# Characteristics of Systems That Rapidly Diamond Turn Non-Rotationally Symmetric Surfaces

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The demand for optics with non-rotationally symmetric (NRS) surfaces has been growing in recent years. This paper examines some of the latest developments in single point diamond turning (SPDT) technology that permit these surfaces to be manufactured in a cost effective way. With some of these techniques it is possible to achieve surfaces with better than 3 nm Ra surface finish and 200 nm form error. Characteristics of each of the five basic system elements are considered: Command Generator, Compensation Filters, Power Electronics/Actuator, Mechanics and Position Sensors.

## 1 Introduction

A NRS surface is one that can readily be described in cylindrical coordinates (r,φ,z). Using standard machine tool conventions, the surface can be created on a lathe with three contouring axes: X, Z and C. While normal turning can create axisymmetric surfaces, z=f(r), the addition of a C axis for controlling workpiece rotation now allows surfaces with a φ dependence to be created, i.e. z=f(r,φ). To make NRS surfaces using the XZC mode of turning puts high demands on Z axis positioning. In this paper, we will focus on systems for positioning in Z, with the assumption that the performance of the X and C axes of a high performance machine tool are adequate. The goal of XZC machining is to obtain the workpiece's form and finish specifications in the fastest time possible. A number of systems are available for positioning in Z, and they range in performance, cost and convenience. All of these systems have basic elements in common with most servo positioning systems, as shown in Figure 1.

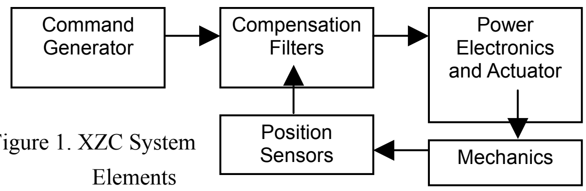


Figure 1. XZC System Elements

## 2 Command Generator

A computer is used to generate the Z position commands. It is critical that these commands are tightly synchronized with the position of the X and C axes. To achieve good surface finish, the commands should be generated at rates exceeding 20 times the frequency response (bandwidth) of the positioning system. Some systems require update rates of 30 KHz or more. These commands must have enough numerical resolution to achieve the nanometer level finishes that are demanded. These commands may require enormous data files if every point is stored. Other systems use fine interpolation algorithms running in real time to reduce the number of stored points. These command files are typically compensated offline for tool radius, but they may also include compensation for other predicable errors, such as sensor nonlinearity and system dynamic response. Each time the tool or the machining conditions (e.g. feed/rev) are changed, a new command file is required.

With the advent of digital signal processors (DSPs) having massive computational power, it is now possible to generate commands in real time at 30 KHz rates from highly interpolated, sparse data sets in 3D, or directly from mathematical equations describing the NRS surface. Tool and error compensation can also be performed in real time with a DSP. Very complex surfaces, such as lenslet arrays, can be easily generated in this manner.

## 3 Compensation Filters

The purpose of this system element is to generate commands for the power electronics based on the position command and the output of the position sensor. This system element can be implemented completely digitally with a microprocessor or a DSP, or it can be partially or completely implemented in analog electronics, particularly if the position sensor has an analog voltage output. The compensation includes special filters to optimize the frequency response of the system and to minimize the effects of noise. Typical filter types include: PID, lead/lag, notch, high order low pass and feedforward. To be implemented digitally at the necessary precision and data rates, such complex filters place very large demands on the processor. With analog compensation, however, the position commands must be converted to an analog voltage. Often, the resolution and speed of the DAC can limit the system performance. A DAC is still needed with digital compensation, but in this case, it is used to generate commands for the power electronics, which need lower resolution than the position commands.

## 4 Power Electronics and Actuator

The three actuator types considered here each have advantages and disadvantages. They all fulfill the fundamental requirement of nanometer level positioning. The advantage of piezos is their high passive stiffness and high force generation capability. However, this is not needed to move lightweight diamond tools when the usual cutting forces are so small. It takes no power to generate a static force with a piezo, but dynamically it behaves like a capacitor. If the loads on the piezo cause negligible strain (i.e. a stiff piezo stack), the piezo's extension or stroke is proportional to the applied voltage. In this case, the power dissipation in the piezo is proportional to the product of frequency and the stroke squared. Note that power is independent of the moving mass, which can be a great advantage. Many piezoelectric materials require voltages in excess of 1000V, but newer materials can utilize safer voltages below 100V. To achieve high frequency actuation, large power levels (>200W) are needed with very low noise levels. This need can make the power electronics very expensive. The ability of the piezo to dissipate heat is their primary power limitation. Piezo materials are damaged at high temperatures. The slew velocity is only limited by the speed of sound in the piezo and the current limit of the amplifier.

The biggest disadvantage of piezos for XZC applications is the nonlinear relationship of extension to voltage. This hysterisis effect, which is temperature, amplitude and frequency dependent, needs to be corrected by the position feedback loop. The higher the control loop bandwidth, the better this error can be compensated for.

The other two actuator types examined here are two versions of linear motors. For short strokes, a voice coil is light and easy to power from a simple current source. For longer strokes a 3 phase, multi-pole linear motor must be used. It is heavier and requires more complicated electronics to power, but is the customary motor in Precitech's machine tool slides. Both types of linear motors generate force that is proportional to current and they have a very linear force to current relationship. This force constant can vary with position however. Linear motors have no passive stiffness, and they require power to generate a static force. Its ability to hold a position is totally dependent on the position feedback loop. The slew limit is only dependent on the drive amplifier's ability to overcome the inductance of the coil. Similar to piezos, one power limit of a linear motor is its ability to dissipate heat; the other is the amplifier in the power electronics. Again a low noise amplifier is necessary here, but because this is much more easily achieved at low powers, the amplifier is often the chosen power limiter. Like piezos, linear motor power is proportional to stroke squared, and unlike piezos, power is also proportional to the square of the moving mass and to the fourth power of frequency. By Newton's Law, acceleration is limited to the maximum current in the motor.

## 5 Mechanics

A mechanical system is required to hold and guide the diamond tool and provide attachment points for the actuator and position sensor. For all XZC systems, low mass and stiff mechanical components are needed. Low mass is important for reducing linear motor power, but it is also important for achieving high natural frequencies. The lowest natural frequency is the typical constraint on the bandwidth of the position control loop. Bandwidth is important to linear motors because it gives them stiffness, and it is needed to linearize the response of piezos. The structure must be stiff and compact so the position sensor accurately reports the position of the tool. Careful placement of the actuator can minimize the excitation of some vibration modes. Because piezos can easily generate large forces, stiff flexures can be used to guide the moving mass in a cheap, frictionless way. Flexure mechanisms are also sometimes used to amplify the limited motion of the piezo. These mechanisms always reduce the system's natural frequency, so we no longer use them.

For longer strokes with no friction, externally pressurized air or oil bearings are used to guide the moving mass. Air bearings have less drag at high velocities, but oil bearings are stiffer and better damped. Because oil and air bearings require no actuator force to hold position, they are ideal for use with linear motors. If very high velocities are needed, oil bearings are not recommended. Not only are the viscous forces large, the slide velocity must not exceed the velocity of the oil exiting the bearing.

Consideration must also be given to how the Z positioning system is mounted to the rest of the lathe. Reaction forces from the actuator can excite vibrations in other machine components if it is not carefully mounted. To minimize this effect, some systems use a reaction mass to absorb the actuation forces. Small travel positioning systems may not be able to accommodate all the Z motion requirements of the machine. In this case, the high frequency positioning system is stacked on the main Z axis of the lathe. This piggybacked axis is then called a W axis or a Fast Tool Servo. In other cases, the slide has enough travel to do both jobs and only one device is needed. When Precitech uses an enhanced version of our standard machine tool slides, which have travels up to 250 mm, we call these Slow Tool Servos. A recently developed, lightweight, 25 mm travel slide is called a Fast Slide Servo, and it can be used either as a W axis or as the main Z slide.

## 6 Position Sensors

Position sensors need to have a measuring range that matches the stroke of the system. The better the repeatability, the linearity, accuracy and resolution of the sensor, the better the system performance, but these come at extra cost. For short travels, analog sensors like capacitance gages, eddy current probes, LVDTs and strain gages can be used. The linearity, accuracy and resolution of these sensors all depend on their range. Furthermore, resolution is dependent on the frequency range of the measurement. If the frequency range of the measurement is reduced by filtering, the resolution improves but the system bandwidth is reduced. For longer travels, linear scales are used. Modern scales can achieve nanometer resolution, but they do have velocity limits where analog sensors do not. The mounting of the scales is particularly critical.

## 7 Examples

Precitech manufactures a number of XZC turning systems. Two utilize a piezo/flexure/capacitance-gage combination with 0.035 and 0.07 mm of stroke with 600 and 900 Hz bandwidths. Two are voice-coil/air-bearing/analog-sensor based, with a reaction mass and strokes of 0.5 and 1.0 mm at a bandwidth exceeding 1000 Hz. Our Fast Slide Servo has air bearings, a three phase motor and a scale. It has a bandwidth of 500 Hz and a travel of 25 mm. Our Slow Tool Servo Slides have oil-bearings/glass-scales/three-phase-motors with travels >180 mm at bandwidths exceeding 70 Hz.

Under the right cutting conditions, all these systems can achieve 5 nm Ra surfaces with less than 400 nm of form error, and some can achieve 3 nm Ra surfaces with 200 nm form. Of course, the strokes and speeds at which these surfaces can be produced vary greatly with the different systems. The amplitude (half stroke) limits of each system are shown in Figure 2 as a function of frequency, e.g. a toroid spinning at 3000 rpm with 0.5 mm of stroke at the outer edge has an amplitude of 0.25 mm at 100 Hz.

Figure 2. Amplitude Limits for XZC Machining