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Methods and Results of Reducing Following Error in the LLNL Large Optics Diamond Turning Machine

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Methods and Results of Reducing Following Error in the LLNL Large Optics Diamond Turning Machine

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Abstract

The USAF Integrated Flight Experiment (IFX) Project is part of the development of the Space Based Laser (SBL) Program. The LLNL Large Optics Diamond Turning Machine (LODTM) is responsible for diamond turning the aspheric laser cavity mirrors. These large optics must be manufactured to micro-inch tolerances. The optics are made of silicon to minimize cooling requirements and weight in the SBL. Diamond turning silicon presents many challenges to the LODTM; one of which is silicon's anisotropic property. When cutting these cones shaped optics, the machine sees many different crystallographic planes of the silicon. These planes present different degrees of material hardness. The tool is held in position but it experiences a force variation as it cuts across the different crystallographic planes. This force variation is reflected back into the machine control system and presents a dynamic disturbance that increases the servo system following error. The affect of this error is to cut a part that is not round but "squareish", i.e. at the micro-inch level.

Two methods were used to reduce the following error or increase the machine dynamic stiffness. Each method relies on the fact that the cutting process is cyclic. The two methods are described below.

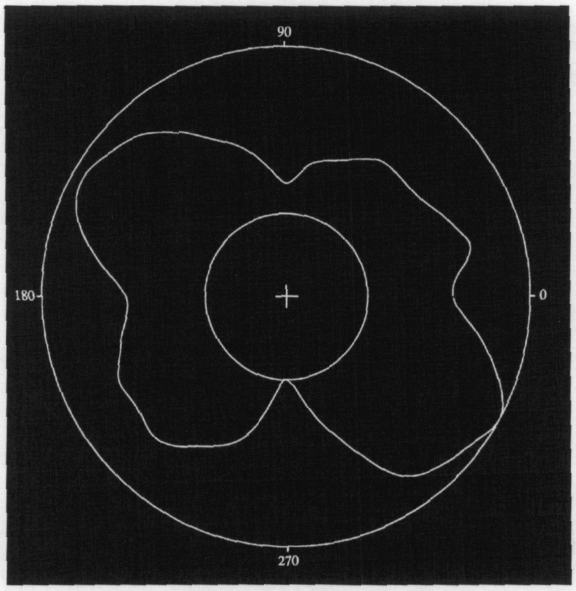
- Method one increases the machine dynamic stiffness and reduces the following error by increasing the servo system bandwidth and the loop gain at the disturbance frequency. The paper discusses how the servo compensation filters were designed to accomplish this goal. The reduction of following error by this method proved very successful and is reported in the paper.
- Method two uses an adaptation of a proprietary controller developed by the Structural Dynamics group of the Lockheed Martin Corporation (LM). The system, know as the DECS controller, works in addition to the present LODTM control system. It observes the LODTM following error and generates a correction signal that adaptively removes any cyclic following error. The DECS controller was originally developed for dither control of telescope IR secondary mirrors. (The Keck telescope and some other observatory telescopes use this system.) The particular DECS algorithm is not discussed in the paper, as it is a proprietary algorithm of LM, however, the results of applying this technology to the LODTM is presented in the paper.

Together, both of these methods have reduced the LODTM position following error to the required micro-inch tolerances. The following error reduction has been shown even at relatively high disturbance frequencies with respect to the servo system bandwidth. Applying these two methods to the LODTM, the machine control system [2] following error is reduced to a level that no longer contributes to part contour error. With essentially no control system error, additional process issues and machine error sources have been identified.

Introduction

Single point diamond turning metals such as copper, aluminum or electroless nickel generates small cutting forces and is well understood. The LLNL Large Optics Diamond Turning Machine (LODTM) has produced many high precision large optics with these metal surfaces. Some of these optics include, the aspheric cavity mirrors of the ALPHA laser, the KECK telescope IR secondary mirrors and a set of off axis mirrors for the NASA SPAce Readiness Coherent Lidar Experiment (SPARCLE). These mirrors have been produced with micro-inch (25 nm) tolerances. To minimize cooling requirements and weight in the SBL, the laser cavity mirrors are fabricated from silicon. Using single point diamond turning, it is more difficult to achieve a high accuracy part in silicon than in metal. There are several factors that contribute to this difficulty including much greater cutting forces than metal and the anisotropic property of silicon. In cutting the cone shaped optics, the tool travel through different crystallographic planes of the silicon. These planes present different degrees of hardness. As the tool cuts through these planes, a force variation is reflected into the machine control system and presents a dynamic disturbance that increases the machine following error. The nominal disturbance frequency is about 4 Hz and is a function of the spindle speed (54 RPM) and the silicon crystal structure. Figure 1 shows an azimuthal or roundness measurement of a silicon part after diamond turning. It shows a dominant four lobe or "squareish" pattern. This paper describes two methods used to reduce the following error as a result of this force disturbance.

SCSi's anisotropy induces contour errors



Azimuthal part error measurement

Figure 1. Azimuthal Error Plot (Inner to outer circle difference less than 10 μ-inches. (250 nm))

The first method relies on servo loop compensation. A new position loop compensator was designed that reduced the following error at the disturbance frequency and therefore increased the machine dynamic stiffness.

The second method is based on a system developed by Lockheed Martin Structural Dynamics Control Group for dither control of telescope secondary mirrors called DECS. The system has been adapted for use on the LODTM. The DECS observes and adaptively removes synchronous following error. The DECS algorithm is a proprietary algorithm of LM and is not discussed in this paper. This paper presents data that demonstrates how effective this system is in reducing following error in the LODTM.

The use of these two methods has reduced the machine following error to a level that it no longer contributes to part error. With this error source eliminated additional process and machine error sources have been found.

Following Error Reduction Method One

Method One focused on servo re-compensation of the LODTM. There were two objectives of the re-compensation effort; A) raise the position loop bandwidth and B) increase the loop gain at the 4 Hz disturbance frequency. The re-compensation was performed on both the X and Z axes of the machine. (For the purpose of this paper, only the X axis compensation is discussed.) The control system of each axis is composed of two major loops, an inner loop or velocity loop and an outer loop or position loop. The servo compensation of each of these loops is constructed in analog circuitry. Although the position loop compensation is analog, the loop is closed in the CNC (The machine control computer.).

The first objective was to increase the position loop bandwidth. Generally, increasing the bandwidth will raise the loop gain at any specific frequency and hence reduce the following error. The limit to the gain increase is the loop phase delay, loop dynamics and the desired gain and phase margins. The velocity loop is contained in the position loop and any phase lag in the velocity loop will add to the 90 degrees phase lag that occurs due to integration of velocity to position. Increasing the velocity loop bandwidth will reduce this additional phase delay and allow an increase in position loop bandwidth. Therefore, re-compensation of the velocity loop was performed first. The LODTM dynamics are quite complex. The original velocity loop compensation required the use of three-second order filters to obtain a bandwidth of about 40 Hz. The re-compensation effort resulted in approximately tripling the velocity loop bandwidth but required the use of seven-second order filters. (See Figure 2.) The net result of improving the velocity loop bandwidth was an improvement in position loop bandwidth of approximately a factor of two. The loop gain at the 4 Hz disturbance frequency was approximately doubled

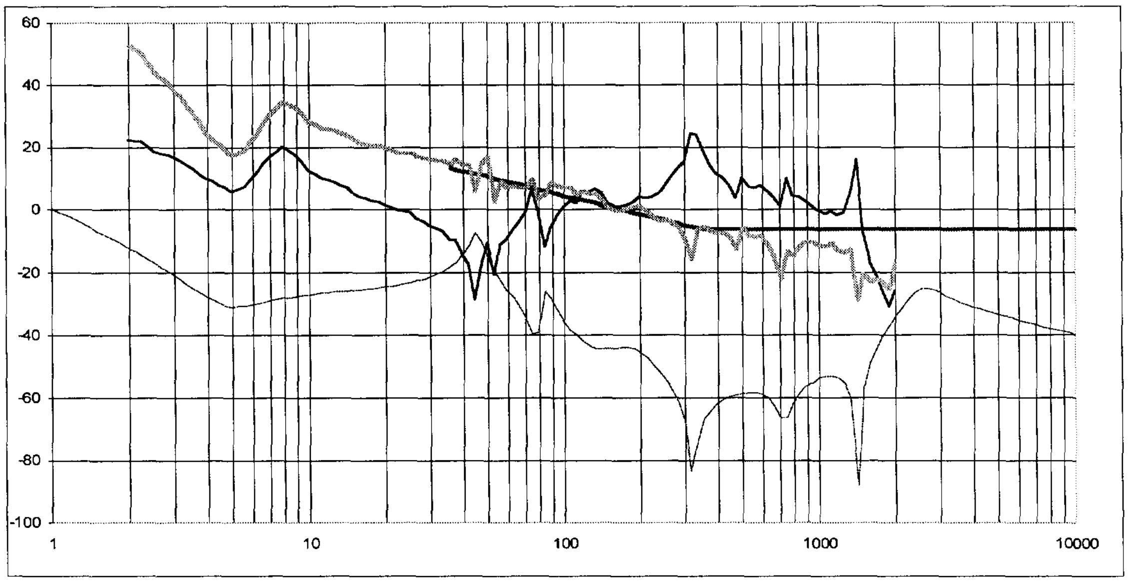


Figure 2. The X-Axis LODTM Open Loop Velocity Response with and without Compensation
Note: The absolute magnitude of the compensation curve is offset for illustration

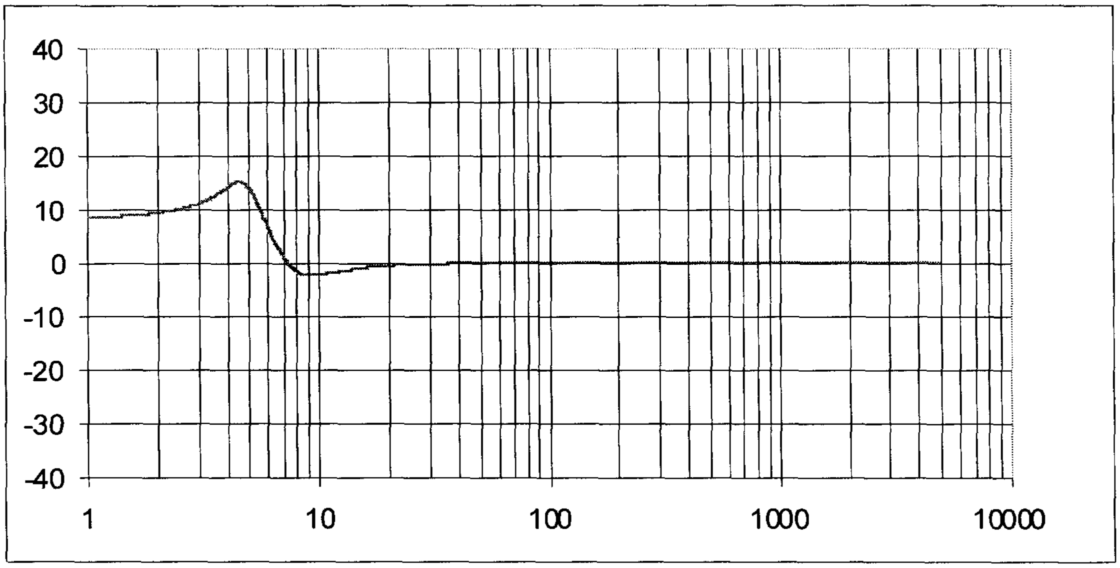


Figure 3. The Position Compensation Filter for Increased Loop Gain at the Disturbance Frequency

This increase was still considered inadequate so a second order filter was added to the position loop compensation. This filter has complex pole zero pairs with the poles located near the disturbance frequency. The zeros are at a higher frequency. It was possible to adjust the damping of the poles and the zeros to develop a response that increased the loop gain by about a factor of four at the disturbance frequency. This gain increase does not come without a penalty. The filter adds additional phase lag to the loop. However, if the frequency of the poles is low compared to the loop crossover frequency the phase lag can be minimized. Figure 3 is the magnitude response of this position loop filter. Figure 4 is the position open loop magnitude response before the addition of this filter. Figure 5 is the position loop response with the new compensation filter. The response clearly shows the increase in loop gain at the disturbance frequency. The combination of an increase in loop bandwidth and the addition of the complex pole zero pairs increased the position loop gain at the disturbance frequency of 4 Hz by about a factor of eight.

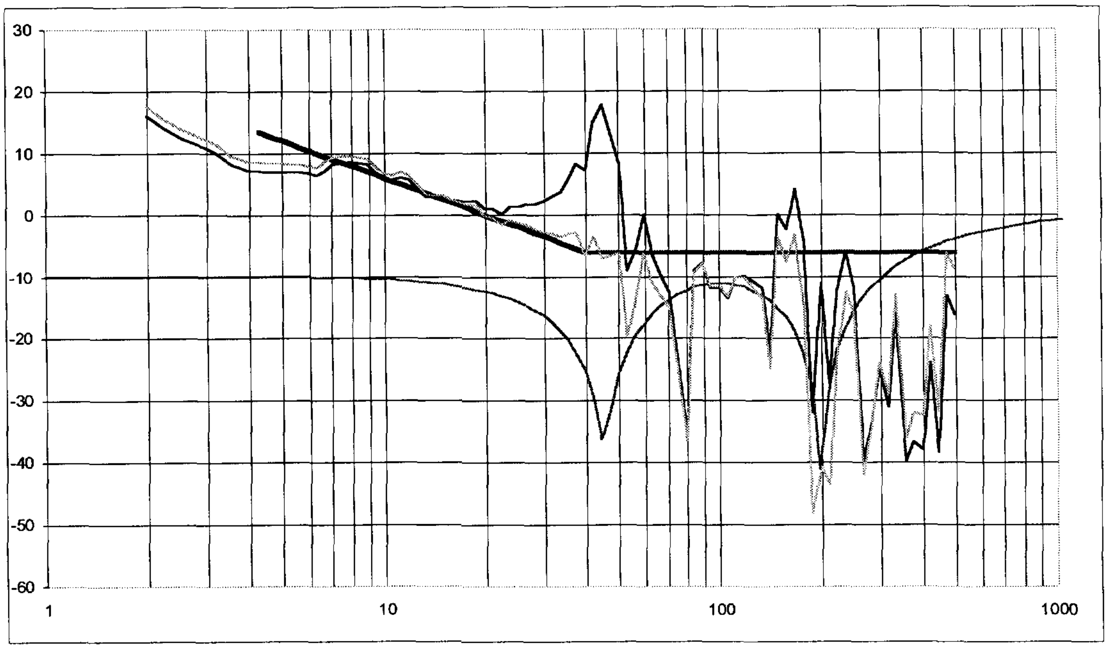


Figure 4. Position Loop Response before Loop Gain Compensation Filter*

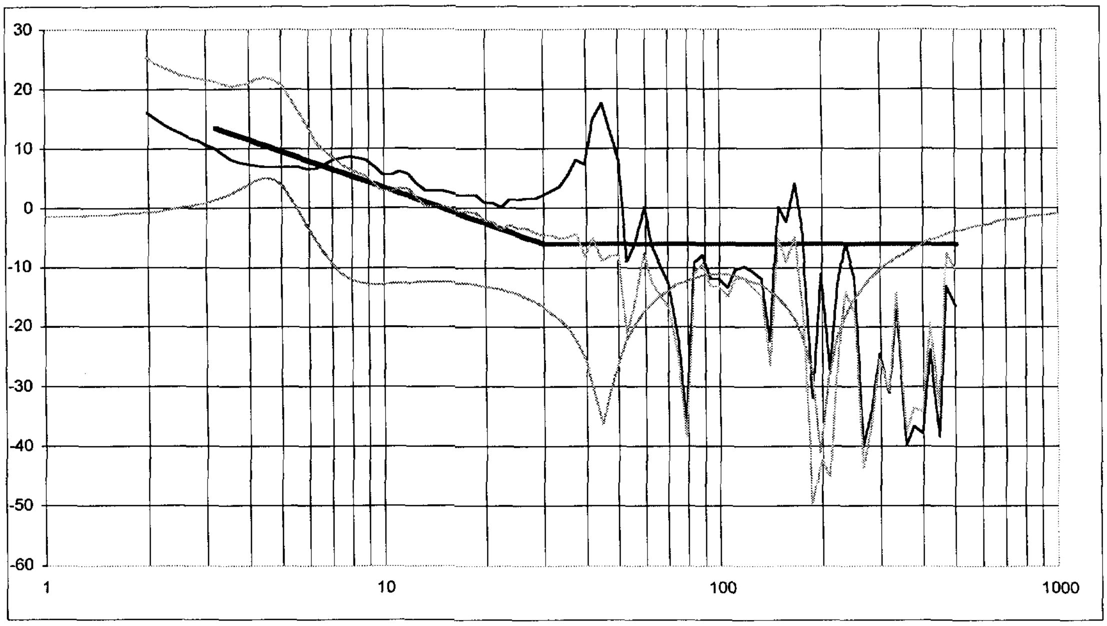


Figure 5. Position Loop Response after the Addition of the Loop Gain Compensation Filter**

Following Error Reduction Method Two

The first method of following error reduction relies on the feedback loop gain to reject disturbances. The frequency of the disturbance may be synchronous or asynchronous to spindle speed or cutting conditions. The disturbance will be rejected or reduced by the amount of loop gain present at the disturbance frequency. The second method of following error reduction relies on removing synchronous or cyclic frequency components of the following error. It does not reduce asynchronous frequency components. For synchronous frequencies, it effectively makes the control system look as if it has a higher bandwidth.

This method uses an adaptation of a proprietary controller developed by the Structural Dynamics Group of the Lockheed Martin Corporation (LM). The system, know as the DECS controller, works in addition to the present LODTM control system. It observes the LODTM following error and generates a correction signal that adaptively removes any cyclic following error. The DECS controller was originally developed for dither control of telescope IR secondary mirrors. (The Keck telescope and other observatory telescopes use this system.) The particular DECS algorithm is a proprietary algorithm of LM and is not discussed in this paper.

A block diagram of the LODTM control system with the DECS system is shown in Figure 5. The DECS input is the LODTM following error and spindle angle. The DECS output is an adaptive correction signal that is summed back into the LODTM control system in such a way as to minimize the input following error signal.

The LODTM controller can generate a composite command signal by setting the coefficients of a Fourier series up to six times the fundamental frequency. (See Figure 6.) The signal is synchronous to spindle position and is normally used for "electronic centering" of parts. To test the effectiveness of the DECS controller, a test was made by setting a large amplitude term (A) for the sine coefficient of one of the frequency harmonics (N) and observing the following error with and without the DECS controller active. Table 1 summarizes the results of this test. Note the data is obtained by observing the peak to peak following error signal on an oscilloscope. The signal is not band limited and contains noise that does not precisely represent the actual error that would be observed at the part. The table data clearly demonstrates the effectiveness of this system.

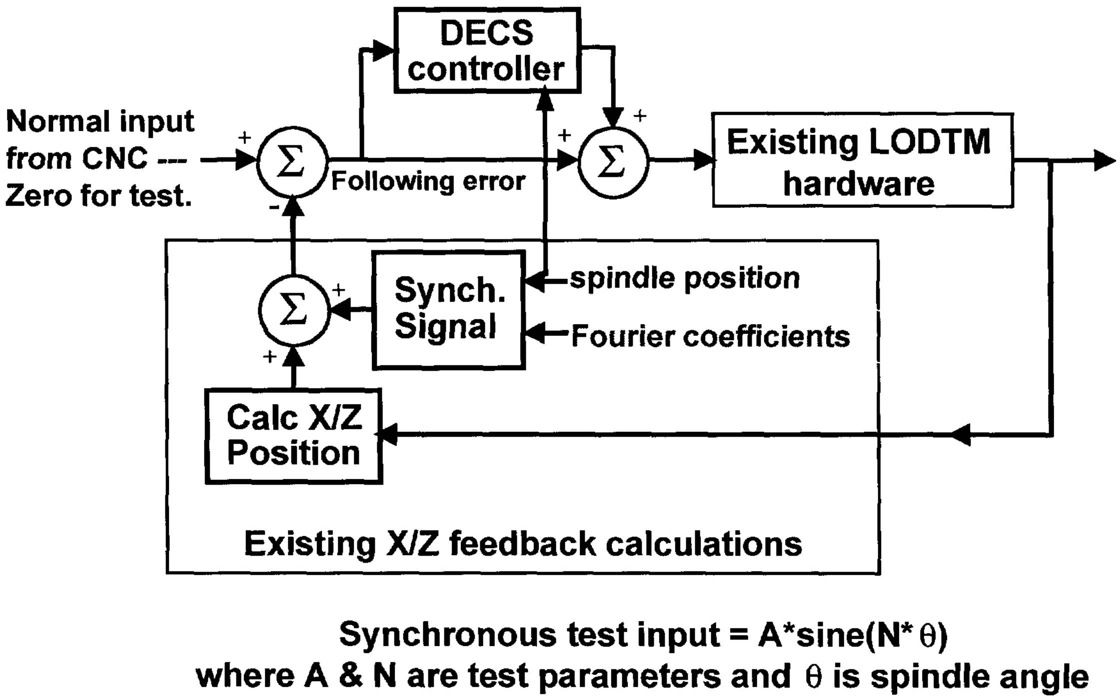


Figure 6. Abbreviated Block Diagram of the LODTM – DECS Control System

Synchronous Test Signal	X axis foll. err. µ" P-P		Z axis foll. err. µ" P-P	
	DECS off	DECS on*	DECS off	DECS on*
A = 0	3.0	1.4	0.9	0.5
A = 30 µ"; N = 1	2.9	1.5	4.7	0.6
A = 30 µ"; N = 2	7.2	1.6	11.8	0.7
A = 30 µ"; N = 3	9.7	1.6	18.8	0.8
A = 30 µ"; N = 4	10.1	1.7	24.9	1.5
A = 30 µ"; N = 5	9.1	1.7	32.2	1.6
A = 30 µ"; N = 6	12.9	1.8	40.0	1.7
A = 0	3.0	1.4	0.9	0.5
A = 10 µ"; N = 4	4.9	1.5	11.1	0.9
A = 30 µ"; N = 4	10.1	1.7	24.9	1.5
A = 100 µ"; N = 4	32.3	2.4	63.0	2.5

Synchronous test input = A*sine(N* θ)
All X and Z axes values are µ" peak-to-peak values.
Spindle Speed 54 RPM

*** Residual following error appears to be asynchronous with spindle p can not see sine by eye in residual signal**

Table 1. DECS Following Error Test Results

Summary

Single point diamond turning of soft metals reflects an extremely small force into the LODTM control system. This force reflection does not cause any significant increase in the LODTM following error. Single point diamond turning of silicon presents a much greater force reflection into the LODTM control system. This force reflection causes an error in the part contour due to an increase in the LODTM following error. The force disturbance frequency is a function of the spindle speed and the silicon crystal structure. This paper presents two methods of minimizing the LODTM following error as a result of this force reflection.

Method one relies on knowing the frequency of the force disturbance and designing a compensation filter that increases the position loop gain at that frequency. The following error will be reduced by the amount of loop gain increase. Method two is based on a system that adaptively removes cyclic following error. Lockheed Martin Corporation originally developed this system for dither control of telescope secondary mirrors. It uses a proprietary software algorithm. It has been very successfully adapted for use on the LODTM for reduction of following error.

The use of these two methods has reduced the machine following error to a level that it no longer contributes to part error. With this error source eliminated additional process and machine error sources have been identified.

References

[1] Donaldson, R.R. and Patterson, S. R., "Design and Construction of a Large Vertical Axis Diamond Turning Machine", SPIE's 27th Annual International Technical Symposium and Instrument Display; Aug. 1983

[2] McCue, Howard K., "The Motion Control System for the Large Optics Diamond Turning Machine (LODTM)", SPIE's 27th Annual International Technical Symposium and Instrument Display; Aug. 1983

Key words: diamond turning, following error, servo system, dynamic disturbance

Acknowledgements
Howard McCue developed Figure 5 and Table 1.

Disclaimer

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* Figure 4 shows the actual open loop LODTM transfer function before compensation and a computer generated plot of the compensation and the addition of these two. The actual measured response is slightly different.

** Figure 5 shows the actual open loop LODTM transfer function before compensation and a computer generated plot of the compensation and the addition of these two. The actual measured response is slightly different.