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ROUGHING INTEGRALLY BLADED ROTORS
USING CUP MILL CUTTERS
METHOD, CUTTER AND PROGRAM DEVELOPMENT

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ROUGHING INTEGRALLY BLADED ROTORS
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METHOD, CUTTER AND PROGRAM DEVELOPMENT

présenté par : PETEAN, Marius
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a été dûment accepté par le jury d'examen constitué de:

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ABSTRACT

Integrally Bladed Rotors (IBRs) are critical parts of gas turbine engines and manufacturing them is an important issue for delivering high quality products. The current machining methods of producing the airfoil blades of IBRs are point milling and flank milling, which are both time consuming.

The project deals with the development of a new technology of manufacturing integrally bladed rotors. This new technology comprises the development of new cutting tools, a new method of roughing IBRs, tool path generation program, and cutting conditions control method.

For productivity reasons, a new cutting tool - the cup mill cutter and a new method of roughing the airfoil blades of integrally bladed rotors using cup mill cutters are proposed. According to this method, the convex suction side and the concave pressure side of the airfoil blades are formed respectively with the inner circumferential surface and the outer circumferential side of the cutting tool, controlling in the same time the bottom side of the cutting tool with respect to the gas path surface.

The developed program is based on the method and it automatically generates the tool path for roughing the airfoil blades of a certain part from the integrally bladed rotor family manufactured at Pratt & Whitney Canada (P&WC). The cutting tool is the cup mill cutter designed and produced at P&WC. The Interactive User Access (IUA) program uses as the input the cup mill cutter geometry and dimensions and specifically selected elements from the CATIA® 3D model of the IBR part. The output is the tool path as a 3D representation in CATIA. The tool path is then used in the NC mill module of CATIA to create the NC mill program, which is transferred to VERICUT® for digital simulation and validation.

A cutting conditions control method is also proposed for roughing the airfoil blades of the integrally bladed rotor part using the cup mill cutter.

The analytical results have been validated by a manufacturing test. The machining test has been performed on a 5-axis machine and on an aluminum test piece using the already created NC mill program.

The proposed new technology proves to be more productive than the current technology of roughing the airfoil blades of integrally bladed rotors. Moreover, it can be implemented for mass production right away and without additional costs.

The increased productivity, tool cost reduction and a more stable milling process, which eliminates additional rework operations, can impose this technology as the roughing manufacturing technology of integrally bladed rotors.

RÉSUMÉ

Les rotors aubage monobloc sont des pièces critiques de turbomoteurs et leur fabrication est un problème important pour livrer des produits de haute qualité. Les méthodes d'usinage courantes des pales de rotors aubage monobloc sont le fraisage par point et le fraisage par flanc d'outil, qui prennent toutes les deux beaucoup de temps.

Le projet traite le développement d'une nouvelle technologie de fabrication des rotors aubage monobloc. Cette nouvelle technologie comporte le développement de nouveaux outils de coupe, une nouvelle méthode de dégrossissage de rotors aubage monobloc, le programme de génération de parcours d'outil, et une méthode de contrôle des conditions de coupe.

Pour des raisons de productivité, un nouvel outil de coupe–l'outil sous forme de pot et une nouvelle méthode de dégrossissage des pales de rotors aubage monobloc avec des outils sous forme de pot sont proposés. Selon cette méthode, le côté convexe d'aspiration et le côté concave de pression des pales sont produits respectivement avec le côté circonférentiel intérieur et le côté circonférentiel extérieur de l'outil de coupe, en contrôlant en même temps le fond de l'outil par rapport à la surface de la veine gazeuse.

Le programme développé est basé sur la méthode et il produit automatiquement le parcours d'outil pour le dégrossissage d'une certaine pièce de la famille de rotors aubage monobloc produite chez Pratt et Whitney Canada (P&WC). L'outil de coupe est l'outil sous forme de pot conçu et fabriqué chez P&WC.

Le programme en Accès Utilisateur Interactif (IUA) utilise comme données d'entrées les dimensions et la géométrie de l'outil sous forme de pot et des éléments spécifiquement choisis du modèle CATIA® 3D du rotor aubage monobloc. La sortie est le parcours d'outil comme une représentation 3D dans CATIA. Le parcours d'outil est alors utilisé dans le module NC mill de CATIA pour créer le programme CN, qui est transféré à VERICUT® pour la simulation numérique et la validation.

On propose également une méthode de contrôle des conditions de coupe pour le dégrossissage des pales du rotor aubage monobloc avec l'outil sous forme de pot.

Les résultats analytiques ont été validés par un essai de fabrication. L'essai d'usinage a été réalisé sur une machine 5 axes et sur une pièce de test en aluminium en utilisant le programme CN déjà créé.

La nouvelle technologie proposée est plus productive que la technologie courante du dégrossissage des pales de rotors aubage monobloc. D'ailleurs, elle peut être mise en application tout de suite pour la production en série et sans des coûts additionnels.

L'augmentation de la productivité, la réduction des coûts d'outil et un processus de fraisage plus stable, qui éliminent des opérations additionnelles de réusinage, peuvent imposer cette technologie comme la technologie de fabrication pour le dégrossissage des rotors aubage monobloc.

CONDENSÉ EN FRANÇAIS

Pratt & Whitney Canada Cie. (P&WC) est un leader mondial parmi les motoristes équipant les hélicoptères, les avions d'affaires et de transport régional. La société construit également des moteurs de technologie évoluée pour applications industrielles. Au Canada, P&WC se situe au premier rang des investisseurs en recherche-développement dans le secteur aérospatial et au deuxième dans le secteur privé.

Un turbomoteur comporte généralement un compresseur à plusieurs étages pour comprimer l'air entrant à la haute pression, une chambre de combustion en laquelle l'air comprimé est mélangé avec le carburant et mis à feu pour produire des gaz à haute pression et à haute vitesse, et d'une turbine pour extraire l'énergie des gaz de combustion. Les moyens conventionnels de construire des systèmes de compression pour des moteurs d'avion doivent produire les pales séparées qui sont attachées à un rotor par des moyens mécaniques. Les nouveaux moteurs de rendement plus élevé exigent les avantages des rotors aubage monobloc. Les rotors aubage monobloc se composent d'un rotor où les pales et le rotor forment un tout. Ils réduisent nettement la complexité de moteur, réduisent le poids et réduisent le coût de cycle de vie du moteur par des avantages d'efficacité.

Des pièces critiques de moteurs d'avion comme les rotors aubage monobloc sont produites exclusivement par Pratt & Whitney Canada. Les pales des rotors aubage monobloc se composent d'une combinaison de surfaces complexes. La façon ordinaire pour produire cette forme complexe est une technologie qui utilise la méthode de fraisage par point. Selon la méthode de fraisage par point, une fraise avec le bout sphérique est employée pour usiner une pale. L'usinage des surfaces complexes des pales des rotors aubage monobloc employant la méthode de fraisage par point prend beaucoup de temps. La productivité relativement faible est expliquée par le fait qu'il prend un nombre énorme de passages pour que l'outil couvre tous les points de la surface de la pale. De plus, l'outil a une rigidité relativement faible, qui limite la charge d'outil.

Chez Pratt & Whitney Canada les pales des rotors aubage monobloc sont produites avec une méthode développée par la compagnie. La méthode consiste en fraisage avec le flanc de fraises cylindriques 3 tailles avec le bout hémisphérique. Il y a des inconvénients avec la méthode actuelle. Les rotors aubage monobloc sont faits en alliage de titane qui imposent certaines limitations pendant l'usinage. Ainsi, le processus d'usinage est caractérisé par un faible taux d'enlèvement de matière et de forces de coupe élevés. La rigidité faible du système machine–outil–pièce donne une déflexion élevée d'outil et de la pièce dans la direction normale à la vitesse d'avance. De plus, la surface résultante est une surface ondulée due à la cinématique complexe de fraisage. Ça implique directement des opérations auxiliaires coûteuses de réusinage. Des coûts importants sont aussi liés aux outils qui sont des fraises monobloc.

La méthode actuelle n'est pas assez productive surtout au regard des opérations de dégrossissage et de semi-finition. Des économies importantes peuvent être réalisées en utilisant un nouveau concept d'outil–l'outil sous forme de pot. Un tel outil a été conçu et fabriqué chez Pratt & Whitney Canada. L'utilisation d'un tel outil pour usiner des rotors aubage monobloc a besoin de l'élaboration d'une nouvelle méthode de dégrossissage des pales de rotors aubage monobloc. La définition de cette méthode et de son développement est l'objectif de ce projet.

Des essais d'usinage ont été faits en utilisant cet outil et un bloc en alliage de titane mais juste pour le fraisage en plongée. L'outil sous forme de pot développé chez Pratt et Whitney Canada est un outil de coupe circulaire avec des plaquettes interchangeables à pas variable. L'outil contient également des trous intérieurs pour un meilleur refroidissement et évacuation de copeaux. Sur un total de 20 plaquettes, 10 sont des plaquettes qui usinent la surface de pression d'une pale et 10 sont des plaquettes qui usinent la surface d'aspiration de la pale consécutive. Les 20 plaquettes interchangeables sont placées sur le corps d'outil tel qu'elles alternent.

La nouvelle méthode de dégrossissage des pales de rotors aubage monobloc est développée en utilisant l'outil sous forme de pot fabriqué chez Pratt & Whitney Canada et un certain rotor aubage monobloc de la famille des rotors aubage monobloc de Pratt &

Whitney Canada. La pièce choisie représente un rotor aubage monobloc d'un compresseur à haute pression d'un turbomoteur. Les raisons pour lesquelles la pièce est choisie sont:

- La distance minimale entre les deux pales consécutives de rotor est près de la longueur de la partie active d'outil sous forme de pot
- La longueur de la lame est appropriée pour l'usinage avec l'outil sous forme de pot
- La pale de rotor est moins torsadée.

Puisque la méthode traite l'opération de dégrossissage, la surface de pression, la surface d'aspiration et la surface de la veine gazeuse de la pièce sont toutes décalées par 0,89 mm ou 0.035 pouces.

La méthode est développée pour le fraisage entre deux pales consécutives du rotor aubage monobloc. Pour le reste de la pièce, l'outil est indexé tel que chaque paire de pales est produite. L'axe d'outil est considéré fixe pour éviter les collisions entre l'outil et la pièce. L'orientation d'axe d'outil est calculée par rapport aux deux directions normales sur la surface de la veine gazeuse et la surface de pression de la pale d'un point critique de la pale - le point extrême de la courbe de bout de la face de pression plus près du bord d'attaque de la pale du rotor. On définit une position de base d'outil entre deux pales consécutives du rotor pour que les collisions entre l'outil et la pièce soient évitées. La position de base de l'outil est la position de l'outil pour la direction déjà déterminée d'axe d'outil, limité au côté circulaire extérieur de l'outil par le point extrême de la courbe de bout de la face décalée de pression plus près du bord d'attaque de la pale du rotor et au côté intérieur par le point extrême de la courbe de bout de la face décalée d'aspiration plus près du bord de fuite de la pale du rotor. On construit par les deux points qui définissent la position de base de l'outil deux lignes parallèles à l'axe d'outil. Ainsi, la ligne intérieure de rotation est la ligne parallèle à l'axe d'outil par le point extrême de la courbe de bout de la face décalée d'aspiration plus près du bord de fuite de la pale du rotor. La ligne extérieure de rotation est la ligne parallèle à l'axe d'outil par le point extrême de la courbe de bout de la face décalée de pression plus près du bord d'attaque de la pale du rotor. Le plan de coupe est le plan qui est normal à l'axe d'outil et est à une distance égale au rayon de la plaquette de la surface du fond d'outil.

Une position libre de collisions de l'outil de coupe par rapport à la surface décalée de la veine gazeuse est déterminée. Cette position (le plus bas niveau axial d'usinage) est donnée par le déplacement axial maximal de l'outil tel qu'il n'y a aucune intersection entre le fond de l'outil de coupe et la surface décalée de la veine gazeuse. Le plus bas niveau axial d'usinage est alors employé pour définir la profondeur axiale maximale de coupe. Pour la direction d'axe d'outil, la profondeur entière de la fente entre deux pales consécutives est divisée en un certain nombre de niveaux axiaux d'usinage. La distance entre deux niveaux axiaux consécutifs d'usinage est la profondeur axiale effective d'usinage. Dans chaque niveau d'usinage, le plan de coupe vient de sectionner respectivement la ligne intérieure de rotation et la ligne extérieure de rotation en le point intérieur de rotation et le point extérieur de rotation.

Pour la profondeur d'usinage entre deux pales consécutives du rotor on définit deux types de mouvements d'outil:

- Un mouvement planaire dans chaque niveau axial d'usinage qui est une rotation du centre d'outil par rapport au point intérieur de rotation et une rotation du centre d'outil par rapport au point extérieur de rotation. Les points extrêmes de ces deux rotations du centre d'outil sont donnés par les positions extrêmes du centre d'outil pour qu'il n'existe pas de collisions respectivement entre la partie extérieure d'outil et la face décalée de pression ou entre la partie intérieure d'outil et la face décalée d'aspiration
- Un mouvement axial de l'outil qui correspond à une interpolation linéaire du centre d'outil entre deux points extrêmes du centre d'outil dans deux niveaux consécutifs d'usinage.

Basé sur la méthode de dégrossissage de rotors aubage monobloc avec des outils sous forme de pot, on développe un programme qui donne automatiquement le parcours d'outil pour l'usinage entre deux pales consécutives de rotor. Pour atteindre l'objectif on utilise le langage d'interprétation (IUA - Accès Utilisateur Interactif) de CATIA V4.

La plus importante caractéristique d'IUA est que la phase d'interaction d'utilisateur (la phase de dialogue) est relativement séparée de la phase d'algorithme. Le programme est divisé en deux parties. Ainsi, pendant la phase de dialogue (la première partie), l'utilisateur est invité à sélectionner différents éléments géométriques spécifiques (points, surfaces faces, et courbes) du modèle 3D du rotor aubage monobloc. La deuxième partie est la phase d'algorithme et les éléments sélectionnés pendant la phase de dialogue sont utilisés pour le calcul du parcours d'outil. Le programme est conçu comme une chaîne de procédures où chaque procédure conséquente est exécutée à la fin de l'ancienne. L'instruction EXEC transfère la commande de l'exécution à la procédure appelée et remplace la valeur des variables externes de la procédure appelée par la valeur des arguments qui sont inclus dans l'instruction EXEC.

La première partie du programme développé est la phase de dialogue. Elle contient les procédures MAINPRG et DATA. Dans cette phase, l'utilisateur (le programmeur NC) est invité à choisir interactivement les éléments géométriques à partir du modèle de CATIA du rotor aubage monobloc tels que: l'origine du système de coordonnées absolu; le point extrême de la courbe de bout de la face décalée de pression plus près du bord d'attaque de la pale du rotor; la surface décalée de la veine gazeuse; la surface décalée de pression de la pale; la face décalée de pression de la pale; la face décalée d'aspiration de la pale; le point extrême de la courbe de bout de la face décalée d'aspiration plus près du bord de fuite de la pale du rotor et la courbe de bout de la face décalée d'aspiration. La procédure DATA inclut également la géométrie et les dimensions de l'outil de coupe respectivement le rayon extérieur, RADEXT, le rayon intérieur, RADINT d'outil sous forme de pot. Elle contient également les dimensions de la plaquette, respectivement le rayon de la plaquette, RADINS et finalement la valeur maximale de la profondeur axiale de coupe, ADCMAX.

La deuxième partie du programme développé est la phase d'algorithme et elle contient les procédures BPTA, BASEPOS, PATHLOW et PATH. La procédure BPTA établit l'orientation d'axe d'outil, la position de l'axe d'outil pour la position de base et le plus bas niveau axial d'usinage. La procédure BASEPOS détermine le point de la rotation intérieure du centre d'outil afin d'éviter la collision entre l'outil et la courbe de bout de la face décalée d'aspiration. La procédure PATHLOW produit le parcours d'outil au plus bas niveau axial d'usinage. La dernière procédure PATH produit le parcours d'outil pour le reste de l'espace entre deux pales consécutives du rotor.

Un des avantages principaux de la nouvelle méthode de dégrossissage de rotors aubage monobloc est que le programme développé peut fournir automatiquement le parcours d'outil par une représentation 3D de parcours d'outil. Ayant la représentation 3D du parcours d'outil, le programmeur CN peut facilement créer le programme CN par les moyens habituels d'un logiciel de fabrication assistée par ordinateur. Le module NC Mill de CATIA V4 est utilisé pour produire le programme CN. Avant n'importe quel essai de fabrication, la sortie de la méthode de dégrossissage (les données CN de parcours d'outil) sont utilisées dans VERICUT pour la simulation et la validation. Le parcours d'outil pour le dégrossissage du rotor aubage monobloc avec l'outil sous forme de pot est simulé et aucune collision ou erreur n'est détectée.

Le fraisage des alliages de titane induit des problèmes de vibration et de contact entre l'outil et la pièce en raison du bas module d'élasticité de titane. Il est souhaitable d'avoir un processus de fraisage stable afin d'éviter ces inconvénients. Un processus de fraisage stable peut être réalisé en contrôlant la vitesse d'avance par dent. En raison des dimensions d'outil sous forme de pot et de la spécificité de la méthode développée, une certaine vitesse d'avance par dent sur la circonférence de l'outil rend une valeur différente de la vitesse d'avance au centre de l'outil. Puisque le centre d'outil est contrôlé, on calcule la vitesse d'avance par dent au centre de l'outil par rapport à une vitesse d'avance par dent constante sur la circonférence de l'outil. On utilise la vitesse d'avance par dent au centre de l'outil pour calculer la vitesse d'avance d'outil et on compare la vitesse d'avance avec la vitesse d'avance par dent sur la circonférence de l'outil. Ça c'est fait pour chacun des mouvements spécifiques d'outil dans deux niveaux axiaux consécutifs d'usinage. Les résultats de calcul montrent que pour les cas où l'outil usine avec le côté qui est opposé au point de rotation (intérieur ou extérieur) il y a une petite variation de la vitesse d'avance. Pour ces deux mouvements on peut conclure que le processus de fraisage est quasi-stable et en employant une valeur moyenne entre les valeurs extrêmes de la variation de la vitesse d'avance, la vitesse d'avance par dent sur la circonférence d'outil a une variation insignifiante. Dans les cas où le point de rotation (intérieur ou extérieur) est du même côté que la partie de l'outil qui usine, la variation de la vitesse d'avance est plus grande et il faut que cette variation soit introduite dans le programme CN afin d'obtenir un processus de fraisage stable.

Afin de valider la méthode de dégrossissage des rotors aubage monobloc avec des outils sous forme de pot, un essai de fabrication a été exécuté. La pièce brute est une copie en aluminium de la pièce brute en alliage de titane du rotor aubage monobloc. L'outil sous forme de pot est l'outil réel qui a été utilisé pour développer la méthode de dégrossissage. La Mitsui Seiki HU80A-5x est un centre d'usinage horizontal 5 axes. Pendant l'usinage de 4 fentes de la pièce, le liquide réfrigérant a été employé en tout temps. L'usinage a commencé avec une vitesse d'avance de 0.381m/min (15 pouces/min). Pour le mouvement axial de l'outil entre deux niveaux axiaux consécutifs d'usinage, l'opérateur a changé la vitesse d'avance de 0.381m/min (15 po/min) à 0.254 m/min (10 pouces/min) à cause des vibrations fortes dans le système.

Pour conclure, une nouvelle méthode de dégrossissage de rotors aubage monobloc avec de nouveaux outils de coupe, les outils sous forme de pot, a été développée. Basé sur la méthode développée, un programme qui produit automatiquement le parcours d'outil est généré. Le parcours d'outil est utilisé alors pour produire le programme CN, qui est ensuite numériquement simulé. Les données CN de parcours d'outil sont employées pour valider la méthode par un essai de fabrication. Une méthode de contrôle des conditions de coupe a été définie et quelques résultats intéressants sont présentés.

Ainsi, on montre maintenant que des outils sous forme de pot peuvent être utilisés pour usiner des surfaces complexes comme les pales de rotors aubage monobloc. La productivité pour le procédé de dégrossissage de rotors aubage monobloc avec l'outil sous forme de pot peut être augmentée 3 fois avec le gain d'un processus de fraisage plus robuste. En utilisant les plaquettes interchangeables, le coût d'outillage peut être réduit en conséquence. De plus, la méthode peut être applicable tout de suite sur le plancher d'atelier.

Quelques développements immédiats sont suggérés. Un essai d'usinage en alliage de titane est nécessaire. La méthode doit être vérifiée sur d'autres rotors aubage monobloc. La méthode de contrôle des conditions de coupe peut être appliquée et employée en définissant les paramètres de fraisage

Quelques développements ultérieurs pourraient être le développement des outils sous forme de pot pour semi-finition et l'élaboration d'une nouvelle méthode de semi-finition de pales des rotors aubage monobloc avec des outils sous forme de pot.

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A

ASFM – Arbitrary surface flank milling

C

CAM – Computer aided manufacturing

CAD – Computer aided design

CATGEO – CATIA geometric interface Fortran routines

CC – Cutter contact

CL – Cutter location

CN – Control numérique

E

ECM – Electrochemical machining

F

FLAMINGO – Flank milling optimization

I

IBR – Integrally bladed rotor

IPM – Feed rate [in/min]

IPT – Feed rate per tooth [in/tooth]

IUA – Interactive user access

M

MED – Manufacturing engineering development

N

NC – Numerical control

P

P&W – Pratt & Whitney

P&WC – Pratt & Whitney Canada

PS – Pressure side surface

R

R&D – Research & development

S

SFC – Specific fuel consumption

SS – Suction side surface

DEFINITIONS

Some of the terms are introduced in order to avoid ambiguities in later discussions.

<u>Definitions 1</u> (*CC* point, *CC* data, *CC* path, *CL* data, offset point)

The definitions are restricted to a toroidal tool but the equation may be extended to other shapes. As shown in the Figure 1, the tangency point *r (u, v)* between the surface part and tool during machining is called the *CC point* (Cutter Contact point). Let $\bar{n}$ be the unit normal vector to the surface at *r (u, v)*, then the pair $(r, \bar{n})$ is called *CC data* (Cutter Contact Data).

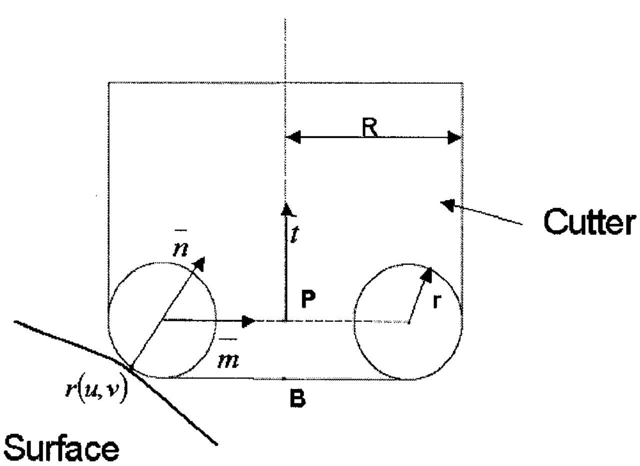


Figure 1 Cutter data

The tool centre position is described by the function *P (u, v)* defined as:

$$P(u,v) = r(u,v) + r \cdot \bar{n}(u,v) + (R - r) \cdot \bar{m}(u,v)$$

where R is the tool radius, r is the radius of the toroidal shape, u and v are the surface parameters, and the vector $m\ (u,\ v)$ (see Figure 1) is defined as

$$\overline{m}(u,v) = \frac{\overline{n}(u,v) - \overline{t}(u,v)}{\left|\overline{n}(u,v) - \overline{t}(u,v)\right|}$$

where $\overline{t}$ is a unit vector, representing the rotational axis of the cutter.

In the case of a ball mill, $R = r$, and the offset point is described by

$$P(u,v) = r(u,v) + r \cdot \overline{n}(u,v)$$

In the case of an end-mill, r = 0, and the offset point is

$$P(u,v) = r(u,v) + R \cdot \overline{m}(u,v)$$

The bottom center point B is expressed as

$$B(u,v) = P(u,v) - r \cdot \overline{t}$$

and the pair $(B,\overline{t})$ is called *CL data* (Cutter Location Data).

For a fixed tool axis,

$$\overline{t} = (0,0,1)$$

A sequence of line segments obtained by connecting the CC points is called the *CC path or tool path.*

<u>Definitions 2</u> (Integrally Bladed Rotor)

Integrally bladed rotors (IBRs or blisks) consist of a rotor where the airfoils and rotors are one part. The geometry definition of an IBR is given in the Figure 2, where:

1. Rotor;
2. Airfoil blade;
3. Gas path surface;
4. Pressure side;
5. Suction side;
6. Leading edge;
7. Trailing edge.

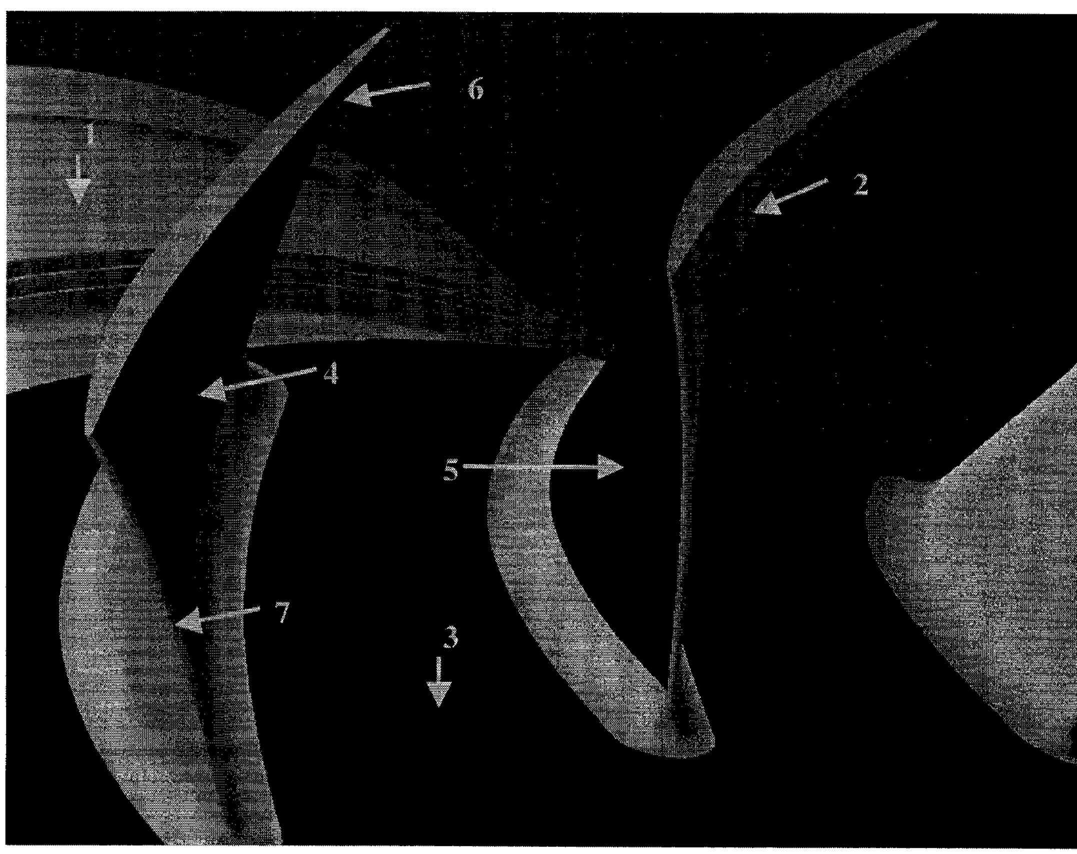


Figure 2 Integrally Bladed Rotor definition

INTRODUCTION

Manufacturing companies today face intense global competition, demanding customers, fragmented markets, increasing product complexity, compressed product cycles, price and profit pressures, strict regulatory and liability environments, systems integration and supply chain issues.

At the beginning of the new millennium, the aerospace industry searches more than ever ways of reducing its costs. This could be achieved either by management improvement and/or by looking for new technical and engineering solutions.

Pratt & Whitney Canada (P&WC), a leader in the design, manufacture and support of engines for commercial, military and general aviation aircraft, space propulsion and power systems is a research and development (R&D) front runner of high technology industries in Canada. Pratt & Whitney designs and manufactures a wide range of high technology propulsion for commercial, military and general aviation aircraft.

A gas turbine engine generally comprises, in serial flow communication, a multistage compressor for compressing the incoming air to high pressure, a combustor in which the compressed air is mixed with fuel and ignited for generating high-pressure, high-velocity gases, and a turbine for extracting energy from the combustion gases. The conventional means of constructing compression systems for aircraft engines are to produce separate airfoil blades that are attached to a rotating structure by mechanical means, typically a dovetail slot. Newer higher performance engines require the performance advantages of integrally bladed rotors. Integrally bladed rotors (IBRs or blisks) consist of a rotor where the airfoils and rotor are one part. IBRs dramatically reduce engine complexity and weight, increase performance and reduce engine hardware life cycle cost via efficiency benefits, which result in improved specific fuel consumption.

Generally, for small gas turbine engines, the high-pressure compressor is a multi stage axial configuration comprised of integrally bladed rotors plus one stage centrifugal impeller manufactured from advanced titanium alloys for weight and durability advantages. The IBRs are critical components of an aircraft engine and the manufacturing of such parts along with other ones remains the exclusivity of P&WC.

The airfoils of the IBRs consist of a combination of complex curved surfaces that are difficult to produce. With the development of NC technologies, multi-axis control permits to deal with work pieces of complicated shapes, which cannot be easily machined by conventional 3-axis NC machine tools. Some tool control methods have been introduced for multi-axis machining tool systems, but all the methods are based on controlling either a point CC-cutter contact point in the case of ball end milling or a curve in the case of flank milling.

The normal manner to produce this complex shape is a technology using the point milling method. According to the point milling method, a ball end mill is used to machine an airfoil. Machining of complex surfaces of airfoil blades using the point milling method is time consuming. The relatively poor productivity is explained by the fact that it takes a huge number of passes for the tool to cover all the airfoil surface points. In addition, the tool has a relatively poor rigidity, which limits the tool load.

In order to increase the material removal rate, flank milling was developed for airfoil machining. In flank milling a ball end mill is used, but rather than milling with the tip of the tool, flank milling cuts with the shaft of the tool, removing greater amounts of material in a single pass. The actual method of machining IBRs is flank milling with ball end mills with variable pitch and the milling process is costly because of its low material removal rate and of the expensive tool. Moreover the flank milling method induces deflections of the blades.

Other methods of IBR manufacture such as electrochemical machining (ECM) have proven to be very expensive.

The IBRs are made of advanced titanium alloys, which also impose certain limitations of the milling process. Machining titanium alloys causes a premature tool wear. Titanium's low modulus of elasticity can cause slender work pieces to deflect more than comparable pieces of steel. This can create problems of chatter, tool-part contact and holding tolerances.

The complex shape of the airfoils, such as gas turbine engine rotor blades, is a characteristic that impedes economical methods of milling.

In order to increase the productivity of machining IBRs, a new tool, the cup mill, was developed at Pratt & Whitney Canada. Prior to the beginning of the project, the cup mill has been used for a few tests on titanium alloys. The idea of further development is based on the results of these tests. Using the cup mill for machining IBRs will increase productivity significantly. The geometry and the dimensions of the cup mill cutter offer a better material removal rate and the variable-pitch flutes a more stable milling process. By using interchangeable inserts placed on a new concept of tool body, the tool cost can be reduced. Machining IBRs with the cup mill cutter means that the convex suction side of the airfoil blades is formed with the inner circumferential surface of the cutting tool and the concave pressure side surface of the airfoil blades is formed with the outer circumferential surface of the cutting tool. Such machining of two consecutive airfoil blades using the outer and inner circumferential surfaces of the cup mill requires a special relative tool-part movement.

The project deals with the development of a new method of roughing IBRs using special tools like cup mill cutters. The approach is to develop a specifically control method for roughing IBRs with the cup mill cutters. Based on this method the tool path is automatically generated using the interpreted language Interactive User Access (IUA) of CATIA V4. The NC mill program is created in CATIA V4 and the NC tool path data is used in VERICUT for the digital simulation and validation of the method. A new method of cutting conditions control is also proposed. A manufacturing test is then performed in order to validate the new method of roughing integrally bladed rotors with cup mill cutters. In the end, some conclusions are drawn and some directions for further developments of machining high volume aerospace parts with this new type of tool are proposed.

CHAPTER 1

BIBLIOGRAPHIC REVIEW

A sculptured surface is generally defined as a surface with variable curvature and is represented mathematically by parametric forms in CAD systems. Sculptured surfaces are mainly encountered in the aerospace, shipbuilding, automotive, glassware, ceramics, dies and moulds industries. Because of the two additional degrees of freedom, five-axis numerically controlled machines are more and more used for machining geometrically complex parts. However, five-axis machining requires a large investment, complex algorithms for gouging avoidance and collision detection, and powerful computer-aided manufacturing (CAM) systems to support various operations.

The complex sculptured surfaces, such as gas turbine engine rotor airfoil blades, have characteristics that impede economical methods of milling. The normal manner to produce this complex shape is a technology using the point milling method. According to the point milling method, a ball end mill is used to machine an airfoil. To obtain higher machining efficiency and a well-finished surface, an optimal cutter orientation for five-axis NC machining of sculptured surfaces is required. Much of the related work has been done on determining the cutter orientation.

Machining using a ball nosed cutter was the first method developed for sculptured surfaces and remains the most popular (Warkentin et al., 2000). As shown in Figure 1.1 a ball nosed tool is in tangential contact with a surface at the cutter point, *CC*. The tool position is offset along the surface normal, *n*, by a distance equal to the tool radius, *r*.

$$t_{pos} = cc + rn \qquad (1)$$

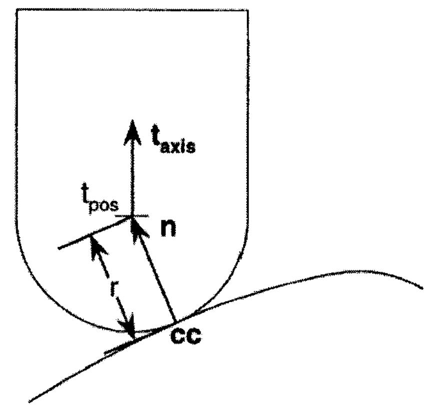


Figure 1.1 Positioning a ball nosed tool for machining a sculptured surface [Warkentin et al., 2000]

In (Vickers et al., 1985) a method called Sturz milling is used to machine compound curvature surfaces. In Sturz milling, the inclination angle is chosen somewhat arbitrarily and remains constant throughout machining. The inclined tool positioning strategy or Sturz milling is the most common of the 5-axis tool positioning strategies (Warkentin et al., 2000). Figure 1.2 shows the inclined tool method for a toroidal cutter. The tool axis is inclined in the feed direction by an angle ϕ and can be positioned by considering the plane containing the tool axis and the feed direction, f. The tool axis can be calculated by:

$$t_{axis} = \cos(\phi)n + \sin(\phi)e \tag{2}$$

and the tool position is given by:

$$t_{pos} = c + R\sin(\phi)n - R\cos(\phi)e \tag{3}$$

where e is a vector that can be constructed using a triple vector product.

$$e = n \times (n \times f) \tag{4}$$

The tool paths for the inclined method are generated by calculating the tool position and the tool axis using equations (2) and (3) for each cutter point.

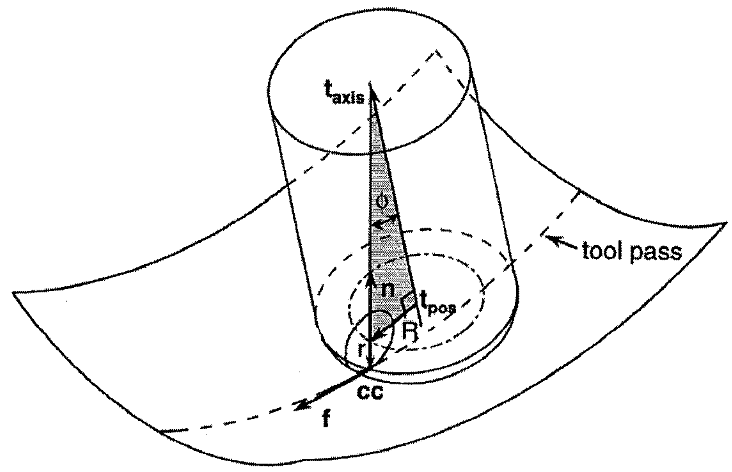


Figure 1.2 Positioning a toroidal cutter according to Sturz milling method [Warkentin et al., 2000]

Varying the orientation of the tool based on local surface curvature characteristics has shown an even greater improvement. The principal axis method is also a method that generates the surface point by point but, as a modification of the inclined tool method, it was formulated such as the surface curvature is incorporated into tool position as shown in Figure 1.3.

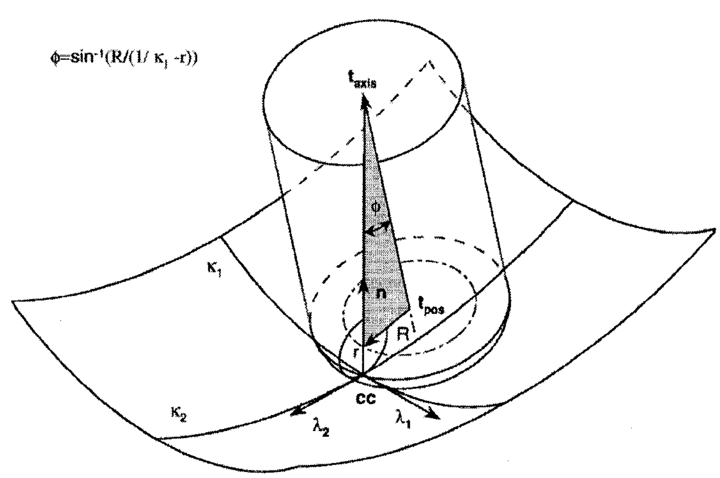


Figure 1.3 Tool positioning according to the principal axis method [Warkentin et al., 2000]

In this method the tool axis plane contains the surface normal in *CC*, *n*, but it does not contain the feed direction as in the inclined tool method. Instead the plane will include the direction of minimum curvature, λ_2.

(Kruth et Klewais, 1994) use the local surface curvature at a CC point to determine the optimal cutter axis orientation. To estimate the appropriate inclination angle of the tool, the surface surrounding the CC point is approximated by a quadratic equation. The filleted end cutter is approximated by a sphere, which is tangential to the surface. The intersection curves between the sphere and the quadratic approximation of the surface are calculated to determine the minimum inclination angle. (Jensen et Anderson, 1993) and (Mullins et al., 1993) propose a new five-axis cutter orientation algorithm based on curvature matching between the cutter and local machined surface regions by applying differential geometry techniques. (Deng et al., 1996) develop a technique to determine the flat-end cutter orientation based on slope and curvature matching for five-axis machining, where the radius of curvature of the cutter is considered as a function of both inclination and tilt angles, and the curvatures are similarly compared to detect local gouging. (Wang et al. – part 1, 1993) and (Wang et al. – part 2, 1993) suggest a method to machine sculptured surfaces with a special disk-type milling cutter such that the envelope formed by the trace of the tool nose in each step and the designed surface have the same derivatives up to the third order, thereby eliminating local gouging.

Machining of complex surfaces of airfoil blades using the point milling method is time consuming. The relatively poor productivity is explained by the fact that it takes a huge number of passes for the tool to cover all the airfoil surface points. In addition, the tool has a relatively poor rigidity, which limits the tool load. One big advantage of the point milling method is that most of the software dedicated to manufacturing use this method to define and manage NC programs dedicated to machining parts designed in 3D wireframe or solids geometry, using 2.5 to 5-axis machining techniques.

In order to increase the material removal rate, flank milling was developed for airfoil machining. In flank milling of airfoil blades, a taper ball end mill is used. Rather than milling with the tip of the tool, flank milling cuts with the shaft of the tool, removing greater amounts of material in a single pass. The taper ball end mill is characterized by a small diameter and long flute length. The tool path is programmed such that the tool has a curved contact surface with the airfoil.

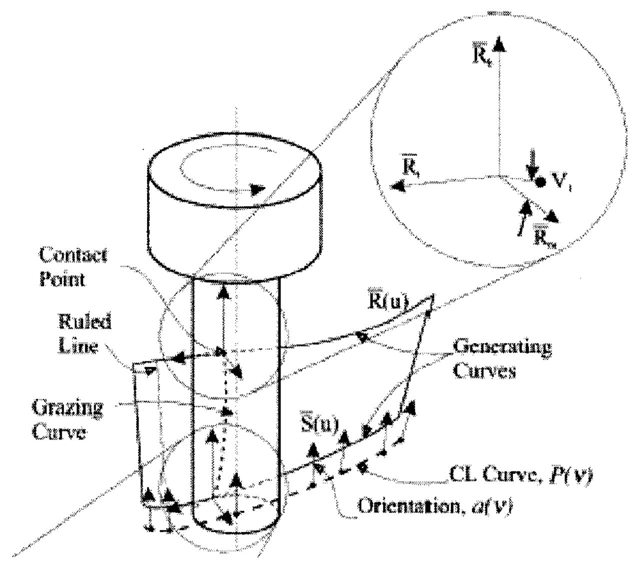


Figure 1.4 Flank milling with a cylindrical cutter along two generating curves [Bedi et al., 2003]

(Bedi et al., 2003) propose a method in which the cutter slides along two rails, being kept tangent to them at every parameter value. The two rails are the known curves, such as the top and the bottom profiles of a blade, and the generated surface is determined by the tool sliding along the rails (Figure 1.4).

The FLAMINGO (Flank Milling Optimization) project brings together in a task team leading developers, manufacturers and suppliers in the field of aero-engines, machine tools manufacturers and research institutes in Europe. Their goal is to develop a new flexible and multi-functional five-axis machining technology for highly efficient flank milling of arbitrary shaped surfaces. The advantages of the 5-axis flank milling, according to (Tonshoff et al., 2001), would be:

- Higher productivity (smaller number of necessary cuts over the surface);

- Higher material removal rate;
- Better surface quality reducing effort for manual lapping and polishing;
- Elimination of after-machining operations (lapping and polishing)
- Tool wear reduction.

Because of the part being milled, the tool shank is very long as well. Flank milling method and the length of the cutting tool reduce tool rigidity. In effective flank milling the radial depth of cut is generally much smaller than the tool diameter. The axial depth of cut is larger than the radial depth cut. This configuration leads to high material removal rates by still generating moderate cutting forces even machining difficult to machine materials. Critical subject still being present is the machining at the flank of the tool. The low stiffness of the system leads to high deflection of the tool and the workpiece especially in the direction normal to the feed rate. For the machining of airfoil blades this results in blade deflection and some time-consuming rework operations. Furthermore hardly any CAM software offers sufficient support for this special kind of machining technique. The poor tool rigidity and the long axial tool immersion limit the tool load. This results in a relatively poor material removal rate, which is not desirable, especially for the roughing operations.

For productivity reasons of roughing flow surfaces of compressor blades, a liaison is done with gear manufacturing.

(Carlsen, 1942) provides a method for generating gears with a face-mill gear cutter (Figure 1.5), in which in a single revolution of the cutter a tooth space of the gear is completely generated and the tooth space is rough-cut while the gear (G) and tool (C) are rolling relative to one another in one direction and is finish-cut while the gear and tool are rolling relative to one another in the opposite direction.

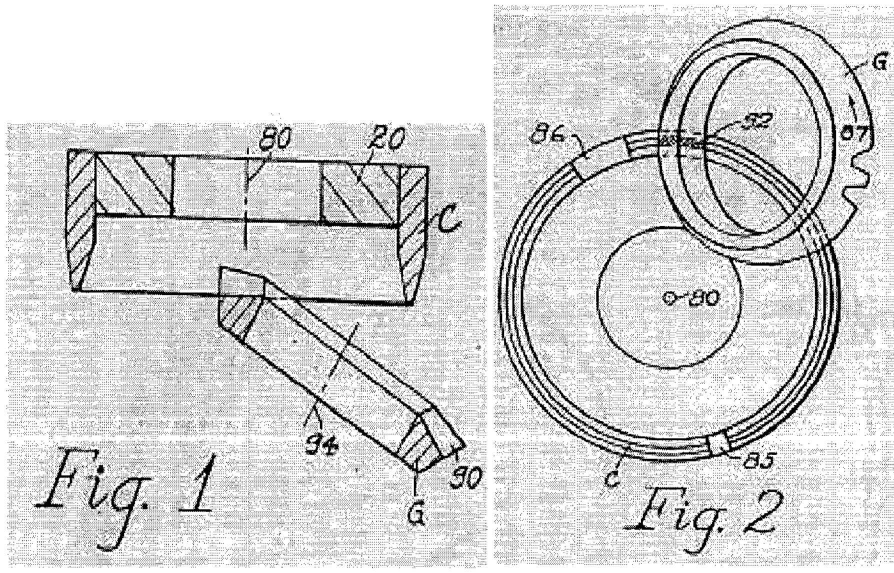


Figure 1.5 Gear generation with face-mill gear cutter [Carlsen, 1942]

For more geometrically complicated spiral bevel gears and hypoid gears, (Soper, 1950) suggests an improved method of generating the teeth of the above-mentioned types of gears, whereby greater accuracy in the cutting such teeth is accomplished (Figure 1.6).

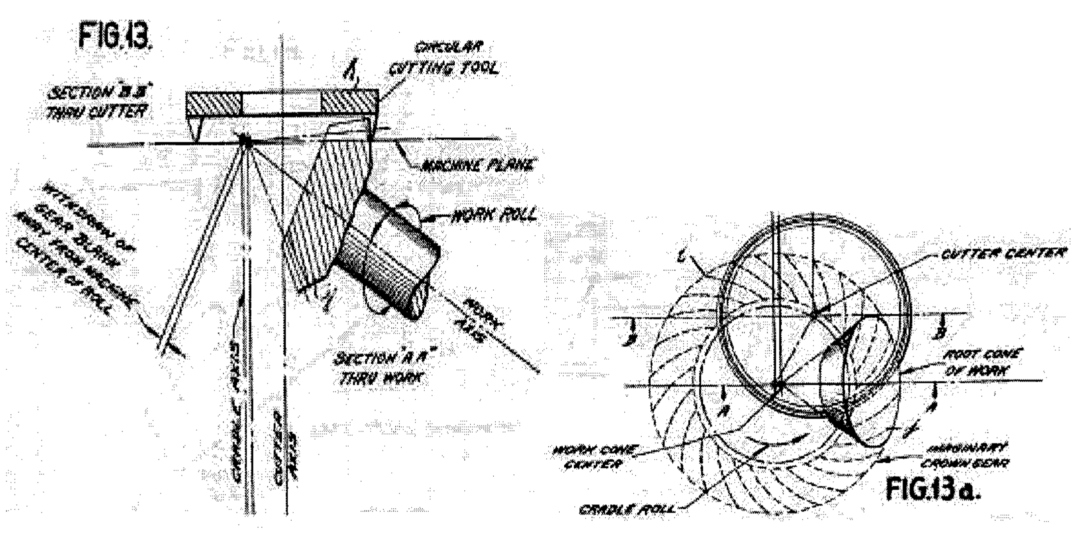


Figure 1.6 An improved method of generating the teeth of spiral bevel gears and hypoid gears using a circular cutter [Soper, 1950]

The concept of generating gears by the means of a circular cutter is used by (Hunt, 1994) in producing an integrally bladed compressor rotor. The tool comprises two annular cutters, rotatable about their axes, which are parallel but not coincident (Figure 1.7). One annular cutter surrounds the other one. The interior annular cutter cuts out the workpiece to form a concave airfoil surface of the blade and the exterior annular cutter cuts out the workpiece to form a convex airfoil surface of the same blade (Figure 1.8).

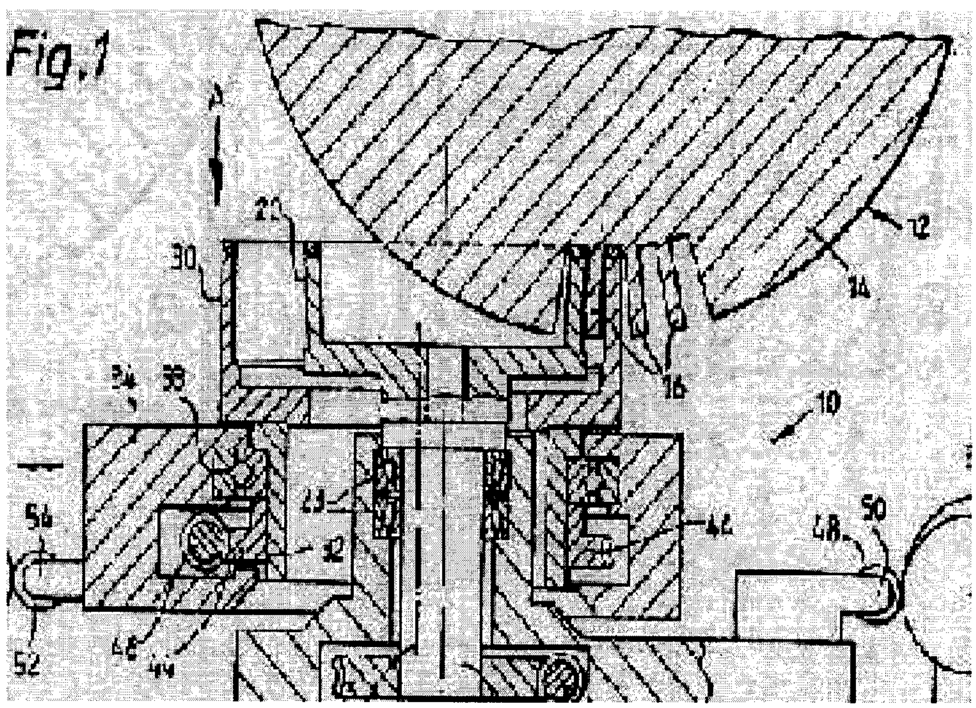


Figure 1.7 Representation of the system tool-workpiece for producing an integrally bladed rotor with two annular cutters [Hunt, 1994]

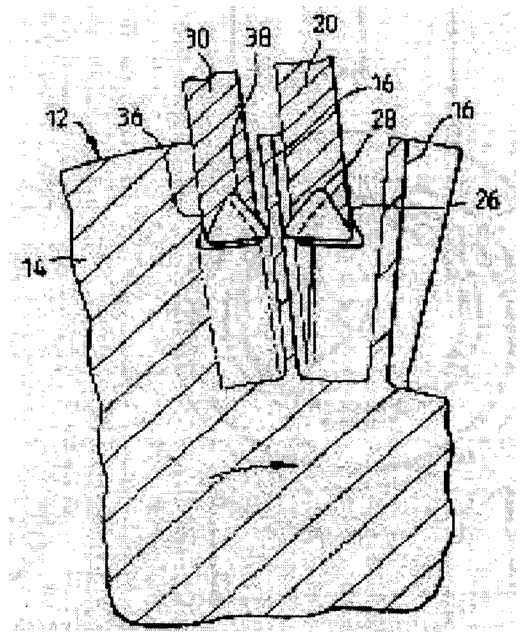


Figure 1.8 The position of the two annular cutters for machining the convex and concave surfaces of an airfoil blade [Hunt, 1994]

Unfortunately there aren't many papers in the technical literature that can be used as reference to our project.

The continuous need of cost reduction at Pratt & Whitney Canada brings out the initiative of Ioan Sasu of Manufacturing Engineering Development (MED) of using cup mill cutters for machining compressor blades. The idea is to start developing new methods of roughing and later of semi finishing of airfoil blades of integrally bladed rotors with cup mill cutters and based on results to implement the methods on the shop floor.

CHAPTER 2

PRESENTATION OF THE CURRENT METHOD OF MACHINING INTEGRALLY BLADED ROTORS

2.1 Integrally Bladed Rotors

2.1.1 Overview

A turbofan engine is a combination between gas turbine engine and a large fan placed in front of the engine. It generally comprises, in serial flow communication, a fan through which ambient air is propelled, a multistage compressor for pressurizing the air, a combustor in which the compressed air is mixed with fuel and ignited for generating hot combustion gases, and a turbine for extracting energy from the combustion gases and driving both the fan and the compressor. Figure 2.1 is a simplified layout of a turbofan engine.

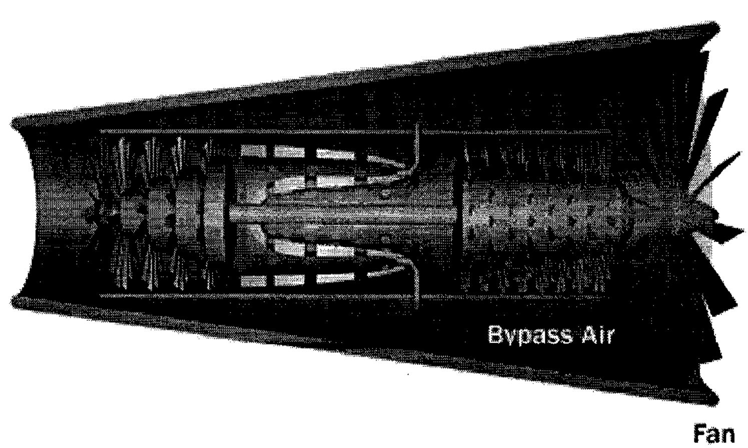


Figure 2.1 The basic layout of a turbofan engine [http://science.howstuffworks.com/turbine6.htm]

Both the fan and the compressor include airfoils in the form of rotor blades extending radially outwardly from the periphery of the disc. The blades can be provided with dovetails, which slide in corresponding dovetail slots defined in the perimeter of the disc or, alternatively, they can extend integrally from the disc to form one-piece unitary assembly, known as integrally bladed rotor (IBR or blisk).

IBRs dramatically reduce engine complexity and weight, increase performance and thrust, and reduce engine hardware life cycle cost via efficiency benefits, which result in improved specific fuel consumption (SFC). Integrally bladed rotors permit blade speeds significantly above conventional rotors and hence stage pressure ratios of >1,8.

In Figure 2.2 an integrally bladed rotor is presented. Its airfoil blades are arbitrary complex surfaces, which are designed to respond dynamically to the required compressor performance.

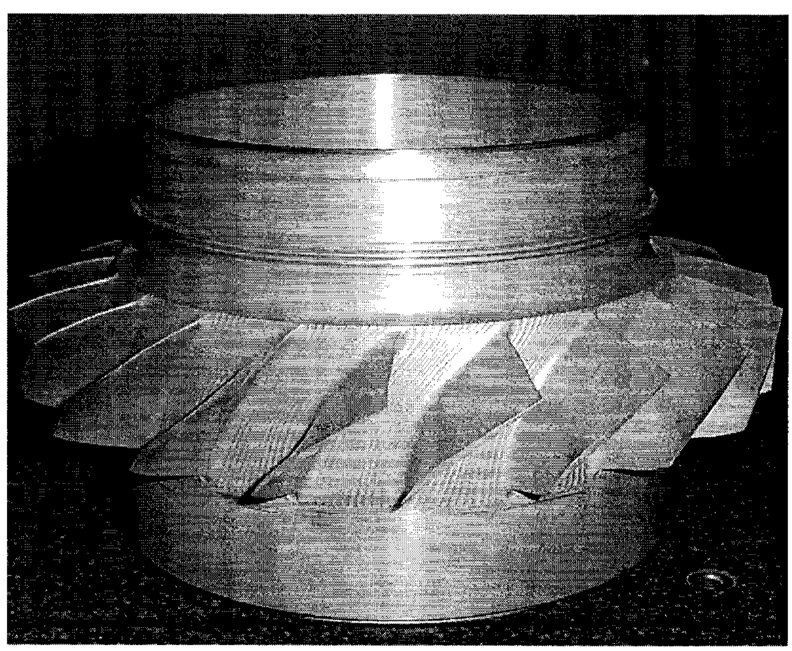


Figure 2.2 An integrally bladed rotor for the multistage compressor of a P&WC gas turbine engine

2.1.2 The machinability of materials for integrally bladed rotors

The machinability of materials can be defined in terms of tool life requirements and surface finish. Of these factors, tool life is usually the most important. In production operations, tool life is usually expressed as the number of pieces machined per tool. In general, the aim is to achieve for a given machining operation the optimum combination of tool life, production rate, power input and surface finish. This optimum condition results in an increase in production rate and a reduction in the cost of performing the operation.

The IBRs are made of advanced titanium alloys, which impose certain limitations. Structural titanium alloys are coming in for increased use because they are light, ductile and have good fatigue and corrosion-resistance properties.

The specific weight of titanium is about two thirds that of steel and about 60 percent higher than that of aluminum. In tensile and sheet stiffness, titanium falls between steel and aluminum. But titanium's strength is far greater than that of many steel alloys, giving it the highest strength-to-weight ratio of any of today's structural metals. Titanium alloys have high melting points, which is usually a sign of excellent temperature stability. However the strength of titanium alloys falls off rapidly at temperatures above 430 degrees Celsius, and their coefficients of expansion are even less than that for steels.

Their unique physical and chemical properties account, to a large extent, for the difficulties in machining titanium. Ti-6Al-4V is one of the titanium alloys used for integrally bladed rotors. It is an alpha+beta alloy that is heat treatable to achieve moderate increases in strength. It comes, as close to being a general-purpose grade as possible in titanium. In fact, it's considered the workhorse titanium alloy and is available in all product forms. This alloy is stable at temperatures ranging from 220 degrees Celsius to over 550 degrees Celsius.

From the manufacturing point of view, titanium has a tendency to gall, and its chips can weld to the cutting edges of the tool. This is particularly so once tool wear begins. Sharp tools should be employed at all times and should be replaced before they dull. A positive rake angle should be used at all times. Titanium's low modulus of elasticity can cause slender work pieces to deflect more than comparable pieces of steel. This can create problems of chatter, tool-part contact and holding tolerances.

2.1.3 Conventional methods of manufacturing integrally bladed rotors

The conventional means of constructing compressors for aircraft engines is to produce separate airfoil blades that are attached to a rotor by mechanical means, typically a dovetail slot. Newer higher performance engines require the performance advantages of integrally bladed rotors (IBRs).

The use of IBRs presents new challenges for manufacturing. Integrally bladed rotors are expensive to manufacture and involve complex forgings and finish machining (conventional and electrochemical) procedures. Conventional methods of manufacturing IBRs consist of machining a forged billet. With conventional milling, material is slowly cut away into chips. This process is time consuming and generates much waste. Other methods of IBR manufacture such as electrochemical machining (ECM) have proven to be very expensive. In order for the full performance benefit of IBRs to be realized, manufacturing costs need to be reduced in order to make this technology affordable.

2.2 Flank milling method of integrally bladed rotors at Pratt & Whitney Canada

Point milling is the most common metal cutting method for compressor airfoil blades. Because point milling is a very time-consuming process and it produces a scalloped surface finish, which directly implies other operations to achieve the required surface finish, at Pratt & Whitney Canada considerable effort has been invested to understand and apply flank milling for machining fans, compressors and impeller blades (Figure 2.3). The main reason is that flank milling offers better productivity over point milling.

Axial compressor rotor blades are generally considered to be not flank millable, owing to the severe twist of the blade surfaces. The technique of multiple pass flank milling is required because the ruled surface criterion is not sufficient to guarantee that a blade surface is flank millable in the conventional single pass manner. The first two moderately complex rotors has been milled by imposing three design curves to lie on a twisted but nevertheless ruled surface and then reducing the deviation between the ruled surface and the machined surface by introducing the technique of multiple pass flank milling (Wu et al., 1983).

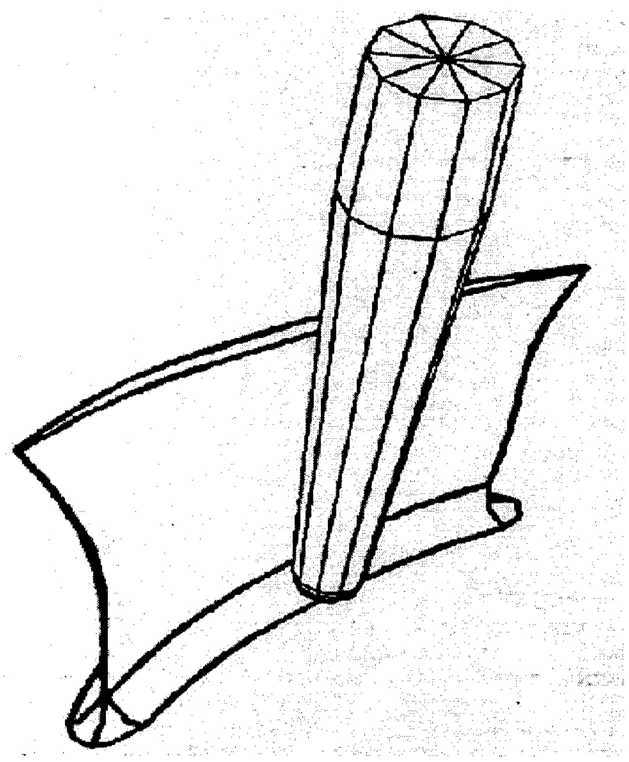


Figure 2.3 Schematic illustration of flank milling [Wu, 1995]

A system called Arbitrary Surface Flank Milling (ASFM) was developed at Pratt & Whitney Canada. It is a flexible and powerful software to facilitate the design of a flank millable blade and generate the tool path efficiently. Actually the ASFM system acts like a CAD/CAM system (see Figure 2.4). It takes the actual design of a blade as the input and it provides a new design of the probable flank millable blade. The probable blade design is then tested from the performance point of view and if it meets the aerodynamical and structural requirements of the design, this new blade design together with the associated tool path will be the output of the ASFM system.

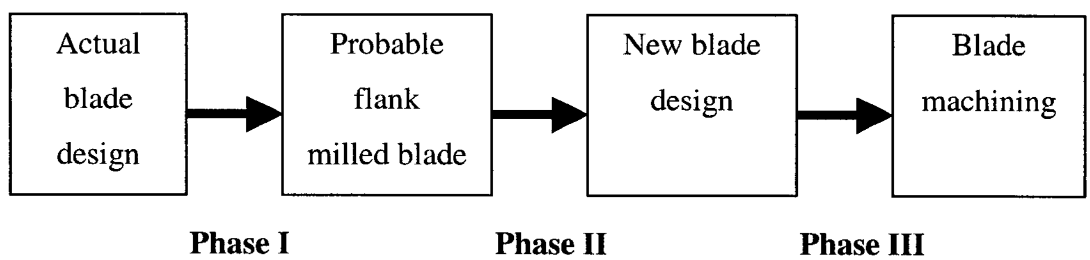


Figure 2.4 The concept of Arbitrary Surface Flank Milling system (Phase I – Test for flank millability, Phase II – Detail matching, Phase III – Manufacturing concerns)

The ASFM system comprises close to 30 batch programs. Each of them performs some special function that belongs to the following three logical phases of the system (Wu, 1995):

Phase I – Test for flank millability

The user may rapidly generate the probable flank milled blade profile with the associated tool paths from a given blade design in the form of a number of curves on its pressure side surface and suction side surface.

Phase II – Detail matching

In this phase each of the enveloping surfaces of the associated cutter trajectories of the probable flank milled blade from Phase I are fine-tuned to obtain a flank milled blade that gives equivalent performances aerodynamically and structurally to the design intent.

Phase III – Manufacturing concerns

While the first two phases are concerned with the finishing cut, this phase deals with the actual metal removal. The roughing cut and semi- finishing cuts are generated while dealing with blade and cutter deflections.

If the blade is highly twisted a multiple pass flank milling is necessary. In Figure 2.5 a computer simulation of two-pass flank milling of a fan blade is shown. Along the boundary curve, the two flank milled surfaces are tangential radially to ensure smooth and continuously blade profiles.

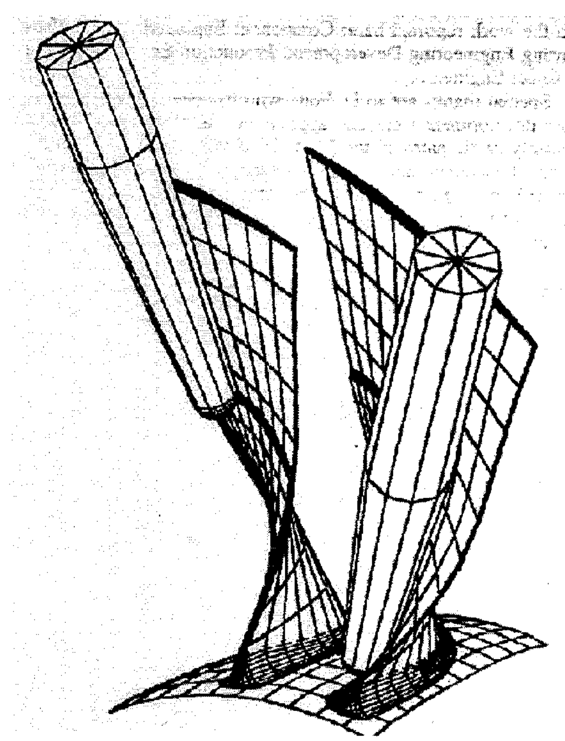


Figure 2.5 Computer simulation of two-pass flank milling of highly twisted fan blades [Wu, 1995]

Due to blade and cutter deflections and the expensive flank milling tools, new methods of roughing moderately complex rotors using more robust cutting tools are necessary to be developed in order to increase productivity and reduce additional costs related to tools and rework operations.

CHAPTER 3

THE DEVELOPMENT OF A NEW METHOD OF ROUGHING INTEGRALLY BLADED ROTORS USING CUP MILL CUTTERS

3.1 Problem description

In order to consolidate its leader position in the gas turbine engine field, Pratt & Whitney Canada must continuously increase the performance and quality of its products and at the same time reduce its manufacturing cost. In this context more productive and more robust technologies are required. The objective of this project is part of the continuous quest of identifying new ways to manufacture the airfoil blades of the integrally bladed rotors using new tools, new processes and new methodologies.

Increased productivity of roughing integrally bladed rotors (IBRs) implies a different tool than the ball end mills from the flank milling method. A large, circular cutting tool, called the cup mill cutter, has been developed at Pratt & Whitney Canada. The use of such a tool for machining the airfoil blades of integrally bladed rotors needs the development of a new method for milling IBRs. The definition of this method and its development is the objective of the project.

3.2 Integrally bladed rotor part and cup mill cutter description and preparation

3.2.1 Cup mill cutter description

The cup mill cutter developed at Pratt & Whitney Canada is a circular cutting tool with interchangeable inserts at variable pitch. The design of the tool also contains interior holes for better cooling and chip evacuation (Figure 3.1).

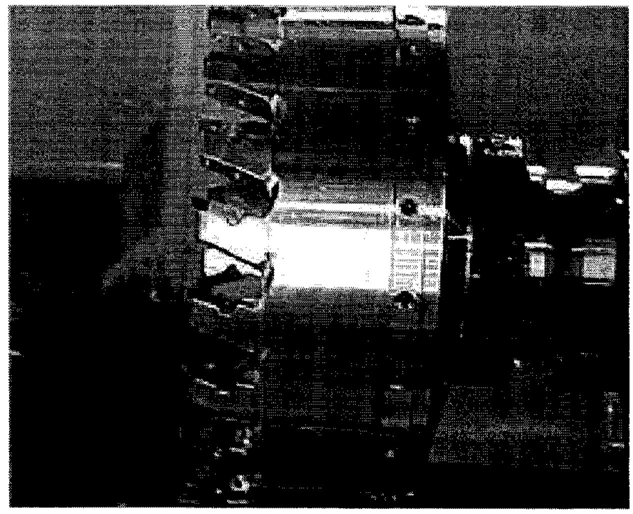


Figure 3.1 The cup mill cutter developed at Pratt & Whitney Canada

The geometry and the dimensions of the cup mill cutter are represented in Figure 3.2.

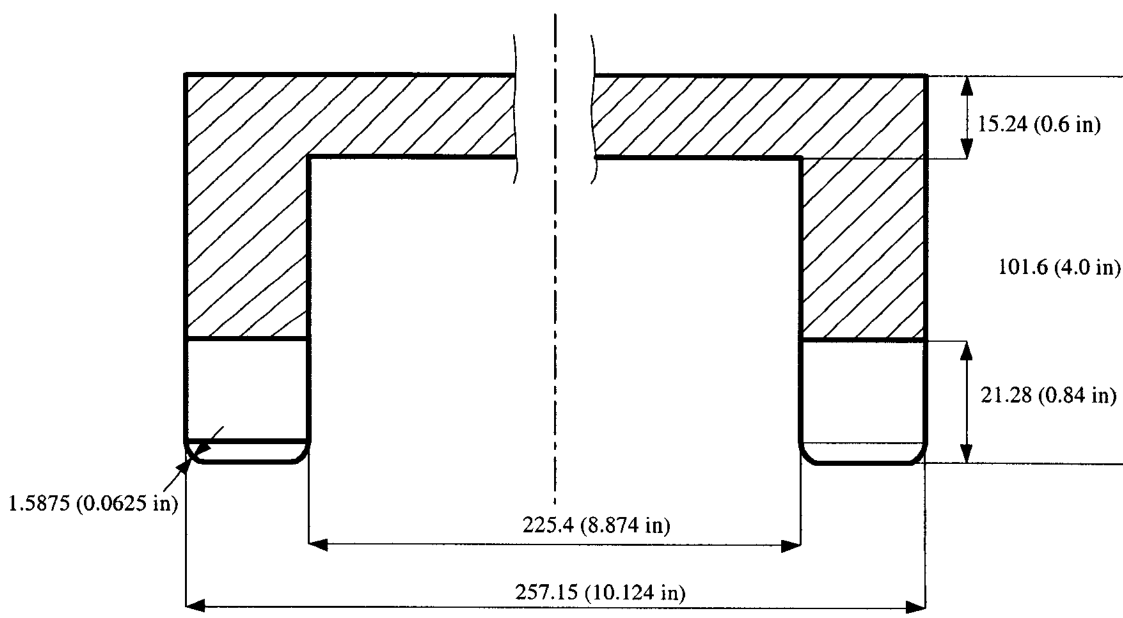


Figure 3.2 Geometry and dimensions of the cup mill cutter

Out of the total of 20 inserts, 10 are inserts that machine the pressure side of the airfoil blade (LFEW-R-LN) and the other 10 are inserts that machine the suction side of the airfoil blade (LFEW-L-LN). The 20 interchangeable inserts are placed on the tool body such as they alternate (one LFEW-L-LN after LFEW-R-LN and so on). The geometry and the dimensions of the interchangeable inserts are shown in the Figure 3.3.

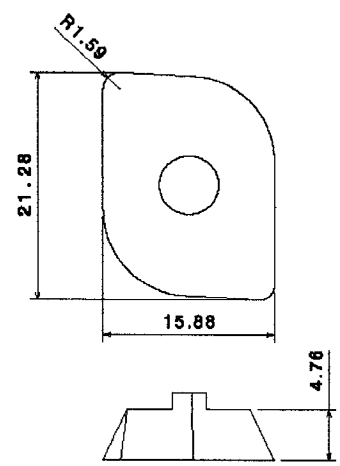


Figure 3.3 The inserts - geometry and dimensions (LFEW-R-LN)

3.2.2 Description and preparation of the integrally bladed rotor part

The approach of defining a new method of roughing integrally bladed rotors (IBRs) using cup mill cutters starts by choosing a part from the IBRs family produced at Pratt & Whitney Canada. The chosen part represents an integrally bladed rotor of a high-pressure compressor of a gas turbine engine. Its 3D model representation is in Figure 3.4. The reasons for which this part is chosen are:

- The minimum distance between the two consecutive blades is close to the active part of the cup mill cutter;
- The length of the blade is appropriate for using the cup mill cutter;
- Less twisted airfoil blade.

Figure 3.4 The 3D model of the integrally bladed rotor part

The 3D models of both the IBR part and the cup mill cutter are represented in Figure 3.5. Since the method deals with the roughing operation, the part is prepared such that the pressure side (PS) face, the suction side (SS) face and the gas path surface are all offset by 0,89 mm (0.035 in).

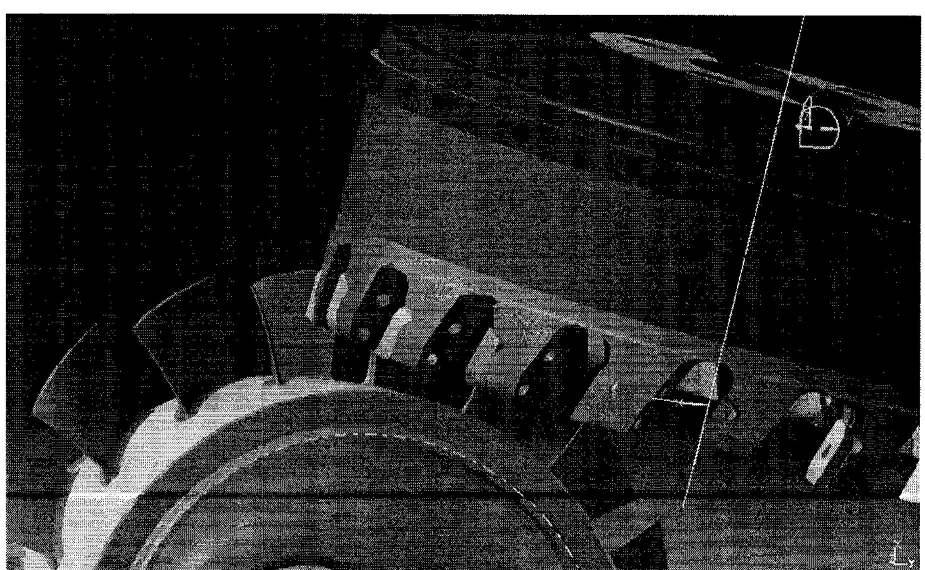


Figure 3.5 The relative machining position of the CATIA 3D models of the IBR part and the cup mill cutter

3.3 The new method of roughing integrally bladed rotors using cup mill cutters

3.3.1 Determining the tool axis orientation

To obtain higher machining efficiency, an optimal cup mill cutter orientation for five-axis NC machining of airfoil blades surfaces is required.

From the very beginning of the approach, it is decided that the tool axis remains fixed when machining one slot between two consecutive blades of the integrally bladed rotor (IBR) part and only the center of the cutter changes its position. This is an important issue because of the specificity of the tool (shape and dimensions) and the geometrical configurations (complex surfaces) of the airfoils and the hub. If our vector of the tool axis changes its direction then it will prove very difficult to control and avoid the collisions between the cutting tool and the stock. The tool axis direction is the same when manufacturing a certain slot of the IBR part and only changes by indexing the cutting tool for machining every other slot of the IBR part.

Determining the tool axis direction takes into consideration that the bottom side of the tool should best fit the gas path surface and this means practically that the material removal along the axial direction is maximized as much as possible. It is also considered that the part is always milled in full material on its pressure side except for the last blade and the outer circumferential side of the tool should be as close as possible to the pressure side. The procedure of determining the cup mill cutter orientation is a combination of two normal lines; one based on gas path surface offset, *LN1* and one based on pressure side (PS) face offset, *LN2* from a very critical point from the point of view of a collision-free machining process - the limit point of the tip curve PS face offset closer to leading edge of the airfoil, *PT1* (see Figure 3.6). The plane through the two normal lines, *LN1* and *LN2* intersects the pressure side face offset along the curve *CRV1*. The line *LN3* through the limit points of the *CRV1* is *the tool axis direction or orientation.* The base plane is the plane normal on the tool axis direction *LN3*.

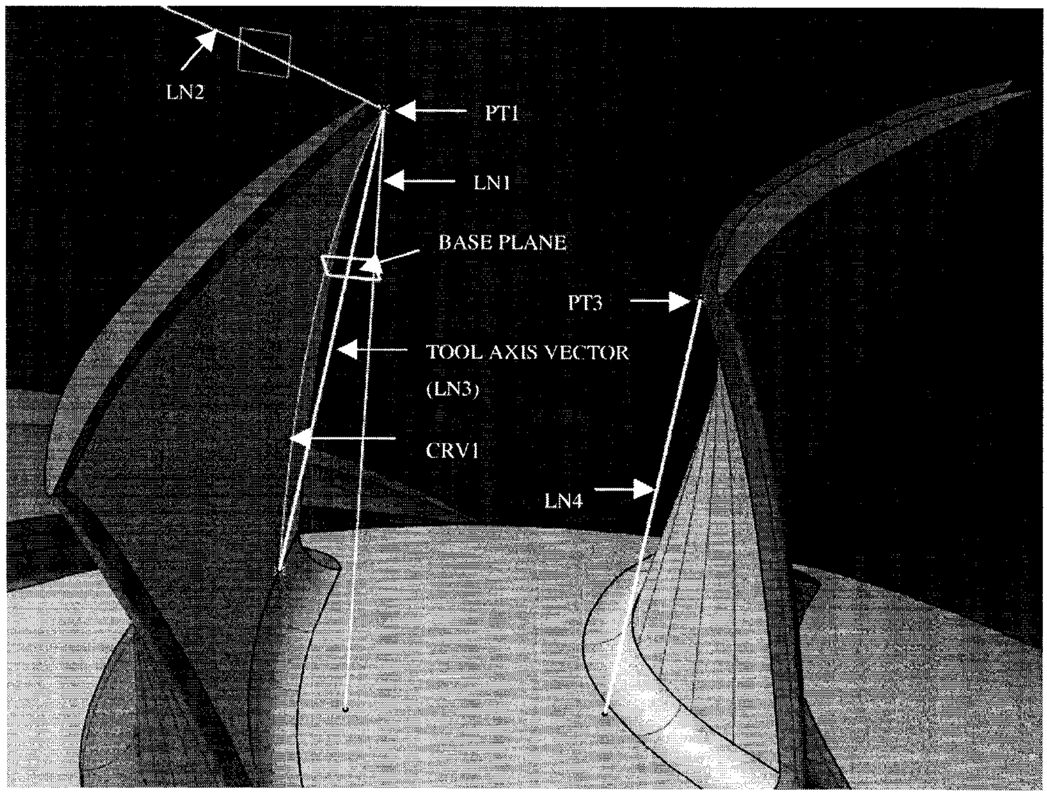


Figure 3.6 Tool axis orientation for machining one slot of the IBR part

3.3.2 The base position of the cup mill cutter between two consecutive integrally bladed rotor blades

Once the tool axis direction is established, it is necessary to calculate the tool axis positions (the tool path) when machining one slot between two consecutive integrally bladed rotor (IBR) blades. Before calculating the tool path, a collision-free position of the tool is determined.

It can be easily observed that if the outer circumferential side of the tool is positioned on *LN3*, in every axial level of machining, the cup mill cutter will be very close to the pressure side surface. As point PT1 is the limit point for the outer circumferential side of the tool, point PT3 (the limit point of the tip curve SS face offset closer to the trailing edge of the next blade) is the limit point for the inner circumferential side of the tool. For the already determined tool axis direction, there is a one and only position of the tool with respect to two consecutive blades, which is a collision-free position for the entire depth of the slot.

The base position of the cup mill cutter is the position of the tool for the already determined tool axis direction, limited at the outer circumferential side of the tool by the limit point of the tip curve PS face offset closer to the leading edge, *PT1* and at the inner side of the tool by the limit point of the tip curve SS face offset closer to the trailing edge of the next blade, *PT3* (Figure 3.7).

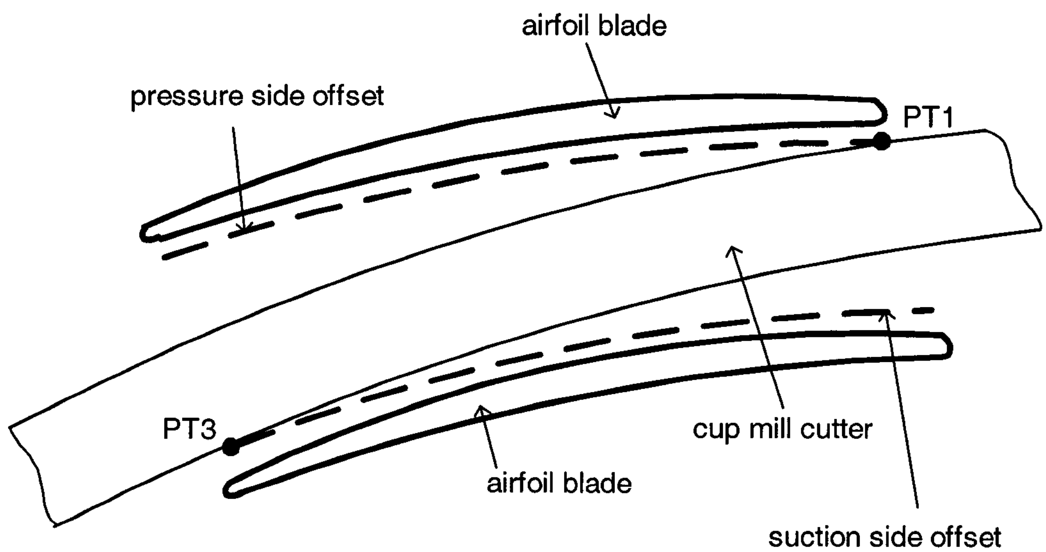


Figure 3.7 The cup mill cutter in the base position

A simplified representation of the cup mill cutter is considered. The outer and inner circumferences of the tool are two concentric cylindrical surfaces. For the base position of the cutting tool and for the entire depth of the slot, the outer cylindrical surface contains the line *LN3* and the inner cylindrical surface contains the normal line, *LN4* onto the base plane from the limit point of the tip curve SS face offset closer to trailing edge, *PT3* (Figure 3.8).

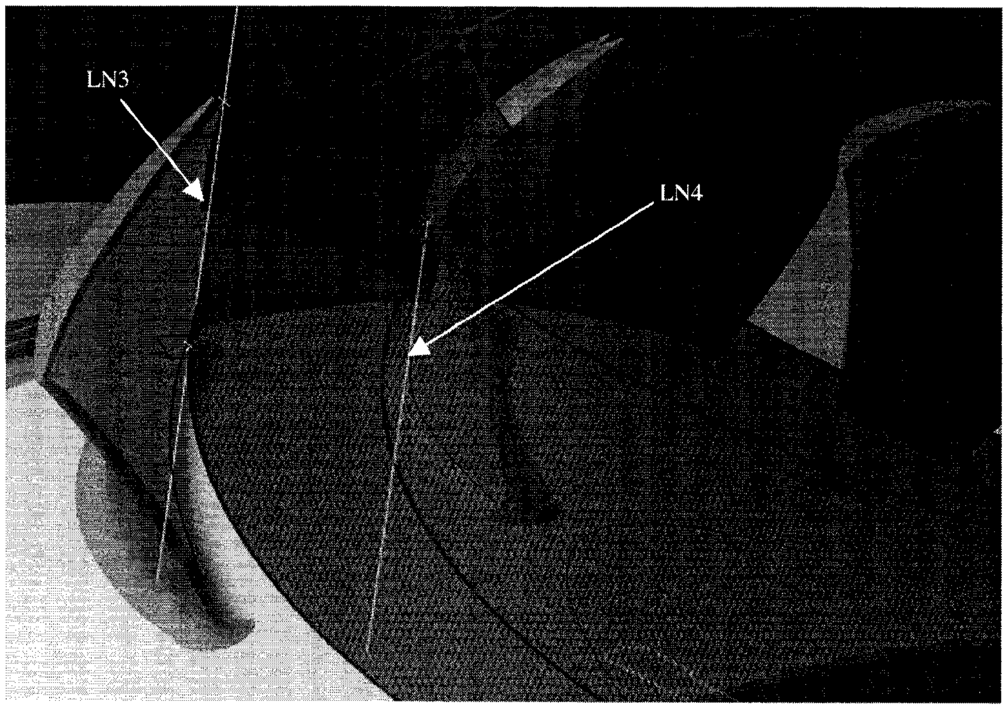


Figure 3.8 Cylindrical representation of the cup mill cutter in the base position

The cutting plane corresponds on the tool to the plane that is normal to the tool axis and at the distance of the insert radius (RADINS) from the bottom plane of the cup mill cutter (see Figure 3.9).

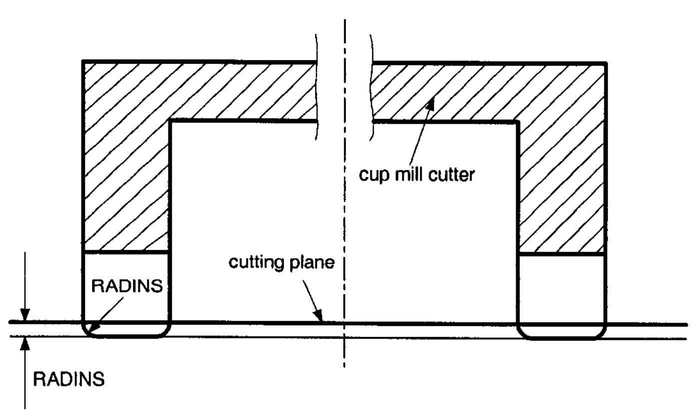


Figure 3.9 The corresponding cutting plane on the cup mill cutter (RADINS – insert radius)

The position of the tool axis of the cup mill cutter in the base position can be easily calculated. For a certain axial level of machining, the cutting plane intersects the two lines that define the base position *LN3* and *LN4* respectively at the points *A* and *B* (see Figure 3.10). For certain dimensions of the tool, the outer radius *R* and the inner radius *r* are known and the distance *a* between the two lines *LN3* and *LN4* is constant.
The position of the tool axis of the cutting tool at the base position for this axial level of machining and the defined dimensions of the cup mill cutter would be at point *C* (Figure 3.10) and it can be calculated from the law of cosines for the triangle *ABC*.

$$\cos\alpha = \frac{R^2 + a^2 - r^2}{2Ra} \tag{5}$$

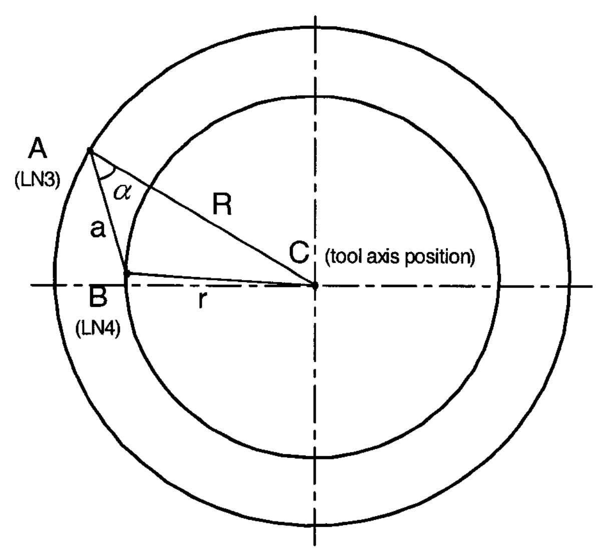


Figure 3.10 Calculus of the tool axis position of the cup mill cutter in the base position

An interesting resulting observation that comes out from the base position concept is that the dimensions of our tool can be optimized in order to best fit the space between two consecutive blades. By increasing the width of the insert, the position of the tool axis changes such as the outer and inner circumferential sides of the tool are closer to respectively, the pressure side and the suction side (Figure 3.11). If the actual outer tool radius is R_2 and the inner radius is r_2, by using a wider insert than the actual one, the new outer tool radius will be $R_1 \rangle R_2$ and the new inner tool radius will be $r_1 \langle r_2$. The new tool is positioned between two consecutive airfoil blades in the new base position (a new tool axis position), for which the two limitation points are the same as for the actual position of the tool; the limit point of the tip curve pressure side face offset closer to the leading edge, *PT1* and the limit point of the tip curve suction side face offset closer to the trailing edge of the next blade, *PT3*. In the new base position, the outer and inner sides of the tool are closer to the pressure side surface and the suction side surface. That implies directly an increased material removal rate by a better positioning of the tool with respect to the two consecutive airfoil blades.

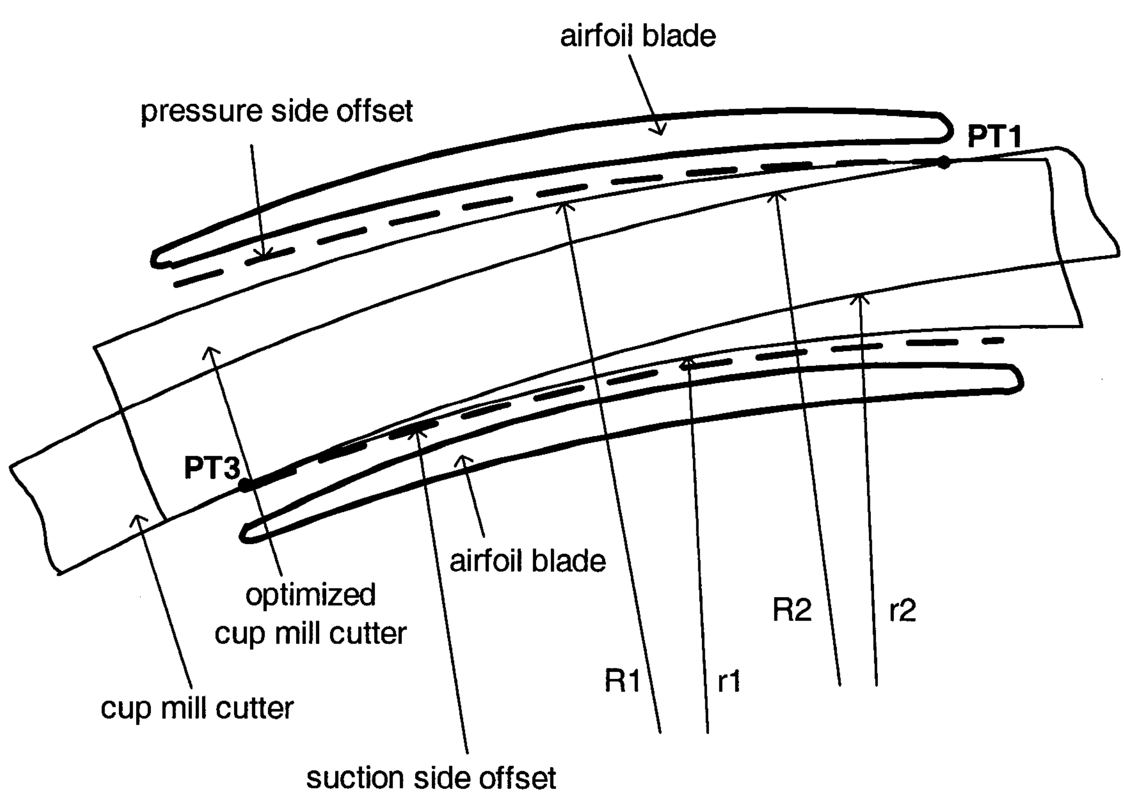


Figure 3.11 Tool design optimization for better productivity

3.3.3 The tool path for the machining of one slot of the integrally bladed rotor part with the cup mill cutter

The tool path is calculated for the roughing operation of one slot between two consecutive blades of the integrally bladed rotor (IBR) part using the cup mill cutter. The tool path contains defined planar and axial movements of the cup mill cutter.

A collision free position of the cutting tool with respect to the gas path surface is determined. This position (the lowest axial level of machining) is given by the maximum axial displacement of the cutting tool such that there is no intersection between the bottom of the cutting tool and the gas path surface offset. The lowest axial level of machining is used to define the maximum axial depth of cut, *ADCMAX = 2,54 mm (0.1 in)*. For the tool axis orientation, the entire depth of the slot is divided into a number of axial levels of machining, for which the distance between two consecutive levels is the effective axial depth of cut, *ADCEFF*, with *ADCEFF* < *ADCMAX* (Figure 3.12).

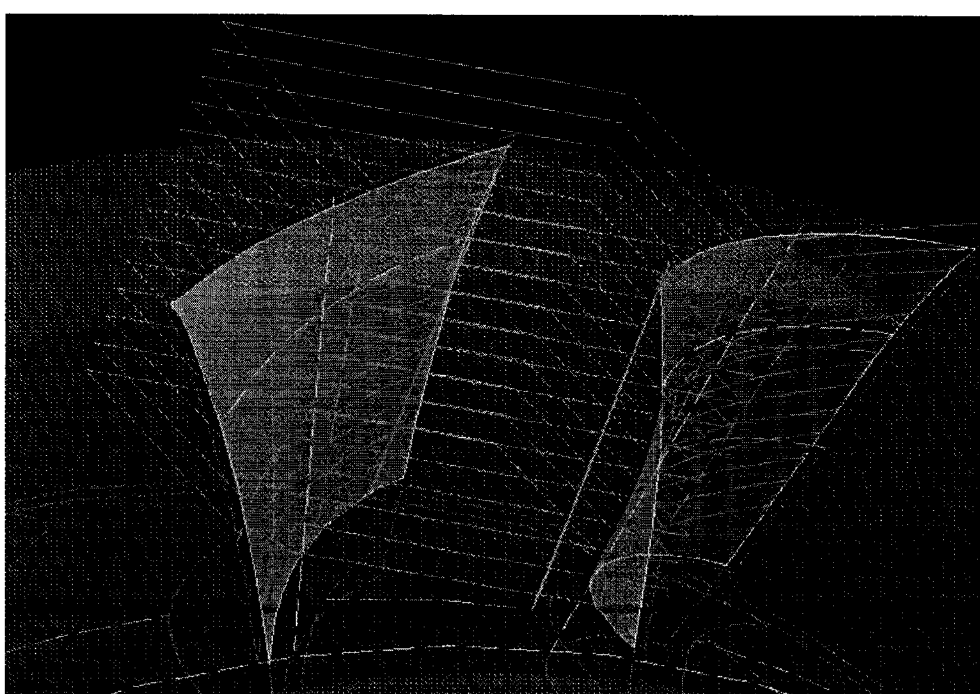


Figure 3.12 The axial levels of machining for the entire depth of the integrally bladed rotor slot

At a certain axial level of machining, *i*, the cutting plane intersects lines *LN3*, *LN4* (Figure 3.8) and the tool axis of the previously defined base position at respectively points *A*, *B* and *C* (Figure 3.10). The tip curve of the suction side surface offset is projected on Plane *i* that corresponds to the axial level of machining, *i*. Because of the twisted form of the tip curve of the suction side surface offset, point B_1 is defined such that it satisfies two conditions:

1. Point B_1 is on the inner circumferential side of the cup mill cutter at the base position;
2. By rotating the tool center around point B_1 the inner circle intersects the suction side surface offset at one point close to the leading edge (Figure 3.13).

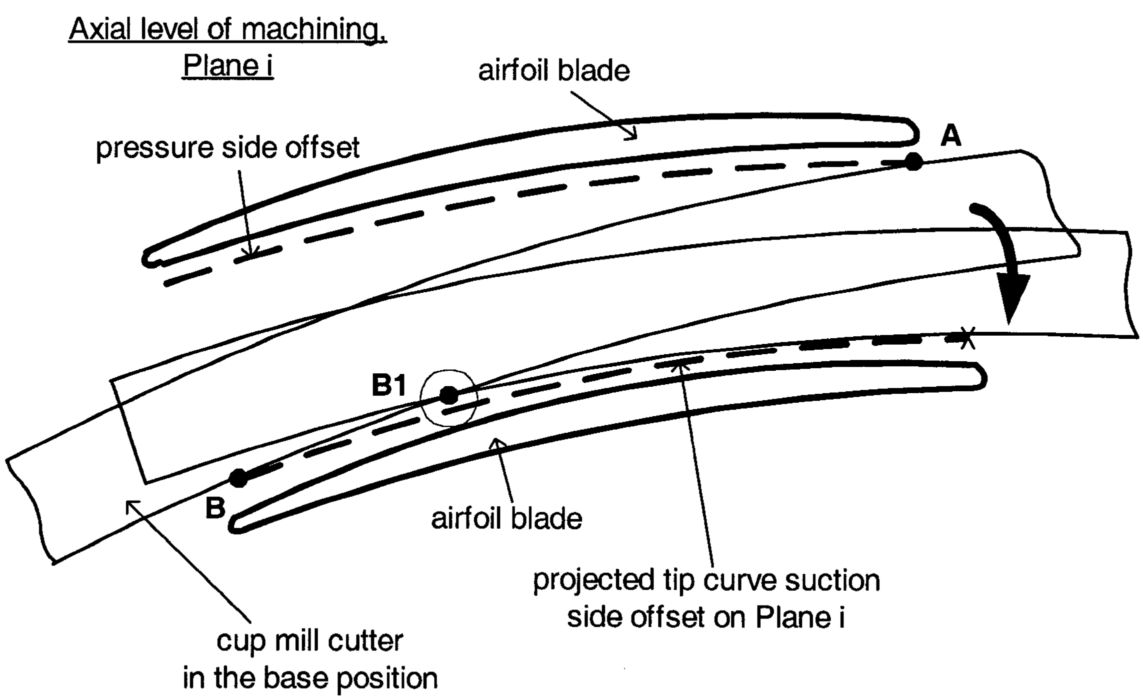


Figure 3.13 Determining the point of interior rotation, B_1

The tool path at the axial level of machining, *i*, is a result of successively displacements of the tool center around respectively points *A* and B_1. Points A and B_1 are in the axial level of machining *i* respectively the point of exterior rotation and the point of interior rotation of the tool center.

The displacement of the tool center around point A means the displacement of the outer circumference of the tool closer to the pressure side surface offset of the blade. The rotation is stopped (point *D* on the tool path) when there is an intersection between respectively the outer toroidal surface of the tool and the pressure side surface offset of the blade or the inner toroidal surface of the tool and the suction side surface offset of the blade (Figure 3.14). The radii of the inserts of the rotating tool give the outer and inner toroidal surfaces.

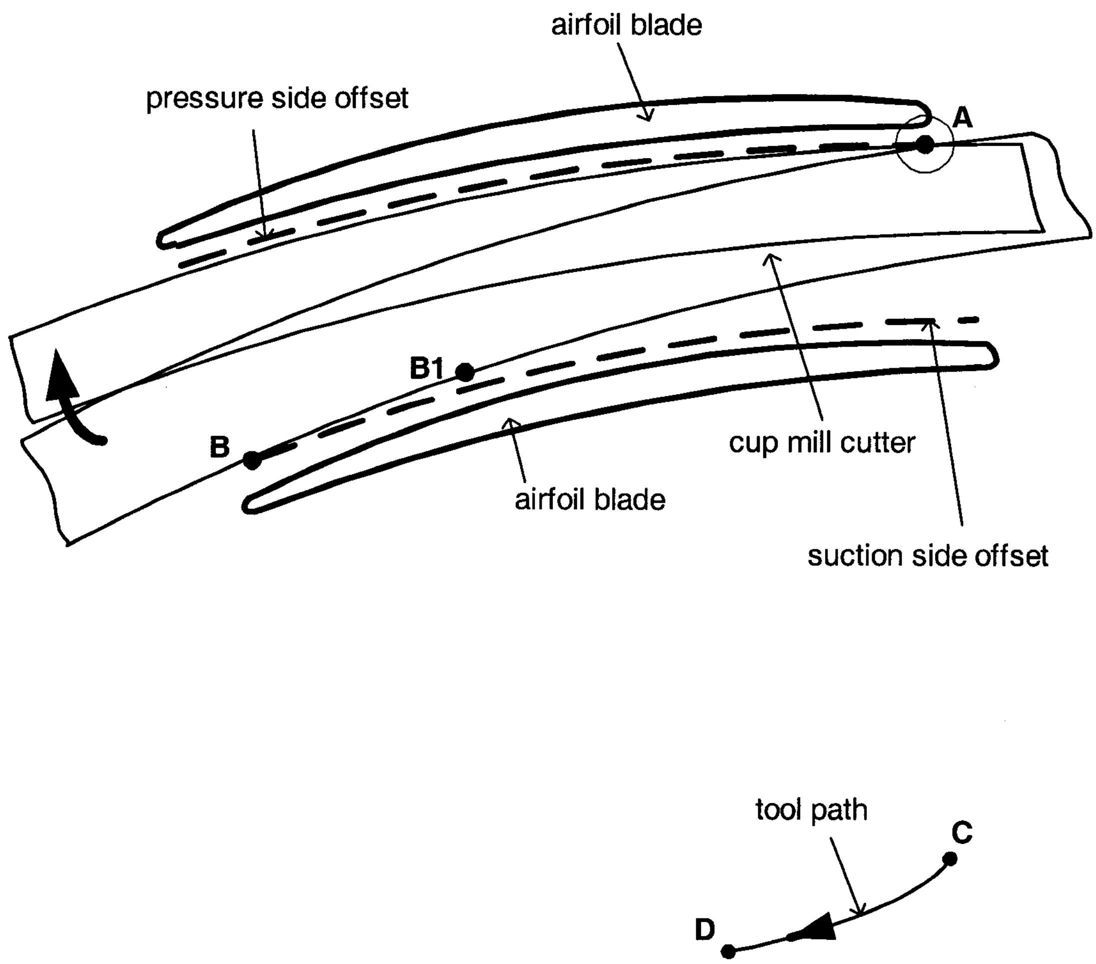


Figure 3.14 Tool movement in one axial level of machining – tool center rotation around point A

The rotation of the tool center around point B_1 means the displacement of the inner circumference of the tool closer to the suction side surface offset of the blade. The rotation is stopped (point E on the tool path) when there is an intersection between the inner toroidal surface of the tool and the suction side surface offset of the blade (Figure 3.15).

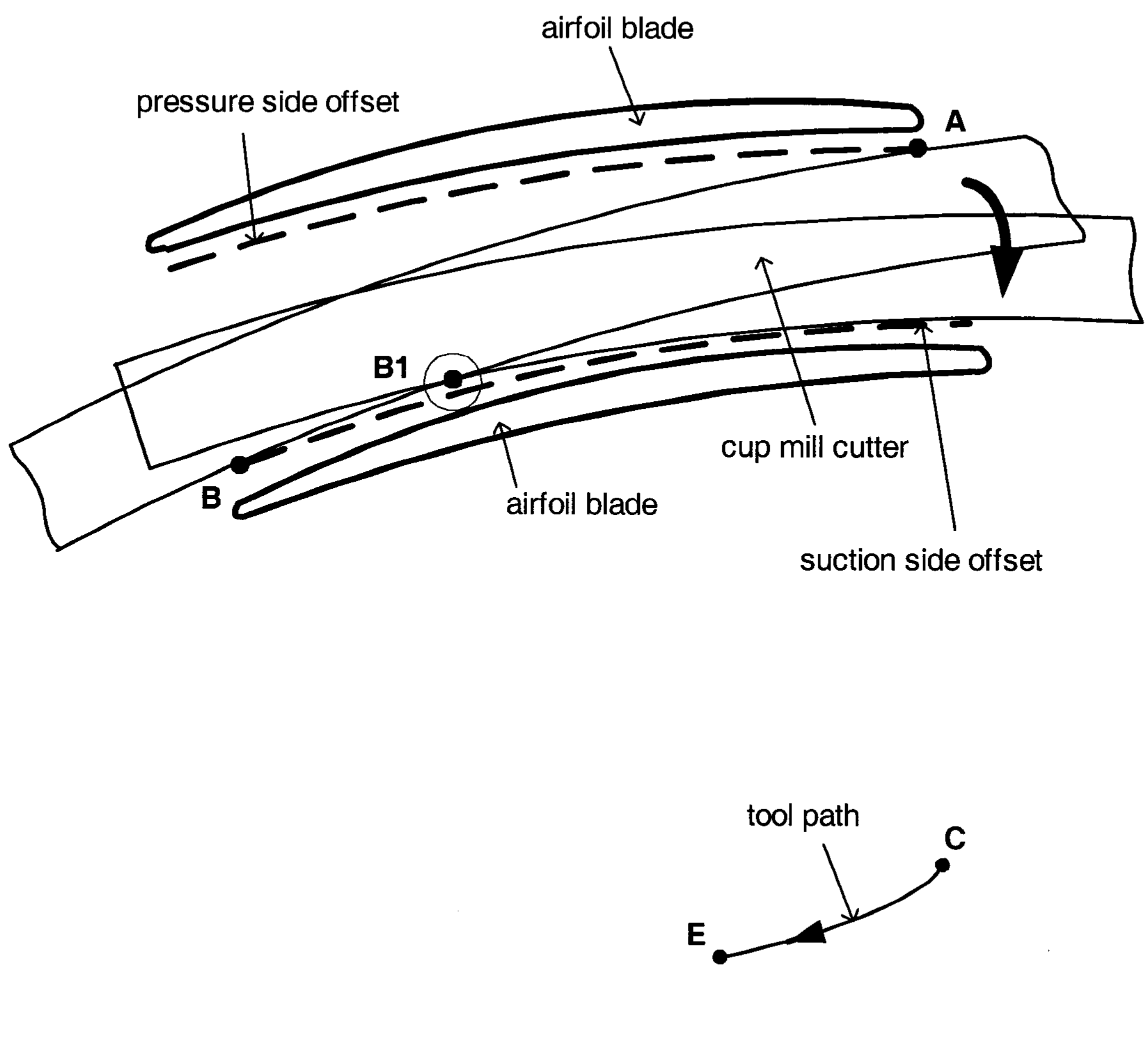


Figure 3.15 Tool movement in one axial level of machining – tool center rotation around point B_1

To summarize, at every determined axial level of machining the tool path is a double circular interpolation of the tool center. Between two consecutive axial levels of machining, the tool path is a linear interpolation between two limit points in the two consecutive axial levels of machining (Figure 3.16).

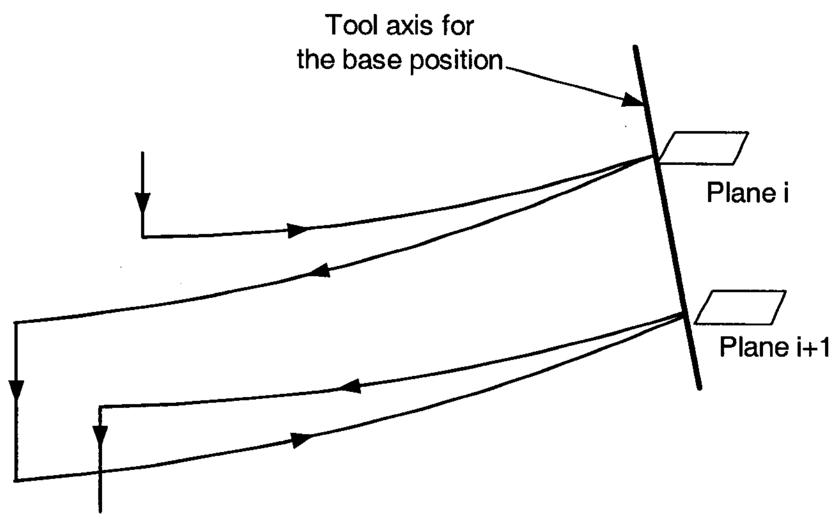


Figure 3.16 The tool path at and between two consecutive axial levels of machining

3.4 The developed program of roughing integrally bladed rotors using the cup mill cutter

3.4.1 The Interactive User Access language

CATIA V4 data are models, project files and libraries. Algorithms available in CATIA are programs enabling for instance to project a curve onto a surface. Data and algorithms are available to the application programmer through CATGEO, which stands for CATIA Geometric Interface Fortran routines. An application can be written in BATCH when the application does not require any user interaction, in GII (Graphic Interactive Interface) that enables writing the application as a CATIA-like function or in IUA (Interactive User Access).

When data require a user interaction but the dialog phase is relatively separated from the algorithm phase, the application can be written in IUA. This feature of IUA fits perfectly with the intention of writing a program, which provides automatically the tool path for roughing the part, using some specifically geometric elements of the IBR part by selecting them from the CATIA model.

IUA is a procedural language. It provides:

- Interactive execution of the procedure written in the IUA macro language;
- Access to a library of IUA procedures used to create and handle most CATIA elements including access to CATGEO capabilities;
- Different types of variables including the notion of geometric variables;
- A set of commands used to manage the dialog;
- Two commands to execute an independent (Fortran or C) load module calling CATGEO routines and provide access to the current model;
- An interactive debug tool for any errors in procedures.

The program is thought as two separate parts. The first one is the dialog phase when the user is asked to select specific geometric elements (points, surfaces, faces, curves) from the integrally bladed rotor part 3D CATIA model. The second one is the algorithm phase in which the selected geometric elements are used to calculate the tool path of roughing one slot of the IBR part using the cup mill cutter.

The program is conceived as a chain of procedures where each consequent procedure is executed at the end of the former one. The EXEC instruction transfers the control of the execution to the called procedure and replaces the value of the external variables of the called procedure by the value of the arguments that are included in the EXEC instruction (Figure 3.17).

Since it's all about a roughing operation, before any interaction of the user, the 3D model is prepared such that the pressure side surface and face, the suction side face and the gas path surface are all offset by 0,89 mm (0.035 in).

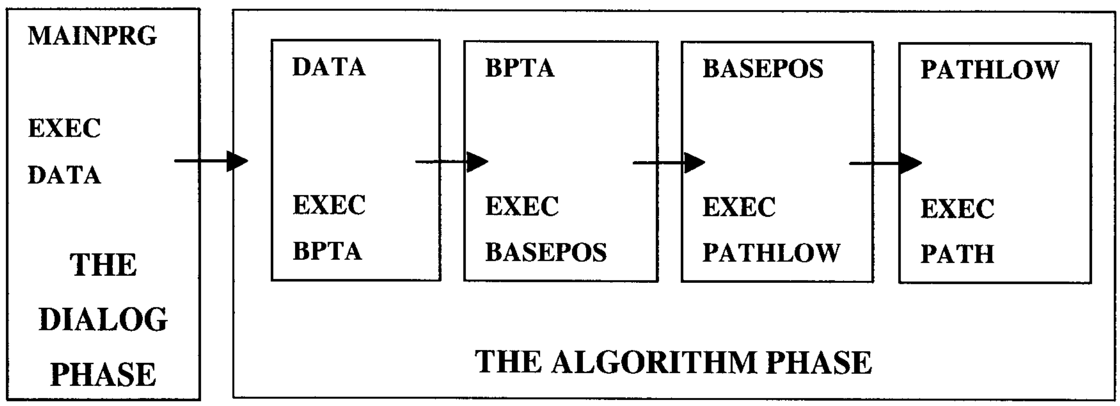


Figure 3.17 The chain of procedures of the developed program of roughing the integrally bladed rotor part using the cup mill cutter

3.4.2 The dialog phase

The first part contains MAINPRG and DATA procedures, which is actually the dialog phase. In this phase the user (NC mill programmer) is asked to interactively select geometric elements from the CATIA model that are in order (Figure 3.18):

- The origin of the absolute axis system, *PT*;
- The limit point of the tip curve PS face offset closer to the leading edge, *PT1*;
- The gas path surface offset, *SURSB*;
- The pressure side (PS) surface offset, *SURPS*;
- The pressure side face offset, *FACPS*;
- The suction side (SS) face offset, *FACSS*;
- The limit point of the tip curve SS face offset closer to the trailing edge, *PT3*;

- The tip curve of the suction side face offset, *CRV1*.

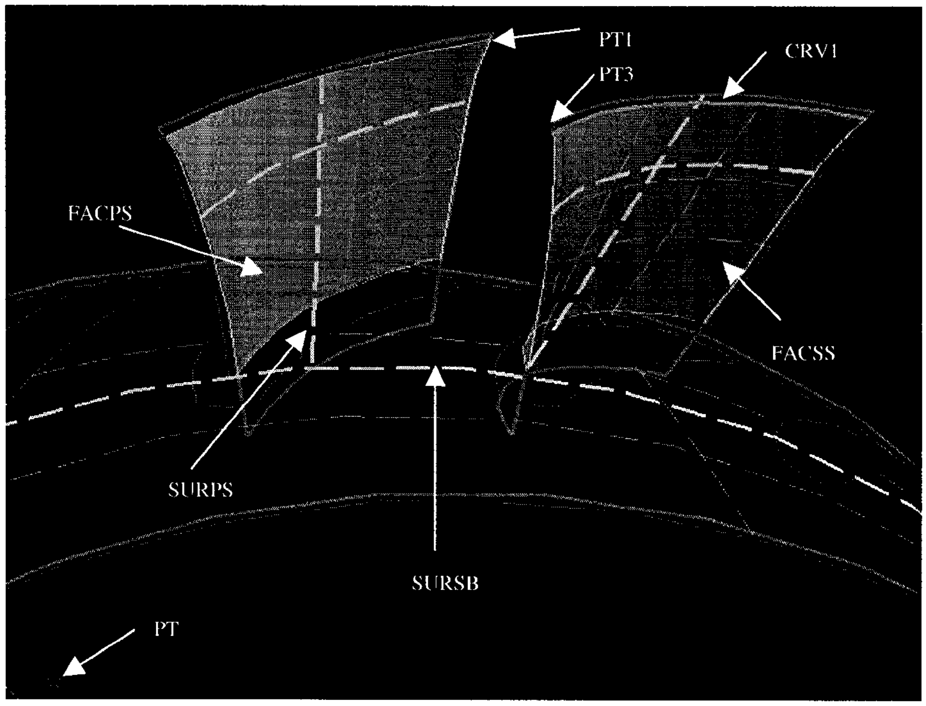


Figure 3.18 The dialog phase – Selection of specific geometric elements from the integrally bladed rotor part CATIA model

All these input geometric elements are specific for the geometry of an integrally bladed rotor and consequently the preparation phase is trivial and the input elements can be easily selected. The DATA procedure also includes the geometry and the dimensions of the cutting tool (Figure 3.19), respectively the outer radius, *RADEXT*, the inner radius, *RADINT*. It also contains the dimensions of the insert (Figure 3.19), respectively the radius of the insert, *RADINS* and finally the maximum value of the axial depth of cut, *ADCMAX*. The program is intended to be generic and to be used for whatever configuration of part number and cup mill. Hence, a NC mill programmer, depending on the actual tool and insert geometry and dimensions, can easily change the values of the variables in the DATA procedure.

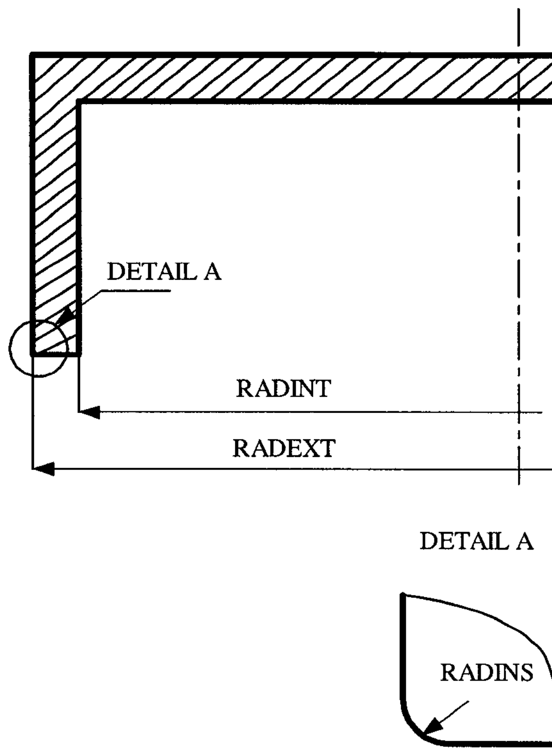


Figure 3.19 The cup mill cutter dimensions input in the developed program (RADINT – tool inner radius; RADEXT - tool outer radius; RADINS – insert radius)

3.4.3 The algorithm phase

The second part of the developed program for roughing integrally bladed rotor part using the cup mill cutter is the algorithm phase and it contains the procedures BPTA, BASEPOS, PATHLOW and PATH.

The BPTA procedure establishes the tool axis orientation, the position of the tool axis for the base position and the lowest axial level of machining. The BASEPOS procedure determines the point of interior rotation of the tool center in order to avoid collision between the tool and the tip curve of the suction side surface offset. The PATHLOW procedure creates the tool path at the lowest axial level of machining. The last procedure PATH generates the tool path for the rest of the integrally bladed rotor slot.

3.4.4 The flowchart

A schematic flowchart of the developed program reveals the main steps in calculating the tool path of roughing the IBR part with the cup mill cutter (Figure 3.20). A more detailed flowchart is presented in Annexes.

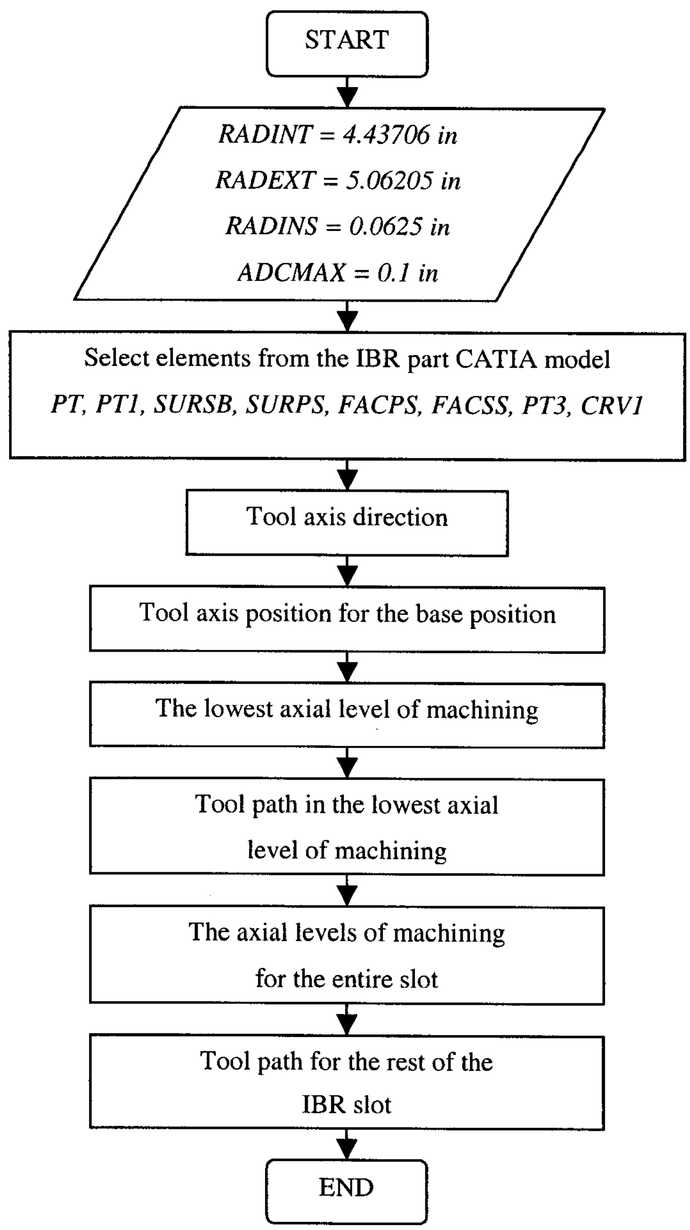


Figure 3.20 Schematic flowchart of the developed program

CHAPTER 4

THE NC MILL PROGRAM OF ROUGHING THE INTEGRALLY BLADED ROTOR PART WITH THE CUP MILL CUTTER

4.1 The NC mill program

One of the main advantages of the new method of roughing IBRs using the cup mill cutter is that the developed program is able to provide automatically the tool path as a 3D representation of the tool center positions. With the automatically 3D generated tool path, the NC mill programmer can easily create the NC mill program by the usual means of a computer-aided manufacturing (CAM) software. The tool path is represented in the CATIA model of the IBR part (Figure 4.1) as a direct output of the developed program.

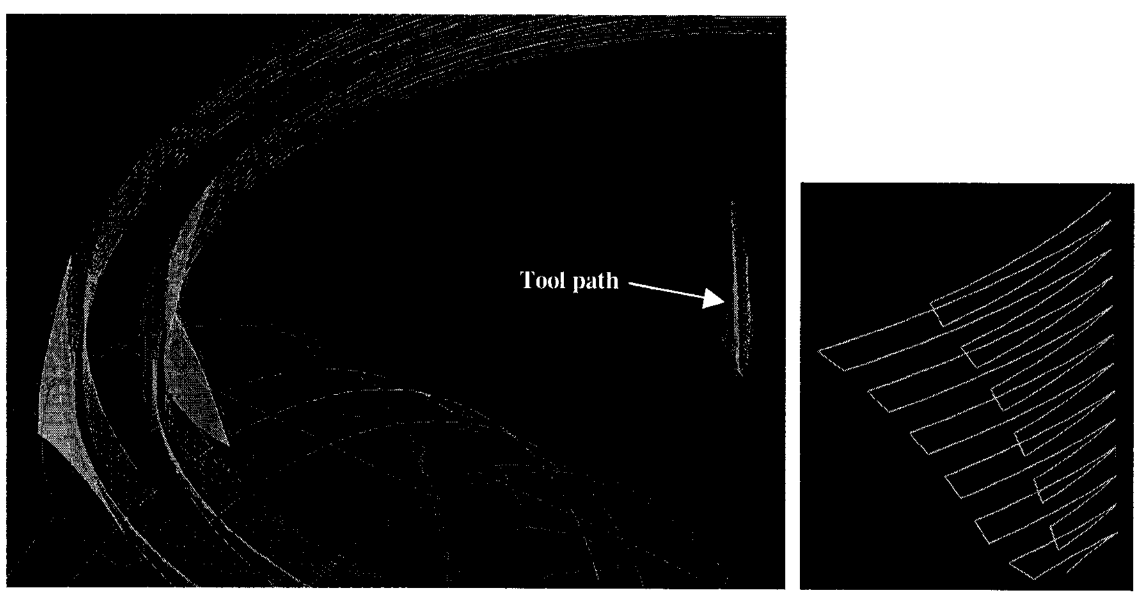


Figure 4.1 The output of the developed program – the tool path of roughing one slot of the IBR part with the cup mill cutter (left) and a closer view of tool path (right)

The dimensions of the modular fixture (Figure 4.2) and the cup mill cutter are defined in the NC mill module of CATIA V4.

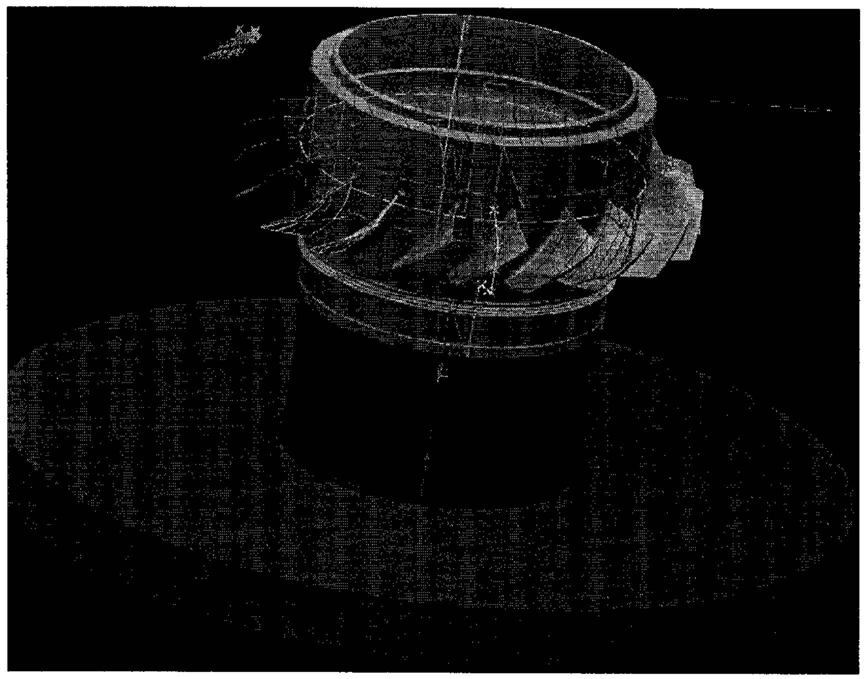


Figure 4.2 The 3D model of the fixture

The tool path is used to generate the NC mill program. In Figure 4.3 is shown a screen print taken during the NC mill program verification with the fixed tool axis following the tool path in one of the axial levels of machining.

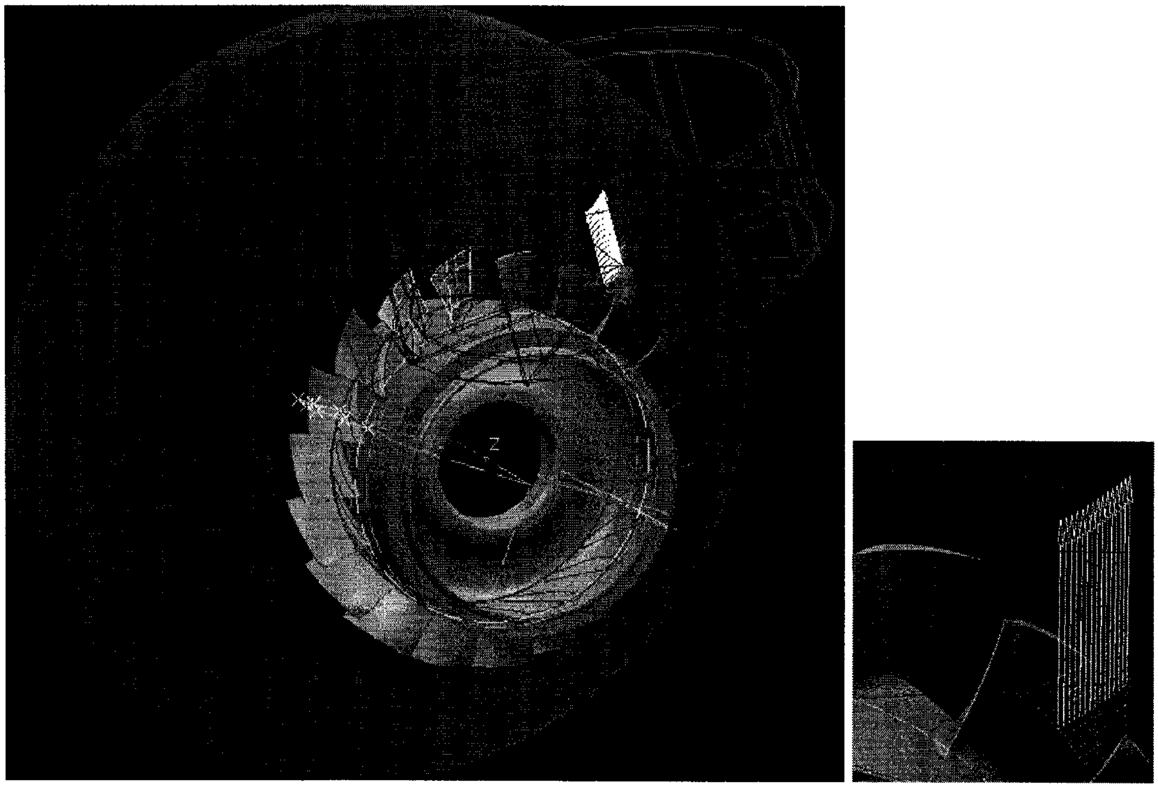


Figure 4.3 NC mill program verification

4.2 Simulation and validation of the NC mill program

Before any manufacturing test, the output of the method of roughing IBRs with cup mill cutters (the NC tool path data) is used in VERICUT for simulation and validation. By simulating the NC tool paths, VERICUT can eliminate the time-consuming and expensive steps of the traditional data prove-outs.

The input into VERICUT is the tool path data from almost any source. G and M code data as well as APT type CL-files are directly processed by VERICUT. Similar to the requirements of machining a real part, VERICUT needs the tool path data, a description of the raw stock material to be machined, and descriptions of the cutting tools used to machine the part. The result of the verification process is a solid model of the machined part and an error Log file reporting any machining errors detected during the simulation (Figure 4.4).

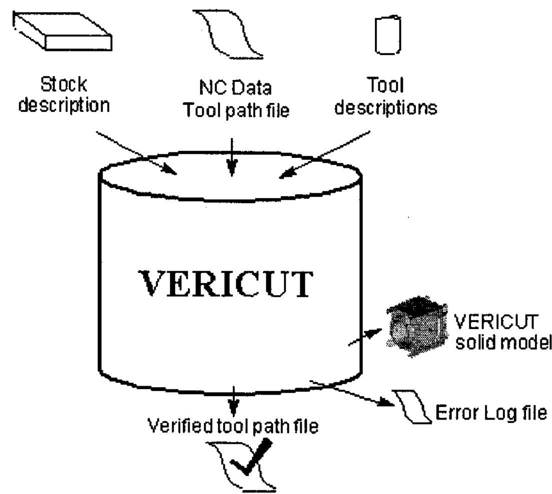


Figure 4.4 VERICUT philosophy

Setting up a tool path to be processed by VERICUT is similar to setting up an NC tool path to run on an NC machine tool. VERICUT requires six things to simulate the cutting action of a tool path as it has been defined by the method of roughing the IBR part with the cup mill cutter. They are the same things that are required to machine the actual part on an NC machine tool:

1. Stock model-IBR part raw material, or "workpiece" to be machined
2. NC data describing cutting tool positions, machine information, and other data required to operate a machine tool-the tool path file in G code format (see Annexes-CATH1546_pch_000_T_Y_20031128)
3. Cutting tool-shape and size of the cup mill cutter used to machine the workpiece
4. Fixture model-hardware used to hold the workpiece for machining
5. Designed part-the theoretical perfect-machined IBR part
6. Operator instructions-notes about actions required by the machine operator which must be followed in order to successfully machine the part, such as: part setup, clamp/fixture changes, tool changes, etc.

Table 4.1 shows the requirements for setting up a simulation of cutting action tool path in VERICUT.

Table 4.1 Requirements for setting up a tool path simulation in VERICUT

Requirement	VERICUT
Workpiece	IBR part stock model
NC data- tool positions and NC machine codes	Tool path file data in G-code format
Cutting tools	Descriptions of the cup mill cutter shape/size
Holding fixtures	Fixture model
Designed part	CAD-designed IBR part model
Operator instructions	Operator instructions

The tool path for roughing the integrally bladed rotor part with the cup mill cutter is simulated and no collisions or errors are detected. Figure 4.5 shows the cutting tool at the end of NC tool path simulation.

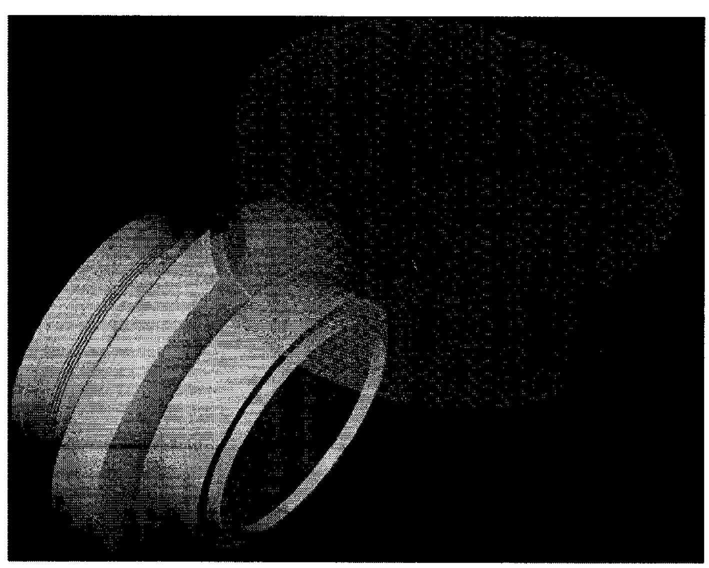


Figure 4.5 NC tool path simulation in VERICUT

CHAPTER 5

THE CUTTING CONDITIONS CONTROL OF THE ROUGHING PROCESS OF INTEGRALLY BLADED ROTORS USING CUP MILL CUTTERS

Milling of titanium alloys induces problems of chatter and tool-part contact because of the titanium low modulus of elasticity. It is desirable then to have a stable milling process in order to avoid these inconveniences. A vibration-free milling process can be achieved by controlling the feed per tooth (IPT). Because of the dimensions of the cup mill cutter, a desired IPT on the circumference of the tool yields a different value of IPT at the centre of the tool. Since the tool centre is controlled, the IPT at the centre of the tool is to be calculated considering that the IPT is constant on the circumference of the tool. The cutting conditions control is performed for the movements of the cutting tool in two consecutive axial levels of machining, *Plane i* and *Plane i+1.* (Figure 5.1) The transition of the cutting tool between the two consecutive axial levels of machining is a linear interpolation between two extreme points of the tool path in these two levels. (Figure 5.1)

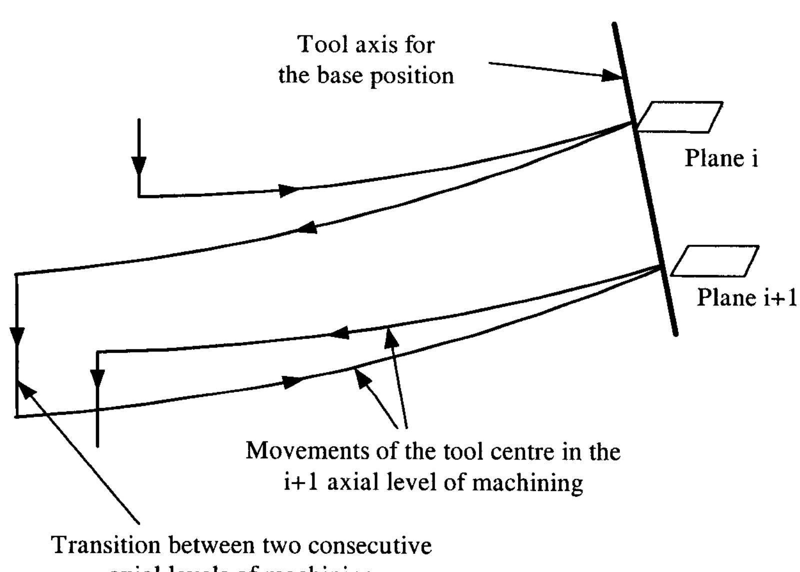


Figure 5.1 The tool path for two consecutive axial levels of machining

5.1 Analysis of tool centre movements

The tool path in two consecutive axial levels of machining, *Plane i* and *Plane i+1,* is analyzed and there are defined four different cases (see Figure 5.2), which depend on the point (exterior or interior) the tool centre is rotated and the side of the tool (inner or outer) that does the machining.

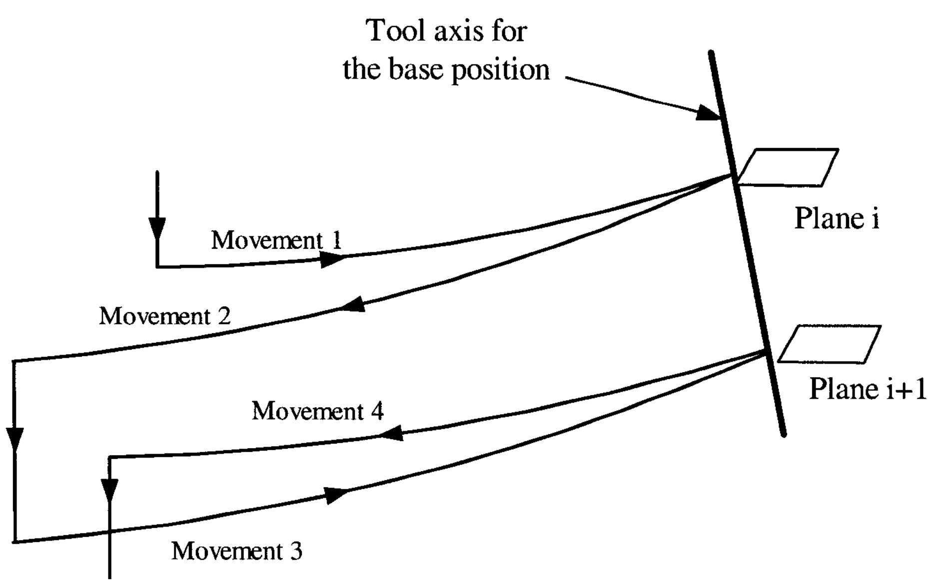


Figure 5.2 The four movements of the tool centre in two consecutive axial levels of machining

The result of the analysis for the four movements is shown in Table 5.1.

Table 5.1 The analysis of the tool movements in two consecutive axial levels of machining

MOVEMENT	POINT OF ROTATION	MACHINING SIDE OF THE TOOL
1	INTERIOR	OUTER
2	EXTERIOR	OUTER
3	EXTERIOR	INNER
4	INTERIOR	INNER

Movement 1 is the rotation of the tool centre around the interior point, A_i, and the machining is done with the outer side of the tool. (Figure 5.3)

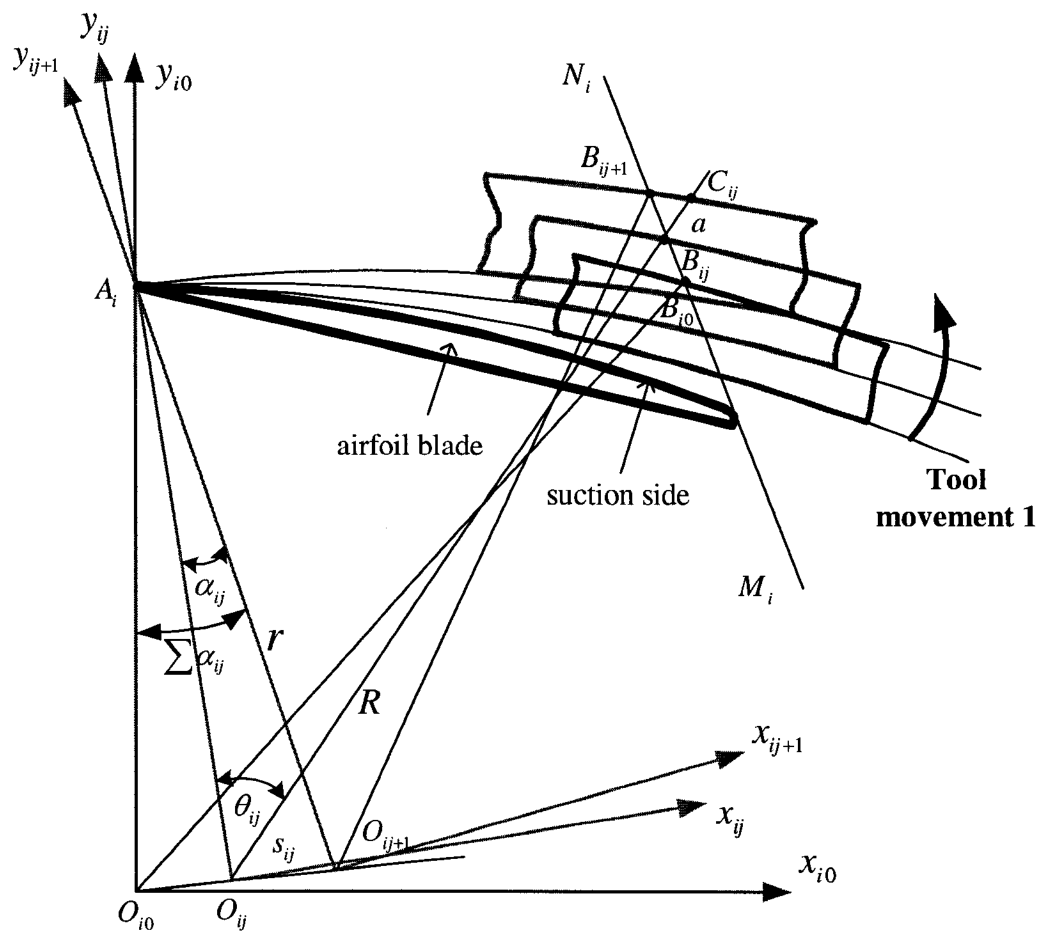


Figure 5.3 Tool movement 1 – the rotation of the tool centre around the interior point, A_i, and the machining done with the outer side of the tool

Movement 2 is the rotation of the tool centre around the exterior point, A_i, and the machining is done with the outer side of the tool. (Figure 5.4)

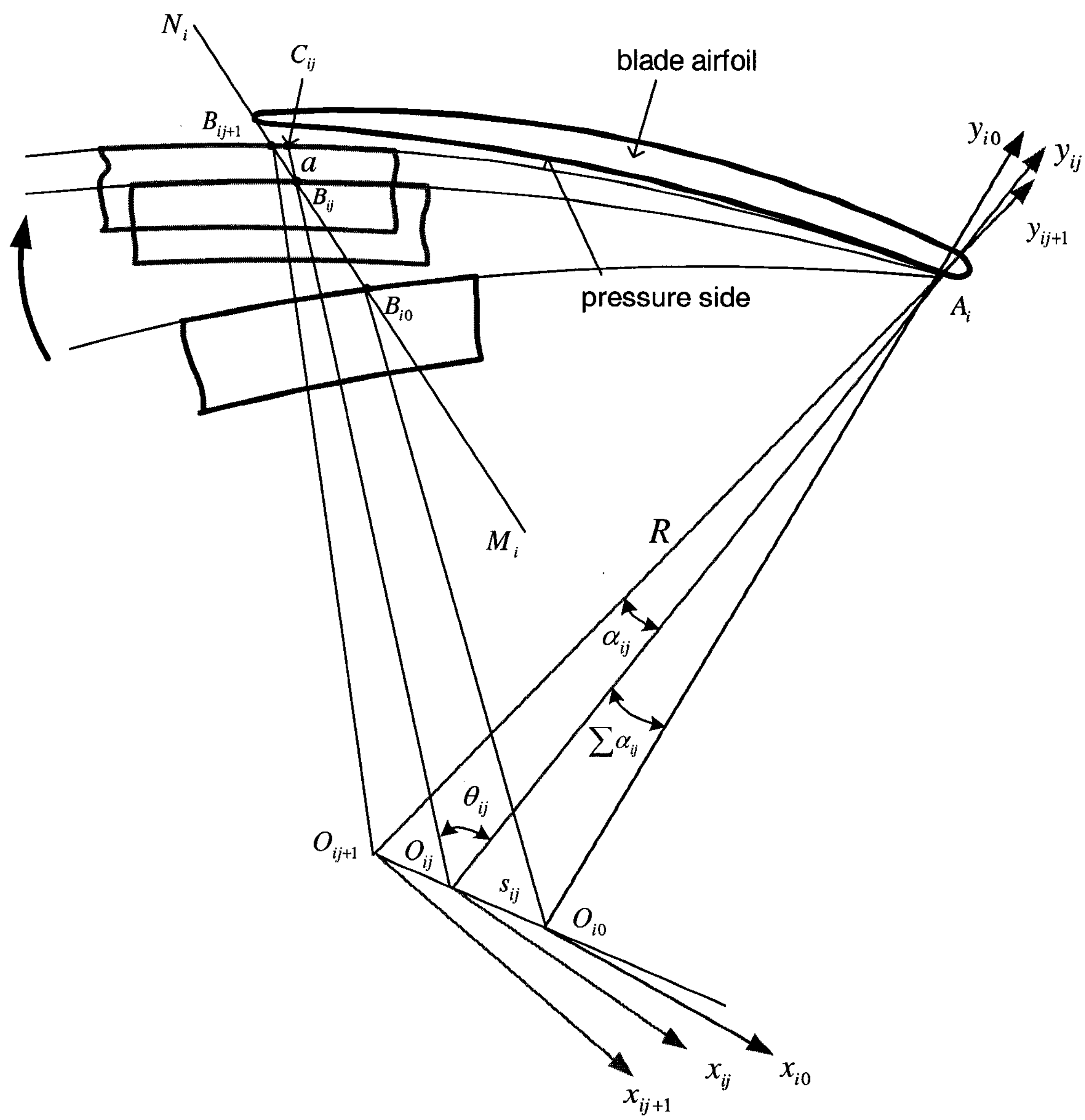


Figure 5.4 Tool movement 2 - the rotation of the tool centre around the exterior point, A_i, and the machining done with the outer side of the tool

Movement 3 is the rotation of the tool centre around the exterior point, A_i, and the machining is done with the inner side of the tool. (Figure 5.5)

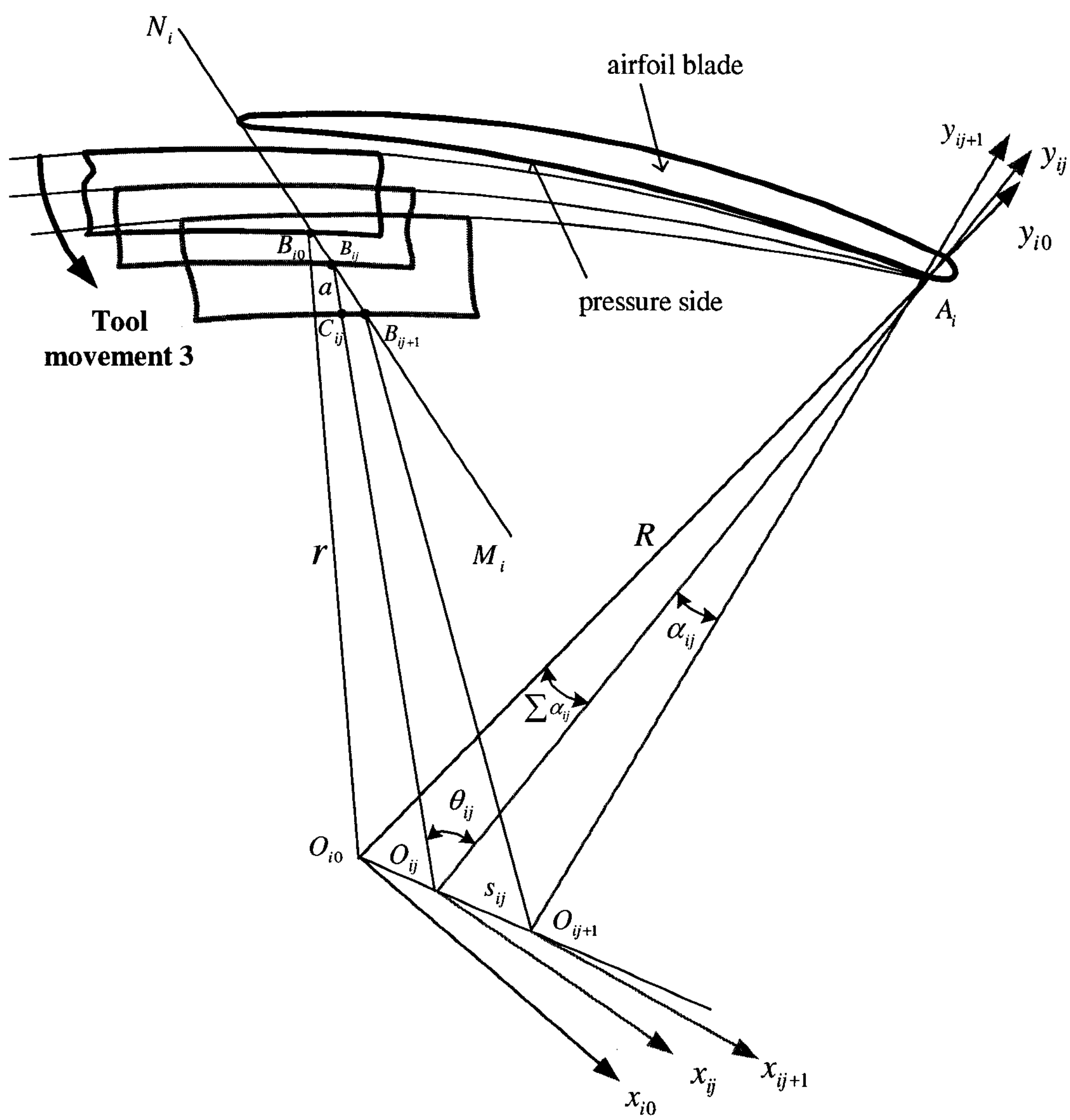


Figure 5.5 Tool movement 3 - the rotation of the tool centre around the exterior point, A_i, and the machining done with the inner side of the tool

Movement 4 is the rotation of the tool centre around the interior point, A_i, and the machining is done with the inner side of the tool. (Figure 5.6)

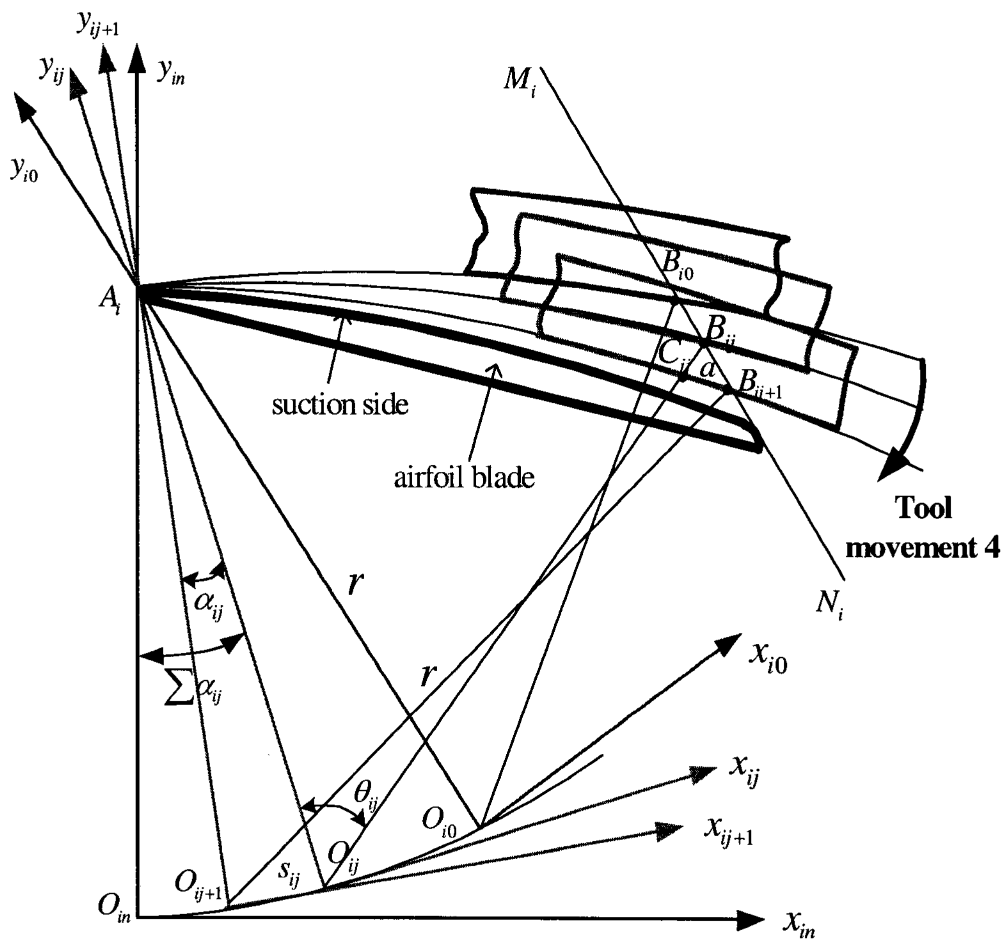


Figure 5.6 Tool movement 4 - the rotation of the tool centre around the interior point, A_i, and the machining done with the inner side of the tool

5.2 The cutting conditions control method of the roughing process of integrally bladed rotor part using the cup mill cutter

Movement 1 (Figure 5.3) is analysed and the considerations are extrapolated to the other three movements. The desired and constant feed rate per tooth (IPT) on the circumference of the tool a, the outer radius of the tool R, and its inner radius r are defined.

A_i is the interior point for tool rotation corresponding to the axial level of machining, i. The inner circumference passes through this point and the tool *Movement 1* is actually a rotation of the tool centre around point A_i with the inner radius of the cutting tool r. For *Movement 1* the cup mill cutter machines with its outer circumference. One of the limit points of the *Movement 1,* O_{in}, is the tool centre position for the tool in the base position in the axial level of machining, i and the other one is given by the last collision-free position of the outer or inner circumferential sides of the tool with respect to respectively pressure side surface offset or suction side surface offset, O_{i0}.

The stock limit in the axial level of machining, i is defined by a line, $\overline{M_i N_i}$ and the coordinates of the limit points of this line, M_i and N_i, can be measured in the integrally bladed rotor part CATIA model.

The initial axis system ΣO_{i0} is considered. It has the origin the limit point of the tool path O_{i0} of *Movement 1* in the axial level of machining, i, its y-axis is the vector $\overline{O_{i0} A_i}$ and its x-axis is the vector perpendicular to y-axis. At the beginning, the coordinates of the points M_i and N_i are expressed in this axis system. Considering that these are respectively x_{Mi0}, y_{Mi0} and x_{Ni0}, y_{Ni0}, the equation of the line $\overline{M_i N_i}$ can be expressed as the line passing through two points:

$$(x - x_{Mi0})(y_{Ni0} - y_{Mi0}) = (y - y_{Mi0})(x_{Ni0} - x_{Mi0}) \tag{6}$$

After some manipulation of the above equation, its general form is:

$$Ax + By + C = 0 \tag{7}$$

where:

$$A = y_{Ni0} - y_{Mi0} \tag{8}$$

$$B = -(x_{Ni0} - x_{Mi0}) \tag{9}$$

$$C = x_{Ni0} y_{Mi0} - x_{Mi0} y_{Ni0} \tag{10}$$

For a certain position of the centre of the tool, O_{ij}, the outer circumference, which actually machines, intersects the line $\overline{M_i N_i}$ in the point B_{ij}. The axis system related to position j of the tool centre in the axial level of machining, i will be ΣO_{ij} with the origin in O_{ij}, the y-axis the vector $\overline{O_{ij} A_i}$ and the x-axis the vector perpendicular to the vector $\overline{O_{ij} A_i}$. The axis system ΣO_{ij} is the current axis system. The coordinates of the points M_i and N_i are to be expressed in this axis system and the way to do this will be explained later.

B_{ij} is the intersection point of a circle with the centre in O_{ij} and radius R and the line $\overline{M_i N_i}$. According to [19] the coordinates of the points of intersection of a circle and a line are:

$$x = (B^2 x_1 - ABy_1 - AC + B\sqrt{Delta1})/(A^2 + B^2) \tag{11}$$

$$y = (A^2 y_1 - ABx_1 - BC - A\sqrt{Delta1})/(A^2 + B^2) \tag{12}$$

and

$$x = (B^2 x_1 - ABy_1 - AC - B\sqrt{Delta1})/(A^2 + B^2) \tag{13}$$

$$y = (A^2 y_1 - ABx_1 - BC + A\sqrt{Delta1})/(A^2 + B^2) \tag{14}$$

where

$$Delta1 = r_0^2 (A^2 + B^2) - (Ax_1 + By_1 + C)^2 \tag{15}$$

with $x_1 = x_{Oij} = 0.0$, $y_1 = y_{Oij} = 0.0$, $r_0 = R$

The coefficients of the line equation A, B, C can be calculated with the above formulas where the coordinates of the points M_i and N_i are expressed in the axis system ΣO_{ij}.

From the two intersection points, the point with positive coordinates is chosen (Figure 5.3).

$$B_{ij} = \max(x, y) \tag{16}$$

From position j, the outer circumferential side of the cutting tool moves to the point C_{ij} with the corresponding value of IPT, a, which is actually the next position of the tool, $j+1$. The centre of the tool moves accordingly from O_{ij} to O_{ij+1}.

For the position $j+1$, the outer circumference of the tool passes through the point C_{ij} and intersects line $\overline{M_i N_i}$ in the point B_{ij+1}. For the tool position $j+1$, an axis system ΣO_{ij+1} is constructed in the same manner the axis system for the position j has been defined.

The IPT at the centre of the tool can be now calculated. It is the arc s_{ij} between the two consecutive positions of the tool, O_{ij} and O_{ij+1}. The angle between the two y-axis, y_{ij} and y_{ij+1} is α_{ij}. For small angles α_{ij} the arc s_{ij} can be approximated with its corresponding chord s_{ij}.

The coordinates of the point C_{ij} expressed in the axis system ΣO_{ij} are:

$$x = \left(R + k_{(a)}a\right)\sin\theta_{ij} \tag{17}$$

$$y = \left(R + k_{(a)}a\right)\cos\theta_{ij} \tag{18}$$

where $k_{(a)}$ is given in Table 5.2 and depends on tool movement cases.

O_{ij+1} is the intersection point between two circles, one with the centre in A_i and radius r and the other with centre in C_{ij} and radius R (see Figure 5.3).

According to [19] the coordinates of the points of intersections of the two circles are:

$$x = \frac{(-[x_1 - x_2][r_1^2 - r_2^2 - x_1^2 + x_2^2] + [x_1 + x_2][y_1 - y_2]^2 + [y_1 - y_2]\sqrt{Delta2}]}{(2[x_1 - x_2]^2 + 2[y_1 - y_2]^2)} \tag{19}$$

$$y = \frac{(-[y_1 - y_2][r_1^2 - r_2^2 - y_1^2 + y_2^2] + [y_1 + y_2][x_1 - x_2]^2 - [x_1 - x_2]\sqrt{Delta2})}{(2[x_1 - x_2]^2 + 2[y_1 - y_2]^2)} \tag{20}$$

and

$$x = \frac{(-[x_1 - x_2][r_1^2 - r_2^2 - x_1^2 + x_2^2] + [x_1 + x_2][y_1 - y_2]^2 - [y_1 - y_2]\sqrt{Delta2})}{(2[x_1 - x_2]^2 + 2[y_1 - y_2]^2)} \tag{21}$$

$$y = \frac{(-[y_1 - y_2][r_1^2 - r_2^2 - y_1^2 + y_2^2] + [y_1 + y_2][x_1 - x_2]^2 + [x_1 - x_2]\sqrt{Delta2})}{(2[x_1 - x_2]^2 + 2[y_1 - y_2]^2)} \tag{22}$$

where

$$Delta2 = -([x_1 - x_2]^2 + [y_1 - y_2]^2 - [r_1 - r_2]^2)([x_1 - x_2]^2 + [y_1 - y_2]^2 - [r_1 + r_2]^2) \tag{23}$$

For *Movement 1* $x_1 = x_{Ai} = 0.0$ and $y_1 = y_{Ai} = r$ are the centre coordinates of the circle with the centre in A_i and $r_1 = r$ its radius and $x_2 = x_{Cij}$ and $y_2 = y_{Cij}$ are the centre coordinates of the circle with the centre in C_{ij} and $r_2 = R$ its radius.

Of the two intersection points, the actual is

$$O_{ij+1} = \min(x, y) \tag{24}$$

Because the coordinates of point O_{ij+1} are expressed in the axis system ΣO_{ij}, s_{ij} can be calculated by:

$$s_{ij} = \sqrt{(x_{Cij}^2 + y_{Cij}^2)} \tag{25}$$

From the cosine theorem [19]:

$$\alpha_{ij} = a\cos\left(1 - \frac{s_{ij}^2}{2r^2}\right) \tag{26}$$

Mapping involves calculating the coordinates of a point with respect to a coordinate system from known coordinates of the same point with respect to another coordinate system. In our case, the coordinates of the points M_i and N_i are calculated with respect to the axis system ΣO_{ij+1} from their coordinates with respect to axis system ΣO_{ij}. (Figure 5.7)

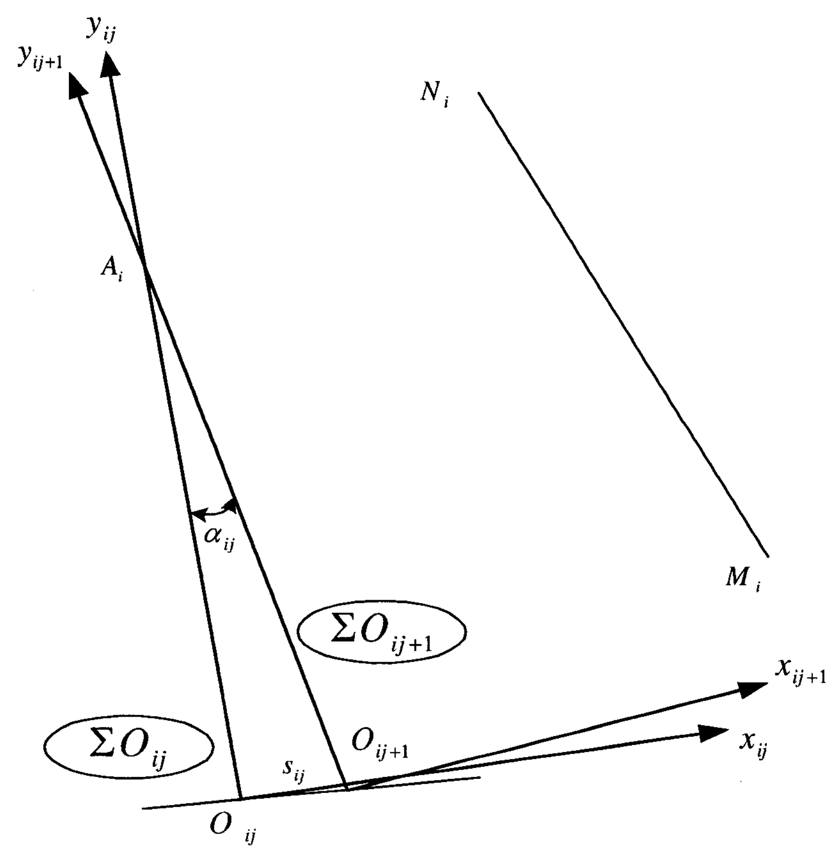


Figure 5.7 Axis systems transformation–Calculating the coordinates of the points M_i and N_i with respect to ΣO_{ij+1} from their known coordinates with respect to ΣO_{ij}

The transformation from the axis system j to the axis system $j+1$ is composed of a translation of the origin and a rotation with angle α_{ij}.

The translation matrix is:

$$T = \begin{bmatrix} 1 & 0 & -x_{Oij+1} \\ 0 & 1 & -y_{Oij+1} \\ 0 & 0 & 1 \end{bmatrix} \qquad (27)$$

The rotation matrix is:

$$R = \begin{bmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{28}$$

Finally the transformation matrix is a product of the translation and rotation matrices:

$$M = T * R = \begin{bmatrix} \cos\alpha & \sin\alpha & -x_{Oij+1} \\ -\sin\alpha & \cos\alpha & -y_{Oij+1} \\ 0 & 0 & 1 \end{bmatrix} \tag{29}$$

For the entire tool path of *Movement 1* the feed rate per tooth (IPT) at the tool centre, $s_{i0}, s_{i1}, \ldots\ldots, s_{ij}, s_{ij+1}, \ldots\ldots, s_{in}$ is calculated. The IPT at the tool centre is then used to calculate the feed rate with:

$$IPM = RPM * Z_{active} * IPT \tag{30}$$

where *RPM* is the rotational speed of the spindle, $Z_{active} = 10$ is the number of active teeth that do the machining and *IPT* is the feed rate per tooth at tool centre.

All the above considerations are made for *Movement 1*. These can be applied to the other three tool movements.

In Table 5.2 the values of the variables of each of the four tool movements are shown.

Table 5.2 The values of the variables for the four tool movements

Movement	CIRCLE RADIUS				$k_{(a)}$
	Y_{Ai}	r_0	r_1	r_2	
1	r	R	r	R	1
2	R	R	R	R	1
3	R	r	R	r	-1
4	r	r	r	r	-1

Table 5.3 shows the correspondent transformation matrices for each of the four tool movements.

Table 5.3 The correspondent transformation matrices for the four tool movements

Movement	Transformation matrix
1	$\begin{bmatrix} \cos\alpha & \sin\alpha & -x_{Oij+1} \\ -\sin\alpha & \cos\alpha & -y_{Oij+1} \\ 0 & 0 & 1 \end{bmatrix}$
2	$\begin{bmatrix} \cos\alpha & -\sin\alpha & -x_{Oij+1} \\ \sin\alpha & \cos\alpha & -y_{Oij+1} \\ 0 & 0 & 1 \end{bmatrix}$
3	$\begin{bmatrix} \cos\alpha & \sin\alpha & -x_{Oij+1} \\ -\sin\alpha & \cos\alpha & -y_{Oij+1} \\ 0 & 0 & 1 \end{bmatrix}$
4	$\begin{bmatrix} \cos\alpha & -\sin\alpha & -x_{Oij+1} \\ \sin\alpha & \cos\alpha & -y_{Oij+1} \\ 0 & 0 & 1 \end{bmatrix}$

The following values of the desired and constant feed per tooth on the circumference of the tool a = *0,1016 mm/tooth (0.004 in/tooth)*, the outer radius of the tool R = *128,58 mm (5.06205 in)* and the inner radius of the tool r = *112,7 mm (4.43706 in)* are used for the numerical application.

For every of the four tool movements, a sheet in Microsoft Excel® is created and the formulas of cutting conditions control method of roughing integrally bladed rotors with cup mill cutters are developed. Finally in a last sheet, the result of the calculus from the previous sheets is analyzed.

5.3 Results analysis of the cutting conditions method of roughing integrally bladed rotors with cup mill cutters

In order to have a stable milling process, a certain and constant value of the feed per tooth (IPT) on the circumference of the tool is desired. Due to the tool dimensions and particularities of the planar tool movements, the IPT at the tool center is different from the IPT on the circumference of the tool. The IPT at the tool center is calculated for a constant IPT on the tool circumference for the four tool movements in two consecutive axial levels of machining. Then the IPT at tool center is used to calculate the feed rate (IPM), which could be actually controlled in the NC mill program. A complete table with the final results is presented.

The analysis of the results of the numerical application is actually the analysis of the influence of the constant IPT on the circumference of the tool on the feed rate for the four tool movements in two consecutive axial levels of machining (Figure 5.8).

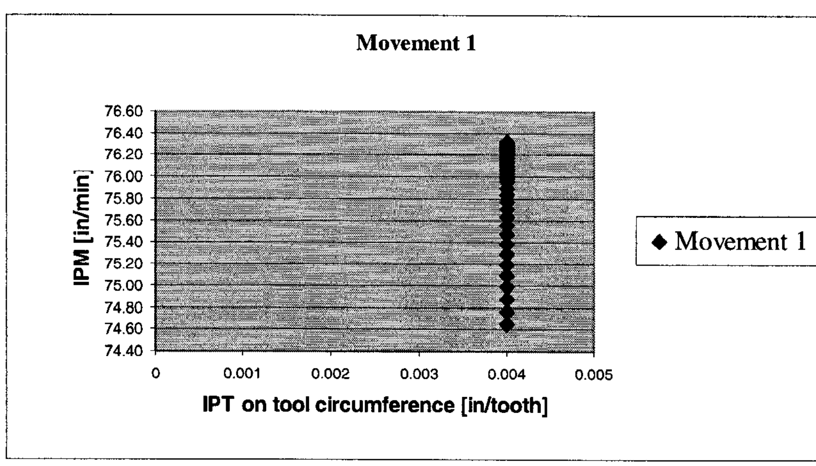


Figure 5.8 The influence of IPT on tool circumference on feed rate for the four movements of the cutting tool in two consecutive axial levels of machining

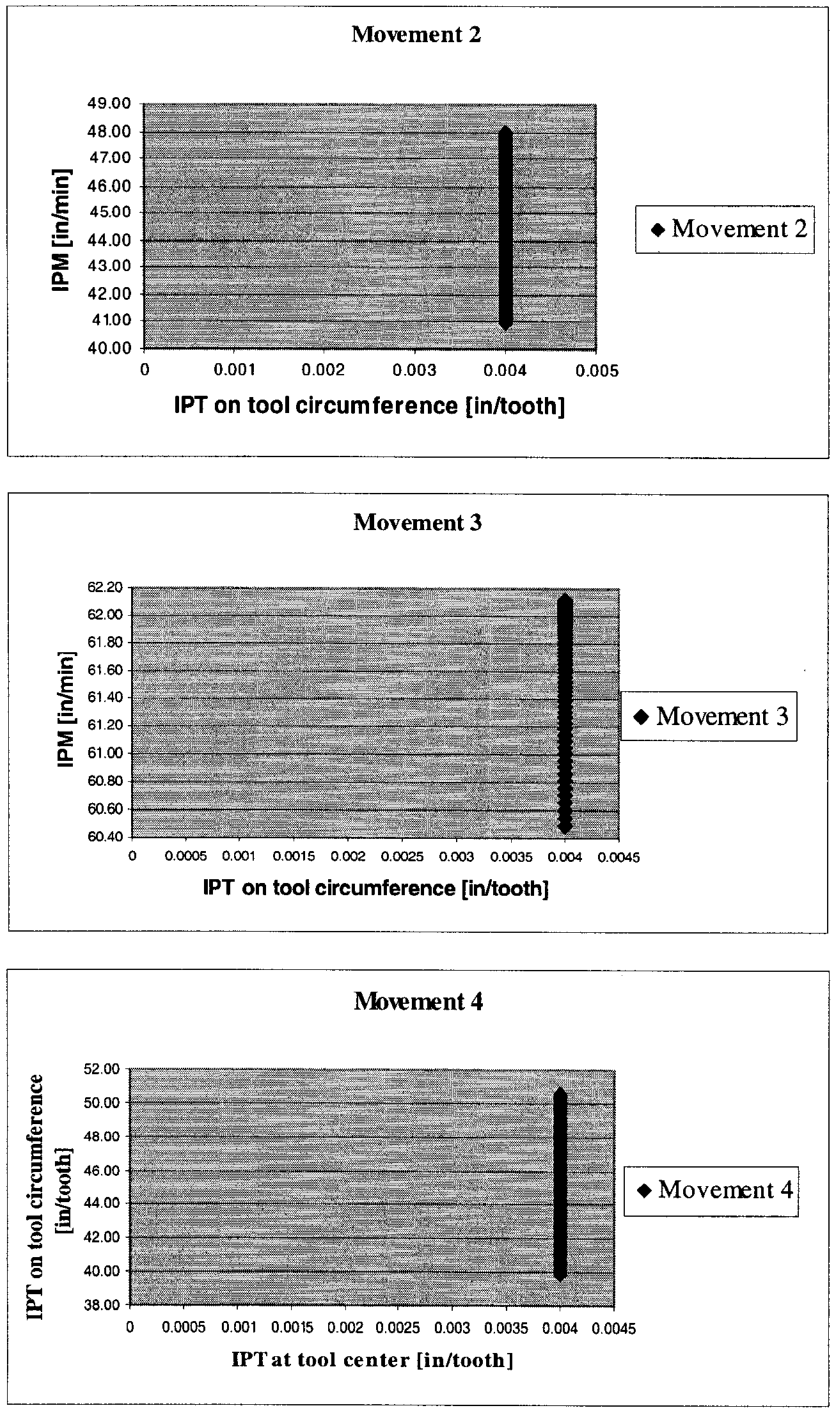


Figure 5.8 The influence of IPT on tool circumference on feed rate for the four movements of the cutting tool in two consecutive axial levels of machining (continuing)

Table 5.4 contains the specific elements of the four movements, the desired IPT on tool circumference and the variation of the feed rate for each movement.

Table 5.4 The variation of feed rate with the IPT on tool circumference for the four tool movements in two consecutive axial levels of machining

Tool movement	Point of rotation	Machining side of the tool	IPT on tool circumference [in/tooth]	IPM [in/min]
1	Interior	Outer	0.004	74.6 - 76.0
2	Exterior	Outer	0.004	41.0 - 48.0
3	Exterior	Inner	0.004	60.5 - 62.0
4	Interior	Inner	0.004	40.0 - 50.6

When the cup mill cutter machines with the side that is opposite of the point of rotation (Movement 1 and Movement 3), then there is a small variation of the feed rate. For these two movements it can be concluded that the milling process is quasi-stable and by using a medium value of feed rate between the limit values of the feed rate variation, the IPT on tool circumference will be quasi-constant.

Another result comes out from the situation when the rotation point is on the same machining side of the tool (Movement 2 and Movement 4). The feed rate variation is bigger and if it is possible corresponding feed rate variation should be introduced in the NC mill program in order to reach the goal of a constant IPT on tool circumference and a stable milling process.

CHAPTER 6

THE MANUFACTURING TEST

In order to validate the method of roughing the integrally bladed rotors (IBRs) with cup mill cutters, a manufacturing test has been performed. The stock is an aluminum copy of the titanium alloy stock of the chosen integrated bladed rotor part on which the roughing method has been developed. The cup mill cutter is the actual tool that has been used to develop the method of roughing IBRs (Figure 6.1).

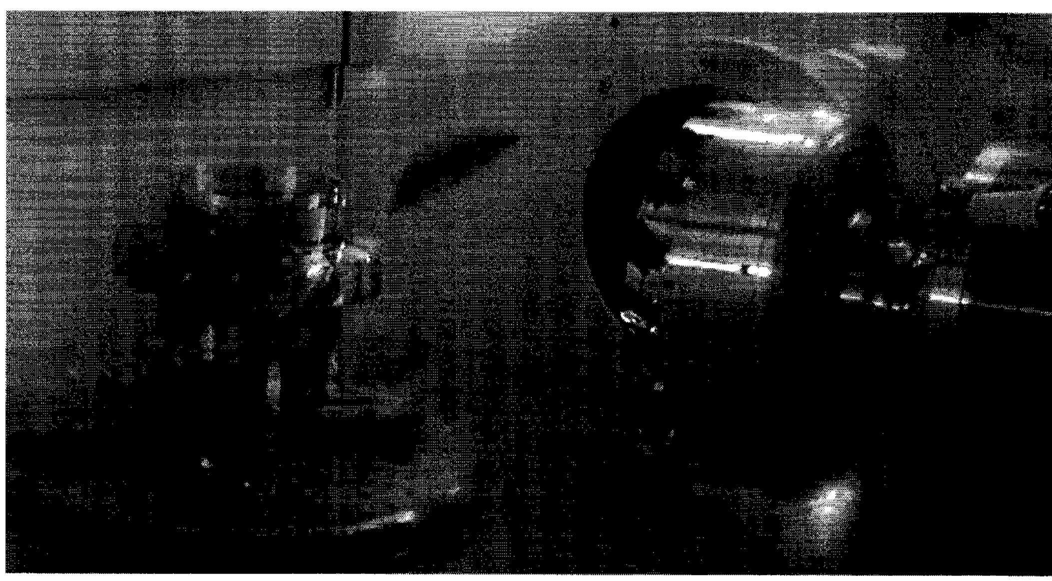


Figure 6.1 The aluminum stock of the IBR part and the cup mill cutter on the 5-axis machine

The NC mill program (see Annexes) is based on the developed method of roughing and it is used to mill the IBR part. The manufacturing test has been performed on a MITSUI SEIKI HU80A-5x 5-axis machine. A picture of a similar, but of a smaller capacity machine is shown in Figure 6.2.

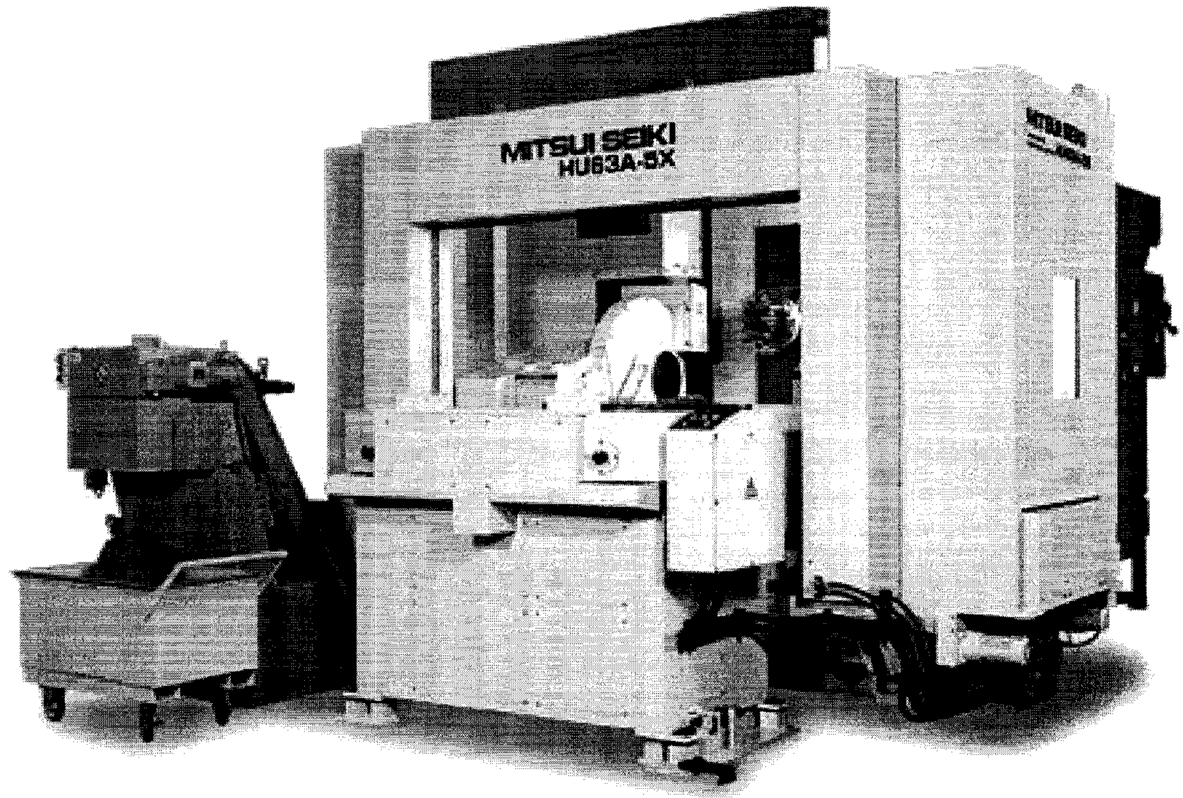


Figure 6.2 The 5-axis machine Mitsui Seiki HU63A-5x
[http://www.mitsuiseiki.co.jp/english/machine/top.htm]

The Mitsui Seiki HU80A-5x is a horizontal machining center. The machine configuration (YZ/XBA - see Figure 6.3) is with a horizontal pallet with a possibility of tilting (A-axis), a linear axis (X-axis) and a rotary axis (B-axis). The spindle can move along the linear axis (Y-axis). It is perpendicular to a vertical column with one linear axis (Z-axis).

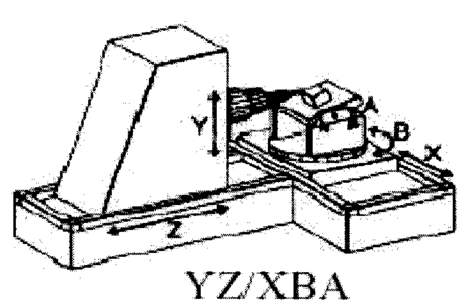


Figure 6.3 The configuration of the 5-axis machine Mitsui Seiki HU80A-5x

Some of the features of Mitsui Seiki HU80A-5x 5-axis machine are presented in Table 6.1.

Table 6.1 Specifications of Mitsui Seiki HU80A-5x machine [http://www.mitsuiseiki.co.jp/english/machine/top.htm]

Item	HU80A-5X
X, Y, Z-axis stroke [mm]	1,200x1,000x1,050
A-axis tilting angle	+5°to -95°
Pallet size [mm]	800x800
Max. part size (Diameter x height) [mm]	Φ1,200x1,000
Permissible load (Evenly spread, A-axis in horizontal) [kg]	1,200
Pallet index resolution [degree]	0.001
Spindle speed [min^{-1}]	15-6,000
Spindle inner taper [ISO 7/24]	No.50
Rapid(X, Y, Z-axis) [m/min]	X: 12, Y & Z: 24
B-axis Rapid [deg./min]	3,600
A-axis Rapid [deg./min]	2,160
Number of tools stored on ATC	60 tools
Number of pallets on APC	OP.
Position detector (X, Y, Z-axis)	Linear scale
B-axis position detector	Scale feedback
A-axis position detector	Scale feedback
NC unit	FANUC 16i-M

During the machining of the 4 slots of the integrally bladed rotor part, the coolant has been used all the time. The approach of the cutting tool has been at feed rate of 1,27 m/min (50 in/min). The machining process has started with a feed rate of 0,381m/min (15 in/min). During the machining, for the axial movement of the cup mill cutter between two consecutive axial levels of machining, the operator has changed the feed rate to 0,254 m/min (10 in/min). This has been necessary due to a much higher feed rate, which has caused strong vibrations in the system. Some pictures taken during the machining test are shown in the Figure 6.4 and 6.5.

In Figure 6.4, the cup mill cutter is shown halted in an intermediate position of machining one slot of the integrally bladed rotor part.

Figure 6.4 The manufacturing test of roughing the IBR part with the cup mill cutter– the cup mill cutter stopped during machining of one slot of the IBR part

In Figure 6.5 the cup mill cutter is approaching the IBR part and coolant is on.

Figure 6.5 The approach of the cup mill cutter

The resulting chip is shown in Figure 6.6

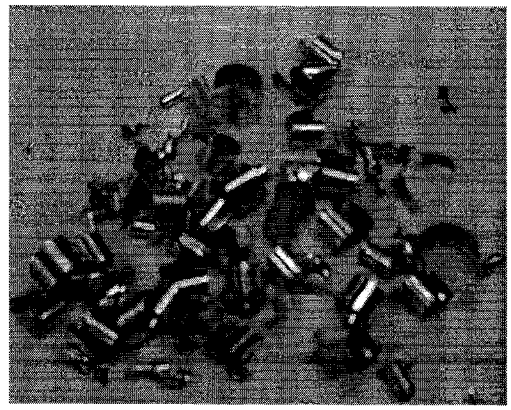


Figure 6.6 The chip produced during the machining test of the roughing method of the IBR part with the cup mill cutter

The integrally rotor part after machining is shown in Figure 6.7.

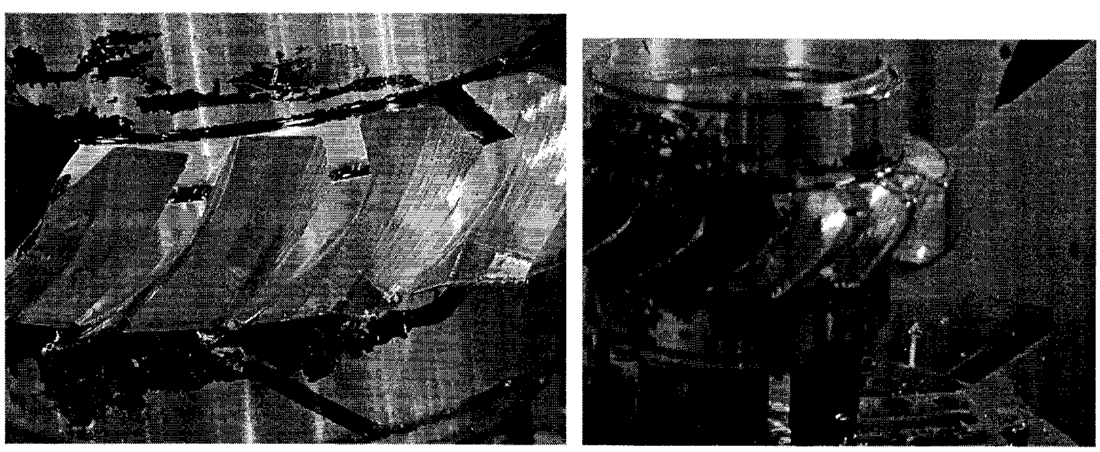
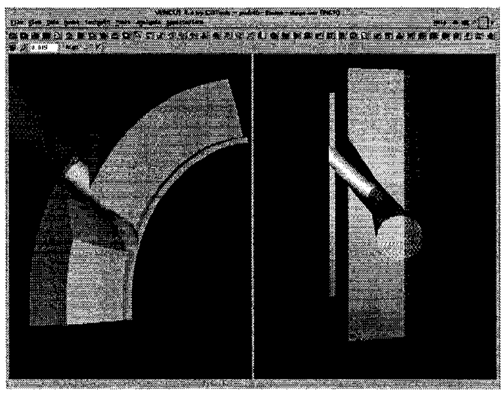


Figure 6.7 The integrally rotor part after machining test

It is estimated that a large amount of material has been removed, which is equivalent to the removable material during the current method of flank milling. The difference is significant in terms of productivity. Figure 6.8 shows the milling time for the current method compared with the new method of roughing.

CURRENT METHOD	NEW METHOD
(Titanium machining)	(Aluminum machining)
1000 RPM & 3 active teeth	100 RPM & 10 active teeth
3.5 IPM	15-20 IPM



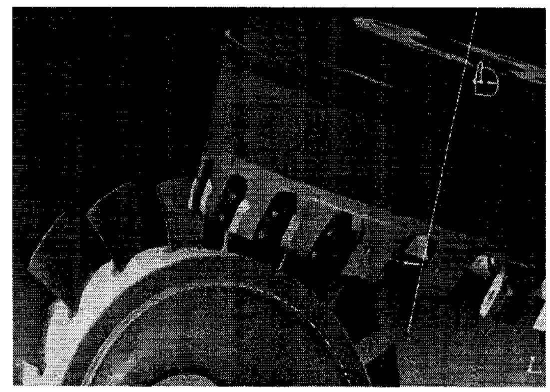


Figure 6.8 Roughing time of current and new method

The machining test confirms what the digital simulation already confirmed that there are no collisions between the cup mill cutter and the IBR part stock. The productivity could be improved significantly. The milling process is stable because at least two teeth are in contact with the material. The robustness of the cup mill cutter avoids tool deflection.

The resulting chip is still too wide (Figure 6.6), which means that special inserts should be employed. These inserts could reduce the dimensions of the chip and consequently reduce the teeth load.

CONCLUSIONS

A new method of roughing integrally bladed rotors with new special cutting tools –cup mill cutters has been developed. Based on the developed method, a program, which generates automatically the tool path is created. The tool path is used then to generate the NC mill program, which is digitally simulated. The NC tool path data is used to validate the method by the means of a manufacturing test. A cutting conditions control method has been defined on the developed method of roughing and some results are presented.

It is now proved that cup mill cutters can be used for machining complex parts like integrally bladed rotors.

The productivity for the roughing process of the integrally bladed rotor part with the cup mill cutter can be increased significantly with the gain of a more robust milling process.

Using interchangeable inserts may reduce the cost of tooling.

Moreover it proves that the method can be implemented right away on the shop floor without much investment.

Some immediate developments are suggested:

- A machining test in titanium alloy is necessary in order to evaluate the method on the actual integrally bladed rotor material
- New cup mill cutters should be designed to improve cutting conditions and limit the tool load
- New inserts should be employed in order to limit the tool load
- The method must be verified on other integrally bladed rotor parts (IBRs) as part of the concept of the generic developed method of roughing IBRs
- The developed method of cutting conditions control may be implemented and used in defining the milling parameters.

Some further developments could be:

- Development of cup mill cutters for semi-finishing
- Development of a new method of semi-finishing airfoil blades of integrally bladed rotors with cup mill cutters
- Design and development of multi flute ball end mills for the finishing operation

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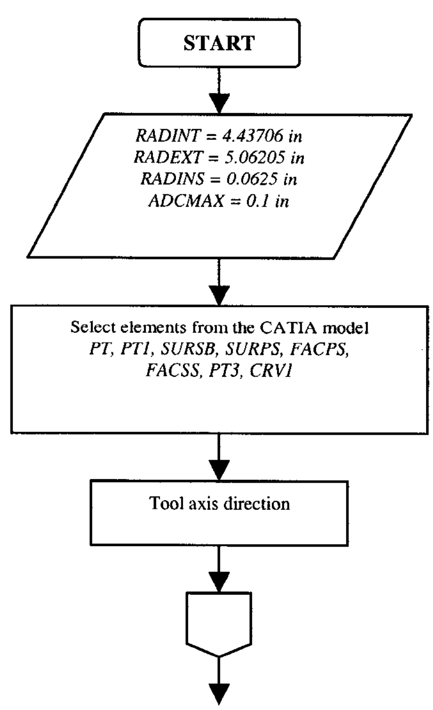
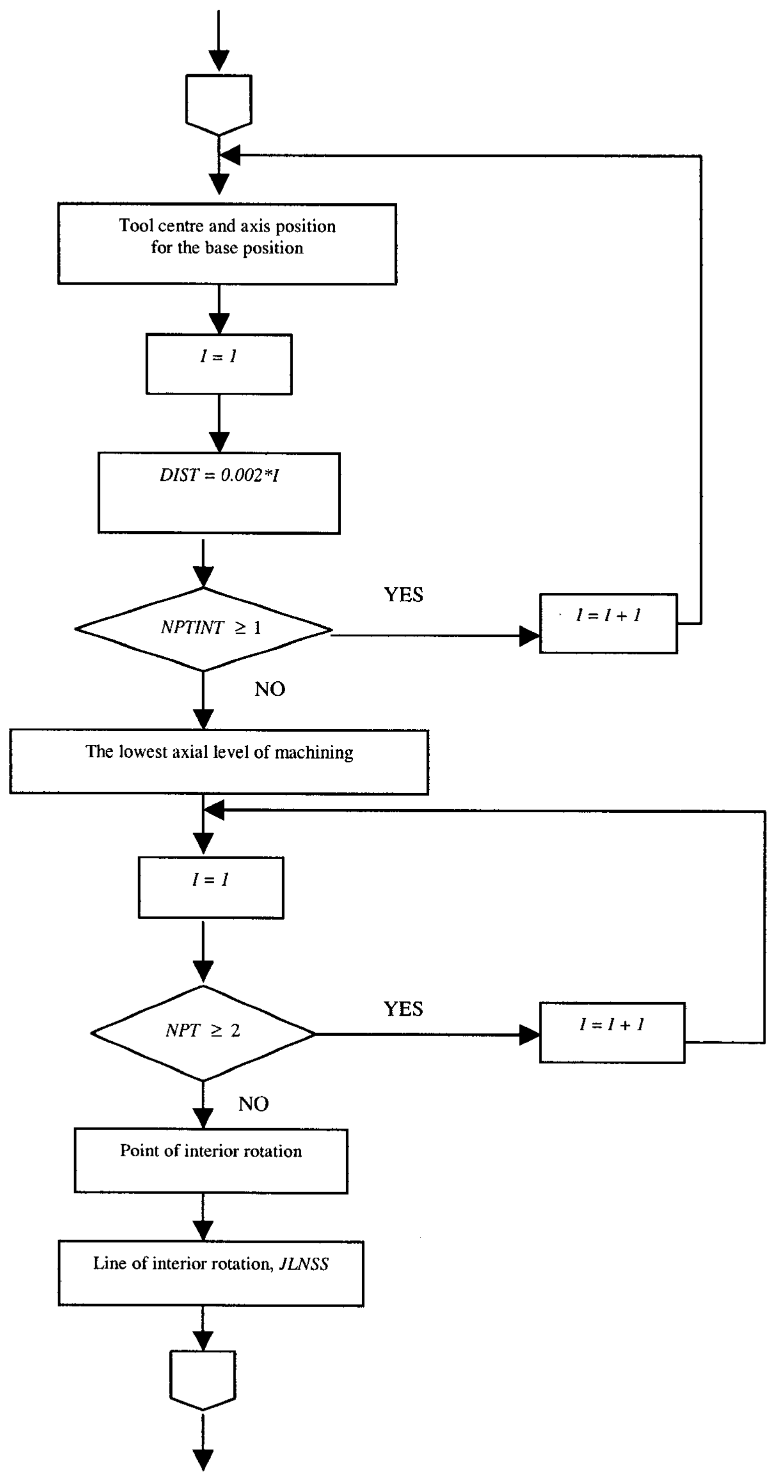
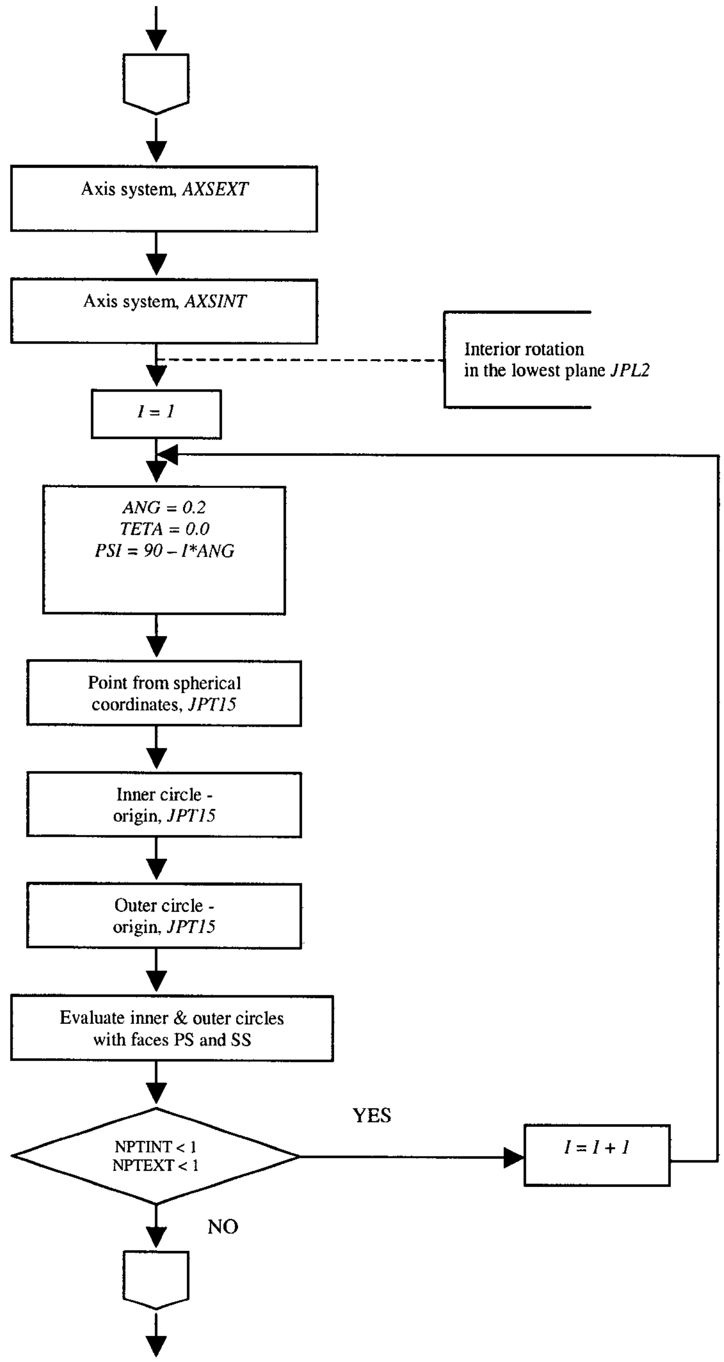
ANNEXES

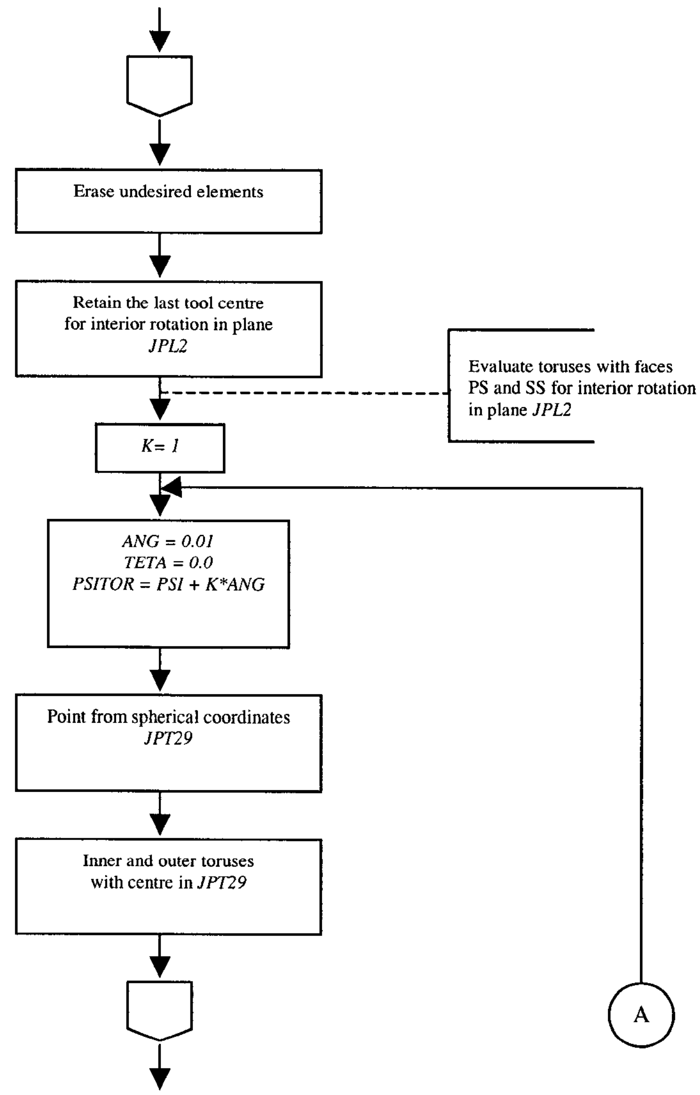
1. THE FLOWCHART OF THE DEVELOPED PROGRAM OF ROUGHING THE INTEGRALLY BLADED ROTOR PART USING THE CUP MILL CUTTER



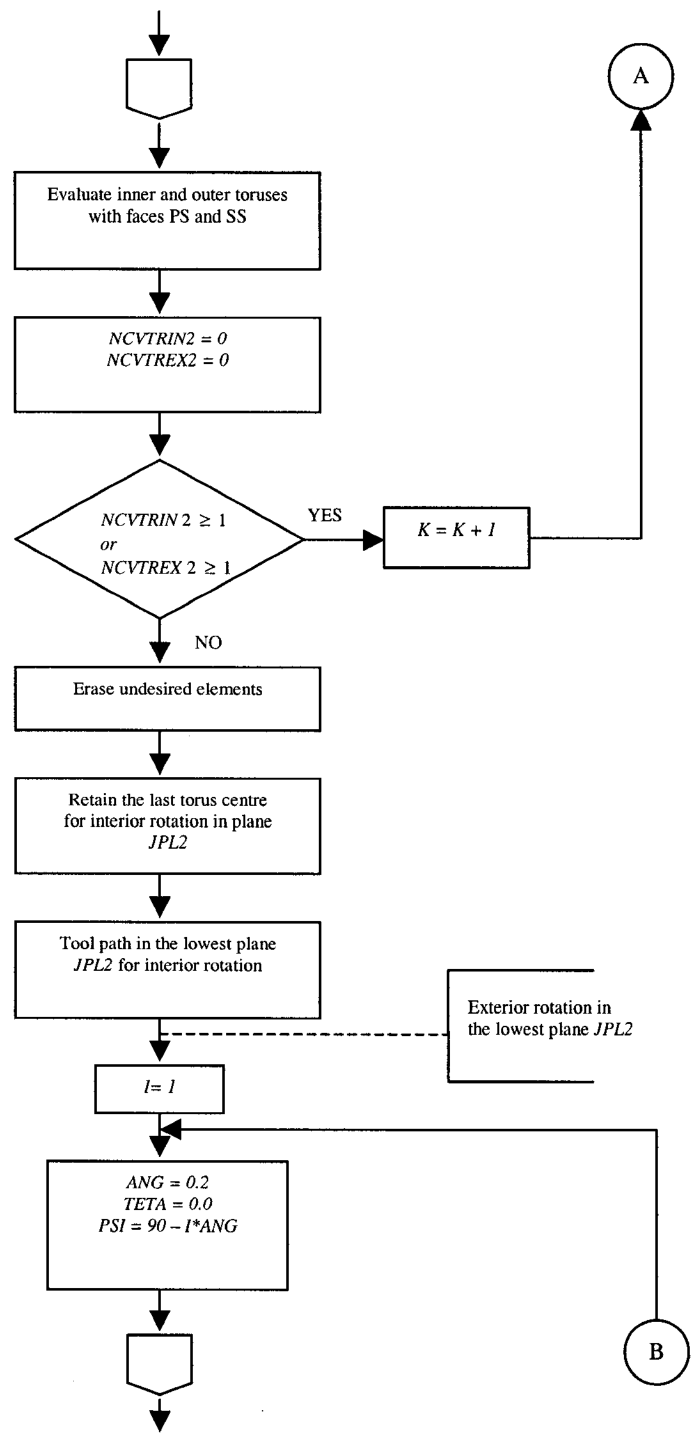

Tool centre and axis position
for the base position
I = I
DIST = 0.002*I
NPTINT ≥ 1
YES
I = I + I
NO
The lowest axial level of machining
I = I
NPT ≥ 2
YES
I = I + I
NO
Point of interior rotation
Line of interior rotation, JLNSS



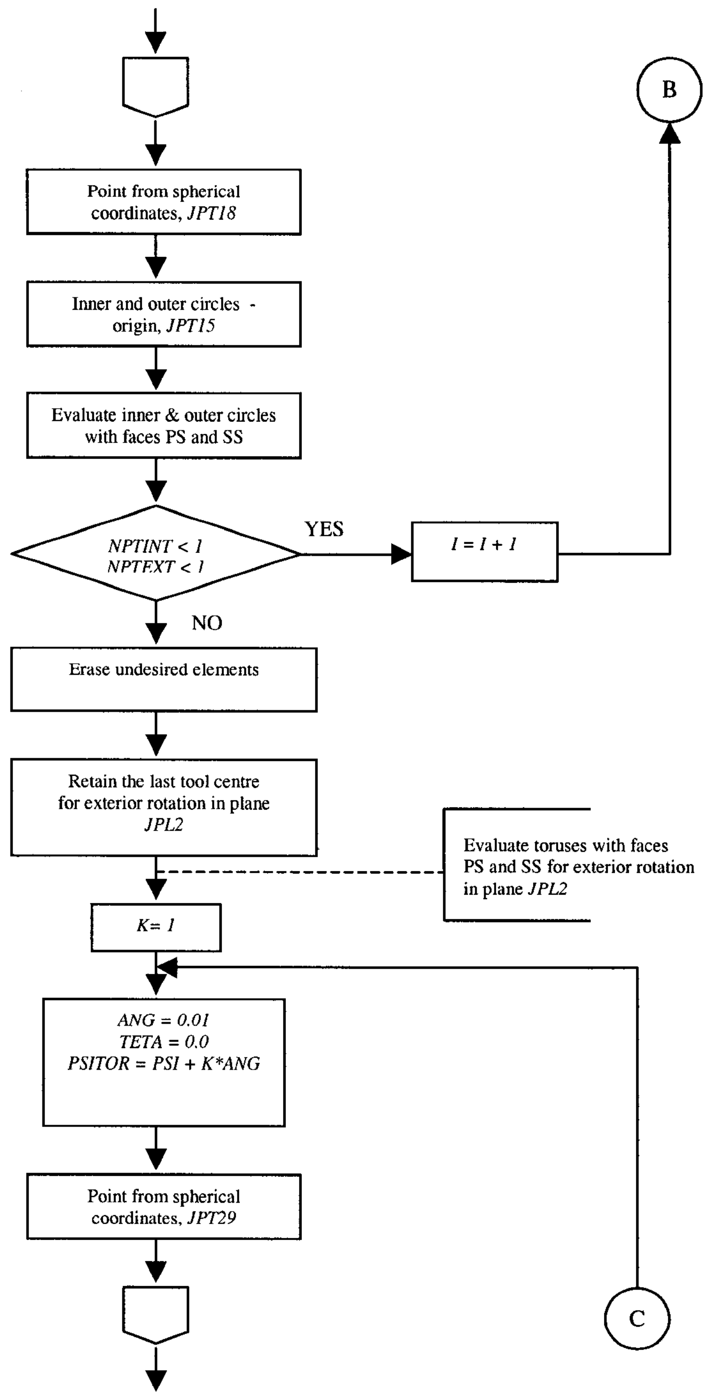
Axis system, *AXSEXT*
Axis system, *AXSINT*
Interior rotation in the lowest plane *JPL2*
I = 1
ANG = 0.2
TETA = 0.0
*PSI = 90 – I*ANG*
Point from spherical coordinates, *JPT15*
Inner circle - origin, *JPT15*
Outer circle - origin, *JPT15*
Evaluate inner & outer circles with faces PS and SS
NPTINT < 1
NPTEXT < 1
YES
I = I + 1
NO

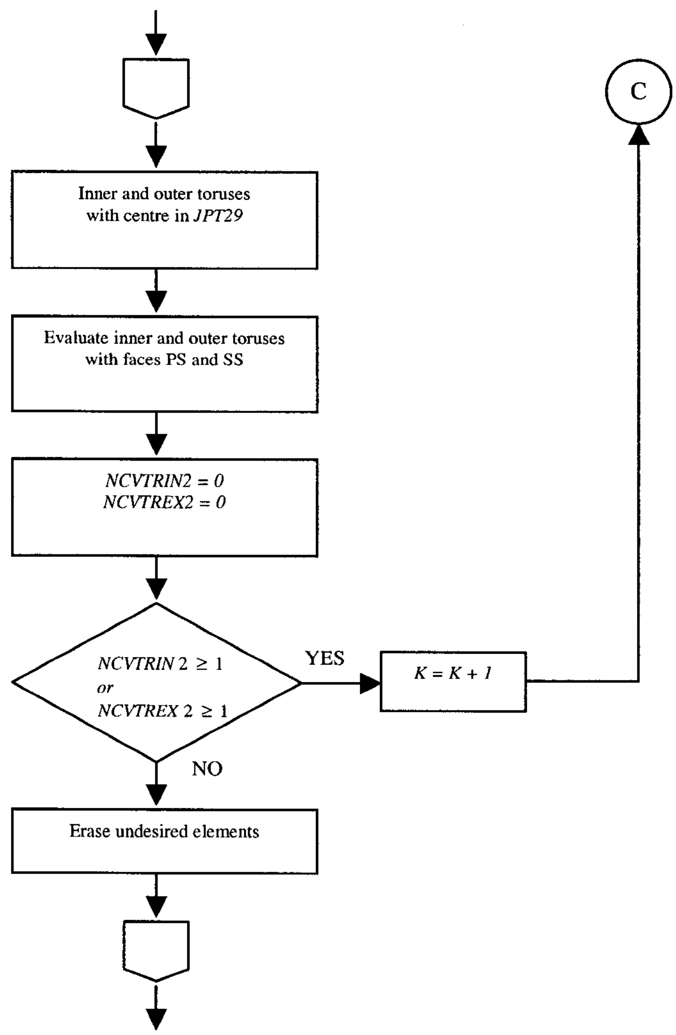


Erase undesired elements
Retain the last tool centre for interior rotation in plane JPL2
Evaluate toruses with faces PS and SS for interior rotation in plane JPL2
K= 1
ANG = 0.01
TETA = 0.0
PSITOR = PSI + K*ANG
Point from spherical coordinates JPT29
Inner and outer toruses with centre in JPT29
A

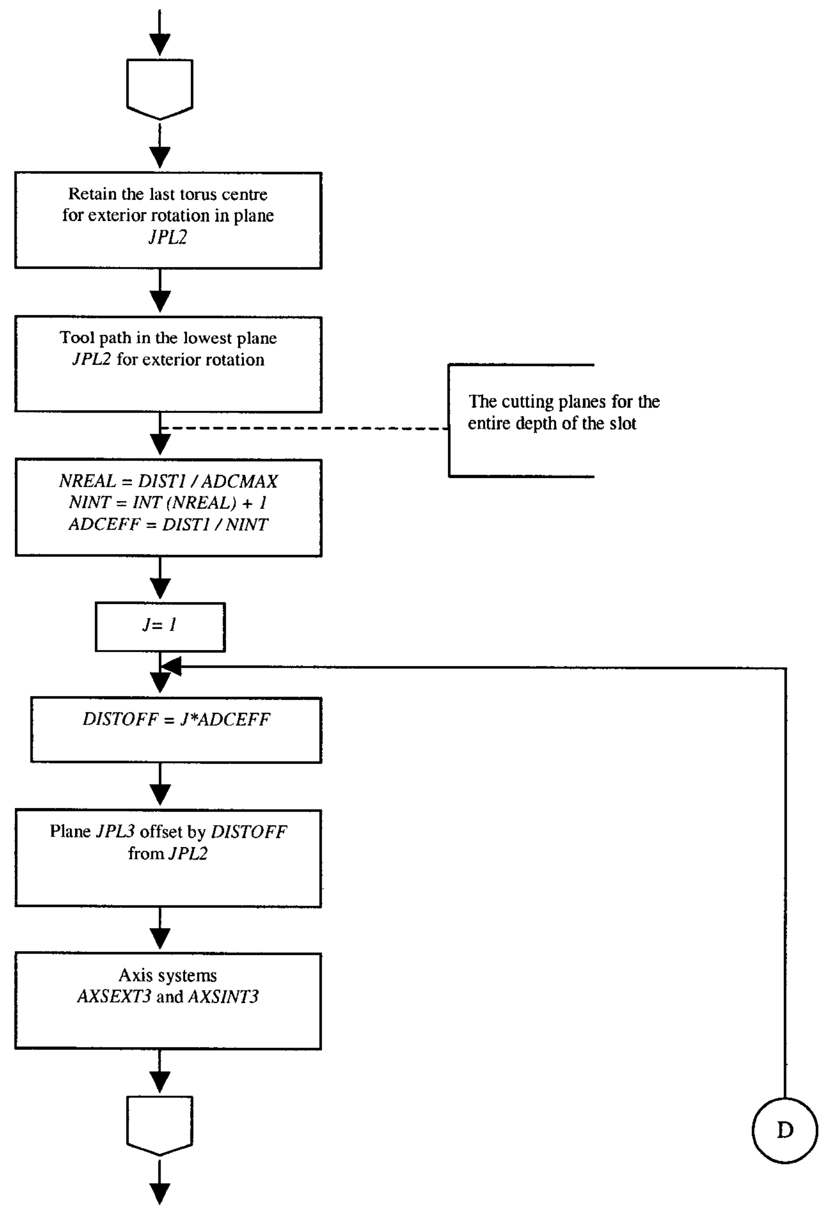


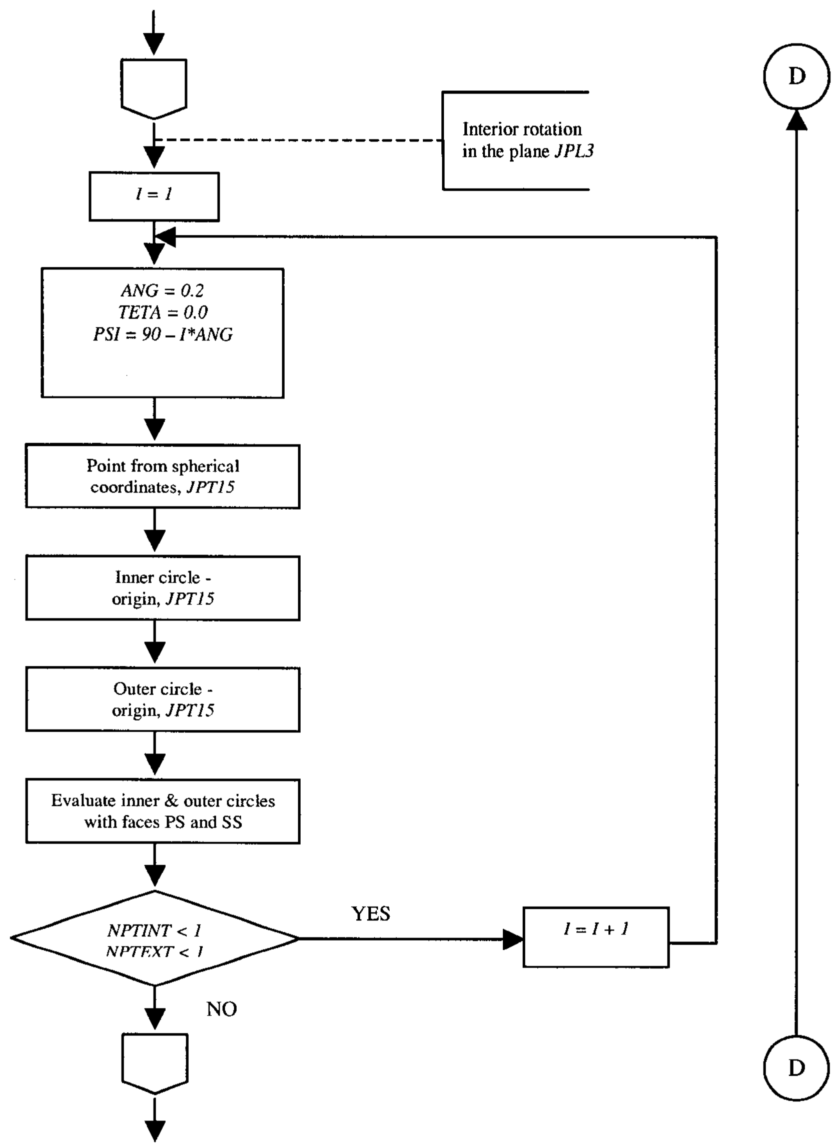
A
Evaluate inner and outer toruses with faces PS and SS
NCVTRIN2 = 0
NCVTREX2 = 0
NCVTRIN 2 ≥ 1
or
NCVTREX 2 ≥ 1
YES
K = K + 1
NO
Erase undesired elements
Retain the last torus centre for interior rotation in plane JPL2
Tool path in the lowest plane JPL2 for interior rotation
Exterior rotation in the lowest plane JPL2
I= 1
ANG = 0.2
TETA = 0.0
PSI = 90 – I*ANG
B

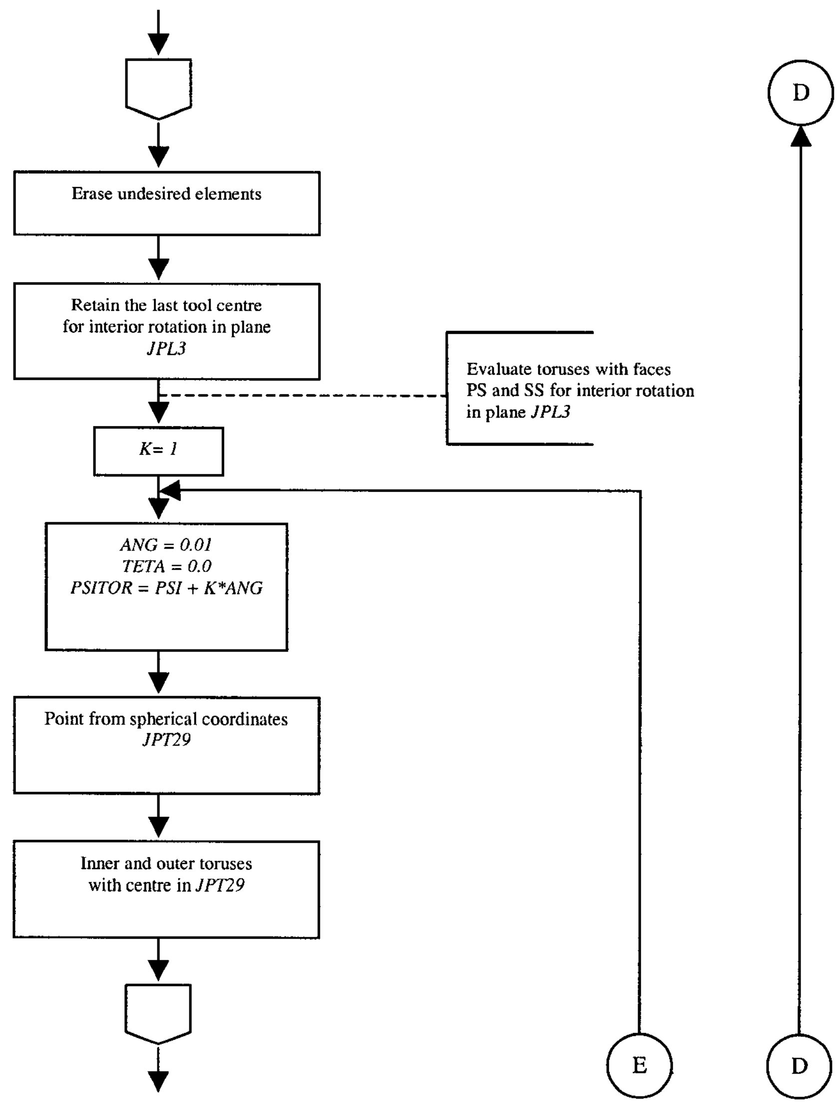

B
Point from spherical coordinates, JPT18
Inner and outer circles - origin, JPT15
Evaluate inner & outer circles with faces PS and SS
NPTINT < 1
NPTEXT < 1
YES
I = I + 1
NO
Erase undesired elements
Retain the last tool centre for exterior rotation in plane JPL2
Evaluate toruses with faces PS and SS for exterior rotation in plane JPL2
K= 1
ANG = 0.01
TETA = 0.0
PSITOR = PSI + K*ANG
Point from spherical coordinates, JPT29
C

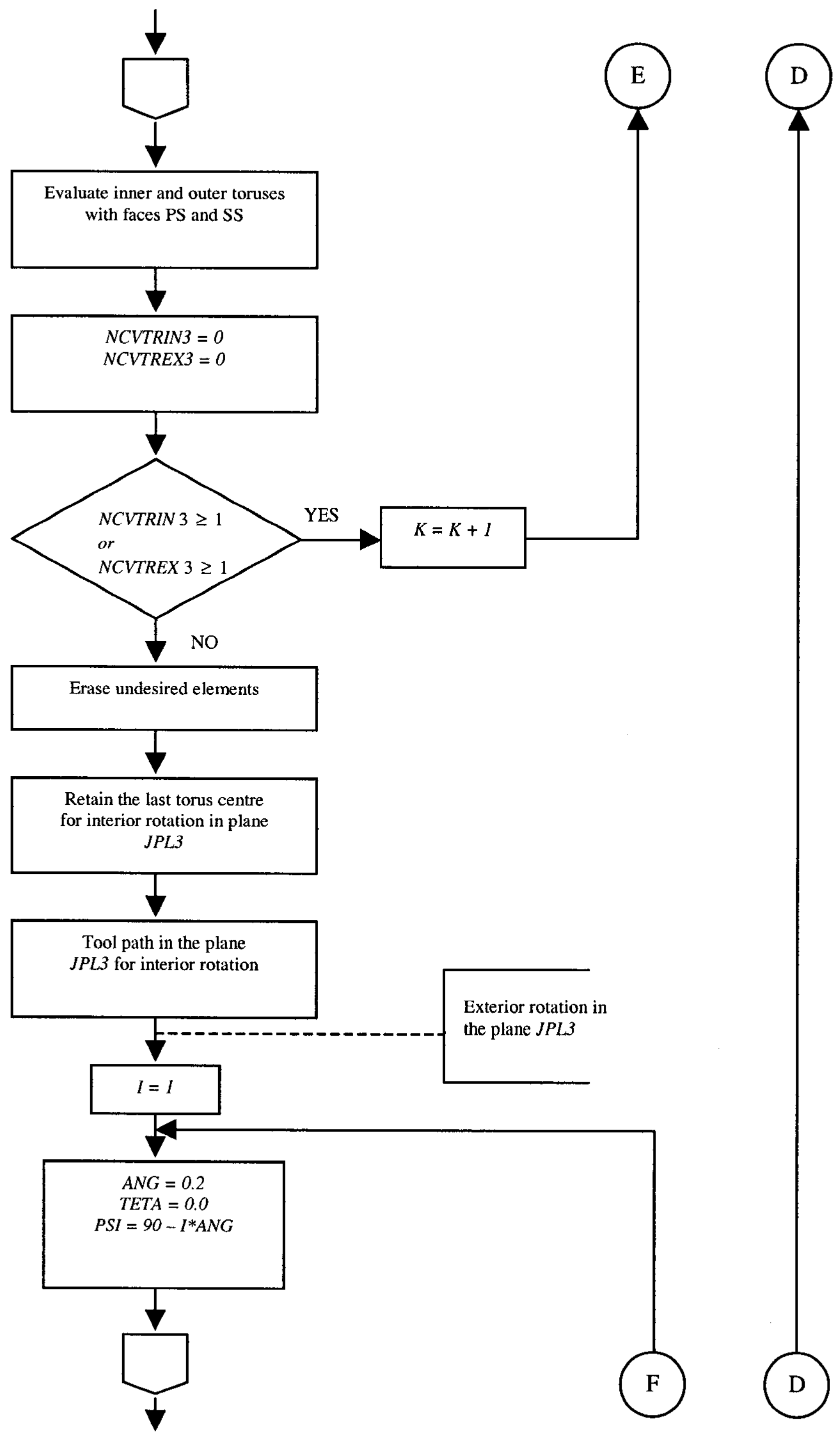


C
Inner and outer toruses with centre in *JPT29*
Evaluate inner and outer toruses with faces PS and SS
NCVTRIN2 = 0
NCVTREX2 = 0
NCVTRIN 2 ≥ 1 *or* *NCVTREX* 2 ≥ 1
YES
K = K + 1
NO
Erase undesired elements

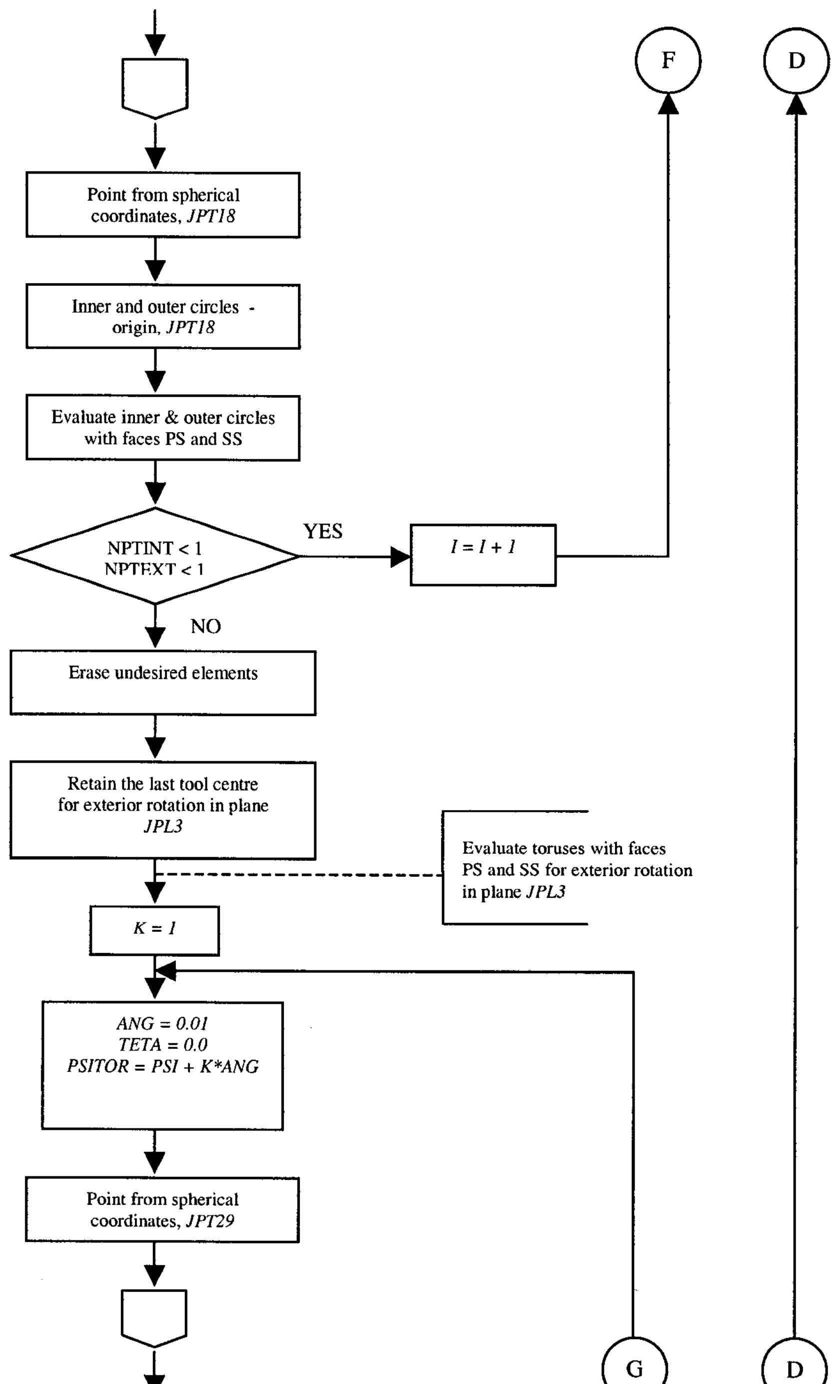

Retain the last torus centre
for exterior rotation in plane
JPL2
Tool path in the lowest plane
JPL2 for exterior rotation
The cutting planes for the
entire depth of the slot
NREAL = DIST1 / ADCMAX
NINT = INT (NREAL) + 1
ADCEFF = DIST1 / NINT
J= 1
DISTOFF = J*ADCEFF
Plane JPL3 offset by DISTOFF
from JPL2
Axis systems
AXSEXT3 and AXSINT3
D


D
Interior rotation
in the plane JPL3
I = 1
ANG = 0.2
TETA = 0.0
PSI = 90 – I*ANG
Point from spherical
coordinates, JPT15
Inner circle -
origin, JPT15
Outer circle -
origin, JPT15
Evaluate inner & outer circles
with faces PS and SS
NPTINT < 1
NPTEXT < 1
YES
I = I + 1
NO
D

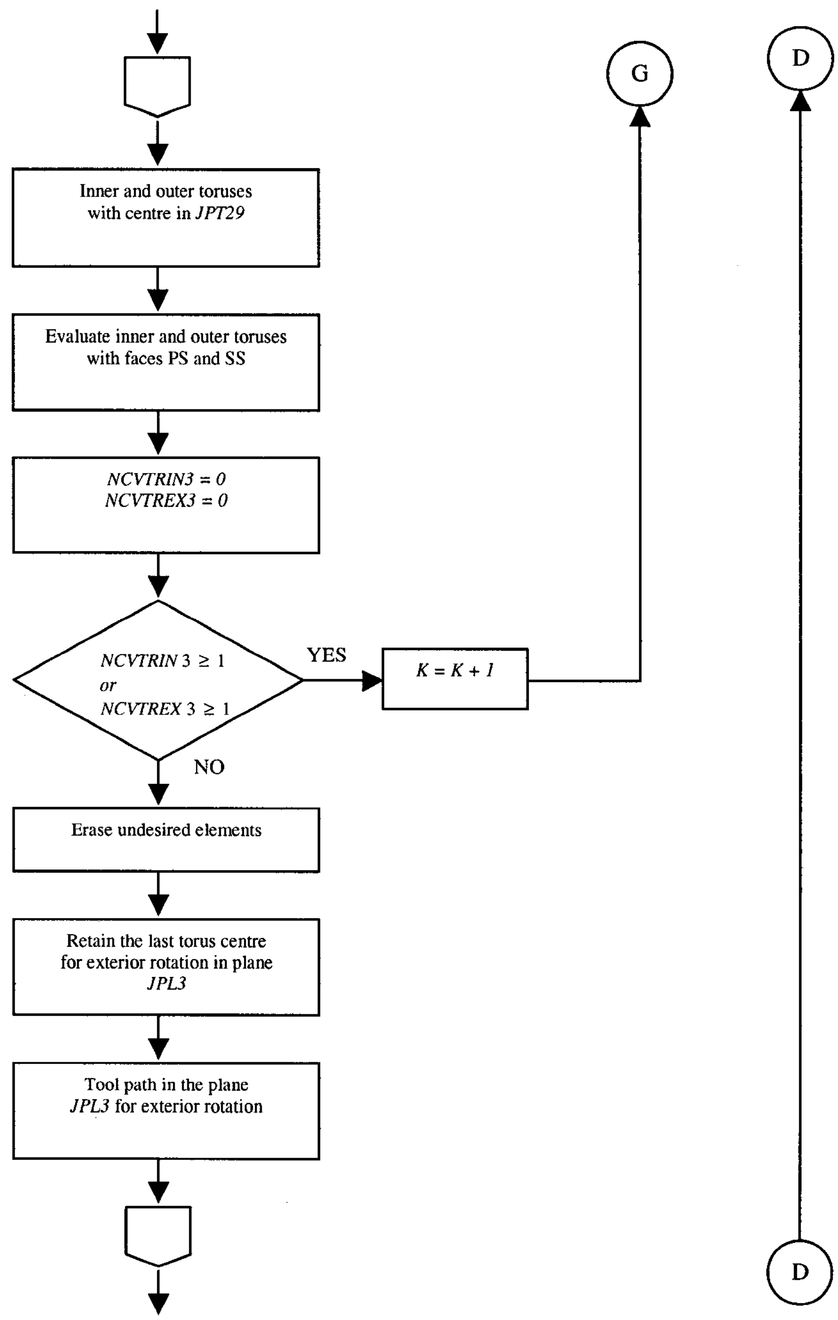

D
Erase undesired elements
Retain the last tool centre
for interior rotation in plane
JPL3
Evaluate toruses with faces
PS and SS for interior rotation
in plane JPL3
K= 1
ANG = 0.01
TETA = 0.0
PSITOR = PSI + K*ANG
Point from spherical coordinates
JPT29
Inner and outer toruses
with centre in JPT29
E
D

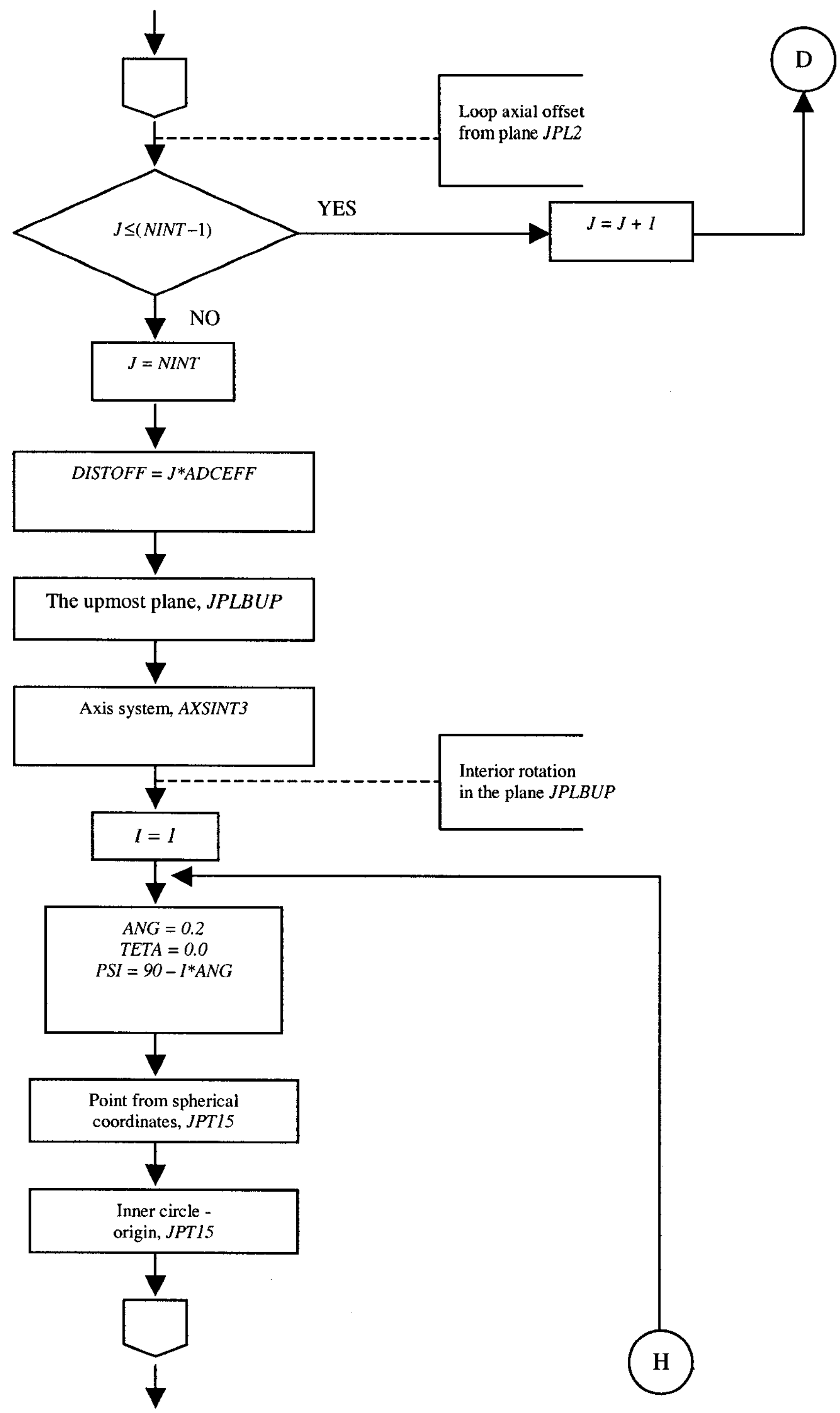


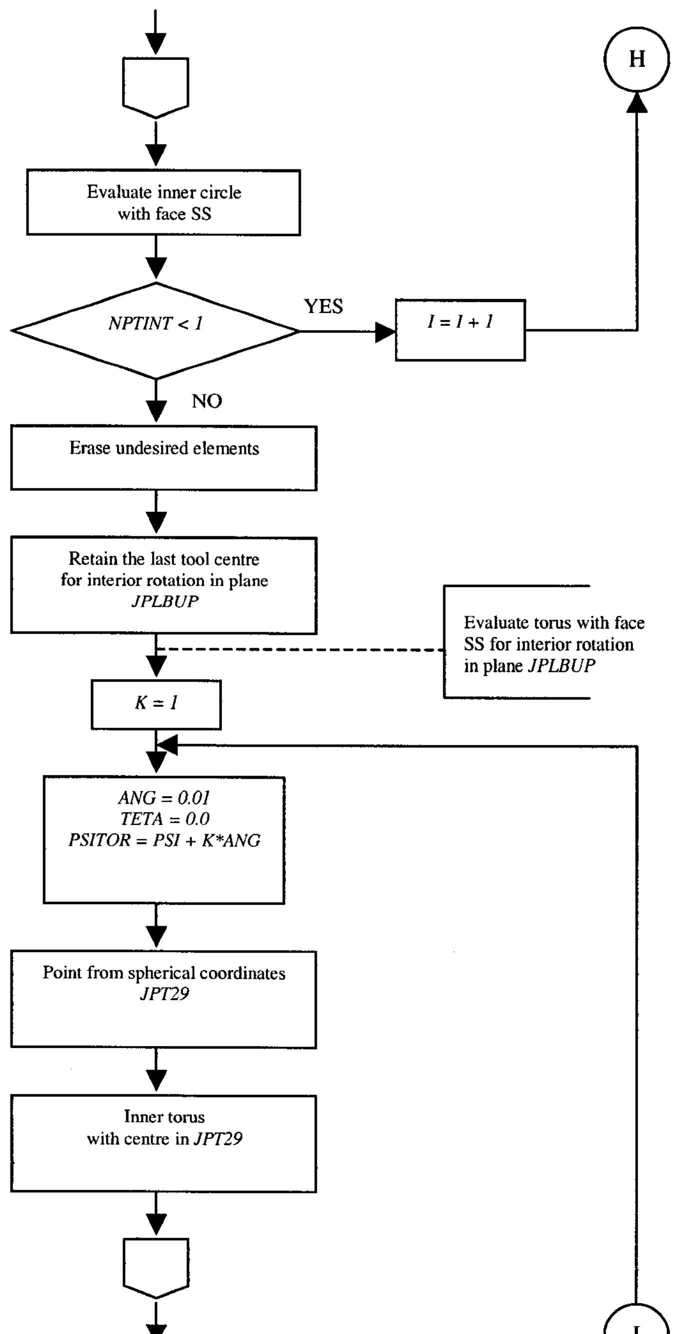
E
D
Evaluate inner and outer toruses with faces PS and SS
NCVTRIN3 = 0
NCVTREX3 = 0
NCVTRIN 3 ≥ 1 or NCVTREX 3 ≥ 1
YES
K = K + 1
NO
Erase undesired elements
Retain the last torus centre for interior rotation in plane JPL3
Tool path in the plane JPL3 for interior rotation
Exterior rotation in the plane JPL3
I = 1
ANG = 0.2
TETA = 0.0
PSI = 90 – I*ANG
F
D

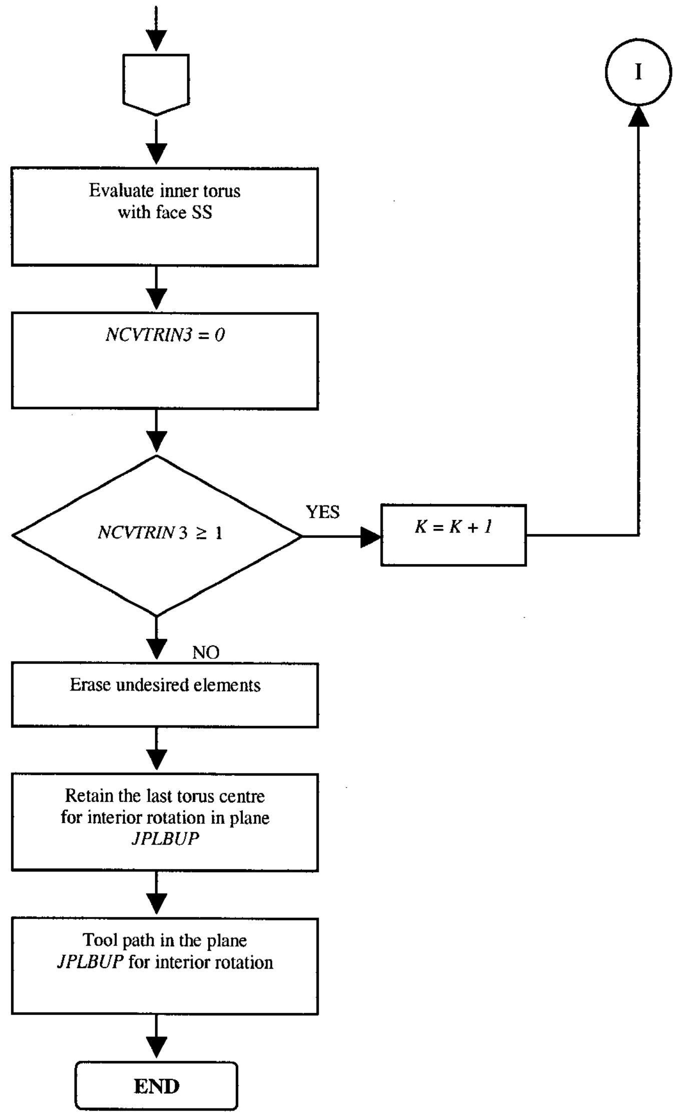


F
D
Point from spherical coordinates, JPT18
Inner and outer circles - origin, JPT18
Evaluate inner & outer circles with faces PS and SS
NPTINT < 1
NPTEXT < 1
YES
I = I + 1
NO
Erase undesired elements
Retain the last tool centre for exterior rotation in plane JPL3
Evaluate toruses with faces PS and SS for exterior rotation in plane JPL3
K = 1
ANG = 0.01
TETA = 0.0
PSITOR = PSI + K*ANG
Point from spherical coordinates, JPT29
G
D


Inner and outer toruses with centre in *JPT29*
Evaluate inner and outer toruses with faces PS and SS
NCVTRIN3 = 0
NCVTREX3 = 0
NCVTRIN 3 ≥ 1
or
NCVTREX 3 ≥ 1
YES
K = K + 1
G
D
NO
Erase undesired elements
Retain the last torus centre for exterior rotation in plane *JPL3*
Tool path in the plane *JPL3* for exterior rotation
D


D
Loop axial offset
from plane JPL2
YES
J≤(NINT−1)
J = J + 1
NO
J = NINT
DISTOFF = J*ADCEFF
The upmost plane, JPLBUP
Axis system, AXSINT3
Interior rotation
in the plane JPLBUP
I = 1
ANG = 0.2
TETA = 0.0
PSI = 90 – I*ANG
Point from spherical
coordinates, JPT15
Inner circle -
origin, JPT15
H


H
Evaluate inner circle
with face SS
NPTINT < 1
YES
I = I + 1
NO
Erase undesired elements
Retain the last tool centre
for interior rotation in plane
JPLBUP
Evaluate torus with face
SS for interior rotation
in plane JPLBUP
K = 1
ANG = 0.01
TETA = 0.0
PSITOR = PSI + K*ANG
Point from spherical coordinates
JPT29
Inner torus
with centre in JPT29
I


I
Evaluate inner torus with face SS
NCVTRIN3 = 0
NCVTRIN 3 ≥ 1
YES
K = K + 1
NO
Erase undesired elements
Retain the last torus centre for interior rotation in plane JPLBUP
Tool path in the plane JPLBUP for interior rotation
END

2. NC TOOL PATH DATA

```
%
OTH1546 (CATH1546 28-NOV-03 12:38:45)
#5204=0
#5205=0
G20G17
M25
(CATIA FILE NAME  : /CATDAT/TPLAN/WK/TP02)
(CATIA MODEL NAME : CTA30J2122-16 MARIUS 24 NOV 2003 MODEL FINI)
(USER ID : BP30669         DATE : FRI NOV 28 12:38:12 2003)
(     MODEL = CTA30J2122-16 MARIUS 24 NOV 2003 MODEL FINI)
(    NC SET = CATH1546)
()
(                     SETUP INFORMATION)
(                     *****************)
()
(      FIXTURE LENGTH TO LOCATION FACE       =  .0000)
(      C AXIS FACE TO B AXIS CENTER DISTANCE =  .0000)
(      TOTAL STACKUP                         =  .0000)
()
(============================================================)
(PROGRAM FAIT PAR B.TURCOTTE   26-NOV-2003 EXT: 5460)
(POUR P/N: TEST SASU)
(---------------------------------------------------)
(-------------------------------------)
(============================================================)
(UTILISE MFXXXXXX          HAUTEUR  XXXXX)
(BASE PLATE PFXXXXXX REV A HAUTEUR  XXXXX)
(TOTAL HAUTEUR                      XXXXX)
(PIN DE LOCATION A MIDI DU  AXIS)
(============================================================)
N2G64
()
(* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *)
(                         TOOLING LIST)
(* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *)
(    MATERIAL: AMS5666 INCONEL          - MACHINABILITY: 15)
(* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *)
( REF.     TOOL         TOOL          TOOL          TOOL      TOOL)
(  NO      STYLE      DIAMETER     DESCRIPTION     ANGLE   MATERIAL)
(******  **********  **********  ***************  *****  *********)
( 14     END MILL       .3400                      180    CARBIDE)
(                         NO FLUTES: 2                 GL= 15.0000)
()
(******  **********  **********  ***************  *****  *********)
(============================================================)
(TOOL # 14 FORM TOOL TO M/C SECT AE SHEET 7        15.0 G/L)
(XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX)
(XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX)
(XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX)
()
(HOLDER XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX)
()
```

```
(ADJUST XXXXXXXXXXXXXXXXXXX)
(=============================================================)
( 22     END MILL      2.0000                          180    CARBIDE)
(                           NO FLUTES: 6                   GL= 15.0000)
()
(******  **********  **********  ***************  *****  *********)
(=============================================================)
(TOOL # 22 FACE MILL 2.0 DIA. .020 RAD.           15.0 G/L)
(PT354609 & PC451343)
()
(HOLDER PT373962)
()
(ADJUST G/L EN TYPE # 1)
(=============================================================)
()
(* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *)
(NO 22                                                 LOAD)
(    END MILLING OPERATION)
(    FINISHING)
()
(         FEED AND SPEED MODIFIED)
(    FEED RATE:   .007 IPR     3.0 IPM)
(    SPINDLE SPEED:   450 RPM)
(* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *)
()
()
N4M5
N6M1
IF[#999EQ22]GOTO12 (RESTART)
N8T22
N10M6
N12M3S450
N14G90G54G0
N16G94
N18M20
N20G90G54G0G43X20.0908Y10.426Z-9.9636A.0B-42.043H22
N22M0
N24(METTRE L'OUTIL MANUELLEMENT )
N26M0
N28(METTRE L'OUTIL MANUELLEMENT )
N30M0
N32(METTRE L'OUTIL MANUELLEMENT )
N34M0
N36M0
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