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**SWITCHING ZONE CONTROL FOR A
SYSTEM WITH AN ELASTIC JOINT**

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INTRODUCTION

A useful and practical approach to the control of mechanisms for many robotic and automation applications is switching zone control (SZC) (refs 1-4). Switching zone control is a robust nonlinear feedback controller with the following characteristics: (1) it is a decentralized controller where each motor/actuator of a multidegree of freedom system can be separately operated with its own electronic or digital controller (coupling is handled as a disturbing torque); (2) it yields near minimum time which approaches the bang-bang minimum time controller in the limit; (3) the designer can specify the peak torques applied by the motor to solve saturation problems; (4) the designer can specify the maximum velocity when, for example, motors used have limited horsepower; and (5) the controller is easy to program using digital or electronic hardware. The SZC approach eliminates the usual problems of overshoot and instability inherent in high gain linear feedback systems where saturation of motors and/or amplifiers becomes a problem.

This report presents extensions of SZC to a mechanical system with elastic joints. The elastic joint is the simplest idealization of the elastic flexible robotic mechanism which is a natural extension of SZC. A summary of the main results and contributions, the details of which are presented later in this report, are given as follows:

1. Stability of a system with an elastic joint is achieved through the use of both co-located and endpoint feedback.
2. Although a single actuator system with an elastic joint is inherently a fourth order system, a second order system approximation is satisfactory in estimating SZC parameters. This greatly simplifies the implementation of SZC.

References are listed at the end of this report.

3. A simple approach is used for adaptive real-time feedforward compensation of gravity, friction, and other disturbing torque effects.
4. Simulation and experimental results of a simple one-degree of freedom system demonstrate the application of the proposed approach to a highly flexible joint case.

The remainder of this report is organized as follows: A brief summary of SZC for a simple second order system is presented. Next, the addition of an elastic joint between the motor or actuator and the payload is considered as are its ramifications on stability. A straightforward approach is presented for stabilizing the resulting system. The determination of SZC parameters is then considered where the second order system approximation is found to provide an adequate controller. Then, experimental results are presented which demonstrate the application of the proposed approach to a highly flexible joint case. Finally, a simple method is presented for handling the real-time compensation of gravity, friction, and other disturbing torque effects that are nonzero in the steady-state limit.

SWITCHING ZONE CONTROL

The basis of SZC is a time optimal bang-bang theory where maximum effort is applied to motors in both negative and positive directions (accelerating and decelerating phases) to move a mechanism from one state to another in minimum time (refs 1-4). Xia and Chang (ref 1) presented in detail the modifications to the bang-bang control theory which are necessary for practical applications. They proposed controlling each link or degree of freedom of a robotic system in a decentralized fashion. Instead of a switching boundary as used in the bang-bang approach, a switching zone is used whereby the torque varies linearly. Outside this zone, the torque takes on the maximum allowable values as in bang-

bang. In addition, the decelerating phase starts at a lower value of speed so that only a fraction of the available torque is needed to guide the system along its decelerating trajectory without overshoot.

Equation (1) shows a simple second order system where all of the interlinking coupling terms of a multilink system, as well as gravity and friction effects, are considered as a single disturbing force, u_{di} :

$$J_i \ddot{\theta} = u_{di}(\underline{\theta}, \dot{\underline{\theta}}, \ddot{\underline{\theta}}) + u_i \quad (1)$$

where

J_i = inertia of the i th link

θ_i = angular position of the i th link

u_i = motor torque at the i th link

u_{di} = disturbing torque which includes Coriolis, centrifugal, gravity, and friction coupling effects.

$(\underline{\theta}, \dot{\underline{\theta}}, \ddot{\underline{\theta}})$ = vectors of position, velocity, and acceleration for a multilink system.

A schematic diagram of the nonlinear switching zone controller for a typical link is shown in Figure 1 where the subscript i has been dropped. The "plant" in Figure 1 can be the simple second order system given as Eq. (1) or a more complicated plant as discussed later in this report. The variables θ_r and $\dot{\theta}_r$ in the figure are the desired reference angle and velocity; e and $\dot{e}$ are the error functions; and the nonlinear blocks N_1 , N_2 , N_3 , and N_4 are defined as follows (ξ = input variable, η = output variable):

$$\begin{aligned} \eta &= k_1 \xi && \text{for } |\xi| \leq u_m/k_1 \\ N_1: \quad \eta &= u_m && \text{for } \xi > u_m/k_1 \\ \eta &= -u_m && \text{for } \xi < -u_m/k_1 \end{aligned} \quad (2)$$

$$N_2: \quad \eta = \frac{J_m}{2au_m} |\xi| \xi \quad (3)$$

$$\eta = k_2 \xi \quad \text{for } |\xi| \leq b/k_2$$

$$\begin{aligned} N_3: \quad \eta &= b & \text{for } \xi > b/k_2 \\ \eta &= -b & \text{for } \xi < -b/k_2 \end{aligned} \quad (4)$$

$$\eta = 0 \quad \text{for } |\xi| \leq v_m$$

$$N_4: \quad \eta = V(\xi - v_m) \quad \text{for } \xi > v_m$$

$$\eta = V(\xi + v_m) \quad \text{for } \xi < -v_m \quad (5)$$

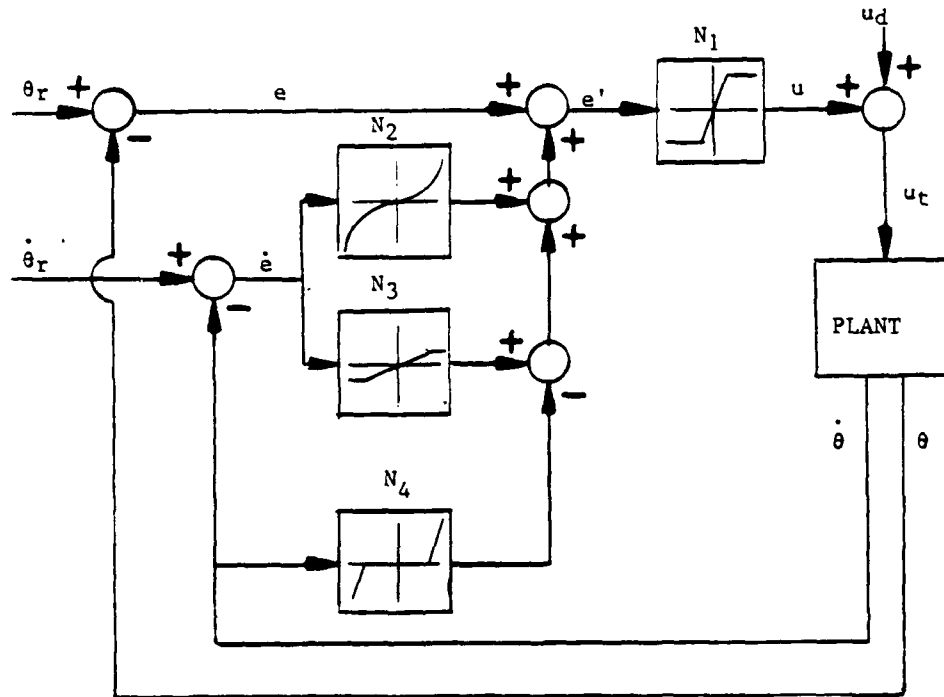


Figure 1. Block diagram of switching zone control system.

The constants k_1 , k_2 , a , b , u_m , v_m , V , and J_m are the controller gains and parameters that need to be specified by the designer. These constants for the second order plant of Eq. (1) are defined as follows:

J_m = inertia where 'm' denotes the maximum value of $J=J(\theta)$

u_m = maximum torque generated by the motor

a = nonlinear function term selected to guarantee sufficient torque at deceleration,

$$= (u_m - u_{dm})/u_m \text{ where } u_{dm} \text{ is the maximum value of } u_d \quad (6)$$

b = constant selected to guarantee no overshoot,

$$= \max(u_m/k_1 \text{ or } k_2 a u_m \lambda_1 / (k_1 (\lambda_1 k_2 - 1))) \quad (7)$$

where

$$\lambda_1 = \frac{k_1 k_2 + \sqrt{(k_1 k_2)^2 - 4 k_1 J}}{2J} \quad (8)$$

v_m = maximum allowable velocity

V = constant chosen to smoothly maintain maximum velocity near v_m

k_1, k_2 = proportional and velocity gains where $k_2 \geq 2\sqrt{J/k_1}$ is required for no overshoot

The maximum torque u_m can be specified arbitrarily or can be fixed based on the motor/amplifier specifications. The gain k_1 is fixed high and is limited primarily by the requirement for no system chatter/jitters, which are common effects in pure bang-bang control. Infinite gain k_1 reduces the control to switching boundary or bang-bang.

A better understanding of the characteristics of the above described SZC can be obtained by examining the resulting phase diagram for the second order system. Figure 2 is a plot of $\dot{\theta}$ versus θ where u_d in Eq. (1) is assumed to be zero. The system with nonzero u_d is considered later in this report. The controller in this case is designed to drive any given nonzero state toward the origin. For example, if the initial state in Figure 2 starts at point A, maximum torque $u = u_m$ is applied at first. The path then eventually enters the zone

between full negative and positive torques. Once in the zone, the state is captured and is driven to the origin with little or no overshoot (see Reference 1 for details). Xia and Chang (ref 1) and Jeng (ref 3), as well as these investigators have found this approach to be very effective, even in the presence of minor time delays and parameter inaccuracies.

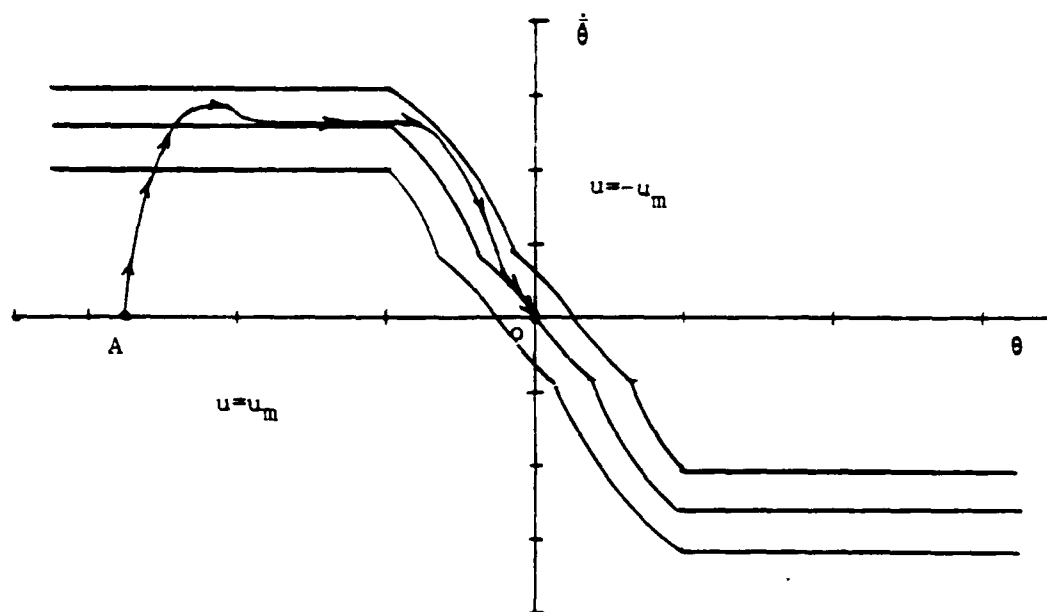


Figure 2. Phase diagram for switching zone control system showing typical trajectory.

SYSTEM WITH ELASTIC JOINT

In this section, the ramifications of including an elastic joint between the motor and the payload on the design of a switching zone controller are considered. This is perhaps the simplest case of the compliant/flexible manipulator. There is considerable interest at the present time in controlling lightweight, flexible mechanical systems, particularly in nonindustrial applications such as space or military where weight and speed of operation become

critical factors. The totally elastic/flexible arm is an infinite degree of freedom system which, in the simplest idealization, reduces to the fourth order spring-mass system shown in Figure 3. The four state variables for this case

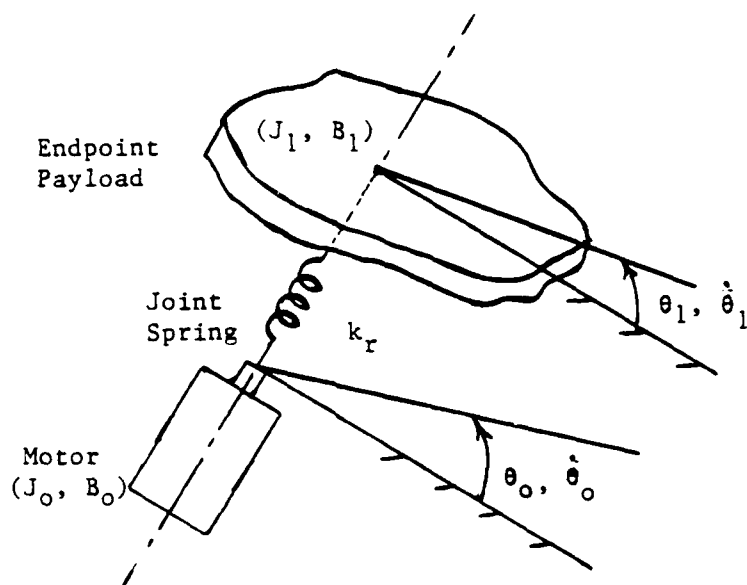


Figure 3. Schematic diagram of system with elastic joint.

include the position and velocity of both the motor and endpoint payload ($\theta_1, \dot{\theta}_1, \theta_0, \dot{\theta}_0$ in Figure 3). The motor with internal rotor inertia J_0 and damping B_0 drives through a spring of constant k_r to reposition a mass of inertia J_1 and damping B_1 . The open-loop transfer function for this case is shown schematically in Figure 4 where

$$H_1(s) = \frac{k_r/H_2(s)}{(J_0s^2+B_0s+k_r)(J_1s^2+B_1s+k_r) - k_r^2} \quad (9)$$

$$H_2(s) = \frac{k_r}{(J_1s^2+B_1s+k_r)} \quad (10)$$

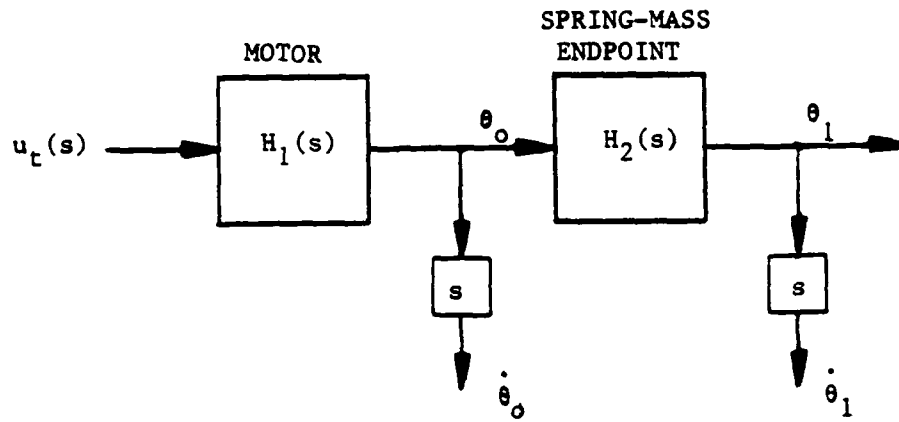


Figure 4. Open-loop block diagram of fourth order spring-mass system.

In general, the closed-loop linear feedback for this case using only end-point information is unstable. In order to assure stability, co-located motor velocity feedback is required in addition to payload position and velocity. These authors found that the most effective configuration leading to stability for the elastic joint case is shown in Figure 5. The resulting closed-loop transfer function for linear feedback is given as Eq. (11)

$$H_{CL}(s) = 1/(a_4s^4 + a_3s^3 + a_2s^2 + a_1s + a_0) \quad (11)$$

where

$$a_4 = J_0J_1/k_r$$

$$a_3 = (J_0B_1 + J_1(B_0 + C_V))/k_r$$

$$a_2 = J_0 + J_1 + B_1(B_0 + C_V)/k_r$$

$$a_1 = B_1 + B_0 + K_V$$

$$a_0 = K_P$$

The Routh-Hurwitz stability conditions (ref 5) for this system become

$$\text{Condition 1: } b_1 = a_2 - a_4a_1/a_3 > 0 \quad (12)$$

$$\text{Condition 2: } a_1 - a_3a_0/b_1 > 0 \quad (13)$$

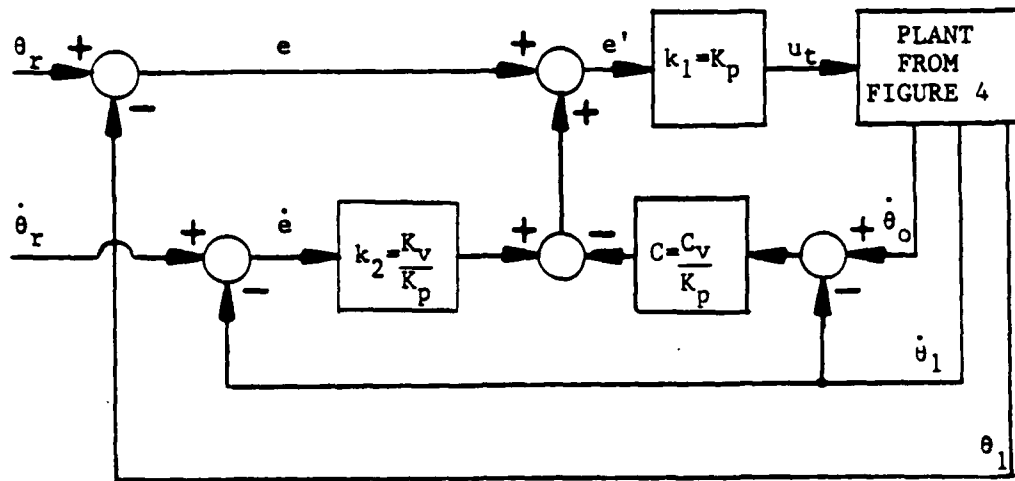


Figure 5. Closed-loop block diagram of spring-mass system for linear feedback.

For low motor and payload damping, Condition 1 reduces to

$$C_v/K_v > 1/(1 + J_1/J_0) \quad (14)$$

plus a condition on K_p . In this instance if payload inertia J_1 is considerably greater than motor inertia J_0 , which is a common occurrence, then C_v can be quite small in comparison to K_v .

The next question of interest is how to best apply the SZC to the elastic joint system just described. The most successful approach studied thus far for practical and relatively flexible mechanisms is shown in Figure 6 in which SZC is of the same configuration as in Figure 1. In the linear region of SZC the principal poles are very close to the poles of the simple second order system. This suggests as a starting point to use the second order approximation for estimating SZC parameters. This indeed turns out to be a good approach based on extensive simulations and some experimental results.

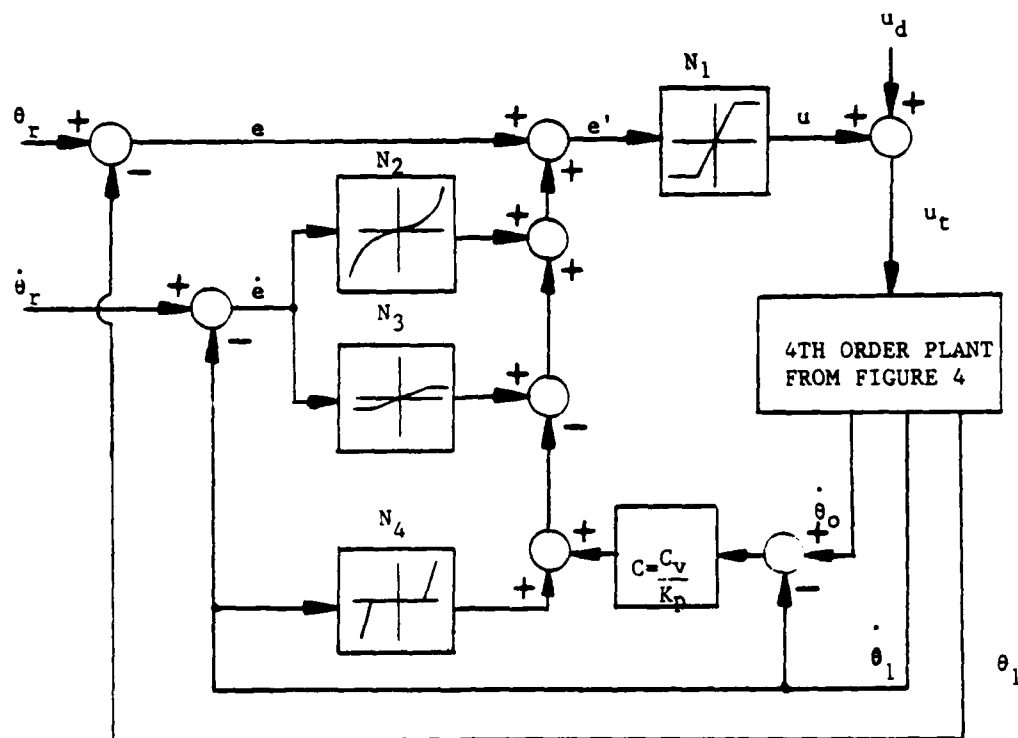


Figure 6. Block diagram of switching zone control system for fourth order spring-mass system.

For the desired no-overshoot condition, the feedback gain requirements are estimated assuming a second order system in which the constants in Eq. (11) are given as follows:

$$a_4 \approx a_3 \approx 0.0$$

$$a_2 \approx J_0 + J_1 = J_t$$

$$a_1 = B_1 + B_0 + K_v = B_t + K_v$$

$$a_0 = K_p \tag{15}$$

The gain K_p is fixed by requiring the maximum torque u_m to be applied by the motor at zero velocity for some given minimum angular error difference Δe , that is,

$$K_p = u_m / \Delta e \tag{16}$$

The characteristic roots for this system are given as

$$\lambda_{1,2} = \frac{-(B_t + K_v) \pm \sqrt{(B_t + K_v)^2 - 4J_t K_p}}{2J_t} \quad (17)$$

Therefore, for critical damping, the expression under the square root sign in Eq. (17) is set to zero from which the following is obtained:

$$K_p = (B_t + K_v)^2 / (4J_t) \quad (18)$$

Solving this equation for K_v for given K_p (Eq. (16)) then gives

$$K_v = 2\sqrt{K_p J_t} - B_t \quad (19)$$

Finally, the gain C_v in Figure 6 is fixed at some small fraction of K_v (say 0.1 to 0.01 of K_v). The other SZC parameters are as given previously in Eqs. (6) through (8) where in these equations $K_p = k_1$ and $K_v = k_1 k_2$.

Experimental application of the derived SZC for an elastic joint case is considered in the next section.

EXPERIMENTAL RESULTS

Simulation of the fourth order elastic joint system presented in the previous section using the Runge-Kutta method for the solution of the equations of motion confirms the stability, no-overshoot, and robustness characteristics of using SZC for a wide variety of cases. In addition to simulation, a number of experiments were conducted on a one-degree of freedom system depicted schematically in Figure 3. The nominal physical parameters for the motor-spring-mass system studied are summarized as follows:

Motor Parameters: (from specifications)	Electro-Craft 0588-33-500 motor $J_0 = 0.001$ in.-lb-sec ² /rad $B_0 = 0.01$ in.-lb-sec/rad Peak static torque = 3.0 in.-lb
Payload-Mass Parameters: (measured)	$J_1 = 0.030$ in.-lb-sec ² /rad $B_1 = 0.05$ in.-lb-sec/rad
Spring Constant (measured):	$k_r = 2.0$ in.-lb/rad

The nominal spring k_r is relatively soft, which gives a natural frequency of vibration of about 1.3 cycles per second. The motor current (torque) was the controlled input signal in these experiments, where static torque saturation occurs at about 3.0 in.-lb. In the switching zone controller, u_m , the maximum torque, can be specified. Figure 7 shows results of varying the maximum torque from $u_m = 0.4$ to 2.8 in.-lb. The remaining SZC parameters used in this study are given as $C_v = 0.005$, $a = 1.0$, $b = 0.12$, $K_p = 3.3$, and $K_v = 0.3$. The initial angle was -120 degrees and the desired final angle was 0.0 degrees. For these trials a digital controller was used with a 100 Hz sampling rate (10 msec sample interval).

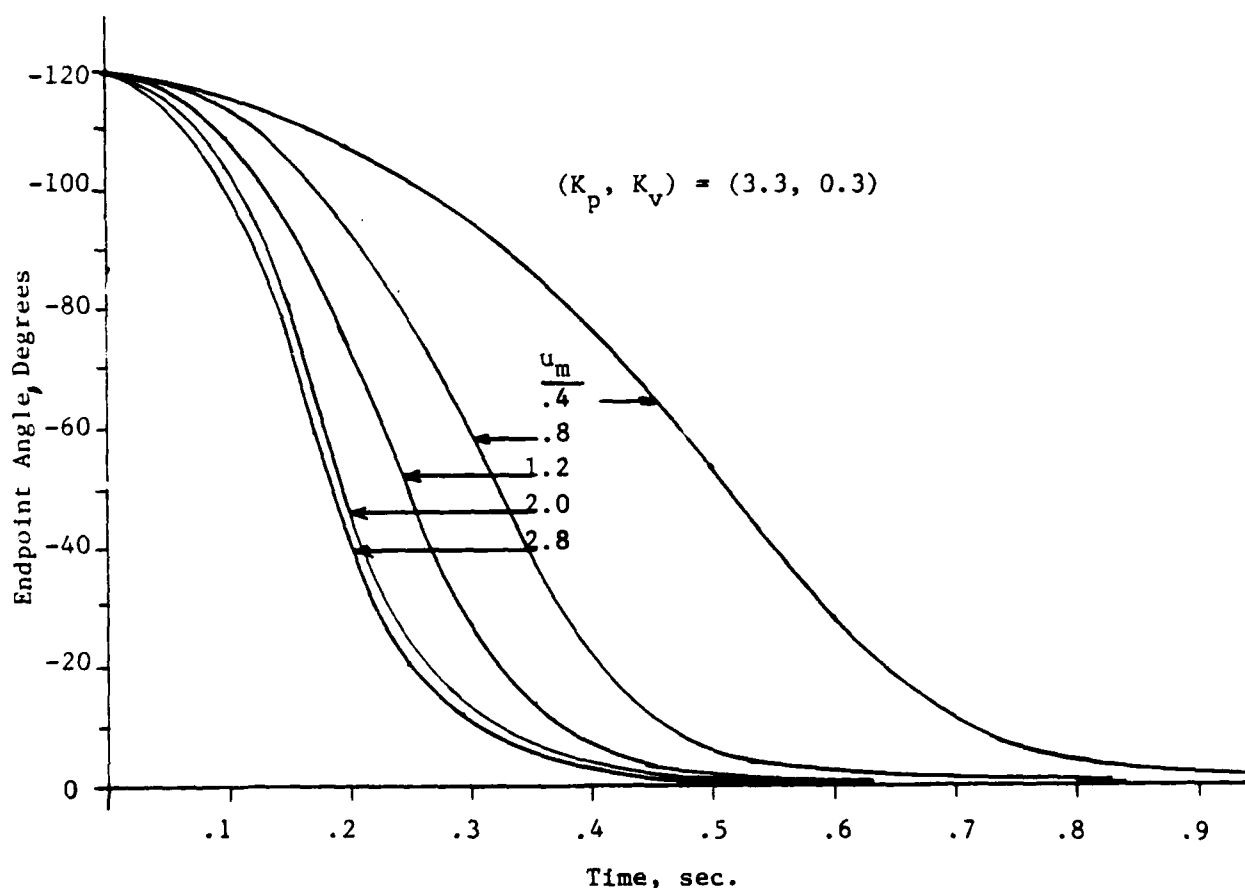


Figure 7. Switching zone control response of system with flexible joint: effect of maximum torque u_m , in.-lbs.

Experimental results indicate that for no motor velocity feedback (that is, $C_v = 0.0$) the elastic joint system is highly unstable as previously discussed. A value of $C_v = 0.005$ stabilized the system for all of the runs conducted. The switching zone controller yielded excellent results as indicated in Figure 7. It can be seen from this figure that as u_m is increased toward the true saturation limit, the cycle time is continuously decreased, all without significant overshoot. Figure 8 shows the switching zone controller for $u_m = 2.8$ compared

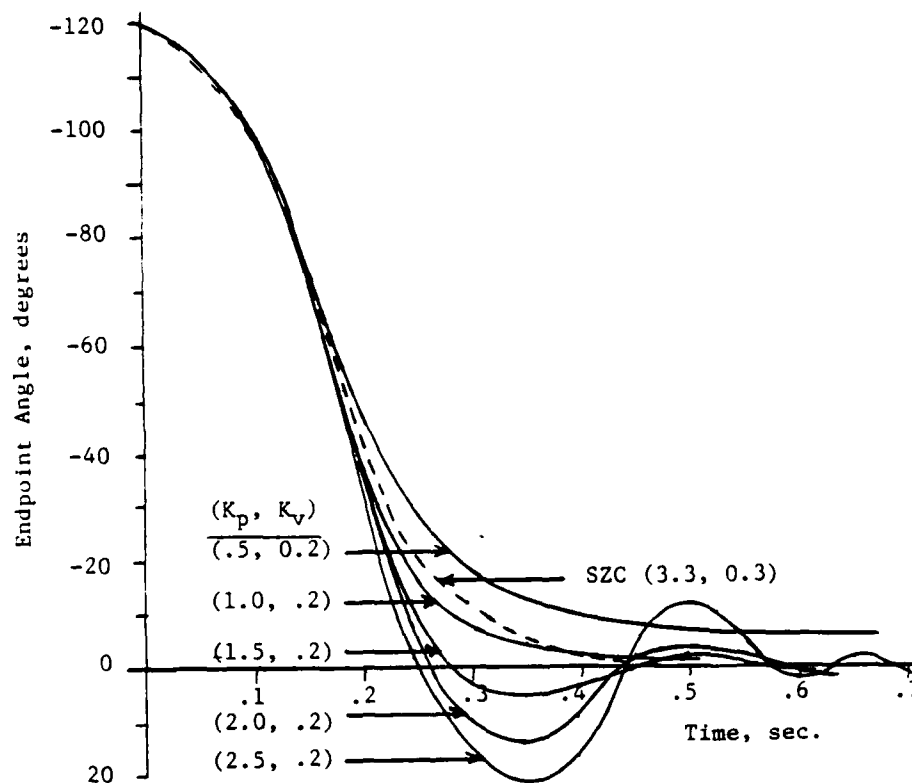


Figure 8. Linear feedback-only--comparison to switching zone control for $u_m = 2.8$ in.-lbs.

to the feedback-only case where different gains were assumed. A proportional gain K_p greater than 2.5 or K_v greater than 0.2 resulted in large, sometimes unstable, vibrations for the feedback-only case. This compares to $K_p = 3.3$ and $K_v = 0.3$ for the switching zone controller. The main problem with using

feedback-only was that for high gains, saturation is inadvertently reached during the cycle resulting in excessive vibrations and overshoot. The switching zone controller, on the other hand, assumes the existence of a saturation point and accounts for it automatically in the repositioning of a mechanism.

NONZERO STEADY-STATE DISTURBING TORQUE

In the derivation of SZC it was assumed that the disturbing torque u_d was zero in the limit. This is generally not the case where gravity, friction, and other effects result in nonzero steady-state disturbances. Consequently, steady-state motor torques are required to overcome these disturbances in order to maintain a desired payload or mechanism position or state. However, the disturbing torque cannot be predicted beforehand since friction effects vary from cycle to cycle and unknown gravity effects may be present. The nonpredictability of the gravity effects is especially true when the payload varies in a random fashion or when a mechanism is placed on a moving vehicle where orientation varies.

The most successful and easiest approach used in these studies was to compute the real-time feedforward term that automatically cancels any steady-state disturbing torques present (ref 5). An efficient way of accomplishing this is to compute both the work performed by the motor as well as the momentum change over a short period of time. Integrating Eq. (1) over the small time interval (t_0, t) gives

$$J(\dot{\theta}(t) - \dot{\theta}(t_0)) = \int_{t_0}^t u(t)dt + \bar{u}_d(t-t_0) \quad (20)$$

in which $\bar{u}_d$ is an approximate average value of the disturbing torque over the time interval $\Delta t = (t-t_0)$. Solving for $\bar{u}_d$ yields

$$\bar{u}_d = (J(\dot{\theta}(t) - \dot{\theta}(t_0)) - \int_{t_0}^t u(t)dt)/\Delta t \quad (21)$$

The quantities on the right-hand side of Eq. (21) are known or can be computed in real time and consequently $\bar{u}_d$ can be calculated in real time. A feedforward term can then be added directly to the input for the motor, effectively counterbalancing steady-state disturbances in real time.

In the experimental runs discussed in the previous section, Δt equal to 50 msec (five times the sampling interval of 10 msec) was used. This was more than adequate to accurately estimate the steady-state disturbing torque caused by payload changes and sliding friction effects.

SUMMARY AND CONCLUSIONS

This report presented an extension of the switching zone controller to the flexible joint case. It outlined and demonstrated experimentally an approach which overcomes problems with stability, overshoot, and robustness inherent in feedback-only approaches in which saturation is a problem. Switching zone control is based on the time optimal bang-bang theory where instead of a switching boundary, a switching zone is used to smoothen out transitions between accelerating and decelerating phases.

The main results of this work were outlined in the Introduction of this report. Basically, a procedure was presented for applying SZC to a single-degree of freedom system with a highly flexible elastic joint between the motor and payload. Problems of stability, controller design, and nonzero steady-state disturbances were resolved for the specific systems studied experimentally. Extensions to other systems should be straightforward. Future work will include application of SZC to multidegree of freedom flexible systems.

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