DEVELOPMENT OF A MAGNETOSTRICTION BASED CUTTING TOOL MICROPOSITIONER

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ABSTRACT

The development of a magnetostriiction-based cutting tool micropositioner is described. The physics associated with the magnetostriiction phenomenon are discussed. Aspects of the design and construction of the Terfenol-based actuator are detailed. The static and dynamic behavior of the micropositioner are characterized. The actuator is seen to offer advantages to hydraulic and piezoelectric-based systems. It is concluded that the micropositioner shows excellent potential for vibration control and the production of irregularly shaped parts in machining applications.

Introduction

The quality of a machining operation is very dependent on the machine tool used to perform the operation. Machine tools are not perfectly rigid, and therefore, cutting forces produce system vibrations which deleteriously effect such process performance measures as the dimensional accuracy and surface texture of a product. To compensate for the vibrations within a machine tool system, one may employ active control techniques. Such techniques require an actuator to manipulate the position of the cutting tool with respect to the workpiece.

In some machining applications, it is desired to generate workpieces with unconventional shapes. For example, engine pistons are often machined with non-circular cross-sections. Employing conventional machine tools for such application is typically not possible, since a conventional lathe is not designed/configured for such high frequency depth of cut manipulations. Augmenting a machine tool with a micropositioner for “fine” cutting tool motions may possible an effective, economical means for producing unconventional shapes.

In general, therefore, the ability to reposition a cutting tool has potential applications in: i) machining vibration control and ii) the production of unconventional workpiece geometries. In the few applications where tool repositioning has been attempted, “piggy-back” mechanisms have been employed. The requirements for such a “piggy back” system include the ability to move a large and heavy table or tool-post that is also acted on by cutting forces, while at the same time delivering fast and accurate cutting tool motions. These requirements (strong, fast, and accurate) typically are met through the use of micropositioning systems that are completely different in character (e.g., piezoelectric or hydraulic). Since no readily available micropositioner simultaneously satisfies all the stated requirements, this work will investigate the development of a micropositioner using an entirely different principle.

The interest in small, lightweight, and fast actuation systems for accurate and fine motion applications has been receiving more attention in the last few years. Several microactuators, based on various technologies are reported in the literature recently. These include electromagnetic drive actuators (Hollis 1985), magnetically levitated micromachines (Pelrine and Busch-Vishniac 1987), electrostatic actuators (Fujita and Omodaka 1987, Mahadevan 1987), and shape memory alloy actuators (Kuribayashi 1986, Walker 1987, Ikuta 1990). However, piezoelectric and hydraulic actuation systems appear to be the most commonly used actuators for manufacturing applications.

Since the piezoelectric effects were first studied by Curie in 1880, many application of piezoelectricity have been reported. For example, Ellis (1962) described the design of several micromanipulators that were driven by three piezoelectric plates through a linkage mechanism. Moriyama, et al. (1988) described the design of a two-axis DC motor driven stage where a piezo-driven fine stage is mounted on the first stage. Wang, et al. (1989) describe the design and characterization of a linear motion piezoelectric microactuator suitable for precise manufacturing applications. Although piezoelectric actuators are lightweight and highly efficient (Kiesewetter 1988), their application to machining processes is somewhat limited since the peak force generated by small size piezoelectric actuators is usually not enough to move the tool-post nor the table of a conventional machine tool.

Hydraulic actuation systems have been employed for many applications requiring accuracy, speed, and strength which piezoelectric actuators cannot provide. Recent research on hydraulic actuation by Wells et al. (1990) investigated the effect of parameter variation on the overall performance of a generic model of a hydraulic actuation system. The paper examined actuator performance as a function of two factors: intrinsic compliance (the physical compliance within the actuator itself) and the control of the actuator valve. Although the hydraulic actuation systems generate strong forces suitable for machining applications,
they have several disadvantages. First of all, the bandwidth of such systems is limited by the bandwidth of the servovalves which is approximately 400 Hz. In addition to the bandwidth limitation, the required system size for microactuation is very large. A hydraulic servo-cylinder sized for microactuation may be small, but the servovalves, servo-valve cable and hydraulic lines may be too large for many manufacturing microactuation applications.

In this paper the design, construction, and characterization of a lightweight, fast, and strong micropositioner is described. This micropositioner uses magnetostrictive actuation suitable for cutting tool positioning in a machining process. The micropositioner also has the unique features of incorporating position and force sensors in a compact fashion. The actuation system is composed of an aluminum flexor and a Terfenol rod (Butler 1988). Terfenol is a "giant" magnetostrictive material based on alloys of rare earth elements and iron. The Terfenol rod converts electrical energy to mechanical energy with accuracy, speed, and strength suitable for repositioning a cutting tool during a cutting operations.

In the following section a brief review of the magnetostriction phenomenon is given. The mechanical design and construction of a micropositioner utilizing a magnetostrictive material is then presented. Several tests are conducted to characterize the dynamic behavior of the system, and the experimental results are presented and discussed. Next, a potential application of the micropositioner is demonstrated. Specifically, the micropositioner is used to generate a precision oval shaped workpiece. Finally, some general conclusions are presented and plans for future work are proposed.

Magnetostriiction

The magnetostrictive effect was first discovered in nickel by James Joule in 1842, related to the change in the geometrical dimensions of a body subjected to a magnetic field. Magnetostriiction is a result of the rotation of small magnetic domains which cause internal stresses in the magnetostriiction material. Cobalt, iron and alloys of these materials were later found to show significant magnetostriiction effects. However, the strains were still limited to 50 ppm. The development of “giant” magnetostriiction materials, based on alloys of rare earth elements with iron, has caused rapid development of new applications for magnetostriiction transduction. This rare earth magnetostriiction material, Terfenol, produces large strains up to approximately 2,000 ppm as a result of a current in a surrounding coil. Commercially, Terfenol is available in a cylinder or rod form. For a detailed discussion on characterization of Terfenol, see (Butler 1988, Moffett et. al. 1991).

A rod of magnetostrictive material, provides linear motions by exciting the rod with a magnetic field. A solenoid coil, driven by an external power supply, surrounds the rod and provides the necessary field. This magnetostriction is a transduction process in which electrical energy is converted into mechanical energy. This action is illustrated in Fig. 1. As the magnetic field intensity $H$ increases, the magnetic field increases and the strain $S$ increases. If the mechanical stress imposed on Terfenol rod is zero, as in the case of a free unloaded Terfenol rod, the linear transduction may be described by the fundamental equation.

$$ S = H d $$

(1)

![Figure 1 illustrative sketch of strain and elongation for a Terfenol rod](image)

The magnetostrictive constant $d$ for Terfenol is estimated as $20 \times 10^{-9}$ m/A. Therefore, increasing the length of a Terfenol rod increases the total displacement for a given magnetic field intensity. On the other hand, increasing the cross sectional area of a Terfenol rod increases the force of the rod for a given current. For example, consider the case of a 42 mm (l) Terfenol rod used for this research with a coil of 1,300 turns (N) and current of two ampere (I). The magnetic field intensity is

$$ H = n I $$

(2)

where $n = N/l$. Therefore the magnetic field intensity $H = 41,700$ A/m and the strain $S = 830$ ppm. Since the strain is defined by

$$ S = \frac{\Delta l}{l} $$

(3)

where $\Delta l$ is the increased length of rod, the displacement or increase in length $\Delta l = 0.035$ mm. If the rod were 10 times as long, the displacement would be 10 times as much. However, it must be noted that mechanically prestressing the rod is necessary for maximum performance. A mechanical load increases the materials' output strain and, at low fields, tends to produce a more linear response. The experimental results reported recently shows that a prestressed rod can be elongated several times more than a rod without prestress at the same magnetic field intensity (Moffett et. al. 1991).

The high energy density of the rod also provides high force. The clamped force generated is

$$ F = \frac{\gamma A \Delta l}{I} $$

(4)
where $y$ is Young's modulus (about $3.5 \times 10^{10}$ Mpa) and $A$ is the cross-sectional area (mm$^2$). It is reported that a 6.35 mm diameter rod typically produces from 220 to 330 N clamped force, while a 50 mm diameter rod generates forces well over 4500 N (Goodfriend 1991).

The magnetostrictive effect produces high forces at nearly instantaneous speeds, and actuators based on this material occupy a small volume and require relatively low voltage. Actuators based on giant magnetostrictive materials therefore show great potential for performing better than piezoelectric devices and hydraulic systems in machining applications.

Design of a Linear Motion Micropositioner

A useful microactuator for positioning the cutting tool during a machining operation must be mechanically robust, accurate, and low cost. The microactuator proposed in this paper has the potential of being all of the above. The design criteria for this microactuator is a linear motion range of about 0.1 mm, no backlash, peak force of about 450 N, and a fast response. These specifications are needed for positioning the cutting tool during a turning operation. The micropositioner designed consists of a flexor, a magnetostrictive actuator, a position sensor, and a force sensor, all integrated in a frame.

Figures 2 and 3 show a drawing of the top view and a photograph of the prototype micropositioner, respectively. The frame of the micropositioner was machined from a solid block of two inch thick aluminum. It has an integral flexor and an integral tool holder for a high speed steel cutting tool. It is designed to be stiff in the tangential and longitudinal directions and flexible in the radial direction. Although designed as a research tool, it is strong and stiff enough for practical cutting operations.

The actuator part of the micropositioner is a 7 mm diameter Terfenol rod. It is mounted inside a coil wound with approximately 1300 turns of 26 AWG copper wire. This coil will drive the rod to beyond its linear range with two amperes current. The Terfenol rod is mechanically prestressed to take best advantage of its magnetostrictive properties. This prestressing effect on the elongation and the strain for a Terfenol rod was discussed in the previous section. The prestressing is accomplished by turning a bolt that then presses into one end of the Terfenol rod.

To make the micropositioner flexible for a variety of tasks, sensors for measuring displacements and forces are incorporated into the design. Due to the small range of travel of the micropositioner, a displacement sensor providing accurate position information for a small range of motion was added to the system. The feedback transducer is an Electro EMDT with Model 4960 sensor and Model PA12D60 converter module. This sensor has a sensitivity of 7.56 millivolts per micron on the steel target used in this micropositioner. The force data is obtained from a load cell mounted under the Terfenol rod. This is a piezoelectric load cell rated at 2200 N full scale and made by PCB. The catalog states that the stiffness of the load cell is comparable to that of a block of steel of similar dimensions (15 mm diameter). Since the load cell is far stiffer than the Terfenol rod, and is mounted on the frame, the stiffness of the load cell was neglected when analyzing the dynamics of the micropositioner.

Terfenol is extremely brittle. The compressive strength is $6.9 \times 10^8$ Mpa, while the tensile strength is only $0.28 \times 10^8$ Mpa. The properties of low tensile strength and total lack of ductility caused severe problems with chipping of the ends of the Terfenol rod. The first micropositioner design had flat ends on the Terfenol rod. These ends chipped when loaded due to less than perfect alignment and flatness of the supports. A second design has a radius on the ends of the Terfenol rod and a matching radius on the end supports. This design supported the rod without chipping under larger loads than the first design, but chipping was still a problem. The chipping problem was...
finally solved by grinding the ends of the rod flat and bonding aluminum end caps to the rod.

**Dynamic Characterization**

The performance of a Terfenol rod improves under compressive mechanical bias. Also, the compressive bias allows the material to be driven under greater tension and strengthens the material under shock conditions. In the design of the micropositioning this prestressing is done with a bolt through the body of the micropositioner bearing against one end of the Terfenol rod. Figure 4 shows a simple model of the combined actuator/flexor system. For such a system the radial force and displacement are related via Eq. (5).

\[ F = -(k_1 + k_2)x \]  \hspace{1cm} (5)

where \( k_2 \) represents the stiffness of the flexor and \( x \) represents the displacement of the rod. The stiffness of the rod \( k_1 \) is given by

\[ k_1 = \frac{A_1}{l_1} \]  \hspace{1cm} (6)

where \( y_1, A_1 \), and \( l_1 \) are Young’s modulus, cross-section area and length of the rod, respectively. The Young’s Modulus of Terfenol is not a constant (Butler 1988). It is a function of both strain and magnetic field. This can be important when measuring the dynamic response of the micropositioner and when designing a controller for it.

With no mechanical force applied to the rod, the displacement, \( x \), is dependent on the strain of the rod, \( S_f \), generated by the magnetic field. The displacement is then:

\[ x = \frac{l_1 S_f}{1 + k_2/k_1} \]  \hspace{1cm} (7)

It can be noted that the displacement is reduced by the stiffness \( k_2 \) and the useful positioning range of the micropositioner is less than would be indicated based solely on the properties of the Terfenol rod. The positioning range is essentially determined by the ratio of the stiffness of the Terfenol rod to the stiffness of the flexor. If the stiffness of the Terfenol rod is large compared to the stiffness of the flexor, the positioning range will approach that predicted from the strain versus magnetic field intensity curves for the Terfenol rod. If the stiffness of the flexor is equal to the stiffness of the Terfenol rod, the response will be about half that of the rod alone. The micropositioner in this paper has flexor stiffness about 0.39 times the stiffness of the Terfenol rod.

The displacement, \( x \), during a cutting operation is not just dependent on the stiffness of the actuator and flexor, it is also dependent on the workpiece flexibility, and the rigidity of the rest of the machining system. The resulting dynamics of the whole machining system are therefore much more complicated than the simple representation of Figure 4. Thus, Eq. (7) cannot be employed for the accurate control of the micropositioner during cutting. A more complex model of the system is required for the design of the controller for accurate position control. As a first step toward the development of such a model, a dynamic model of the micropositioner is required.

**Figure 4 Actuator with spring and external masses**

To characterize the dynamic behavior of the micropositioner, the system may be represented as a single degree of freedom system, with an effective mass and spring constant. The equation of motion for such a system is

\[ M_e \ddot{x} = F \]  \hspace{1cm} (8)

where \( M_e \) is the effective mass of the tool holder. For this second order system, the natural frequency is given by

\[ \omega_n = \sqrt{(k_1 + k_2)/M_e} \]  \hspace{1cm} (9)

For the purpose of identifying the dynamic behavior of the micropositioner, several tests were performed. These include step and frequency response tests and tests for estimating the stiffness of both the Terfenol rod and the flexor. A block diagram of the components of the open loop system is shown in Figure 5. Figure 6 also shows the overall setup for the experiment.

Since the flexor is integrated into the frame of the micropositioner, its stiffness \( k_2 \) may not be easily calculated from its dimensions and Young’s modulus. To estimate the stiffness \( k_2 \) the bolt designed for mechanical prestressing of the rod was tightened while recording both force and displacement of the flexor using the displacement transducer mounted on the micropositioner. Figure 7 shows the relationship between the displacement and the force generated. The stiffness of the flexor, \( k_2 \), was estimated to be \( 2.1 \times 10^6 \) N/m. The combined value of stiffness for the flexor/Terfenol rod together was measured by forcing the cutting tool tip into a stationary workpiece using the lathe cross slide feed while recording force and displacement. Figure 8 shows the relationship between the displacement and the force generated. The combined stiffness was estimated as about \( 8.2 \times 10^6 \) N/m.
The resonant frequency of the assembly (approximately 2000 Hz) was measured by observing the response of the displacement transducer to a force impulse applied to the tool holder part of the micropositioner.

Figure 6 The overall setup for the experiment

Figure 7 Force vs. displacement of flexor only

Figure 8 Force vs. displacement of flexor/Terfenol rod assembly

Figure 9 shows the system response to a step input in the current supplied by the power amplifier. The step input in the current (from 0 to 4 amperes with a slight overshoot) was achieved with the aid of a mechanical switch. The noise in the current signal due to the switch closing has been removed from Figure 9, and thus we only see the portion of the current input from 1 to 4 amperes. The displacement at a current of 1 ampere is seen to be approximately zero, and rises to 0.047 mm.

Figure 10 shows the response of the micropositioner to a sinusoidal input signal of 5 Hz (voltage input to the power amplifier) with and without the cutting operation being performed. The “butterfly” curves of Figure 10 illustrate a hysteresis effect, which could be important in very-fine position applications. This hysteresis effect is relatively small for Terfenol and may be ignored in most applications.
In summary, the natural frequency of the micropositioner system was found through experiments to be 2000 Hz. This is an important finding because the micropositioner is actuated via a time varying magnetic field. Time varying magnetic fields induce eddy currents in materials that are electrical conductors. These eddy currents have several effects. They cause power to be lost due to $I^2R$ losses - eddy current squared times the resistance of the Terfenol rod in this case. This lost power shows up as a temperature rise in the rod - reducing the power efficiency. The eddy currents also produce a magnetic field that opposes the magnetic field applied by the coil. This eddy current effect increases with frequency. For a Terfenol rod 7 mm in diameter, the eddy current generated magnetic field becomes significant at frequencies above 1500 Hz. Both the natural frequency of the micropositioner system and the frequency at which significant eddy current effects begin are well above most frequencies required for active machining control. Therefore, the micropositioner system shows good potential for machining applications.

### Machining of a Non-cylindrical Part

The purpose of this section is to suggest and demonstrate one potential use of the micropositioner. This is accomplished through an experiment machining a precision oval shaped workpiece. Such an operation is representative of applications such as the precision machining of non-cylindrical parts. The micropositioner described here has sufficient frequency response to machine both the taper and the oval as part of the finish cut and do this at high speeds. A Monarch lathe was used for the investigation. Table 1 describes the cutting conditions that were used for the experiment.

Once the surface was generated via the turning process, a roundness profile was collected using a Talylor 100. An IBM PS/2 Model 70 and an A/D conversion board were employed to obtain digitized data from the analog signals of the Taylor 100. The digitized surface profiles were composed of 512 data points.

#### Table 1: Cutting Conditions for Turning Experiment

<table>
<thead>
<tr>
<th>Workpiece material</th>
<th>aluminum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workpiece diameter</td>
<td>76 mm</td>
</tr>
<tr>
<td>Length to diameter ratio</td>
<td>4:1</td>
</tr>
<tr>
<td>Tool</td>
<td>High Speed Steel</td>
</tr>
<tr>
<td>Nose radius</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Spindle speed</td>
<td>300 rpm (5 Hz)</td>
</tr>
<tr>
<td>Feed</td>
<td>0.132 mm</td>
</tr>
<tr>
<td>Depth of cut</td>
<td>0.25 mm</td>
</tr>
<tr>
<td>Rake angle</td>
<td>0°</td>
</tr>
<tr>
<td>Micropositioner input frequency</td>
<td>5 Hz</td>
</tr>
</tbody>
</table>

One of the experimentally collected roundness profiles from the machined workpiece is shown in Figure 11. From the figure it is apparent that the roundness profile has an oval shape, and the difference between the maximum height and a perfect circle is approximately 0.015 mm. Although the deviation from the perfect circle has been exaggerated, the figure clearly demonstrates that the micropositioner has the capability to generate a non-cylindrical workpiece using a conventional machine tool and conventional cutting speeds.
Figure 11: An oval shaped cylinder machined with the micropositioner

Summary

A micropositioner for application in machining processes has been developed. This micropositioner employs a magnetostrictively-based actuator, position and force sensors. The dynamic characterization of the microactuator shows good potential for machining applications, but does exhibit some nonlinear behavior that is both amplitude and frequency dependent. An application of the micropositioner on a general purpose lathe for machining a non-round (e.g., oval) shape has been demonstrated.

For practical use of the micropositioner, a closed loop controller is needed. The dynamics of the microactuator indicate the need for a nonlinear compensator as well. The development of a controller design is underway, and once developed, the controller will be implemented on a lathe. The fully developed system then may be applied to improve the surface texture, vibration, and roundness in a turning operation in addition to the application described in this paper.

References


