JP0150530

ICANS-XV
15th Meeting of the International Collaboration on Advanced Neutron Sources
November 6-9, 2000
Tsukuba, Japan

8.4

Timing Reference Generators And Chopper Controllers For Neutron Sources

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Abstract

Due to AC-power-grid frequency fluctuations, the designers for accelerator-based spallation-neutron facilities have worked to optimize the competing and contrasting demands of accelerator and neutron chopper performance. Powerful new simulation techniques have enabled the modeling of the timing systems that integrate chopper controllers and chopper hardware. For the first time, we are able to quantitatively access the tradeoffs between these two constraints and design or upgrade a facility to optimize total system performance. Thus, at LANSCE, we now operate multiple chopper systems and the accelerator as simple slaves to a single master-timing-reference generator. For the SNS we recommend a similar system that is somewhat less tightly coupled to the power grid.

1. Introduction

Through careful target and moderator design at a spallation source, one can tailor the neutron energy spectrum to match the requirements of the neutron scattering instruments. But there are limits to what can be accomplished with these techniques, and so it is often necessary to further "filter" the neutron beam as it emerges from the neutron source and begins its journey through the instrument. Neutron choppers are rotating electro-mechanical devices that remove undesired energy components from the neutron beam. So called time zero or "T-zero" (T_0) choppers rotate a large mass through the beam to effectively place a beam stop in the path of the beam when it is at its peak intensity. This eliminates the high-energy neutrons that occur early in the neutron pulse. We use another type of chopper to block most neutrons except those in a narrow energy band. Generally we place this energy selector (E_0) chopper downstream from a companion T_0 chopper. We must operate such choppers in phase with the production of the neutron pulses and in phase with one another so that the energy distribution in each neutron pulse into the instrument remains constant.

Unfortunately, accelerators that are closely coupled to the AC-power-grid have not always allowed the delivery of proton beam to the target in a precise and repeatable manner. As shown in Figure 1, fluctuations of the phase in the power grid give rise to fluctuations in the time-of-arrival of the protons on target and hence to the time-of-arrival of the neutrons in the instrument. To maintain a constant neutron energy spectrum at an instrument, we must continually alter the phase of the rotating chopper blades to match the phase of the accelerator that follows the power grid. Since the choppers consist of massive rotating blades with lethargic response times, they can not easily track and follow these phase changes. On the other hand, the RF power modulators in the accelerator operate best when they are able to follow phase fluctuations in the power grid. Clearly we have a synchronization problem if the accelerator phases beam delivery with the power grid while the choppers operate at a fixed frequency. Hence over the past 20 years, system designers have implemented accelerator and chopper controls that are engineering compromises that work adequately for neutron scattering facilities at LANL[1,2,3] and ANL[4,5,6].

During an upgrade to our LANSCE systems and for the design of the timing system for the new Spallation Neutron Source (SNS), we have reviewed the engineering compromises and we find new options thanks to better analysis tools and to new technologies available for high-performance implementations. This paper presents the system engineering analysis we have performed and experimental results obtained with prototype systems.

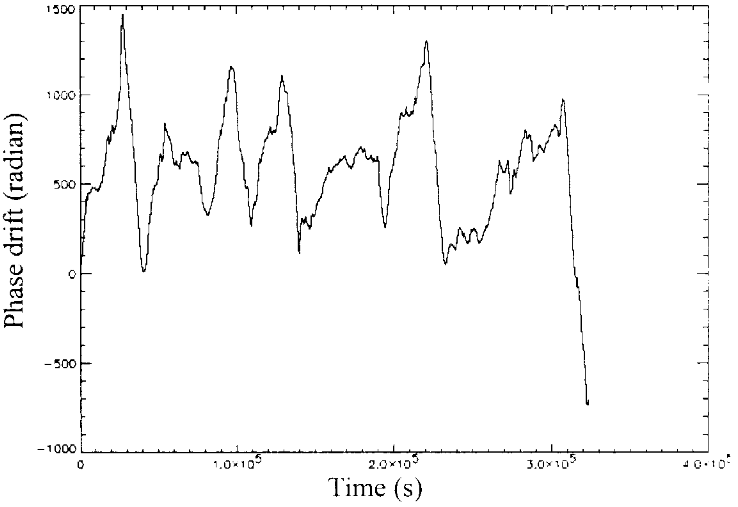

Figure 1. 90 hours of phase drift data. The drift is measured with respect to an ideal 60-Hz source. Note that the drift is substantial. 1500 radians corresponds to 240 cycles or 4 s on a motor-driven clock. The challenge for the chopper is to follow these changes through acceleration and deceleration.

2. Approach

To predict and analyze neutron-chopper performance we modelled all subsystems beginning at the AC-power grid and ending at the rotating chopper blade. All simulations were performed with MATLAB and SIMULINK software packages running on PCs. The model has four major components: the power grid; the timing-reference generator; the chopper controllers; and the choppers (see Figure 2). Initially we measured phase variations in the power grid using a zero-crossing detector and GPS-based time-stamping techniques. We then developed a DSP algorithm based on 3-phase power-line measurements that extracts the grid phase drift measured with respect to an ideal 60-Hz reference [7]. Using the DSP, we recorded phase drift data that we subsequently used as input into our simulations. Figure 1 shows the phase-drift data recorded during a 90-hour period, which dramatically makes the point that the phase of the power grid wanders. Although it is easy to work with, the algorithm does bandwidth limit the input data because of its weighted-least-squares algorithm.

The proposed timing-reference generator takes the phase information from the grid and smoothes it. By varying the smoothing parameters, one can effectively limit the phase

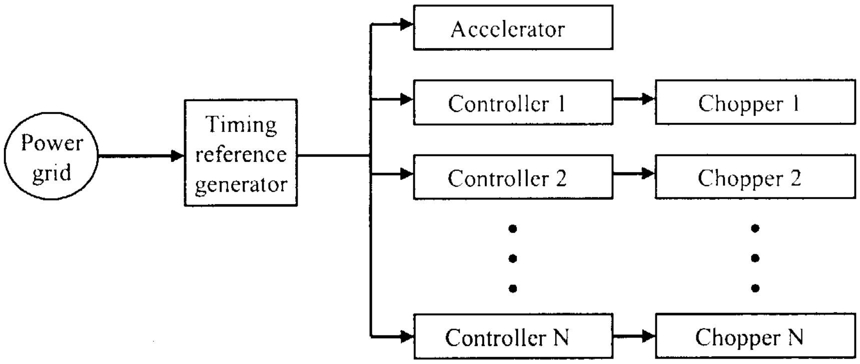

Figure 2. Block diagram for timing system dependencies. Accelerator and chopper controllers act strictly as slaves to the master timing reference generator.

acceleration passed along to the choppers. Figure 3 illustrates the concept of smoothing beginning with the waveform from the power grid. The zero-crossing pulses mark the phase of the grid as it passes through half cycles. We have developed several "algorithms" to generate the smoothed timing-reference pulses. Each algorithm forms a phase difference by subtracting the smoothed phase from the raw grid phase. The phase difference is then processed with various filters and proportional-integral (PI) compensators. This combination produces a correction signal that modulates the frequency of the software-controlled frequency generator.

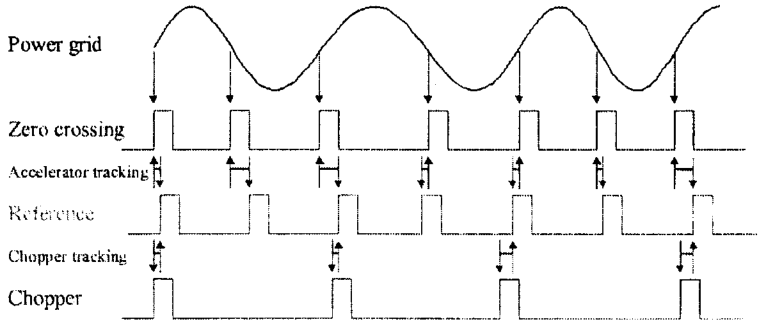

Figure 3. Illustration of key timing concepts. The timing-reference signal is a "smoothed" version of the zero-crossing signal that is appropriate for controlling choppers and simultaneously satisfies the accelerator

To realistically model a neutron scattering facility, we selected a family of choppers that span the range of performance. For this work we chose 20-Hz T_0, 60-Hz T_0, and 600-Hz E_0 choppers. Each chopper is paired with its own controller. Since controllers for frame overlap choppers are identical to T_0-chopper controllers, except for the tuning required for the smaller moments-of-inertia, frame-overlap choppers are omitted from the modelled systems.

To compare the results of simulations with real hardware performance we constructed prototype controllers for T_0 choppers and operated them with chopper hardware already installed at the Lujan Center. E_0-chopper data came from the Revolve Technologies Inc. system now under acceptance testing.

Since the performance of the various choppers, as well as the performance of the accelerator is linked to the amount of coupling to the AC-power grid, we wanted to quantify this coupling. Hence, we measured the standard deviation of the timing-reference phase with respect to the raw-grid phase. We define this metric as the accelerator-tracking sigma. We can vary the accelerator-tracking sigma by changing the smoothing parameters in the timing reference generator. Traditionally, accelerators prefer a low accelerator-tracking sigma (tight grid coupling) while choppers prefer it large (loose grid coupling). We also wanted to quantify chopper performance, so we measured the standard deviation of the chopper arrival at top-dead-center (TDC) with respect to the timing-reference pulse. Analogously we define this metric as the chopper-tracking sigma. Figure 3 illustrates both the accelerator-tracking and the chopper-tracking intervals.

As a function of increasing accelerator-tracking sigma, we expect the chopper-tracking sigma to decrease. To understand this, realize that increasing accelerator-tracking sigma allows the timing-reference phase to wander further from the grid phase thereby averaging out some of the high-frequency variations of the grid. Thus, the choppers have an easier time following only the slower variations of the grid. In the limit, for large accelerator-tracking sigmas, the timing-reference generator ignores the grid and the choppers run at nearly a constant timing reference frequency, which is the mean grid frequency.

So our goal of performing a tradeoff between accelerator and chopper performance becomes one of calculating and then measuring the chopper-tracking sigmas as a function of the accelerator-tracking sigma. Then with this data in hand an accelerator designer can immediately determine the consequence on chopper performance for any choice of accelerator-tracking sigma. Also note that the chopper veto rate can be derived from the chopper-tracking sigma if the veto window is specified and the chopper-tracking time data distribution is Gaussian. Preliminary data suggest an essentially Gaussian distribution.

3. Simulations and measurement

The simulations are performed as a two step process. Using the grid phase-drift data captured earlier, the first step of the process smoothes it subject to the selected parameters, calculates the accelerator-tracking sigma for the smoothing process, and writes out a test vector file. In the second step, this test vector file is used as the timing reference for all the choppers in the test suite. Each chopper and controller responds to an identical stimulus so comparisons between choppers are valid and most importantly repeatable. During the simulations, the chopper-tracking sigma is recorded for each chopper and test vector combination. The results are summarized in Figure 4.

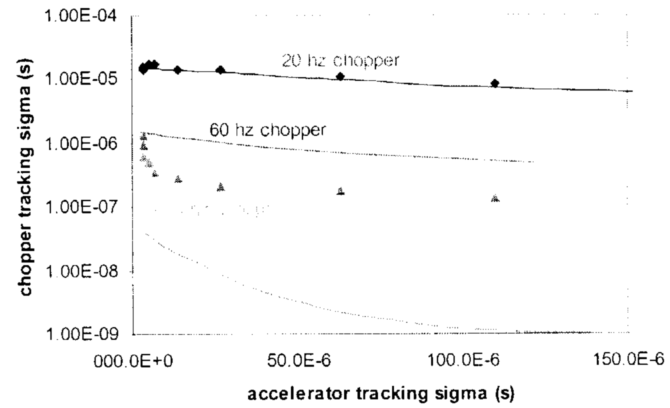

Figure 4. The results of the simulations and measurements. The lines show predictions for the chopper suite. At this time we have data for only the 20-Hz and 600-Hz choppers.

Ideally, all empirical measurements on working choppers would have identical power grid phase and frequency fluctuations. Unfortunately this can not be arranged, so we have to sample the fluctuations and assume they are typical. Since each of our measurements spanned only five minutes, we can improve the statistical correlation of each measurement by extending the measurement time.

4. Discussion

The data from the simulations shown in Figure 4 produce the expected trends. If the timing reference generator smoothes out variations in the grid, then the choppers can follow the smoothed phase drift better. Greater smoothing produces still smaller chopper-tracking sigmas. However, we see diminishing returns as the timing reference generator increases the smoothing, the chopper-tracking sigmas asymptotically approach a value near zero. They will not approach zero because of system noise, quantizing errors, and control circuit internal timing jitter.

The simulations for the 600-Hz chopper produce sigmas that are far too optimistic (<100 ns) in comparison with measured data (200 ns at a accelerator-tracking sigma of 22 μs). While the low-speed models do account for quantization, truncation, and discrete time sampling, the 600-Hz model does not, so it is not surprising that such a small sigma would be underestimated. However this modeling problem is not a serious concern overall since the measured performance of the 600-Hz chopper-tracking sigmas are excellent. At these levels, they make no significant contribution to the resolution of the instruments.

The simulations show that the phase errors for all choppers with identical transfer functions and operating at the same speed are similar in magnitude and that they are coherent. To understand this effect, consider the case where multiple, identical choppers are synchronized to the grid. Now, suppose that the phase of the grid randomly shifts. Initially this leaves the choppers with the same phase error. When they catch up as best they can, the grid moves again and the process repeats itself. Because the choppers have identical response functions and are operating at the same speed, their phase errors are also identical.

Choppers running at different speeds have a somewhat different response. The chopper-tracking sigmas for choppers that operate at different velocities ought to scale in inverse proportion to their velocities. For example the chopper-tracking sigma of a chopper operating at 60 Hz should be one-third the chopper-tracking sigma of a chopper operating at 20 Hz. This trend is seen in Figure 4. But the widely different moments-of-inertia for this chopper suite contribute to the failure of this simple model. The high-speed chopper has a moment-of-inertia of approximately 0.01 kg-m^2 while the moments-of-inertia of the low-speed choppers range from 8 to 12 kg-m^2. The smaller moment-of-inertia of the high-speed chopper allows for much greater chopper bandwidth and thus lower timing jitter.

Since power-grid variations uniformly alter the phase error of choppers running at different speeds and non-uniformly alter the timing errors, then techniques for beam extraction from the storage ring or triggering the accelerator may improve the timing for choppers operating at one speed while degrading the timing at other speeds. Since the chopper-tracking sigmas are smallest for high-speed choppers, such techniques can improve the already high-performance of these choppers without adversely impacting the slower choppers. The inverse is not true. Therefore these techniques are of marginal value unless extreme precision is required. Generally other timing problems (e.g. moderator holdup times) would render this precision meaningless.

5. Conclusions

Low-speed T-zero and frame-overlap choppers present the worst timing-synchronization problems because of their high moment-of-inertia rotors and resultant low intrinsic bandwidth. Often, the question is posed whether or not additional motor torque would help reduce the chopper-tracking sigma. We have verified through models and empirical data that our motors have ample torque. Since motors do not develop their full rated torque instantaneously, they typically do not have a chance to apply more than a small fraction of their rated torque during phase corrections. In other words, more torque will not reduce the timing jitter. The fundamental problem is that of control system bandwidth relating to rotor moment-of-inertia and the loop stability at high gain.

For LANSCE, the current timing-reference controller [3] that gives an accelerator-tracking sigma of 25 μs is good enough. The Lujan Center chopper controllers have improved so much that to obtain another factor of two in the chopper-tracking sigma for the 20-Hz chopper, we would require the accelerator-tracking sigma to increase a factor of four. Current LANSCE accelerator operations will not permit such a large change. Furthermore, we chose to continue operations with an accelerator-tracking sigma of 25 μs, since the chopper-tracking sigmas are well matched to other resolution limiting characteristics of instruments and moderators.

For SNS, an accelerator-tracking sigma of 125 μs is a very good choice. At this value, chopper-tracking sigmas are well matched to other resolution limiting characteristics of the SNS. An accelerator-tracking sigma of 125 μs allows a 20-Hz chopper with a large moment-of-inertia to operate with a chopper-tracking sigma of 7 μs. From the accelerator perspective, operating with this accelerator-tracking sigma allows the timing reference generator to be within ±4 sigma or ±500 μs of the power grid 99.99% of the time.

LANSCE now phases the choppers and the accelerator to a master timing reference generator and has eliminated the complications of ring extraction and beam triggering. However, the accelerator must deliver the beam to the target at a fixed phase. SNS should plan to do likewise.

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