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Review:

Current State of the Art of Multi-Axis Control Machine Tools and CAM System

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Multi-axis numerical control (NC) machine tools such as 5-axis control machining centers and 5-axis control multi-tasking machines are widely used in machine shops. NC data, which are prepared using computer-aided manufacturing (CAM) systems, are used with multi-axis control NC machine tools that have a variety of advantages. This article describes the advantages of multi-axis control machining. The structure of CAM systems used for multi-axis control machining and the important role of collision avoidance in generating cutter location (CL) data are then explained. The transformation of CL data to NC data for use in machining, which is performed by a post-processor, is presented. Finally, an efficient machining method and unique shape creation via 6-axis control machining are explained.

Keywords: multi-axis-control NC machine tools, CAM system, CL data, NC data, efficient machining

Fig. 1. Jet engine parts required for 5-axis control machining (P&WC).

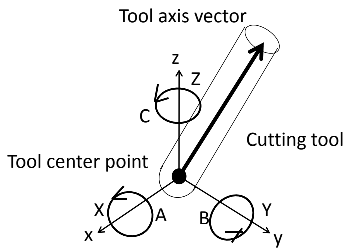


Fig. 2. Tool position and attitude within working space.

1. Introduction

Numerical control (NC) technology has developed since its invention in 1952 to the point that multi-axis control NC machine tools, such as 5-axis control machining centers and 5-axis control multi-tasking machines, are now widely used in machine shops. The advantages of multi-axis control machining are the ability to handle workpieces with complicated shapes that are difficult to machine using conventional 3-axis control machine tools and the reduction in the amount of preparatory work required, such as mounting and unmounting workpieces. This is possible because of the high numbers of degrees of freedom provided with respect to the movement required. Multi-axis-control NC machine tools have become essential equipment for manufacturing automation [1]. A typical example of a complicated workpiece, known as an impeller or a blisk, which is used in jet engines, is shown in **Fig. 1**.

By the way, NC data is inevitable to make the most of multi-axis control NC machine tools having a variety of advantages. NC data is prepared by use of Computer Aided Manufacturing (CAM) system. Without it, multi-axis control NC machine tools are left unused. Here in the article, the constitution and the state of the art of CAM system for 5-axis control machining are explained together with 5-axis control machine tools.

2. Multi-Axis Control Machining

To create complicated workpiece shapes, it is necessary to position a cutting tool at an arbitrary point in space with an arbitrary attitude. To perform the cutting, six axes, i.e., six degrees of freedom are required. Thus, NC machine tools can be equipped with three translational movement functions, along the X-axis, Y-axis, and Z-axis, for positioning, and three rotational movement functions; A around the X-axis; B around the Y-axis and C around the Z-axis, as illustrated in **Fig. 2**. Most 3-axis control machine tools possess three translational movement functions. Multi-axis control machine tools are tools with more than three movement functions. In general, the Z-axis is along the main spindle of a tool. If a rotational cutting tool such as an end mill or ball end mill is used, the Z-axis is not controllable. Thus, 5-axis control is a necessary and sufficient condition when using rotational cut-

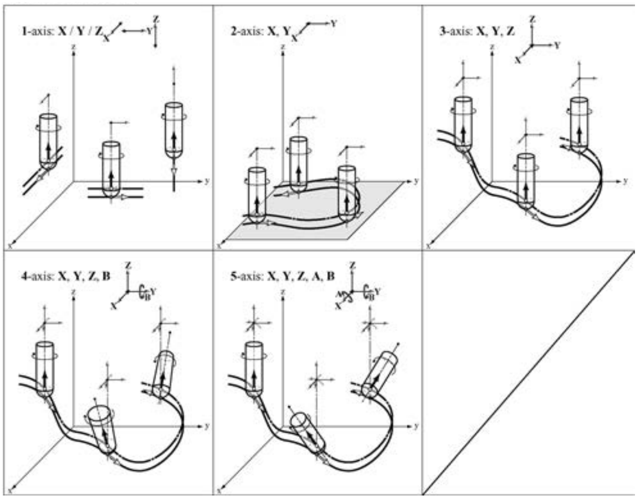


Fig. 3. Number of control axes and movement of rotational cutting tool.

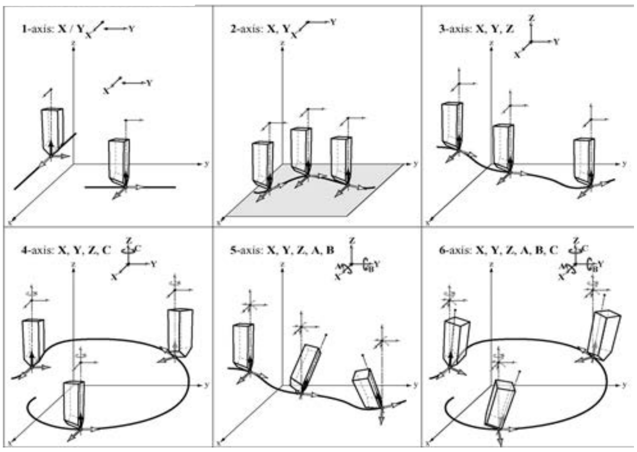


Fig. 4. Number of control axes and movement of non-rotational cutting tool.

ting tools. The use of non-rotational cutting tools requires 6-axis control. **Figs. 3** and **4** illustrate the relationship between the number of control axes and the movement of rotational and non-rotational tools, respectively.

3. CAM System for Multi-Axis Control Machining

A CAM system for multi-axis control machining is shown in **Fig. 5**. Such a system typically consists of two processors: a main-processor and a post-processor.

The role of the main-processor is to generate collision-free cutter location (CL) data, based on three-dimensional (3D) computer-aided design (CAD) data for parts or products. CL data describe the positions of the tool and tool axis vector at any cutting location, which are defined with respect to the CAD coordinate system. Thus, CL data do not pertain to the structure of a 5-axis control machining center or 5-axis control multi-tasking machine. If a collision between a tool and a workpiece takes place, collision avoidance, which is very important, especially in multi-axis control machining, is performed to carry out the machining correctly.

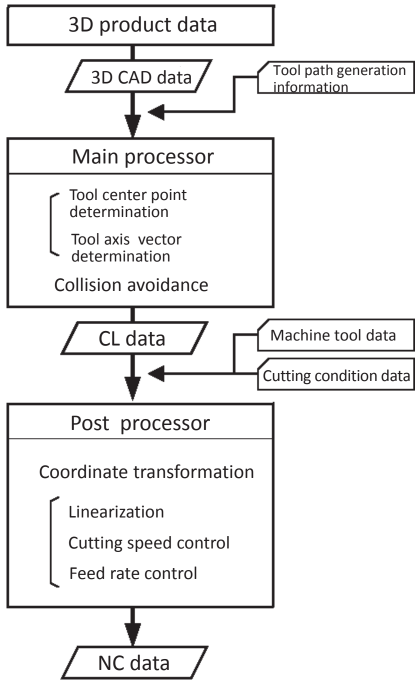


Fig. 5. Structure of 5-axis control CAM system.

The post-processor plays an important role in generating NC data that are used to operate 5-axis control machine tools, based on CL data. The post-processor takes into account the structure of the 5-axis machine tool and the cutting condition so that it can generate practical NC data.

The post-processor performs the coordinate transformation from the CAD coordinate system to the machine coordinate system, taking into consideration "linearization" to avoid over-cutting or under-cutting, as well as cutting speed control and feed rate control to maintain a constant cutting speed and feed rate at any cutting position.

4. Collision-Free Tool Path Generation

An important concern in multi-axis control machining is the potential for a collision between a tool and a workpiece. Collision avoidance can be achieved by trial-and-error so that the provisional determination of the tool attitude is repeated until the collision is avoided. This approach to collision avoidance seems to be common in commercially available five-dimensional (5D) CAM systems. With this approach, there is no method to know why a tool attitude is selected from among other possible attitudes that do not cause collisions. There is no method to modify the tool attitude if the tool attitudes obtained are unsatisfactory.

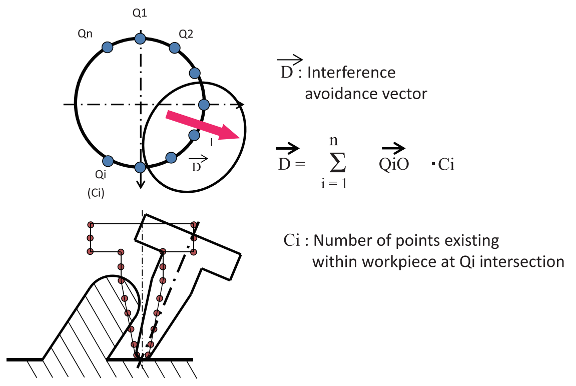


Fig. 6. Determination of interference avoidance by use of check points.

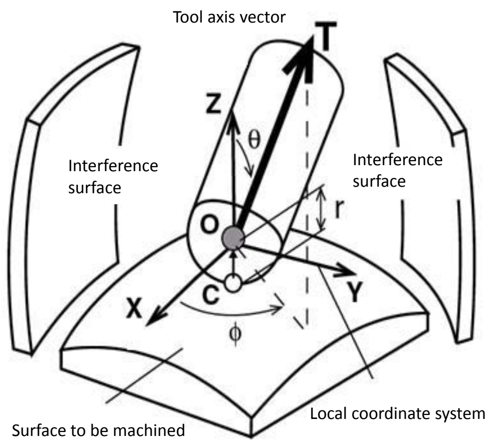


Fig. 7. Tool attitude at a cutting point.

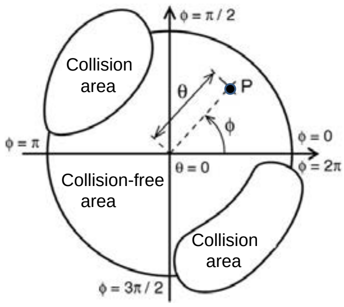
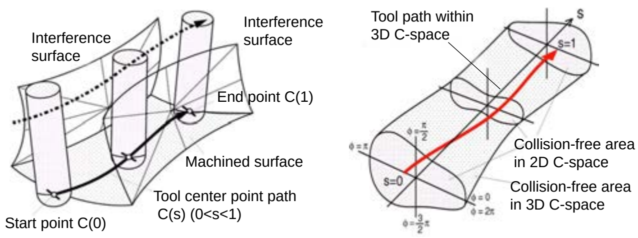


Fig. 8. 2D C-space standing for tool attitude.



(a) (b)

Fig. 9. Creation of 3D C-space along tool path.

A collision check method is proposed to make use of the inside-outside distinction of tool shape [2]. Using this method, rapid processing is conducted to approximate the tool shape by designating a set of check points in the circumferential and longitudinal directions of the tool, as shown in **Fig. 6**. A collision check is performed by examining whether the check points exist within the workpiece. In the event of collision, the tool attitude at the cutting point is changed by finding the collision avoidance vector ***D***. The collision avoidance vector ***D*** is determined in the following manner.

First, the number of check points, C_i, within the workpiece along a row Q_i is counted using the inside-outside distinction of the tool shape. The collision avoidance vector ***D*** is defined using C_i, as shown in **Fig. 6**, with C_i playing the role of a weight. The direction of collision avoidance is determined; however, the magnitude of the vector ***D*** is not yet determined. The original tool axis vector is inclined toward the vector ***D*** by degrees to finding the nearest collision-free attitude of the tool. The collision avoidance tool axis vector is obtained by adding the vector ***D*** to the original tool axis vector.

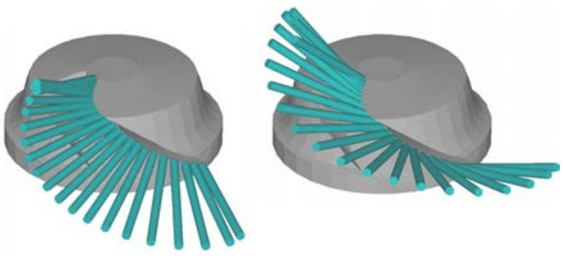
This approach to finding collision avoidance tool attitude has been successfully employed in 5-axis control machining but is considered to be a type of trial-and-error methods. The concept of a C-space, which is used in robot motion planning [3], has also been applied to the collision avoidance problem in 5-axis control machining.

Figure 7 shows the relationship between the tool attitude and the cutting point. The tool attitude stands for the tool axis vector T, which is inclined by the angle θ from the normal vector (Z-axis) and is rotated by the angle ϕ from the tool feed direction (X-axis).

At each cutting point at which a tool collision is detected, a two-dimensional (2D) C-space is generated using a 3D CAD model [4]. A 2D C-space devised in this study shows the relationship between all tool attitudes and the existence of collision, as illustrated in **Fig. 8**. The distance between a point in the 2D C-space and the origin of the 2D C-space corresponds to the inclination angle θ, and the rotational angle around the origin corresponds to the angle ϕ. In other words, a point in the C-space corresponds to only one tool attitude in the real space. Let us call these points in C-space "tool attitude points." By projecting the obstacles onto the C-space as the "collision area," collisions can be easily detected by judging whether a point in the C-space lies within the "collision area."

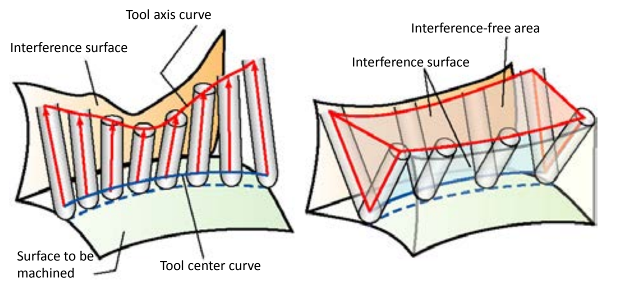
A 3D C-space is a 2D C-space extended by adding a parameter representing the tool movement. **Fig. 9** shows the concept of tool path generation based on a 3D C-space. **Fig. 9(a)** is a trajectory curve $C(s)$ of the tool center point of a ball end mill from the start point to the end point. The boundaries of the "free area" of the 2D C-space, except for the collision area, are arranged in the 3D C-space represented by three parameters: θ, ϕ, and s. A tube is constructed to interpolate the boundaries of the free area. The inside of the tube corresponds to only one combination of a tool center position and attitude [5].

If the curve running from the front of the tube to the back is found and does not intersect with the inside surface of the tube, collision-free CL data can be obtained



(a) Moving tool halfway between both collision surfaces
(b) Inclining tool forward in addition to (a)

Fig. 10. Influence of strategy on tool attitude for the same tool path.



(a) Boundary curved surface creation based on tool center curve
(b) Interference-free area generation between boundary curved surfaces

Fig. 11. Interference-free tool path generation based on boundary curved surfaces.

that takes the continuity of attitude change into consideration. The employment of a 3D C-space allows us to transform a complicated tool path generation in the real space into a simpler one, that is, to find the curve passing through the inside of the tube. There is a serious problem concerning how to determine the curve $C(s)$ because there are an infinite number of curves that do not intersect with the tube. Thus, the curve should be restrained by various machining conditions, such as the safest tool path, the most suitable tool attitude and so on. The determination of the curve $C(s)$ makes it possible to generate a tool path that reflects a user's machining strategy. **Fig. 10** illustrates the determination of the safest tool path and a suitable tool attitude with respect to the machining surface. The machining strategy has been found to have an influence on the tool attitude, even for the same tool path. The concept of a 3D C-space has also been applied to more complicated workpiece machining [6].

Although the use of a 3D C-space is a sophisticated collision avoidance method, it requires a long calculation time, which is a problem. Another method has been proposed that uses a curved surface interpolation to generate tool axis vectors along a tool path on the basis of the concept of an "interference-free curved surface" [7], rather than determining tool axis vectors at every cutting point, as illustrated in **Fig. 11**. By extending the "interference-free curved surface concept," an "interference-free space" can be defined with respect to the surface to be machined. The division of this space along each tool path makes it possible to identify corresponding interference-free curved surfaces, which can be used to easily determine all cutting points and tool attitudes. As a result, the method can drastically reduce the processing time required to obtain collision avoidance CL data [8].

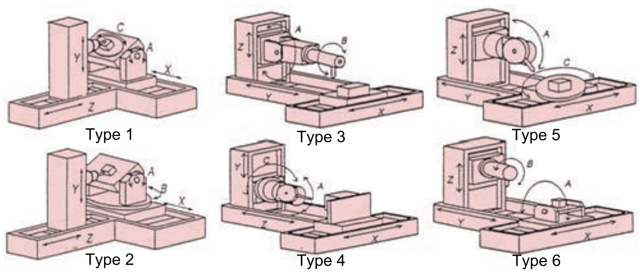


Fig. 12. Typical structures of 5-axis control machine tool.

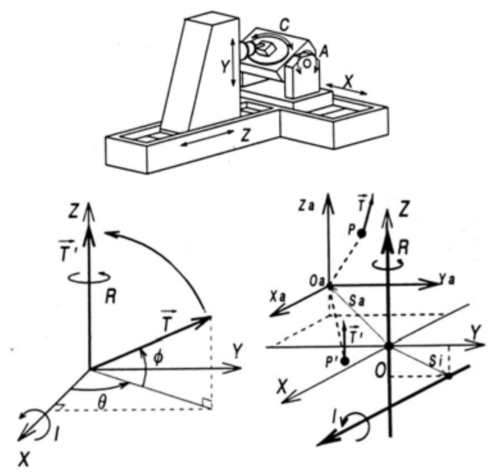
5. Transformation of CL Data to NC Data by Post-Processor

As mentioned previously, the main-processor generates collision-free CL data in the work coordinate system, based on 3D CAD data for the workpiece. The CL data generated by the 3D CAD system has nothing to do with the actual machine tool structure and cannot be used in machining operations without being transformed to NC data. The transformation of CL data to NC data for machine tools is performed by the post-processor. The role of the post-processors is to generate actual NC data by taking into account the actual machine tool structure.

Figure 12 shows the typical structures of a 5-axis control machining center consisting of three translational axes and two rotational movements of rotation and tilt. As the figure shows, the structures can be classified mainly into three categories according to the arrangement of the two rotational movement units: table-tilting structures (Types 1 and 2), spindle-tilting structures (Types 3 and 4), and spindle- and table-tilting structures (Types 5 and 6).

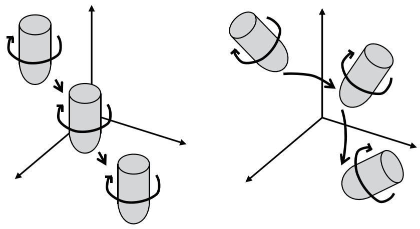
Using the Type 1 structure, let us explain briefly the transformation of CL data to NC data [9], assuming that the directions of the X, Y and Z-axes in the workpiece coordinate system (WCS) are equal to those in the machine coordinate system (MCS). First, the rotation angles of the table, r and i, are determined to make the tool axis correspond to the Z-axis because the direction of the main spindle with a cutting tool is defined as the Z-axis in the MCS. Then, the coordinate values of the tool center point, P, in the WCS becomes P' in the MCS after the rotational movement, as illustrated in **Fig. 13(a)**. Let us consider this rotational movement in the MCS, as shown in **Fig. 13(b)**, where the difference vector of the i-axis from the origin within the YZ plane and the position vector of the origin in the MCS are $\boldsymbol{S}_i$ and $\boldsymbol{S}_a$, respectively. The relationship between P and P' is then given by the following equation:

$$P' = M(\boldsymbol{S}_i - \boldsymbol{S}_a)E^x(i)M(-\boldsymbol{S}_i)E^z(r)M(\boldsymbol{S}_a)P,$$



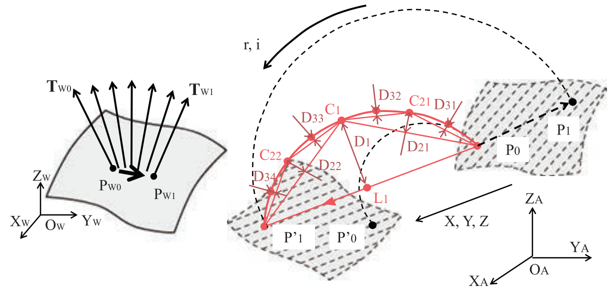
(a) Workpiece coordinate system (b) Machine coordinate system

Fig. 13. Coordinate transformation of Type 1.



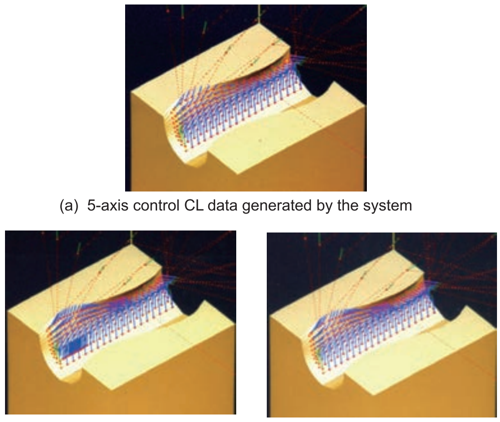
(a) 3-axis control (b) 5-axis control

Fig. 14. Actual tool movement in simultaneous 5-axis control.



(a) Tool path in the workpiece coordinate (b) Tool path in the machine coordinate

Fig. 15. Necessity of linearization.



(a) 5-axis control CL data generated by the system

(b) NC data in Type 1 (c) NC data in Type 2

Fig. 16. Effect of post-processor.

where $M(\boldsymbol{a})$ is a matrix for the translational movement by the vector $\boldsymbol{a}$ and $E^x(\beta)$ is a matrix for the rotational movement around the X-axis by angle β. For the other types of structures, the same method of translation is applicable, taking into account the machine tool structure. The position of the cutting tool in the MCS, P', is that in the NC data.

Let us consider linear movement over a short distance because the tool path required to create a sculptured surface consisting of curved lines is usually a set of short line segments. In simultaneous 5-axis control machining, the movement of the tool axis to direct it to the Z-axis in the MCS accompanies the rotation of the table, which results in unexpected movement of the tool, as illustrated in **Fig. 14**. Although this poses no problem in 3-axis control, the deviation along the tool path takes place in the simultaneous 5-axis control even though the line segment is short.

Let us suppose that the tool center moves from P_{w0} to P_{w1} in the WCS, as illustrated in **Fig. 15(a)**, while changing the tool axis vector from $\boldsymbol{T}_{w0}$ to $\boldsymbol{T}_{w1}$. The tool center then moves from P to P_1 in the MCS, as illustrated in **Fig. 15(b)**. P' and P'_1 are the points corresponding to the points P and P_1 due to the rotation of r of the table and the tilt i. The tool actually moves from P to P'_1, as shown by the bold solid circular arc, in spite of the linear movement. The deviation D_1 takes place and affects the machining accuracy. To suppress the deviation, the tool path is divided into two paths at the point C_1 based on the assumption that the maximum deviation takes place in the middle of the tool path. The new deviations D_{21} and D_{22} can then be calculated. Such a division continues until the deviation is less than the tolerance limit. As a result, the number of divisions increases, which causes an increase in the amount of NC data. This operation is called "linearization," and is very important to generating correct NC data.

Figure 16 demonstrates the effect of linearization. **Fig. 16(a)** shows the tool center points and the tool axis vectors at each cutting point for collision-free CL data generated by the main-processor. Based on the CL data, the post-processor generates NC data for 5-axis control machining centers of Types 1 and 2. **Figs. 16(b)** and **(c)** show the results of "linearization" for these two types of structures, respectively.

In place of the linearization operation program, an NC controller with a tool end point control function can carry out "linearization," as illustrated in **Fig. 17** [10].

6. Efficient Machining

6.1. Curved Interpolation

From the perspective of machining efficiency, curved interpolation using a nonuniform rational B-spline (NURBS) is very useful. Because NC data for multi-axis control machining are typically created in current CAM

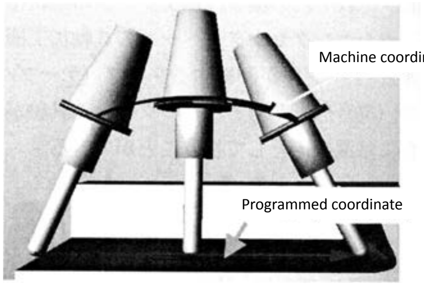


Fig. 17. Tool end point control to carry out linearization within NC controller.

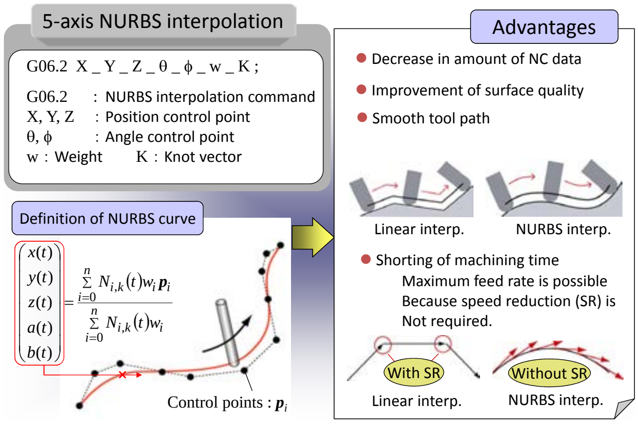


Fig. 18. Advantages of curved interpolation.

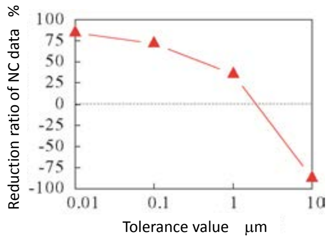


Fig. 19. Reduction ratio of amount of NC data.

systems by expressing a trajectory curve for the tool center point with small line segments, a very small tolerance must be set to fabricate workpieces with high accuracy. The tolerance is defined as the error caused by expressing an arbitrary tool path with small line segments whose lengths are typically in the range of approximately 1 to 10 μm. A small tolerance inevitably increases the volume of NC data generated and puts an enormous burden on NC controllers. As a result, a small tolerance may prevent machine tools from increasing the feed rate. In addition, a small tolerance reduces the tool movement speed to moderate the tool path errors that occur at the corners of small segments.

To solve these problems and maximize 5-axis machine tool performances, 5-axis NURBS-interpolated machining can be performed [11, 12]. The development of CAM systems that can generate 5-axis NURBS-interpolated NC data is much anticipated. NURBS is a mathematical formula that is used to express free-form curves and surfaces in most current CAM systems. 5-axis NURBS-interpolated NC data mainly consist of a few parameters required to define free-form curves in CAD systems. When the NC data are transmitted to an NC controller, free-form curves are immediately interpolated using the parameters within an NC controller, and then a tool can move smoothly along the interpolated curves. Consequently, 5-axis NURBS-interpolated machining is equivalent to 5-axis linearly interpolated machining, whose tolerance is very small. Nevertheless, the NC data volume associated with NURBS-interpolated machining is smaller than that associated with linear interpolated machining, as illustrated in **Fig. 18**.

Curve-interpolated machining has been applied successfully to 3-axis control machining but not to 5-axis control machining. One reason for this is that useful CAM systems that can generate 5-axis curve-interpolated NC data do not exist. The existing CAM systems generally transform linearly interpolated NC data into curve-interpolated data by the least squares method, which requires many calculation processes. When a CAM system receives an overwhelming amount of linearly interpolated NC data, it takes a long time to convert data into curve-interpolated data. Furthermore, two types of error are associated with the generation of NC data. One type of error is the linear approximation error inherent in the original linearly interpolated data; the other is the error associated with least squares approximation. A main processor developed against such a background can generate curve-interpolated CL data directly from CAD modeling data [13], thus directly employing CAD modeling data in machining without introducing linear approximation error. However, this approach also requires long calculation times to generate CL data because collision avoidance must be considered for each tool path. Furthermore, a post-processor for that particular type of main-processor has not been developed yet.

Accordingly, a more useful CAM system has been developed that can effectively generate curve-interpolated CL data directly from CAD modeling data, while considering collision avoidance between a tool and a workpiece. This system can also convert the CL data into curve-interpolated NC data. In the main-processor of the system, collision-free space is defined in advance, and the CL data are generated by utilizing the space. Because the space is formed in one process of collision avoidance, the calculation time required to generate the CL data is drastically reduced in comparison to the previously described methods. In the system's post-processor, the curve-interpolated NC data are efficiently converted from the CL data [14]. This system can address various axis compositions of 5-axis control machine tools. To check the feasibility of this CAM system, the reduction rate of the NC data is examined. The results show that reducing the tolerance dramatically reduces the amount of NC data, as shown in **Fig. 19**. An experiment involving machining of a cylindrical surface using a ball end mill shows the difference in surface quality achieved using linearly interpo-

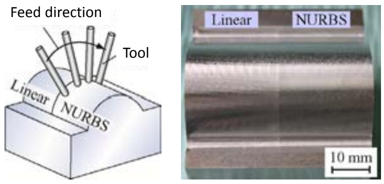


Fig. 20. Comparison of machined surface between linear interpolation and NURBS interpolation.

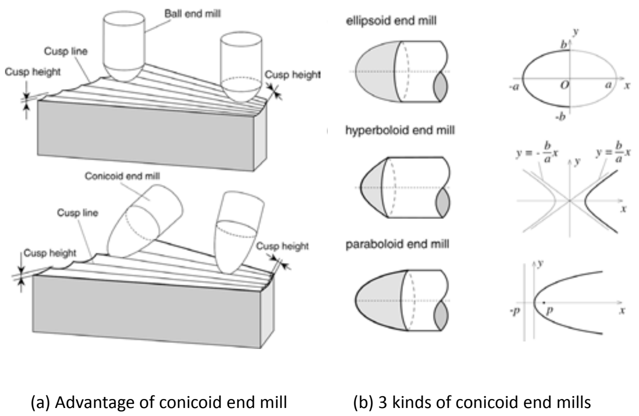


Fig. 21. Conicoid end mill employing conic curves.

lated NC data and that achieved using curve-interpolated data, as shown in **Fig. 20**.

6.2. Conicoid End Mill

A ball end mill is typically used to finish sculptured surfaces, and the smallest radius used depends on the center radius of curvature of all surfaces to be machined. This results in long machining times because the number of tool paths increase for sculptured surfaces with large radii of curvature. To solve this problem, a ball end mill with a changeable radius, as illustrated in **Fig. 21(a)**, would be preferable: however, such a ball end mill does not exist. Thus, a conicoid end mill has been devised, using a conic curve. A conicoid end mill consists of a rotational body with three types of conic curves: an ellipsoid end mill, a hyperboloid end mill, and a paraboloid end mill, as illustrated in **Fig. 21(b)**. Their curvature radii can be changed along their cutting edges, which means that 5-axis control is required to make the most of a conicoid end mill. The change in the attitude of a conicoid end mill is conducted within a plane perpendicular to the feed direction, so the problem becomes simple. An example of machining using this type of end mill is described in the literature [15].

The manufacture of conicoid end mills is discussed in the literature [16]. Of course, 5-axis control is required to manufacture a conicoid end mill using a grinding machine.

6.3. Rough Cutting Using 3+2-Axis Control Machining

Three+two-axis control machining means milling with the rotational axes clamped in some direction, as illustrated in **Fig. 22**. Compared to 5-axis control milling, it is simpler to generate a tool path in this manner and enables the tool to feed quickly. **Fig. 23** shows an example application of 3+2-axis control face milling for rough cutting [17]. The rough cutting time is much shorter than in typical 3-axis control milling.

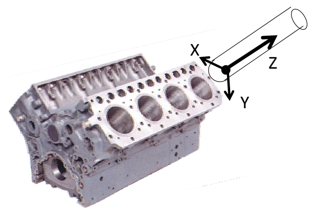


Fig. 22. Shape suitable for 3+2-axis control machining.

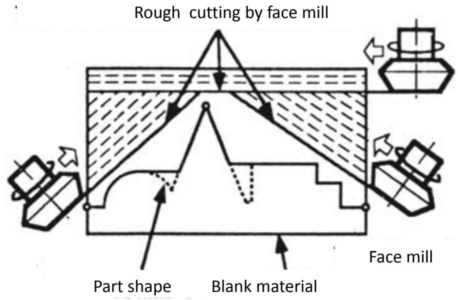


Fig. 23. Rough cutting system for face milling.

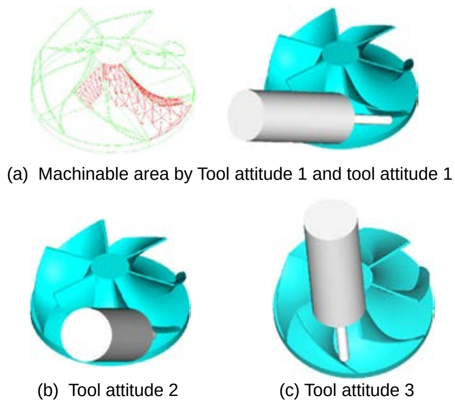


Fig. 24. Tool attitudes obtained.

Efficient 3+2-axis control rough milling of an arbitrarily curved surface requires the determination of the combination of tooling and the tool attitude. That is, a process planning system is required. Let us introduce an automatic process planning system [18] in which the tool attitude candidates are searched after the machinable area of each tool attitude is calculated by dividing the surface to be machined into small polygons. Next, the combination of tool attitude and tool diameter is determined by applying a multi-stage decision process. Minimizing the change in tool attitude permits highly efficient rough cutting. The effectiveness of the process planning for 3+2-axis control rough milling is demonstrated by a machining simulation of an impeller, illustrated in **Fig. 24**, which shows three types of tool attitudes for rough cutting.

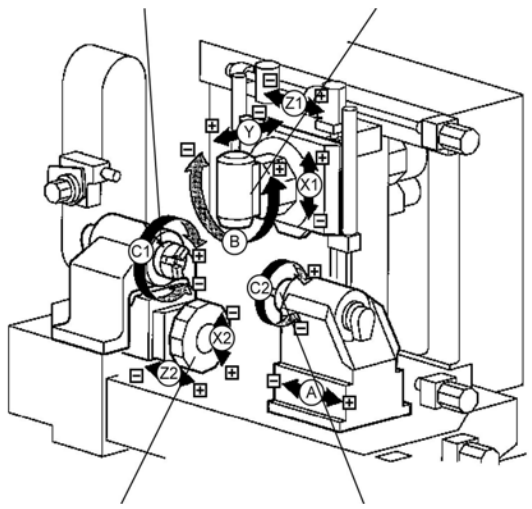


Fig. 25. Example of multi-axis control multi-tasking machine (MORISEIKI Co.).

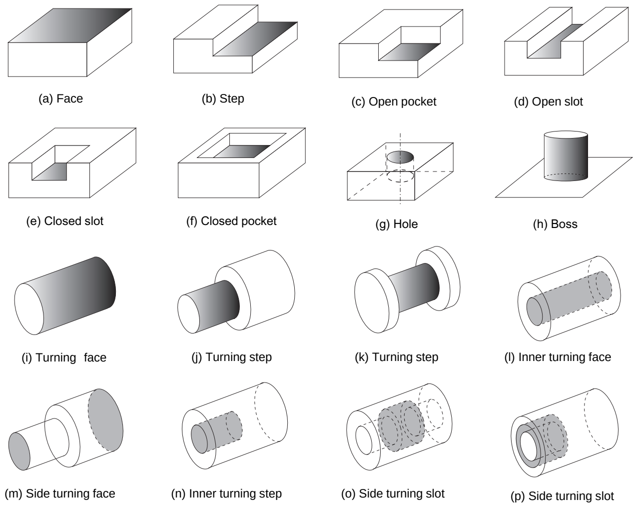


Fig. 26. Features prepared in the system.

7. Complicated Shape Manufacture Using a Multi-Axis Control Multi-Tasking Machine

Manufacturing tends to be characterized by highly mixed low-volume production because product models change frequently and new products are released in quick succession. Thus, it is important to minimize the development and manufacturing lead time of products. Highly efficient machining using multi-tasking machines has attracted attention as a means of shortening manufacturing lead times [19]. Multi-tasking machines perform both milling and turning functions and generally have two main spindles and multiple tool posts. **Fig. 25** illustrates a multi-tasking machine.

The use of multi-tasking machines offers many advantages. However, machining using a multi-tasking machine is usually difficult because of the highly complicated machine tool structure. Thus, NC programming for multi-tasking machines requires considerable time and labor. In addition, self-collision of the machine tool, meaning collisions between the machine tool components during machining, has to be considered. Therefore, a CAM system must minimize the time and labor associated with NC programming to perform highly efficient machining.

There are some CAM systems for multi-tasking machines, but these systems have some problems. For example, the parts must be chosen one by one to generate tool paths, and the self-collision of the machine tools cannot be detected unless the machine motion is completely simulated [20]. Furthermore, the NC program has to be revised manually by trial and error when self-collision is detected. Another problem with these systems is the need for operators to decide the order of turning and milling. The time and labor required for NC programming are not necessarily reduced.

An unprecedented CAM system has been developed that can achieve process planning and generate NC programs automatically for multi-tasking machines, taking self-collision into consideration, based on 3D CAD data. With this CAM system, the machining features of workpieces are recognized, tool paths are automatically generated for milling and turning, and the machining order is determined. Following the development of a CAM system for 3-axis-control milling [21], a CAM system capable of 5-axis control milling was developed that performs self-collision avoidance of machine tools [22].

The CAM system divides a target shape defined by 3D CAD into a set of unit solids called a “shell.” The parts to be made by turning are recognized, and the tool path for turning is generated. The parts to be made by milling are then recognized, and the tool path for milling is generated, assuming that the blank shape is cylindrical. The CAM system recognizes the “shell” of a cylinder and a circular truncated cone, and generates the tool paths for turning. The system successively recognizes the milling parts of the “shell” on the basis of twelve types of shape patterns, as shown in **Fig. 26**. If the shape pattern has an overhanging portion, the system forms several planes and arranges tool paths on the planes to remove the overhanging portion.

Using this system, tool paths are generated for a target shape with an overhanging portion and sculptured surfaces as shown in **Fig. 27**. Ball-end milling tool paths for machining the overhanging portion and sculptured surfaces are shown in **Fig. 28**. The generated tool paths successfully perform the milling without any inappropriate interference. A machining experiment was conducted using a 5-axis control multi-tasking machine. **Fig. 29** shows the machined result, which demonstrates that the system is to perform process planning and generate tool paths automatically, based on the cylindrical blank material shape and the target shape defined by 3D CAD. The system was further expanded to improve the logic of process planning by extracting machining features for more complicated workpiece shapes [23].

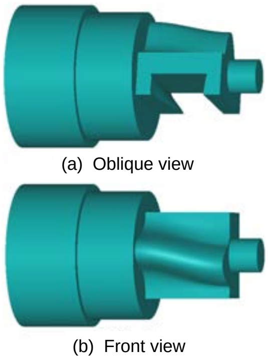


Fig. 27. 3D model with overhanging portion and sculptured surface.

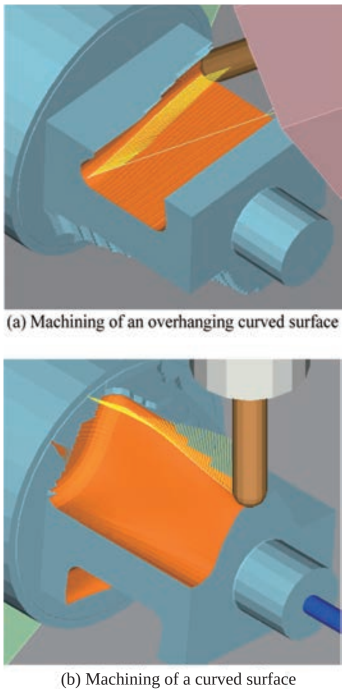


Fig. 28. Milling simulation.

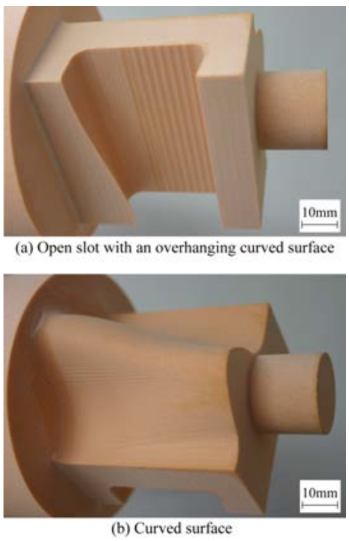


Fig. 29. Machined results.

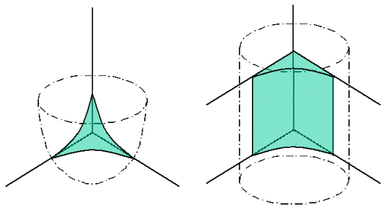


Fig. 30. Area at the corner not removable by rotational cutting tools.

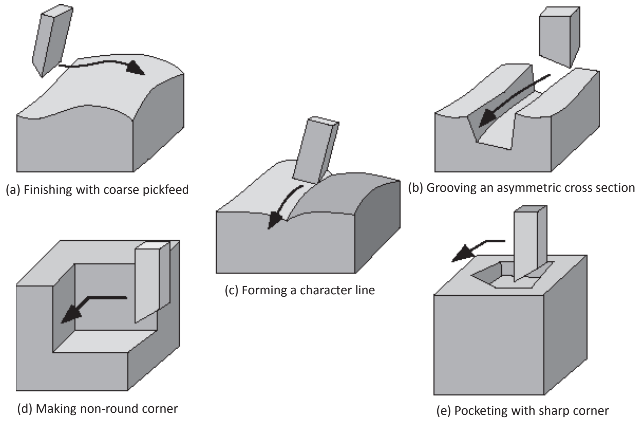


Fig. 31. Characteristics of 6-axis control machining.

8. Unique Shape Creation by 6-Axis Control Machining

6-axis control machining with a non-rotational cutting tool is suitable for finishing processes because the cutting speed is equal to the feed rate, which results in low machining efficiency. In addition, the use of rotational cutting tools results in irremovable material, as shown in **Fig. 30**, even if the tool diameter is small. The most desirable approach is to make the most of conventional machining with rotational cutting tools and up to 5-axis control, taking the total machining efficiency into account. Thus, 6-axis control machining has to be employed in the finishing process to accomplish specific machining processes.

Typical 6-axis control machining is illustrated in **Fig. 31**, where **(a)** shows finishing with a coarse pickfeed: **(b)** shows grooving with an asymmetric cross-section on a sculptured surface: **(c)** shows forming of a character line, that is, a line of intersection between sculptured surfaces: **(d)** shows the making of a non-round corner: and **(e)** shows pocketing with a sharp corner. These shapes cannot be machined using of rotational cutting tools.

Let us demonstrate 6-axis control grooving of an asymmetric cross-section on a sculptured surface [24]. First, a groove route and its cross-section are defined. Then, the groove route is projected onto a sculptured surface, as illustrated in **Fig. 32**. The case of a steep groove path, for which cuts may overlap each other on the inner side, is shown in **Fig. 33(a)**. Although a non-rotational cutting tool has a certain clearance angle at the side of the edge, the reverse side of the tool may collide with the groove

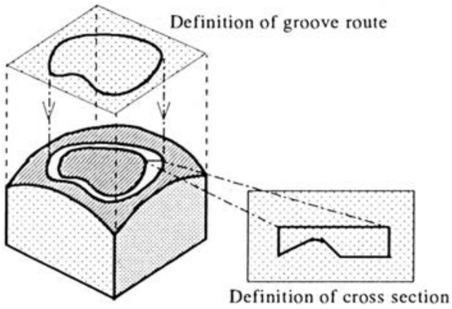
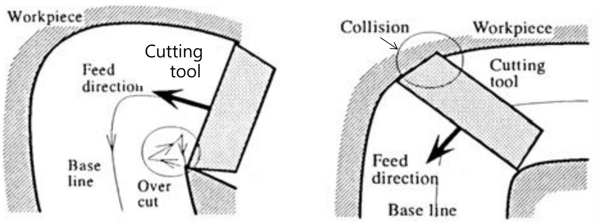


Fig. 32. Mapped asymmetrical cross section along a curved line on a sculptured surface.



(a) Overcut of groove route (b) Contact with groove

Fig. 33. Tool interference along an asymmetrical groove route.

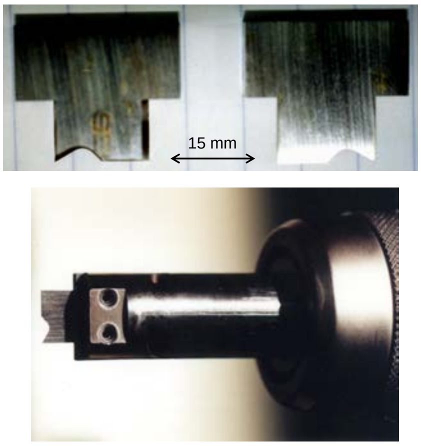


Fig. 34. Non-rotational cutting tool for asymmetrical groove shape.

side, as shown in **Fig. 33(b)**. These cases correspond to collisions and cannot be machined.

6-axis control grooving was performed on a sculptured surface machined by 5-axis control finishing with a 10-mm-diameter ball-end mill after 3-axis control rough machining with a 10-mm-diameter flat-end mill. The workpiece was chemically treated wood 200 mm × 200 mm × 150 mm in size. The width of the asymmetric groove was 15 mm. The width, clearance angle, and thickness of the non-rotational cutting tool were 15 mm, 10°, and 6 mm, respectively, as shown in **Fig. 34**. The feed rate is set to be 600 mm/min, and the depth of cut per one cutting was 20 μm. The grooving operation was repeated many times to reach the desired depth of the groove.

The groove and the CL data for the sculptured surface

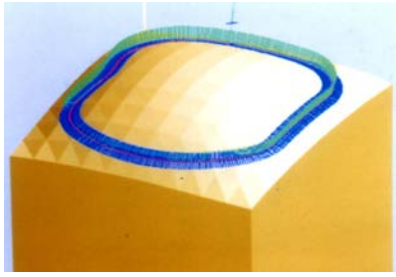


Fig. 35. Generated cutter location data for groove with asymmetrical cross section.

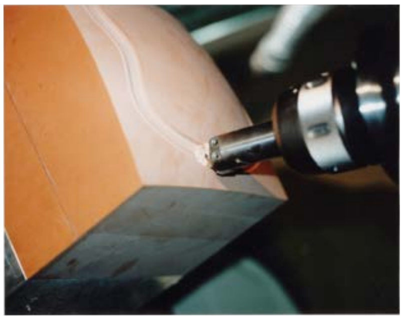


Fig. 36. Non-rotational cutter movement for grooving.

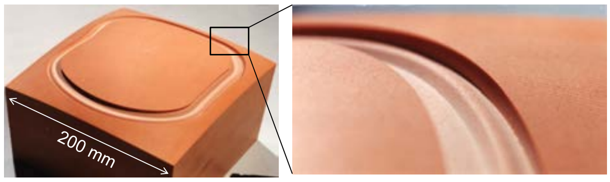


Fig. 37. Groove created with asymmetrical cross section on a sculptured surface.

are shown in **Fig. 35**. **Fig. 36** shows the actual 6-axis control grooving. The machined workpiece is shown together with an enlarged portion in **Fig. 37**. The groove shape on a sculptured surface is the reverse of the cutter shape shown in **Fig. 34**. The total cutting time was approximately 225 min.

More complicated grooving methods have been developed by applying ultrasonic vibration so that the low cutting speed of 6-axis control machining can be improved [25–27].

9. Conclusion

CAM systems make the most of the large number of multi-axis control NC machine tools that are used in machine shops and make the most of the many advantages of these tools. The article describes the structure and the state of the art of CAM systems for multi-axis control machining, together with 5-axis control machine tools. In addition, an efficient machining method and unique shape creation using 6-axis control machining are also described as example of future developments of this technology.

References:

[1] K. Nakamoto and K. Shirase, "Simulation Technologies for the Development of an Autonomous and Intelligent Machine Tools," Int. J. of Automation Technology, Vol.7, No.1, pp. 6-15, 2013.

[2] Y. Takeuchi and T. Idemura, "5-Axis Control Machining and Grinding Based on Solid Model," Annals of the CIRP, Vol.40/1, pp. 455-458, 1991.

[3] T. Lozano-Perez, "Special planning: a configuration space approach," IEEE Trans. on Computers, Vol.32, No.2, pp. 108-120, 1983.

[4] K. Morishige, K. Kase, and Y. Takeuchi, "Collision-Free Tool Path Generation Using 2-Dimensional C-Space for 5-Axis Control Machining," Int. J. of Advanced Manufacturing Technology, Vol.13, No.6, pp. 393-400, 1997.

[5] K. Morishige, Y. Takeuchi, and K. Kase, "Tool Path Generation Using C-Space for 5-Axis Control machining," J. of Manufacturing Science and Engineering, Trans. of the ASME, Vol.121, No.1, pp. 144-149, 1999.

[6] K. Morishige and Y. Takeuchi, "Strategic Tool Attitude Determination for Five-Axis Control Machining Based on Configuration Space," CIRP-J. of Manufacturing Systems, Vol.31, No.3 pp. 247-252, 2002.

[7] M. Morikawa, T. Ishida, K. Teramoto, and Y. Takeuch, "5-Axis Control Tool Path Generation Using Curved Surface Interpolation," JSME Int. J. Series C, Vol.49, No.4, pp. 1209-1214, 2006.

[8] T. Inoue, T. Ishida, and Y. Takeuchi, "Rapid 5-Axis Control Tool Path Generation by Means of Interference-free Space Concept," Proc. of 4th Int. Conf. on LEM21, JSME, Fukuoka pp. 489-494, 2007.

[9] Y. Takeuchi and T. Watanabe, "Generation of 5-Axis Control Collision-Free Tool Path and Postprocessing for NC Data," Annals of the CIRP, Vol.41/1 pp. 539-542, 1992.

[10] M. Sudo, "The Advanced Control Technologies for 5-axis Machining," Proc. of 12th Int. Machine Tool Engineers' Conf. (IMEC), Tokyo, pp. 248-257, 2006.

[11] S. Takahashi, K. Morishige, and Y. Takeuchi, "NC Data Generation for Five-axis Control Machining Using Curved Interpolation (Application of Five-dimensional Non-Uniform B-Spline Curve)," J. of the Japan Society for Precision Engineering, Vol.65, No.12, pp. 1740-1744, 1999 (in Japanese).

[12] K. Konishi, Y. Fukuda, and K. Iwata, "Development of CAM system for 5-Axis Controlled Machine Tool Using NURBS Interpolation," Trans. of the Japan Society of Mechanical Engineers, Series C, Vol.67, No.657, pp. 1675-1681, 2001 (in Japanese).

[13] Y. Tominaga, K. Teramoto, T. Ishida, H. Honda, and Y. Takeuchi, "Curved Interpolation CL Data Creation for 5-axis Control Machining Expressed by Non-Uniform B-Spline," Trans. of the Japan Society of Mechanical Engineers, Series C, Vol.72, No.719, pp. 2286-2292, 2006 (in Japanese).

[14] Y. Ueda, T. Ishida, and Y. Takeuchi, "Development of CAM System for 5-axis NURBS Interpolated Machining (NC Data Generation by Generalized Post-Processor)," Trans. of the Japan Society of Mechanical Engineers, Series C, Vol.75, No.749, pp. 216-222, 2009 (in Japanese).

[15] K. Morishige, T. Nasu, and Y. Takeuchi, "Five-Axis Control Sculptured Surface Machining Using Conicoid End Mill," G. J. Olling, B. K. Choi, and R. B. Jerard (Eds.), Machining Impossible Shapes, pp. 366-375, 1998.

[16] S. Ishizuka, K. Morishige, K. Kase, and Y. Takeuchi, "Development of Tool Grinding System for Conicoid End Mill," J. of JSPE, Vol.64, No.10, pp. 1456-1460, 1998 (in Japanese).

[17] H. Suzuki, Y. Kuwano, K. Goto, Y. Takeuchi, and M. Sato, "Development of CAM System for 5-Axis Controlled Machine Tools," Proc. 23rd North American Metal Research Conf., NAMRI/SME pp. 187-192, 1995.

[18] T. Umehara, K. Nakamoto, T. Ishida, and Y. Takeuchi, "Development of a Process Planning System for 3+2 Control Rough Milling," Proc. of Int. Symp. on Flexible Automation, CD-ROM (JPL2660), pp. 1-6, 2010.

[19] T. Moriwaki, "Multi-functional Machine Tool," Annals of the CIRP, Vol.57/2, pp. 736-749, 2008.

[20] Y. f. Chen, Z. d. Huang, L. p. Chen, and Q. f. Wang, "Parametric Process Planning Based on Feature Parameters of Parts," Int. J. of Advanced Manufacturing Technology, Springer, Vol.28, No.78, pp. 727-736, 2006.

[21] K. Kubota, T. Kotani, K. Nakamoto, T. Ishida, and Y. Takeuchi, "Development of CAM System for Multi-Tasking Machine Tools," J. of Adv. Mech. Design, Systems, and Manuf., JSME, Vol.4, No.5, pp. 816-826, 2010.

[22] K. Nakamoto, K. Kubota, T. Ishida, and Y. Takeuchi, "Development of 5-axis Control CAM System for Multi-tasking Machine Tools," Proc. of 45st CIRP Conf. on Manufacturing Systems (CIRP-CMS2012), Athens, pp. 266-270, 2012.

[23] K. Nakamoto, D. Hamada, and Y. Takeuchi, "Development of CAPP System for Multi-tasking Machining of Complex Shapes," Proc. of 6th Int. Conf. on LEM21, JSME, Matsushima, SD-Card, pp. 527-530, 2013.

[24] Y. Takeuchi, M. Sato, and H. Suzuki, "New Concept of Machining by Means of Six-Axis Control," Annals of the CIRP, Vol.43/1, pp. 341-344, 1994.

[25] F. H. Japitana, K. Morishige, and Y. Takeuchi, "6-Axis Controlled Ultrasonic Vibration Cutting in Fabrication of Sharp Corner," Int. J. of Advanced Manufacturing Technology, Vol.21, No.8, pp. 564-570, 2003.

[26] F. H. Japitana, K. Morishige, and Y. Takeuchi, "6-Axis Control Cutting of Overhanging Curved Grooves by Means of Non-Rotational Tool with Application of Ultrasonic Vibrations," Int. J. of Machine Tools & Manufacture, Vol.44, pp. 479-486, 2004.

[27] F. H. Japitana, K. Morishige, and Y. Takeuchi, "Highly efficient manufacture of groove with sharp corner on adjoining surfaces by 6-axis control ultrasonic vibration cutting," Precision Engineering, Vol.29, pp. 431-439, 2005.

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