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Parametric Modeling System for Cooling Turbine Blade Based on Feature Design

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Abstract: Based on feature modeling and mathematical analysis methods, a process-oriented and modular parametric design system for advanced turbine cooling blade is developed with UG API, aiming at the structural complexity and high design difficulty of aero-engine cooling turbine blade. The relationship between the external and internal body features, the body attached feature is analyzed as viewed from the feature and parameter terms. The parametric design processes and design examples of the external body shape, tenon, platform and internal body shape, ribs, pin fins are introduced. The system improves the design efficiency of cooling turbine blade and establishes the foundation of multidisciplinary design optimization procedure for it.

Key words: parametric modeling; cooling turbine blade; UG API

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0 Introduction

With the development of the aero-engine, the turbine inlet temperature is getting higher, which makes the turbine blade working conditions more severe[1]. Using sophisticated cooling structure in the design of turbine blade is a necessary measure to ensure the safety and reliability of the turbine blade working at high temperature, high pressure and high rotated speed[2-3]. The structural style of turbine blade develops from solid blade to hollow air-cooled blade with typical features like platform, tenon, cooling rib, partition rib, pin fin and so on[4-5].

For cooling turbine blade, the design requirement including the exterior and interior blade body, the structural feature and the parameters of the features is quite strict. The structure of turbine blade should be adjusted during the design flow to meet the performance requirement, cooling requirement, strength requirement and the processing technical requirement of the aero-engine. The modeling of cooling turbine blade is difficult, which is generally established by the general CAD systems. The design cycle needs many iterations and it takes a long time[6]. As to cooling turbine blade, the modification of one feature may influence the total modeling process, which leads to repeating designs of the 3D blade model and increases the workloads of the designers[7].

For the efficient design method of 3D CAD blade model is needed by structural and computational fluid dynamics (CFD) designers, many researchers are involved in the geometrical design and optimization of turbomachinery components.

Miller et al.[8] provided a methodology for interactive design of turbomachinery blades. An intuitive user interface was provided to input thickness function parameters of each control points and control angles of mean camber to control the shape of the blade section. The completed blade design was rep-

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resented as a non-uniform rational B-spline surface and was written to a standard initial graphics exchange specification (IGES) file.

Qiu et al.[9] outlined an integrated design system for turbomachinery such as gas turbines, hydraulic turbines, pumps and the system incorporated flow modeling, structural analysis, and manufacturing simulation under one integrated design environment. Geometry modeling starts with curve manipulation, such as hub/shroud curve, blade angle, or thickness profiles and most parameters are defined though interactively editable Bezier curves. These inputs are ultimately constructed into a series of curves in three-dimensional space defined as non-uniform rational B-splines (NURBS) and these curves then evolve into NURBS surfaces that eventually define the full 3D geometry.

Koini et al.[10] presented a software tool for the conceptual design of turbomachinery blades, which provides the ability to interactively construct parametric 3D blade rows of various types. The design parameters used for the blades as well as the hub and shroud surfaces construction correspond to 2D sections, and the resulting geometries are modeled as NURBS 3D surfaces. They can be imported to other CAD or analysis software.

Since the methodologies provided above are used for solid blade and the methodologies presented in the open literature concerning the parametric modeling of cooling blades are few, a cooling turbine blade design system based on user defined feature (UDF)[11] is quite necessary. In recent years, some parametric modeling systems of cooling blades have been proposed in several research[12-14]. However, such research only model the exterior and interior blade bodys, without the design of platform and tenon feature (TF), which may bring inconvenience to the subsequent blade strength analysis.

In this paper, a parametric modeling system for cooling turbine blade is introduced, which includes an exterior/interior blade body feature design module, a platform feature (PF) design module and a TF design module. Compared with the parametric design module in commercial software, this system can easily design the inner and outer surfaces of blades and obtain variable thickness wall. With the system, parametric feature modeling based on a given topology can be conducted by designers and the 3D blade model can be established. The system can also be used to support the subsequent analysis and optimization to shorten the modeling-analysis-optimization design cycle.

1 Modeling System Based on UG Secondary Development

The parametric design methodology in this paper focuses on the process of structure design. The blade is decomposed to several typical features and each feature is analyzed in a parametric way. Taking unigraphics NX (UG)/Open as a development tool, a widely applicable parametric modeling system containing all cooling feature modules for cooling turbine blade is developed using C++ programming language[15]. The efficiency of blade iterative design process can be improved by the proposed system[16].

The UG/Open secondary development module is one of the secondary development tool sets in Unigraphics NX. Designers can develop their personal customized CAD modeling system in NX with UG/Open to meet the needs of the design.

In this paper, the parametric modeling system is developed with modeling functions provided by UG/Open application programming interface (API) and dialog box created by Microsoft foundation classes (MFC) based on C++ programming language to realize the modeling modules of the typical features in cooling turbine blade. The UG/open manuscript tool is used to create personal custom menus for the cooling turbine blade parametric modeling system, as shown in Fig.1.

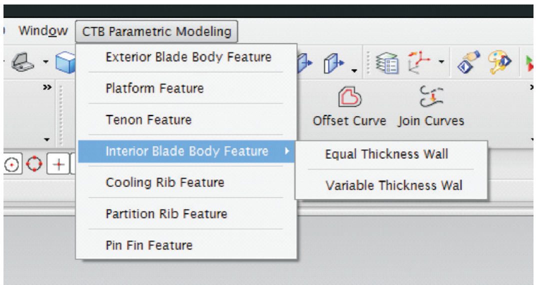


Fig.1 Customized user menu

The MFC box is used to response the operations from the custom menu and provides a dialog box for choosing modeling operations and inputting datas. The API functions transform the information from the dialog box to actual modeling operations in UG and the design is accomplished.

2 UDF of Cooling Turbine Blade

Parametric modeling is an automated simulation of the manual modeling process. The working procedures and sequences in the program should be in accord with the manual modeling. In the view of modular modeling process, the cooling turbine blade is composed of the exterior blade body feature (EBBF), the interior blade body feature (IBBF) and the appendix blade body feature.

The structure design flow and feature decomposition of cooling turbine blade are shown in Fig.2.

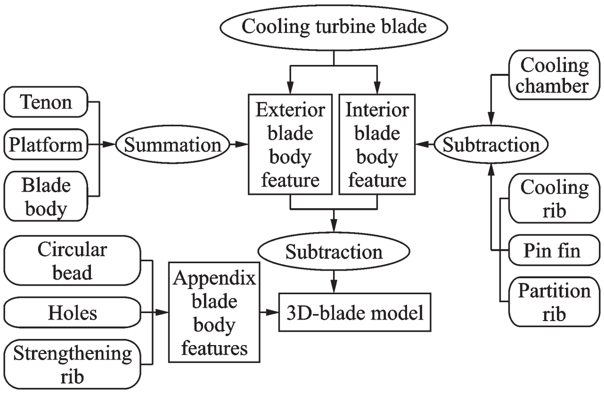


Fig.2 Design flow and feature decomposition

The EBBF includes blade body entity feature (BBEF), PF and TF. These features are assembled by their positional relations and the boundary condition is the flow field.

The IBBF includes interior blade body entity (IBBE) and other independent cooling features. The IBBE is viewed as a positive entity. The cooling rib feature (CRF), partition rib feature (PRF) and pin fin feature (PFF) are viewed as negative entities. Through Boolean subtraction of the negative entity and positive entities, the IBBF is created.

Through Boolean subtraction of IBBF and EBBF, the 3D entity model of cooling turbine blade is created.

The appendix blade body features (ABBF) such as strengthening rib, circular bead and surface film hole are added to the 3D entity blade model for reasons like structural strength requirements, adjusting the center of gravity position and improving cooling efficiency. The geometrical shape, orientation and quantity of ABBF should be adjusted according to the results of blade performance analysis, and its modeling process cannot be standardized. For these reasons, the modeling system in this paper does not contain the module for ABBF.

3 Parametric Design Modules of Turbine Blade

The design process of the parametric design modules of turbine blade is discussed. The flow chart of this modules is shown in Fig.3. The feature of exterior blade body entity, platform, tenon, wall, cooling rib, partition rib and pin fin are modeled separately, and finally are combined based on UG.

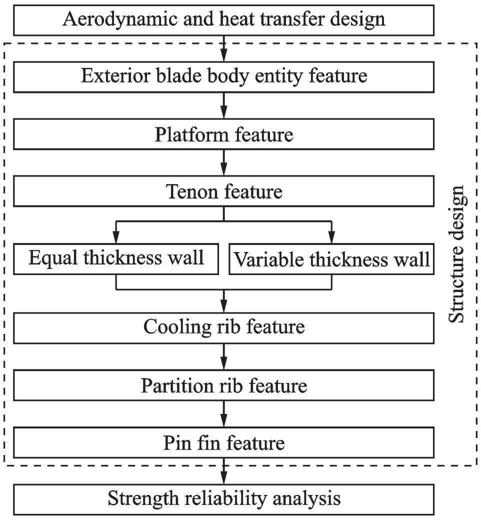
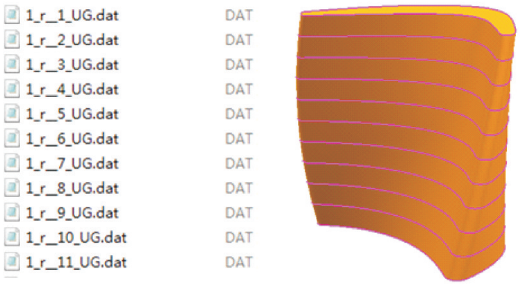


Fig.3 Flow chart of parametric design modules

3.1 Exterior blade body entity feature

The modeling of EBBF starts from the aerodynamic design. In this module, the entity model is created with several splines formed by blade section spline points data in DAT form provided by aerodynamic designers, as shown in Fig.4.

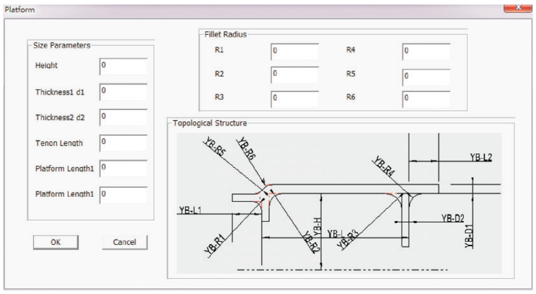


1_r_1_UG.dat	DAT
1_r_2_UG.dat	DAT
1_r_3_UG.dat	DAT
1_r_4_UG.dat	DAT
1_r_5_UG.dat	DAT
1_r_6_UG.dat	DAT
1_r_7_UG.dat	DAT
1_r_8_UG.dat	DAT
1_r_9_UG.dat	DAT
1_r_10_UG.dat	DAT
1_r_11_UG.dat	DAT

Fig.4　EBBF created with data of points

3.2　Platform feature

The PF is used to connect the tenon and the blade entity. Its upper surface is limited by the flow passage shape and lower surface is connected with the root extending segment of the tenon. There are two kinds of shapes for flow passage in turbine, i. e., the axial expanding type and the axial unchanged type. Taking the unchanged type as an example, the parameter input and the topological structure interface of platform modeling module are shown in Fig.5. Fig.6 shows the platform models created with different sets of design parameters. In the model of this study, the parameters of platform feature include the height of platform, two thicknesses of platform, the length of tenon, three lengths of platform and six fillet radiuses, which are listed in Table 1.



Platform

Size Parameters
Height 0
Thickness1 d1 0
Thickness2 d2 0
Tenon Length 0
Platform Length1 0
Platform Length1 0

Fillet Radius
R1 0
R2 0
R3 0
R4 0
R5 0
R6 0

Fig.5　Parameter input and topological structure interface of platform

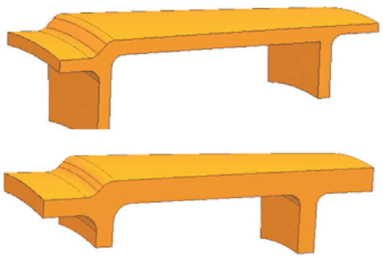


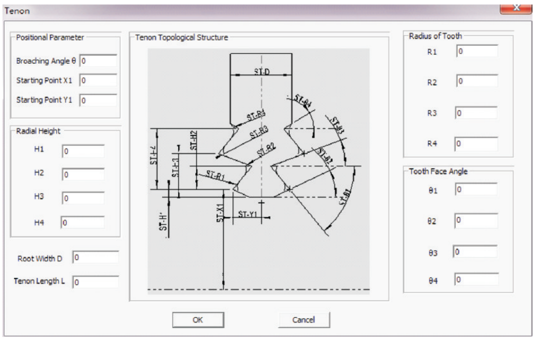
Fig.6　Different platform models created with PF module

Table 1　Parameters of PF

Parameter	Notation
Height	YB-H
Thickness 1	YB-D1
Thickness 2	YB-D2
Tenon length	YB-L
Platform length 1	YB-L1
Platform length 2	YB-L2
Fillet radius 1	YB-R1
Fillet radius 2	YB-R2
Fillet radius 3	YB-R3
Fillet radius 4	YB-R4
Fillet radius 5	YB-R5
Fillet radius 6	YB-R6

3.3　Tenon feature

For the TF is used to connect the blade and disk, there are high demands for the dimensional accuracy and positionaI accuracy between tenon and mortise. According to the actual application requirements, topology analysis for fir-tree tenon with two or more teeth is performed to extract sufficiently accurate parameters for the parametric modeling in the system. The TF has several correlations with PF, such as the radial position. The length of the tenon should be equal to the distance between front and back fixture fringes of PF and the shape of strengthening rib in PF should be relevant to the shape of tenon tooth. The correlations are restrained in the modeling programs to ensure the assemblability between TF and PF models. Taking two-tooth fir-tree tenon as an example, the input parameters and topological structure interface of tenon modeling module are shown in Fig.7. Fig.8 shows the tenon models created with different sets of design parameters.



Tenon

Positional Parameter
Broaching Angle θ 0
Starting Point X1 0
Starting Point Y1 0

Radial Height
H1 0
H2 0
H3 0
H4 0

Root Width D 0
Tenon Length L 0

Radius of Tooth
R1 0
R2 0
R3 0
R4 0

Tooth Face Angle
θ1 0
θ2 0
θ3 0
θ4 0

Fig.7　Parameter input and topological structure interface of tenon

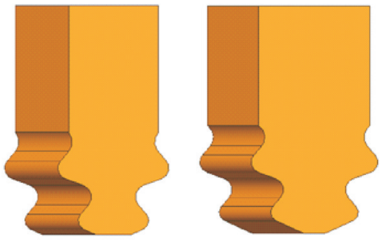


Fig.8 Different tenon models created by the module

The tenon parametric modeling module can also be used to create mortise in turbine disk through the Boolean subtraction of tenon model and disk model. In the model of this study, the parameters of tenon feature include the broad angle, the starting point (X_1, Y_1) at the bottom of tenon, four radial heights, the root width, the tenon length, four radiuses of tooth, and four tooth face angles, which are listed in Table 2.

Table 2 Parameters of TF

Parameter	Notation
Broad angle θ	ST-θ
Starting point X_1	ST-X1
Starting point Y_1	ST-Y1
Radial height H_1	ST-H1
Radial height H_2	ST-H2
Radial height H_3	ST-H3
Radial height H_4	ST-H4
Root width D	ST-D
Tenon length L	ST-L
Radius of tooth R_1	ST-R1
Radius of tooth R_2	ST-R2
Radius of tooth R_3	ST-R3
Radius of tooth R_4	ST-R4
Tooth face angle θ_1	ST-θ1
Tooth face angle θ_2	ST-θ2
Tooth face angle θ_3	ST-θ3
Tooth face angle θ_4	ST-θ4

3.4 Interior blade body entity

The IBBE design can be divided into two types, that is, the simple equal thickness wall design and the variable thickness wall design based on mathematical analysis. Generally, variable thickness wall design is adopted in cooling turbine blade design considering constraints like the uneven surface stress of blade and losing weight. This paper provides two modeling modules for each type of IBBE design.

3.4.1 Equal thickness wall

The core idea of equal thickness wall design is offsetting splines provided by aerodynamic designers with modeling function: UF_CURVE_creat_offset_curve() and offset distance E to create interior blade body section splines. However, the offset section splines would be self-intersecting and folded when the radius of blade trailing edge R is less than the offset distance E: $E>R$.

Then in this paper, another offset method is used to develop the equal thickness wall interior blade.

Firstly, create blade section splines with the aerodynamic data points. Then get the tangent vector (u_n, v_n) to the spline at every data point (X_n, Y_n). According to offset distance E, offset each point along normal direction to the tangent vector to get the point data (X_n', Y_n') in interior body section spline. Point coordinates (X_n', Y_n') is derived from the following equations

$$\sqrt{(X_n - X_n')^2 + (Y_n - Y_n')^2} = E \tag{1}$$

$$Y_n - Y_n' = -\frac{u_n}{v_n}(X_n - X_n') \tag{2}$$

Finally, create splines with the offset points and create interior blade body with the splines, as shown in Fig.9.

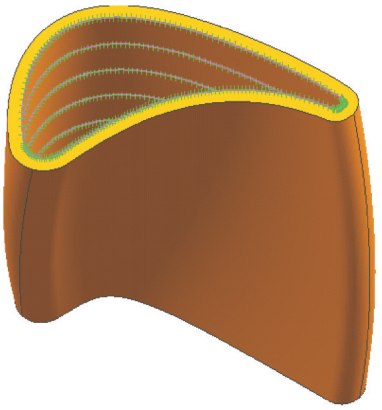


Fig.9 Equal thickness wall blade model in offset distance E

3.4.2 Variable thickness wall

The variable thickness wall design module is developed by the camber line method. The first step of the program is to get the camber line of blade section at arbitrary height of the blade. The second step is to figure out the interior blade body section spline based on camber line with the selected thickness interpolation function. The flow chart of the design process is shown in Fig.10.

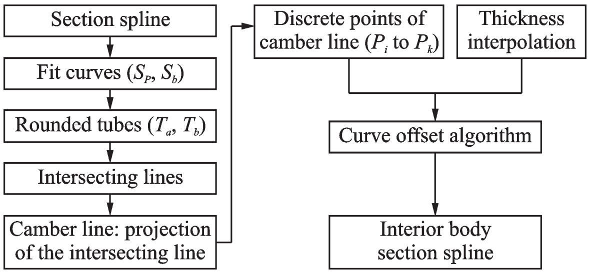


Fig.10 Flow chart of design process of variable thickness wall

The camber line design module is developed by a method which creates rounded tubes and finds intersection of the tubes to calculate the camber line of blade section. The programmed algorithm is described as follows:

(1) Get the section spline of blade model at radial height h and disperse the spline to get the coordinates array of points with modeling function: UF_CURVE_ask_point_data().

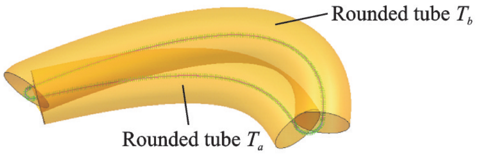
(2) Divide the coordinates array into two parts and create fit curves (S_P, S_b) on suction and pressure surfaces respectively.

(3) As shown in Fig.11(a), create rounded tubes (T_a, T_b) along S_P and S_b with the same radius R. The radius R should be greater than the maximum wall thickness $R_{\max}$ of blade section to ensure the intersecting lines of T_a and T_b is integrated: $R > R_{\max}$.

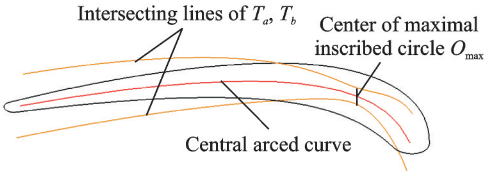
(4) Project the intersecting lines to the plane of blade section to get the camber line, as shown in Fig.11(b).

(5) The project location of point nearest to the section plane in the intersecting line is the center $O_{\max}$ of maximal inscribed circle of the section spline.

According to the definition, camber line is a set of centers of inscribed circles of blade section spline and Fig.12 proves the correctness of the algorithm.



(a) Rounded tubes T_a and T_b



(b) Intersecting lines and camber line

Fig.11 Camber line design procedures

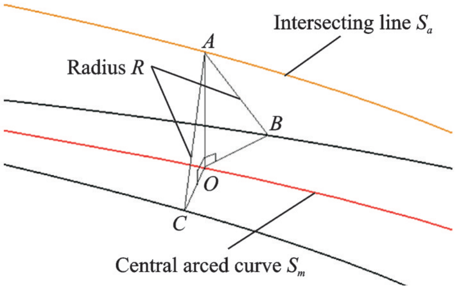


Fig.12 Proving of camber line algorithm

For point A is on the intersecting line S_a of tubes T_a and T_b with the same radius R, the section planes of T_a and T_b containing point A intersect with suction and pressure curves at points C and B, respectively. Segment AO is on the intersecting line of the two section planes. It can be deduced that segments AC and AB are of equal length and segments OC and OB are of equal length. Then the correctness of the algorithm is proved.

Based on the camber line, the variable thickness wall can be created by offsetting algorithm similar to the one used in equal thickness wall design and the steps of the algorithm are shown as:

(1) Disperse the camber line to obtain the coordinates array of points and save part of them (P_i to P_k) for offsetting on the basis of design demands.

(2) The thickness interpolation algorithm can be linear interpolation, parabola interpolation and cubic polynomial interpolation and so on. Taking the linear interpolation as an example, the interpolation function of interior body section spline on suction surface is shown in Fig.13.

The point P_j in the camber line is corresponding to the largest interpolation thickness $t_{\max}$ of the blade section. The interpolation thickness t of arbitrarily point P_n between P_i and P_j is

$$t = \frac{t_{\max} - t_i}{j - i} \times (n - i) \tag{3}$$

The interpolation thickness t of arbitrarily point

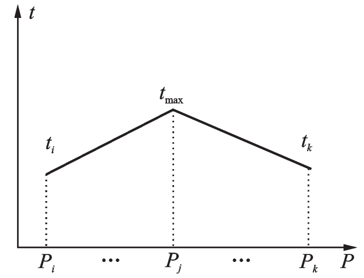


Fig.13 Thickness interpolation function

between P_j and P_k is

$$t = t_{\max} + \frac{t_{\max} - t_k}{k - j} \times (m - j) \tag{4}$$

With the same algorithm as Eq.(1) and Eq.(2), replace offset distance E with thickness function $t(n)$ and calculate coordinates of each point in interior body section spline on suction surface. Point coordinates (X_n', Y_n') are derived from equations

$$\sqrt{(X_n - X_n')^2 + (Y_n - Y_n')^2} = t(n) \tag{5}$$

$$Y_n - Y_n' = -\frac{u_n}{v_n}(X_n - X_n') \tag{6}$$

(3) The create the pressure surface section spline with the same method and to connect two splines with arc segments to complete the modeling of the interior body section spline, as shown in Fig.14.

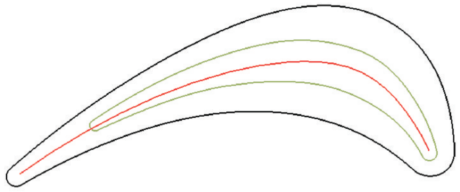


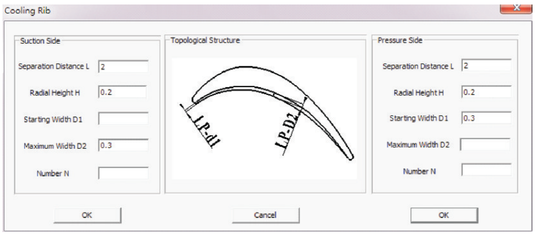
Fig.14 Camber line of arbitrary blade section

3.5 Cooling rib feature

In the design of advanced cooling turbine blade, the CRFs are added to the interior surface of the cooling chamber along radial direction to increase heat transfer area and enhance air disturbance in cooling chamber.

Generally, the width of CRF is considered as variable and the rib shape cannot be offset from the interior body section spline. In traditional modeling method, every rib shape is created by picking points according to the width function manually. The process is complicated and the model is with less modifiability.

The CRF parametric modeling module in this paper works on the basis of interior blade body and the shape of rib is controlled by parameters in the program. Designers can create a set of ribs along the radial direction by inputting design parameters. The parameter input and topological structure interface of CRF modeling module are shown in Fig.15. In the model of this study, the parameters of cooling rib feature in suction side of the blade include the separation distance, the radial height, the starting width, the maximum width, and the number of cooling rib. The cooling rib feature parameters in the pressure side are the same as those in the suction side (Table 3).


Cooling Rib

Suction Side
Separation Distance L: 2
Radial Height H: 0.2
Starting Width D1:
Maximum Width D2: 0.3
Number N:

Pressure Side
Separation Distance L: 2
Radial Height H: 0.2
Starting Width D1: 0.3
Maximum Width D2:
Number N:

Fig.15 Parameter input and topological structure interface of cooling rib

Table 3 Parameters of CRF

Side	Parameter	Notation
Suction side	Separation distance L	LS-L
	Radial height H	LS-H
	Starting width D_1	LS-d1
	Maximum width D_2	LS-d2
	Number N	LS-N
Pressure side	Separation distance L	LP-L
	Radial height H	LP-H
	Starting width D_1	LP-d1
	Maximum width D_2	LP-d2
	Number N	LP-N

Taking the rib on suction side as an example, the programmed algorithm is shown as follows:

(1) Get the section spline of interior blade body at radial height h and disperse the spline to get the coordinate array of points. Save the points between P_i and P_k, where P_i is the starting point of the rib and P_k is the terminal point.

(2) Taking trapezoidal distribution interpolation as an example, as shown in Fig. 16, calculate

the coordinates of each points in rib shape using Eqs.(5), (6).

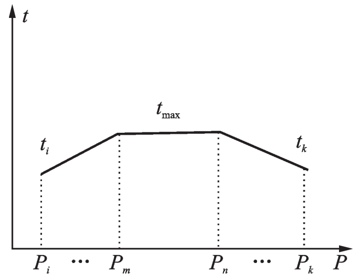


Fig.16 Width interpolation function

(3) Connect points in Step (2) with two other points out of the blade section to make the rib shape closed and stretch the closed curve to the rib body with thickness L. Subtract the body from interior blade body, as shown in Fig.17.

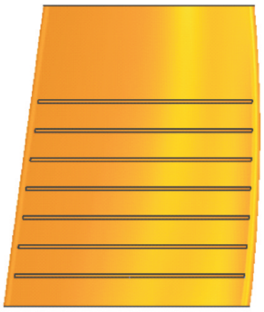


Fig.17 IBBE model with cooling ribs

(4) Loop the operation in Step (3) with rib number N and separation distance D to create a set of ribs in interior blade body.

3.6 Partition rib feature

PRF divides the cooling chamber into several parts as passages for cooling air to increase heat transfer area and enhance the strength of cooling blade. In the PRF parametric modeling module in this paper, designers create PRF with design parameters such as starting position, azimuth angle θ, thickness d, height h, and subtract it from interior blade body. Fig.18 shows the model created by the module. In the model of this study, the parameters of partition rib feature include the starting position (X_1, Y_1) of partition rib, the azimuth angle, the thickness of partition rib and the height of partition rib, which are listed in Table 4.

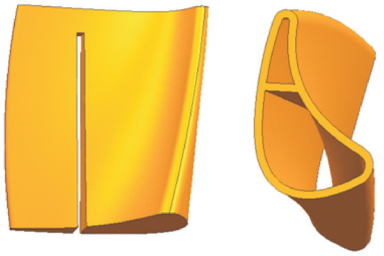


Fig.18 Partition rib created by IBBE and EBBF

Table 4 Parameters of partition rib feature

Parameter	Notation
Starting position X_1	PR-X1
Starting position Y_1	PR-Y1
Azimuth angle θ	PR-θ
Thickness d	PR-d
Height h	PR-h

3.7 Pin fin feature

The PFFs are added to the trailing edge cooling chamber along radial direction to increase heat transfer area and enhance air disturbance in cooling chamber. The shape of PFF is usually cylindrical. In the PFF parametric modeling module, designers create PFF with design parameters such as the starting position, azimuth angle θ of PFF center line, diameter d, separation distance l, and number n. In the model of this study, the parameters of pin fin feature include the starting position (X_1, Y_1) of pin fin, the azimuth angle of PFF center line, the diameter of pin fins, the separation distance and the number of pin fins, which are listed in Table 5. Fig.19 shows the model created by the module.

Table 5 Parameters of pin fin feature

Parameter	Notation
Starting position X_1	PF-X1
Starting position Y_1	PF-Y1
Azimuth angle θ of PFF center line	PF-θ
Diameter d	PF-d
Separation distance l	PF-l
Number n	PF-n

The design process of the parametric design modules of turbine blade is discussed. The module has the following functions:

(1) Exterior blade body entity creation and modification, which is defined by several splines

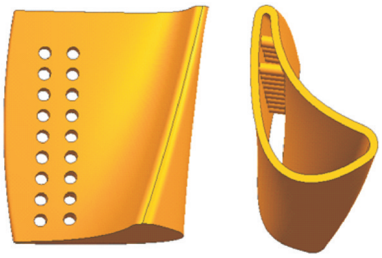


Fig.19 Pin fin created by IBBE and EBBF

provided by aerodynamic designers.

(2) Platform and tenon creation and modification, which is defined by user-defined feature parameters.

(3) IBBE creation and modification, which is defined by the value of wall thickness (for equal thickness wall) or the function of the wall thickness (for variable thickness wall).

(4) Cooling ribs, partition ribs and pin fins creation and modification, which is defined by user-defined feature parameters.

With the help of this parametric modeling system, designers can quickly adjust the blade geometry, which may shorten the blade design cycle. However, this parametric modeling system can only deal with the problems of the existing topological structure, but cannot generate a new topological structure, which will be improved in the future.

4 Conclusions

The working platform of the parametric design system for cooling turbine blade is UG NX. The Visual Studio 2010 along with the function library of the UG/Open API and Microsoft C++ is used as programming tools. With the selected design module and parameters imported by the designer, the feature structure can be directly created. The modules in this system are mutually independent from each other, and therefore the independent modifiability of feature designed by the system is strong.

According to practice, in the design of a high-pressure turbine blade model of a particular type of turboshaft engine, the modeling takes designers two weeks to finish with UG NX graphical user interface. The design time can be shortened to one day and the design efficiency is significantly improved using the parametric design system.

The system can be applied to the computational fluid dynamics (CFD), strength, vibration and reliability analysis of the cooling turbine blade and establishes the foundation of the subsequent multidisciplinary design optimization procedure.

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基于特征设计的气冷涡轮叶片参数化建模系统

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摘 要:航空发动机气冷涡轮叶片结构复杂、设计难度高。为此,基于特征建模和几何关系量化分析方法,利用UG API开发了面向过程的、模块化的先进涡轮气冷叶片参数化设计系统。分析了气冷涡轮叶片内外结构及其附件的特征与参数关系,并阐述叶片内外形状、榫槽、叶根平台、肋片、扰流柱的参数化设计过程和设计实例。所设计的系统提高了气冷涡轮叶片的设计效率,为其多学科设计优化程序的建立奠定了基础。

关键字:参数化建模;气冷涡轮叶片;UG API