DSC-Vol. 57-2, 1995 IMECE
Proceedings of the ASME Dynamic Systems and Control Division
ASME 1995

FORCE CONTROL EXPERIMENTS FOR ENGINEERING GRADUATE STUDENTS

Hodge E. Jenkins
The George W. Woodruff School
of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0405

Thomas R. Kurfess
The George W. Woodruff School
of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0405

Mark L. Nagurka
Industry Systems Group
Carnegie Mellon Research Institute
700 Technology Drive
Pittsburgh, PA 15230-2950

ABSTRACT

This paper describes a series of experiments for beginning graduate students in control engineering. The design of a servo driven force controller is the framework for the experiments. Principles of classical and modern control, signal processing, system identification, and design robustness are presented and applied in the elements of experiments. Electronic and mechanical (mechatronic) hardware familiarity is also addressed. Force control methodologies including impedance matching and PID control are studied for stability and achievability of the desired response.

Control is studied both in terms of the frequency response and time response. The implemented controller design is digital, using an Intel 486-PC based system. System response under variations of sampling times is examined. Signal processing is introduced in terms of the quadrature motor shaft encoders as well as analog force and position sensors. Anti-aliasing filters are designed and built for the analog sensors. With the instrumentation in place, system identification experiments are conducted to determine appropriate system models. These models are used for controller design.

In controller design students become familiar with MATLAB control and signal processing tools. Bode plots, root loci, gain plots and parametric plots along with simulations are used to determine an appropriate controller design, based on the student's desired specifications and identified model. After successful designs are simulated, they are then implemented on the servo system. Controller hardware and software allows the capture of sensor and state time history data for later analysis, and design validation.

INTRODUCTION

Many industrial applications require force control to varying degrees. In the area of precision systems, the delicate regulation of force is paramount. Variations in force can severely affect a machined part dimension, a ground part's surface finish, as well as the dimensional accuracy of a measurement Thus, experiments in force control can provide a graduate student with a unique perspective.

SYSTEM DESCRIPTION

The system in these experiments consists of a three-axis prismatic servo stage, as shown in Figure 1. However, to perform these experiments only one axis is needed. The servo stage is controlled by a programmable multi-axis controller (PMAC by Delta Tau Data Systems) at a sampling rate of 2.26 kHz (the maximum sampling rate of the PMAC system). The power amplifier for the PMAC has output limits of 24V and 150W.

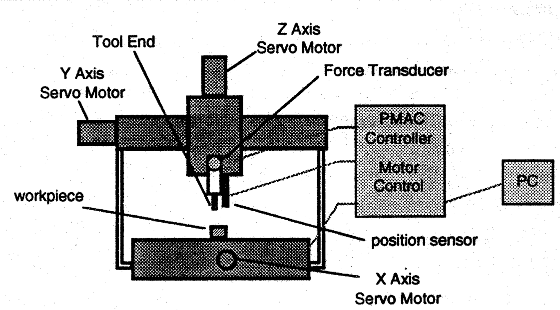


Figure 1. System Schematic.

The PMAC has an analog to digital converter (A/D), allowing four analog voltage inputs. An Assurance Technology 6-axis analog force sensor is used to measure force in all three axial directions. A 500-line optical encoder with quadrature is connected to each motor shaft for feedback. An eddy current probe is used to directly measure the relative displacement between the servo stage end (or tool) and the environment (workpiece). An LVDT would also be a good choice for these experiments. The shaft encoders and analog sensors are connected to the PMAC controller and also sampled at 2.26 kHz.

Analog voltage signals from the force transducer and eddy current sensor are low pass filtered prior to sampling to prevent aliasing.

EXPERIMENTAL OVERVIEW AND OBJECTIVE

A specific control objective is set for the experiment. Typical experiments might include maintaining a constant force, following a force trajectory, or moving of the stage according to a spring law. Constant force regulation on a single axis is the objective for these experiments.

Students can learn much in the work required for the system assembly and the experimental setup. During the equipment setup, students become familiar with design of filters for feedback sensors. Basic movements of the servo stage and system identification techniques are learned, as a transfer function between commanded position and the force output is estimated. Classical and digital control concepts are emphasized as students develop the control algorithms. Students can see classical and digital control concepts applied in the PMAC-based force controller, while designing and experimentally verifying the force control. A proportional, integral, and differential (PID) control is designed for the position feedback loop. An outer force control loop is used to regulate the normal force along the Z-axis. Considerations on the controller gains are minimal overshoot and rise time, as well as actuator achievability (no saturation). Frequency and digital designs are analyzed using traditional and robust design tools. Implementation of various controllers gives students the experience needed to design a digital controller. Test runs for force servoing are performed on the system to verify controller design gains and modify them as necessary to achieve the desired closed-loop response attributes.

Construction of Anti-Aliasing Filters for Sensors

The design, construction, and validation of second or higher order, analog, Butterworth filters help familiarize the student with analog electronic designs as well as the properties of various filters (elliptic, Chebyshev, and Butterworth). Low pass filters are necessary for sampling the outputs signals of the analog force and eddy current position sensors, to limit their frequency content. The cut-off frequency is set by the student based on anticipated closed-loop response and the sampling rate (a typical cut-off frequency is 500 Hz). The response of the filters is verified by the student using an oscilloscope and frequency generator, or by a transfer function analyzer, if available. A fourth order Butterworth low-pass filter transfer function from an actual filter is given in Figure 2.

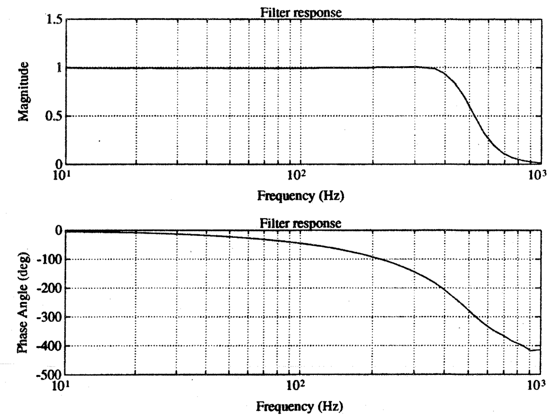


Figure 2. Magnitude and Phase Plots of Anti-Aliasing (4th Order Butterworth Low-Pass) Filter.

System Identification and Characterization

Familiarity of equipment hardware and creating an analytic model the system are achieved as students successfully performs system identification. Both an analytical and experimental model are needed. Experiments with the servo stage are used to characterize the system in terms of its open loop response. This is a critical element in the controller design process. Several approaches may be taken. Input voltage to each axis motor in the form of a step, pulse, or other multi-frequency input may be used. Since students will be using a limited displacement system, a square pulse of limited duration is probably the easiest accomplished input form for identification. In another approach, white noise might be injected to determine the system response; however, the stability of the experiment and potential lack of frequency content in a limited signal favor the use of the former input signals. If available, a stepped sine input transfer function generator would yield a good frequency response characterization.

Typically, the velocity or position of the servo stage encoder is the measured output. Here, a relation between position and force must also be determined by the student. Compliance of the system may be experimentally determined, or a known value of stiffness may be introduced so that the force response may be linearly related to position control (neglecting inertial and damping effects). Measurement of compliance requires absolute force and position measurements, so an eddy current sensor or LVDT must be used to measure position. Although force might also be measured and servoed directly from the force sensor, it is advantageous to have position commands for the servo stage for ease of the experimental setup. It is not advised in these experiments to change the feedback variable between position and force. Issues associated with the transitional stability should not be introduced at this time.

For the experiment, the student will record the known input voltage and output position/velocity of the axis to obtain data for off-line identification analysis. This is usually accomplished through the PC-based motor controller. However, analog signals may be obtained using a separate analog to digital converter board. The experiments should be repeated to verify the results.

The student should also derive an analytic expression for the system position response to input voltage (based on the motor torque, speed and voltage relationships of equation 1). This will indicate the expected form of the identified system.

$$J\dot{\Omega} + \frac{K_t K_e}{R_a}\Omega = \frac{K_t}{R_a} v_a + T_l \qquad (1)$$

where Ω is the angular velocity of the motor shaft, J, K_t, K_e, and R_a are motor constants, and T_l is the torque load.

Figure 3 represents the block diagram of the servo stage. C(s) is the position compensator. The transfer function between the controller output voltage, U(s), and the achieved angular velocity, $\Omega(s)$, is given by a first order transfer function, M(s). Linear speed is related to the angular velocity by the pitch of the lead screw, L. Positional output is the integral of velocity.

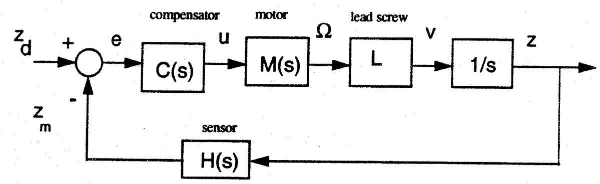


Figure 3. Position System Block Diagram.

Having developed an analytic model and obtained experimental system response data, the student is introduced to system identification techniques using computer aided design tools such as the System Identification Toolbox in MATLAB. At this point estimation algorithms are discussed. Recent research papers relating to parameter estimation are also introduced to the student. The student will become familiar with digital filtering and various regressive techniques for model identification in this process. Generally a least squares technique such as the autoregressive external input (ARX) parameter estimation method (Ljung 1987) yields satisfactory results for identification of a low order system. Previous work has indicated that ARX models tend to favor higher frequencies (Tung and Tomizuka 1993). Therefore, the sampled system data should be digitally filtered to remove frequencies greater than upper bound expected frequency, prior to identification. The student will apply digital low-pass filtering on the experimental data at the desired cut-off frequency. This is done prior to the use of ARX techniques. Parameter estimations are then derived using experimental voltage input, u(t), and output data y(t). The desired form of the model should be the same as the analytic expression. Least squares estimates of the unknown state space parameters are obtained as follows.

$$\begin{aligned} y(t) &= G(q)u(t) + H(q)e(t) \\ e(t) &= H^{-1}(q)[y(t) - G(q)u(t)] \equiv \text{error} \end{aligned} \qquad (2)$$

$$[\hat{G}_N, \hat{H}_N] = \min \sum_{t=1}^{N} e^2(t) \qquad (3)$$

The resulting first order system L M(s) is given as

$$\frac{V(s)}{U(s)} = L\,M(s) = \frac{397}{s + 2.95}\left[\frac{mm/s}{volt}\right] \qquad (4)$$

Simulation results using the estimated system with the experimental input data can be compared to the actual system response. Figure 4 shows the result of such an identification process. The top figure depicts both the actual data and the response of the identified model to the voltage input of the lower figure. Iteration on filtering and estimation is usually required to obtain an acceptable model.

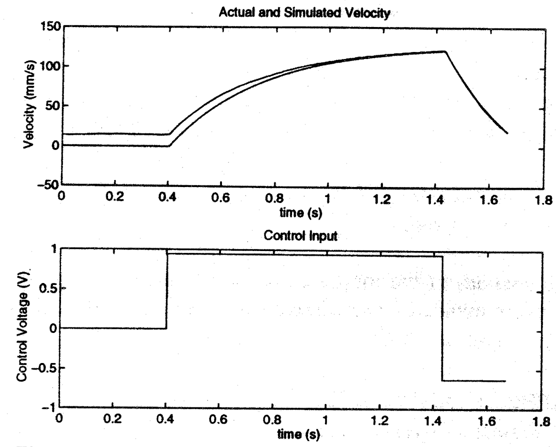


Figure 4. System Identification: Actual and Model.

Multi-axis system allows for further experiments by graduate students. For multi-dimensional systems such as the one of Figure 1, there are several inputs and outputs for each axis. Cross coupling of the inputs and outputs can occur. For example, if the desired outputs of two dimensions are force and velocity, an increase in force of one axis may slow the velocity of the other axis as the load is increased. Treatment of two-axis systems with cross coupling can be found in (Jenkins, Kurfess and Dorf, 1994). The system described in that research used one axis to control velocity while the other axis provides force regulation. Although not presented here, the issues of axial cross coupling are suitable for additional experiments.

SPECIFICATIONS

In order for the student to design a system force controller, a set of desired performance specifications for the servo stage must be established. These specifications are a combination of minimum acceptable performance requirements and physical constraints. Once these are detailed the control design and parameters may be determined. The following paragraphs discuss the selection of control criteria to be applied. This also serves as a review of control objectives for the student. It is also good for the student to think in terms of designing a force control for a specific application such as a machining operation.

Steady State Error

To ensure repeatability of machine deflection and to prevent tool damage, it is desired to maintain a constant force level. Thus, the system must have zero steady state error to a constant command in force. Many external influences can create disturbances, to induce force variation during a processing operation (*i.e.*, initial tool contact and retraction.) Thus the student should desire the final force response to have no steady state error.

Root Sensitivity.

The maximum root sensitivity is an indicator of how the closed loop poles vary as various parameters change. For this particular design, we are interested in the magnitude of the root sensitivity with respect to the forward loop gain, $|S_k|$. For consistent system performance the closed-loop system poles must not move substantially during the system's operation. In particular, poles must remain in position as the forward loop gain changes due to analog system variations (*e.g.*, heating of servo amplifiers, etc.). Thus, root sensitivity must be relatively small. If the force loop has tight tolerances, $|S_k|$, is extremely critical, thus it is required that $|S_k|$ be as low as possible. It should be noted that the root sensitivity magnitude is always extremely high in the vicinity of break-in and break-out points on the root locus. Thus, values of the loop gain that place poles in these locations are to be avoided. The student should select the system poles to have minimum sensitivity to root variation.

Percent Overshoot and Settling Time.

Trajectory overshoot is a major concern for the force loop. If the system overshoots the desired force level, damage could occur to the work piece or the tool end of the axis. Therefore, it is required that the maximum overshoot permitted in the force loop is within 2% of the commanded level for a step input. The 2% settling time is also desired to be as low as possible. Expectations for settling times are under 1 second for the force loop. Depending the specific system properties the appropriate value should be selected.

Servo Command Signal (Voltage and Power Constraints).

In addition to the performance specifications, physical limitations must be considered. For the particular system used in our experiments, the control command signal from the power amplifier is limited to ±24V. Outside of this ±24 V range the control system is saturated. To ensure that the power amplifier is not saturated, a maximum of ±24 V is permitted on the amplified command signal when a step input of 1 N is commanded in force

Voltage is not the only concern for the power amplifiers. Fore example it is necessary that the system will not require more power than the amplifier can provide (even if the driving voltage is within the ±24 V limits). Experience has demonstrated that limits on the peak power rather than the continuous load limit the system performance. For the system of Figure 1, the maximum possible peak power that the amplifiers are capable of delivering is 120 W (24 V at 5 A). To approximate the power used by the system, a measured winding resistance of 1.04 Ω is used in conjunction with the amplifier voltage.

CONTROLLER DESIGN

The student is now ready to design the controller for the particular system. The student will use the model(s) derived from system identification techniques and control design tools that address classical, digital, and robust issue. If force is being controlled via position, then two control loops must be designed, a position loop and force loop.

Position Controller.

Since the force is controlled via position, a position control loop must be implemented first. The PID position control for the step position plunge is determined using the PMAC to achieve a minimum acceptable bandwidth on the position control loop with a unity damping ratio. Integral control is used to eliminate steady state position errors. Typical overshoot is less than 1% for the range of experimental step displacement commands.

Based on the previously identified system, the student can derive PID-type controllers to achieve the desired response. (Note that integral control for position may not be desired when the position loop is integrated into the force loop. Integral control can cause unwanted position/force oscillations.) The servo amplifier limitations must also be accounted for to assure a linear response. The student should simulate the motor/axis response to determine the limitations on position controller gains. Many PC-based motion control systems will provide a tuning utility to the determine the position loop gains for a desired bandwidth. These are usually based on the Ziegler-Nichols (Franklin 1992) PID tuning techniques.

Force Controller.

In order to perform the constant force experiments, a PI force controller is designed for the system. A block diagram of the complete system and controller is shown in Figure 5. The system model consists of several functional blocks, PI force controller, $G_{FC}(s)$, PMAC position control loop, $G_{PC}(s)$, the tool to workpiece interaction, $G_{TW}(s)$, as well as the force sensor response, $G_{FS}(s)$.

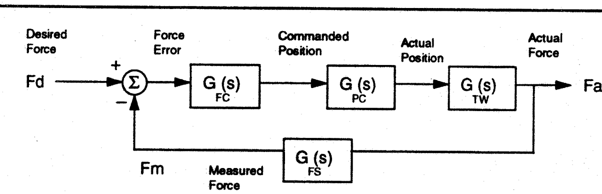


Figure 5. System Dynamic Model and Force Controller.

The position loop transfer function, $G_{PC}(s)$, is the block between the commanded position and the actual position of the Z-axis. Depending on the characteristics (non-linearities) of the particular controller, an experimental model of the controller may be needed. It is also a good idea for the student to verify the position loop design. A linear, first order model of the position loop servo response with the tool in contact with the workpiece, $G_{PC}(s)$, is estimated using the same ARX techniques as outlined earlier. A second order system should also be identified. The additional pole found in the second order system estimation is significantly larger than the first pole, indicating that a first order system is, indeed, a good representation.

An ARX position model is verified by simulation using experimental data for input and comparison. The experimental data should be in agreement with the identified model as can be seen in Figure 6, for the system used in our experiments. For this case the correlation coefficient is 0.997. The effective force loop sampling is also determined from the data of Figure 6. The resulting frequency domain transfer function between the commanded position and the actual position of the Z-axis is given in equation (5).

$$G_{PC}(s) = \frac{19.5}{s + 23.4} \qquad (5)$$

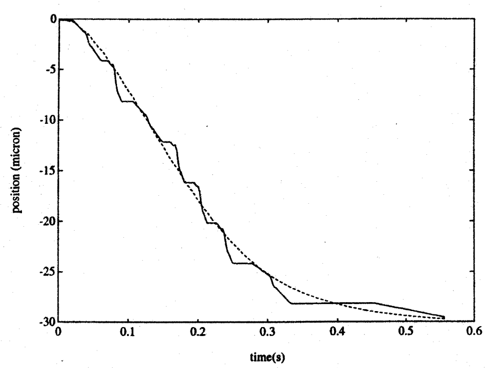


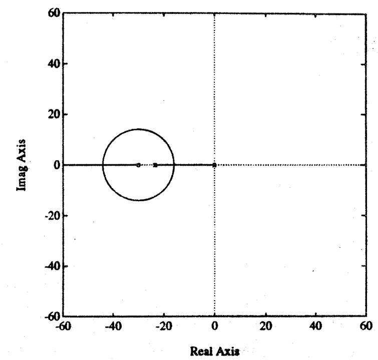
Figure 6. System Output Data and ARX Model Response to Commanded Input Displacement.

The tool to workpiece interaction, $G_{GP}(s)$, is modeled as a linear spring. The vertical stiffness of the grinder (assuming a rigid workpiece) is known to be 233 N/mm. The resultant force is also dependent on the force sensor response transfer function, $G_{FS}(s)$, assumed as a unity in this case.

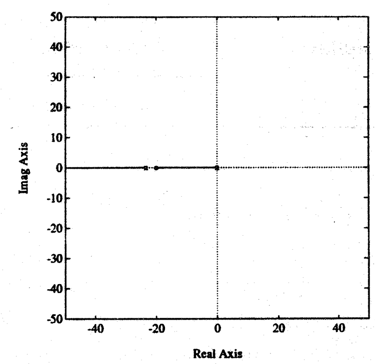
Having estimated a plant model, the controller design can proceed. Generally a PI controller will yield acceptable performance (to eliminate the steady state force error), although the student is free to select the form desired. A PI force controller transfer function, $G_{FC}(s)$, for the given system is described as follows.

$$G_{FC}(s) = K_{prop}\left(s + \frac{K_{int}}{K_{prop}}\right)\frac{1}{s} \qquad (6)$$

The integral and proportional gains, K_{int} and K_{prop}, respectively, must be determined. From a frequency domain perspective it is desirable to have a high ratio of integral to proportional gain, placing the transmission zero farther along the negative real axis, away from the origin. A non-oscillatory force response is to be avoided, implying the upper bound of the ratio of integral to proportional gain is the system pole. Larger values of this ratio will cause the system roots to move away from the real axis as the proportional gain is increased. This can be seen in the root locus plots of Figure 7. Other considerations for setting the ratio of integral to proportional gain are the amount of force overshoot at initial contact of the axis to the part, the rise time of the force regulation, as well as actuator saturation.



(a) Zero at -30



(b) Zero at -20

Figure 7. Root Locus Plots for Various Zero Placement.

Once the ratio of integral to proportional gain (K_{int}/K_{prop}) has been decided, frequency domain analysis indicates that the larger the proportional gain the better. However, another consideration is that a digital position controller is used. As such, the force resolution and stability are directly affected by the proportional gain. (For perfect impedance matching the proportional gain is the inverse of the axis/contact stiffness.) If the effective sampling rate is greater than 20 times the system frequency response then the controller gain values will be nearly the same in both the z-plane design and s-plane design.

Figure 8 plots the z-domain root locus vs. the proportional gain. (Note all roots are real.) Upon inspection of Figure 8, it can be seen that for system stability the proportional gain must be less than 100. Real process deviations from the simplified model could lead to instability, if a proportional is selected near the "knee" of the curve in Figure 8, where the system dynamics change rapidly. Thus, a proportional gain of 3 farther away from this point is selected for good system stability and reduced root sensitivity (Kurfess and Nagurka 1994). (The system vertical stiffness is part of the proportional gain, so the selected value of 3 is divided by the known tool-to-part stiffness for implementation in the controller.) It is interesting to note that the location of the plant zero (K_{int}/K_{prop}) has little effect on selecting the limiting system proportional gain.

The integral gain, K_{int}, is selected by limiting the amount of force overshoot to a step input. A value of 2 for K_{int}/K_{prop} is selected to limit the initial contact force overshoot, and to achieve a rise time of less than 1 second. See Figure 9. The system should experience no actuator saturation as a result of the selected controller gains.

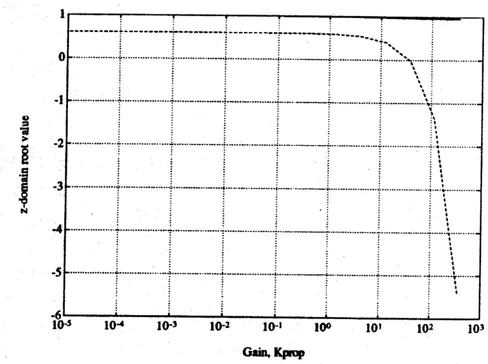


Figure 8. Digital Root Real Value vs. Proportional Gain.

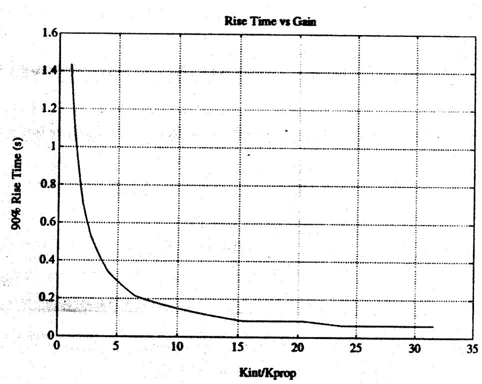
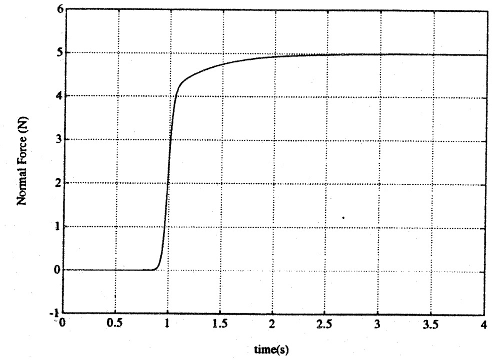


Figure 9. 90% Rise Time vs. K_{int}/K_{prop}.

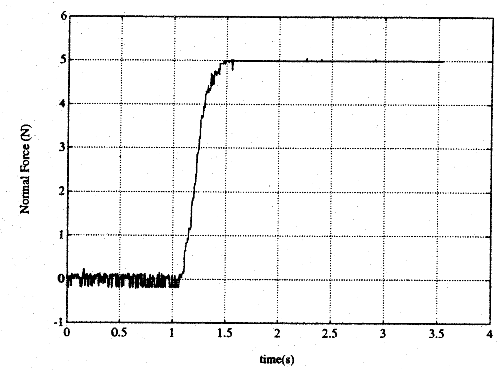
VERIFICATION EXPERIMENTS AND SIMULATIONS

With the controller designed, a last set of experiments is conducted to verify the force response. The contact specimen and axis are aligned and the desired force level is set. The servo stage tool end is positioned near the part surface. The PMAC force controller is activated, recording motor encoder, force and displacement data at 4.45 ms. The tool end of the axis is servoed downward from the force error, eventually making contact with the part and increasing the applied force to the desired set point.

The experimental result can be compared to the simulated response. Constant force servoing is simulated in MATLAB. The experiment force response and the response of the model to a commanded 5 N step in normal force is displayed in Figure 10. The model and experimental force response data are in agreement.



(a) Simulation



(b) Experimental Results

Figure 10. Experimental and Simulated Force Control

The following step approximation is used for simulations (Nunes, 1993). This step approximation is shown in Figure 10.

$$u = \frac{t^N}{t^N + 1}, \qquad \text{where } N = 45 \tag{7}$$

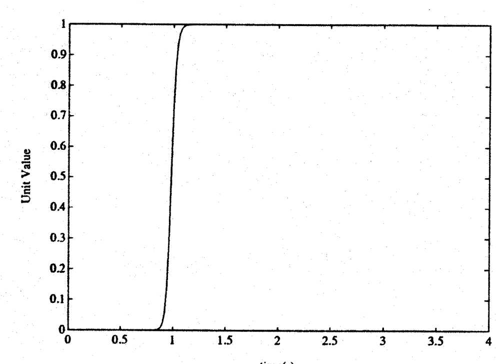


Figure 10. Sigmoidal Step Approximation

POTENTIAL PITFALLS

There are few potential pitfalls in these experiments. However, availability and familiarity of hardware and software

are critical. The interface of the sensors and hardware to the controller and servo stage must planned, carefully to assure compatibility. Also, it is prudent to build safety into the system, both in terms of hardware and software limits. The force sensor must be able to safely withstand a stall-torque motor condition. Likewise circuit breakers or fuses should be connected to the motors to mitigate any thermal problems from excessive current.

CONCLUSIONS

In these experiments we have a developed a training method for a new graduate student in controls to develop an understanding of force control servoing both from a software and hardware perspective. The student will gain a fundamental understanding of classical control and digital control theory from first hand observation. Laboratory experience is also gained in filter design, application of sensors for feedback, system dynamics, and system identification.

This work can serve as a foundation for more advanced experiments or research in multi-axis systems with cross coupling and low velocity stiction. Experiments in real-time transitions from position to force servoing (with a preview sensor) or impedance matching might also be explored depending the research interests of the professor and student.

ACKNOWLEDGMENT

This work was funded by the National Science Foundation under Grant Numbers DDM-9350159, EEC-9256665, and DDM-9257514. The government has certain rights in this material. Any opinions, findings and conclusions or recommendations are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

Franklin, G. F., Powell, J. D., Workman, M. L., 1992, *Digital Control of Dynamic Systems*, 2nd ed., Addison-Wesley.

Jenkins, H. E., Kurfess, T. R., Dorf, R. C., 1994, "Design of a Robust Controller for a Grinding System," *The Third IEEE Conference on Control Applications*, Vol. 3, pp. 1579-1584.

Kurfess, T. R., Nagurka, M. L., 1994, "A Geometric Representation of Root Sensitivity," *ASME Journal of Dynamic Systems, Measurement, and Control*, Vol. 116, No. 4, pp. 305-309.

Ljung, L. , 1987, *System Identification: Theory for the User*, Prentice Hall , Englewood Cliffs, NJ.

Oaki, J., 1991, "Stable Force Controller Design Based on Frequency Response Identification," *IEEE Workshop of Intelligent Robots and Systems*, pp. 1116-1121.

Nunes, A. C., 1993, "Rounded Approximate Step Function for Interpolation," *NASA Tech Briefs*, Vol. 17, No. 7, pp. 84.

Tung, E., Tomizuka, M., 1993, "Feedforward Tracking Controller Design Based on the Identification of Low Frequency Dynamics," *Journal of Dynamic Systems, Measurement and Control,* Vol. 115, pp. 348-356.