Hal Broberg

Paul Lin

Indiana University, Purdue University,
Fort Wayne, IN 46805

Joe Predina

ITT Industries
(Aerospace-Communications Division)

Periodic, Multi-Step Tracking Control for a Weather Satellite Scanning Mirror[1]

Weather satellite scan mirror performance often demands high pointing accuracy, rapid reposition times, and low peak power consumption. This work addresses and compares various techniques for optimizing these specific performances when the scan pattern is repetitive. We find that a technique combining open and closed-loop control in a timed sequence can often lead to the lowest pointing error in the shortest time interval while minimizing peak power. The technique applies equally well to applications such as robotics, automated manufacturing or any other electromechanical control system where quick, accurate response is needed while minimizing peak power.

[DOI: 10.1115/1.1344880]

Introduction

Images on many weather satellite platforms are produced by scanning a mirror in a repetitive fashion to steer images obtained by using different ground positions into a sensitive radiometer. Repetitive control techniques can be used to improve the tracking performance of these high precision servomechanisms. One such technique (Broberg [1]) is currently flying on the GOES (Geostationary Operational Environmental Satellite) series of weather satellite platforms that were first launched in April 1994, with the latest launch occurring in Spring 2000. The GOES satellites continue to provide weather data and imagery for regional and national weather forecasting. This use of repetitive control is responsible for achieving 50 parts-per-million scan linearity of high resolution, whole earth, GOES images comprised of 19,000 ×11,000 pixels. The accurate mapping of each individual pixel to a specific location on the earth is typically reproducible to within 0.6 kilometers from a geosynchronous orbit of approximately 35,900 kilometers. This performance would gradually degrade with age and over different operating temperatures that occur during a 24-hour orbit without the use of a repetitive controller. Based on this successful application, an NSF grant was awarded to investigate repetitive and other control techniques available to further increase the precision of weather satellite servo systems. One area of interest was application of repetitive control and other techniques to repetitive step/dwell scan mirror systems. The following material discusses some techniques for providing precise, rapid response of repetitive step/dwell systems while maintaining a minimum peak power draw on the satellite.

Literature Review and General Description

Several recent precision positioning techniques by Li and Cheng [2], Robeck et al. [3], Smith et al. [4], and Vira and Alagudu [5] are applicable. A conventional, closed-loop, precision tuning approach, Kurfess and Jenkins [6] was selected for comparison with the adaptive methods.

Modeling of various types of friction must be based on determination of the electromechanical mechanisms causing disturbances and their effects, Armstrong-Helouvry et al. [7]. Some friction effects that are included in the motor model are static friction, viscous friction, and Dahl friction (Dahl [8]). The validity of the friction effects modeled has been verified for over seven years in servo simulations of a currently operational series of weather satellites.

Repetitive control has been used as a method of adaptive control since the early papers of Inoue et al. [9,10], with Tomizuka [11,12] as a major contributor to the effective use of digital techniques. In repetitive control, canceling the phase of the closed-loop plant (Tomizuka [11], Wang and Longman [13]) improves system performance. The work on hard disk drives by Chew and Tomizuka [14] provides an example of the effectiveness of this method of control. Continuous repetitive control is useful for most waveforms, but there are drawbacks when an input, such as a step, has high frequency content. Switched repetitive control (Tomizuka et al. [15], Broberg [1]) can be used to ensure that the repetitive control is only active during a desired portion of the waveform.

Open-loop control techniques used by Ozasik [16] and Ozasik and Keltie [17] have been shown to be effective. Initial, open loop control followed by transition to closed-loop control, called switching zone control by Xia and Chang [18] and modified bang-bang control by Racicot [19,20], has been applied successfully. Predina [21] introduced a new method of open switched to closed-loop control that adjusts the open loop bang-bang amplitude based on the closed-loop response.

Techniques to reduce residual vibration (overshoot error and damped oscillation) were developed by Ho [22], Meckl and Kinceler [23], and Singhose et al. [24] and can be used to reduce low-level oscillations due to mechanical resonances in the system. Development of robust minimum time solutions by Pao and Singhose [25] and methods of creation of practical time-optimal commands by Tuttle and Seering [26] could also be used to determine initial bang-bang type commands.

The objective was to determine the best method of control for use with a periodic, multiple-step response in a rotational application. Conventional closed-loop control was used as the basis for comparison with and without adaptive methods. Several forms of repetitive control were simulated. Open switched to closed-loop control, Predina [21], with bang-bang amplitude adjustment based on final position from a previous step response was also simulated. A new form of control was also simulated that adjusts the open loop, bang-bang input amplitude based on minimizing closed-loop residual vibrations, which occur due to mechanical modes excited by the motor torque applied during the step.

The desired system must provide rapid rise time and fast settling time, to within a small fraction of the step size, while minimizing peak power. The optimal solution for minimum time

---

[1] This work was supported by NSF GOALI grant# 9633015 ''Advanced Weather Satellite Instrumentation'' and performed at the ITT (Aerospace-Communications) facility in Fort Wayne, IN.

Contributed by the Dynamic Systems and Control Division for publication in the JOURNAL OF DYNAMIC SYSTEMS, MEASUREMENT, AND CONTROL. Manuscript received by the Dynamic Systems and Control Division November 12, 1999. Associate Editor: T. Kurfess.

movement is to use a bang-bang input. This method also minimizes the peak power required, but perturbs resonances and nonlinearity effects in a real system. The desired system must minimize residual oscillations and have a response time that is close to optimal despite nonlinearity and slowly varying parameters of the plant such as bearing friction, motor time constant, motor torque constant, mechanical mode frequencies, and damping.

In this paper, the problem and approach are considered, followed by a discussion of the plant model and the conventional, closed-loop system used for comparison. Several repetitive methods are introduced along with two amplitude adjusted, open switched to closed-loop methods. Finally, a combination of the open switched to closed-loop method with switched repetitive control is described and comparisons provided.

Problem Definition and Approach

The problem is based on a typical set of scan requirements for a weather satellite. Each step of the rotational, multiple step response was required to be 3.3 deg with the amplitude of the residual oscillations minimized in as brief a time as possible. A full 360 deg rotation occurs each 8 seconds and multiple step and dwell events occur at 200 millisecond intervals within this period. Figure 1 illustrates the required trajectory for one rotation of the servo. The portions of the cycle where the mirror is swept rapidly to the next position and the two long dwells, used for calibration during each cycle are not difficult servo problems. The 30, rapid step responses where the mirror is held stationary so that data can be gathered from the atmosphere and the earth's surface were the difficult problem. This paper focuses on these step responses and considers a single step that would be repeated 30 times per cycle.

Selection of the method of control is linked to satellite mass/power considerations. Peak power must be minimized which means using the smallest motor possible. A larger motor (increased weight/power) can be used to reduce response time but adaptive control combined with minimum time methods may be more effective. The relative effect of increasing motor size can be shown by assuming linear motor characteristics and using the following relationships between current (i), torque (τ), and acceleration (α):

$$i(t) \propto \tau(t) \propto \alpha(t)$$

Electrical power, P, is proportional to i^2, and therefore proportional to α^2. Based on this, given a minimum time of t_m seconds and a bang-bang acceleration input to the motor, a relationship between minimum time and peak power, $P_{\max}$, is shown in Eq. (1).

$$t_m \propto \frac{1}{\alpha^{1/2}} \quad \text{and} \quad P_{\max} \propto \frac{1}{t_m^4} \tag{1}$$

This relationship, for a bang-bang input, shows that doubling the peak power decreases the minimum time by a factor of $2^{1/4} = 1.19$. Thus, increasing the size (which increases the weight and electric power input) of the motor as a direct means of improving the step response is not ideal for space operation. An open loop, bang-bang input minimizes peak power for a given motor, so this type of input was chosen. The relationship between peak power and minimum time in Eq. (1) was used to ensure that peak power requirements were met for the system, and can be used to estimate the power required for a given minimum time specification.

A commercially available three-phase, delta wound, brushless, D.C. torque motor was selected that would provide the required acceleration using the estimated inertia of the system. The motor selected produces a maximum acceleration of approximately 400 rad/s^2 with the defined load. This maximum acceleration was used as the bang-bang acceleration/deceleration with a step size of 3.3 deg, to calculate a minimum time of 24 milliseconds for the system to complete a step movement. This minimum time was determined by integrating the bang-bang acceleration-deceleration twice with zero initial conditions. A step position input (or a bang-bang torque input) was used throughout the simulations.

A detailed, high order, nonlinear model of a servo-motor was developed by engineers at ITT (A/C) for simulation of mirror pointing systems and has been used successfully for over 7 years to simulate weather satellite servo systems. This proprietary model contains many internal parameters for a three-phase, DC, brushless motor and the associated wide bandwidth current driver. Parameter variations associated with precision control and with long, unattended space operation can also be simulated. The effect

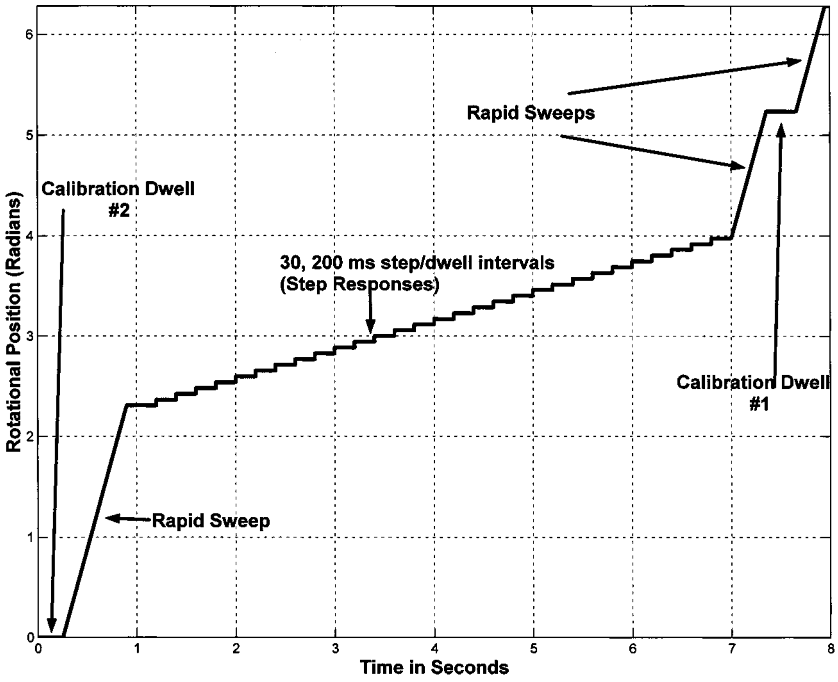

Fig. 1 One rotation of mirror servo

Table 1 Motor model parameters

Parameter	Value
Load inertia (mirror)	45.4 gm-cm^2
Motor inertia	3.02 gm-cm^2
Motor torque constant	3460 gm-cm/amp
Winding resistance	3.7 ohms
Winding inductance	.018 Henries
Detent torque	(nonlinear) 2% of Motor Torque
Back EMF Constant	.342 V/Radian

of significant factors such as detent torque, friction (static, viscous, and Dahl), bearing torque, temperature fluctuation, structural resonances, and prolonged radiation exposure was assessed using this model. Table 1 shows some of the parameters that have the greatest effect on weather satellite servos and on the simulations. For instance, normal temperature fluctuation of the motor during one rotation of the earth can result in a ±5% change in winding resistance.

A conventional feedback control system, using precision techniques, Kurfess and Jenkins [6], was used as the basis for the adaptive methods and for performance comparison. This conventional control is shown in Fig. 2. Note that the repetitive controller block in Fig. 2 is not connected for conventional control. The position gain of the system of Fig. 2 (without the repetitive block) was tuned, with 1 percent accuracy, for minimum residual vibration using a step-like input with reduced high frequency content (a 5-millisecond ramp of 3.3 deg). The basic model of Fig. 2 was also used with the repetitive and open switched to closed-loop methods for consistency.

Modeling and simulation techniques were used to determine the best methods available to approach optimal, bang-bang control with minimum residual oscillation for a multiple-step, repetitive system using Matlab[2] with Simulink and Control System and Signal Processing toolboxes. A sampling interval of 10^{-4} seconds was used in all simulations.

Repetitive Control

Several forms of digital repetitive control were simulated to improve the step-settle performance of the benchmark system. Switches are not shown in the figures, but are inserted at the input and output of the repetitive controller block in Fig. 2.

Basic Repetitive Control. The Matlab/Simulink block diagram of a basic repetitive control circuit, shown in Fig. 3, can be used to illustrate the effect of this simple form of repetitive control on a periodic step-settle response. Publications by Inoue et al. [9,10] introduced this form of repetitive control. It is currently used to provide precise positioning of a mirror-servomotor aboard geosynchronous weather satellites, Broberg and Molyet [27].

The low-pass filter in Fig. 3 acts as both the anti-aliasing filter and the repetitive loop filter in the on-orbit configuration. The time-advance (using information from the previous cycle) effectively cancels the phase shift of the filter within its pass-band. The loop gain K, in Fig. 3, is small (reducing added noise but increasing the number of repetitions required for disturbance reduction) and the bandwidth of the low-pass filter is within the bandwidth of the closed-loop servo to ensure stability. The applicable equations, Inoue et al. [9,10] for this form of repetitive control, expressed in the frequency domain, are discussed below.

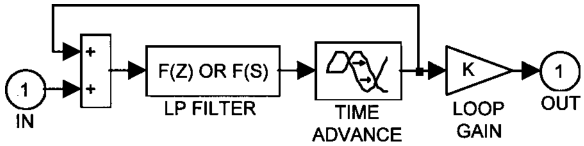

Fig. 3 Basic repetitive control

The equation for the analog low-pass filter and the time-advance, shown in Fig. 3, can be expressed as a function of frequency. This is provided in Eq. (2), and represents the Q filter in repetitive control literature. In Eq. (2), T_A is the time-advance and f_c is the cutoff frequency (Hz) of the low-pass filter.

$$Q(f)=\frac{e^{j\times 2\times\pi\times f\times T_A}}{1+j\times\dfrac{f}{f_c}} \tag{2}$$

The stability of the system with repetitive control can be determined from Eq. (3), given that $G(f)$ is the system closed-loop frequency response without repetitive control. If the stability factor, S, is less than one in Eq. (3), the system, with repetitive control, is stable.

$$S=|Q(f)|\times|1-G(f)| \tag{3}$$

The ability of the system, with repetitive control, to eliminate repetitive errors can be determined from Eq. (4). The improvement in tracking of the repetitive controller is inversely proportional to the tracking factor, T. For instance, if $T=0.1$ at a specific frequency, the system with repetitive control will reduce the tracking error at that frequency by a factor of 10.

$$T=\frac{|1-Q(f)|}{|1-Q(f)\times(1-G(f))|} \tag{4}$$

The relative noise power of the system with repetitive control can be found from Eq. (5), where N represents the relative noise power and the noise power without repetitive control is one.

$$N=1+|Q(f)|^2\times\frac{|G(f)|^2}{1-|Q(f)|^2\times|1-G(f)|^2} \tag{5}$$

N should be kept as close to one as possible. Although it is apparent from Eq. (5) that noise is always increased by repetitive control ($N>1$), decreasing K in Figs. 3, 5, or 6 can reduce N to near one so that noise added by the repetitive action is not a significant factor.

Figures 4 and 7 show the servo error of the conventionally tuned closed-loop system without repetitive control and of four forms of repetitive control. The step (fast ramp) input begins at 0.1 seconds in both figures. Repetitive responses are superimposed on the same time axis and provide significant improvement after several learning cycles. The number of learning cycles required to provide the best improvement varies dependent on the

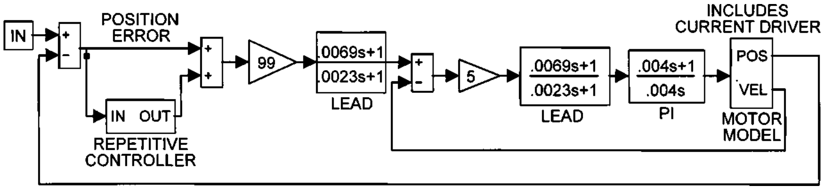

Fig. 2 Conventional precision control

---

[2] Matlab and Simulink, Copyright, The MathWorks Inc., 24 Prime Park Way, Natick, MA 01760, www.mathworks.com

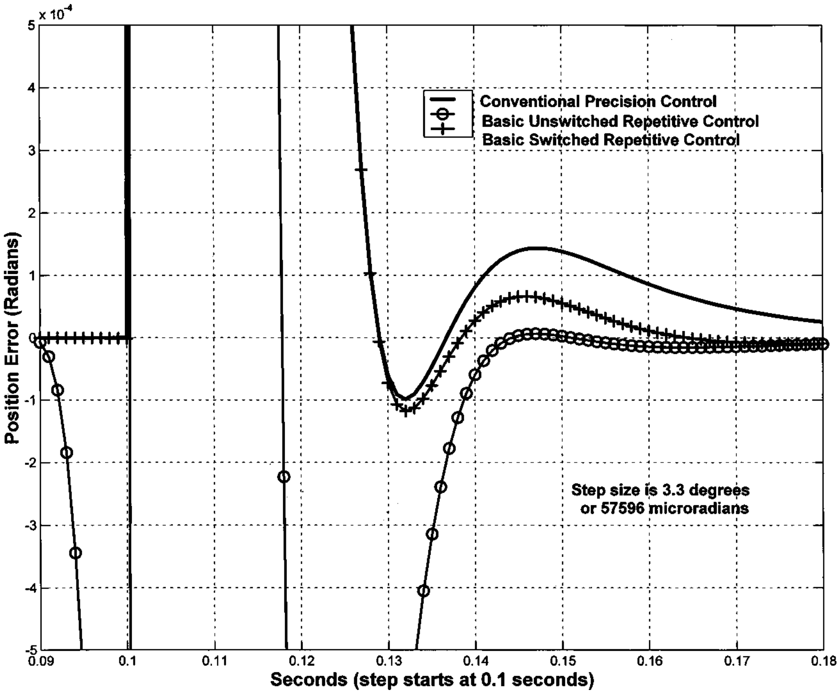

Fig. 4 Servo error for conventional and repetitive control

loop gain, *K*, (see Fig. 3, 5, and 6) but is usually 2–20 cycles. A 100 Hz, first-order, low-pass filter and a loop gain of one were used for all repetitive controllers. The repetitive bandwidth is within the bandwidth of the servo. In Fig. 4:

1 With conventional precision control (no repetitive control) the error initially (at .1 seconds) jumps to 57596 microradians (the size of the step), and rapidly settles toward zero error. Note the significant residual vibration with this method.

2 The basic unswitched repetitive control response is shown after several cycles of repetitive learning and represents the effect of Fig. 3, inserted in the repetitive control block of Fig. 2. This form of repetitive control uses information from previous cycles to smooth the entire error signal. Smoothing of the high frequency portions of the waveform (between 0.1 and 0.13 seconds on the graph) is accomplished by anticipating the input command. This anticipation (prior to 0.1 seconds on the graph) disturbs the previous holding position of the servo and is unsatisfactory for a multiple step application (see Fig. 1). This form of repetitive control is also the only form that does not produce a maximum error equal to the size of the required step.

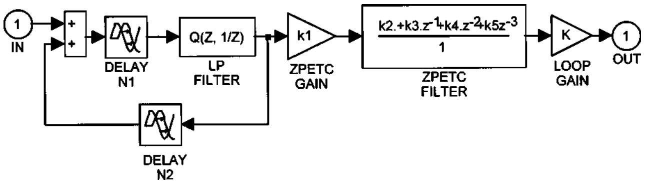

Fig. 5 Digital repetitive control with ZPETC

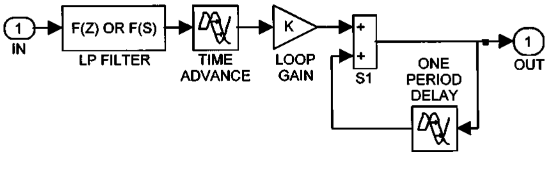

Fig. 6 Digital repetitive control with time advance

3 The basic switched repetitive control response occurs when the repetitive controller of Fig. 3 is switched off for the first 26 milliseconds of the input command during each cycle. The switching time of 26 milliseconds was chosen based on calculation of the minimum time required with the torque and inertias used and is the same for all switched responses. This switching time is less sensitive to other system factors. Switching removes the anticipatory action and many of the high frequency components of the input from repetitive action, thus, reducing the residual vibration.

Digital Repetitive Control With ZPETC. Tomizuka [11,12] investigated digital repetitive control and introduced the use of a zero phase error-tracking controller (ZPETC). This form of repetitive control, shown in Fig. 5, can be connected in the repetitive control block of Fig. 2. An applicable equation, Cosner et al. [28], for the repetitive signal generator, band-limited by the low-pass filter is shown as Eq. (6).

$$\text{Rep}=\frac{q(z,z^{-1})\times z^{-N_1}}{1-q(z,z^{-1})\times z^{-(N_1+N_2)}} \tag{6}$$

This ZPETC filter transfer function, Fig. 5, is an approximation of the inverse transfer function of the closed-loop system that is designed to cancel the phase shift. The variables shown (k1–k5) were calculated based on a second-order linear approximation of the plant transfer function. Equations for calculation of second-order ZPETC filter coefficients from a second-order Laplace low-pass filter transform approximation of the closed-loop transfer function of a system are shown below. Consider that the second-order *z*-transform of the Laplace approximation of the closed-loop transfer function of the system shown in Fig. 2 (without the repetitive controller) is given by Eq. (7).

$$G(z)=\frac{C_1z+C_2}{z^2+C_3z+C_4} \tag{7}$$

The ZPETC coefficients can then be calculated using Eqs. (8)–(9)

$$\beta=\left(1+\frac{C_2}{C_1}\right)^2 \tag{8}$$

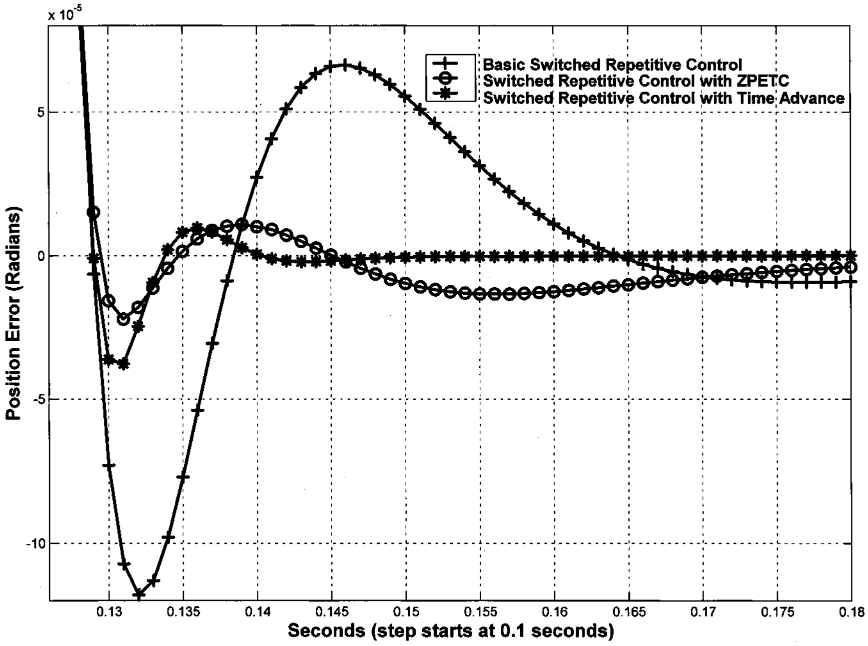

Fig. 7 Servo error for switched repetitive control

$$k1=\frac{1}{C_1\times\beta}\quad k2=\frac{C_2}{C_1}\quad k3=\frac{C_3\times C_2}{C_1}+1\quad k4=\frac{C_4\times C_2}{C_1}+C_3$$

$$k5=C_4 \tag{9}$$

Some properties of the form of digital repetitive control shown in Fig. 5 are:

1 The $q(z,z^{-1})$ block is a low-pass filter to ensure stability. A zero-phase moving average filter is commonly used to provide this function in repetitive control literature.
2 N2 is the phase delay (expressed as an integer number of samples) of the system plus the number of uncancellable zeros of the closed-loop system.
3 The total delay in the repetitive loop (N1+N2) is the period of the repetitive input expressed as an integer number of samples.
4 The form of repetitive control shown in Fig. 2 can be derived by making the following modifications to Fig. 4:

(a) setting N2=0,
(b) using a first-order low-pass filter as $q(z,z^{-1})$
(c) setting the delay N1 equal to one period minus $1/\omega_c$ (where ω_c is the cutoff frequency of the low-pass filter), and
(d) removing the ZPETC gain and ZPETC filter blocks.

Digital Repetitive Control With Time-Advance. Figure 6 shows a modification of the digital repetitive control of Fig. 5 that is treated separately in the literature, Wang and Longman [13]. This form of repetitive control provides low-pass filtering of the error signal external to the ideal repetitive loop ($q(z,z^{-1})=1$ and N_1 and N_2 are appropriately selected in Eq. (6)). Figure 6, with switching at .126 seconds, can also be inserted in the repetitive control block in Fig. 2. A time-advance (time delay of one period minus the desired time) cancels the phase delay of the closed-loop system as well as the phase shift of the low-pass filter. The time-advance technique provides good cancellation of the phase shift of a first order filter within its bandwidth, Broberg [1]. It can also cancel the phase shift of a second-order, closed-loop plant with a linear phase shift. The low-pass filter in Fig. 6 can be analog, digital, or convolution with a rectangular window, Wang and Longman [13].

Responses based on simulation of switched repetitive control with ZPETC and with time-advance phase cancellation are shown in Fig. 7. The step (fast ramp) begins at 0.1 seconds. Repetitive responses (after several learning cycles) are superimposed on the same time axis. In Fig. 7:

1 The basic switched repetitive control response is repeated from Fig. 4 for comparison.
2 The switched repetitive control w/ZPETC response uses a second-order ZPETC model for phase cancellation and improves the settling time.
3 The switched repetitive control with time advance response is effective for systems with a closed-loop phase shift that is close to linear.

Open Switched to Closed-Loop. Repetitive methods provide an accurate step-settle response for a periodic input waveform. The literature indicates that open loop control may have advantages for this type of application. Ozasik and Keltie [17] allude to this type of control, Xia and Chang [18] describe a switching zone controller. Racicot [19,20] specifies a ''modified bang-bang'' controller that switches from open loop to closed-loop control. The following assumptions were used for this method of control:

1 That the plant is open loop stable. The simulated system is tuned to ensure that this is true.

2 That motor position and servo error are measured and stored in memory for each cycle. The simulation provided this capability, which could be implemented in hardware and software on a physical system.

3 Operating the system in nonlinear regions (near or in saturation of some electronic components) is more likely to excite resonances. Bang-bang control implies using the maximum acceleration and deceleration that the plant will produce. However, in this discussion, bang-bang control means using a desired maximum acceleration followed by a desired maximum deceleration so that the plant (motor) and associated electronics remain within the linear region. Eliminating nonlinearities, such as opamp saturation, reduces excitement of higher frequency structural resonances. The maximum acceleration and decelerations chosen for these simulations ensured that the opamp and other electronics were not saturated.

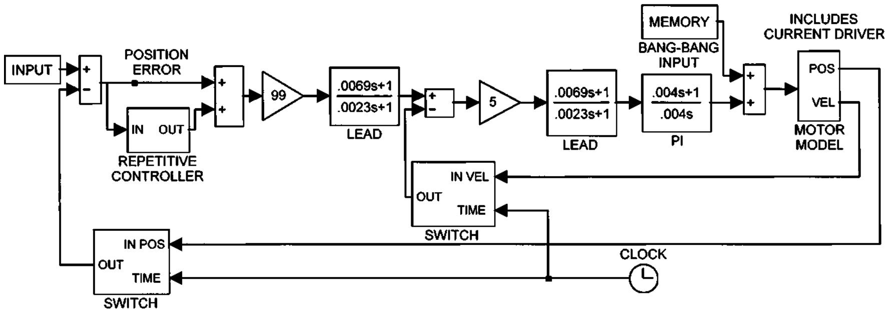

Fig. 8 Open switched to closed-loop control

4 That closed-loop control is required to reduce the effect of disturbances and accurately hold the final position. Without closed-loop control, the final position would drift away from the desired position due to system fluctuations and external effects. This is true for the model used here and for most real systems.

5 That plant variations are small from cycle to cycle. A servomotor generally has small variations from cycle to cycle, but can have relatively large variations over a life cycle. The motor model used in the simulation can be programmed to vary from cycle to cycle.

A block diagram of the resulting simulation is shown in Fig. 8. An open-loop, bang-bang, voltage input (from the memory block) to the high bandwidth current driver rapidly drives the output to a desired position. The velocity and position loops are closed immediately after the end of this open loop input. The duration of this bang-bang voltage input is 26 milliseconds. The closed-loop input (shown on the left of Fig. 8) is the final commanded position. The bang-bang amplitude is adjusted after each cycle based on the closed-loop system responding to the initial conditions created by the open-loop command. Repetitive adjustment of the open-loop, bang-bang amplitude is based on:

1 If the position at the end of the open-loop input is close to the final position, with small velocity and acceleration components, the closed-loop system will rapidly approach the desired final position with little residual oscillation.

2 If the position is not close to the final position, the amplitude of the bang-bang input requires adjustment prior to the next cycle.

In Fig. 8, the initial open-loop, bang-bang voltage command was determined based on the motor model. Adjustment of this open-loop input to minimize rise-time and residual vibration is accomplished in two stages. During the first stage, the program adjusts the amplitude of the open-loop, bang-bang input so the output position when the loop is closed is close to but does not go beyond the final position (no overshoot). During the second stage, the program adjusts the amplitude of the open loop waveform to minimize the peak amplitude of closed-loop residual vibrations. These two stages are complementary since the desired response is to reach the final position and settle there with no residual vibration. The initial amplitude adjustment ensures that the final position is approached by the open-loop system, while the second stage, after the loop is closed, measures the amplitude of the residual vibrations and calculates amplitude adjustments to reduce

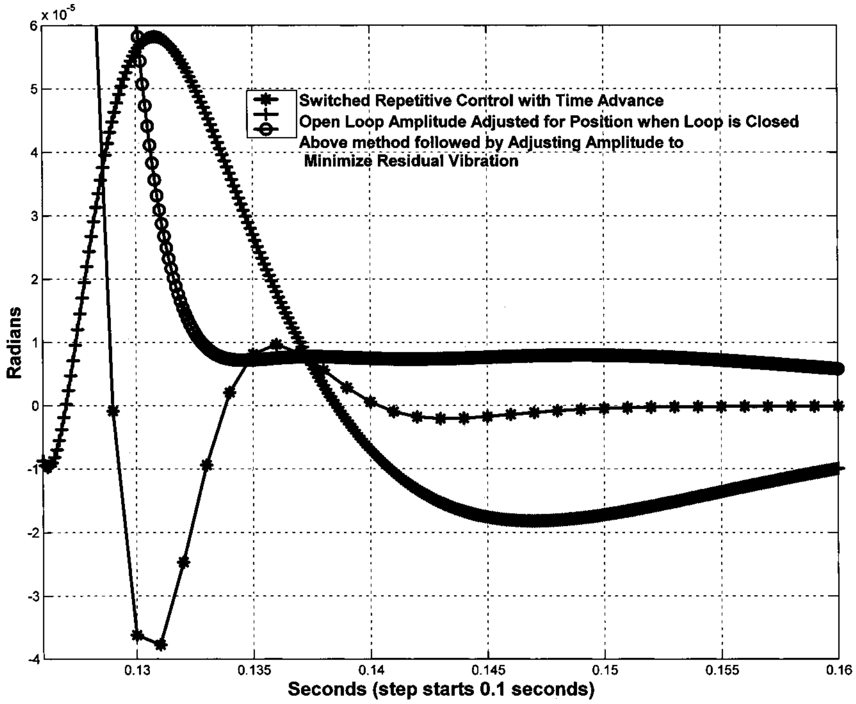

Fig. 9 Servo error for open-loop amplitude adjustment

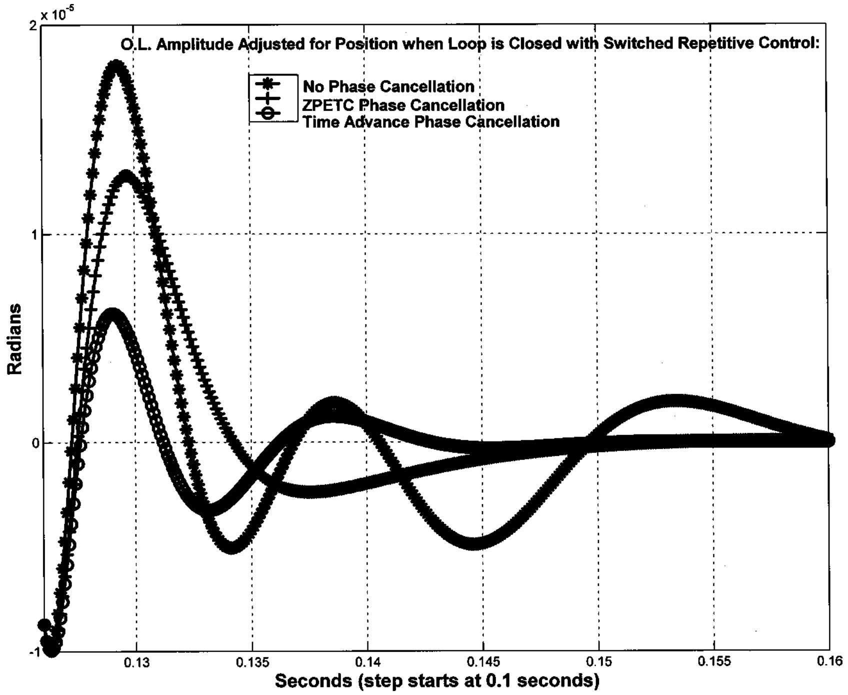

Fig. 10 Servo error for O.L. amplitude adjustment with switched repetitive control

these vibrations during the next cycle. There are two distinct stages in this open loop switched to closed-loop system, and each stage requires a separate adjustment of the input amplitude.

Open Switched to Closed-Loop System Without Repetitive Control. The system shown in Fig. 8 was simulated, with no repetitive control and the resulting servo error is shown in Fig. 9. In Fig. 9:

1 The switched repetitive control with time advance response is shown from Fig. 7 for comparison.

2 The response for open-loop amplitude adjusted for position when loop is closed is better than some previous responses at eliminating residual vibrations.

3 When the adjustment of 2, above is followed by adjusting amplitude to minimize residual vibration, the error was reduced to less than 10 microradians within 33 milliseconds of the step.

Open Switched to Closed-Loop System Followed by Repetitive Closed-Loop Control. Several types of repetitive control were also used in the block diagram of Fig. 8 *after* initial adjustment of the bang-bang amplitude for position. Results showed that using repetitive control after adjusting the open loop input amplitude improved the response. Three cases are shown in Fig. 10.

1 The response with no phase cancellation showed a substantial improvement when compared with two similar methods: basic switched repetitive control in Fig. 7 or open-loop amplitude adjusted for position when loop is closed in Fig. 9.

2 The response with ZPETC Phase Cancellation shows an improvement when compared with two similar methods: switched repetitive control with ZPETC in Fig. 7 or open-loop amplitude adjusted for position when loop is closed in Fig. 9.

3 The response with time advance phase cancellation shows an improvement when compared with two similar methods: switched repetitive control with time advance in Fig. 7 or open-loop amplitude adjusted for position when loop is closed in Fig. 9.

It was not feasible to use repetitive control with open switched to closed-loop control when the bang-bang input amplitude was also adjusted based on minimization of the closed-loop residual oscillations. The repetitive control and the closed-loop adjustment are both forms of adaptive control and the interaction resulted in instability.

Summary

Table 2 provides a summary and comparison of the peak residual oscillation and the time in milliseconds. The input step is 3.3 deg (57,596 microradians, with the specification in microradians), calculated minimum time for an ideal, bang-bang input (of ±400-radians/s^2 acceleration) is ≈24 milliseconds, and all switch-

Table 2 Summary of results

#	Graph/method of control	Peak residual osc. and time μrads@ms	Comments
1	Fig. 4/pi & Lead	+140@47	1% tuning
2	Fig. 4/Basic repetitive	−60@40	Anticipates
3	Fig. 4/Basic switched rep.	+70@45	Improved compared to #1
4	Fig. 7/Switched Repetitive with ZPETC	−17@55	Osc. due to incomplete phase cancellation
5	Fig. 7/Switched rep. with T.A.	+12@36	Better phase cancellation
6	Fig. 9/O.L. ampl. adjusted	−19@47	Comparable to previous
7	Fig. 9/O.L. ampl. adjusted +min. resid. Vib	9@33	Settles slowly No overshoot
8	Fig. 10/O.L. ampl. adjusted &Sw.Rep.entl.	±5@33	Osc. due to incomplete phase canc.
9	Fig. 10/#8 w/ZPETC	+3 after 33	Improved Phase cancellation
10	Fig. 10/#8 w/T.A.	−3@33	Best phase canc. for this plant

Step size: 3.3°=57596 microradians

Min. Time: 24 ms for all cases

ing is at 26 milliseconds. Line 1 of the table shows that conventional control provides a peak residual oscillation of 140 microradians. This method is not adaptive and would require periodic retuning due to parameter variations. The remainder of the methods would adapt to the slowly (with respect to the period of the input) varying parameters and are more suitable to long term, unattended operation.

Repetitive control methods, lines 2–5 of Table 2, are easily implemented, and, with accurate phase cancellation and wide bandwidth, provide reduced residual oscillations. The best of the simulated repetitive control methods (line 5 of the table) had a peak residual oscillation of $+12$ microradians at 36 milliseconds after switching.

The open switched to closed-loop method, lines 6–7 of Table 2, also displayed reduced residual oscillation. This method is particularly effective when the open-loop bang-bang-input amplitude is adjusted twice: First so the output is close to the final position when the loop is closed and then to minimize closed-loop peak residual vibration. This method, line 7 of the table, provided a peak residual oscillation of $+9$ microradians at 33 milliseconds after switching. When the open switched to closed-loop method, with the amplitude adjusted based on final position was followed by various forms of repetitive control, further improvements were apparent (lines 8–10 of Table 2). Line 10 showed the best response of the simulations performed with a peak residual oscillation of -3 microradians at 33 milliseconds after switching and the fastest settling.

Conclusion

For a precision, periodic multi-step response, a form of switched adaptive control is necessary to eliminate a causal, anticipatory action. Switched repetitive control, with ZPETC or with time advance phase cancellation (dependent on the plant), provides excellent response and relatively easy implementation. Open switched to closed-loop control with adjustment of the open-loop input amplitude based only on the position when the loop is closed provides a response comparable to switched, repetitive control. An open-loop, bang-bang input with amplitude adjustment based on position followed by continued adjustment of the bang-bang input amplitude based on minimization of the closed-loop, residual vibration produced a better response than conventional repetitive methods. The best response was found for open-loop, bang-bang input with amplitude adjustment based on position followed by closed-loop repetitive control.

Based on the simulation results, open loop switched to closed-loop methods should be considered for any periodic multiple step response input requiring rapid rise time, fast, precise settling, and minimization of peak power.

References

[1] Broberg, H. L., 1993, ''Theory and Optimization: The Coherent Error Integrator, East-West Mirror Servomechanism, Geostationary Operational Environmental Satellite (GOES),'' Ph.D. dissertation, University of Toledo.

[2] Li, W., and Cheng, X., 1994, ''Adaptive High-Precision Control of Positioning Tables-Theory and experiments,'' IEEE Trans. Control Syst. Technol. **3**, No. 3, pp. 265–270.

[3] Robeck, L., Rathbun, D., and Lehman, D., 1991, IEEE Control Syst. Mag. **11**, No. 3, pp. 46–52.

[4] Smith, M., Annaswamy, A., and Slocum, A., 1995, ''Adaptive control strategies for a precision machine tool axis,'' Precis. Eng. **17**, No. 3, pp. 192–206.

[5] Vira, N., and Alagudu, M., 1995, ''Precision measurements and control of an automated two-dimensional grid plate testing machine,'' ISA Trans. **34**, 101–116.

[6] Kurfess, T. R., and Jenkins, H., 1996, ''Ultra-High Precision Control,'' *The Control Handbook*, W. S. Levine, ed., CRC Press and IEEE Press, Chap. 77.3, pp. 1386–1405.

[7] Armstrong-Helouvry, B., Dupont, P., and Canudas De Wit, C., 1994,''A Survey of Models, Analysis Tools and Compensation Methods for the Control of Machines with Friction,'' Automatica **30**, No. 7, pp 1083–1138.

[8] Dahl, P., 1975, ''Solid Friction Damping of Spacecraft Oscillations,'' The Aerospace Corporation, AIAA Paper No. 75-1104.

[9] Inoue, T., Nakano, M., and Iwai, S., 1981, ''High Accuracy Control of Servomechanism for Repeated Contouring,'' *Proceedings of the 10th Annual Symposium on Incremental Motion Control Systems and Devices*, pp. 285–292.

[10] Inoue, T., Nakano, M., Kubo, T., Matsumoto, S., and Baba, H., 1981, ''High Accuracy Control of a Proton Synchrotron Magnet Power Supply,'' International Federation of Automatic Control (IFAC) *8th Triennial World Congress*, Kyoto, Japan, published by Pergamon Press for IFAC, pp. 3137–3142.

[11] Tomizuka, M., 1987, ''Zero Phase Error Tracking Algorithm for Digital Control,'' ASME J. Dyn. Syst., Meas., Control **109**, 65–68.

[12] Tomizuka, M., 1993, ''On the Design of Digital Tracking Controllers,'' ASME J. Dyn. Syst., Meas., Control **115**, 412–418.

[13] Wang, Y., and Longman, R., 1996, ''Use of Non-Causal Digital Signal Processing in Learning and Repetitive Control,'' Adv. Astronaut. Sci., **90**, 649–668.

[14] Chew, K., and Tomizuka, M., 1990, ''Digital Control of Repetitive Errors in Disk Drive Systems,'' IEEE Control Syst. Mag. **10**, pp. 16–20.

[15] Tomizuka, M., Anwar, G., and Fang, B., 1988, ''Control of Robot Manipulators under Repetitive Tasks-Segmented Repetitive Control Approach,'' *Proceedings IEEE Workshop on Intelligent Robot Systems*, pp.157–163.

[16] Ozisik, H., 1989, ''Development and implementation of a high speed open loop control technique for micropositioning of mechanical structures,'' Precis. Eng. **11**, No. 4, pp. 225–230.

[17] Ozisik, H., and Keltie, R. F., 1991, ''Implementation of an open loop control technique for high-speed micropositioning in a single-point diamond turning process,'' Precis. Eng. **13**, No. 2, pp. 83–94.

[18] Xia, Z., and Chang, S., 1986, ''A Simple Robust Nonlinear Robotic Controller,'' *Recent Trends in Robotics*, Jamshidi, Luh, and Shahinpoor, eds., North-Holland, New York, pp. 318–328.

[19] Racicot, R. L., 1993, ''Increasing Mission Reliability by Using Open Loop Control,'' IEEE Trans. Reliab. **42**, No. 3, pp. 384–392.

[20] Racicot, R. L., 1993, ''Limiting Servo Motor Torque Gradients with Near Minimum Time Repositioning,'' IEEE Trans. Control Syst. Technol. **1**, No. 4, pp. 284–289.

[21] Predina, J., 1991, Draft ITT (Aerospace-Communications) proposal for the High-Resolution Infrared Sounder (HIRS).

[22] Ho, H. T., 1997, ''Fast Bang-Bang Seek Control,'' IEEE Trans. Magn. **29**, No. 6, pp. 4522–4527.

[23] Meckl, P. H., and Kinceler, R., 1994, ''Robust Motion Control of Flexible Systems Using Feedforward Forcing Functions,'' IEEE Trans. Control Syst. Technol. **2**, No. 3, pp. 245–254.

[24] Singhose, W., Singer, N., and Seering, W., 1995, ''Comparison of Command Shaping Methods for Reducing Residual Vibration,'' *Proceedings of the 3rd European Control Conference*, pp. 1126–1131.

[25] Pao, L. Y., and Singhose, W. E., 1998, ''Robust Minimum Time Control of Flexible Structures,'' Vol. 34, No. 2, pp. 229–236.

[26] Tuttle, T. D., and Seering, W. P., 1999, ''Creating Time-Optimal Commands with Practical Constraints,'' J. Guid. Control Dyn. **22**, No. 2, pp. 241–250.

[27] Broberg, H., and Molyet R., 1992, ''Reduction of Repetitive Errors in Tracking of Periodic Signals: Theory and Application of Repetitive Control,'' *Proceedings of the 1st IEEE Conference on Control Applications*, Dayton, OH.

[28] Cosner, C., Anwar, G., and Tomizuka, M., 1990, ''Plug in Repetitive Control for Industrial Robotic Manipulators,'' *Proceedings of the IEEE International Conference on Robotics and Automation*, pp. 1970–1975.