MACHINING NON-AXISYMMETRIC OPTICS

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Current single point diamond turning machines have the capability of fabricating complex aspheric optical surfaces. However, these surfaces are limited, by the machine tool, to be surfaces of revolution. With the introduction of two additional axes, spindle position and a high bandwidth axis parallel to the spindle axis, and a high speed control system, the possibility exists to machine surfaces that are non-axisymmetric.

A limited amount of work has been performed by several researchers to machine non-axisymmetric components using both conventional and diamond tools. Douglass[1] made some of the earliest attempts at diamond machining non-axisymmetric surfaces, but encountered problems with the tool actuator and control system that prevented generating optical quality surfaces. Meinel[2] was later able to achieve good results when using a piezoelectric actuator to machine a phase corrector plate. In the realm of conventional machining, Tsao and Tomizuka[3] successfully machined non-circular cylindrical parts.

This paper reports efforts to single point diamond turn non-axisymmetric optical surfaces that are off-axis segments of larger optics. These segments would be used as either off-axis mirrors or as segments to make up a much larger on-axis mirror. An example of the later is the 10 meter Keck Telescope currently under construction[4]. Geometry of these segments will first be described followed by an example to illustrate some of the key implementation details. A description of the experimental machining setup along with cutting results will also be given.

Non-Axisymmetric Geometry

The parent optic considered in this project is a general conic of revolution. This was chosen because a closed form description of the off-axis segment surface is known and can be put into a form that lends itself to real time implementation by a high speed controller. It is important to note that implementation details must be considered at every step in the development of this machining system.

The following equation describes the surface of an off-axis conic segment in cylindrical coordinates,

$$z_3(\rho,\phi) = d_1 + d_2\rho\cos(\phi) \pm \sqrt{d_3 + d_4\rho\cos(\phi) + d_5\rho^2 + d_6\rho^2\cos^2(\phi)} \qquad (1)$$

where z_3 is the segment sagitta, ρ the radius from segment center, ϕ the angular position around the segment and the d_i's are functions of the parent optic and how far the segment is from the parent axis. A detailed development of this equation and a full description of the surface has been given by Gerchman[5].

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Implementation

Machining the non-axisymmetric segment surface is achieved by coordinating motion of the machine's X and Z axes and the tool servo, defined here as the Z' axis. As the segment is rotated by the machine spindle, tool servo motion is generated based on measured spindle position. A key to obtaining the proper segment surface is in separating out the Z and Z' motions so the resulting surface is described by Equation 1. This is done by separating the equation into one part that is ϕ and ρ dependent and another that is only dependent on ρ.

An optimum method to make this separation (in the sense that Z' motion is minimized) is to precalculate X and Z motions at each value of ρ. By finding the max and min values of $z_3(\phi)$ at each ρ and picking a point half way between them as the reference, a baseline motion for the machine slides can be established. This value at each ρ is then subtracted from $z_3(\rho, \phi)$ to give tool servo motion. By this method the tool servo motion can be described with the following expression,

$$Z'(\rho, \phi) = z_3(\rho, \phi) - \frac{[z_{3\max}(\rho) + z_{3\min}(\rho)]}{2} \tag{2}$$

An example of tool motion based on using this optimal baseline is shown in Figure 1 where tool servo motion is plotted as a function of the angular position ϕ. The solid line is motion at $\rho_{\max}$, dashed line motion at $\frac{3}{4}\rho$, the dash-dot line at $\frac{1}{2}\rho$ and the dotted line at $\frac{1}{4}\rho$. This example is for cutting an off-axis segment of a paraboloid. It should be noted that the motion appears somewhat like a decaying sinusoid, but, as shown by the dotted line, this is not the case toward the center of the segment.

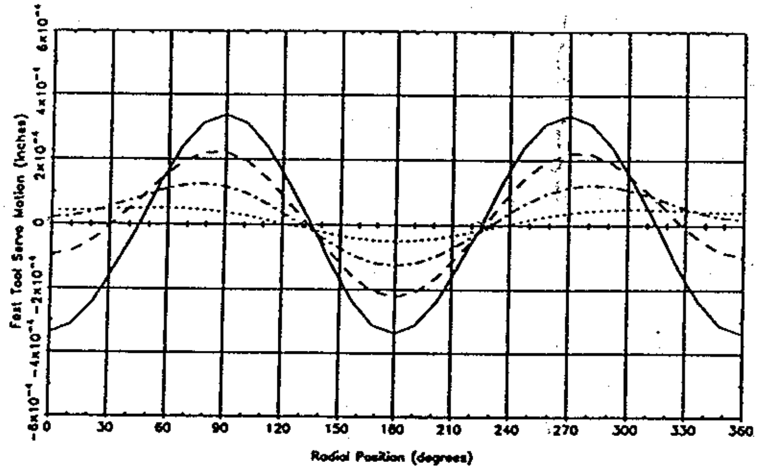

Figure 1: Tool servo motion with optimum baseline subtracted. Solid line is tool motion at $\rho_{\max}$.

Machining Setup

Machining experiments were performed on a Rank Pneumo ASG-2500 using a device known as the Fast Tool Servo (FTS)[6]. This is a short range high bandwidth linear tool motion device based on a piezoelectric actuator. There is an integral capacitance gage used for position feedback to compensate for non-linearities in the actuator. The current device has a range of 20 μm and a bandwidth greater than 1 KHz.

Two other components are needed to make up the complete machining system. First is a High Voltage Amplifier (HVA) that takes a low voltage control signal and amplifies it to a high voltage, high current drive signal for the piezoelectric actuator. Second is the high speed controller that

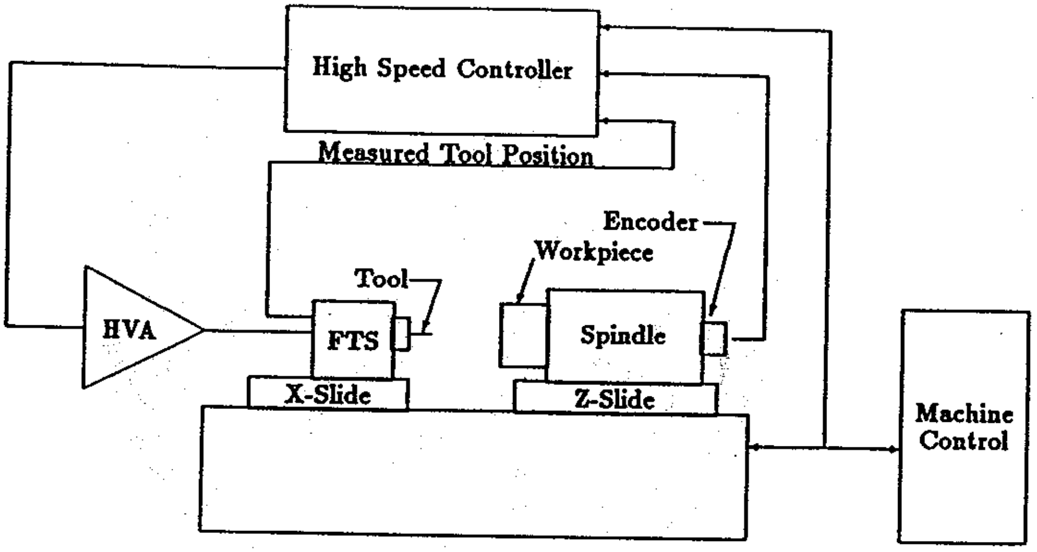

Figure 2: Diagram of experimental setup.

ties all the components together and produces the control signal for the actuator. Figure 2 shows all components of the experimental setup and the interconnections.

Results

A number of different non-axisymmetric surfaces have been fabricated to show the viability of this type of machining and to illustrate some of the possible error sources. For example, a flat surface tilted with respect to the plane perpendicular to the spindle rotation axis was fabricated by generating a decaying, once per revolution sinusoidal signal for the tool servo. An interferogram of this tilted flat with a normal reference flat around its periphery is shown in Figure 3. The inner flat is tilted so that the distance between its lowest and highest point in about 5 μm. The diameter of this tilted surface is 20 mm.

Two surface errors became apparent when machining this tilted surface under less than ideal conditions. Initial attempts at machining were done with no feedback from the capacitance gage and as a result, a non-symmetric surface error appeared. In addition, the X-axis position was not used initially but estimated based on feedrate and X starting position. This produced, as expected, a coma-like surface error – a once per revolution type error. Both of these errors have served to illustrate the importance of a good control system with sufficient inputs.

Summary

Initial experiments machining non-axisymmetric optical surfaces on a diamond turning machine have illustrated the validity of the concept. These experiments have also shown the importance of several key components that make up a system for this kind machining. These components include the high bandwidth tool servo, a high voltage amplifier, a high speed control system with a sufficient number of inputs and efficient software to generate the proper control signal.

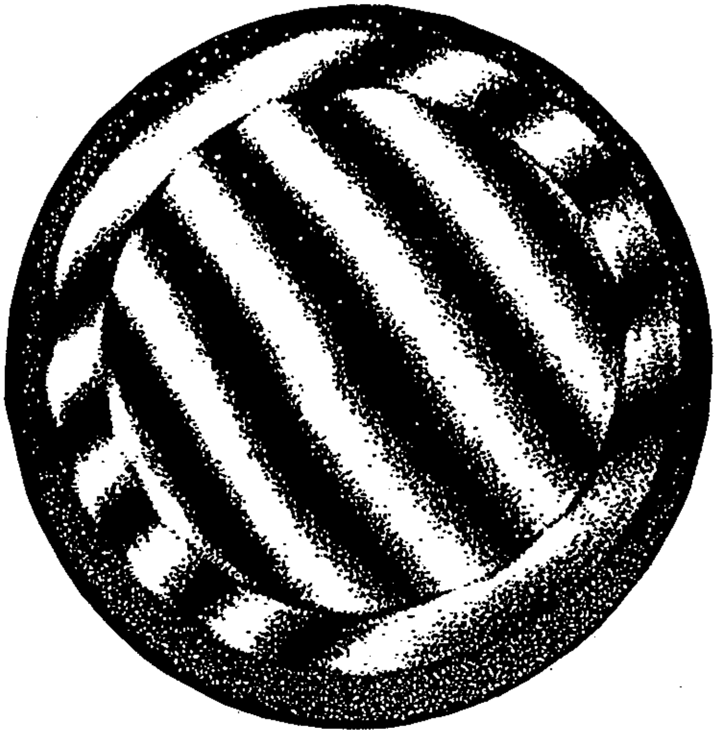

Figure 3: Interferogram of tilted flat surface machined with tool servo at a spindle speed of 480 rpm.

Further work is needed to provide a system with the capability to machine off-axis segments of aconicoid surfaces. Work is currently underway to develop a method that uses Zernike Polynomials to define a more general non-axisymmetric surface and also to develop the control system that uses this description.

References

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