APPLICATION OF AN ACTIVELY CONTROLLED MAGNETOSTRICTIVE ACTUATOR TO VIBRATION ABATEMENT IN THE TURNING PROCESS

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ABSTRACT
An active vibration control system for a turning process is presented. The system employs a magnetostrictive actuation and a rate feedback control scheme to suppress vibration in the turning process. A specially designed tool holder is developed to implement the actuation and the control scheme effectively. A model for the control system is described. The model accounts for the dynamic response of the cutting process and the control system. The effectiveness of the vibration control system is studied via a series of experiments. A disturbance force is applied to the system by a shaker and the dynamic response of the system is observed. The experimental data show that the rate feedback control scheme can add additional damping to the system and reduces the vibration. Finally, a cutting experiment is conducted using the controlled system and the experimentally obtained surface profiles are compared to the surface profiles obtained without the vibration control. It is shown that the system can improve the surface texture generated by the turning process.

INTRODUCTION
Turning is one of the most common machining processes and has many applications. The dimensional accuracy and surface quality of a machined part are of primary importance in the turning process. It is known that the dimensional accuracy and surface quality are directly affected by a dynamic displacement (vibration) between tool and workpiece which arises during the cutting process. The vibration, particularly in the radial direction, is recognized to have a harmful effect on the machined surface texture.

Active control of machining operation has long held the attention of metal cutting practitioners and researchers. For turning operation, much research has been performed to investigate the active control of cutting tool position for the purpose of process improvement. For example, Tsao and Tomizuka (1988, 1994) have explored the idea of changing the depth of cut during a turning operation. Specifically the depth of cut was varied using a hydraulic actuator to generate a non-cylindrical workpiece. Although hydraulic actuators can deliver the force necessary to manipulate the depth of cut during the turning operation, they typically have a low bandwidth frequency response, thus their application is generally limited to situations in which the depth of cut is to be manipulated with a slow speed. Other researchers have used piezoelectric actuators in active control schemes. These actuators have a higher bandwidth, but their actuation is somewhat limited to low force applications (Kiesewetter, 1988). Stepping motors have also been used as actuators in active control (Shiraiishi, et al, 1991), but the limitations are similar to that of hydraulic actuators.

In addition to the work related to manipulating cutting tool position, some research has been performed to manipulate cutting speed during the process. For example, Jemiomenk and Widota (1984) applied a variable spindle speed to reduce the tool/work vibration. Since the method requires speeding up and slowing down the spindle speed in a periodic manner, the inertia of the spindle and drive system becomes a limiting factor. Research has not been limited to just turning operations. In (Liang and Perry, 1994) the actuation of workpiece has been explored to compensate the effect of cutter runout in milling operation.

The purpose of this paper is to present a magnetostriction-based micro-actuation system that can provide active, on-line manipulation of cutting tool in the turning process. In this paper, the basic concept of magnetostrictive actuation is described. A specially designed tool holder assembly is introduced. The
magnetostrictive actuator is integrated into the tool holder assembly with sensors. The tool holder assembly is designed to manipulate the cutting tool in the radial direction only. A model describing the turning process and the actuation system is then developed and studied to understand the vibration arising during the cutting process. A rate feedback control scheme is then introduced in order to suppress the vibration. The purpose of employing rate feedback control is to provide increased damping to the system. Next, the results from a series of experiments are studied to understand the dynamic response of the actuation system. Experimentally collected surface profiles are also studied to evaluate the effectiveness of the active vibration control system. Finally, some conclusions are made.

MAGNETOSTRICTIVE ACTUATION

One of the unique aspects of this work is the employment of an actuator which utilizes magnetostrictive material. The magnetostrictive effect, which was first discovered in nickel by Joule in 1840, relates changes in the geometrical dimensions of a body to changes of a magnetic field applied to the body. A commercially available magnetostrictive material is Terfenol-D which is an alloy of terbium, dysprosium, and iron.

The Terfenol-D rod provides a linear motion when it is excited by a magnetic field. A solenoid coil, driven by an external power supply, surrounds the rod and provides the necessary magnetic field. This magnetostriction is a transduction process in which electrical energy is converted into mechanical energy. This mechanism is illustrated in Figure 1.

As the magnetic field intensity $H$ increases, the strain $S$ increases. If the mechanical stress imposed on the Terfenol-D rod is zero, the linear elongation may be described by a fundamental equation,

$$S = \Delta l / l = H / d$$  \hspace{1cm} (1)

where $d$ is the magnetostrictive constant, $\Delta l$ is the elongation of the rod, and $l$ is the length of the rod. The magnetic field is

$$H = n I$$  \hspace{1cm} (2)

where $I$ is the current and $n$ is a constant. The relation between output force and strain of the Terfenol-D rod can be described as

$$F = \frac{y A \Delta l}{l}$$  \hspace{1cm} (3)

Where $y$ is Young's modulus and $A$ is the cross-sectional area.

Magnetostrictive actuators are suitable for applications with high speed and force (Moffett, et al., 1991). They produce high force at nearly instantaneous speed and have a good compressive toughness. This work utilizes the properties of a magnetostrictive actuator for the manipulation of a cutting tool. The potential use of such magnetostrictive actuation in machining has already been demonstrated in several papers (Michler, et al., 1993, Kashani, et al., 1993). For example, Michler, et al. (1993) have developed a cutting tool positioner that incorporates a magnetostrictive actuator and successfully employed it in a non-circular machining application.

A MODEL OF TURNING PROCESS UNDER RATE FEEDBACK CONTROL

In this work, a tool holder is developed to integrate the magnetostrictive actuator, sensors, and a cutting tool into an assembly. A sketch of the tool holder assembly is shown in Figure 2. In general, the vibration between the tool and the workpiece arises in three dimensional directions, however only the vibration in the radial direction is considered in this paper. The flexor in the tool holder is designed to be rigid in the cutting and feed (tangential and longitudinal) directions and flexible in the radial direction.

Considering the tool holder assembly as a lumped mass system, the structural dynamics of the system may be represented by a single degree of freedom system as shown in Figure 3. 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 $N_r$, the mass of the tool holder is $m$, $k$ is the stiffness of the actuation system, and $c$ is the damping coefficient of the system.

The radial force generated by the cutting process may be approximated as
\[ U(s) = \frac{K_u}{Ls + R} \cdot V(s) \]  

where \( L \) is the coil inductance, \( R \) is the resistance of the coil, \( K_u \) is the force constant, and \( V(s) \) is the Laplace transform of the voltage applied to the actuator.

From Equation (6), it may be noted that a radial force applied to the mass can cause a tool displacement with respect to the workpiece. The tool displacement, of course, can result in a harmful effect on the surface texture generated by the turning (Moon and Sutherland, 1994).

It is well known that the addition of rate feedback essentially serves to increase the amount of system damping. The increased damping, thus, can reduce the tool vibration arising in the cutting situation. In this paper, an acceleration signal is obtained and integrated to provide the velocity signal for the rate feedback control since an accelerometer can measure the tool vibration with efficiency. In the rate feedback control scheme, a compensator is used to provide the rate signal from the accelerometer to the system. The transfer function of the compensator can be described as:

\[ K(s) = \frac{V(s)}{A(s)} = \frac{\omega_c^2 s^2}{s^2 + 2\zeta \omega_c s + \omega_c^2} \]  

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

Figure 4 shows the frequency response of the compensator. From the figure, it can be seen that the compensator acts as a differentiator for the frequencies below the cut off, but as an integrator for the frequencies above the corner frequency. Because the vibration frequency in the turning process is generally much higher than the corner frequency (about 8 Hz), the compensator acts just as an integrator to the acceleration signal.

A block diagram of the turning process combined with the actuation system is shown in Figure 5. In the figure, the compensator provides a voltage \( V_{in} \) to the actuator. Block \( G \) represents the adjustable gain of the power amplifier for the voltage \( V_{in} \) which is used to drive the actuator. In fact the net voltage, \( V_{net} \), applied to the actuator is not same as the voltage provided by the amplifier. When the Terfenol-D rod is strained, a back voltage, \( V_{back} \), is induced from the transducer-like feedback nature of the Terfenol-D rod and coil. Therefore the induced \( V_{back} \) reduces the voltage from the amplifier by impeding the drive current. The magnitude of \( V_{back} \) is proportional to the rate of the change in the Terfenol-D rod displacement.

**OPEN AND CLOSED LOOP FREQUENCY RESPONSE CHARACTERISTICS**

In order to characterize the dynamic response of the actuation system a series of experiments were conducted. The experimental setup is shown in Figure 6. In the experimental setup, a shaker was employed to simulate the tool vibration for a cutting situation. The attachment of the shaker to the tool holder assembly provides a disturbance force in a manner intended to replicate actual cutting. The dynamic motion of the tool holder and the actuator are monitored via several sensors and a HP35670 frequency analyzer.
which is used to capture the data and generate the frequency response functions. A fiber optic displacement sensor is used to measure both the static and dynamic deflections of the tool holder. In addition, an accelerometer is also mounted between the shaker and the tool to monitor the vibration. The system was examined via both with (closed-loop) and without (open-loop) the rate feedback.

For an open loop test, the shaker introduces a disturbance force as a periodic chirp signal (bandwidth of 100Hz to 1700Hz) to the tool holder assembly. In the experiment, the ten frequency response measurements were averaged and shown in Figures 7 and 8. The figures shows a clear resonance frequency (about 1100 Hz) in the system.

For a closed loop test, the same conditions were applied as for the open loop test. An MB250VCF power amplifier was used to drive the actuator. Figures 7 and 8 shows the average of the ten frequency response measurements from the accelerometer and the displacement sensor, respectively.

The comparison between the open loop and the closed loop tests shows that the rate feedback control scheme can suppress the vibration very effectively. From the closed loop frequency responses in Figures 7 and 8, it is apparent that the peak has been completely removed. In fact, a maximum amplitude reduction of 14dB has been achieved in the acceleration signal. The displacement signal also shows a maximum amplitude reduction of 16dB. The phase transition also shows a clear indication of additional damping in the system.

CUTTING EXPERIMENT

Cutting experiments were conducted to evaluate the performance of the active vibration control system under actual cutting conditions. Figure 9 shows the tool holder assembly mounted on the turret of a Cincinnati Milacron 850C chucking center.

Turning operations often involve interrupted cutting. It is known that interrupted cutting produces a significant amount of vibration of the cutting tool relative to the workpiece which in turn degrades the surface generated by the process. In this experiment the active vibration control system was used for the abatement of vibrations arising during the interrupted cutting. For the experiment, an aluminum workpiece 82.55 mm (3.25 in) in diameter and 342.9 mm (13.5 in) in length was used and is shown in Figure 10. It can be seen from the figure that a slot of 9.52 mm (3/8 in) wide and 12.7 mm (1/2 in) deep was milled along the length of the workpiece to produce the interrupted cutting condition.

For the experiment, the feed and the depth of cut were set to be 0.0762 mm, (0.003 in) and 0.635 mm (0.025 in), respectively. The cutting experiment was carried out without control for the first half length of the workpiece, and then the actuation system was switched on for the turning of the last half length of the workpiece. The cutting experiment was carefully designed to hold the same cutting condition for the test and provide a fair comparison. 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 by
measuring along the axis of the workpiece. An IBM PS2 model 70 and an A/D conversion board were employed to obtain digitized profile data from the instrument. The surface profiles are shown in Figures 11 and 12.

The surface profiles obtained without control are shown in Figure 11. From the figure it is apparent that the distance between the maximum and minimum height is 66.00µm for the workpiece entrance side and 59.44µm for the workpiece exit side. Since the feed is 76.20µm, we expect to see about 52 feedmarks within the profile. Although the feedmarks are evident, the figure clearly demonstrate that the tool vibration contributes to the variation in the surface profile heights. The observation that the exit side profile has less height variation than the entrance side may be attributed to the fact that the interruption induced vibration of the cutting tool diminishes over time (back rotation) due to the damping in the system.

Figure 12 shows the surface profiles obtained with control. The Rs and Rmax values are 7.02µm and 40.25µm for workpiece entrance side and are 6.58µm and 34.22µm for the exit side, respectively. Comparing the profile with that in Figure 11, it is evident that the active vibration control system can suppress the vibration effectively. About 40% of improvement in the surface roughness has been achieved in the experiment.

CONCLUSIONS

An active vibration control system in the turning process has been presented. A magnetostrictive actuation and a rate feedback control scheme has been described. The magnetostrictive actuator produces high force at nearly instantaneous speed and has a good compressive toughness. These properties are very suitable for machining applications. The rate feedback control scheme adds additional damping to the system.

A series of experiments have been carried out to demonstrate