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MODELING AND CONTROL OF A MAGNETOSTRICTIVE TOOL SERVO SYSTEM

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1. ABSTRACT

This paper addresses the modeling and development of a nonlinear control methodology for a magnetostrictive system. As an application of smart materials, magnetostrictive transducers can generate high mechanical strain with a broadband response and provide accurate positioning. Even though these properties characterize a good tool servo application in precision machining, the actuators contain significant magnetic hysteresis and are highly nonlinear when combined with 2^{nd} order dynamics of a tool fixture. Full utilization of these transducers generally requires an advanced controller as well as accurate model of the transducer dynamics in response to various inputs. At moderate to high drives, the magnetostrictive actuator develops highly significant hysteresis on top of the dynamics of a tool fixture. Many sophisticated control schemes have been proposed to deal with this nonlinearity. This paper presents the development of a sliding mode controller to control a tool servo system for various inputs in the presence of highly nonlinear dynamics.

2. EXPERIMENTAL APPARATUS

With an optical sensor, the stroke of the actuator can be measured under various voltage inputs at different frequencies and amplitudes. When the dynamics of the actuator is acquired, a DSP board, which integrates A/D and D/A converters, is needed to generate a control signal to the actuator. The signal follows the control algorithm in order to deal with the hysteresis and nonlinearities issues. Based on the feedback signal from measurement, a PID and nonlinear control approach, sliding mode control are developed. A signal is generated through the D/A channel from the DSP board and directed to the actuator as shown in Figure 1.

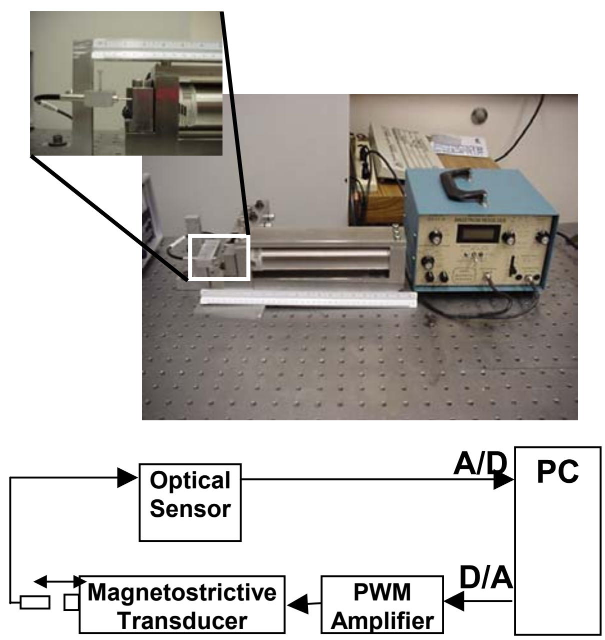

Figure 1: Closed Loop Magnetostrictive Transducer

2.1 MAGNETOSTRICTIVE TRANSDUCERS

In the presence of a magnetic field, a magnetostrictive material, Terfenol-D, generates mechanical stroke by rotating

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internal magnetic domains in the direction of the field causing an elongation. The more intense field; more domains rotate until the saturation is reached.

Figure 2 illustrates the component of the transducer. A Terfenol-D rod is surrounded by a solenoid, which produces a changing magnetic field. This changing magnetic field causes Terfenol-D to stretch and, then contract when the field is removed, producing a stroke and force output. A preload and bias magnetic field is installed to achieve bi-directional motion. The amplitude of motion is proportional to the magnetic field provided by the coil system.

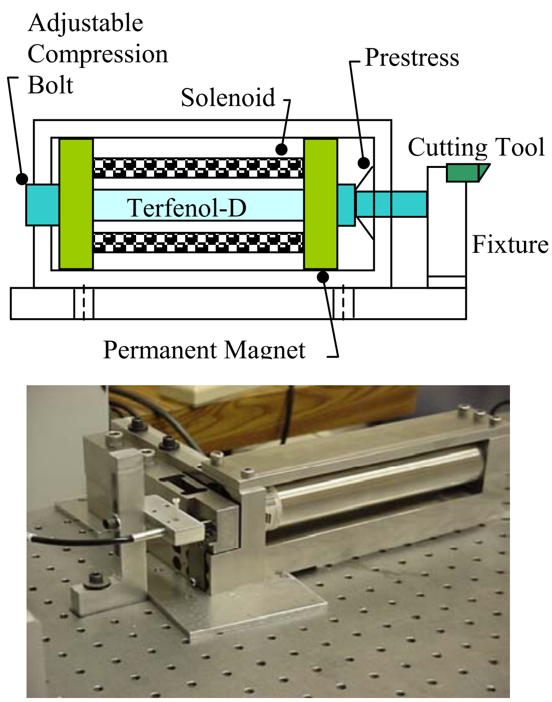

Figure 2: Component of Magnetostrictive Tool Servo System

3. MAGNETIC HYSTERESIS MODEL

When a magnetostrictive material is subjected to a magnetic field, the domains inside the material crystal rotate, resulting in changes of its shape. If the crystal is perfect, the material can expand and contract without loosing energy. However, the crystal usually contains inclusions or pinning sites, which impede the rotation of the domains. The relationship between the input current and the induced magnetostriction displays significant hysteresis and saturation effects at high drive levels as shown in Figure 3. The

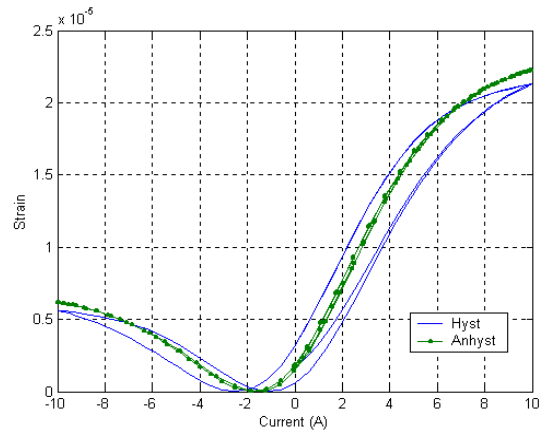

Figure 3: Profile of Magnetostriction with Bias Magnetization and Preload

dashed line represents the anhysteretic (hysteresis-free) magnetization while the solid line portrays the hysteretic magnetization. When the applied magnetic field increases, both magnetizations evolve until they reach the saturation.

The *quasi-macroscopic* model used to characterize the transducer dynamics is described by Calkins, Smith, and Flatau [1, 2]. The magnetization component of this model is based on the Jiles-Atherton mean field theory for ferromagnetic materials [3-7]. Figure 4 shows the data flow in the dynamics model of a magnetostrictive core when the current is given as a command input.

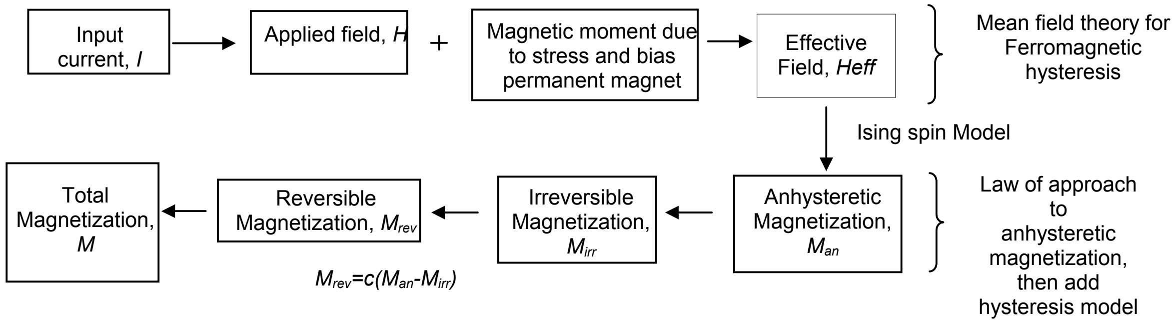

Figure 4: Flow Chart of a Computational Magnetization for a Magnetostrictive Core

Figure 5 illustrates the comparison of the actuator dynamics between the actual (left) and simulation (right) when applying a sinusoid input current at 10Hz. The dynamics is linear with the current at low amplitude. At high amplitude, the actuator yields a significantly nonlinear output. The simulation properly captures the transition of the in change dynamics.

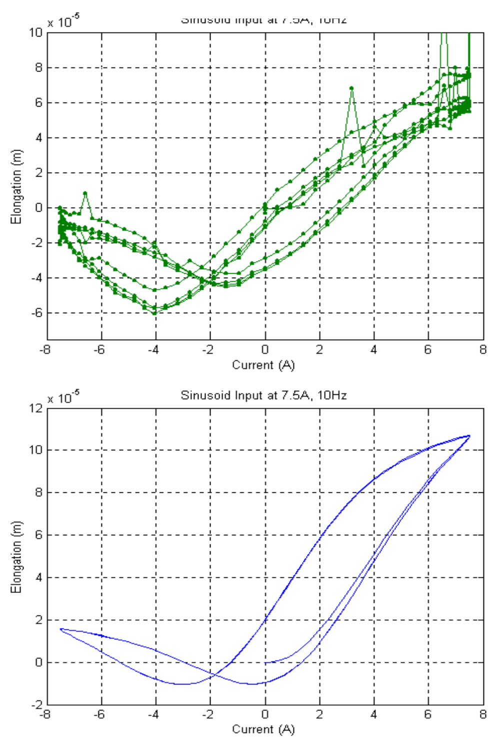

Figure 5: Comparisons Between Actual And Simulated Elongation Evolution At 10 Hz

The profiles of forces corresponding to different current magnitudes behave similarly to the strain profiles. All anhysteretic forces, however, evolve in the same path. While hysteresis forces develop different sizes of major loops. This behavior will be applied for the proposed control scheme.

4. SLIDING MODE CONTROL

As a robust control scheme, sliding mode control can offer many good properties, such as insensitivity to parameter variations or uncertainties. The modeling inaccuracies can have strong adverse effects on a control system. The model imprecision may come from unknown system dynamics, or intentionally simplifying a representation of the system dynamics [8]. Sliding mode control is a simple approach to a robust control designed to handle these problems. The controller is often employed in robotic applications [9] as well as precision machining [10].

With Sliding control, the complicated hysteresis model can be expressed in a simple representation by using an anhysteresis model as a center, and then correcting the effect of hysteresis gap. This idea can be applied to the structure of a robust controller, which constitutes a nominal part, while additional terms deal with model uncertainties. By inverting the anhysteresis, the amount of equivalent control can be determined. To restrain uncertainties such as noise, unmodeled dynamics, the Lyapunov stability condition was introduced to calculate the switching gain.

Figure 6 displays a comparison of the amount of measured current amplitude and predicted equivalent control in order to achieve a certain elongation magnitude. The current difference indicates the effects of the hysteresis gap, 2nd order dynamics, and the imprecise parameters. This difference can be corrected by applying the variable switching gain. The next section will show the controller performance through a simulation.

5. SIMULATION OF MAGNETO-STRICTIVE TRANSDUCER

The simulated results of two controllers at 50 Hz are demonstrated in Figure 7. The simulation integrates imprecise parameters of the fixture dynamics to investigate the robustness of the sliding controller. PID (left) performs slightly worse in terms of tracking ability especially at the peaks of command elongation. Here, the sliding control (right) is virtually on top of the desired trajectory for the entire simulation period.

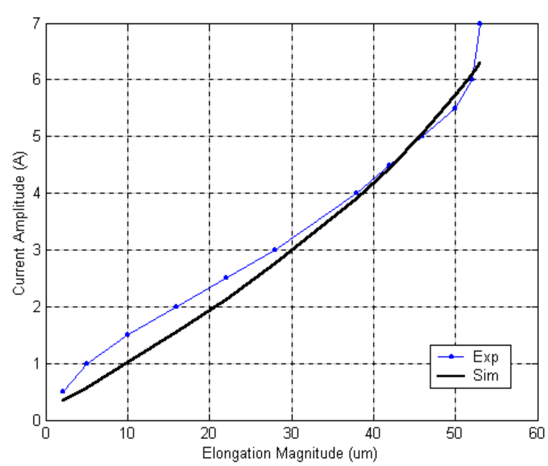

Figure 6: Measured Current and Simulated Equivalent Control

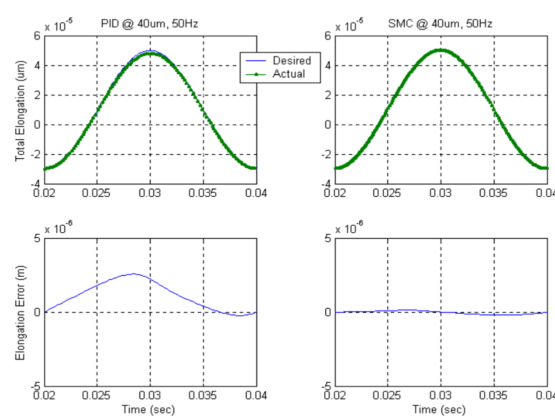

Figure 7: Comparisons Between Simulated PID And Sliding Mode Controller

6. EXPERIMENTAL RESULTS

The closed loop actuator was investigated at low to high amplitude. The PID gains were adjusted for a particular frequency by referring to Ziegler-Nichols technique, while the parameters of the sliding mode controller (SMC) were continuously used for every input frequency.

Typically, the performance of SMC increases with sampling frequency. However, this is not the case for a magnetostrictive transducer. Since the amount of applied magnetic field *H* depends on the rate change of the input current, the output force and stroke intrinsically associate with the magnitude of SMC parameters and the sampling frequency. In the experiment, the sampling frequency was about 40 times of the stroke frequency. To operate the transducer at 100 Hz, the sliding control employed a sampling frequency of 4000 Hz, for example. This factor affects the bandwidth of the SMC servo system since the DSP board can acquire the measured data at a maximum rate of 10,000 Hz. Accordingly, the SMC transducer can work up to 250 Hz, while the PID system has no such limitation. In general, the stroke frequency of 100 Hz is high enough to drive most applications and to study the influence of hysteresis. The SMC parameters do not need a re-calibration unless a frequency more than 250 Hz is required.

Shown in Figure 8, a comparison between PID (left) and SMC (right) shows a significant delay in PID outputs, whereas the SMC travels mostly on top of the desired trajectory.

To evaluate the performance in terms of the robustness, a mass was attached against the tool fixture. Then, the results were compared with the closed loop actuator when driving without load. The comparison is shown in Figure 9. The PID output is slightly worse when operating with the load on. More wavy profile can be noticed. The SMC profile, however, behave better with the load variation.

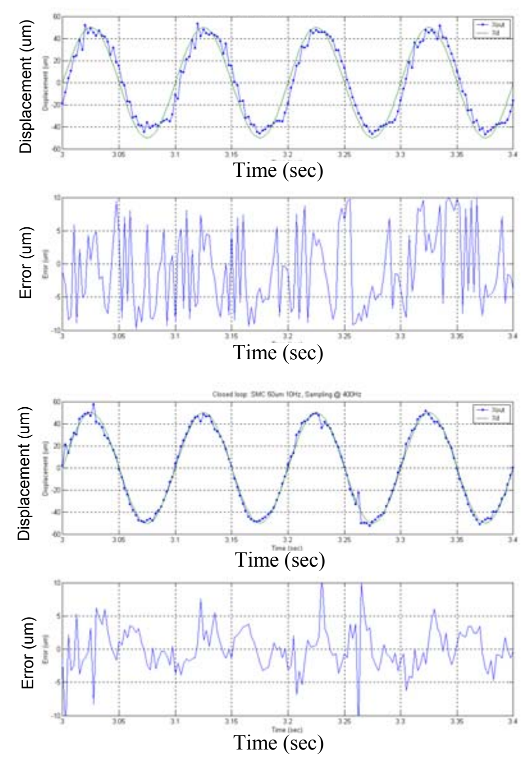

Figure 8: Experimental comparison between PID (left) and SMC (right) performance for a 50µm 10Hz sine wave command.

7. CONCLUSION

To fully understand how to control a magnetostrictive tool servo system, the magnetostriction phenomenon including inherent hysteresis has been studied. Sliding mode control with a variable switching gain was presented to deal with uncertainties such as disturbances, or unmodeled dynamics. The anhysteresis based on a *quasi-macroscopic* model was used to compute the equivalent control. The

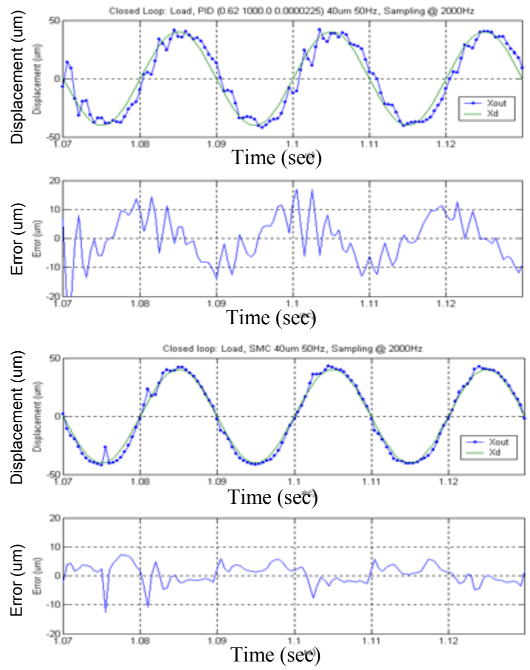

Figure 9: Comparison at frequency of 40 μm 50 Hz with a load of 5 kg.

hysteresis gap and the dynamics tool fixture were, then, corrected by the switching gain based on the Lyapunov stability condition. The proposed controller was analytically tested through the numerical simulation. The experimental examples drew the comparisons between the two controllers. PID cannot overcome the influences of hysteresis, resulting in a significant output delay, while sliding mode control yielded better tracking performance and more robustness.

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