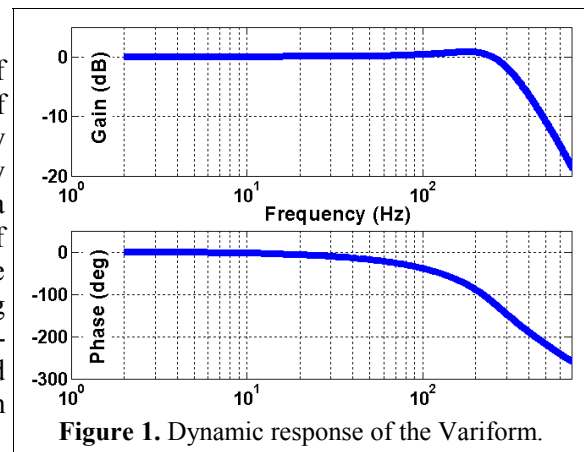


# Error Compensation via Command Signal Deconvolution

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A signal processing technique has been developed to dramatically increase both the usable bandwidth and tracking accuracy of an actuator. All actuators exhibit varying amplitude and phase response to multiple frequency input signals. This makes it difficult to utilize their full small-signal bandwidth for high precision motion. For example, even a small phase lag in an axis of a turning machine may result in significant form errors due to the high relative velocity of the spinning workpiece and the cutting tool. The goal of this research is to use an understanding of the dynamics of an actuator to create an input command compensation technique to correct for anticipated motion errors. Deconvolution is a mathematical procedure that can produce a modified input to reverse the effects of attenuation and phase if the impulse response of the dynamic system is known. Since the modified signal is not calculated from the position feedback information, there is no delay in the response. The algorithm differs from feedback control in that it is implemented off-line to make use of the entire command signal to produce a modified actuator input signal. When the actuator is driven with this modified signal its motion will exhibit attenuation and phase lag that convolves with its dynamic response to produce the original desired position trajectory. In this way the individual motions of the axes can be synchronized to produce the correct machined surface. This technique critically depends on knowledge of the actuator dynamics and does not replace the feedback controller. Rather it works with the control system to improve the response of an actuator by compensating for high frequency dynamics that the servo feedback loop cannot correct due to its reactive nature and saturation of the drive system. When applied to a long-range fast tool servo, the result is a dramatic reduction in following error especially for high frequency motion [1].

**Background** A diamond turning lathe is capable of producing high quality surfaces in a variety of nonferrous materials. However, its use is normally limited to surfaces of revolution that are realized by moving the tool and/or workpiece through one-half of a cross section of the desired shape while the rotation of the workpiece on a spindle causes a symmetric surface of revolution to be machined. Advantages of turning are reduced process times as compared to milling or fly-cutting due to the continuous high cutting speed achieved via rotation of the workpiece, excellent form fidelity and optical quality surface finish.



It is desirable to produce optical systems with the diamond turning process that have features of high spatial frequency or are non-rotationally symmetric (NRS). The addition of a high-bandwidth fast tool servo (FTS) is one technique that has been used to add low amplitude, sub-revolution features to an asphere or sphere. Examples include torics and segmented off-axis conics. The slow-slide servo technique uses the axes of the machine to directly produce NRS features in a rotating workpiece. Both techniques depend on the proper synchronization of the machine tool axes at high relative frequencies.

This work experimentally validates an inverse dynamics command signal modification algorithm with a commercially available Variform fast tool servo and a diamond turning machine. The relevant linear systems theory, the algorithm, its implementation and preliminary experiments are described elsewhere [1,2]. The Variform has a 400  $\mu\text{m}$  range and a bandwidth of 350 Hz. The response of this actuator is

predominately second order although nonlinearities are present for large amplitude command signals. The nominal dynamic response of the Variform is shown in Figure 1. The top graph shows the ratio of the amplitude of the output to the input as a function of frequency. At low frequency, the output is equal to the input and the ratio is unity giving a dB value of zero. As the frequency is increased, the amplitude response peaks at about 200 Hz and then drops rapidly for higher frequencies. The lower graph in the figure shows the phase angle between the input and the output. At lower frequencies these signals are nominally in phase, but even a small lag of less than a degree represents a significant length of arc if the actuator is at a large radius from the axis of spindle rotation. As the frequency rises the output increasingly lags the input. At 100 Hz this lag is about  $45^\circ$  and at 340 Hz it is about  $180^\circ$ . The goal of this project was to accurately machine NRS surfaces with a Variform operating at frequencies above 200 Hz. A significant complication is that the dynamics shown in Figure 1 are not correct for all amplitude and frequency combinations. The actuator velocity saturates at about 140 mm/sec and behaves nonlinearly if the driving command exceeds this limit. Figure 3 shows an expanded frequency response for the Variform as a function of excitation amplitude.

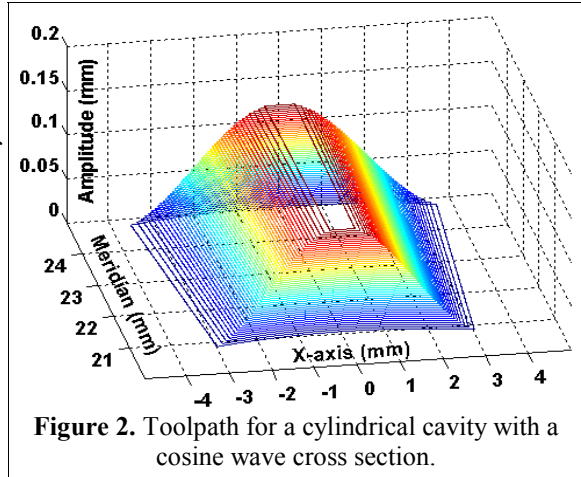


Figure 2. Toolpath for a cylindrical cavity with a cosine wave cross section.

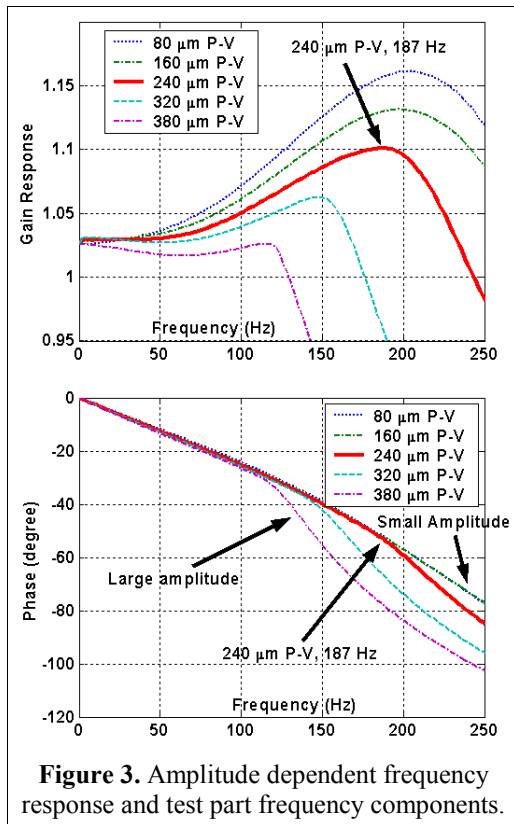


Figure 3. Amplitude dependent frequency response and test part frequency components.

**Experimental Verification** A cavity with the cross section of a cosine wave was selected as a test shape to verify the deconvolution technique. The shape is shown in Figure 2 where a full period cosine wave is smoothly integrated into a flat surface. As a result, no sharp corners exist in the tool trajectory and, since the cavity has a constant depth, the same tool excursion can be replicated for every revolution. Turning this feature does not require tool radius compensation so the input command modification technique can be clearly validated without the influence of other corrective schemes. This profile is easily measured with a profilometer and the machining parameters can be adjusted to obtain a specific frequency and amplitude in the command signal.

The desired shape is an 18-degree wide, off-axis cosine groove with a  $240\ \mu\text{m}$  peak-to-valley sag. If machined at 561 rpm, the dominant frequency will be  $187\ \text{Hz}$ <sup>1</sup>, which is close to a peak of the gain response of the Variform FTS as shown in Figure 3(a). At this frequency, the output trajectory will be amplified by 10% and delayed by  $52^\circ$  resulting in a significant path difference with respect to the desired cosine wave. The overlap-add block convolution method [3] was used to filter the designated tool path with the inverse of the dynamics shown in Figure 3. The operation was performed

in the time domain where the desired excursion is segmented into blocks of arbitrary size and each block is individually filtered (ie, convolved) with the inverse impulse response. The overlap-add algorithm prescribes how the resulting blocks are combined to produce a complete filtered output signal.

<sup>1</sup>If machined continuously around the part, there would be 20 waves and the temporal frequency would be 187 Hz.

A simulated output trajectory is shown in Figure 4. The actuator motion (points) associated with a modified input command (circles) is very close to the desired path (squares). The estimated error (a dashed line) is less than 200 nm P-V.

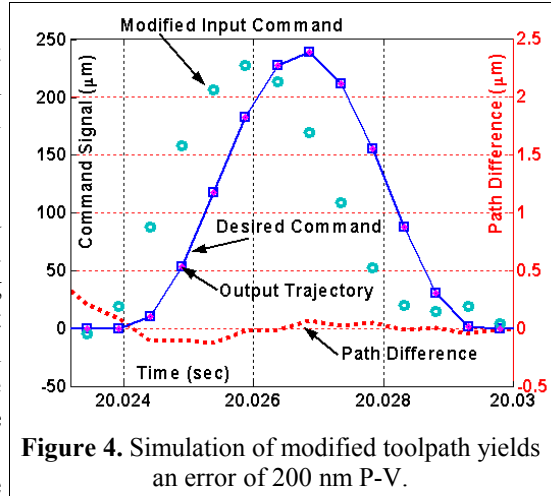


Figure 4. Simulation of modified toolpath yields an error of 200 nm P-V.

Next the modified input signal was experimentally verified by mounting the Variform FTS on an optical table and measuring its displacement with a distance-measuring laser interferometer. Figure 5(a) illustrates the agreement of the FTS motion (x marks) and that of the simulation (Figure 4). The output trajectory was in-phase and the path difference was  $\pm 1 \mu\text{m}$  near the peak and  $8 \mu\text{m}$  at the edges. A mismatch between the gain response used in the deconvolution operation and the actual response of the FTS may cause the path difference of the actual tool trajectory to be larger than that of the model. On the other hand, the tool trajectory (x marks in Figure 5 (b)) associated with an unmodified signal was, as expected,  $10 \mu\text{m}$  bigger, and  $52^\circ$  out of phase with respect to the desired path (a solid line). The dynamic response of the Variform results in a path difference (a solid line) that resembles a sinusoidal profile with a magnitude of  $225 \mu\text{m}$  P-V.

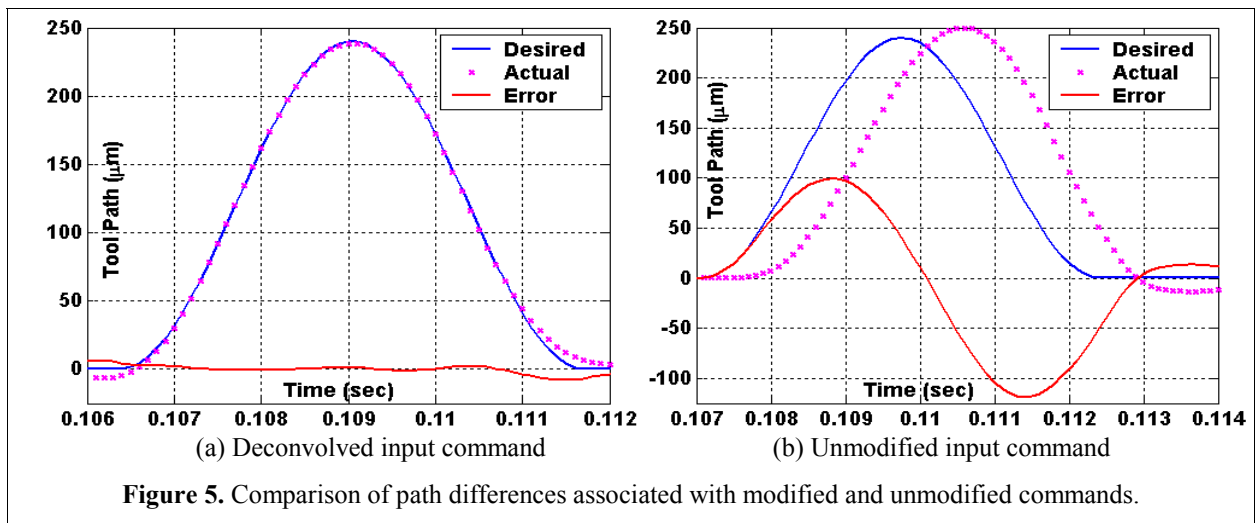


Figure 5. Comparison of path differences associated with modified and unmodified commands.

**Machined Features** The cylindrical cavity with a cosine cross section profile was fabricated into a copper blank. The location of the desired machined feature was created at  $0^\circ$  with respect to the reference flat. In Figure 6, the cosine groove close to the outside of the copper blank was machined using the modified input command whereas the other surface close to the center was associated with the unmodified input command.

A comparison of the form errors between the modified and unmodified surfaces was made using the Talysurf profilometer and the phase angles of the machined surfaces were measured using a microscope with linear scales on the axes of its sample translation table. This located the features in Cartesian coordinates which were then transformed to polar coordinates  $(r, \theta)$ . The profile of the machined surface associated with the deconvolved input command (measured along the trace (A) in Figure 7) is depicted as a solid line in the top graph of Figure 8(a), and the profile of the unmodified surface (measured along the trace (B) in Figure 7) is illustrated in Figure 8(b). The path differences with respect to the desired surface profile are plotted in the bottom graphs of both Figure 8(a) and 8(b) and show that the unmodified

surface was  $50^\circ$  out of phase resulting in a path difference of  $122\ \mu\text{m}$  P-V. The deconvolved surface was in-phase yielding a significant reduction in form error of almost two orders of magnitude ( $4\ \mu\text{m}$  P-V) as shown in the bottom graph of Figure 8(a). However, the average of the path difference is about  $10\ \mu\text{m}$ . This means that the amplitude of the modified surface is short by  $10\ \mu\text{m}$  with respect to the desired surface.

**Conclusions** The modified input signal created by the deconvolution technique improves the form fidelity of a machined surface when compared to that of the unmodified signal. The figure errors can be reduced by two orders of magnitudes due mostly to the correction of the phase errors. This result is true even if the machining conditions do not exactly match those designated. The machining experiments corroborate the simulated results and the tool path measurements using the laser interferometer when the Variform is mounted on an optical table. The results are also superior to those obtained if the phase and gain were adjusted based on the attenuation and lag at the operating frequency because the shape of the desired input command will not be correct. The shape of the input command signal must be modified to yield the output tool path close to the desired excursion.

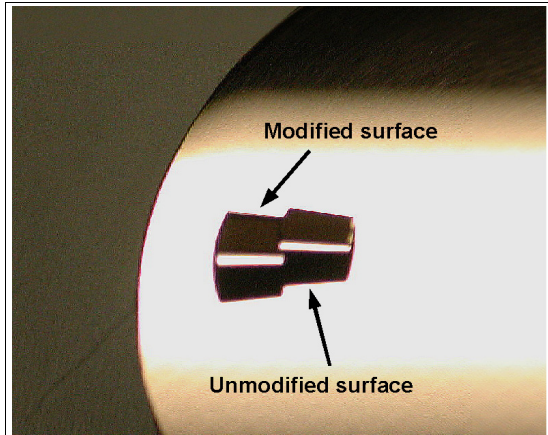


Figure 6. Machined surfaces.

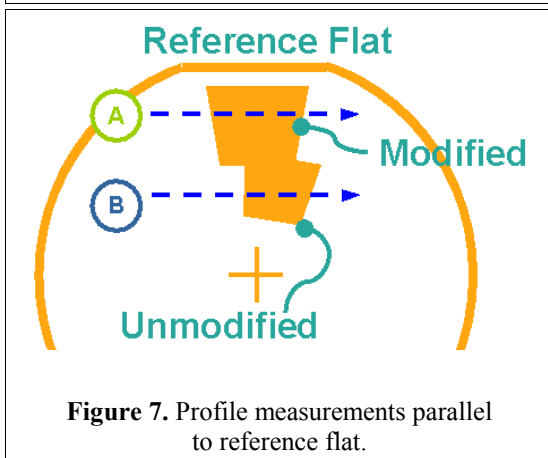


Figure 7. Profile measurements parallel to reference flat.

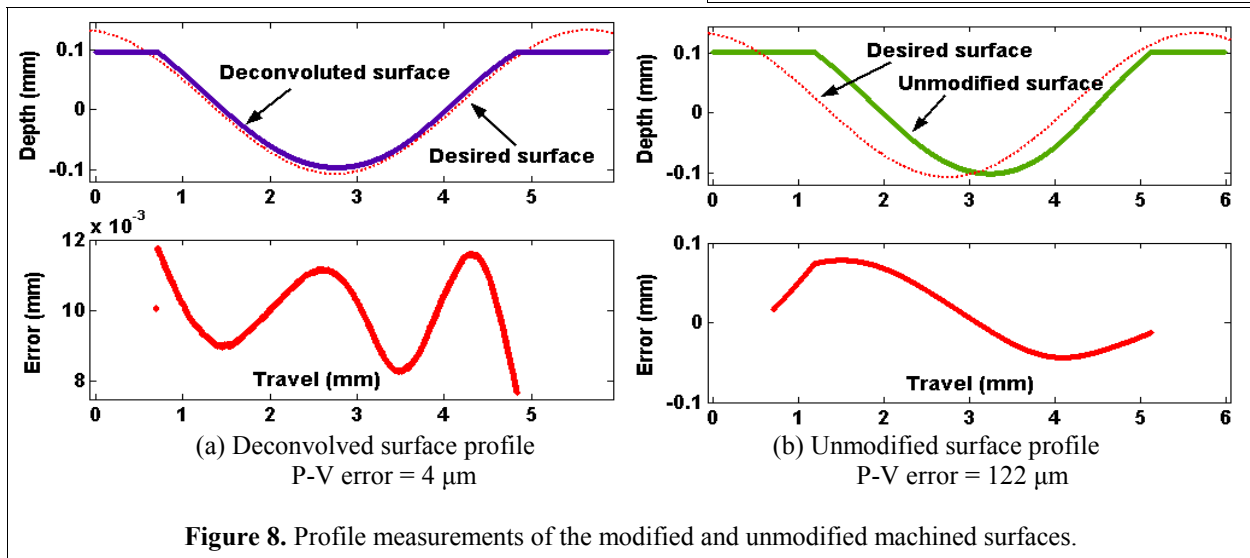


Figure 8. Profile measurements of the modified and unmodified machined surfaces.

## References

- [1] Panusittikorn, W. Error Compensation using Inverse Actuator Dynamics. PhD Dissertation, North Carolina State University (2004).
- [2] Panusittikorn, W., K.P. Garrard and T.A. Dow. Error Compensation using Inverse Actuator Dynamics. Proceedings of the Eighteenth Annual Meeting of the ASPE, 30, 107-110, (2003).
- [3] Oppenheim, A.V. and R.W. Schaffer. *Discrete-Time Signal Processing*. Prentice-Hall (1999).