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Creation of Curved Surface by Lathe Turning -Development of CAM system using original tool layout-

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Abstract

The machining of 3D curved surfaces with an un-axisymmetric axis by lathe turning is proposed considering the best machinable tool layout. The best offset tool layout from the central axis of a spindle enables us to machine curved surfaces and to obtain a long tool life for hard material workpieces using a rotary tool. A dedicated NC program for the 3D surface using the original CAM system has been developed and applied to what. The machining results and the validity of our system are evaluated in this paper.

Keywords: Lathe cutting, Grinding, Multiaxis control, Non-circle cutting, 3D surface, CAD/CAM

1. Introduction

A new CNC lathe driven by a linear motor has been developed to improve its productivity through high-speed motion. Recently, a linear motor-driven lathe as a typical high-speed machining tool has been offered commercially. The merit of this system is the reduction in air cut time and consequently the shortening of the limited machining time. There are a few applications that take advantage of the high-speed feed rate of this NC lathe.

On the other hand, the machining of curved surfaces with complex non-axisymmetric shapes such as eccentric axes, and conical cams is realized by milling and grinding [1]. In this case, there is a serious problem. It takes a long time to machine by milling or grinding. Furthermore, the machining point between a curved surface and a milling tool or a grinding wheel is a single point contact, the just as in same as lathe turning.

Two methods of machining have been introduced by machine tool companies [2]-[5]. One is plunge grinding, which is used for machining 3D curved surface profiles by calculating the NC code for each cross sectional profile along the Z-axis direction [6]. This method is the most practical in the manufacturing industry. The only key change is in the profile of the grinding wheel, according to the 3D curved surface profile. Although no modification of the grinding machine is needed in this method, there exists a serious problem, that is, the profile is strictly limited by the radius of the grinding wheel.

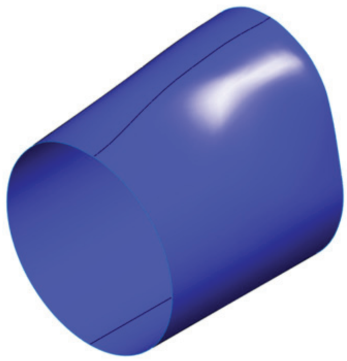

Fig. 1 Example of un-axisymmetric curved surface

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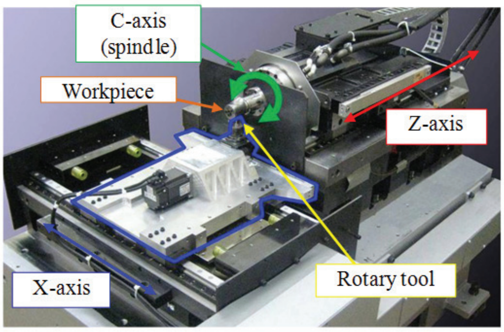

Fig.2 Appearance of linear-motor-driven NC lathe

Table 1 Specifications of lathe developed

Items of specification		
Head stock	Max. spindle speed [min^{-1}]	10000
	Power of main motor [kW]	1.0/2.64
	Storoke on Z direction [mm]	200
	Max. acceleration on Z [m/s^2]	12.1(1.23G)
Carriage	Storoke on X direction [mm]	90
	Max. acceleration on X [m/s2]	98.0(10G)
	Weight [kg]	26.4
Bed	Size [mm]	720×498×1300

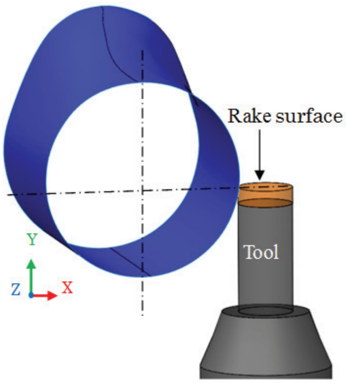

Fig.3 Conventional tool layout of curved surface by lathe cutting

The other method is traverse grinding [7]. This method is rather complex to apply for practical use. This conventional machining method cannot achieve significant advancement in productivity.

Therefore, a new cutting process instead of milling or grinding is strongly required by the manufacturing industry.

Then, we apply lathe turning to the machining of a curved surface. Our new prototype CNC lathe has been developed for machining curved profiles by turning instead of by conventional machining. The key factor for a breakthrough is to speed up tool posting on a moving table.

In this paper, the best machinable tool layout by lathe turning has been proposed for machining curved non-axisymmetric surfaces. A new rotary tool is used to obtain a long tool life for the hard material workpiece.

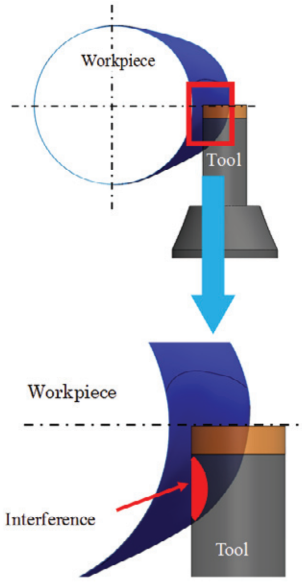

Fig.4 Occurrence of interference between tool flank surface and workpiece

A dedicated NC program for curved surfaces is needed for machining curved surfaces. An original CAM system has also been developed. This system enables us to automatically derive such an NC program by the proposed method. The creation of a dedicated NC program including some conversion processes is needed for building curved paths for lathe turning. To create an efficient and exact tool path from shape data, such conversion processes should be calculated carefully. The original CAM system devised extracts the data of all the points on a curved surface from 3D CAD to obtain a precise tool path. Our original CAM system turns complex processes into simple processes and can sufficiently derive an accurate NC program.

In this report, the proposed system is also evaluated from the machining results of representative examples. The measurement results of the machined examples are reported.

2. Machining method for curved surfaces

Figure 1 shows an example of a workpiece with a curved surface profile. To machine this workpiece by lathe turning, a linear motor-driven NC lathe has been developed, which is shown in Fig. 2. The developed lathe has orthogonal 2 axes, and is of the Swiss type with two linear motors. Its main specifications are shown in Table 1.

Figure 3 shows the conventional tool layout. The Z-axis corresponds to the spindle rotational axis. In this figure, the horizontal center line of the spindle axis of the curved surface corresponds to the height of the tool rake surface set on the X-axis. A spindle axis, which holds a workpiece and rotates, and the C-axis, which can position rotational angle, are equipped on the Z-axis table. A linear encoder is set in both the X- and Z-axes. The least resolution is 10 nm. Encoders are set to minimize the effect of yawing motion and to detect accurate table positions. In the case of machining a curved surface, high-speed acceleration is not always needed for the Z and C-axes.

On the other hand, a high acceleration and a high response are needed for the X-axis. The C-axis is needed to rotate with a constant revolution and to follow the X- and Z-axes. Therefore, a linear motor is used to obtain a high acceleration for the X-axis table.

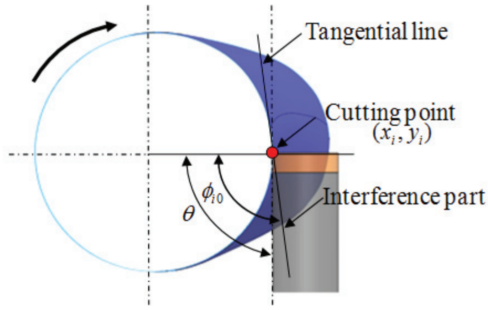

Fig.5 Interference part by conventional tool layout

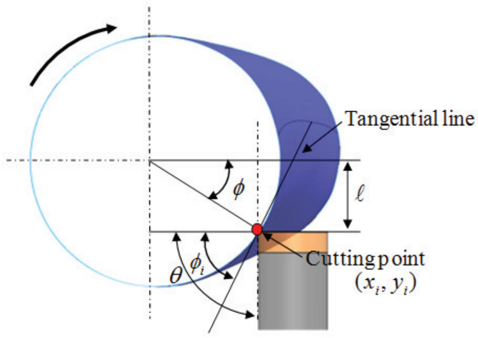

Fig.6 Proposed machinable tool layout

3. Proposed lathe cutting for curved surfaces

3.1. Proposed new tool

Figure 4 shows the conventional tool layout. In the case of lathe cutting, the height of the tool rake surface is set to that of the horizontal center line of the spindle rotational axis, as shown in Fig. 3. A non-axisymmetric curved surface always changes its radius depending on spindle rotational angle. Therefore, the interference between the tool flank face and the workpiece surface must be considered, as shown in Fig. 4. This result leads us to a failure in applying the turning process to the curved surface machining. Turning cannot avoid interferences at the curved surface using the conventional tool layout [8].

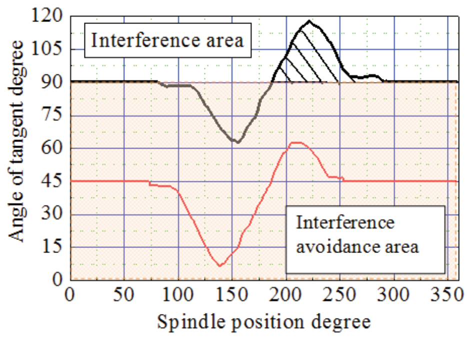

Fig.7 Detection of interference area by tool offset

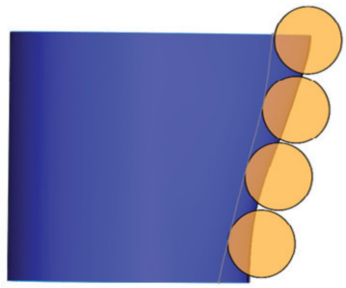

Fig.8 Top view of tool layout and calculated spline curve

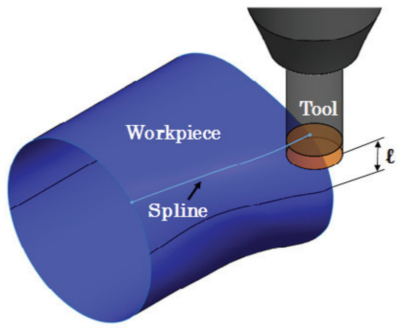

Fig.9 Isometric view of tool offset and calculated spline curve

To avoid interferences, the unique and processible tool layout for the curved surface has been proposed. The tool cutting edge always moves along the curved surface by the proposed method.

3.2. Detection of interference and avoidance method

The occurrence of the interference between the workpiece and the cutting tool can be avoided using a new tool layout. Interference is evaluated by the following method. The representative cross section is chosen and its tangential angle at the cutting point is calculated. Figure 5 shows the conventional tool layout.

ϕ_{i0} is the tangential angle at the cutting point on the curved surface, and θ is the angle between the tool rake face and the tool flank face. In this case, interference occurs when ϕ_{i0} becomes larger than θ. To avoid this interference problem, it is necessary for the tool to offset to the Y-direction, where the inclination angle ϕ_i is smaller than θ as shown in Fig. 6. ϕ is the angle determined tool offset at the cutting point. Figure 7 shows the change in the inclination angle ϕ_i at the representative cross-sectional contour of the workpiece.

Offset angle ϕ is generally set to be 90 degrees or less, the rotary tool is also in this range. From Fig. 7, a portion whose ϕ_{i0} exceeds 90 degrees can be seen at the spindle position from 180 to 270 degrees. In this range, interference occurred. The red line shows the result of change in inclination angle ϕ_i, where the tool offset ℓ is applied in the Y-direction. In this tool layout, when the change of ϕ_i does not exceed 90 degrees, no interference occurs.

4. Method of calculating tool path

In conventional lathe turning, the NC program is made from the X- and Z-axes. In the case of machining a curved surface, as shown in Fig. 1, the X-axis has to be changed depending on the rotational position of the spindle. Therefore, the synchronization control of the X-, Z- and C-axes must be considered to calculate the tool path of the curved surface by lathe turning. As the conventional CAM system does not accept our tool layout, an original CAM system has been developed.

4.1. Creation of NC program using original CAM system

The original CAM system requires 6 steps to obtain the NC program. The steps are as follows:

(1) Reading of curved surface data

The IGES data are read using conventional 3D-CAD.

(2) Creation of line at intersection between tool rake face and curved surface

The spline of the intersection for the curved surface and tool rake face at the representative spindle position is obtained, as shown in Figs. 8 and 9. This spline is part of the tool path at the tool cutting edge at a representative rotational angle. From this figure, the tool offset ℓ is determined, where no interference occurs.

(3) Extraction of data points on each spline curve

The point data created from the spline curve are extracted according to the feed rate of the Z-axis.

(4) Calculation of tool radius offset data

The previous operation for a curved surface only derives cutting positions on the surface. In this process, tool radius is considered. Therefore, the tool radius offset for the rotary tool at the cutting point data is considered, as shown in Fig. 10. When the tool offset is completed, as shown in Fig. 10, cutting points become uneven in the Z-direction because the feed rate by the tool path calculated from the tool center is not considered. Therefore, the distance of the tool path data in the Z-axis direction is not constant. Spline curve approximation is performed again to equalize feed rate. By this operation, a constant interval of the Z-axis can be obtained.

(5) Concatenation of spline data points

Figure 11 shows the calculation method of concatenating data points from spline curves depending on rotational angle. These are consolidated sequentially for lathe turning as spiral trajectory data in our system.

(6) Completion of NC program

The NC program for a curved surface machining is completed by these operations. This data is fed to the high-speed servo controller.

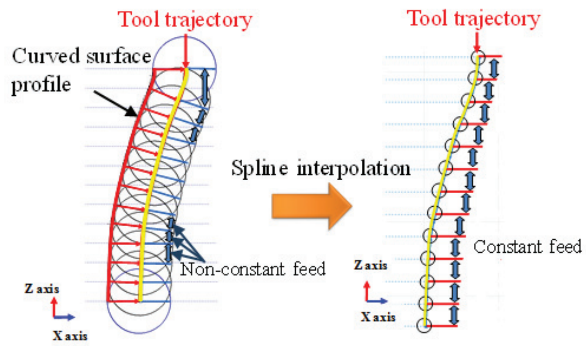

Fig.10 Method of calculating tool path

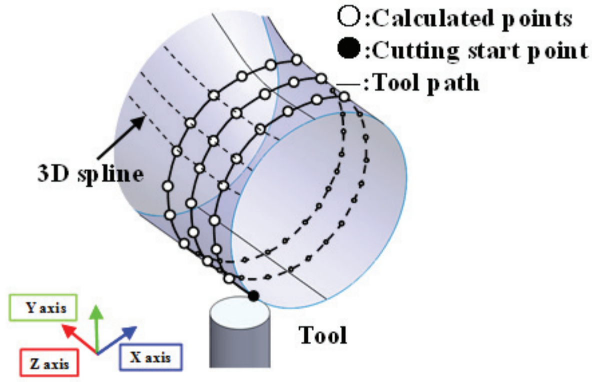

Fig.11 Concatenation of cutting points

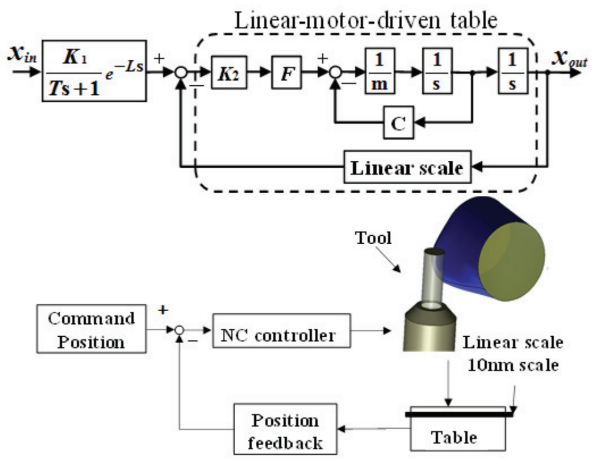

Fig.12 Block diagram of linear-motor-driven lathe

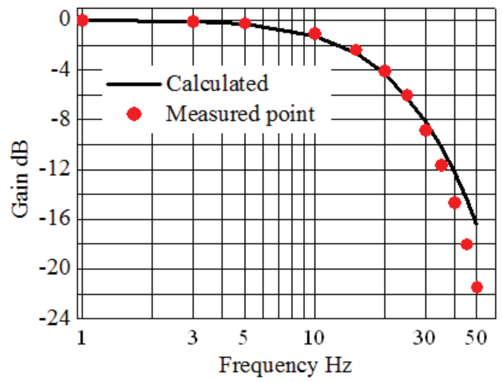

Fig.13 Frequency response of X-axis table

5. Frequency response of tool post

The frequency response of a linear motor-driven NC lathe is the most important characteristic of curved-surface cutting, because the position of the X-axis table (tool post) is controlled depending on the spindle position. Figure 12 shows the block diagram of the linear-motor-driven table. The table response is measured using both sinusoidal inputs and table positions from the linear scale. Figure 13 shows the measurement result. The response can be assumed using the second lag system, which is a typical feature of a linear-motor-driven NC table. There is a time lag for the motion of this table. Therefore, by adding the element of the primary delay system, the equivalent transfer function of the second lag system can be expressed as

$$G(s)=\frac{K_1}{T_s+1}e^{-Ls}\frac{K_2 F}{ms^2+cs+K_2 F}, \qquad (1)$$

where, K_1 and K_2 are coefficients, m, c, and F denote the mass, damping coefficient, and thrust force, respectively.

In Fig. 13, the solid line shows the calculation result obtained using Eq. (1). The red dots show the experimental results. This model shows good agreement with the experiment.

The frequency response shows good performance up to 20 Hz. No distinct resonant frequency appears in this frequency range. This system can be used for machining a curved surface from the experimental result.

6. Table behaviour during lathe cutting

6.1. Experimental setup

The linear-motor-driven NC lathe for machining the curved surface is operated using the created NC program. In this case, the NC table behavior recorded in the memory of the CNC system is used to compensate for the linear motor motion. This experiment is executed using the installed rotary tool and originally calculated NC program. The NC program is verified by comparing the NC program with the measured positions of the table motion. Figure 14 shows the experimental result for the maximum stroke of the tool post motion. In Fig. 14, the black solid line shows the designed curve. The red solid line shows the NC table motion measured from the linear encoder. On the other hand, the blue solid line shows the acceleration of the designed curve. The green solid line shows the acceleration calculated from the measured position.

As shown in this figure, high-speed processing is actually performed. Our main purpose is to verify the table motion and to evaluate our CAM system. The cutting experiment has been executed by air cutting as previously described. After the confirmation of the tool post motion, machinable wax is machined by the proposed method. A workpiece is machined previously using an end mill. Lathe turning is performed to finish cutting. In this process, according to the calculated NC program, the X-, Z-, and C-axes are controlled by a simultaneously synchronized operation.

6.2. Experimental result

The supposed cutting conditions to achieve the desired curved surface are shown in Table 2. The NC table motion that shows rapid acceleration and deceleration follows with the designed profile. The acceleration calculated using a linear encoder exceeds 6G at its peak. On the other hand, the measured maximum stroke of the X-axis motion is 10 mm. The present setup shows that the measured value cannot reach the target value. The NC table motion has to be improved for the finish machining of the curved surface. Figure 15 shows an enlarged image of Fig. 14. This figures shows the controlled results compensated for in the cases of feed-forward control and repetitive control. The X-axis table position is designed to move by an 10.5 mm stroke, and responses of 10.3 mm (feed forward control), and 10.5 mm (repetitive control) are obtained using the compensated NC program by these two methods. In particular, the responses are actually improved to the desired points of the surface. Both compensation methods are available for the control of cutting tools. The setting of repetitive control is easier than that of feed-forward control. We apply this control method to curved surface machining. Figure 16 shows a machined-curved surface obtained by our lathe turning. This experimental procedure demonstrated that our system is sufficiently practical for machining curved surfaces by lathe turning.

Table 2 Cutting conditions

Spindle revolution V [min^{-1}]	375
Feed f [mm/rev]	0.2
Depth of cut d [mm]	0.2
Control method	Synchronized control
Workpiece material	Machinable wax

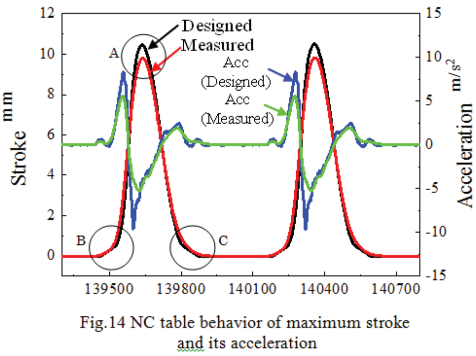

Fig.14 NC table behavior of maximum stroke and its acceleration

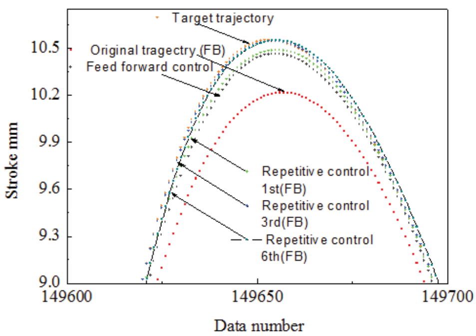

Fig.15 NC table behavior of maximum position

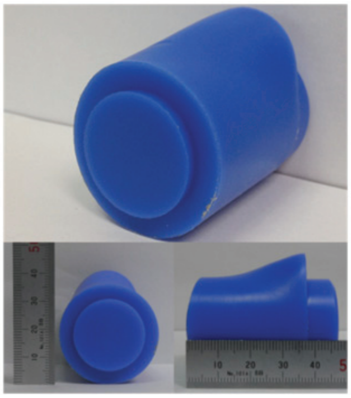

Fig.16 Curved surface machined using our developed system

7. Conclusions

A new method of machining curved surfaces by lathe turning has been proposed and its feasibility is evaluated by experiments. The following findings are obtained.

(1) A new tool layout for machining of curved surfaces has been developed.
(2) The interference between a tool and a workpiece can be avoided by our proposed tool layout.
(3) A curved surface can be machined using the original CAM system.
(4) Our system is feasible for machining curved surfaces by lathe turning.

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