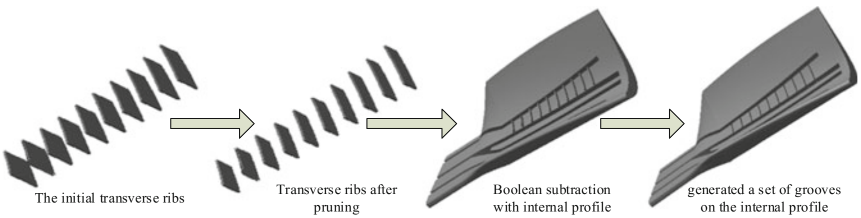


Fig. 2.25 Process of generating the final grooves of transverse ribs

transverse ribs (leading-edge transverse ribs are divided by one longitudinal rib only).

Transverse ribs are achieved by the method, which embodied in internal profile of the blade is a series of grooves. From the position of transverse ribs, it can be seen that transverse ribs on both sides of the surface are determined by the longitudinal ribs. Surface along the direction of the bump has a similar shape with the blade body surface, which is decided by the blade internal profile surface and inward offset surface, along *Z*-axis is the face that parallel to *X*-*Y* plane, and it is determined by the related parallel surface. To create a groove with the above characteristics in the internal profile of blade, it is necessary to generate the corresponding entity first, and then calculate Boolean operation with the internal profile. The whole modeling process is described by the following example, which is a set of transverse ribs on pressure surface.

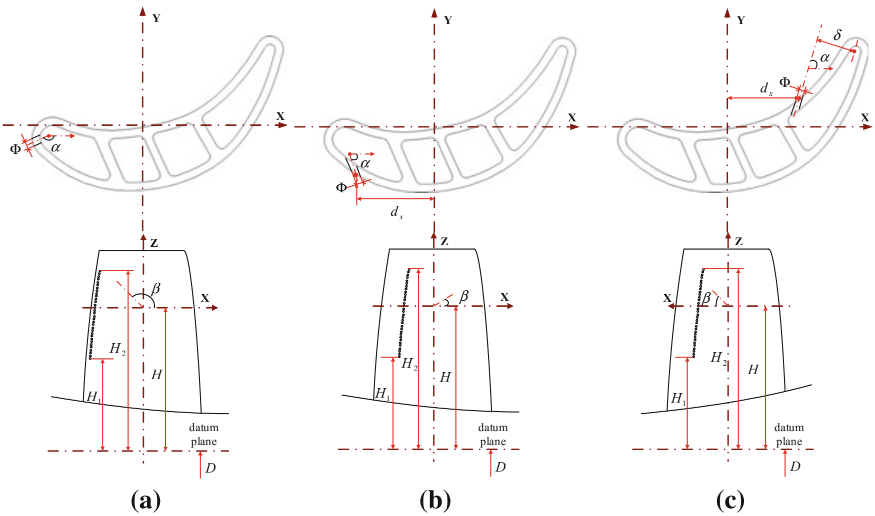


Fig. 2.26 The distribution of cooling holes

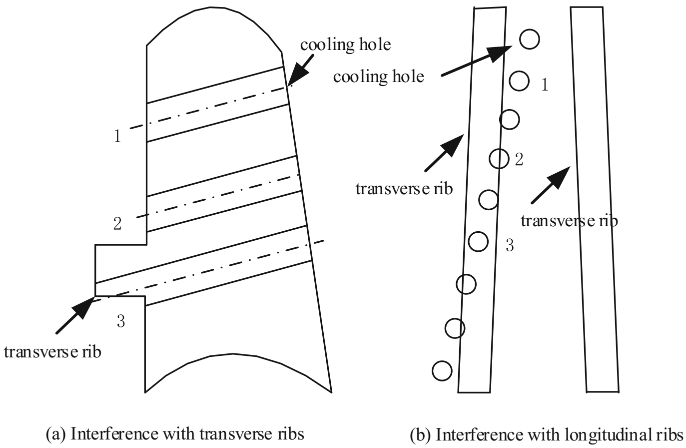


Fig. 2.27 Cooling holes interference

First of all, on the basis of the internal profile of blade body, trim with longitudinal ribs surface, keep the solid part that is going to generate transverse ribs. Process is shown in Fig. 2.23.

Second, in order to ensure that the generated solid can carry on the Boolean difference with internal profile. It is needed to offset a small thickness δ from surface of the solid which generated in the previous step, and then take the distribution size of transverse ribs along the Z-axis as basis, break up the offset solid, keep parts in need, which is the initial transverse ribs, as shown in Fig. 2.24.

Finally, further clip the transverse ribs which generated in the previous step in accordance with its depth, and then operate Boolean subtraction for clipped ribs and the internal profile, then generate a set of grooves that reflect characteristics of transverse ribs, as shown in Fig. 2.25.

4. The cooling holes modeling

Cooling holes are located at the external profile, roughly configuring along the direction of blade stacking axis, which characterized by its very small pore size and the dense distribution. From the distribution of cooling holes, they can be further divided into three categories, leading edge cooling holes, suction surface cooling holes, and pressure surface cooling holes. The reason why they are classified like this is because of the variety of cooling holes parameters on different location. Figure 2.26a–c are the three cases of the cooling holes parameters schematic diagram.

The central axis of leading edge cooling hole passes through the center of the circle of leading edge. Parameters of holes on each row include: initial height H_1 of drilling hole, end height H_2 of drilling hole, diameter of hole Φ, hole spacing dz (not marked on the diagram), angle α between central axis of the hole in X-Y plane projection and X-axis, angle β between central axis of the hole in X-Z plane projection and X-axis, datum plane from the center of engine shaft distance D. For the suction surface cooling hole, since the central axis of the hole does not pass through the center of the leading edge, thus besides the above parameters, it is necessary to add a parameter dx for the location of the positioning hole. For the pressure surface cooling hole, except the parameter dx, the problem of tool interference during process should also be taken into account. In other words, the hole at the center of the shaft and the blade trailing edge ought to keep enough distance between each other, which is denoted by parameter δ in Fig. 2.27c.

During actual design process, the interference from transverse ribs and longitudinal ribs should be considered when coming to positioning cooling holes, since the cooling holes interfere with the inner blend structure. As shown in Fig. 2.27, in Fig. 2.27a transverse ribs intersect with cooling holes, and in Fig. 2.27b the longitudinal ribs intersect with cooling holes. Three positions of cooling holes that are relative to longitudinal ribs or transverse ribs are denoted by 1, 2, 3. In Fig. 2.27a 1 and 2 cooling holes and transverse ribs are reasonable because the cooling holes do not interfere with the transverse ribs. However, 3 cooling holes and transverse ribs are not because they interfere with each other.

2.2.6 *Typical Feature Modeling*

1. Fir tree root modeling

Fir tree root, a structure that connects blade and disk, can sustain 100–150 kN centrifugal load under 600–700 °C. Therefore, the strength and thermal conductivity of fir tree root can directly affect the reliability of blade. The shape of fir tree root is diverse, and the fir tree shape is widely used at present [10].

Similarly, fir tree root modeling consists of internal profile modeling and external profile modeling. Although there are many kinds of external profile, the

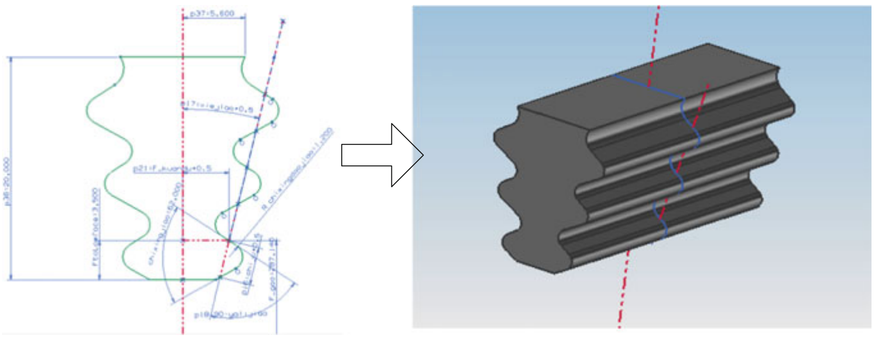


Fig. 2.28 The generation of external profile

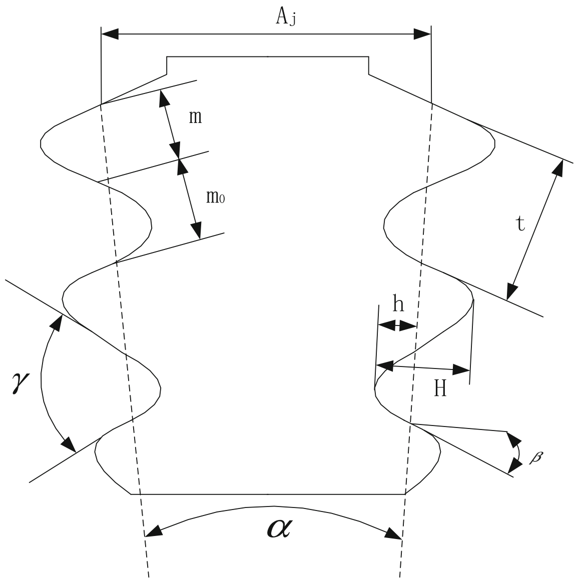


Fig. 2.29 Parameters of fir tree root

modeling process is not complex. It can be summarized as follows: (1) Model the cross-section sketch of root, (2) Obtain the external profile's body by extruding the sketch as show in Fig. 2.28.

The section sketch of external profile consists of line and arc segment. The topological relation between line and arc segment is established by sketch constraints, and the size of line and arc segment is established by parameter expressions. After constraining section sketch, the three dimensional solid of fir tree root can be generated by extruding feature.

As show in Fig. 2.29, α is the angle between two pitch lines. Pitch A_j is the distance between two points on the fir tree serration respectively. The serration pitch t is the distance between two serration points on the same side. H is the distance from serration head to serration root along the direction that is perpendicular to pitch line. Addendum height of the serration h is the width of tenon slot. Tooth thickness is marked by m, and m_0 is the width of tenon slot on the pitch line.

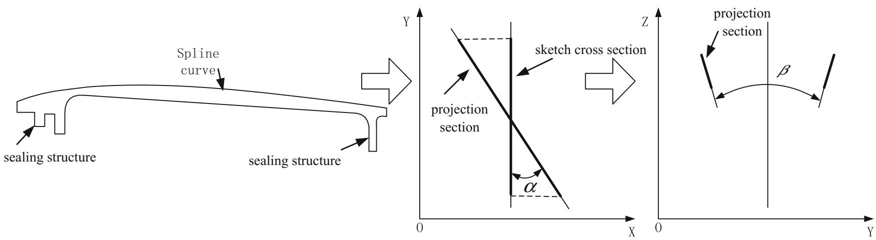


Fig. 2.30 Platform modeling process

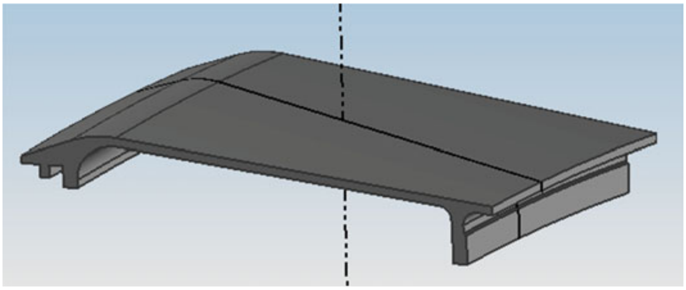


Fig. 2.31 Platform model

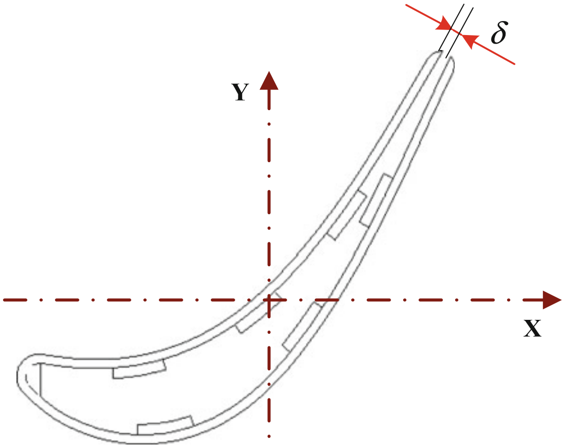
β is the pressure angle that represents the angle between tenon tooth surface and the linear with vertical the pitch line. γ is the tooth profile angle that represents the angle between tenon tooth surface and non-working surface.

The internal profile of fir tree root is similar to the internal profile of blade body and root extending segment. The regular and closed cross section curves constitute the internal profile, and its entity relies on extruding these closed curves.

2. Platform modeling

Platform consists of flow course plate and some sub-features. The shape of flow course plate is decided by aerodynamic data. Sub-features can be divided into sealing groove, sealing gear, fixture fringe, sealing boss and spigot according to the function. Every platform has at least one sub feature that is located in the left or right side of the flow course plate. When designing tools, designer is required to choose the necessary sub-features, and then possesses Boolean operation with the flow course plate to obtain the platform entity.

Fig. 2.32 Trailing edge slot



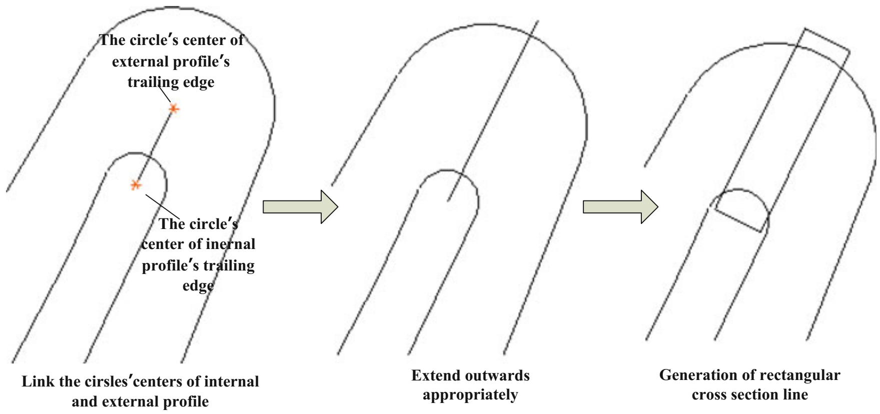


Fig. 2.33 Deterministic process of the section curves of the slot entity

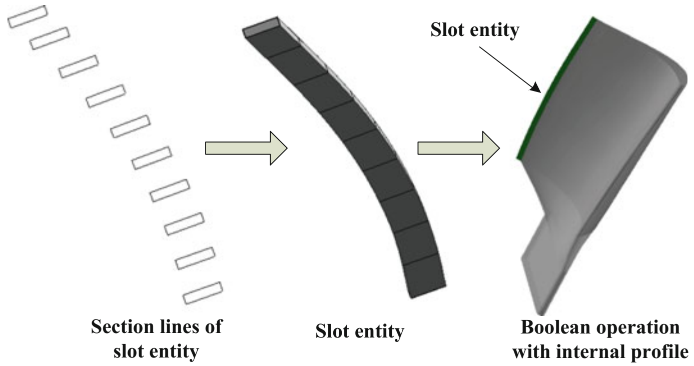


Fig. 2.34 Modeling process of trailing edge slot

Platform modeling is similar with the fir tree root modeling. Initially, draw the sketch for the cross section of platform. Then build the topological structure among sketch elements by constraints. And use parameter expressions to describe the geometric dimensioning, as show in Figs. 2.30 and 2.31.

(1) Draw the sketch for the cross section of platform. The spline curve on the cross section is the flow passage. The rest can be built as parametric sealing structures.
(2) Project the cross section onto the plane rotated angle α along the stacking axis and then get the projection section.
(3) Rotate the projection section angle β along the engine's axis and then get the 3D entity with the Rotary Draw Method.

3. Trailing edge slot modeling

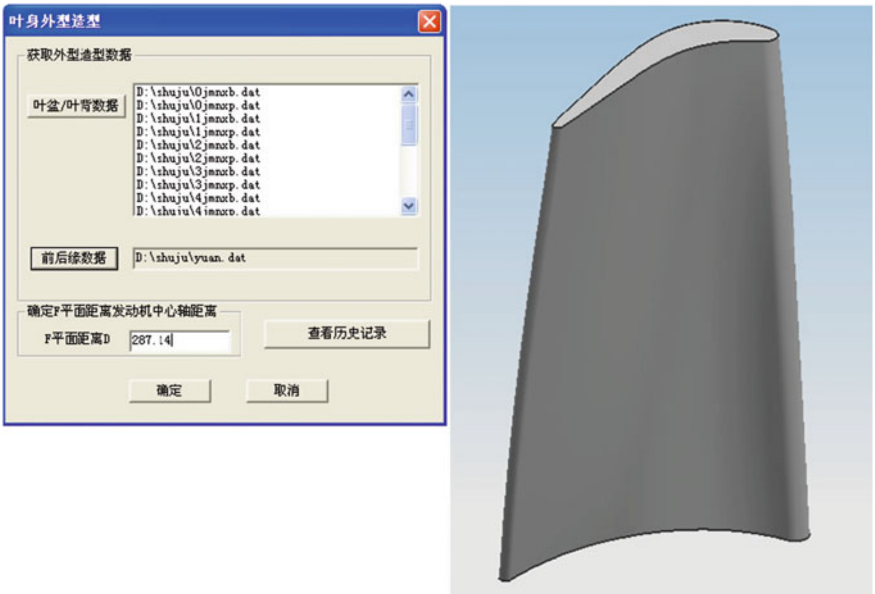


Fig. 2.35 External profile solid of blade body

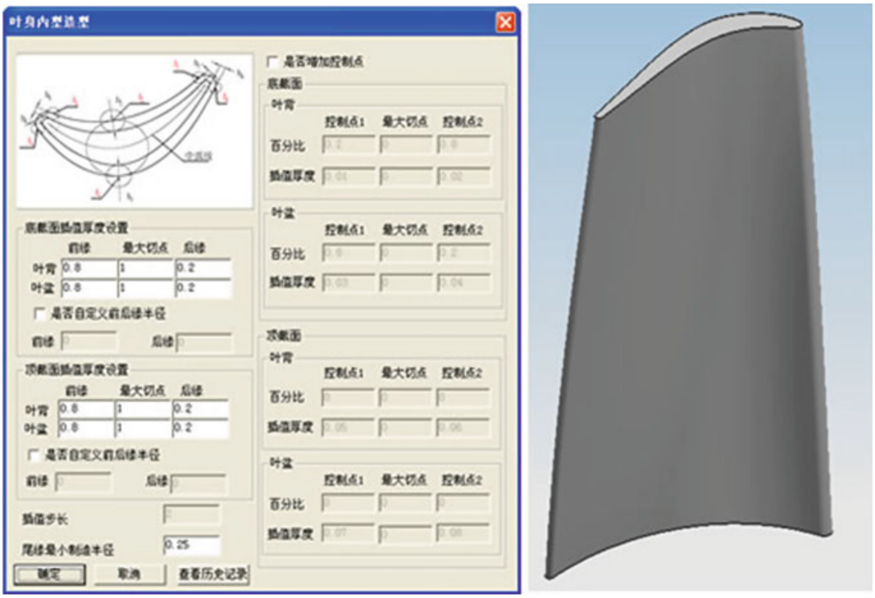


Fig. 2.36 Internal profile solid of blade body

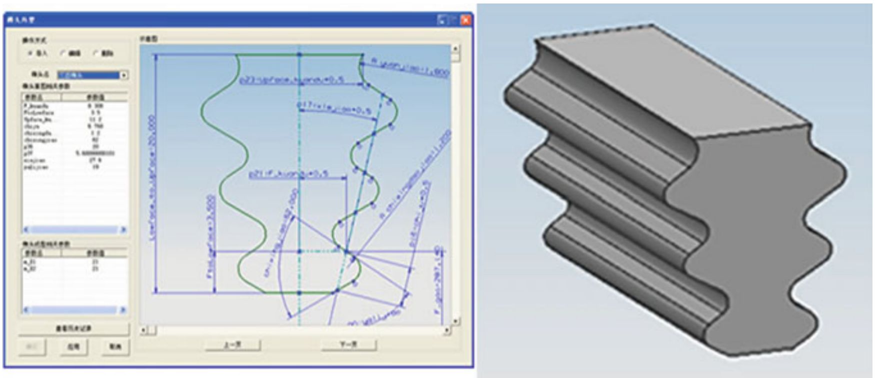


Fig. 2.37 External profile solid of fir tree root

The trailing edge slot of turbine blade plays the role of exhausting cooling gas and cooling the trail edge. In general, the slot can be divided into two parts: half slot and whole slot. Moreover, the cooling effect of whole slot is slightly better than half slot, but the former requires larger trailing edge radius to ensure the strength. This chapter takes whole slot as shown in Fig. 2.32.

It can be seen that the structure of trailing edge slot is much simpler than structures like pin fins and others. Trailing edge slot only has one parameter, slot

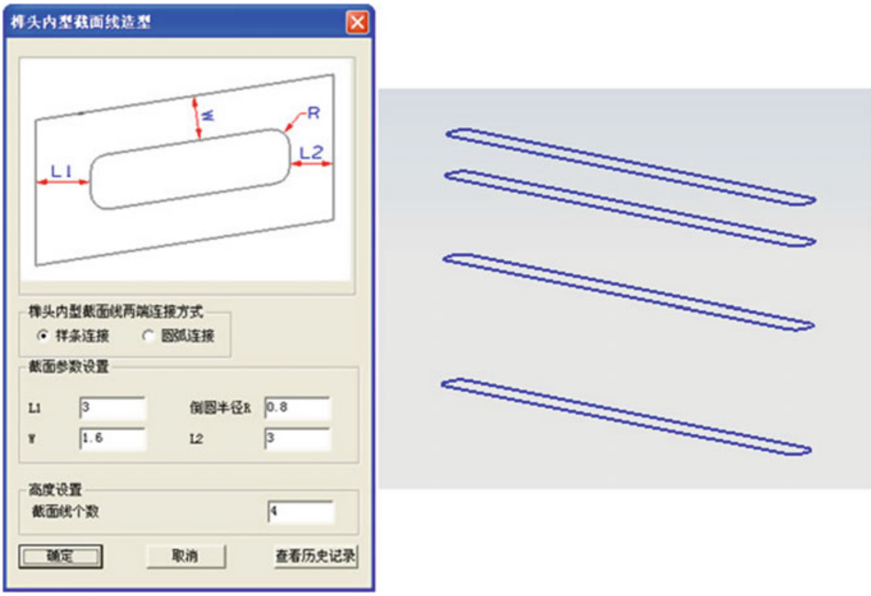


Fig. 2.38 Section curves of internal profiles of fir tree root

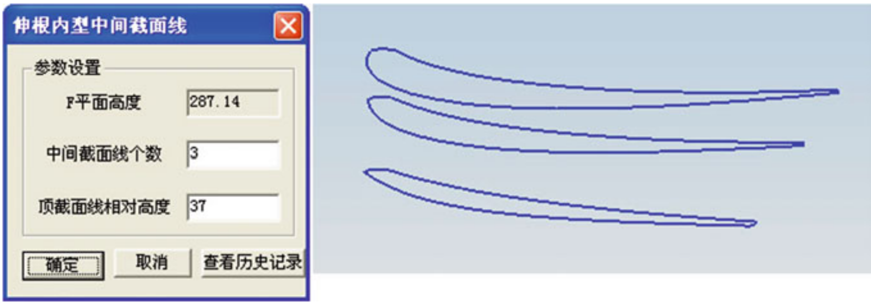


Fig. 2.39 Section lines of internal profiles of root extending section

width δ. As for the height and position of trailing edge slot in Z-direction, can be directly determined by the structure of blade entity. The trait of trailing edge slot is reflected on the internal profile by extruding out a boss structure at the blade trailing edge that can be acquired by Boolean operation a strip solid called slot solid, and the internal profile of the blade. Therefore, the key to modeling trailing edge slot is to generate the slot entity. From the parameters and the position of trailing edge slot, which are given by the picture, it can be easily seen that the slot entity has similar modeling traits with the internal profile of blades. It also, at first, needs a

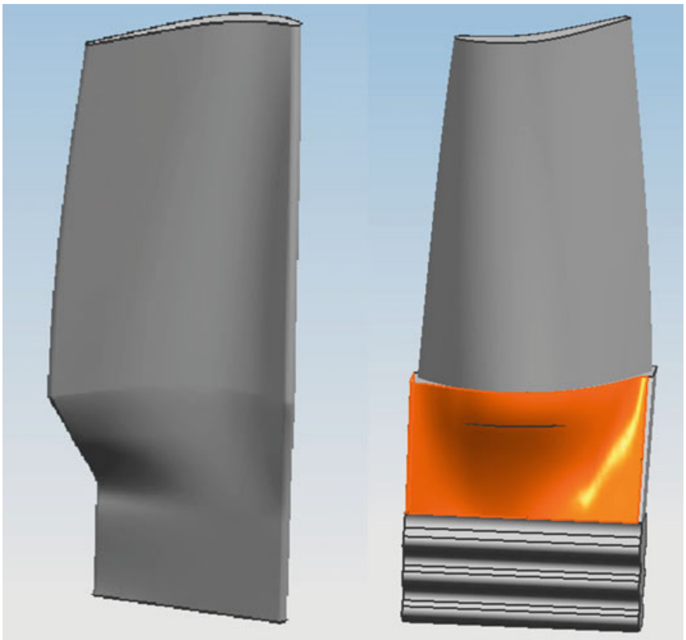


Fig. 2.40 Section curves of internal profiles of root extending section

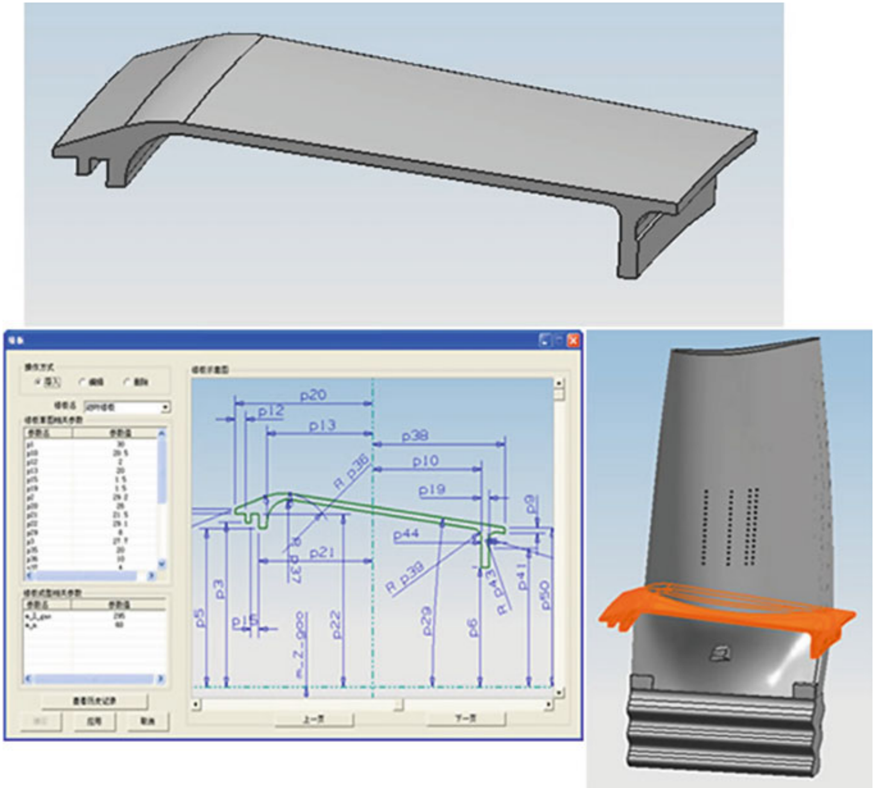


Fig. 2.41 Feature model of the platform

series of section curves, and then solid features can be acquired by using skinning method along the stacking axis. While the difference is that the section curve of slot entity is one single ordinary rectangle. The width of the rectangle is denoted as parameter δ as depicted in Fig. 2.24. The length is decided by the distance of the circle's center between trailing edges of section curves in external and internal profiles at the same level. In order to ensure that the Boolean operation can be carried out smoothly, the length needs an additional length Δx to the distance of the circles' centers. The deterministic process of the section curves of the slot entity is shown in Fig. 2.33.

After confirming all section lines, slot entity can be generated from the skinning method. Finally, the boss structure can be acquired by using Boolean operation on slot entity and the entity of internal profile. The modeling process is shown in Fig. 2.34.

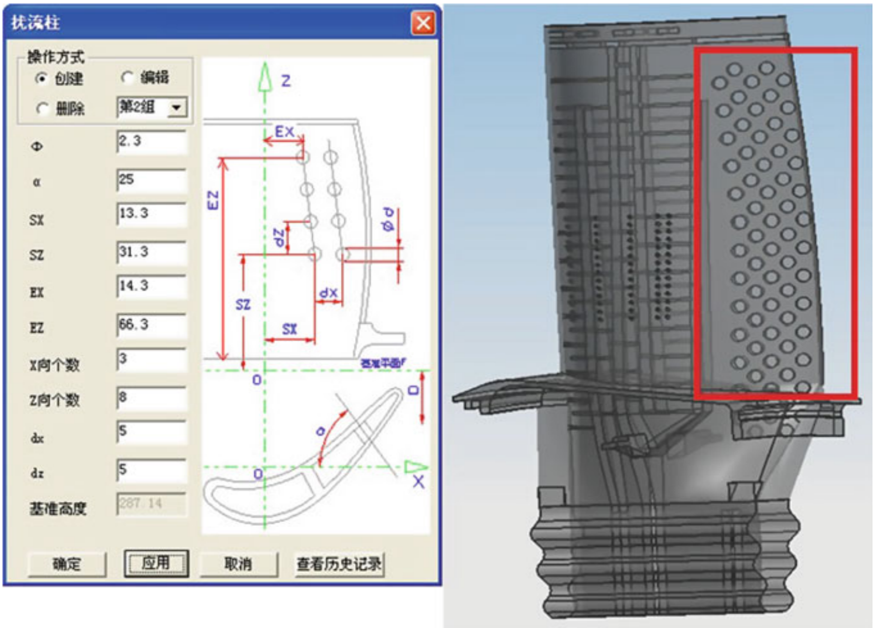


Fig. 2.42 Feature model of pin fins

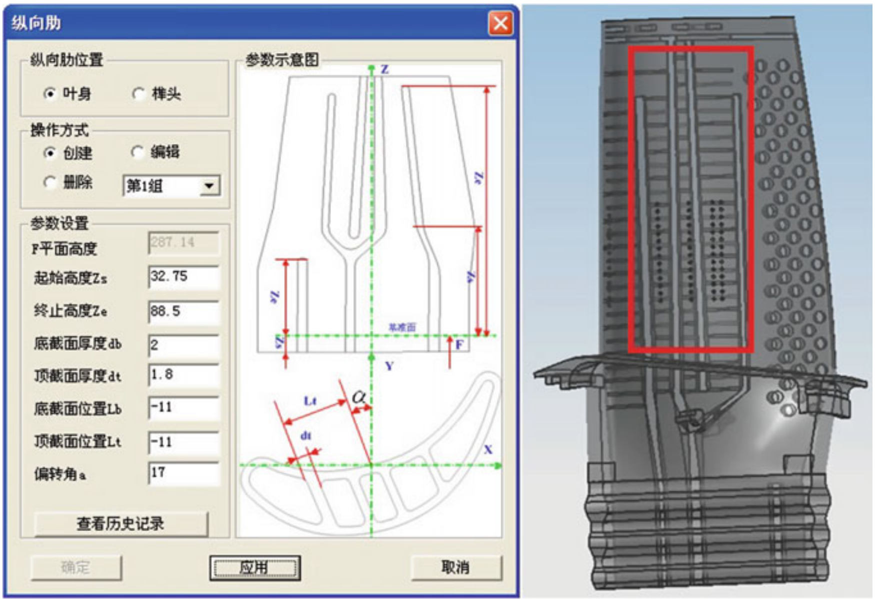


Fig. 2.43 Feature model of longitudinal ribs

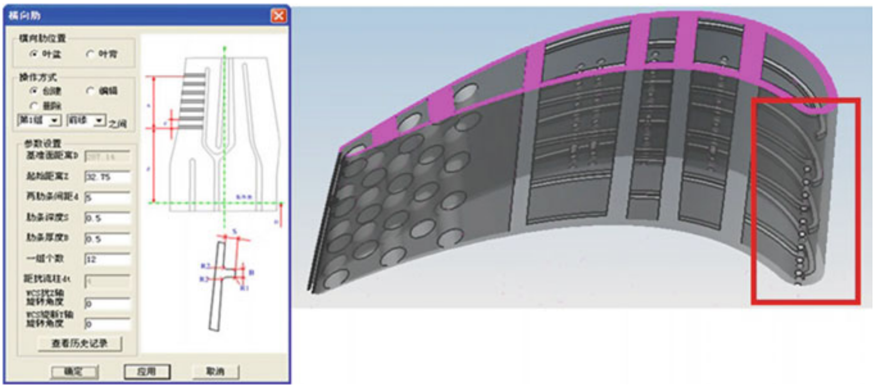


Fig. 2.44 Feature model of transverse ribs

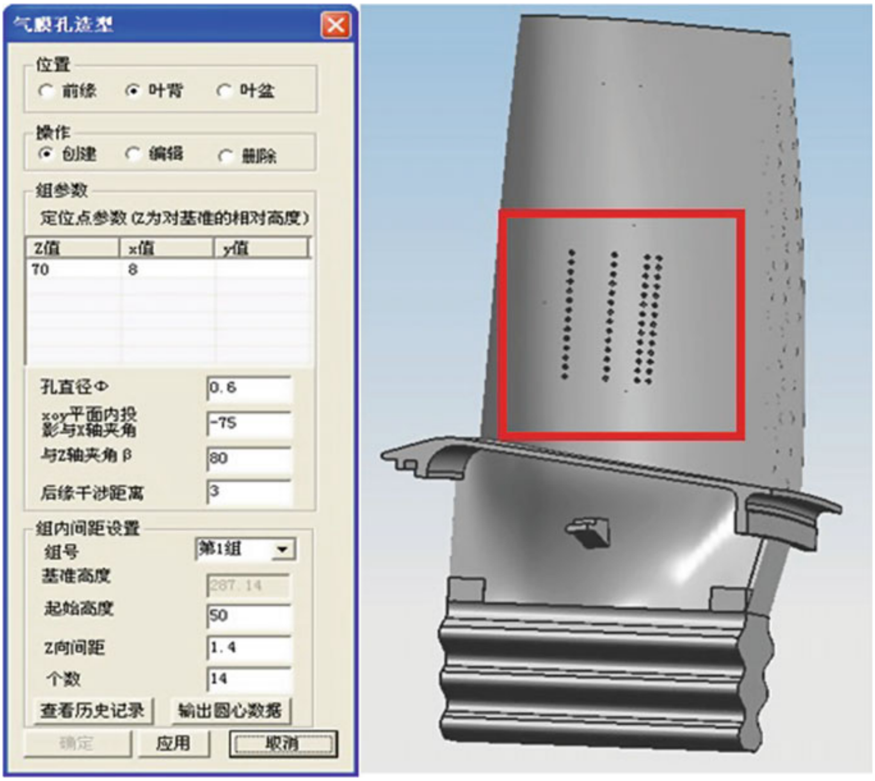


Fig. 2.45 Feature model of cooling holes

Fig. 2.46 Feature model of trailing edge slot

2.3 Case Study

This section takes parametric modeling process of rotor blade in the turbine blade for an example, analyzing and explaining the methods on character parameter modeling of turbine blade.

In the external profile modeling of blade body, section curve strings of the external profile are formed by inputting sectional data of leading and trailing edge. Also the solid model of external profile is generated by using extruding feature that passing through curves, as shown in Fig. 2.35.

Internal profile model of blade body can be obtained by offsetting inwards section curves of external profile based on nonuniform wall thickness of valves. By using the method of assigning control points of multiple locations section curves of internal profile can be figured out. Solid model can be generated by extruding section curves of internal profile of blade body lastly. However, the internal profile is not complete as lacking of a good deal of detail features from internal profile at this time, as shown in Fig. 2.36.

The external profile of fir tree root has certain geometry rules, and can be divided into different types of forms. Every form can be summed up in sketch features that can be driven by parameters. Designers only need to process modeling once and add expressions, and then they can be used as reusable features for other designs, as shown in Fig. 2.37.

To build the internal profile of fir tree root, section curves are required to be built first. Then after extruding the section curves and ones of internal profiles of root extending section together, the internal profile can be obtained, as shown in Fig. 2.38.

The section curves of internal profile of root extending section, are transition part from section curves of internal profile of blade body to ones of fir tree root, which can be obtained by using interpolation an algorithm, as shown in Fig. 2.39.

The internal profile can be obtained by extruding section curves of internal profiles of blade body, root extending section and fir tree root, as shown in Fig. 2.40.

The principle of parametric modeling for the platform is similar to the one for external profile of fir tree root, which can be processed by using parametric sketch and rotating the feature, as shown in Fig. 2.41.

Pin fins are distributed in the internal profile of blade body according to the rules specified by a user. The rules and radii of pin fins are both parameterized, as shown in Fig. 2.42.

The geometry of the longitudinal rib can be defined according to the group amount of ribs and the position and parameters of each group, as shown in Fig. 2.43.

Transverse ribs are ribs distributing among the longitudinal ribs. Modeling needs to appoint the distribution of the location, location parameters, geometric parameters, the number of groups and other information, then finally determines the geometry of transverse ribs, as shown in Fig. 2.44.

Cooling holes, running through the external and internal profile of blade body, are distributed according to a certain rule. Designers appoint the rule, location of distribution, location parameters and other information to create corresponding cooling holes on the blade body, as shown in Fig. 2.45.

The trailing edge slot is one crack at the trailing edge of blade body that is used for ventilation, as shown in Fig. 2.46.

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