Flank Millable Surface Design in 5-axis Machining

Chenggang Li^1 (1), Sanjeev Bedi ^{1} (2), Stephen Mann^2 (3)
^{1}Dept. of Mechanical Engineering, University of Waterloo, Ont., Canada N2L 3G1
^{2}David R. Cheriton School of Computer Science, University of Waterloo, Ont., Canada N2L 3G1
Submitted by Chenggang Li (1), Waterloo, Canada

Abstract

Machining with 5-axis flank milling produces a doubly curved surface. However, given a doubly curved surface, the flank milling tool path required to make it is not known. This mismatch between what can be produced with the flank milling and how to create a tool path to produce a specific surface is a problem. To resolve this, ruled surfaces are used to approximate the design parts and then tool positioning methods iteratively position the cutting tool to machine an approximate ruled surface. The accumulated approximations are not acceptable for many engineering applications as they many result in loss of performance efficiency. There is a need for a method to design a surface that can be flank milled exactly on a 5-axis machine (Flank Millable Surfaces) if flank milling is to become a mainstream method of production and is the topic of this paper.

In this paper, three methods to design NURBS based Flank Millable surfaces are presented. Of the three methods, the least square method guarantees a high degree of the accuracy in the designed surface; however, it is computationally expensive. The other two methods are easy to use and computationally inexpensive, but are slightly lower in accuracy. The accuracy of the surface in these methods is improved by adding control points to reach any desired tolerance.

The proposed surface designed method opens the door for engineers to use doubly curved surfaces in design of impellers, turbine blades and other performance critical objects. An example is presented to demonstrate the proposed surface design methods.

Keywords:
Surface design; Flank milling; Surface numerical analysis; Surface error control.

1 INTRODUCTION

Flank milling is a popular machining method that is widely used in the manufacturing industry. In flank milling, the side of cutter touches the surface; the stock in front of the cutter is removed. High material removal rate, high machining efficiency and good surface finish are hall marks of this method. The advantages of flank milling have attracted engineers to apply this method to machining of curved surfaces. Today, flank milling is used to machine turbine blades, fan impellers and other engineering parts.

In industry, 5–axis flank milling is often used to machine ruled surfaces. Even researchers have mainly focused on developing flank milling for ruled surfaces only. The reason for this focus was that, until recently, the exact shape of the surface machined by a flank milling tool path was not known and so it was approximated by a ruled surface. This promoted the use of the ruled surface in design. The different tool positioning methods that have been developed since focused on ruled surfaces, and attempted to reduce the deviation between the machined surface and the given ruled surface [1-5] with geometric or/and numerical approaches.

With the development in flank milling, researchers now know more about the machined surface. A mathematical expression of the machined surface has been used to evaluate the quality of tool positioning methods and to inspect the error of the machined surface. A swept surface was introduced to approximate the machined surface. Bedi et al. [6] suggested a cross product method to calculate the swept surface, and Mann et al. [7] generalized this method and applied it to tools with a general surface of revolution. Lartigue et al. [8] presented a similar method to determine the swept surface. Senatore et al. [9] used a similar method to define the grazing points and the envelop surface. They also provided geometrical proof that the contact points (between the cutter and guiding curves, the cutter and the rule) are located on the swept surface at each tool position. The development of swept surface is fundamental to the analysis of machined surface error and is the basis of getting high accuracy machined surfaces. Based on the swept surface, Li et al. [12] analyzed the different surface error measurement metrics and developed a method to accurately measure the surface error. Lartigue et al. [8] also used the swept surface in their surface deformation analysis. Li et al. [11] and Menzel et al. [10] used the swept surface to optimize tool positions and generate the machined surface that can closely match the design surface.

The swept surface broadened the view of researchers and influenced the development in flank milling. Close study of the swept surface shows that, because of rotation in 5-axis machining, the machined surface is not a ruled surface, but a curved surface. At each tool position, the effective contact between the cutting tool and the swept surface is a curve, not a straight line. In this paper, this character is exploited and an effective way to use the flank milling technique in surface design is proposed. In this proposed method, the swept surface, generated by different flank milling tool positioning methods, is directly used as the design surface in performance critical objects such as surfaces of impellers and blades. This is a fresh perspective on combining design and manufacture. For a design engineer, if the exact definition of the machined surface is known and is used in his/her design, the performance requirements of the design part (surface of impellers or turbine blades, for example) can be incorporated in the manufactured part with no worry about any compromises during the machining phase. On the other hand, for a manufacturing engineer, the flank milling technique can be used to precisely machine the part with no worry about surface error generated by the tool positioning method affecting the part performance. Thus, in this research, this proposed method is investigated and developed to benefit both design and manufacturing engineers.

To achieve this target, the definition of the machined surface or the swept surface is needed. In previous works, a method to define the swept surface has been established. A close look at the swept surface shows that this surface is defined as a bundle of discrete points and is hard to use in engineering applications. An engineering object is composed of many surfaces connected together with specified continuity. To apply this proposed method, explicit definition of the swept surface is required. A popular method of defining surfaces is a Non Uniform Rational B-Spline (NURBS) definition. This is widely used in industry and is favoured by engineers. The NURBS definition of a surface also allows the surface to be easily used in existing CAD systems. Thus, in this research, methods to find a NURBS definition of the swept surface are presented.

The organization of this paper is as follows. The introduction is given in this section. The proposed surface design methods are studied and presented in the following section. An example is given in the section 3 to demonstrate the proposed surface design method. The paper is closed with conclusions in the section 4.

2 FLANK MILLABLE SURFACE GENERATION

The swept surface is proposed to be used as the designed surface. The swept surface is a function of the tool positioning method and different methods generate their unique swept surfaces. Thus, a particular flank millable surface has its corresponding tool positioning method. In this paper, Bedi et al.'s tool positioning method [6] is used to test the proposed surface design method. The generated flank millable surface will be evaluated by the parametrical error measurement method [12]. A cylindrical tool is used in this research. This surface design method can be adapted to any of other developed tool positioning methods.

2.1 Surface design with the least square approach [13]

The grazing surface (or the swept surface) is composed of a bundle of discrete points. To fit a bundle of discrete points with a surface, the most popular method is the least squares surface fitting method. The discrete points on the grazing surface are used as the sample points, and a NURBS surface is used to approximate these sample points. The knot vectors, the degrees of the surface and the number of control points along two parametric directions are specified by the user. An approximate NURBS surface can be obtained based on the least square formulation as given in [13]. The error between the approximate surface and the grazing surface is evaluated with the parametric error measurement method given before.

The test results showed that with the change of the knot vectors, the degrees and the number of control points of the surface, the accuracy of the approximate NURBS surface can be controlled. High accuracy surface can be achieved with this method. The tests also showed that this method is computationally expensive [13]. A new surface fitting method based on an uncomplicated computational process is developed. This method is presented below.

2.2 Surface design with weighted interior control points [14]

In this surface fitting method, the grazing curve at one end of the grazing surface is modelled with a NURBS curve. The control points of the grazing curve are then moved along the guiding curves in a manner that ensures the true grazing curves do not vary greatly from the approximate grazing curve to build a NURBS surface.

Modelling the grazing curve

The grazing curve is an effective contact between the cutting tool and the grazing surface. Thus, it is not only located on the grazing surface, but also lies on the cutting tool surface. When this grazing curve is projected onto a plane which is perpendicular to the cutting tool axis, a 2D arc is obtained as shown in Figure 1. This arc can be exactly defined by a NURBS curve with three weighted control points. These points are then stretched along the tool axis direction as shown in Figure 2. After this stretching, the 2D NURBS representation becomes a 3D NURBS curve. This 3D NURBS representation is used to approximate the grazing curve.

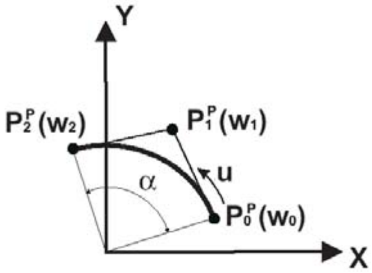

Figure 1 : Arc with its control points.

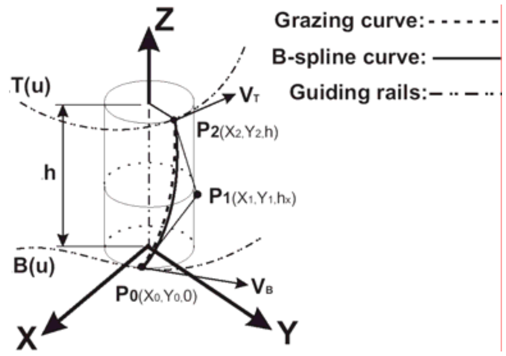

Figure 2 : Grazing curve and its control points on a cylindrical surface.

The motions of control points are determined in a manner that minimizes the error between the grazing curve and its NURBS representation. The parametric error measurement method is used to evaluate the error of the approximate curve. If the maximum error of the curve exceeds the user defined tolerance, more control points can be added to reduce the curve error. The test results showed that the maximum curve error can be controlled and the approximate curves closely match the grazing curves.

Modelling the grazing surface

A few NURBS representations of grazing curves located along the guiding curves are used to construct the flank millable surface that approximates the grazing surface. This is shown in Figure 3.

The design starts with two guiding curves, $T(u)$ and $B(u)$. As an example, each of them has three control points. Three grazing curves spread out along the guiding curves are used to build the NURBS surface. These grazing curves are located at the start ($u=0$), the end ($u=1$) and any interior position ($u=u_0$). The selection of u_0 is based on equi-distant spacing in 3D space or on other criteria described in [14]. Each grazing curve (shown as dashed line) is represented by a NURBS curve with three weighted control points. The control points, at

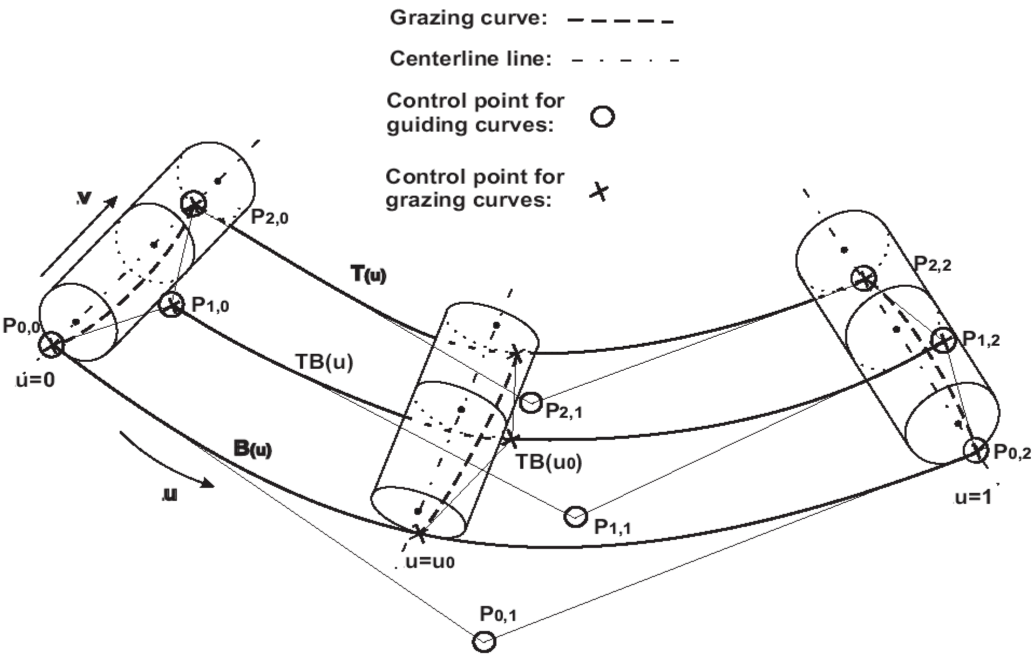

Figure 3 : NURBS surface representation and its control points.

$u=0$ and $u=1$, form the boundary of the control polygon of the flank millable surface along the v direction. The control points of the guiding curves form the boundary control polygon of the flank millable surface along the u direction. Only one control point, $P_{1,1}$, is still undetermined. This flank millable surface is generated from three NURBS curves.

Based on the relationship between the control points and the NURBS surface, the curve at the interior tool position (at $u=u_0$) is used to determine the control point $P_{1,1}$ [14]. The weight of each interior control point (namely $P_{1,0}$, $P_{1,1}$ and $P_{1,2}$) is inherited from the weight of its corresponding grazing curve, and these values are averaged to be assigned to each of them [14].

After the control polygon has been determined, a quadratic NURBS surface can be built. The parametric method is used to measure the surface error between the grazing surface and the approximate NURBS surface. If the maximum surface error exceeds the tolerance defined by the user, more control points can be added to the u and/or the v directions (or change knot vectors in the u and/or the v directions) to reduce the surface error. With the increase in the number of control points, this surface error can be effectively controlled.

The test results show that, just like the least squares method, the NURBS surface closely matches the grazing surface and satisfies the requirements of engineering applications. Different surface accuracy can be achieved by this method.

To design the surface, the weights of the interior control points are determined using the average weight of the corresponding weight of the grazing curves. This averaging procedure is ad hoc but results in a good surface. The selection of the average weight will influence the final surface design and surface error distribution. Further more, weighted control points also make the surface design procedure more complex. As a result, another method that does not require the averaging of weights is developed.

2.3 Surface design with non-weighted interior control points [15]

In this alternative surface design method, each grazing curve is also projected to a plane that is perpendicular to the tool axis direction to form an arc. Instead of using three weighted control points to define this arc, four non-weighted control points (developed by Dokken et al. [16]) are used to construct a 2-D NUBS curve to approximate this arc. Similar to the method described in the section 2.2, these 2-D control points are stretched along the tool axis direction to build a 3-D NUBS curve to approximate the grazing curve. A few grazing curves along the guiding curves are used to construct a flank millable surface to represent the grazing surface. The error of this surface can be controlled with an increase in the number of control points. As the methods given above, different accuracy of the designed surface can be obtained with this alternative surface design method. This method, however, doesn't require the calculation of weights.

3 EXAMPLE

The blade of an impeller is designed to test and demonstrate the usability of the methods in engineering applications. The method described in section 2.2 is used in the design of the flank millable surfaces. The examples for methods given in section 2.1 and 2.3 can refer to [13] and [15]. The design starts with the specification of guiding curves by the designer. A cylindrical cutter with the radius $R=5$ is rolled along the guiding curves to machine the surface. The control points of the guiding curves for pressure surface and suction surface are given in Table 1. The degree of these guiding curves is 2. The knot vector of the curves is $[0,0,0,1,1,1]$.

Bedi et al.'s tool positioning method is used to generate tool paths. The exact surfaces that will be machined with the generated tool paths are calculated using the swept surface technique [6]. The grazing surfaces and the guiding curves for the suction surface and the pressure surface are plotted in Figure 4.

	T0/ B0	T1/ B1	T2/ B2
Suction surface	(72,14,45) (75,15,5)	(20,24,41) (20,20,5)	**(0,64,37)** **(0,60,5)**
Pressure surface	(72,17,45) (75,18,5)	(20,28,41) (20,24,5)	**(1,71,37)** **(1,67,5)**
w **(weight)**	**1/1**	**1/1**	**1/1**

Table 1 : Control points for guiding curves [mm].

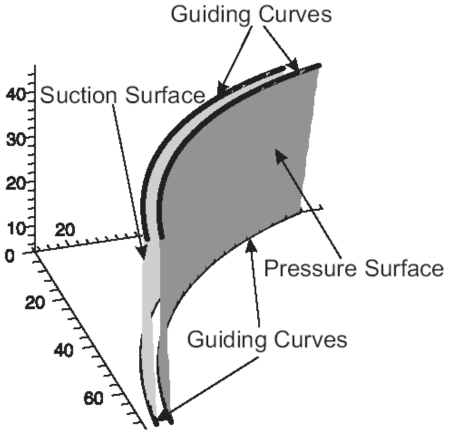

Figure 4 : The grazing surfaces and the guiding curves.

Two quadratic NURBS surfaces, each with a 3 by 3 control polygon, are developed to approximate the grazing surfaces. The knot vectors along the grazing curve and the guiding curve directions are $[0,0,0,1,1,1]$ for both surfaces. The parametric method is used to measure the error between the machined surface (the grazing surface) and the flank millable surface (the designed surface). Plots of these surface errors are shown in Figure 5 and Figure 6.

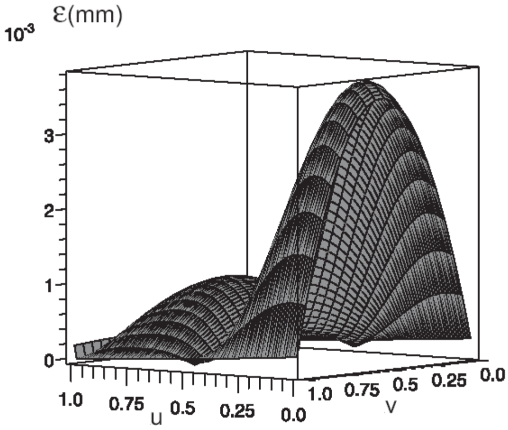

Figure 5 : Deviation of the NURBS surface for suction surface.

The deviation between the grazing surface and the approximate surface for the suction surface is in the range [0, 0.0037]. The maximum surface error is less then 0.0037. The deviation between the grazing surface and the approximate surface for the pressure surface is in the range [0, 0.0035]. The maximum surface error is less then 0.0035. If the maximum error still exceeds the user defined tolerance, more control points can be added to the control polygon of the designed NURBS surfaces. With the number of control points increased, the surface error can be effectively controlled.

After the flank millable surfaces are defined with NURBS, the geometry of the surfaces can be input into a CAD system to design the impeller. In this case, the control polygons and the knot vectors of the suction surface and the pressure surface are transferred to SolidWorks using IGES files. The suction surface and the pressure surface can be built by SolidWorks as shown in Figure 7. Consequently, the solid part of the blade is constructed with these surfaces (Figure 8). Using this solid part, one blade of the impeller can be designed (Figure 9). Designer can fillet or chamfer the edge of the part to make it more suitable for design and manufacturing requirements (Figure 10).

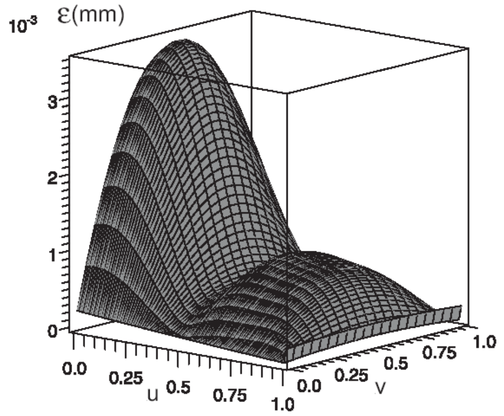

Figure 6 : Deviation of the NURBS surface for pressure surface.

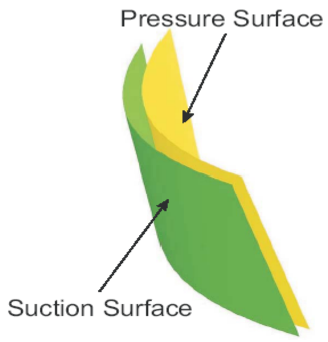

Figure 7 : Two surfaces of the blade.

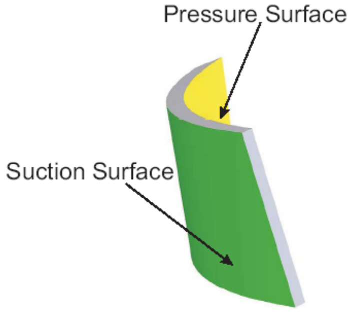

Figure 8 : Solid part of the blade.

An entire impeller is designed and shown in Figure 11.

4 CONCLUSIONS

In this paper, methods to design the flank millable surface have been applied to an engineering application. Three ways to approximate the grazing surface were presented. The least square method gives the best fit between the grazing surface and the approximate NURBS surface, but the whole computation process is expensive. The averaging of weight for each interior control point method results in a good surface, but averaging weight is influenced by the selection of tool positions. Weight computation further makes the surface design procedure complex. The method based on non-weighted interior control point provides an easy way to design the surface and guarantee the designed surface accuracy. All these methods can offer a high accuracy in design.

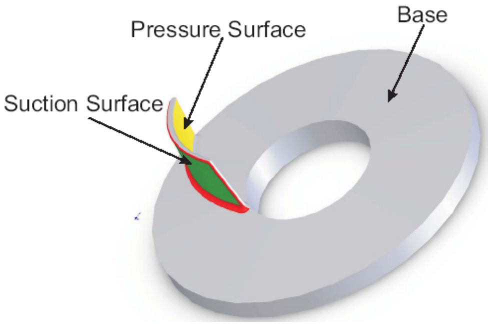

Figure 9 : an impeller with one blade.

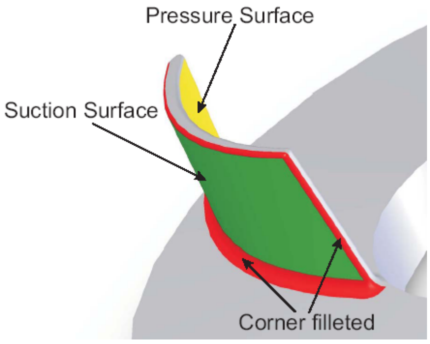

Figure 10 : Details for one blade.

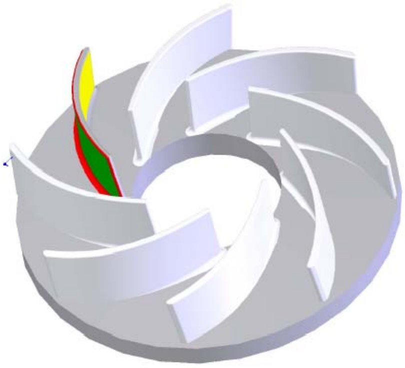

Figure 11: An impeller with its blades.

Application of these developed surface design methods will broaden the scope of engineers. Doubly curved surfaces can now be used in surface design of impellers, turbine blades and other critical engineering parts. Furthermore, it is also possible to design freeform surfaces with these methods for flank milling. The NURBS definition of the designed surface makes it easy be transferred to a CAD system. Within a CAD system, it is convenient to connect it to surrounding surfaces to fulfill the performance requirements of the designed part.

Even though these methods were tested using Bedi et al.'s tool positioning method [6], they can easily be applied to other developed flank milling tool positioning techniques.

In addition, the proposed surface design methods can also be applied to conical tools and barrel tools to further satisfy engineering applications.

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