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Generating the 3D Curved Surfaces in CNC using Part Programming

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Abstract: The proposed method deals with the generation of curved surfaces (un-axis symmetrical) using CNC lathe turning. The CODE generated for producing 3D-Curved surfaces was applied for different materials like Aluminum, Magnesium and Stainless Steels using CNC SIMULATOR v2.0 software. The optimization of the path was altered by the virtual simulation prior to the experimentation and validated through the experimentation. It was observed the machining error is drastically controlled and simulation shows the generated method has the capability to simulate the curved surface in the 3D-CNC turning. It also provided a clear-cut understanding of the tool path movement and the feedback device units during actual machining operation.

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. 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.

In order to machine a surface by means of a cutting tool on a CNC machine tool, a series of 3D or 2D coordinates that define its motion must be supplied. These points are usually referred to as tool centre positions. In this way, the problem can be expressed as *obtaining a trajectory of tool centres* that defines the desired object to be machined with a given precision, in literature the problem is also known as the tool compensation problem .

With a given object and tool, a solution cannot always be found because of the curvature of the surfaces. In these cases, the problem is redefined in order to obtain a trajectory that defines the closest surface that contains the desired object (that is, without collision). Figure 1 shows the trajectory (tool path) of a circle centre point in order to define a surface. In this case, for the sake of simplicity, the problem is presented in 2D. For 3D surfaces the problem becomes more complex.

Partial solutions to this problem use surface offsets generated by different methods. However, these offset-surfaces are restricted to one-radius tools (i.e spherical, cylindrical and conical) and are not valid for more complex tools, such as toroidal ones with two radii. Moreover, in most cases, self-intersection problems arise according to the surface curvature. Thus, more sophisticated and higher cost computing techniques are needed to detect and solve these problems.

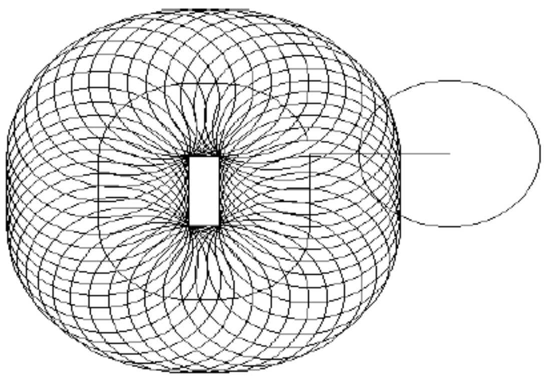

Fig.1. Circle trajectory in order to get a rectangle

Two methods of machining have been introduced

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by machine tool companies. 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. 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. 2 Example of un-axisymmetric curved surface

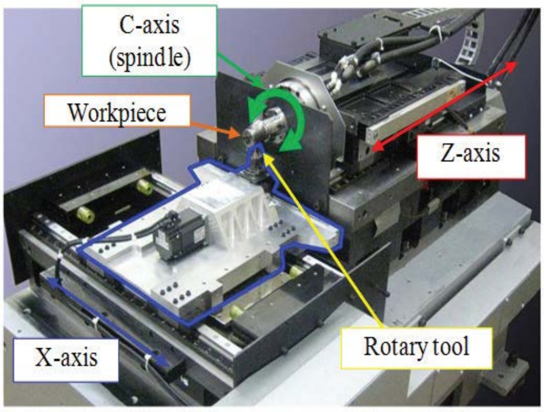

Fig.3 Appearance of linear-motor-driven NC lathe

The other method is traverse grinding. 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 work piece.

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.

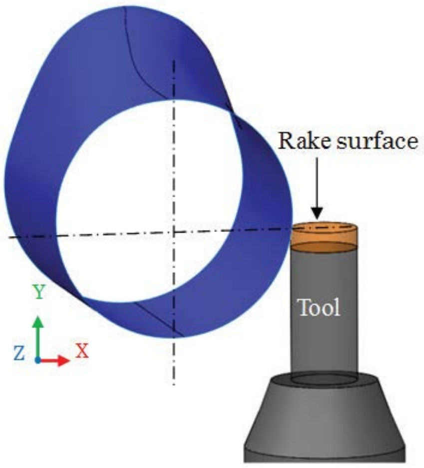

Fig.4 Conventional tool layout of curved surface by lathe cutting

Figure 2 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. 3. The developed lathe has orthogonal 2 axes, and is of the Swiss type with two linear motors.

Figure 4 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 work piece 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.

II. Proposed Lathe Cutting For Curved Surfaces

3.1. Proposed new tool

Figure 5 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.

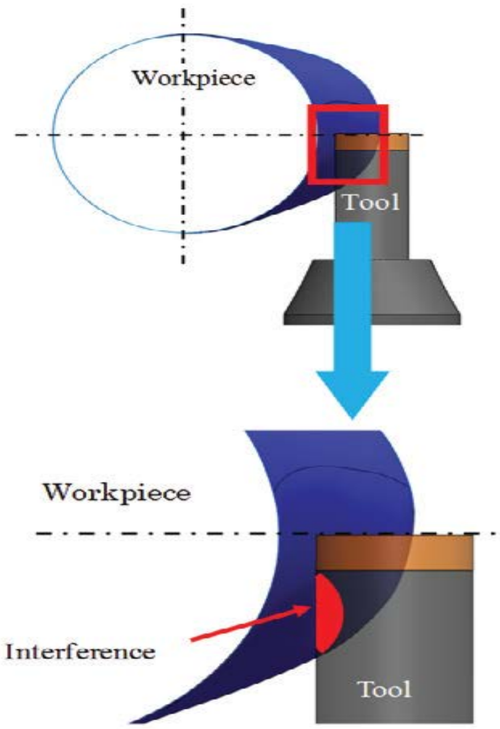

Fig.5 Occurrence of interference between tool flank surface and work piece

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 6 shows the conventional tool layout. $\emptyset_{i0}$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 $\emptyset_{i0}$ becomes larger than .To avoid this interference problem, it is necessary for the tool to offset to the Y-direction, where the inclination angle is$\emptyset_{i0}$ smaller than θ as shown in Fig. 7. φ is the angle determined tool offset at the cutting point.

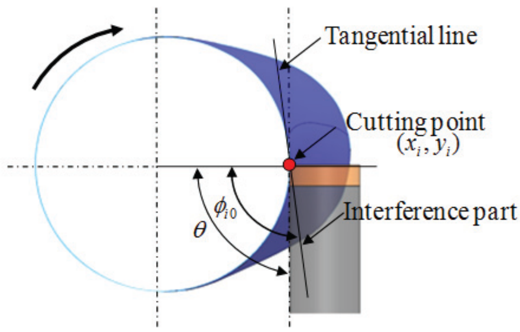

Fig.6 Interference part by conventional tool layout

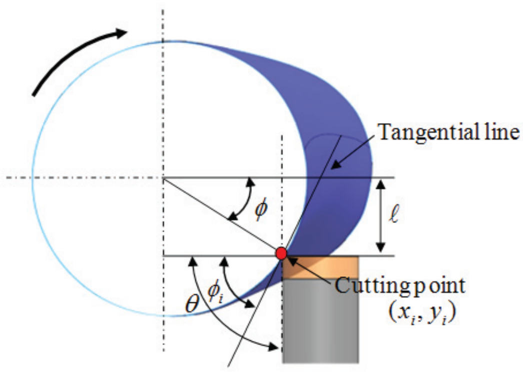

Fig.7 Proposed machinable tool layout

Figure 8 shows the change in the inclination angle 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. 8, a portion whose $\emptyset_{i0}$ 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 $\emptyset_{i0}$, where the tool offset θ is applied in the Y-direction. In this tool layout, when

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the change of $\emptyset_{i0}$ does not exceed 90 degrees, no interference occurs.

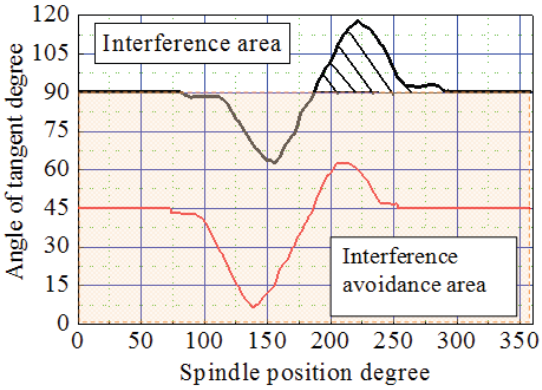

Fig.8 Detection of interference area by tool offset

III. 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. 2, 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.

3.1. 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 3DCAD.

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

(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. 9. When the tool offset is completed, as shown in Fig. 9, 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 10 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.

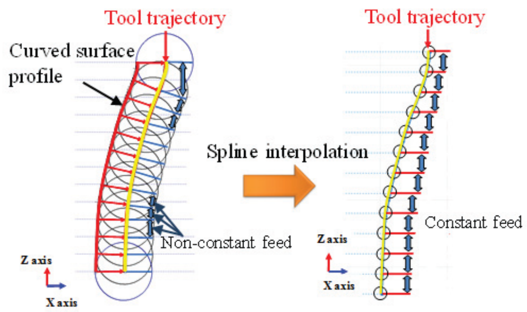

Fig.9 Method of calculating tool path

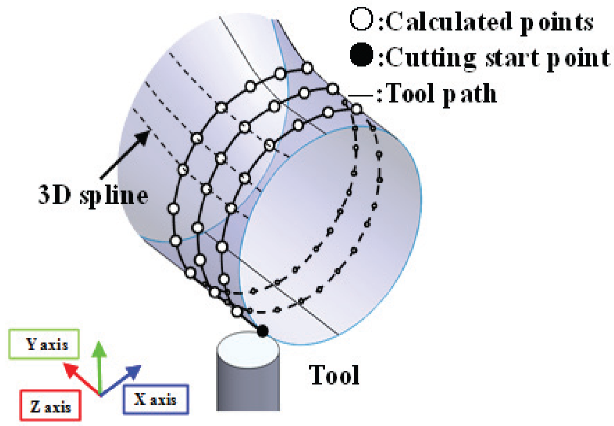

Fig.10 Concatenation of cutting points

3.2. 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 11 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 12 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

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

where, $K1$ and $K2$ are coefficients, m, c, and F denote the mass, damping coefficient, and thrust force, respectively.

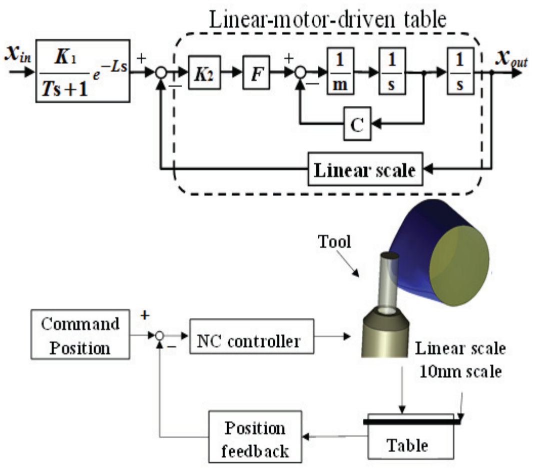

Fig.11 Block diagram of linear-motor-driven lathe

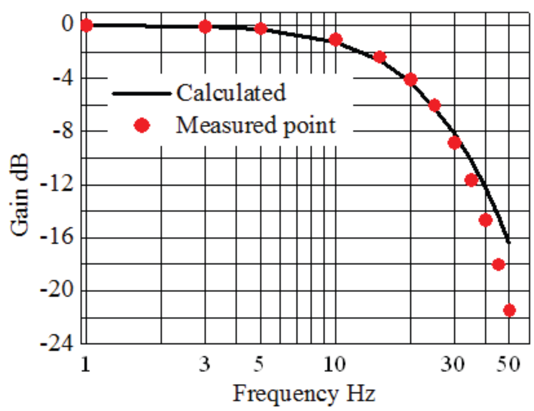

Fig.12 Frequency response of X-axis table

In Fig. 12, the solid line shows the calculation result obtained using above equation. 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.

IV. EXPERIMENTAL RESULTS

The supposed cutting conditions to achieve the desired curved surface are shown in Table 1. 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 14 shows an enlarged image of Fig. 13. 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 15 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 1 Cutting conditions

Spindle Revolution	375
Feed	0.2
Depth of Cut	0.2
Control Method	Synchronized Control
Work piece Material	Machinable wax

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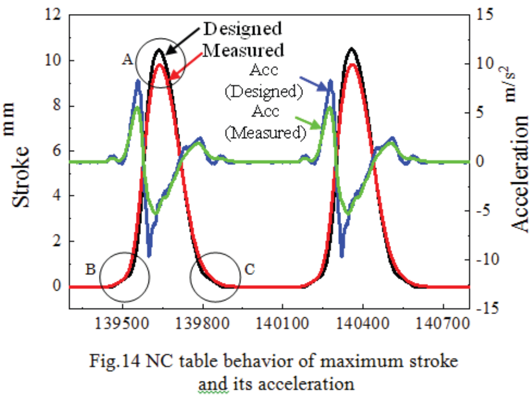

Fig.13 NC table behavior of maximum stroke and its acceleration

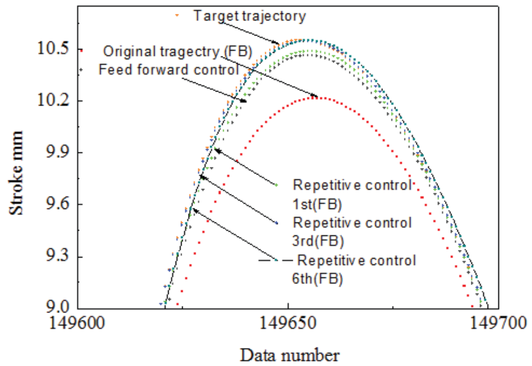

Fig.14 NC table behavior of maximum position

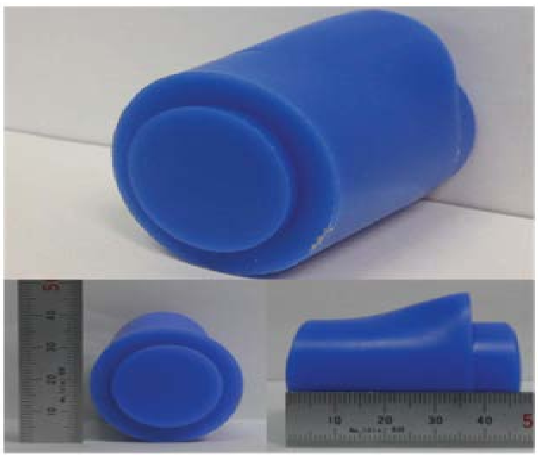

Fig.15 Curved surface machined using our developed system

V. 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.

- A new tool layout for machining of curved surfaces has been developed.
- The interference between a tool and a work piece can be avoided by our proposed tool layout.
- A curved surface can be machined using the original CAM system.
- Our system is feasible for machining curved surfaces by lathe turning.

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