A magnetostrictive actuator based micropositioner
and its application in turning

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ABSTRACT

The surface finish of a turned part is primarily generated from process parameters such as feed, tool geometry, and cutting speed. A micropositioner system utilizing a magnetostrictive material, Terfenol-D, as a linear motor is presented as a means to actively control the process. The system has an actuator clamped in a flexor that is rigid in the feed and main cutting force directions, yet is flexible in the radial direction. Using control algorithms implemented on a digital computer, the system can provide a means to compensate for deleterious vibrations. The system has also been used to manipulate the tool position in the radial direction so that non-circular turning can be accomplished.

Keywords: Magnetostriction, Active Control, Smart Material, Micropositioner, Precision Machining

1. INTRODUCTION

The quality of a turned part is directly influenced by: tool geometry, feed, and the relative displacement between the tool and the workpiece in the radial direction. Under ideal operating conditions the process parameters are constant, however the dynamic properties of the turning process introduce vibrations in the feed, radial, and cutting directions. These vibrations, particularly in the radial direction, are recognized to have a harmful effect on the machined surface texture (Moon and Sutherland, 1994)\textsuperscript{5}. Due to the random nature, small amplitude, and large bandwidth of the vibration it is difficult to design passive vibration absorbers for machine tools, therefore an active compensation system is needed.

Research to enhance the performance of machine tools by active control has been conducted for years. For example, Tsao and Tomizuka(1988, 1994)\textsuperscript{5,10} have explored the idea of using actuators to generate a non-cylindrical workpiece. Shiraishi, et al. (1991)\textsuperscript{8} actively controlled the process through the use of a stepping motor to eliminate chatter in turning. However, because of the low bandwidth of these actuators, the approaches used in these works are difficult to apply to a machine tool using high cutting speeds.

In an effort to overcome the limitations of traditional actuators, more attention is being focused on novel actuators made from "smart materials". Currently, the most commonly used materials are piezoelectric ceramics. They have been used in many applications on machine tools (Liang and Perry, 1994; Dow, Miller and Falter, 1991; Okazaki, 1990)\textsuperscript{2,1,7}. Another relatively new smart material is the magnetostrictive material. The magnetostrictive effect was observed in Nickel by Joule in 1840, and applications have recently begun to increase with the development of "giant" magnetostrictive materials. One such material is Terfenol-D, an alloy composed of iron, terbium and dysprosium. Terfenol-D can produce large strains, up to 2000 ppm, in the presence of a magnetic field.

Michler, et al. (1993)\textsuperscript{3} presented a design for a magnetostrictive based micropositioner for use in turning that used Terfenol-D as a linear motor. This paper presents the continuing work on the closed-loop controller design and simulation, and experimental verification of the actuator system. A model describing the turning process and
actuation system is presented. A vibration compensation control scheme utilizing rate feedback is then introduced. A positional, PID, control scheme is then presented. Simulations for both control strategies are utilized to help fine tune the controllers. Cutting experiments are then carried out to verify the feasibility of the system. Finally, some conclusions are made.

2. MICROPUSONER

A device is needed to transmit the motion from the magnetostrictive material to the cutting tool. The structure chosen is a simple flexor hinge. The side view of the tool holder, with the magnetostrictive actuator (Etrema 50-6 MP) mounted, is shown in Figure 1. The flexible structure was chosen because it has less friction than a slider mechanism and lower transmission error compared to conventional linkages. An accelerometer (PCB U353) is installed to measure the vibration of the tool in the radial direction, also an eddy current type displacement sensor (Indikon 590-LG) and a force sensor (PCB M112) are used to measure the displacement and force in radial direction. The bolt is used to ensure that the actuator and tool are in constant contact.

![Figure 1: Actuator Assembly](image)

The commercially available actuator takes advantage of some of Terfenol-D’s properties and helps to easily incorporate the material into the micropusonner system. The actuator comes equipped with a preloading spring to take advantage of the fact that for the same magnetic field intensity a prestressed rod can elongate several times more than a rod without the prestress (Moffett et al., 1991)\(^4\). Also, by utilizing a permanent magnet to bias the Terfenol-D the actuator can provide motion in the forward and reverse directions. The maximum motion range of the actuator in this work is about 50 microns peak to peak and the maximum output force is 490 N.

3. TURNING PROCESS AND ACTUATOR MODEL

In general, the vibration between the tool and the workpiece arises in three directions, feed, radial, and cutting. However in this paper only the vibration in the radial direction is considered because of its importance in the surface generation process. If the tool holder assembly is represented as a lumped mass system, the structural dynamics of the system may be described by the one degree of freedom system illustrated in Figure 2. In the figure the nominal depth of cut for the turning operation is \(d_0\), the feed is \(f\), the spindle speed of the workpiece is \(N_s\), the mass of the tool holder is \(m\), the stiffness of the actuation system is \(k\), and the damping coefficient of the system is \(c\).

The radial force, \(F_r\) in Figure 2, acting on the tool can be approximated by multiplying the chip load by a scaling factor:
\[ F_r = K_f f d_0 \]  \hspace{1cm} (1)

where \( K_f \) is the radial scaling coefficient and \( f d_0 \) is the nominal chip load. The chipload is actually a function of the present cut and the previous cut, this is known as the regeneration effect. A lag term that describes the system one revolution previous to the current revolution needs to be incorporated into Eq. (1), this suggests that the equation be modified to represent the radial force as:

\[ F_r = K_f f (d_0 - x(t) + x(t-\tau)) \]  \hspace{1cm} (2)

where \( x(t) \) is the radial displacement at time \( t \), \( x(t-\tau) \) is the radial displacement at time \( t-\tau \), and \( \tau \) is the time required for one revolution of the workpiece. From the above considerations the motion of the cutting tool can be described by a second order differential equation:

\[ m\ddot{x}(t) + c\dot{x}(t) + kx(t) = K_f f (d_0 - x(t) + x(t-\tau)) - u(t) \]  \hspace{1cm} (3)

where \( u(t) \) is the force applied to the tool holder by the actuator. The transfer function of Eq. (3) in the Laplace domain is:

\[ \left( m s^2 + cs + k \right) X(s) = K_f f \left( d_0 - X(s) + e^{-\tau s} X(s) \right) - U(s) \]  \hspace{1cm} (4)

where \( X(s) \) is the Laplace transform of the radial displacement and \( U(s) \) is the Laplace transform of the output force generated by the actuator.

![Figure 2: Cutting Process](image)

The actuator consists of an electrical circuit and Terfenol-D rod. Using equations for a simple circuit containing an inductor and resistor, the transfer function relating the output force generated by the actuator to the input voltage may be described as:

\[ U(s) = \frac{K_p}{Ls + R} V(s) \]  \hspace{1cm} (5)

where \( L \) is the coil inductance, \( R \) is the resistance of the coil, \( K_p \) is the force constant, and \( V(s) \) is the Laplace transform of the voltage applied to the actuator.
4. PARAMETER IDENTIFICATION FOR THE MICROPPOSITIONER

In the absence of the cutting process, and based on Eqs. (1 - 5), the transfer function relating tool position to the voltage applied to the micropositioner is:

\[
\frac{X(s)}{V(s)} = \frac{K}{(\tau_1 s + 1) \left( \frac{s^2}{\omega_n^2} + \left( \frac{2\zeta}{\omega_n} \right) s + 1 \right)}
\]  

(6)

where \( \tau_1 = L/R \) is a time constant, \( \omega_n^2 = k/m \) is the natural frequency of the micropositioner, \( \zeta = \frac{1}{2\omega_n} \left( \frac{c}{m} \right) \) is the damping coefficient of the system and \( K = \frac{Gk}{Lm\omega_n^2} \) is the total gain of the actuation system.

The values for \( \tau_1 \), \( \omega_n \) and \( \zeta \) are critical with respect to the dynamic performance of the micropositioner and a great influence on the design of the controller for the micropositioner. Experiments were conducted to measure the frequency response function of the micropositioner to obtain these parameters. The experimental scheme is shown in Figure 3.

![Figure 3: Experimental Setup to Measure the FRF of the Micropositioner](image)

In addition to being a data collection device the HP35660 may also serve as a signal generator and can produce different signals of various amplitudes and bandwidths. A periodic chirp signal of 0-3.6 kHz was put through the power amplifier (MB Dynamic SS250VCF) and into the micropositioner. This input signal was also sent to the dynamic signal analyzer. The displacement signal from the micropositioner was collected by an eddy current displacement sensor and fed into the dynamic signal analyzer. The frequency response function for the micropositioner, shown in Figure 4, is actually the response of the power amplifier, micropositioner and displacement sensor. However both the amplifier and the sensor are wide band electronic devices (bandwidth up to 20 kHz), therefore it is reasonable to assume that they will only have an effect on the total gain of the system. It was found that \( f_n = 1810 \text{ Hz} \), \( \zeta = 0.06 \) and \( \tau_1 = 0.27 \text{ ms} \). The frequency response of the model, associated with Eq. (6), with these parameters is plotted as a dashed line in Figure 4.

4.1 Rate Feedback For Vibration Control

Increased damping can be added to the system by exciting the actuator in the radial direction proportional to the velocity of the cutting tool. The success of such control, known as rate feedback, depends on the accuracy of the velocity measurement at the tool tip. Because of the limitation of space on the micropositioner and the conditions that exist in the cutting process (chips, heat, etc.), it is difficult to directly measure the velocity signal. One solution is to mount an accelerometer and integrate the signal to obtain the velocity. However, floating saturation can occur in the
integration process, consequently a simple integrator does not provide satisfactory results. For this rate feedback control scheme, a compensator is used to provide the velocity signal from the acceleration at the tool tip. The transfer function of the compensator can be described as:

$$K(s) = \frac{V(s)}{A(s)} = \frac{\omega_c^2}{s^2 + 2\zeta_c \omega_c s + \omega_c^2}$$  \hspace{1cm} (7)$$

where $V(s)$ and $A(s)$ are voltage and acceleration in the Laplace domain, $\zeta_c$ is the compensator damping factor, and $\omega_c$ is the natural frequency of the compensator.

![Figure 4: Measured and Modeled Frequency Response](image)

Figure 4 shows the frequency response of the compensator. The figure shows that the compensator acts as a differentiator below the cutoff frequency (6 Hz) and an integrator above it. Because the vibration frequency in the turning process is generally much higher than the corner frequency, the compensator acts as an integrator to the acceleration signal.

![Figure 5: Bandwidth Filter Transfer Function](image)

Figure 5: Bandwidth Filter Transfer Function
A simulation was devised to check the effectiveness of the rate feedback system to suppress vibration caused by random excitation. The feed, spindle speed, and material used in the simulation are 0.075 mm, 1000 rpm, and aluminum respectively. The depth of cut used is \( d_c = 0.76 + \delta \) mm, where \( \delta \) is a zero mean normally distributed random variable with a standard deviation 0.07 mm, about 10% of the nominal depth of cut. The regenerative feedback term was approximated by a second order Pade model. The variance of the tool displacement was used to measure the performance of the system. The gain of the power amplifier was ranged from 0 to 100. The compensator reduced the variance in the displacement signal, and increasing the controller gain further decreases the variance, but diminishing returns are shown above a gain of 40.

4.2 PID Positional Controller

A characteristic of Terfenol is that the induced strain changes with the load exerted on the rod, which means that the changing cutting forces will cause the micropositioner to deflect. To avoid this, the static error of the controller should be zero. By introducing an integral part into the controller’s transfer function this can be accomplished. Also the damping of the micropositioner is very small. It is possible to increase the damping of a controlled system by introducing a differential term into the controller. With consideration given to the above statements, it can be seen that a PID controller is a good choice for the system. The closed-loop control system diagram for the micropositioner is shown in Figure 6. The power amplifier and the micropositioner combination is the plant for the control system and can be described by Eq. 6. A digital computer was implemented as the controller.

![Control System Diagram for the Micropositioner](image)

Figure 6: Control System Diagram for the Micropositioner

The PID controller was first tuned with the Ziegler-Nichols\(^6\) rules. To fine tune the controller, a simulation was conducted. The parameters for the simulation were: \( N_s = 2000, f = 0.2 \) mm/rev (0.008 ipr), a sampling rate of 2 kHz, and the material was aluminum. The step response of the tuned digital PID controller, under the specified cutting conditions, is shown in Figure 7. From the figure, it can be seen that there is no over shoot and the settling time is short (less than 5 ms).

![Simulated Step Response](image)

Figure 7: Simulated Step Response
5. EXPERIMENTS

5.1 Rate Feedback

To determine the effectiveness of the rate feedback compensator a $2^3$ factorial experiment was performed. The three factors studied were: depth of cut, spindle speed and control status (with or without rate feedback control). The feed used in the experiment was 0.0762 mm/rev (0.003 ipr). The gain, which influences the damping added to the system, was tuned to limit the input current to the magnetostrictive actuator to less than 1.5 amperes as recommended by the manufacturer. The value of the gain for the experiment was 75. An aluminum workpiece 56.5 mm in diameter and 153 mm in length was cut in the experiments. A high speed steel cutting tool with $0^\circ$ rake angle and 0.064 mm nose radius was used. A large lead angle ($70^\circ$) was chosen such that the vibration of the tool is primarily in the radial direction. It should be noted that chatter was not observed for any of the tests.

Once the surface was generated via the turning experiment, surface profiles were collected using a stylus-type instrument (Perth-O-Meter). The profiles were collected along the axis of the workpiece, and the data was digitized using an IBM PS2 model 70 and an A/D conversion board. The data was then used to calculate the $R_a$ value for each experiment. It was found that the $R_a$ improved for the control action in every set.

A set of data from a controlled and uncontrolled cutting case is shown in figure 8. It is clearly evident that the controlled experiment (bottom trace) has less variation than the top or uncontrolled case. Analysis of variance (ANOVA) was used to analyze the performance of the system. The results indicate that the control status has a significant effect on surface finish, with 90% confidence, and that both depth of cut and spindle speed do not have a significant effect. This clearly indicates that the rate feedback compensator improves the quality of the turned part.

![Surface profile](image)

**Figure 8: Profile Traces**

5.2 Positional Control

To determine the linearity of the system, with the PID controller, a plot of output (displacement) and input (voltage) was constructed. Because the dynamic signal analyzer cannot produce or measure a DC signal, a 30Hz low frequency sine signal was used. The displacement signal from the eddy current sensor and the 30 Hz sine signal were measured with the analyzer. The input voltages were ranged from 20mv to 340mv and were measured in random order. The results are plotted in Figure 9. From the figure it can be seen that the input output relationship can be well described by a straight line.
The micropositioner was then installed into a turning center and a 76mm diameter aluminum workpiece was cut. The operating parameters of the experiment were: \( N_s = 600 \text{ RPM} \), \( f_s = 0.05 \text{ mm/rev} \) (0.002 ipr), and \( d_o = 0.18 \text{ mm} \) (0.007 in). The input signal to the plant was chosen to be a 60 Hz sine wave. The output signal of the displacement sensor was recorded by the dynamic signal analyzer. Both the input and output signals are plotted in Figure 10. It can be seen that the positioner follows the signal well, with little distortion and lag. Next, three frequencies were chosen to machine non-circular parts of different cross section. The three frequencies were chosen to be 20 Hz, 30 Hz, and 40 Hz, such that they would generate 2, 3, and 4 lobes on the workpiece.

![Figure 9: Input-Output Relation of the Micropositioner](image)

![Figure 10: Following of a 60 Hz Sine Wave During Cutting](image)

After the experiments were conducted the roundness profiles were collected using a Talyrond 100. An IBM PS/2 Model 70 and an A/D conversion board were employed to digitize the analog signal. The digitized surface profiles consisted of 512 data points for one revolution of the workpiece. The data sets were plotted to display the noncircular profiles that were generated by the micropositioner. The plots shown in figure 11 parts a, b, and c, show the capability of the system to produce non-circular parts of different geometrical configurations.

![Figure 11: Exaggerated Noncircular Turning Profiles](image)

6. RESULTS AND CONCLUSIONS

An actively controlled magnetostrictive actuator based micro tool holder for the turning process has been presented. The magnetostrictive actuator produces high force nearly instantaneously and has a good compressive toughness. These properties make it very suitable for machining applications.

A simple rate feedback control scheme was employed to add additional damping to the micro tool holder system. A model of the micro-toolholder combined with the turning process was derived and the simulation based on the model
showed the effectiveness of the micro tool holder to suppress vibration caused by random excitation. A $2^3$ designed experiment was conducted, and ANOVA techniques were used to verify that the rate feedback compensator improved the surface finish of the turned part with 90% confidence.

A PID controller was implemented to demonstrate the ability of the micropositioner to machine non-circular parts. Three different cross sections (2, 3, and 4 lobes) were machined into an aluminum workpiece at 600 RPM, corresponding to a frequency of 10 Hz. This is a substantial increase in turning frequency over other systems in literature.

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8. REFERENCES