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STUDY ON DECREASING TORQUE NOISE RESULTING FROM FEEDBACK NOISE FOR THE MODIFIED BANG-BANG CONTROLLER

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13. ABSTRACT (*Maximum 200 words*)

The main problem with using the modified bang-bang controller is that moderate amounts of feedback noise can lead to high levels of torque noise. This stems from a velocity squared term in the controller. This report presents computer simulation results from a study aimed at decreasing torque noise. Two approaches are (1) decrease feedback noise directly, and (2) modify the controller so that it is less sensitive to feedback noise. We recommend that the control designer decrease feedback noise as much as practical and then decrease controller gains as a function of velocity until acceptable levels of torque noise are achieved.

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The modified bang-bang controller (refs 1-4) (called MBB in this report) has several important characteristics in controlling servomechanisms. Two of the more important of these are (1) the MBB controller repositions a mechanism in near minimum time, and (2) the control designer can specify the maximum allowable motor torques. One major drawback of this controller, however, is that it is sensitive to velocity feedback noise. Moderate amounts of velocity noise can result in high torque noise, which in turn may be unacceptable from electrical efficiency and/or mechanical reliability viewpoints. The source of the high torque noise stems from a velocity squared term in the MBB controller.

We at Benet Laboratories encountered the problem of high torque noise in our work on the development of a controller for a large caliber tank cannon autoloader. The ramming mechanism on this autoloader requires a servomotor that drives a sprocket-boom assembly. Figure 1 shows data from a typical (early) run of the autoloader ramming mechanism. This figure is a plot of position, velocity, and net motor force (force = torque/sprocket radius) as a function of time and shows somewhat high motor torque noise. High torque noise has caused localized damage to the bocm by the sprocket teeth.

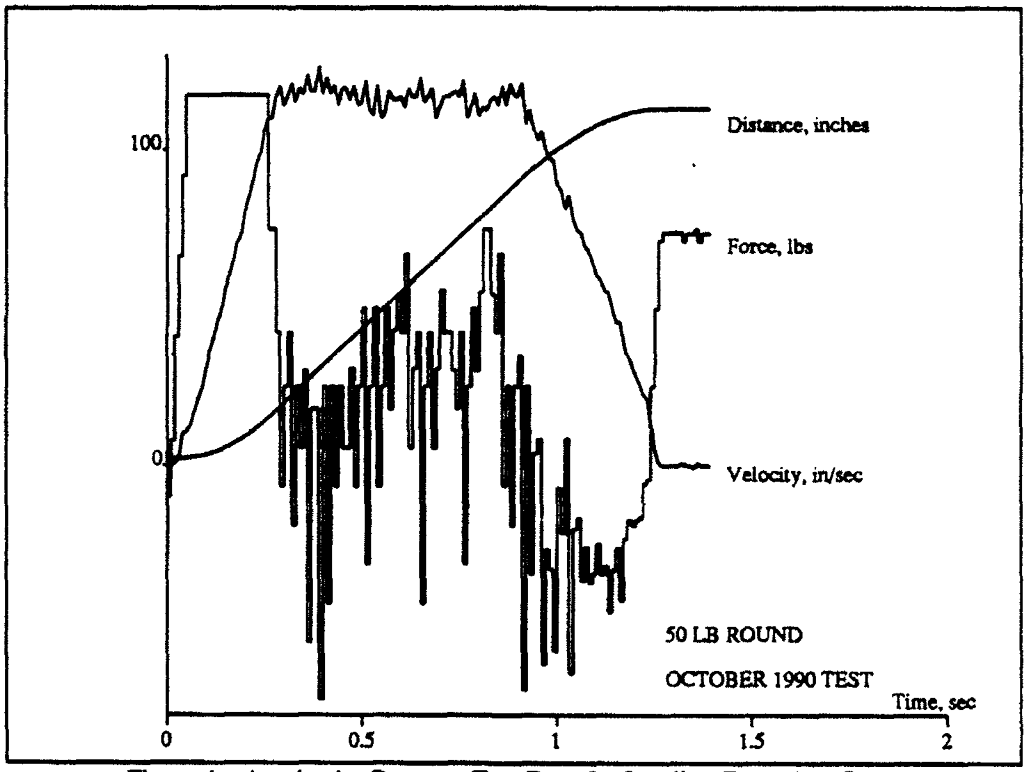

Figure 1. Autoloader Rammer Test Data for Loading-Extension Cycle

We conducted theoretical and simulation studies to find suitable approaches for decreasing torque noise. From these studies, we determined that velocity feedback noise was the primary cause of the motor torque noise. We then considered two approaches for decreasing noise: (1) decreasing velocity feedback noise directly, and (2) modifying the controller to render it less sensitive to noise. Two kinds of velocity feedback considered were analog and digital. The analog velocity sensor could be a tachometer in which the velocity signal is a voltage

INTRODUCTION

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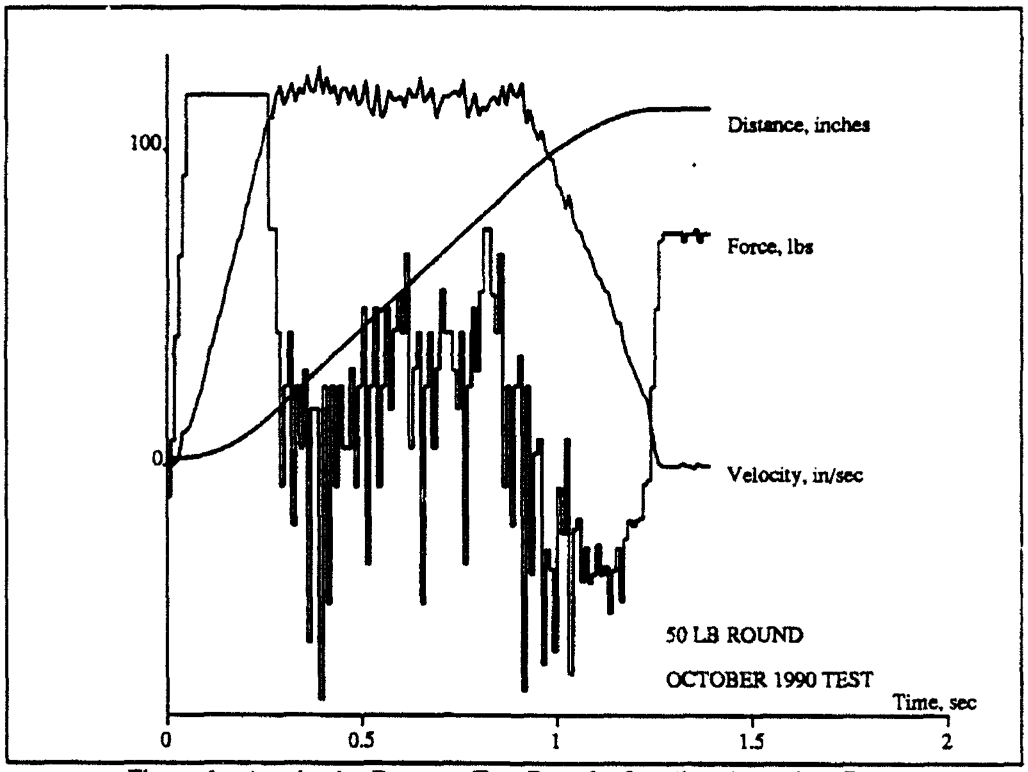

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SUMMARY AND CONCLUSIONS

Our simulation results show that MBB torque noise can be adequately reduced in different ways. One way is to provide standard signal filtering for analog velocity feedback sensors (ref 5). One drawback of this approach, however, is that the noise-to-signal ratio required is low, of the order of 0.5 to 1.0 percent. Analog feedback signals are also susceptible to ground loops and other sources of extraneous voltage disturbances.

Digital encoder feedback provides somewhat clean positional information except for quantization error. In the autoloader case, determining velocity from an absolute encoder resulted in some quantization error with resultant high torque noise. Using a longer time increment or suitable digital filtering (refs 6-8) to estimate velocity resulted in satisfactorily reducing the velocity noise.

The control designer also can reduce torque noise by modifying the controller to render it less sensitive to noise, particularly at the higher velocities. This can be done by decreasing the velocity gain at the higher velocities. As the mechanism nears its commanded positional goal, the gain can either be increased gradually or instantaneously. The controller may need higher gain near the end of the cycle to give satisfactory positioning accuracy.

The main drawback with decreasing the gain at the higher velocities is that the controller becomes less efficient. The controller requires longer repositioning times and is less responsive to disturbing forces.

The recommended approach is to use encoder feedback with some decrease in gain at the higher velocities. Any significant quantization error in the velocity calculation needs to be reduced by either increasing the time interval used or by providing more encoder counts per unit of distance travelled.

The remainder of this report consists of the following:

- Noise effects in the MBB controller
- Encoder positional noise
- Tachometer/resolver noise
- Controller modification to reduce torque noise

NOISE EFFECTS IN THE MBB CONTROLLER

Figure 2 is a schematic diagram of the modified bang-bang controller. This controller is also called switching zone control elsewhere (ref 1).

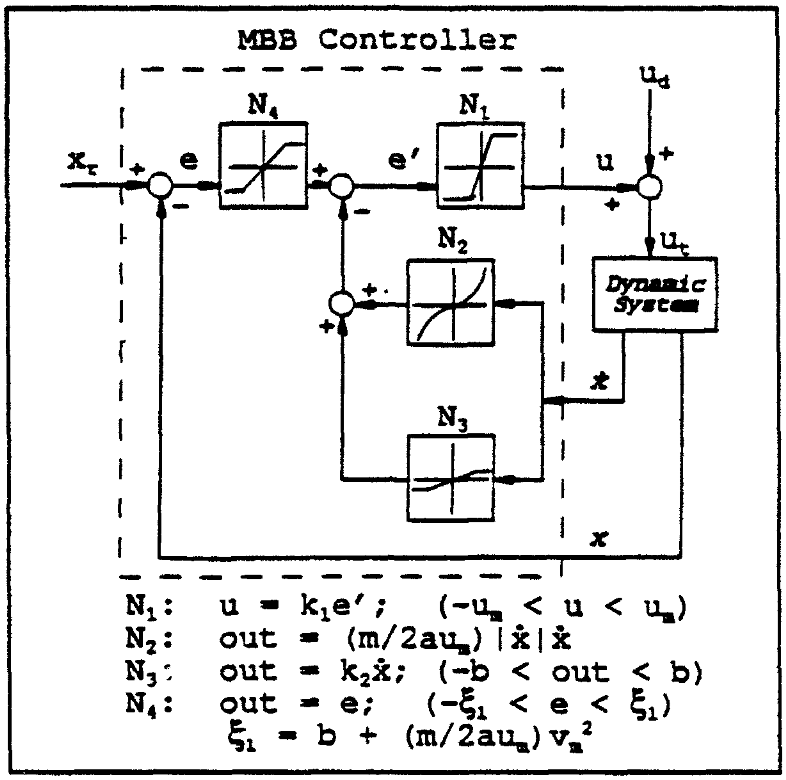

Figure 2. Block Diagram of Modified Bang-Bang Controller

The variables and parameters shown in Figure 2 are defined as follows:

m	=	system mass
x	=	position of the mass
x_r	=	desired position
u	=	motor force applied to mass m = torque/lever arm
u_d	=	disturbing force
u_m	=	specified maximum motor force or torque
a	=	nonlinear function term selected to guarantee sufficient force for deceleration
	=	$(u_m-u_{dm})/u_m$ where u_{dm} is the maximum value of the disturbance force u_d
b	=	constant selected to guarantee no overshoot,
	=	$2au_m/k_1$
k_1,k_2	=	positional and velocity gains
ξ_1	=	$b + mv_m^2/(2au_m)$ where ξ_1 is essentially dependent on the specified maximum velocity v_m

Details of the MBB controller are described elsewhere (refs 1,3,4,9). The term in the MBB controller that causes the most problem is block N_2 in Figure 2. N_2 contains a velocity squared feedback term that is necessary for guaranteeing enough torque during the deceleration phase of bang-bang control. Any noise in the velocity becomes magnified by the velocity squared term.

We studied the MBB control problem using the simulation package called SIMNON (ref 10) on a 286 microcomputer. Simulation results confirm that the most significant noise source is velocity feedback.

Figure 3 shows a typical simulation of the autoloader rammer mechanism. For this problem, we assume that noise is present in the positional feedback term from which we calculate velocity. For this case, we calculated velocity using two-point numerical differentiation for the sample time increment $\Delta t = 0.01$ second. Two-point differentiation gives the most noise possible from noisy positional information. Figure 3 shows that there is high torque noise. The data in this figure is comparable to the actual data previously shown in Figure 1.

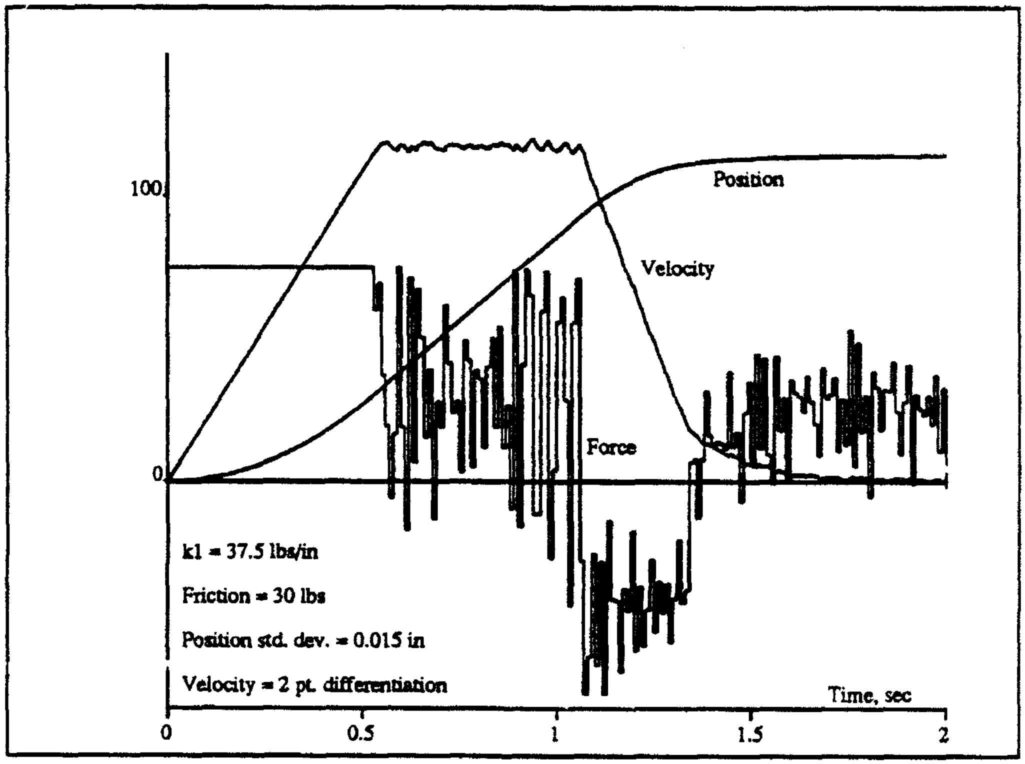

Figure 3. Simulation of Two-Point Velocity Calculation

The remainder of this report discusses various approaches to minimize the velocity feedback noise effects on torque noise.

ENCODER POSITIONAL NOISE

The use of digital encoders provides very accurate positional information in feedback systems. The main sources of noise or errors in using encoders are mechanical and quantization. Any electrical noise can be minimized by providing adequate grounding and shielding. Mechanical noise can arise from resonance effects in coupling the encoder to the motor/mechanism and from backlash effects in the coupling gears. Quantization noise is a direct result of dividing distance into discrete pulses by the encoder. Consequently, we only know position in discrete steps of Δe inches per encoder pulse.

Velocity can be calculated numerically from the encoder positional information (refs 6,7). If we calculate velocity this way, then the quantization error will be magnified by the differentiation process and will be a function of the time increment over which we differentiate the discrete positional data.

The encoder quantization error turned out to be a significant source of torque noise in our initial trials with the autoloader rammer. We used an absolute encoder that provided approximately 15,000 discrete points (14-bit accuracy) over 115 inches of ramming distance. This gives a potential positional error of 0.0077 inch at any given time. We also calculated velocity using only 2 points for each sample time increment $\Delta t = 0.01$ second. This gives a velocity error of from zero to 1.54 inches/second. This in turn represents a motor torque error of from zero to 20 pounds of force, which is significant.

Introducing digital filtering can reduce MBB torque noise significantly. For example, in simulation trials we assumed the same encoder error that we used to generate the data shown previously in Figure 3. We increased the time interval for calculating velocity to 3 time steps by passing a least squares straight line fit through 4 positional points. Figure 4 shows the results of this simulation run, which is a considerable improvement over the results in Figure 3.

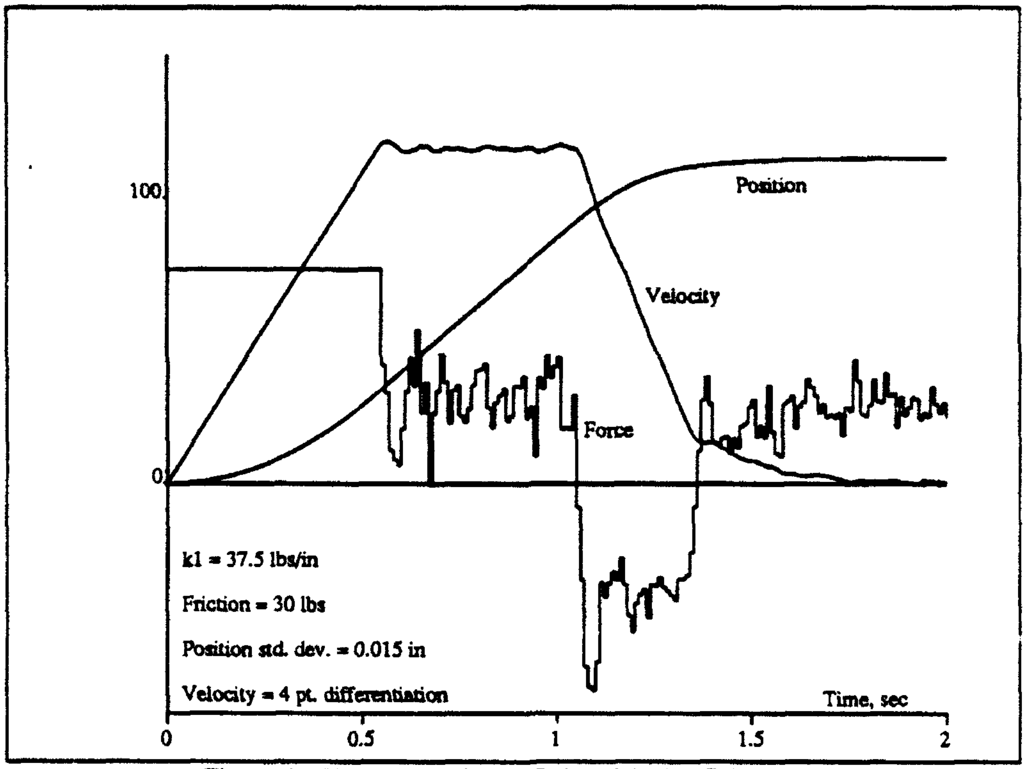

Figure 4. Simulation of Four-Point Velocity Calculation

It should be noted that the quantization error in velocity is independent of velocity and so exists even at low velocities. Digital filtering using a large enough time interval significantly reduces both mechanical and quantization noise at all velocities.

TACHOMETER/RESOLVER NOISE

The MBB controller can use direct measurements of velocity from, for example, a tachometer. If this is done, then adequate signal conditioning and filtering are required to eliminate excessive noise (ref 5). As previously discussed, velocity noise is even more of a problem when using MBB because of the velocity squared term in the controller.

Figure 5 shows simulation data using unfiltered velocity feedback from a typical tachometer. Here, torque noise is excessive. In Figure 6, we used signal filtering to decrease torque noise to acceptable levels. For the simulation in Figure 6, we used a noise-to-signal ratio of 0.8 percent.

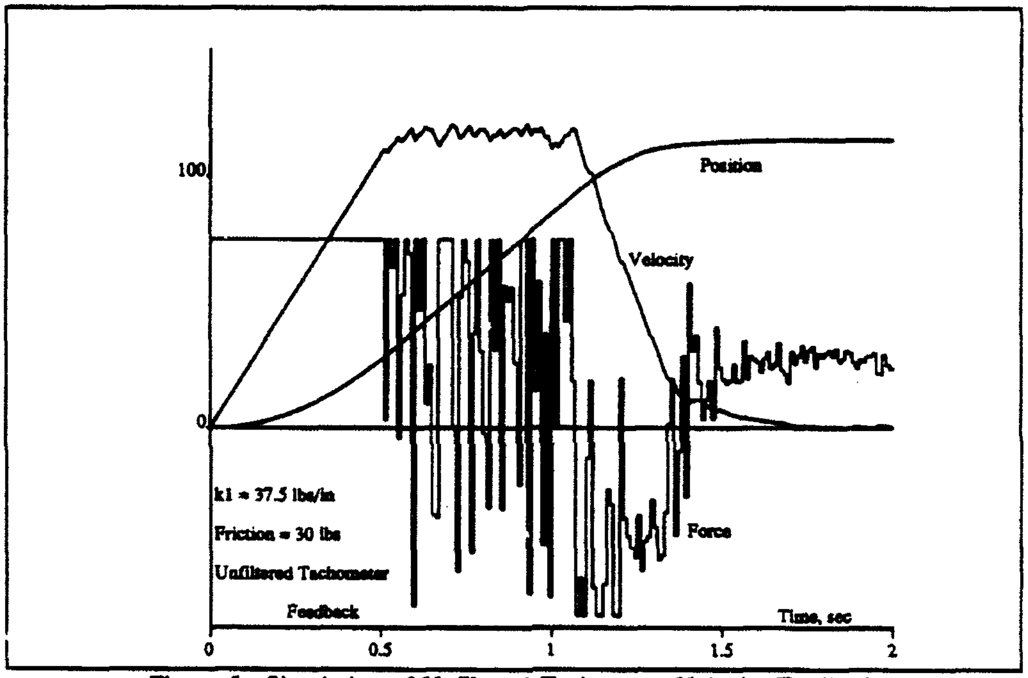

Figure 5. Simulation of Unfiltered Tachometer Velocity Feedback

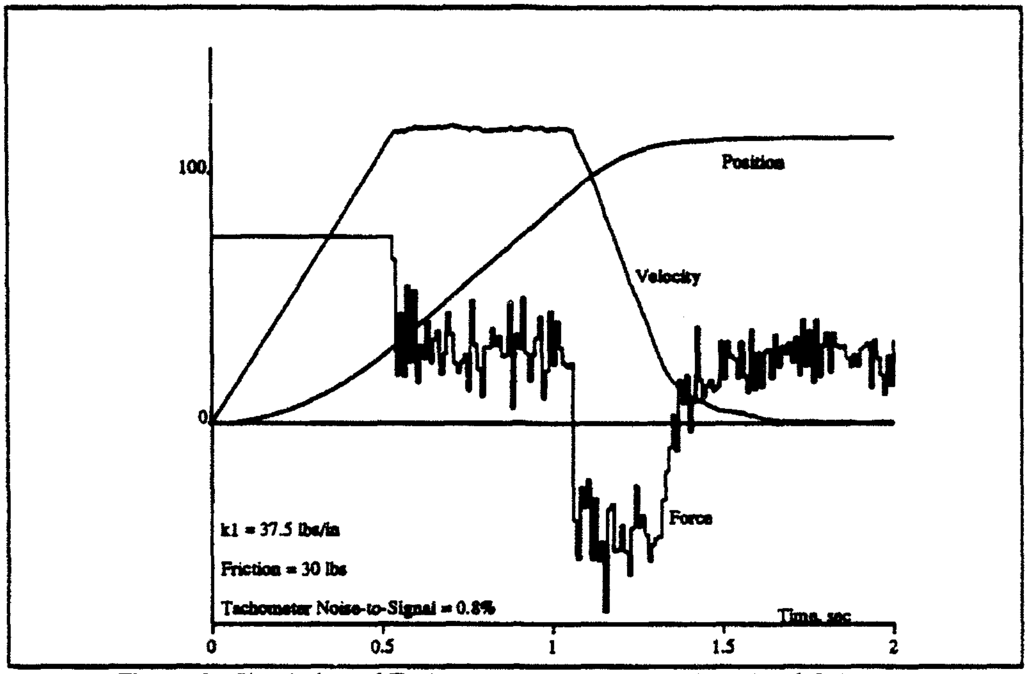

Figure 6. Simulation of Tachometer Filter Noise-to-Signal = 0.8 Percent

CONTROLLER MODIFICATION TO REDUCE TORQUE NOISE

A general approach for reducing excessive torque noise is to modify the MBB controller to render it less sensitive to feedback noise. The control designer can decrease the controller sensitivity by decreasing the gain k_1 in block N_1 of Figure 2, perhaps as a function of velocity. Block N_1 would then be less sensitive to feedback noise and other variations.

The easiest way for the designer to decrease torque noise is to decrease k_1 directly. In Figure 7 we decreased the gain from $k_1 = 37.5$ used for Figure 3 to 12.5. By comparing Figures 3 and 7, the reader can see not only the expected decrease in torque noise, but also the resultant increase in repositioning time by lowering the gain.

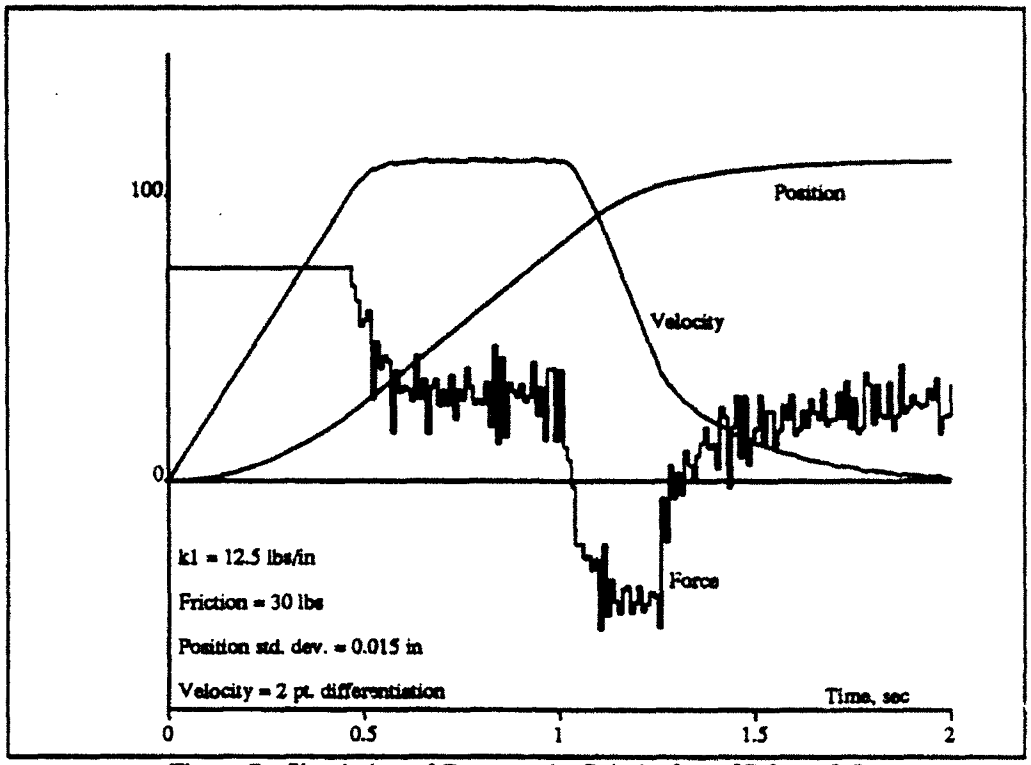

Figure 7. Simulation of Decrease in Gain k_1 from 37.5 to 12.5

If the control situation requires a fixed higher value of k_1 near the end of a cycle, then a variable k_1 called k_1^* as a function of velocity could be used. One possible equation for k_1^* is given as follows:

$$k_1^* = k_1 \; abs\left[1 - \alpha \frac{(\dot{x} - v_b)}{(v_m - v_b)}\right]; \qquad \dot{x} \geq v_b \tag{1}$$

$$= k_1 \; ; \qquad 0 \leq \dot{x} \leq v_b$$

in which α is a new controller parameter between 0.0 and 1.0, and $v_b = b/k_2$. For $\alpha = 0.0$, we have constant k_1 for all velocities.

In equation (1), k_1^* is seen to increase as velocity decreases. To insure no overshoot at the end of the cycle, then the control parameters b and k_2 shown in Figure 2 need to be redefined as a function of k_1^*:

$$\begin{aligned} b^* &= 2 a u_m / k_1^* \\ k_2^* &= 2\sqrt{m/k_1^*} \end{aligned} \tag{2}$$

When the velocity decreases to v_b, then b^* goes to b and k_2^* goes to k_2. The controller remains stable and there will be no overshoot.

Figures 8 and 9 are plots for values of $\alpha = 0.40$ and 0.80. These plots show the decrease in torque noise at the higher velocities.

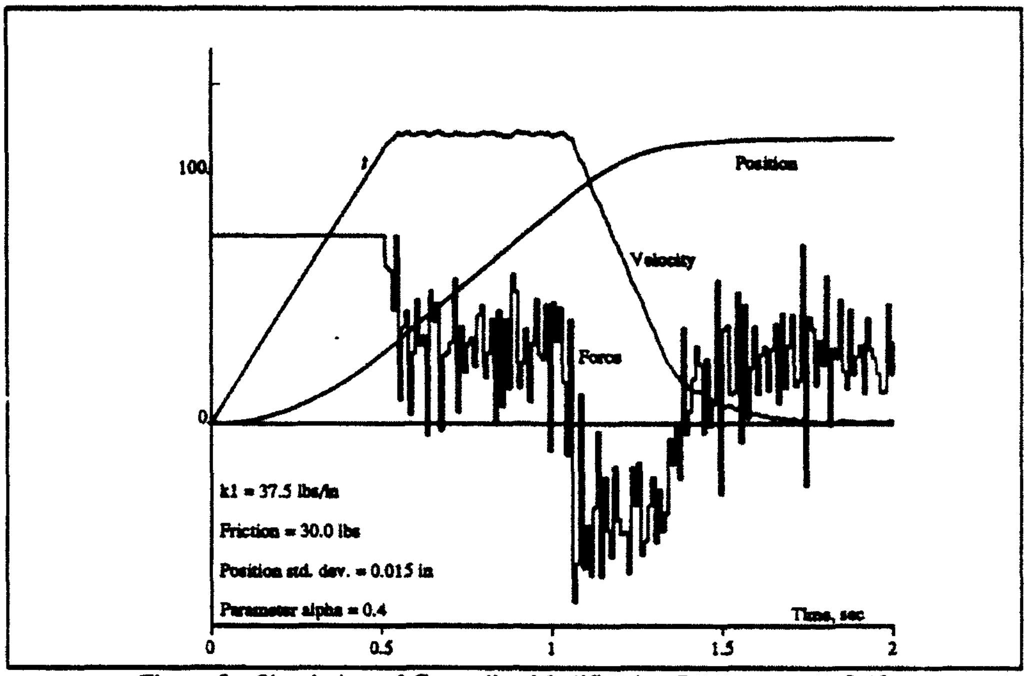

Figure 8. Simulation of Controller Modification Parameter $\alpha = 0.40$

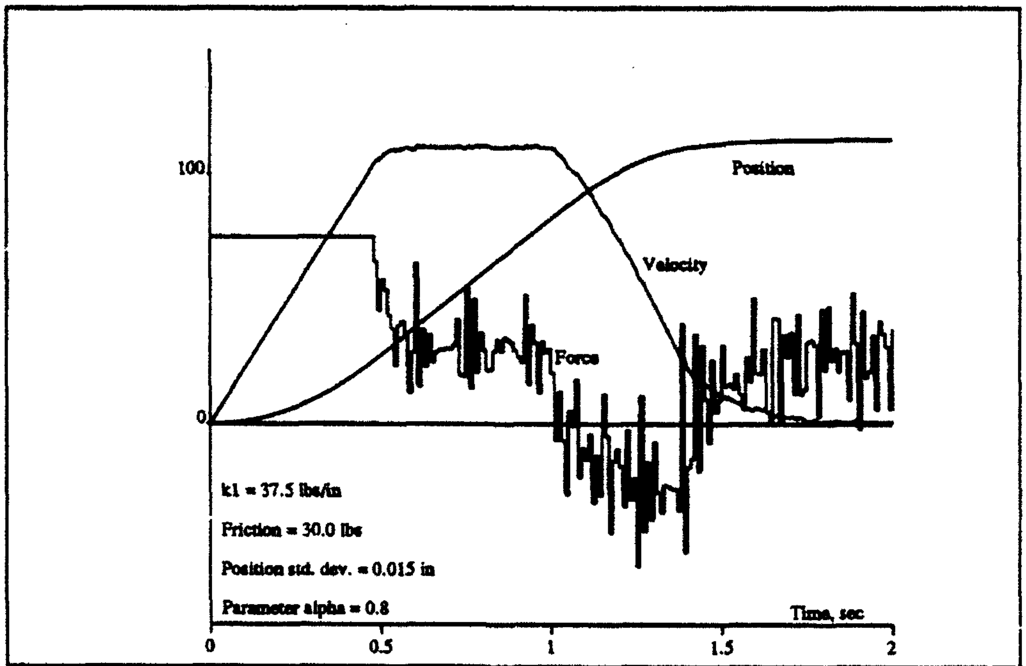

Figure 9. Simulation of Controller Modification Parameter $\alpha = 0.80$

In all cases studied, decreasing the gain k_1 generally increased cycle times. A tradeoff is required between cycle time, controller efficiency, and torque noise when adjusting the gains. The best approach is to decrease feedback noise as much as practical and then to decrease controller gains until acceptable levels of torque noise are achieved.

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