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MAXIMUM SPEED OF MECHANICAL DEVICES IN A DIGITAL COMPARISON POSITIONING SYSTEM

J. A. Curtiss

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Collider Accelerator Department

Brookhaven National Laboratory

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Accelerator Department
BROOKHAVEN NATIONAL LABORATORY
Associated Universities, Inc.
Upton, New York 11973

ADDENDUM TO

AGS DIVISION TECHNICAL NOTE

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I am forever indebted to D. Lowenstein and H. Weisberg for pointing out that in the last equation in Tech. Note #139, 0.061 inch/sec multiplied by 60 is not 0.96 inch/min, but 3.66 inch/min.

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During the design of components for the SEB'78 Switchyard, it has become necessary to determine the maximum speed of mechanical devices in a digital comparison positioning system. In systems under development, a voltage corresponding to device position is continuously digitized and compared to a digital word representing desired position. When digital coincidence is detected, power is removed from the drive system and the device is expected to stop within the coincident digitization interval. Stable reference sources and noise-free analog position signals are implied in the physical realization of such a system. In the AGS environment, readout linearity is not as important as repeatability.

The analog position information may be considered to be a band-limited signal. The Sampling Theorem states that any $2f_{max}$ independent samples per second will completely characterize a band-limited signal. In our case, the Nyquist, or sampling, interval is the A/D cycling rate. The rate at which the position signal may vary, f_{max}, is then one least-significant-bit worth (one 2^nth of the reference voltage) divided by twice the maximum A/D rate, expressed in volts per second. The maximum rate at which the device may travel is total travel distance times the position signal rate. Expressed algebraically:

$$S_{max} \leq \frac{d}{2^n(2)(t_{min})} \quad \text{and} \quad \delta \geq \frac{d}{2^n}$$

where

S = net device mechanical traversing speed
d = total travel
n = number of A/D converter bits
t = A/D converter cycling time
δ = minimum design interval desired

Example I

Assume we need to position a device accurately to one-half mil over a two-inch travel. Then, using $\delta \geq d/2^n$, we find $2^n \geq d/\delta = \frac{2.000 \text{ inch}}{0.0005 \text{ inch}} =$ 4000, which is satisfied for n = 12, since $2^{12} = 4096$. We must therefore use a 12-bit A/D converter. Should we use an integrating type for maximum noise immunity, then a typical converter cycle time t_{min} is approximately 12 msec. By substitution, we find:

$$S_{max} \leq \frac{d}{2^n \ (2)(t_{min})} = \frac{2.000 \quad \text{inch}}{2^{12}(2)(0.012 \text{ sec})} = 0.020 \frac{\text{inch}}{\text{sec}} = 1.2 \frac{\text{inch}}{\text{min}} .$$

Example II

Same device, but at a meeting the stated accuracy requirement was one part per thousand (or 2-mil accuracy). Then $2^n \geq d/\delta = \frac{2.000 \text{ inch}}{0.002 \text{ inch}} =$ 1000, which is satisfied by n = 10, since $2^{10} = 1024$. For our integrating converter,

$$S_{max} \leq \frac{d}{2^n(2)(t_{min})} = \frac{2.000 \quad \text{inch}}{2^{10}(2)(0.012 \text{ sec})} = 0.08 \frac{\text{inch}}{\text{sec}} = 4.8 \frac{\text{inch}}{\text{min}} .$$

Now, for the bad news! While a stepping motor incrementally divides each revolution into 200 steps, or 260/200 = 1.8 degree segments, a synchronous slo-syn used for higher drive torque will coast to a stop within five mechanical degrees.[1,2] This stopping, which varies relatively unpredictably between zero and five degrees, must fall within a one-half A/D spatial increment, or $d/2^n(2)$. This will insure that the device will stop within the same A/D interval wherein stop-coincidence was detected.

With 72 rpm synchronous motors, the angular velocity is $\frac{72 \times 360 \text{ degrees}}{\text{min}} \times \frac{1 \text{ min}}{60 \text{ sec}} = 432$ degrees/sec. Traversal of five mechanical degrees will require (5/432) sec, or 0.0116 sec. Since the stopping distance in this time must be less than $d/2^n(2)$, the maximum operating speed cannot exceed $d/2^n(2)$ per 0.0116 sec. Substituting, we find that

$$S_{max} \leq \frac{d \qquad \text{inch}}{2^n(2)(0.0116 \text{ sec})} , \text{ and } S_{max} \leq \frac{d \quad \text{inch}}{2^n(2)(t_{min})} ,$$

or $t_{min} = 0.0116$ sec. In other words, we have an additional speed restriction imposed on the system by motor coast considerations, and samples more frequent than 0.0116 sec are redundant. We may now design a dedicated integrated A/D positioning system with a 10 msec cycle time. We may also design a positioning system using higher speed converters scanning several drives, but the bad news is we will be unable, thanks to Nyquist and the Superior Electric Company, to lower t_{min} below 0.0116 sec for synchronous motors.

Should we be able to use a 200 step/sec stepping motor, then one step is 1/200 sec, or 0.005 sec (compared to 0.0116 sec for the synchronous motor). By following the above considerations, t_{min} is reduced to 0.005 sec. For the same position accuracy, the best traversal rate we can accomplish with stepping motors in digital comparison positioning systems is little better than twice the high-torque synchronous motor rate.

It is anticipated that an increasing (from the present zero) number of devices will be driven by an A/D digital positioning system. Those selecting mechanical drive components for use with such systems may now apply the earlier stated formulae, with t_{min} set to 0.012 for synchronous motor systems and t_{min} set to 0.005 for stepping motor systems.

Note that those responsible for originating specifications on device position accuracy should be careful not to overspecify. Not only will device speed be unnecessarily reduced, but a false sense of accuracy will be obtained. The coefficient of thermal expansion of aluminum is approximately 13×10^{-6} inch per inch/degree F. A ten-foot long device will change length by 1.5 mils for every degree F variation. The AGS ring temperature controls maintain ring temperature constant within a two degree variation. The area of the Interim Switchyard will vary from about 60 F in the winter to about 90 F in August. There is, however, no need to panic: unsecured ends of ten-foot straight sections are not flailing about ready to injure unwary passersby. The diameter of a pencil lead is about 45 mils. This paragraph is simply included in appreciation for those who are able to cope with such effects in meeting design criteria.

For those devices designed to be controlled by the present EP&S design, the MP2600 integrating A/D converter cycles at 0.008 msec, but is shared by two devices; the design t_{min} is therefore 0.016 msec. On the other hand, those responsible for operations have agreed that one part per thousand accuracy is sufficient, so n = 10. The speed of our intermin BC Split traverse drives for the electrostatic splitter and the Lambertson magnet must therefore be limited to:

$$S_{max} \leq \frac{2.000 \quad \text{inch}}{2^{10}(2)(0.016\ \text{sec})} = 0.061\ \frac{\text{inch}}{\text{sec}} = 0.96\ \frac{\text{inch}}{\text{min}} \ .$$

References

1. Characteristics of a Synchronous Induction Motor, by Snowden and Madson of the Superior Electric Company, Transactions of the American Institute of Electrical Engineers, Volume 81-1962, Part II; Applications and Industry, Institute of Electrical and Electronics Engineers, Inc., c1963.

2. Catalog MD174-1, The Superior Electric Company, Bristol, Conn. c1974.

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