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Three-Coordinate Milling of Large Second-Order Surfaces

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Abstract—A new technology is proposed for the precision machining of large second-order surfaces on a three-coordinate horizontal-milling machine, rather than large turret lathes or five-coordinate milling machines.

Keywords: machining, second-order surfaces, three-coordinate milling
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Currently, turret lathes and numerically controlled milling machines are used in the machining of high-precision second-order surfaces for parts with a diameter greater than 5 m [1–6].

On turret lathes, the blank rotates, while the cutter moves within a vertical plane [1–5]. Deficiencies of this method include the need to use specialized equipment; size limitations on double-curvature second-order surfaces (blank diameter no greater than 22 m); and a large idling path in machining an asymmetric recess if it is larger than a few meters and is at the periphery of the second-order surface. In Fig. 1, we show the KU 299 universal turret lathe (a) and the one-off KU 446 turret lathe manufactured at Kolomensk heavy-machinery plant (now ZAO Kolomenskii Zavod Tyazhelykh Stankov). The maximum size of the blank is 20 m for the KU 299 machine (with a displaced gantry) and 22 m for the KU 466 machine (when using an attachment to increase the supporting surface). In 1970, the KU 299 machine was supplied to Japan for Hitachi, while a KU 466 machine (developed with the Schiess company) was supplied to the Atommash plant (Volgodonsk) [6]. At present, the largest turret lathe produced by ZAO Kolomenskii Zavod Tyazhelykh Stankov is the multifunctional numerically controlled single-column 1K580F4 machine with a working-table diameter of 8 m, for machining blanks of diameter up to 18 m [5].

In the machining of second-order surfaces on numerically controlled five-coordinate milling machines, the

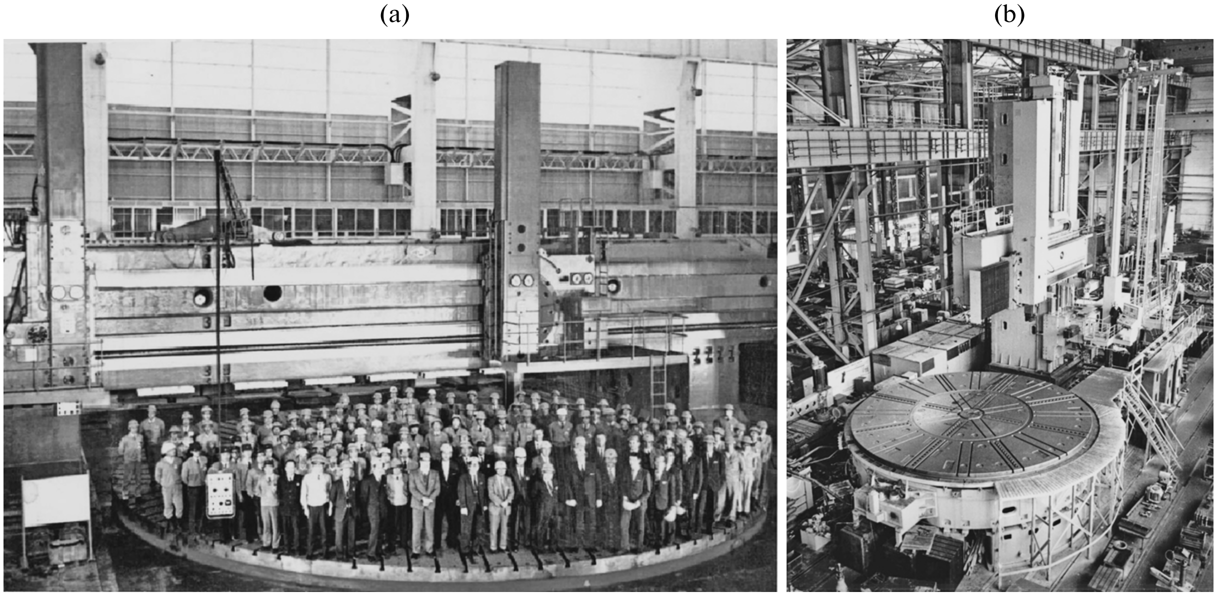

Fig. 1. KU 299 (a) and KU 466 (b) turret lathes.

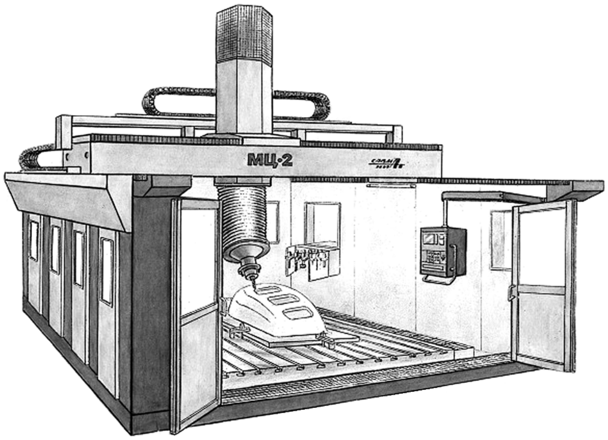

Fig. 2. MTs-2 high-speed five-coordinate machining center.

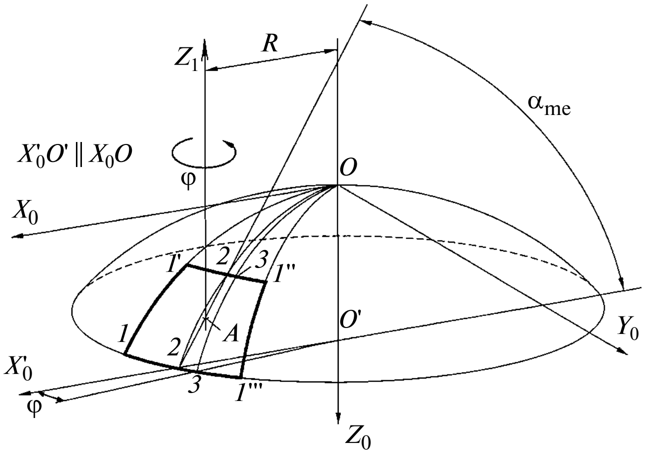

Fig. 3. Position of the machining section on a second-order surface (paraboloid of revolution).

mill performs three linear motions and two rotary motions [1–3, 6, 7]. However, the use of such machines is very expensive, because of their distinctive design and the high machining costs. At OAO Savelovskii Mashinostroitel'nyi Zavod, the MTs-2 high-speed five-coordinate machining center for the precision production of large second-order surfaces has been produced (Fig. 2). The maximum motion is 6000, 3000, and 1000 mm with respect to the X, Y, and Z axes, respectively [6]. Numerically controlled three-coordinate milling machines, equipped with a special device for moving the blank, are more widely available [3].

In Fig. 3, we show the machining of a matrix with an asymmetric recess 1–$1'$–$1''$–$1'''$ on the basis of a paraboloid of revolution in a three-coordinate milling machine. The mill is capable of one rotary motion and two linear supply motions within the X_0Z_0 plane. The other required supply motions—a second rotary motion (around the Z_1 axis parallel to the symmetry axis of the paraboloid) and a third linear motion (displacement along the Z_1 axis perpendicular to the X_0Y_0 plane)—depend on a special rotary table: the Z_1 axis passes through the center A of the blank, which is inclined at α_{me} to the X_0Y_0 plane. A cylindrical face mill, moving over the generatrix in the meridional planes of the blank, forms the second-order surface in several passes; before each pass, the blank is turned by an angle φ. After each rotation of the blank, the Z_1 axis is moved relative to the X_0Y_0 plane with the following coordinate variation: $X_0 = R\sin\varphi$, $Y_0 = R(1 - \cos\varphi)$. Here R is the distance from the symmetry axis Z_0 of the paraboloid to the Z_1 axis. According to the technical specifications, we need independent monitoring of the geometry of the matrix or reflective plate—for example, by means of an optical laser head mounted directly on the moving part of the milling machine, such that the measuring error does not depend on the errors of the machine tool. Plane meridional or transverse templates with concave or convex parabolic profile may also be used for monitoring; the precision of the templates must be an order of magnitude greater than the required precision of the machined surface. The working profile of the meridional template (flag template) should be one of the branches of a second-order curve—for example, a parabola, whose symmetry axis is the precision axis of template rotation and is aligned with the focal axis of the machined parabolic surface.

The surface is monitored by means of probes after each template rotation by a specified angle. Such templates prove unwieldy in the case of high precision requirements [3]. Transverse templates with a parabolic profile are more compact. Their use in monitoring the geometry of a parabolic surface is based on the affine property of a paraboloid: any family of parallel planes parallel to the focal axis Z_0 (Fig. 3) intersects a paraboloid over the same and parallel parabolas; their diameters are parallel to the focal axis [8]. Thus, if the initial parabola moves parallel to the focal axis over another orthogonal (meridional) parabola, the surface of a specified paraboloid is obtained. Accordingly, the length of the transverse parabolic template does not depend on the diameter of the paraboloid of revolution and is comparable with the length of the peripheral chord of arc 1–$1'''$. The practical use of this template in monitoring the reflective surface of the plates in the parabolic antenna of the RT16 radiotelescope was described in [9].

Deficiencies of this machining method include the following. In two successive passes, the machined sections overlap, which results in unnecessary increase in the number of passes. The technological system is complicated by adding a fifth motion (rotation of the blank about an axis parallel to the symmetry axis of the second-order surface) to the four basic motions (mill rotation, its linear motion with respect to two coordinates, and motion of the blank relative to a third coordinate). The development of the control software

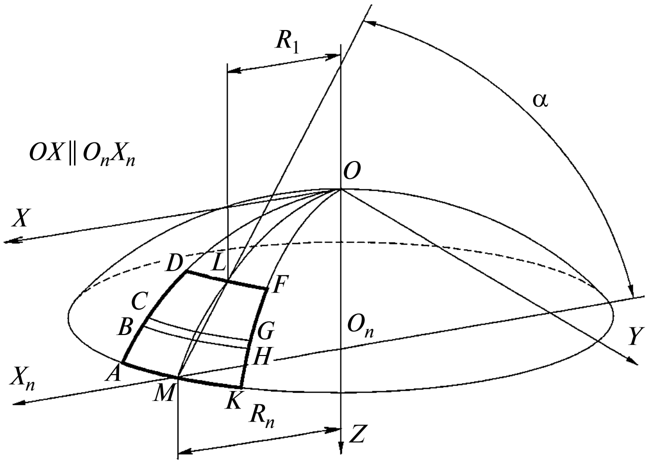

Fig. 4. Position of the machined section on the second-order surface.

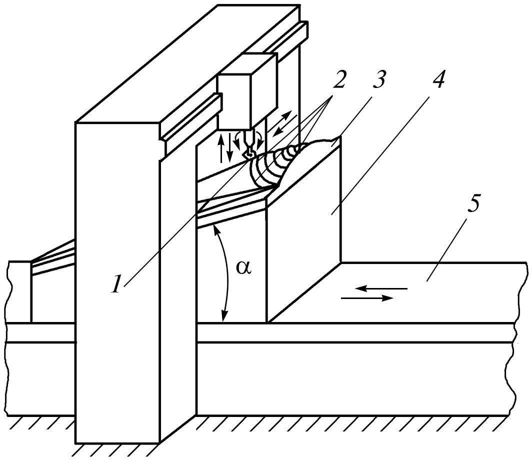

Fig. 5. Position of the blank in machining a second-order surface on a numerically controlled 6M616 three-coordinate longitudinal-milling machine.

is also more complex; it is larger than for a circular mill trajectory, because of the subcomponents for the linear mill motion in machining a concave second-order surface and the table motion in machining a convex second-order surface. To ensure the required machining precision, the axis of mill rotation must be carefully aligned with the normal to the second-order surface at the machining point or else the number of passes must be increased. That complicates the design of the system and increases mill wear.

The affine property of a parabola may be used not only to monitor the reflective surface of the plates in the parabolic antenna by means of a plane parabolic transverse template [8, 9] but also directly in machining a parabolic surface by a disk mill in a three-coordinate milling machine. The practical aspects of machining the parabolic surface of a trapezoidal mirror segment by a disk mill in a numerically controlled milling center were considered in [10]. The algorithm for preparing the initial data used by the machining center permits the use of only three coordinates for the tool motion, rather than four or five. That significantly reduces the manufacturing time and cost for the mirror segments. After traveling over a parabolic curve in the meridional plane (Fig. 3), the mill's cutting edge moves parallel to this curve and completes the machining of the segment surface.

This technology has the following drawbacks.

(1) Nonuniform wear and heating of the disk mill on account of the use of only one of its cutting edges. That reduces the machining precision and increases the number of mill passes.

(2) The maximum flexure of the machined parabolic surface is limited by the mill radius (in view of the spindle geometry) and its required rigidity.

In the present work, we propose a new technology for precision machining of large second-order surfaces on a three-coordinate horizontal-milling machine [11, 12]. This approach does not require the use of special large turret lathes or five-coordinate milling machines or the acquisition of additional two-coordinate attachments for three-coordinate milling machines. The new method improves the machining precision, simplifies the control software and the equipment, reduces mill wear, and shortens the machining time.

The machined section of the second-order surface (Fig. 4) is defined by the boundary *ADFK*. The second-order surface is generated by rotating the second-order line *OM* around symmetry axis *Z* [13]. The angle α is formed by the axis X_n (parallel to axis *X*) and chord *ML* passing through the center of arcs *DF* and *AK* of circles of radius R_1 and R_n. Machining proceeds along arcs *BH* and *CG* of circles lying in the cross sections of the second-order surface perpendicular to the *Z* axis (middle cross sections). For this method, the blank *3* is inclined at angle α on support *4*, which rests on table *5* of a numerically controlled three-coordinate milling machine (Fig. 5). The second-order surface is machined along arc *2* of face mill *1* with a spherical working surface (radius *r*). The axis *Z* of mill rotation is parallel to the symmetry axis of the second-order surface (Fig. 4). The mill may have a one-piece or composite cutting section.

With simultaneous advance of the mill along the *Y* axis (Fig. 4) and the blank along the *X* axis, the resultant shaping motion is tangential to the arc formed by the middle cross section of the second-order surface. The ratio of the mill supply and blank supply is determined from the change in the coordinates of the contact point *K* of the spherical mill surface *1* and the machined surface *2* at the intersection of the normal *N*–*N* to this surface and the arc of the middle section of the second-order surface (Fig. 6). In pass *i*, the radius of the circle is $R_i = \sqrt{x_i^2 + y_i^2}$, where x_i and y_i are the coordinates of the contact point *K*.

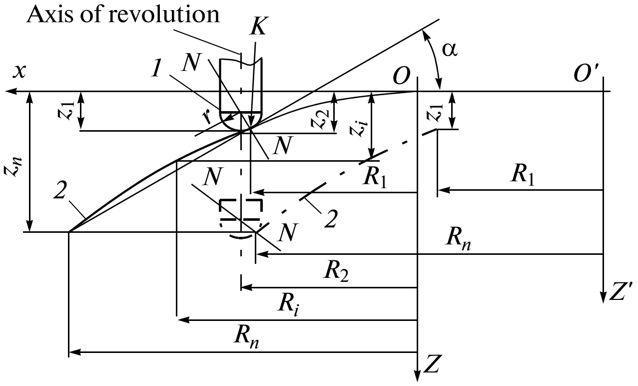

Fig. 6. Configuration of the mill and the meridional profile of the second-order surface.

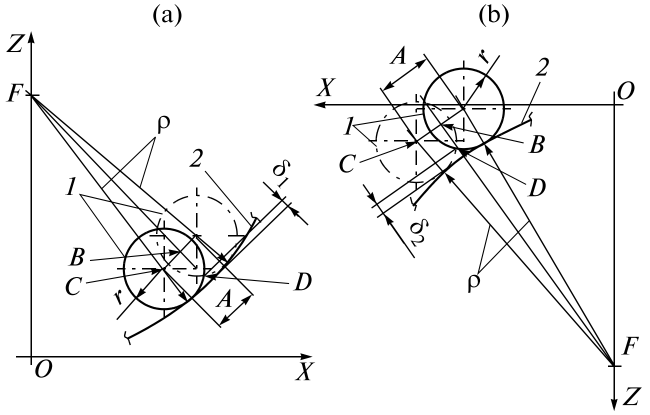

Fig. 7. Calculating the deviations of the concave (a) and convex (b) second-order surfaces from their theoretical positions.

After the first pass, the blank is machined over an arc (radius R_1) in the cross section with coordinate z_1. Then the mill moves in accordance with the control program over its axis of rotation parallel to the Z axis, by an amount $z_2 - z_1$; the blank moves a distance $R_2 - R_1$ along the X axis. In the second pass, the mill moves over an arc (radius R_2) in the cross section with coordinate z_2. Machining ends after pass n, when point O is at point O. The mill moves over an arc (radius R_n) in the cross section with coordinate z_n. Where necessary, finishing may be preceded by roughing according to the corresponding control program.

The machining precision depends on the geometric parameters of mill *1* and the second-order surface produced by the rotation of generatrix *2* around the Z axis (Fig. 7).

The deviation of the concave second-order surface from its theoretical position (Fig. 7a) is

$$\delta_1 = \rho - FB - BD,$$

where

$$BD = \sqrt{r^2 - CB^2} = \sqrt{r^2 - (A/2)^2};$$

ρ is the radius of curvature of the second-order surface's generatrix; A is the distance between the positions of the center of the spherical mill surface in two successive passes ($0 < A \leq 2r$).

The deviation of the convex second-order surface from its theoretical position (Fig. 7b) is

$$\delta_2 = FB - \rho - BD,$$

where

$$FB = \sqrt{FC^2 - CB^2} = \sqrt{(\rho + r)^2 - (A/2)^2};$$
$$BD = \sqrt{r^2 - (A/2)^2}.$$

Thus

$$\left.\begin{aligned} \delta_1 &= \rho - \sqrt{(\rho - r)^2 - (A/2)^2} - \sqrt{r^2 - (A/2)^2}; \\ \delta_2 &= \sqrt{(\rho + r)^2 - (A/2)^2} - \rho - \sqrt{r^2 - (A/2)^2}. \end{aligned}\right\} \quad (1)$$

We now consider the use of the proposed method in machining concave and convex second-order surfaces on the numerically controlled 6M616 three-coordinate longitudinal-milling machine (Fig. 5) by a mill of radius $r = 75$ mm. The table dimensions are 1600 × 5000 mm; the maximum height of the machined part is 1200 mm. The specified machining precision is $\delta_1 = 0.08$ mm and $\delta_2 = 0.005$ mm for the concave and convex second-order surfaces, respectively, with $\rho = 3000$ mm in two successive passes $A = 6$ and 1.5 mm. Substituting the numerical values into Eq. (1), we obtain $\delta_1 = 0.0617$ mm and $\delta_2 = 0.0037$ mm.

The proposed machining technology for second-order surfaces permits circular interpolation with stepwise change in the arc radius of the pass and its height relative to the tip of the second-order surface. That significantly simplifies the control program, especially in the machining of parabolic surfaces.

The new method has been successful used in manufacturing a matrix for the formation of carbon–plastic facets on the working surface of an asymmetric parabolic reflector [14]. The working (convex) reflector surface, assembled from seven facets (a central facet and six peripheral facets) is formed by the intersection of a paraboloid of revolution (focal length 3.5 m) and a cylinder (diameter 3.5 m). The cylinder axis is parallel to the focal axis and displaced by a distance of 2 m. Thus, the distance from the periphery of the reflector's working edge to the axis of the paraboloid of revolution is 3.75 m. In the manufacture of a matrix on a turret lathe, a faceplate diameter of 7.5 m would be required.

To monitor the deviation of the matrix's working surface from its theoretical form, 40 points are selected arbitrarily on the theoretical surface, their coordinates are calculated, and the difference in the coordinates of adjacent points is determined. Then, a clock-type indicator (scale division 0.01 mm) is mounted on the spindle, and the relative coordinate increment of adjacent points is measured. The results are compared with the calculated differences. The precision of the machined surface is not monitored by means of the control program in this case, but manually from the control panel. The maximum deviation of the machined surface from the theoretical surface for a 1300 × 1800 × 70 mm matrix is no more than 0.05 mm. That is acceptable.

The proposed technology improves the efficiency and precision in machining second-order surfaces and simplifies the design of the special-purpose equipment, since the additional rotary and longitudinal motions have been eliminated.

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