AC 2010-147: IMPLEMENTING THE DIGITAL SPEED CONTROLLER TUNING OF A LABORATORY ROTARY HYDRAULIC SYSTEM

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ABSTRACT

The objective is to give the students practical experience in tuning a digital speed controller for a rotary hydraulic system starting with the Ziegler-Nichols method. Digital controller basics and the tuning method are discussed. In using this method the critical tuning area of system operation must first be determined. This impacts the selection of fixed controller tuning parameters which are used for command changes, load changes and startup. For this system, as long as transient startup is acceptable, it was concluded that the settings should be selected for the more restrictive minimum speed operating condition. The resulting operation at higher operating speeds is then somewhat less responsive than the selected tuning point.

BACKGROUND

An assembled automatic control loop[1,2,5] must have the controller gains properly selected to provide a completed suitable response. The Zeigler-Nichols (Z-N) method helps the students to more easily tune or select the proportional, integral, and derivative gains as needed in a practical laboratory environment by selecting an initial starting point for further trial and error work. Engineering education occurs as the students are able to progress from their own poorly selected gains and the resulting poor responses to more desirable gains and responses in a timely "hands on" manner. Although no actual student surveys are available at this time, the conclusion of one student group lab report[6] does state "The results that were achieved for this experiment appear to be very good. The plots of the system response versus the load appear to match up very well with what was expected. The values of the ultimate gain and ultimate period seem appropriate, as do the estimated initial controller settings determined using the Ziegler-Nichols tuning method." Thus, loop response improvements similar to those shown here have been made in a timely manner and do give a positive indication of student learning. The Z-N method is also presently used by the other professors teaching these courses. Having benefited by this engineering education the students will be able to use it as a fundamental tool in other appropriate industrial applications in the wide world of automatic control.

The physical system arrangement will now be described. The plant consists of an axial piston motor which drives an identical axial piston pump through a shaft mounted torque speed transducer. The pump is loaded using a remotely controlled relief valve in the output loop. A rotational speed feedback signal is available from a speed transducer system using a pickup and 60 toothed wheel. The shaft torque and additional pressures and flows are displayed on the stand panel face. Additional instrumentation is available to provide and select needed electrical signals. The system is shown schematically and pictorially in figures 1 - 4. Note: The schematic omits the clutch and frictionally driven flywheel.

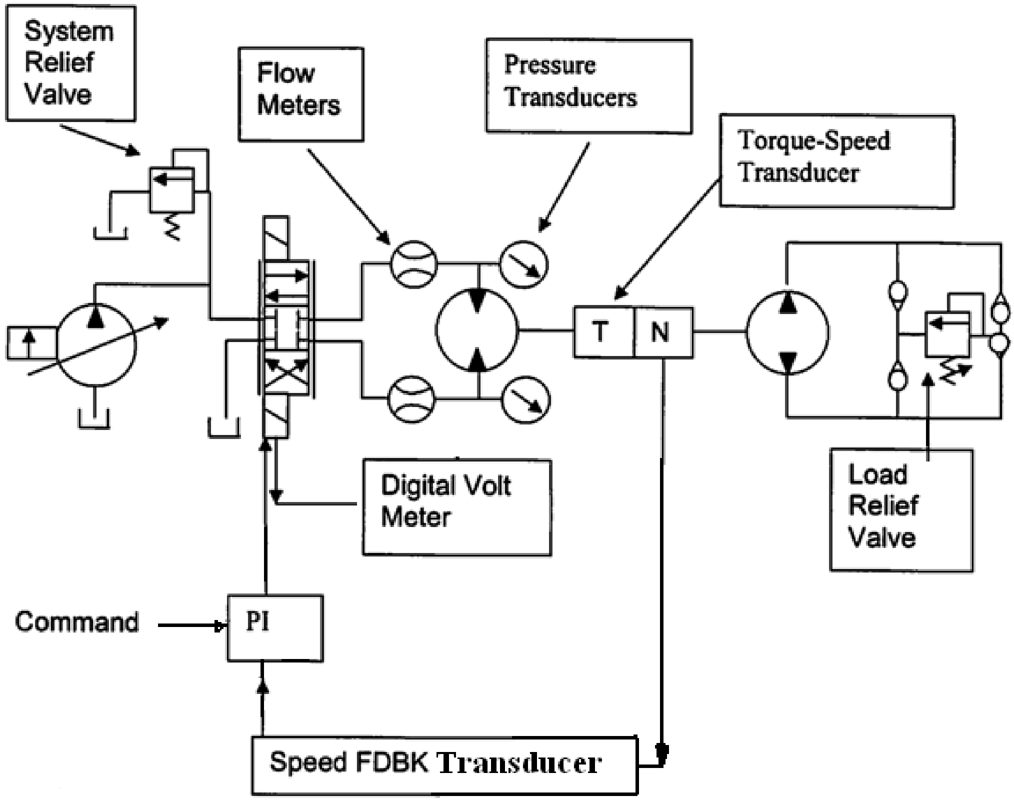

Figure 1 Rotary Speed Control Arrangement Schematic[3]

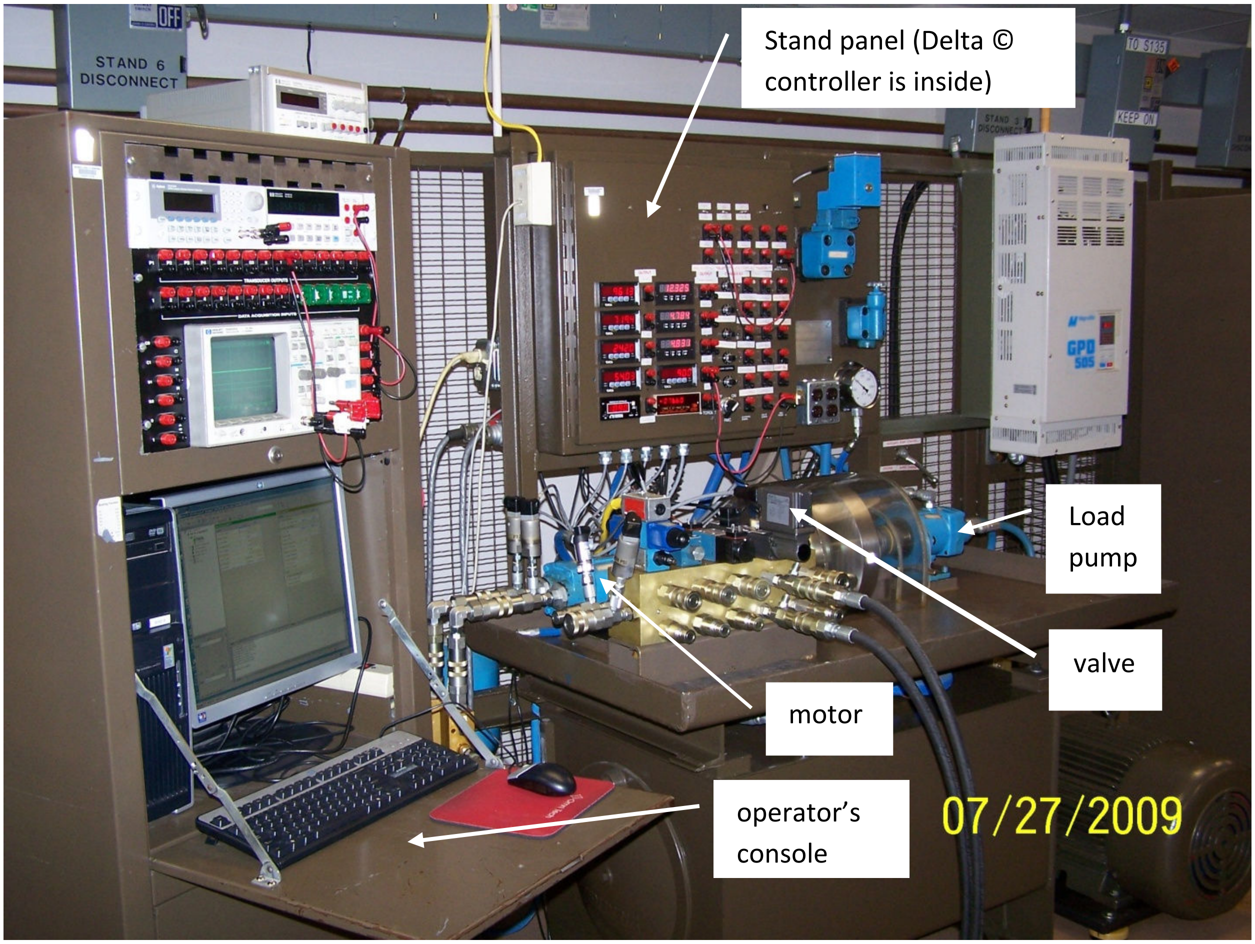

Figure 2 Physical Arrangement

The control system is arranged to provide rotational speed control for various speed levels and load disturbances. The direct digital control system is implemented using a Delta© RMC-70 series controller with its software and an ATOS© electro-hydraulic proportional control valve as shown in figure 2. The control valve will accept analog ±10 V input signals to position the valve using an internal position control loop and provide an analog ±10 V output signal representing the actual valve position.

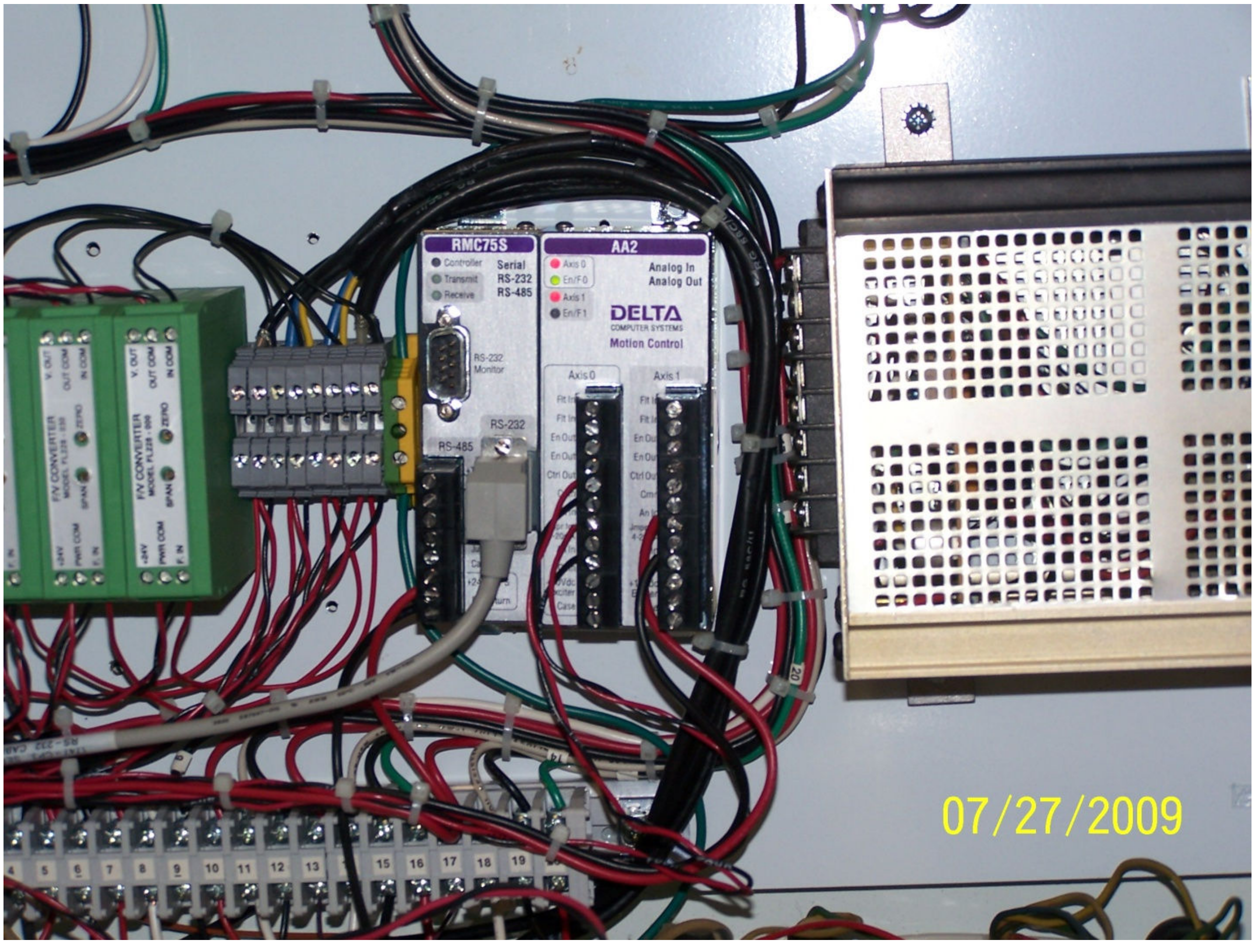

Figure 3 Delta© Controller

The software is arranged for operator interface with the controller inside the stand panel. In the most basic format the feedback speed signal is compared to the desired speed signal resulting in an error signal which is used by the controller to produce an output to the valve. The student operator interface for the controller is located on the operator's console and includes access to operating commands as well as tuning parameters and plotting functions.

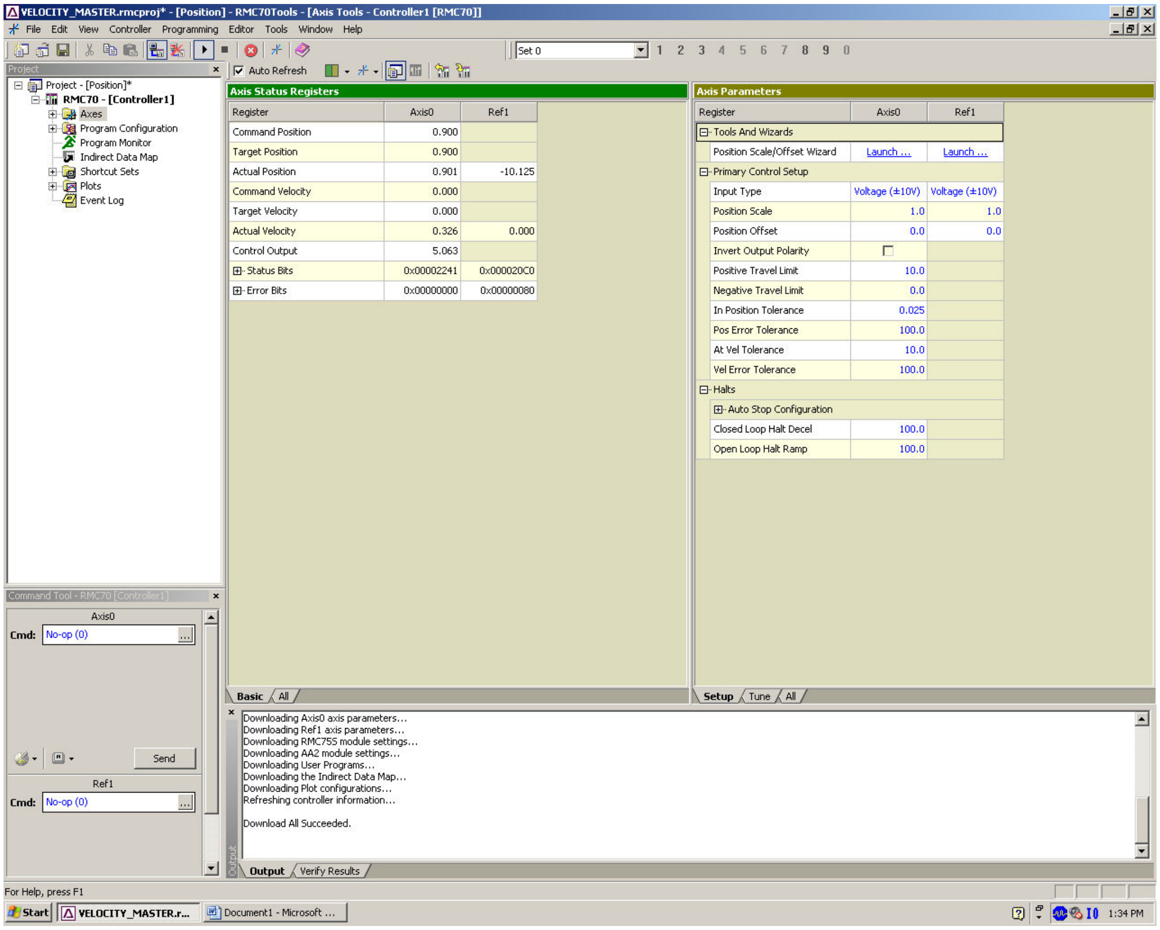

Figure 4 Delta© Controller Operator Interface

Basic Theory

Despite the fact that the proprietary Delta© software is unknown, generic equations for a basic digital PID control are given for helpful background information. In this discussion, the total sample time is shown in multiples of the time between each completed individual sample, T. The equation terms are illustrated using the figures 5-8 as sampled values compared to some arbitrary continuous signals. Please note that the following curves are for illustrative purposes only without any scale and thus are not numerically summed.

The basic equation[4] (1) is:

$$u(k) - u(k-1) = K_p[e(k) - e(k-1)] + \frac{K_i T}{2}[e(k) + e(k-1)] + \frac{K_d}{T}[e(k) - 2e(k-1) + e(k-2)] \qquad (1)$$

u(k) represents the controller output signal at time kT.

u(k-1) represents the controller output signal at time (k-1)T.

e(k) represents the error signal at time kT.

e(k-1) represents the error signal at time (k-1)T.

K_p = the proportional gain.

K_i = the integral gain.

K_d = the derivative gain.

T = the time between completed samples called the sample time.

K_u = ultimate gain (to be used below in text and table 2).

P_u = ultimate period (to be used below in text and table 2)

Table 1 Terminology

Equation (1) indicates that the change in controller output, u(k) – u(k-1) is due to the sum of a proportional, P, term plus an integral, I, term plus a derivative, D, term. This change in the output signal u(k) – u(k-1) occurs from time (k-1)T to time kT. This is called a velocity format[4] which includes the advantage that the output signal to the valve may remain at its last value in some failure situations. The controller output values are diagrammed in figure 5.

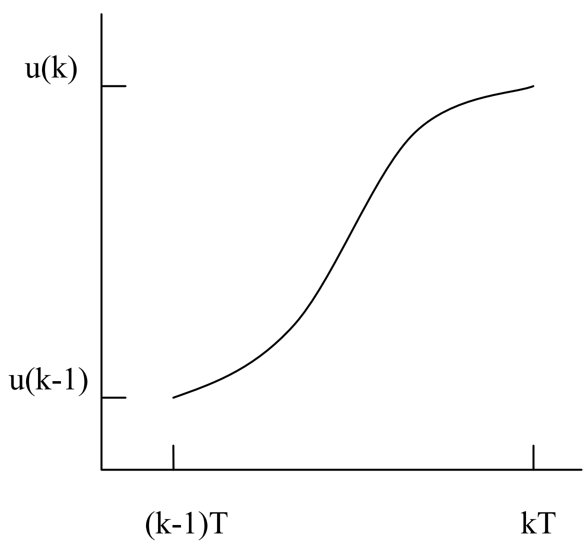

Figure 5 Output Values

The proportional term is the product of a proportional gain, K_p, and the change in the error e(k) – e(k-1).

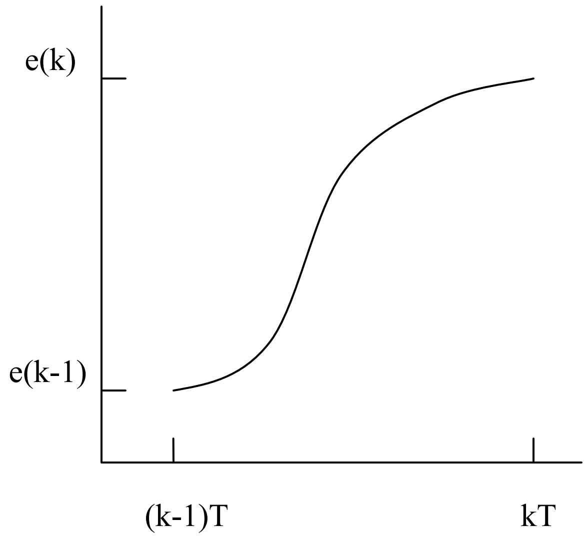

Figure 6 Error values for Proportional Term

The integral term is due to the product of an integral gain, K_i, and a trapezoidal approximation of the integral of the error over the period. The approximation uses the area under the error curve as the average height, e ave times the width, T.

$$\{e\ ave\}T = \left\{\frac{[e(k)+e(k-1)]}{2}\right\}T$$

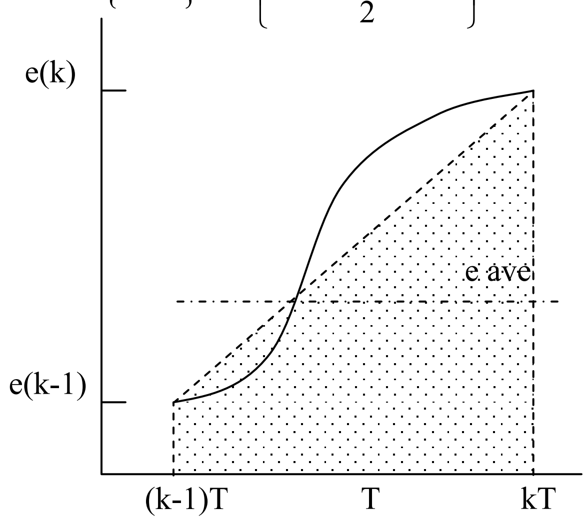

Figure 7 Trapezoidal Integration

The derivative term is due to the product of the derivative gain, K_d, and differences of the two derivatives. This is computed as the difference between the two slopes which is taken as:

{[e(k) - e(k-1)]/T – [e(k-1) – e(k-2]/T} or {[e(k) – 2e(k-1) + e(k-2)]/T}.

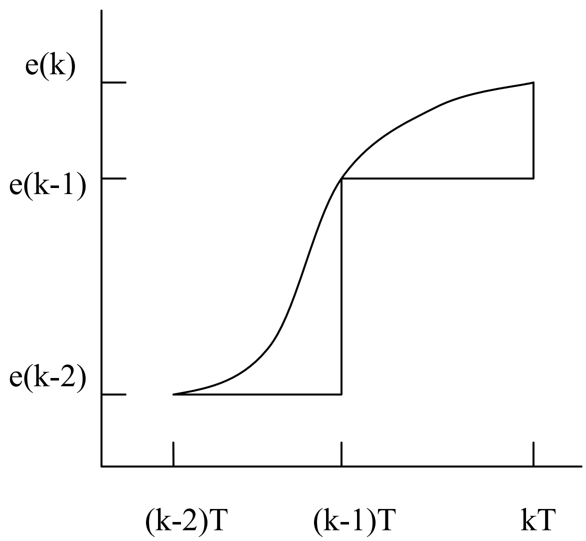

Figure 8 Backward Differences

Equation (1) may also be expressed in the z domain for use in Simulink© by remembering that Z^{-1} serves as a unit delay function[4].

$$U(Z) - Z^{-1}U(Z) = K_p[E(Z) - Z^{-1}E(Z)] + \frac{K_i T}{2}[E(Z) - Z^{-1}E(Z)]$$
$$+ \frac{K_d}{T}[E(Z) - 2Z^{-1}E(Z) + Z^{-2}E(Z)] \qquad (2)$$

The resulting transfer function is

$$D(z) = \frac{U(Z)}{E(Z)} = K_p + \frac{K_i T}{2}\left(\frac{Z+1}{Z-1}\right) + \frac{K_d}{T}\left(\frac{Z-1}{Z}\right) \qquad (3)$$

TUNING

If the sample time is small enough, a sampled curve approximates an analog curve. In this case, as a starting point, the digital controller gains were initially approximated by the gains obtained using a Zeigler-Nichols type method on a digital computer.

Ideally the command should exactly duplicate the step command change and show no change following a disturbance input. Various tuning methods have been employed. In this case, the basic practical Ziegler-Nichols (ZN) ultimate cycle method is quite successful even when the non-linear effects are included as discussed below. This is often implemented using a two channel digital storage scope found on the student console. The Delta© controller also provides a plotting function which provides additional information for comparison purposes when tuning.

For student instructional purposes, basic controller tuning can be divided into three parts. First, some slow settings of proportional and integral gains are used with command and disturbance load changes to set reference responses. Secondly, the Ziegler Nichols method is used to determine some ball park setting estimates. Finally, individual customized settings are developed to obtain the best results.

For this system, slow settings are arbitrarily chosen as a proportional gain of 25 and an integral gain of 100. At a minimum torque of approximately 63 in-lbs, the command speed is changed from 900 rpm to 700 rpm and returned. At 900 rpm, the shaft torque is changed from approximately 68 to 119 in-lbs and returned. Slow responses are observed as shown below in figures 9 and 10.

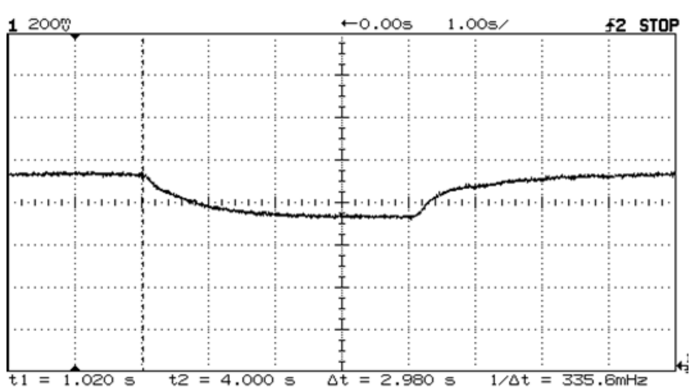

Figure 9 Scope Command Change Slow Response

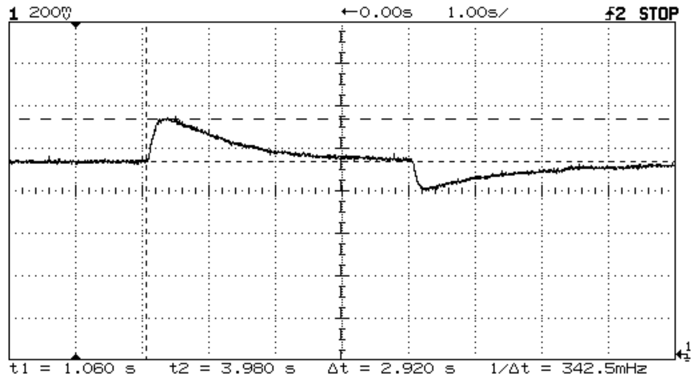

Figure 10 Scope Load Change Slow Response

Fundamental to the Ziegler-Nichols (ZN) method is obtaining the ultimate cycle. This involves using proportional only control and raising the gain until the system exhibits a small equal amplitude continuous cycle. This implies the presence of at least one set of complex conjugate roots on the imaginary axis. This ultimate gain is called K_u and the ultimate period is called P_u. For this system it was determined that the values of K_u vary with the average value of the cycling rpm, N_u. Thus, K_u at the low end of the continuous operating range (700 rpm) is approximately 200 which is substantially less than K_u at a continuous higher end (900 rpm) of approximately 400. The controller is then tuned at 700 rpm and is less under damped at 900 rpm. The ultimate cycle initial data obtained near 700 rpm was ~0.063 seconds which was approximately that obtained near 900 rpm. These values were used even though subsequent values of ~ 0.073 were observed for both speeds which would have beneficially reduced the integral gain. Tuning begins using table 2.

CONT. TYPE	K_p	T_i	T_d
P	$0.5K_u$	∞	0
PI	$0.45\ K_u$	P_u /1.2	0
PID	$0.6\ K_u$	P_u /2	P_u /8
K_u = ultimate gain	P_u = ultimate period		T_i = Integral time
T_d = derivative time	K_i = integral gain= K_p / T_i		K_d = der. gain =K_p*T_d

Table 2 ZN Values and Related Terms[2]

Note that the integral time is the time required for the integral term to repeat the proportional correction. The derivative time is the time saved by derivative action.

Experience shows that the PI controller performs better than the Proportional plus Integral plus Derivative (PID) controller for this system so the PI controller will be selected. Using the ZN table 2, the Proportional plus Integral (PI) controller gains obtained are $K_p = 90$ and $K_i = K_p / T_i = \sim 1700$.

The tuned load change responses are expected to have small changes in rpm and to be of short duration. The quick startup transition from 0 to 700 rpm is oscillatory but is expected to still be acceptable here.

If the responses obtained are too aggressive and oscillatory, individual customized settings are then developed. Recall that the ZN settings are intended to give ¼ decay response which definitely may not be desirable for everyone. Parameters may be adjusted by trial and error following basic definitions for each mode.

If desired, the Delta© controller also provides a plotting function presently arranged for five channels as shown below in figures 11 – 13 which provides additional information for comparison purposes when tuning. This provides additional insight into the effects of parameter changes on the response. Responses will vary but tend to be closer to the theoretical command and disturbance values.

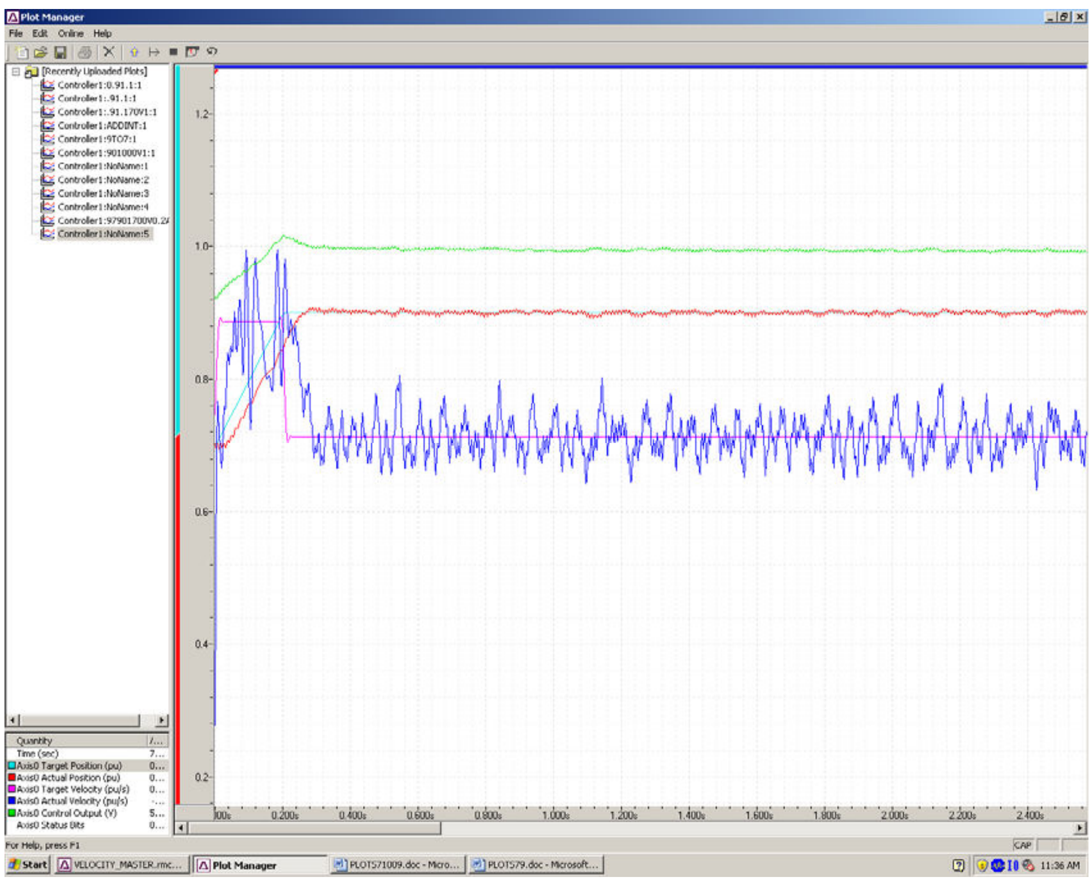

Figure 11 Sample Delta© Controller Increasing Command Change Response Plot

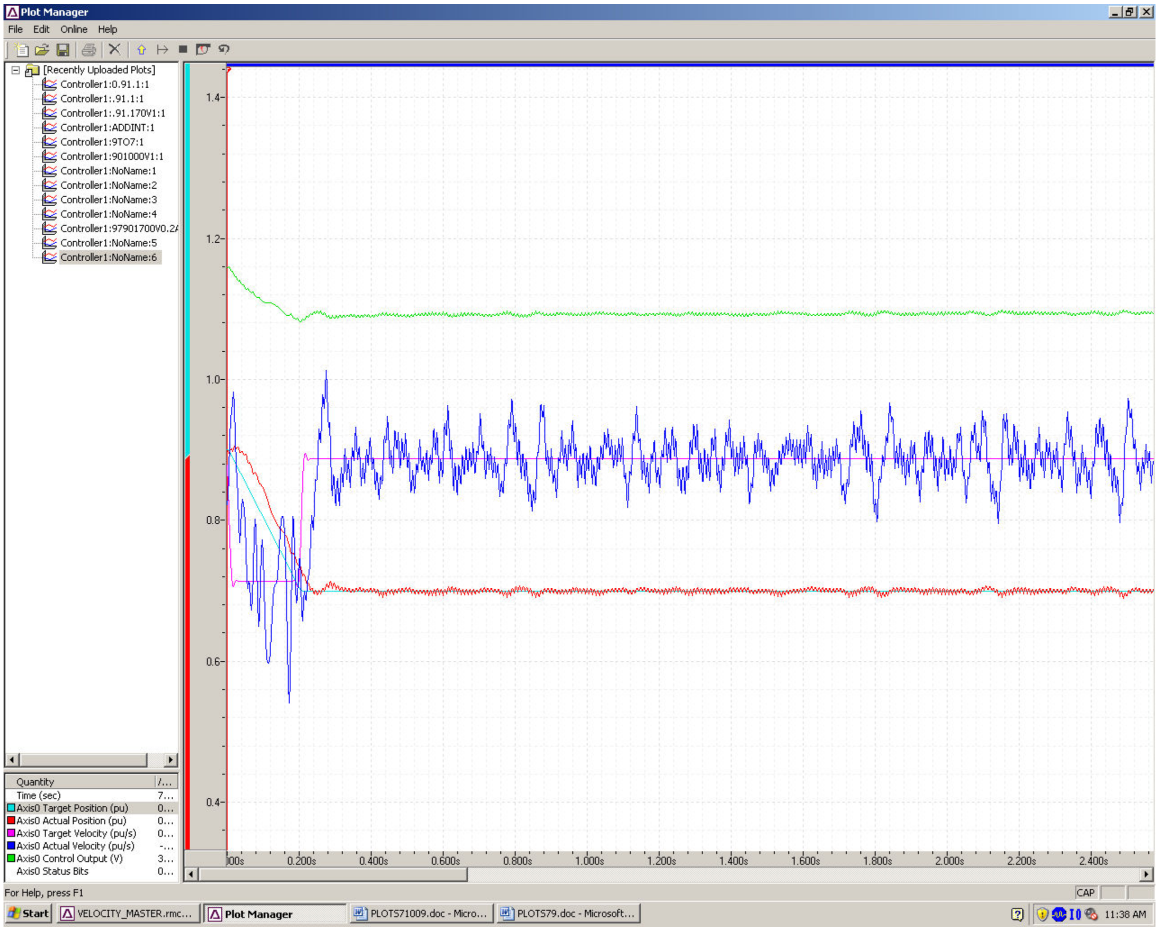

Figure 12 Sample Delta© Controller Decreasing Command Change Response Plot

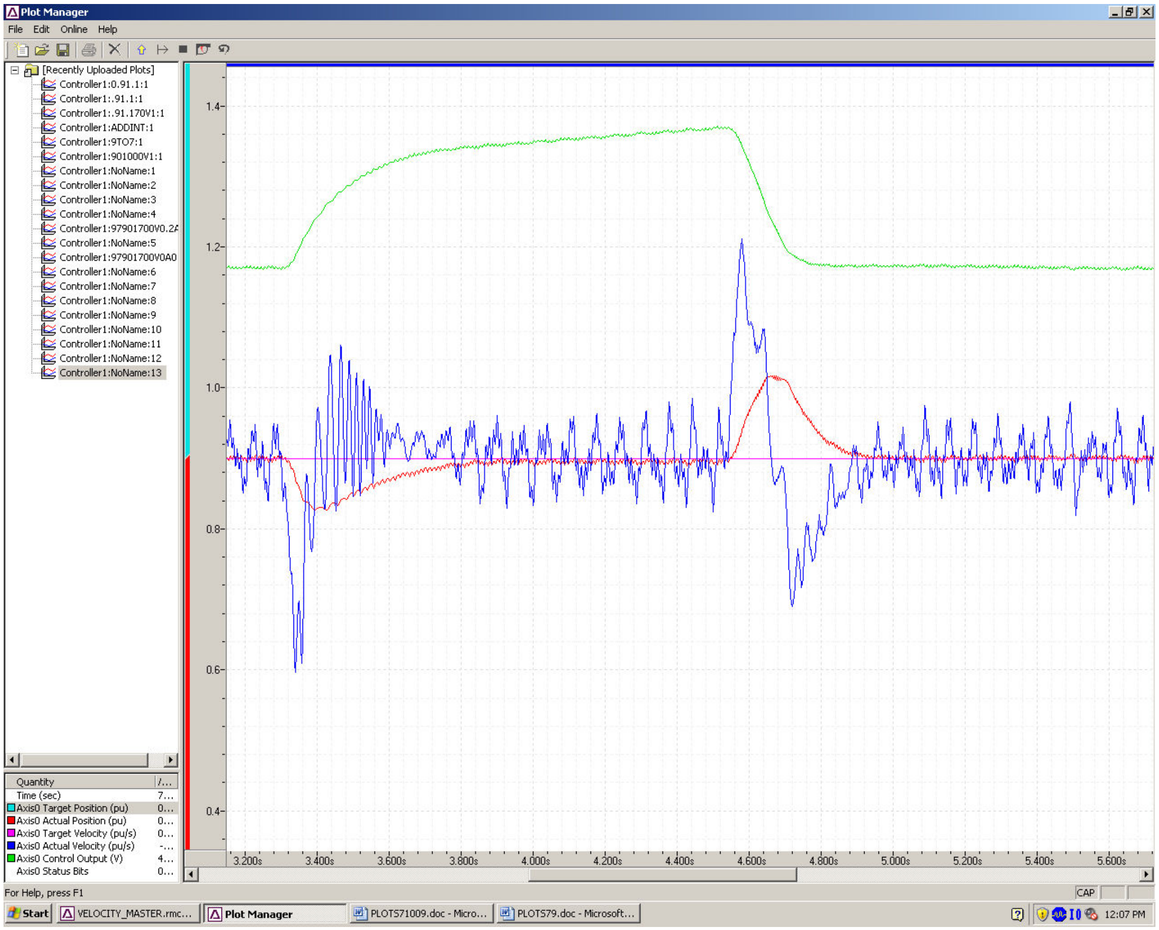

Figure 13 Sample Delta© Controller Load Change Response Plots

Some scope responses are shown in figures 14 – 16 using PI control with $K_p = 90$ and $K_i = 1700$. Some additional work could be done to reduce the small oscillation about 700 rpm.

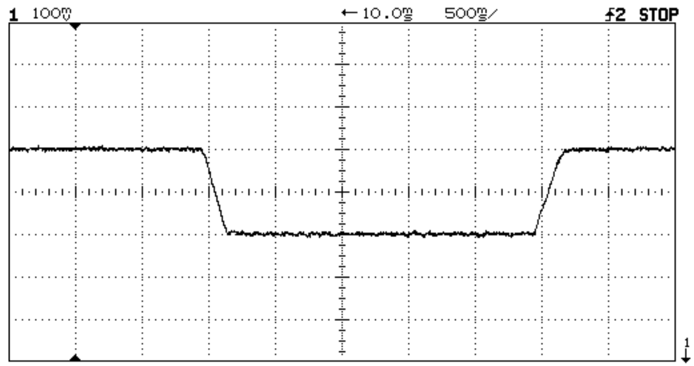

Figure 14 A Resulting Scope 900 -700 -900 Rpm Command Change Response

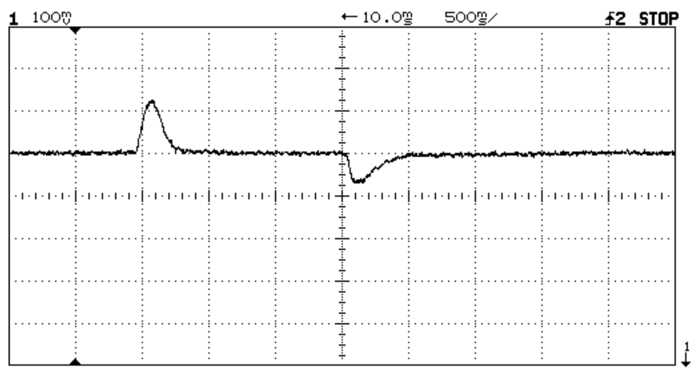

Figure 15 A Resulting Scope Load Change Response

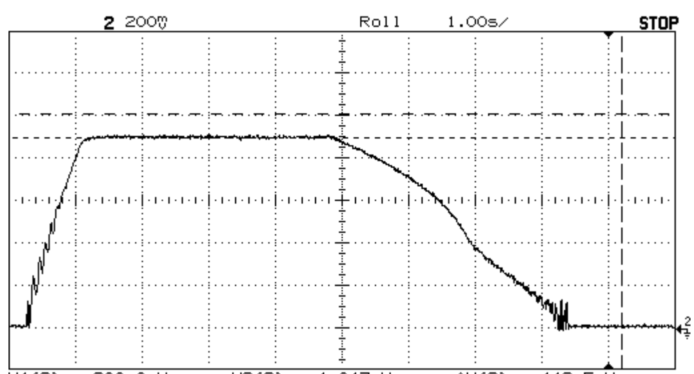

Figure 16 A Resulting Scope Startup & Shutdown Response (0-700 – 0 Rpm)

CONCLUSION

For this system, the PI controller is tuned at the lowest (more critical) operating speed of 700 rpm starting with the Zeigler-Nichols method and is less under damped at 900 rpm. The scope response using PI control with $K_p = 90$ and $K_i = 1700$ is shown in figures 14 – 16. The command changes are made at approximately minimum load. This is a substantial improvement over the untuned responses shown in figures 9 – 10. The command changes are quicker and the tuned load change responses have smaller changes in rpm and are of shorter duration. The quick startup transition from 0 to 700 rpm is oscillatory but is expected to still be acceptable in this case. These settings are those calculated from the ZN table and could use some additional work to reduce the small oscillation about 700 rpm. In general, substantial work is often required especially to meet some special user requirements

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