*Computer-Aided Design and Applications*

http://www.cadanda.com

# Near Net-shape Five-axis CL Data Generation by Considering Tool Swept Surface in Face Milling of Sculptured Surface

J. G. Lee[1], Y. H. Cho[2], S. J. Yang[3] and J. W. Park[4]

[1]Yeungnam University, South Korea, cadcam@ynu.ac.kr
[2]Yeungnam University, South Korea, tigerjr@ynu.ac.kr
[3]Yeungnam University, South Korea, thesheell_yn@nate.com
[4]Yeungnam University, South Korea, jwpark@ynu.ac.kr

## ABSTRACT

It is well known that the five-axis machining has advantages of tool accessibility and machined surface quality when compared with conventional three-axis machining. Traditional researches on the five-axis tool-path generation have addressed interferences such as cutter gouging, collision, machine kinematics and optimization of a CL(cutter location) or a cutter position. In the paper it is presented that optimal CL data for a face-milling cutter moving on a tool-path are obtained by incorporating TSS(tool swept surface) model. The TSS model from current CL position to the next CL position is constructed based on machine kinematics as well as cutter geometry, with which the deviation from the design surface can be computed. Then the next CC(cutter-contact) point should be adjusted such that the deviation conforms to given machining tolerance value. The proposed algorithm was implemented and applied to a marine propeller machining, which proved effective from a quantitative point of view. In addition, the algorithm using the TSS can also be applied to avoid cutter convex interferences in general three-axis NC machining.

**Keywords:** five-axis machining, tool swept surface model, optimal tool position, machining error
**DOI:** 10.3722/cadaps.2008.442-451

## 1. INTRODUCTION

It is well known that 5-axis NC machining has comparative merits such as tool accessibility, surface finish, and reduced set-up time [1-3]. Conventional 5-axis machining has mainly applied to machining turbine blades [1], impellers [4], and marine propellers [5] by specialized machines. In addition the mold & die manufacturing industry is also eager to apply 5-axis machining in order to reduce lead time but also to enhance surface quality.
Fig. 1 depicts general procedure for 5-axis NC data generation, and the research issues include: cutter-interference (gouging) and collision avoidance, machine kinematics modeling, optimization of cutter location, and tool-path smoothing [4,6-11].

The CL (cutter location) optimization at CC (cutter contact) points can be divided into three issues as follows:

(1) CL point optimization: optimization of a single CL at a CC point,
(2) CL path optimization: optimization of cutter location data of a series of CC points,
(3) Optimal step-over distance computation.

The first research issue has been covered by many works in which each CL optimization is performed based on cusp height or curvature value, while the second issue has dealt with tool-path smoothing in configuration space [8, 16]. The last one focuses on obtaining proper path-interval between two consecutive tool-paths.

The conventional CL computation procedure tends to focus on a single CC point where cutter interference is avoided for given position and orientation. The tool movement between CC points or CL points is rarely considered. However, there possibly exists intolerable discrepancy between the design surface and machined workpiece due to overcut or uncut, even if CC intervals are calculated according to given machining tolerance. Therefore, it is needed to cope with such machining inaccuracy.

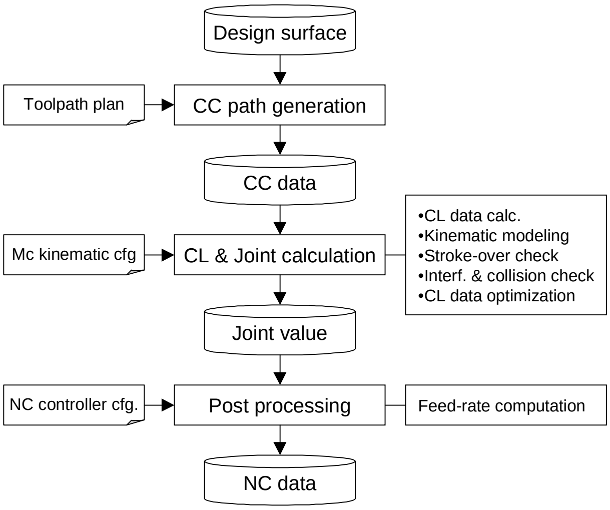


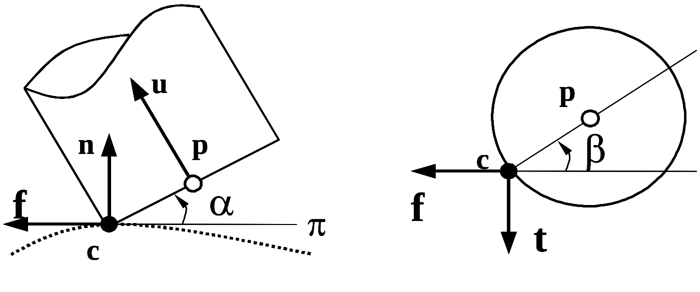
Fig. 1: General five-axis NC data generation procedure.

In this paper, it is presented 5-axis CL data generation for near-net-shape machining by taking into account of TSS (tool swept surface) between two consecutive CC points, which adaptively adjusts CC position and tool pose to make the difference between the design surface and machined workpiece be less than given tolerance. The CL point optimization at a single CC point is done by the previous research [5].
Section 2 and the next section present a few definitions, and problem statement. The overall procedure is presented in section 4, followed by a case study in section 5.

## 2. PREPARATORY DEFINITIONS

### 2.1 Tool Orientation Angles

CC data (**c**, **n**) consists of cutter contact position **c** and unit normal vector **n**, and CL data (**p**, **u**) at (**c**, **n**) is defined by tool reference position **p** and tool axis vector **u** (see Fig. 2). In addition, **f** denotes feed direction vector, while **t** is defined by **n**×**f**.
Tool orientation angles of face milling or flat-end milling cutter for 5-axis machining are defined as shown in Fig. 2: 'tilt angle' and 'yaw angle' denoted as (a, ß) in the figure [5]. The tool orientation angles are two additional degrees of freedom that can control the tool pose. The CL data (**p**, **u**) for given (**f**, **t**, **n**, **c**) can be represented by Eqn. (1).



(a) Tilt-angle (b) Yaw-angle
Fig. 2: Tool orientation angles.

$$u = n\cos\alpha + \sin\beta(f\cos\beta + t\sin\beta)$$
$$p = \begin{cases} c + R(u\times n\times u)/(u\times n) & |\, u\times n \,| > 0 \\ c - Rf & |\, u\times n \,| = 0 \end{cases} \quad \text{where R = cutter radius.} \tag{1}$$

## 2.2 Tool Swept Surface

TSS (tool swept surface) between two consecutive CC points is generated by computing tool Silhouette curves at discrete instances of a tool movement [14, 17]. It should be noted that the 5-axis tool movement must be mathematically modeled by considering the applying NC controller's interpolation scheme. Fig. 3 shows an example of TSS for calculating machining error. The overall TSS is a union of total $TSS_i$'s– tool swept surface from $CC_{i-1}$ to $CC_i$.

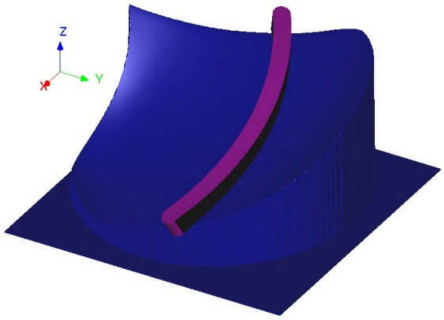
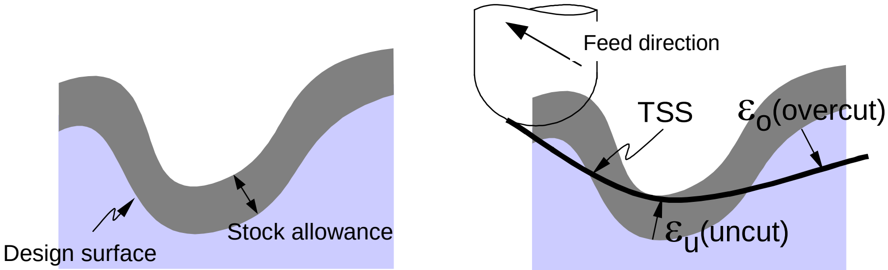



Fig. 3: Overall tool swept surface for a path.

## 2.3 Machining Error

Fig. 4 depicts definition of machining error ($e_M$), which is classified into overcut and uncut. Overcut ($e_O$) means the machined surface intrudes the design surface, while uncut ($e_U$) means the inverse case. The maximum overcut and uncut amounts should not exceed given machining tolerance in generating CL data. The machining error $e_M$ is defined as follows:

$e_U = W_M - S_D$ and $e_O = S_D - W_M$,
where $W_M = W_i - S_T$, $S_T$ = TSS, $W_M$ = machined workpiece,
$S_D$ = design surface, $W_i$ = initial stock (workpiece).




(a) Surface and stock-allowance (b) TSS, overcut and uncut values

Fig. 4: Machining error.

## 3. PROBLEM DEFINITION

The machining error defined in section 2.3 is inevitable in practical machining operation, whose minimization is a common purpose of many previous research works. Its origin can be categorized as geometric and physical reasons; the former is mainly because TSS intrudes into the design surface or leaves excessive material, while the later comes from machine accuracy, tool deflection or chattering that are not considered in this paper.

Minimization of the geometric machining error is divided into following two cases:

- On a CC point,
- On a CC segment (two consecutive CC points).

Concave interference [9] or gouging problem on a single CC point has been handled in lots of previous works, which can be avoided by relatively simple calculation [5]. On the other hand, minimization of machining error on a CC segment is to minimize the overcut and uncut amounts caused by the tool movement on the segment. In practice, step-lengths of a tool-path on a sculptured surface are adaptively defined by considering curvature values of local surface geometry and milling cutter geometry [9]. It is, however, still prone to machining error due to ignoring tool sweeping on a CC segment.

The problems of this research can be summarized as follows:

(1) Find an optimal CL (tool pose) on a CC point so as to remove material as much as possible without concave interference,

(2) Find (adjust) next CC position on a CC segment such that machining error by the tool movement is less than given machining tolerance.

The first case utilizes effective radius of the cutting tool [15], while the second case tool swept surface, as explained in the following sections,

## 4. CL DATA GENERATION

### 4.1 Overall Procedure

A CC path that will be composed of CC points is supposed to be given by a curve $\mathbf{r}(t)$; $0 \le t \le 1$ on the design surface $\mathbf{r}(u,v)$, and its start point is $\mathbf{r}(0)$. The machining tolerance is given as $\tau$, and the initial step-length is calculated from the normal curvature along the feed direction [9].

The optimal tool pose ($CL_{i-1}$) on a CC point is obtained such effective radius of the tool at the cutter contact position should be maximized, without creating any concave interference [15]. Then an initial position of the next CC point is computed via initial step-length ( $\lambda$ ), and its optimal tool pose ($CL_i$) is obtained similarly. The TSS is constructed from the CL data, which is used to perform cutting simulation (i.e., Boolean operation) to obtain the machining error ($e$). The step-length ( $\lambda$ ) is then adjusted in the case of excessive difference of e to machining tolerance $\tau$, otherwise, we can go the next step. The procedure is summarized as follows.

***Procedure Generate_CL;***

*0. Input: $\tau$ = machining tolerance, $\mathbf{r}(t)$ = CC path;*
*1. i = 1, t = 0, evaluate 1st CC: $C_{i-1} = \mathbf{r}(0)$;*
*2. Determine optimal CL at $C_{i-1}$: $CL_{i-1}$;*
*3. Determine step-length: $\lambda \leftarrow \tau$ ;*
*4. Evaluate CC point: $C_i = \mathbf{r}(t+\lambda)$;*
*5. Determine optimal CL at $C_i$: $CL_i$;*
*6. Compute tool swept surface: $TSS_i \leftarrow CL_{i-1}, CL_i$;*
*7. Compute machining error: $e \leftarrow TSS_i$;*
*8. If $e > \tau$ then adjust step-length $\lambda$ and go to 4,*
*9. $i = i+1$, $t = t+\lambda$ ;*
*10. If t = 1 then stop else go to 3.*

### 4.2 Optimal CL at a CC Point

In order to obtain the TSS at a CC segment, it is required to compute proper tool poses (CL) at two boundary CC points. The optimal tool pose or tool orientation angles (a,ß) at each CC point can be obtained by various methods [5,15], one of which is used in our research [15]. It utilizes C-space (configuration space) concept and projected effective radius.

Traditional C-space originated from robot path planning methodology [12], which represents feasible joint space. C-space in 5-axis machining is an (a,ß)-domain that represents feasible tool orientation angles at a CC point.

As shown in Fig. 5, the tool geometry is projected onto the **n-t** plane, and radius of curvature at cutter contact position c is defined as the effective radius. Then the feasible (a,ß) with maximum effective radius is searched to be the optimal CL at the CC point.

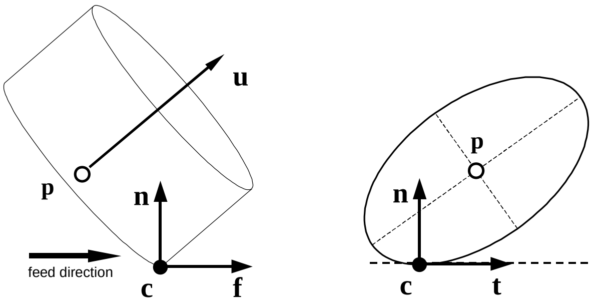
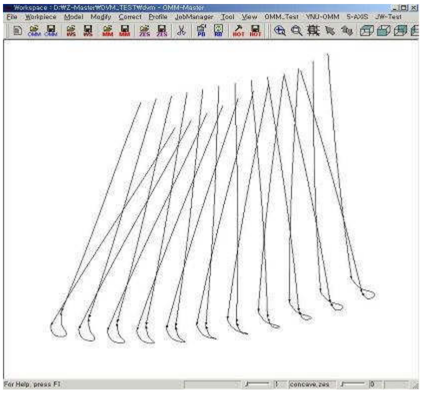


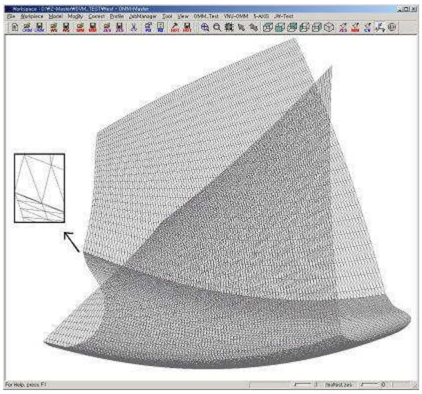

Fig. 5: Projected tool silhouette.

### 4.3 TSS Modeling

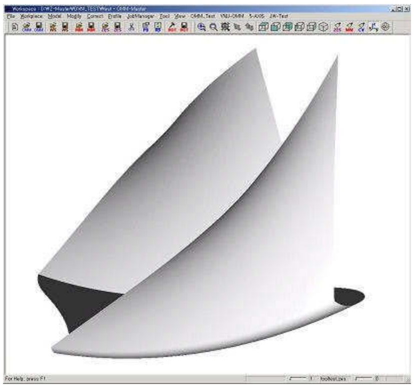
Now that we can have proper CL data at $CC_{i-1}$ and $CC_i$, the corresponding tool swept surface $TSS_i$ is obtained to compute overcut and uncut amounts. The machining error caused by tool movement on the CC segment (from $CC_{i-1}$ to $CC_i$) is calculated by comparing $TSS_i$ with the design surface. The authors used a previous method [17] whose example is shown in Fig. 6.



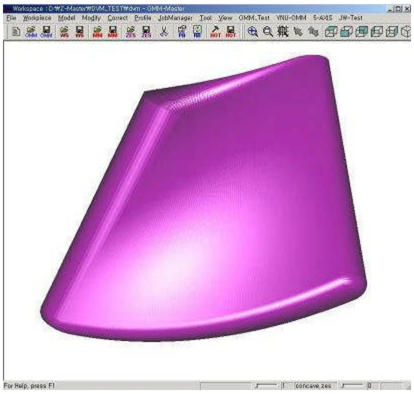
(a) Silhouette curves



(b) Ruled surface



(c) Shaded ruled surface



(d) Complete TSS

Fig. 6: Five-axis TSS example on a CC segment.

**4.4 Computation of Overcut Amount**

The overcut amount on each CC segment is obtained via cutting simulation method based on z-map [9]. To be more precise, the cut-simulated stock model by given $TSS_i$ is compared with the design surface. In addition, only the cut region for the $TSS_i$ is considered to minimize computing time (see Fig. 7). For z-directional differencing, the overcut amount is defined as follows:

$$e_o = \mathrm{MIN}(Z_T\text{-}Z_D, 0) \text{ within a given area,}$$
$$\text{where } Z_T = \text{height of } TSS_i,\ Z_D = \text{height of design surface.}$$

It is, however, not so accurate in a slanted area. Another comparing method is to compute the normal difference that is measured (in mm) along surface normal vectors, which has been adopted in this paper.

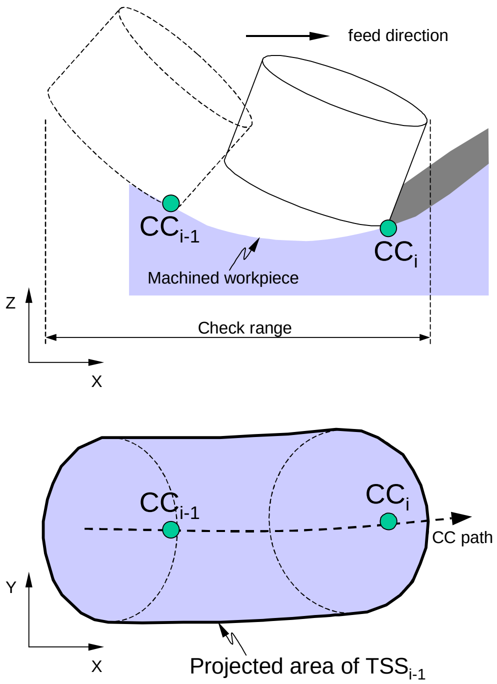



Fig. 7: Overcut check.

**4.5 Computation of Uncut Amount**

The overcut amount can be obtained by direct differencing of each $TSS_i$ from the design surface, while the calculation of uncut amount is done in another way. It is noted that the neighboring CC paths are not considered in the overcut or uncut amount computation (in mm). So a three-dimensional reference curve from $CC_{i-1}$ to $CC_i$ projected on the design surface is generated, the maximum difference to given $TSS_i$ is defined to be the uncut amount as follows (see Fig. 8).

$$e_u = \mathrm{MAX}(L_T, 0), \textit{ on the reference curve.}$$

**4.6 Machining Error and CC positioning**

The machining error ($e_M$) on a CC segment from $CC_{i-1}$ to $CC_i$ is defined as follows:

$$e_M = \mathrm{MAX}(|e_o|, |e_u|) > 0.$$

Given machining tolerance ($\tau$), there can be following two cases if we compute the machining error for initial CC positions ($CC_{i-1}$ to $CC_i$): (1) $e_M \le \tau$, (2) $e_M > \tau$. The former case does not require position adjustment of $CC_i$, while the second case should be remedied so as to be $e_M \le \tau$.

In the second case, correction of $CC_i$ position followed by computation of $e_M$ is repeated until $e_M \le \tau$ (i.e., step-length to $CC_i$ is reduced). The general bi-section method is adopted for estimating the new CC position. A schematic diagram is depicted in Fig. 9.

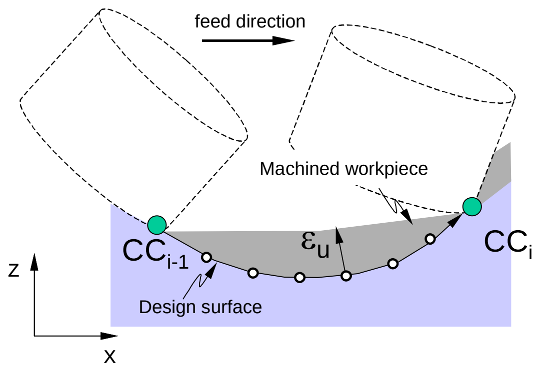
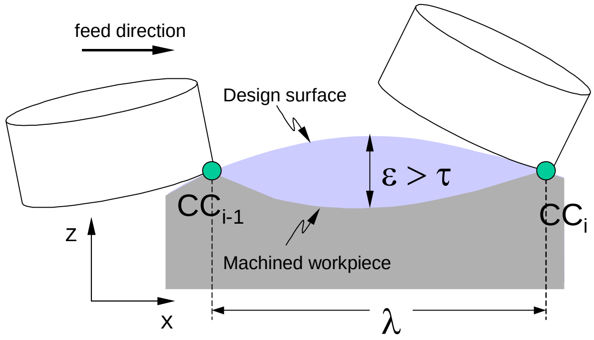
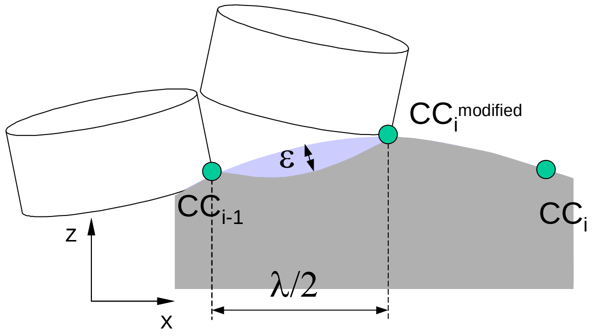



Fig. 8: Uncut check.




(a) Initial CC position: $e > \tau$




(b) Move CC position by $\lambda/2$

Fig. 9: Initial & modified CC position.

## 5. IMPLEMENTATION AND ILLUSTRATED EXAMPLE

The methodology has been applied to large marine propeller machining conducted in a ship building company in Korea. Typical marine propellers have 4 to 6 blades, 6 to 10m diameter, of which initial stock is made of bronze cast. Fig. 10 shows the specialized NC machine with 9 axes total. Surface model of a propeller and sample CC tool-paths on z-map model are illustrated in Fig. 11 and Fig. 12. The u value in Fig. 12 denotes corresponding isoparametric value of the blade surface. In addition the given machining tolerance is 0.1mm, and a face-milling cutter of 250mm diameter.

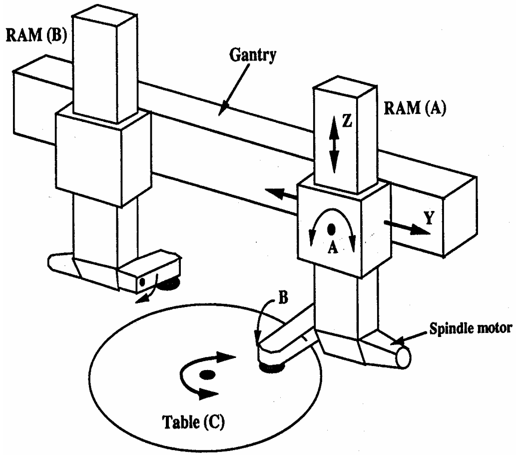



Fig. 10: NC machine for marine propeller machining.

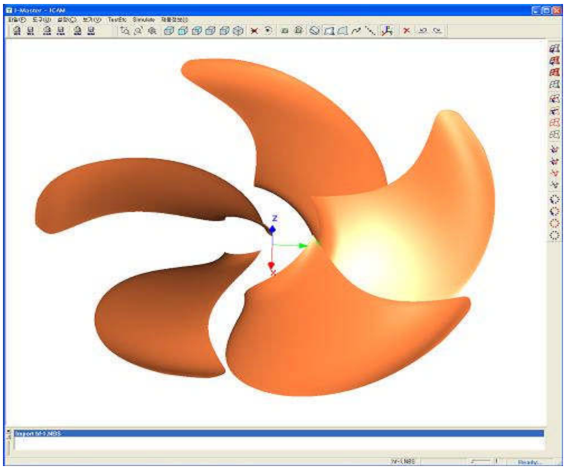


Fig. 11: Blade CAD model.

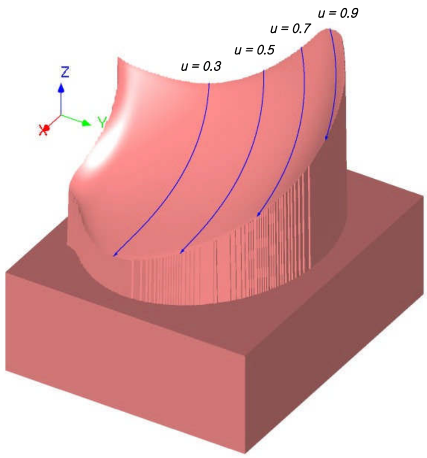



Fig. 12: Blade z-map model and CC paths.

Two resultant cases are shown in Fig. 13 and Fig. 14, for u = 0.9 and u = 0.5, respectively. The machining error plots without any correction of CC position as well as those after correction are illustrated in the figures. The horizontal axis represents x-coordinate of CC points. It can be noted that initial machining error at each CC point is fairly small, but we can see some cases that initial machining error caused by the TSS on each CC segment exceeds given tolerance. On the other hand, machining error (i.e., overcut and uncut amounts) after optimization is observed to be reduced within given tolerance.

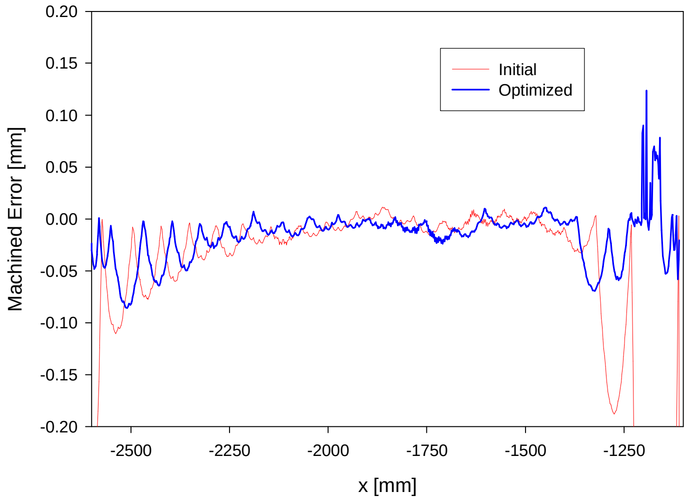



Fig. 13: Machining error before & after optimization: case 1.

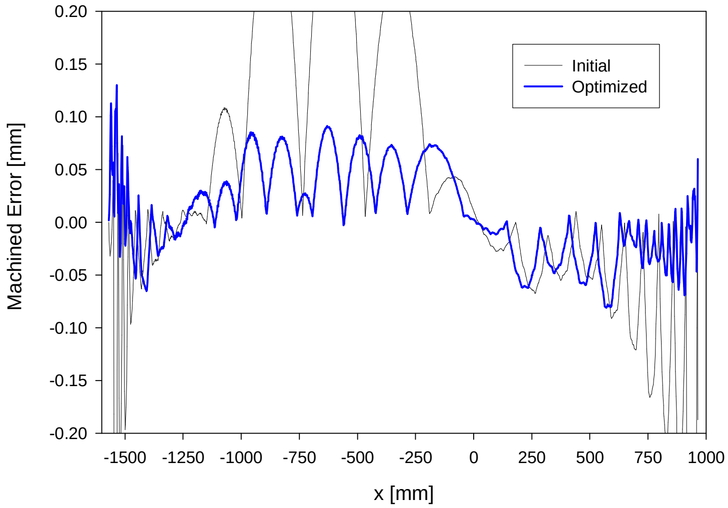



Fig. 14: Machining error before & after optimization: case 2.

## 6. CONCLUSION

Optimal CL generation algorithm has been presented in this paper, both on a CC point and CC segments, which considers overcut & uncut machining errors via cutting simulation by the tool swept surface on each CC segment. The approach has been applied to 5-axis marine propeller machining by a face-milling cutter, and is observed to be fairly successful on the shop floor. In addition, it should be noted that the some volumetric measure of overcut amount and the uncut amount (see Section 4.4 and 4.5) could enhance the overall accuracy, the implementation of which is left as a further research.

## 7. REFERENCES


[1] Mason, F.: 5×5 for High-productivity Airfoil Milling, American Machinist, Nov, 1991, 37-39.

[2] Ralph, W. L.; Loftus, M.: The Application of an Inclined End Mill Machining Strategy on 3-Axis Machining Centers, Int. J. Mach. Tools Manufact., 33(2), 1993, 115-133.

[3] Tonshoff, H. K.; Hernaadex-Camacho, J.: Die Manufacturing by 5-and 3-Axis Milling, J. of Mechanical Working Technology, 20, 1989, 105-119.

[4] Takeuchi, Y.; Watanbe, T.: Generation of 5 Axis Control Collision-free Tool Path and Post-processing for NC Data, Anals of the CIRP, 41(1), 1992, 535-542.

[5] Choi, B. K.: Park, J. W.; Jun, C. S.: Cutter-location Data Optimization in 5-Axis Surface Machining, Computer Aided Design, 25(6), 1993, 377-386.

[6] Takeuchi, Y.; Idemura, T.: 5-axis control machining and grinding based on solid model, Anals. of CIRP, 40(1), 1991, 455-458.

[7] Li, S. X.; Jerard, R. B.: 5-axis machining of sculptured surfaces with a flat-end cutter, Computer Aided Design, 26(3), 1994, 165-178.

[8] Morishige, K.; Kase, K.; Takeuchi, Y.: Collision-free Tool Path Generation Using 2-Dimensional C-Space for 5-Axis Control Machining, International Journal of Advanced Manufacturing Technology, 13(6), 1997, 393-400.

[9] Choi, B. K.; Jerard, R. B.: Sculptured Surface Machining, Kluwer Academic Publishers, 1998.

[10] Hwang, J. S.: Five-axis NC machining of compound sculptured surface, Ph. D. Thesis, Purdue Univ., 1997.

[11] Lee, Y. S.; Chang, T. C.: 2-Phase approach to global tool interference avoidance in 5-axis machining, Computer-Aided Design, 27(10), 1995, 715-729.

[12] Perez, T.: A simple motion-planning algorithm for general robot manipulators, IEEE Journal of Robotics and Automation, RA-3(3), 1987, 224-238.

[13] Kohler, M.; Spreng, M.: Fast computation of the C-space of convex 2D algebraic objects, Int'l Journal of Robotics Research, 14(6), 1995.

[14] Park, J. W.; Chung, Y. C.; Jeong, H. M.: Five-axis Tool-path Verification via DVM, Proceeding of the 32nd ISR, 2001, 79-83.

[15] Park, J. W.; Lee, J. G.: CL-data optimization of 5-axis face-milling via C-space and effective-radius map, Journal of society of CAD/CAM engineers, 7(1), 2002, 34-41, In Korean.

[16] Jun, C.-S.; Cha, K.; Lee, Y.-S.: Optimizing tool orientations for 5-axis machining by configuration-space search method, Computer-Aided Design, 35(6), 2003, 549-566.

[17] Park, J. W.; Shin, Y. H.; Chung, Y. C.: Hybrid cutting simulation via discrete vector model, Computer-Aided Design, 37, 2005, 419-430.