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Machining and Measurement Plans for Impeller Manufacturing

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ABSTRACT

The hub and blade surfaces of an impeller are conventionally machined by a 5-axis numerically controlled machine. Efficient rough machining process plans are required in impeller manufacturing, especially, for the rough machining area partitioning and machining data verification. The blade surfaces of a machined impeller have to be measured exactly to secure the machining tolerance and surface finish of the impeller. Although a coordinate measurement machine with a rotating/tilting probe is used for this measurement, it is not easy to evaluate all the points on impeller surfaces since the measurement is very time consuming. Thus, this paper presents efficient machining and measurement plans for impeller manufacturing. A hybrid rough cut plan is proposed, first, which combines 3-axis and 5-axis machining on a machine. Second, a measurement path generation method based on a unit measurement region is introduced. A case example for an impeller is shown to demonstrate the effectiveness of proposed machining and measurement plans.

Keywords: impeller, NC rough machining, machining and measurement plan, CMM.
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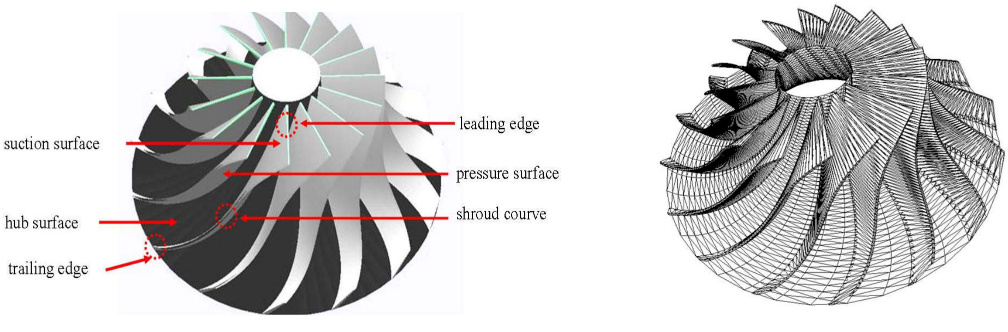
1. INTRODUCTION

An impeller, composed of a hub body and several blades, is a high-speed rotor used to compress or transfer fluid in a high speed, high pressure, and high temperature environment. The hub and blade surfaces of an impeller are conventionally machined by a 5-axis numerically controlled (NC) machine, because the weight and shape imbalance of the impeller often causes noise and vibrations which can lead to blade breakage. The final shape of an impeller is obtained from a cylindrical blank, through rough and final-finish machining. However, much of the machining time of the impeller, approximately 60 percent, is expended in the rough cut stage where unnecessary stock materials are removed. Thus, it is necessary to build NC tool path plans to ensure that they can decrease the rough machining time, but still meet the specified surface quality for the final-finish machining. In the rough machining with a 5-axis NC machine, the appropriate partitioning and layering of a machining area is very important since it determines the number of tool change, and the resulting overall machining, time. Recently on the other hand, in order to reduce the rough machining time, a 3-axis simultaneous rough machining plan with an advanced machine bed setup has been introduced. Although this plan can generate efficient tool paths in terms of machining time, it does not support the surface quality required for the finish cut. The cutting marks on the rough machined surfaces affect the finish machining processes, especially in the case of the flank milling of impeller blades. Hence, this study presents a rough-cut machining plan (RMP) that combines 3-axis and 5-axis machining together, so that the plan can generate efficient rough-cut tool paths with acceptable surface quality for the final finish cut.

Much research has been carried out on impeller machining in recent years. However, this was mostly focused on the effective tool path generation of a 5-aixs NC machine without bringing any collisions between the tool body and the impeller blades. Bohez *et al.* [2] presented an overall procedure to machine an impeller, by applying flank milling to the blade surfaces represented by ruled surfaces. Young and Chuang [11] and Chuang and Young [5] suggested more integrated approaches to impeller surface machining, which are compared to other studies focusing on individual machining issues of an impeller, such as collision avoidance between a tool and blades, and the determination of cutter contact or CL data on a hub or blade surface. They considered the quality requirements of a machined part, tool collision or interference, and machining error comparison issues concurrently. Especially, they attempted to improve the tool path planning of rough machining using the constant scallop height method in the latter paper. Further, they conducted graphic simulation for machining the blade, hub, and leading edge surface with the software package Anvil Verify.

Morishige and Takeuchi [8] first presented the rough-cut issue associated with an impeller, and generated the 5-axis RMP cutter location (CL) data of an impeller-like shape. Balasubramaniam *et al.* [1] suggested a general method of generating 5-axis RMPs directly from tessellated geometric entities, including impeller shaped parts. Nevertheless, these studies did not make use of the properties of the ruled surfaces of blades in RMP. Young et al. [10] developed a 5-axis rough machining module of an impeller by focusing on RMP generation in the narrow and deep machining area of a deep die cavity. They suggested an iso-parametric method to mill machining sections on the blades, considering the residual tool path to prevent the blade from over-cutting. Furthermore, they considered the minimization of the change in cutting forces in a rough machining process by using the concept of constant scallop height and uniform depth of cut. However, their study did not consider the efficiency of their RMPs in terms of overall machining time. Especially, the parametric cutting method for the machining of blade surfaces is likely to decrease the rate of metal removal since it has to control all the five axes coordinately to trace the CL data in the RMP.

In previous research, a RMP method was proposed by Kim *et al.* [7], which differed from conventional RMPs. Tool paths, using all the five axes, are iso-parametrically produced based on the given characteristic curves such as a shroud curve and a hub curve. A rough-cut machining area between the two impeller blades is divided into several sub-areas considering the tool size at each sub-area. Instead, we partitioned a rough machining area, first, into several unit machining regions (UMRs), as shown in Fig. 2, so as to secure certain machine bed setup postures, while avoiding any collisions between the tool and neighboring blades. The partitioning is conducted based on the shroud and hub curves of a blank and a finished impeller, dividing the rough machining area into a certain number of UMRs.



(a) Characteristic geometric shapes

(b) CAD drawing

Fig. 1: Typical impeller configurations.

However, the authors did not consider the surface quality of the rough machined area that is machined through a simultaneous, 3-axis control of a 5-axis NC machine with an advanced, fixed machine bed setup. The impeller blade or hub surfaces are likely to suffer from cutting marks which, consequently, affect the finish machining processes. Thus, the RMP should be devised so that it does not influence the finish machining stage by applying the 5-axis NC machining into a few of the UMRs that are on the bottom of the blade and/or hub surfaces. Hence, in this study, the proposed machining strategy is referred to as a hybrid RMP (H-RMP), since it combines 3-axis and 5-axis machining, that partitions the rough machining area first by using the characteristic curves of an impeller and the projection graphs of the curves. The H-RMP can generate efficient rough-cut tool paths with acceptable surface quality for the final finish cut.

After the machining of an impeller, the blade surfaces of a machined impeller have to be measured exactly to secure the machining tolerance and surface finish of the impeller. Conventionally, a coordinate measurement machine (CMM) with a rotating/tilting probe is used for this measurement. However, it is not easy to evaluate all the points on impeller surfaces since the measurement is very time consuming. Much research has been done to determine the number of measurement points, measurement paths, and probe approach motion. Yau *et al.* [9] investigated the optimal number of measurement points, using an accessibility cone to obtain the feasible orientations for collision-free measurement. Chang and Lin [3] proposed an automatic inspection of turbine blades using a 3-axis CMM together with a 2-axis dividing head. Although it can be employed for the measurement of turbine blades, but it cannot be extended to the closely overlapped blades of an impeller, as depicted in Fig. 1. The probe could not easily access the measurement points near the center hub.

This paper takes advantage of the design information for an impeller such as the geometric data of the blade surfaces of an impeller, which are conventionally composed of ruled surfaces. The properties of a ruled surface enable a machine tool to comfortably machine the blade surfaces in a 5-axis NC machine [4]. Similarly, we can use the ruled line information of machined blade surfaces, such as the normal and position vectors of inspection points that are given along the ruled lines, to find an approach motion vector of a CMM probe.

2. H-RMP

The first stage of H-RMP is performed by the 3-axis machining of the impeller blade. Here, a rough-cut machining area between two impeller blades has to be partitioned into several sub-areas, namely the unit machining regions, as shown in Fig. 2 (on the right), so as to secure certain machine bed setup postures that support collision-free tool motions between the tool and its neighboring blades during the machining in each unit machining region. In addition, a tool diameter in each UMR has to be considered for the effective metal removal as well as the collision avoidance. As shown in Fig. 1 and 2, the size of the tool diameter is limited as the tool moves from the trailing edge to the leading edge, and also from the shroud surface to the hub surface.

The entrance area in the leading edge side of two facing blades, when viewed from the hub axis direction, is relatively narrower than the trailing edge side. Thus, when 3-axis machining is employed, a tool with the smallest diameter in the available tool set should be chosen first in the leading edge side, so as not to be affected by the tool collision, while a tool with the biggest diameter is chosen for the machining of the trailing edge side. Note that the tools in the available tool set are pre-determined by considering the relationship between the tool and the geometric features of the impeller.

However, when 5-axis machining is employed as the second stage of the H-RMP for the rough machining of the deep cavity in the vicinity near the hub body, the biggest tool in the 5-axis tool set is chosen first to improve the machining efficiency, as well as to reduce machining time. Note that the tool diameters for the 5-axis machining are smaller than those for the 3-axis machining in the available tool set. Of course, there is no need to adjust the machine bed set up at this time. Furthermore, a tapered end mill instead of a ball end mill is chosen so as to prevent the engaged tool from breaking, as the tool approaches near to the hub (bottom) surface. Thus, in the 5-axis machining planning, the tool size and the tool configuration have to be considered for determining the 5-axis tool axis vector without causing any collisions between the tool and impeller blades.

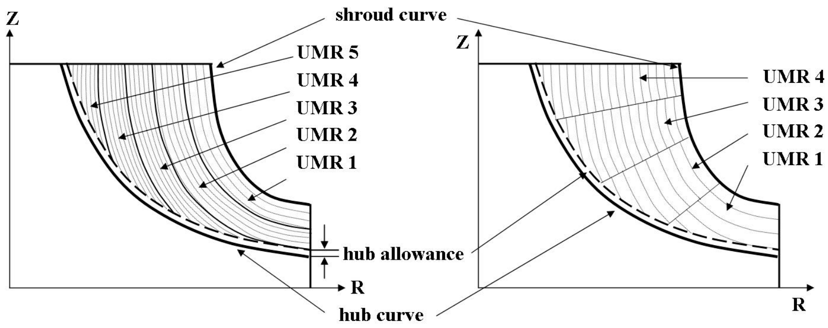
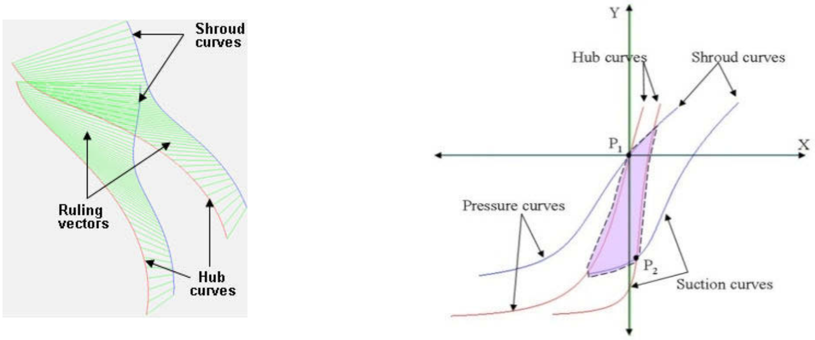


Fig. 2: Conventional rough cut plan (left) vs. proposed partitioning of a machining area (right).

2.1 Partitioning of Rough Machining Area

The partitioning for 3-axis NC machining is performed, based on the ruling lines of the blade surfaces of an impeller, to ensure that a tool can successfully access the entire ruling lines of the machining area, while the rotating and tilting axes in a machine bed are fixed in each UMR to keep the approach vector of a machine tool constant. The representative ruling vectors of pressure and suction surfaces are used to determine the rotating and tilting angles (α and β) of a machine bed (Fig. 3-(a)). An arbitrary ruling vector can be selected on a ruled surface of a blade to coincide with the tool axis (or approach) vector. Then, the feasible region accessed by the fixed tool axis can be determined by the projection curves obtained through a few rotation transformations as detailed in Kim *et al.* [7]. After these transformations, two pairs of hub and shroud curves are projected onto the XY-plane. Fig. 3-(b) shows that the shaded area is the collision-free region, in which the cutter, having a fixed tool axis vector, can move on the hub surface without any collision with the blades of the impeller. At this time, the rotating and tilting angles of a machine bed can be determined by the transformation angles, α and β, respectively.



(a) ruling vectors of blade surfaces (b) projected blade curves

Fig. 3: Projection of blade curves onto XY-plane.

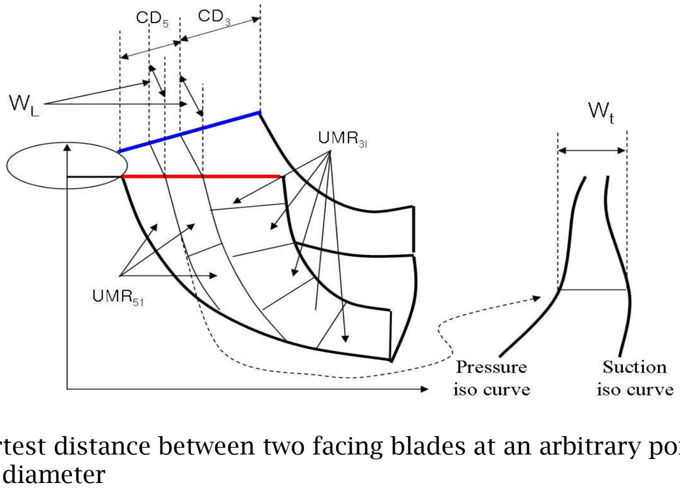
2.2 Partitioning Method

The rough machining of an impeller is first performed by dividing an entire rough machining area into a 3-axis machining area and a 5-axis machining area. Alternatively, this division can be conducted by separating the 3-axis machining area first. The 3-axis machining area is determined by partitioning an initial machining area into several UMRs as discussed here. The partitioning method can vary according to the size of an impeller, the geometric configuration of a blade, the number of blades, tool diameters, and tool configuration. Thus, it is essential to find efficient partitioning methods, or alternatives, for the H-RMP by considering the blade and tool information.

Most manufacturing companies usually use pre-determined, available tools in the shop floor, following the pre-designated cutting conditions in the recommended tool tables of tool manufacturing companies. In this sense, a set of available tools is assumed such as ball end-mills of 12ϕ, 10ϕ, and 8ϕ, for 3-axis machining, and tapered end-mills of 6ϕ and 4ϕ for the 5-axis machining. Note that the tool diameters for 3-axis machining are bigger than those for 5-axis machining. Then, a rough machining area is divided into 3-axis UMRs UMR3 and 5-axis UMRs UMR5. The UMR3 can be further partitioned into UMR3i (i=1,…,I) and UMR5 into UMR5j, (j=1,…,J), respectively, as shown in Fig. 4.

The partitioning process for the 3-axis machining is as follows: (1) Determine, in advance, a tool set T3 for the 3-axis machining. (2) Choose the smallest tool in the T3, and locate a feasible UMR from the leading edge side, where the feasible UMR means that a given tool can remove materials in a UMR by 3-axis machining without any collisions. (3) Determine the i^{th} unit machining region, UMR3i, which can be machined without changing the tool posture in the region by moving the tool toward the trailing edge. If a collision happens in the current tool posture, change the machine bed set up so that 3-axis machining will be feasible, and establish the next region, UMR3(i+1). Note that a possible collision can be found in advance by using the projection graphs of the shroud and hub curves (see Fig. 3(b)). (4) Select the next smaller tool in the tool set T3 and repeat step (3), until the tool reaches the trailing edge. If there is no more area to cut using the 3-axis machining manner, stop the partitioning process.

The machining area partitioning process for the 5-axis machining part is composed of the following steps: (1) Arrange the tools in T5 by the order of largest first as this will be the first to be used. (2) Determine the depth of cut with the selected tool from the leading edge side. At this point, select a tapered end mill when the tool approaches the deep side of the blade. (3) Start the partitioning of the UMR5 as the tool moves towards the trailing edge. At this point, if Wt larger than *b*DT, where *b* is constant and DT is a tool diameter (see Fig. 4), define a new region UMR5(j+1). (4) Select the next tool from T5 and perform the next partitioning process. Repeat this step over the entire UMR5. Several partitioning alternatives can be obtained by applying the partitioning process over available tool sets. Namely, three alternatives exist if there are three available tool sets, such as [{(T3),(T5)}] = [{(12ϕ), (10ϕ, 8ϕ, 6ϕ, 4ϕ) }, {(10ϕ, 12ϕ), (8ϕ, 6ϕ, 4ϕ) }, {(8ϕ, 10ϕ, 12ϕ), (6ϕ, 4ϕ) }].



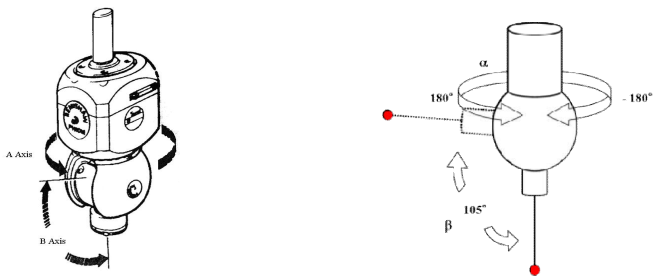
WL: shortest distance between two facing blades at an arbitrary point in the leading edge.
DT: tool diameter
CD3: depth of cut in the leading edge side for the 3-axis machining
CD5: depth of cut in the leading edge side for the 5-axis machining
Wt: shortest distance between two curves on a hub surface

Fig. 4: Illustrative example of UMR3 and UMR5.

3. CMM MEASUREMENT PLAN

3.1 CMM with A Rotating and Tilting Probe

If a work part is machined by a 5-axis NC machine, then it has to be inspected or measured on a 5-axis coordinate measurement machine (CMM). But, a usual CMM is a 3-axis device with a fixed probe. Thus, two additional degrees of freedom are required to inspect 5-axis machined parts. In this case, a rotating and tilting probe is commonly used to secure such flexibility as shown in Fig. 5. Then, the CMM is composed of a 3-axis body and a 2-axis probe. These additional two axes enable the probe to approach deeply into the surfaces of the impeller blades. Fig. 5 (a) shows a commercial probe employed in this paper, which can rotate and tilt simultaneously. The stylus of the probe stops its probing motion when it touches an object. The α-axis can rotate from -180° to 180° and the β-axis can tilt from 0° to 105°, and they can move by 7.5° for each pulsed command.



(a) A commercial probe (b) CAD drawing

Fig. 5: A rotating and tilting probe.

3.2 Probe Approach Motion

To exactly inspect points on a blade surface, a probe has to gauge all the points on blade surfaces. But, theoretically, there are an unlimited number of points on the surfaces. Thus, a certain number of characteristic points have to be sampled first to employ the probe to gauge the points on blade surfaces. Fig. 6 depicts regularly sampled points along the ruled lines of a blade surface. Although regularly sampled points are provided, these points are still difficult to inspect by using only CMM with a teaching joystick. Fig. 7 represents a probe approach motion to a point on a blade surface of an impeller. The probe, first at its starting position S, has to rotate the rotating and tilting axes to align its stylus with the approach direction of a blade surface. Then, it has to move to an offset point *O*, which is an offset point from a point P about an offset distance d. This approach motion follows the approach (direction) vector of a blade surface, which is a representative ruled line vector in a partitioned region discussed in the later section. Finally, the probe has to slowly position to an inspection point along the normal vector Nij, of the point until it touches the target point *P*.

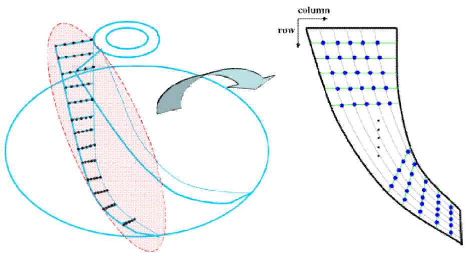


Fig. 6: Sampled measurement points on a blade surface of an impeller.

CAD data in a design database can effectively facilitate the probe to approach and position to the points on blade surfaces, since they provide all the necessary information for generating measurement paths for a CMM probe. Approach direction vectors for probe approaching motions, and the normal vectors of inspection points are easily produced from geometric information such as ruled surface data in the CAD database. Thus, we can determine these approach vectors and normal vectors based on the ruled surface information to successfully generate the measurement paths of a probe for each blade. But, actual measurement operations still take a lot of time in aligning probe postures, as well as in obtaining the collision-free paths of a probe with the blades of an impeller.

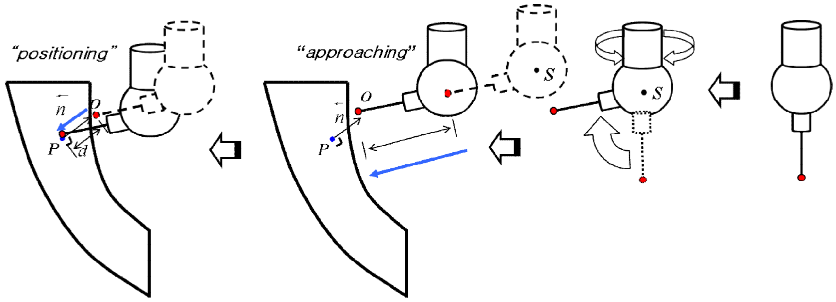


Fig. 7: A probe approach motion to a point of a blade surface.

3.3 Partitioning of Blade Surfaces

The collision between a probe and impeller blades can be verified through projected blade curves on the xy-plane, as shown in Fig. 3(b). Upon examination of a number of collisions shown in projection graphs, we found that a probe does not collide with blade surfaces if the probe approaches to an inspection point along the probe approach vector as shown in Fig. 8, at an appropriate approach inclination angle ϕ. Note that the probe approach vector maintains an approach inclination angle ϕ, to secure a minimum offset distance (d) for the position of the probe from O to Pij, as marked in Fig. 7 and 8, as well as to secure collision-free probe motion.

Although a blade surface is composed of a ruled surface including ruled lines, the ruled line vectors are different from each other since the blade surface is geometrically twisted. As discussed in the previous section, thus, the approach directions of a probe continuously vary according to the ruled line vectors of a blade surface. However, if the approach directions (or vectors) of a probe can be simplified into several ones, the CMM measurement operation can be much simplified and shortened in terms of the probe approach motion or inspection time. Thus, a target blade surface must be divided into several measurement regions (Fig. 9), so that a representative probe approach vector is kept within each measurement regions to prevent any collision between the probe and blades.

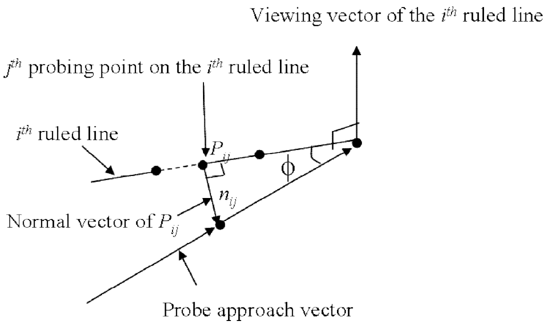


Fig. 8: Measuring point Pij and probe approach vector.

A measurement area (a blade surface) is partitioned into smaller regions as follows. First, ruled line vectors of a blade surface are projected onto the xy-plane by using rotational transformations as described in [4], such that the z-axis coincides with the viewing vector as depicted in Fig. 8. Then, a group of ruled lines that are within the boundary of the approach inclination angle ϕ are drawn and these lines are assigned to the 1st measuring region. The approach inclination angle ϕ is usually set to the largest value that the probe can take against the blade surface without bringing collision with blade surfaces. The 1st ruled line corresponding to the x-axis, then, can be selected as the approach vector of a probe in the 1st measurement region. Similarly, we can determine the 2nd region and the 2nd approach vector, considering the angle ϕ, while moving the x-axis further into the next ruled line just outside the 1st region. Note, that there may be only a few lines included in the last region. Thus, if we can happen to increase the approach inclination angle ϕ, then, the last measurement region might be merged into the previous one. This is possible since a CMM probe can approach an inspection point easily without any collision, as the probe closes to a trailing edge. Hence, the measurement regions can be determined via this process, picking out the representative approach vector of a probe in each region.

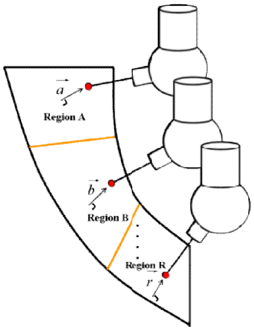


Fig. 9: Partitioning of measuring area into several region.

4. EXPERIMENTAL RESULTS

4.1 Comparison of NC Machining Times

The machining time can be measured by computing the entire machining distance over a feed rate. However, it is difficult to generate entire tool paths, as well as to apply machining simulations over all the unit machining regions. Thus, this study proposes an evaluation method that utilizes the cutting volumes to measuring the machine time and the surface roughness. UMRs can be transformed into their matching right-angled hexahedra, reflecting their cut volumes as detailed in [6]. Then, the machining time can be determined by computing the time needed for machining the hexahedra.

To compare the performance of simultaneous, H-RMP with that of the conventional 5-axis rough-cut plan, the machining time were experimentally measured for a 16-blade impeller with a height of 48.45 mm, an inner radius of 57.84 mm and an outer radius of 99.99 mm. The blank material was aluminum and the blades were twisted counterclockwise. Based on the characteristic curves of the impeller, the H-RMP module partitioned the machining area into several UMRs and computed the rotating and tilting angles of the machine bed to support 3-axis machining. The final tool paths of rough machining involved in the UMRs were verified by using the cutting simulation function of Vericut®. Ball end mills with diameters of 12, 10, 8, 6, and 4 mm were used successively in each UMR. A part program for the generation of the tool paths was written by a conventional part programming language, Automatically Programmed Tools (APT).

Tab. 1 shows the experimental rough-cut times of a machining area between two neighboring blades of the impeller using the proposed H-RMP and the conventional, simultaneous 5-axis control. Note that the entire machining area was divided into 5 partitioned regions (UMRs). This was because the machining area is conventionally divided into five UMRs in real machining, so as to avoid any collisions between cutters and blades and to alleviate machining loads on the tool. This also indicates that at least 5 cutters have to be changed when 5-axis control, rough machining is employed. Rough machining times were measured at the feed rate of 1,000 mm/min for the 3-axis machining, but 500 mm/min for the 5-axis machining. Nominal rough machining time was determined based on the APT codes, which was obtained by dividing the total NC block length by the feed rate.

Machining Length/Time	Tool Diameter	No Hybrid 5-Axis only	Hybrid I		Hybrid II		Hybrid III	
			3-Axis	5-Axis	3-Axis	5-Axis	3-Axis	5-Axis
Estimated Machining Length (mm)	12 φ	5,526.568	5,526.568	-	6,788.612	-	4,128.251	-
	10 φ	1,947.386	-	1,947.386	2,230.352	-	4,321.013	-
	8 φ	2,366.221	-	2,366.221	-	2,366.221	2,466.928	-
	6 φ	2,429.583	-	2,429.583	-	2,429.583	-	2,429.583
	4 φ	2,215.352	-	2,215.352	-	2,215.352	-	2,215.352
Machining Length (mm)		14,485.109	5,526.568	8,958.542	9,018.965	7,011.156	10,916.191	4,644.935
Estimated Machining Time (min.)		57.940	5.527	35.834	9.019	28.045	10.916	18.580
Total Estimated Machining Time (min.)		57.940	41.361		37.064		29.496	

Tab. 1: Comparison of rough machining times.

For the experiment, 3 H-RMPs were considered based on the number of 3-axis machining UMRs. Tab. 1 shows the nominal machining times for a 5-axis RMP and 3 H-RMPs, where big-diameter tools were firstly used for 3-axis machining UMRs. In the Hybrid I method, only a UMR is machined by the 3-axis control, however, 2 UMRs in Hybrid II, and 3 UMRs in Hybrid III. As shown in Tab. 1, machining times using 5-axis control were much higher than those using 3-axis control. The more UMRs were machined by the 3-axis control, the less machining times were consumed. Especially, the estimated machining time by the 5-axis control is 1.96-fold larger than the Hybrid III method. In terms of actual machining time, however, the former will take more than twice as long as the latter at the test feed rates. Thus, the Hybrid III will take 8 hours less than the existing 5-axis, roughing method in actual machining when all the machining areas between all the blades, i.e., 16 areas/80 UMRs, are machined at the given feed rates. Thus, the H-RMP outperformed the conventional, 5-axis control, rough-cut method.

4.2 Comparison of CMM Measurement Times

The total measurement time of an impeller can be obtained by the summation of the probe travel time, probe posture change time (for approach motion), and actual measurement time. In this study, however, only the probe traveling time and the probe posture change time are used to compare the total measurement times, since they do not depend on the number of measurement points. The impeller mentioned in the previous section was used for this experimental measurement. The impeller has 16 blades, including 32 surfaces on both sides. A blade surface has 50 ruled lines and 5 inspection points per line, and thus, it has 250 inspection points per surface, and 500 points per blade. A 3-axis CMM with a rotating and tilting probe is employed, in which the rotating and tilting axes have the same specification as mentioned in Section 3.1. The probe starts from a point *S* that is located between the suction surface of a blade and the pressure surface of an adjacent blade. The approach feed rate of the probe is set as 200 mm/sec., and the positioning feed rate as 3 mm/sec. The approach inclination angle ϕ for the probe against a blade surface is given as 15°. Hub axis indexing time for blade shifting is neglected only in our case.

Tab. 2 provides the experimental result of the CMM measurement on two blade surfaces, namely suction and pressure surfaces. Probe travel time and point measurement (inspection) time are the same regardless of whether or not the blade surface is partitioned, while the posture change time of the probe varies according to the partitioning. The total measurement time of a blade surface with area partitioning is shorter than that without partitioning by as much as about 80 to 100 seconds. Thus, when a probe inspects all the 32 impeller blade surfaces, the former takes one hour less than the latter. Consequently, it can be said that the measurement path generation (MPG) of CMM with a rotating and tilting probe considering the measurement area partitioning outperforms that not considering the partitioning.

Blade surface type	Measurement area partitioning	Probe travel time (unit: sec.) (a)	Posture change time (unit: sec.) (b)	Measurement time (unit: sec.) (c)	Total measurement time (unit: sec.) (d)= (a)+(b)+(c)	No. of probe posture change
Suction surface	Without partitioning	1,217	140	150	1,507	7
	With partitioning	1,217	40	150	1,407	2
Pressure surface	Without partitioning	1,203	160	150	1,513	8
	With partitioning	1,203	80	150	1,433	4

Tab. 2: Measurement time on two blade surfaces.

5. CONCLUSIONS

Conventional 5-axis rough machining requires considerably more time than 3-axis machining as it has to control all the machine axes simultaneously at each CL point. This study, first, has presented H-RMP that effectively removes the unwanted materials from a blank, employing the simultaneous 3-axis machining first, and removes the remaining materials by the simultaneous 5-axis machining with almost uniform path intervals, to meet the requirements for the final surface quality. The rough machining area is first divided into a 3-axis machining area and then a 5-axis machining area. Over these two divided areas, major partitioning processes are conducted to get the unit machining regions. However, there are a number of partitioning alternatives according to the available tool sets. Thus, to find an efficient partitioning alternative, each UMR has to be transformed into a volume-equivalent right-angled hexahedron. Then, the rough machining time, as well as the machined surface uniformity, can be easily obtained to ensure that an efficient rough machining strategy is determined.

3 H-RMPs were considered based on the number of 3-axis machining UMRs through the experiment. As shown in Tab. 1, the more UMRs were machined by the 3-axis control, the less machining times were consumed. The estimated nominal machining time by the 5-axis control is 1.96-fold larger than a Hybrid method. In terms of actual machining time, the Hybrid method can take 8 hours less than the existing 5-axis, roughing method if all the machining areas between all the blades, i.e., 16 areas/80 UMRs, are machined at the given feed rates. Thus, the H-RMP method clearly outperforms the conventional, 5-axis control, rough-cut method. Further studies are required to verify the performance of the proposed H-RMP application into the shop floor.

CAD data in a design database can effectively facilitate the CMM probe to approach and position to the points on blade surfaces. Approach direction vectors for probe approaching motions, and the normal vectors of inspection points for probe positioning motions can be produced from geometric information such as the ruled surface data in the CAD database. Thus, we can determine these approach vectors and normal vectors for the MPG of a probe. But, actual measurement operations still take much time because probe postures have to be aligned at each inspection point and the collision-free paths between a probe and the blades have to be obtained. Hence, an effective MPG method is suggested to reduce the probe teaching and measurement time for impeller blades and thus, to decrease the production lead time of a shop floor.

Our proposed MPG method is based on the ruled line information of a CAD database for impeller blades, partitioning the target blade surface into several regions, which keeps the same probe approach vector in each measurement region so as not to change the orientation of the probe stylus. Then, the probe can be taught quite simply in advance based on the ruled line information of the blade surfaces. Throughout an experimental study, it was found that in the inspection of impeller blade surfaces, MPG with area partitioning outperforms both the existing joystick-based teaching method and the simple travel-and-inspection method without considering partitioning. Further research will focus on the effective determination of the approach inclination angle ϕ without collision between the probe and blades, as well as on measurement experiments for different impellers.

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