2006-571: A JITTER EDUCATION: AN INTRODUCTION TO JITTER FOR THE FRESHMAN

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A Jitter Education:
An Introduction to Timing Jitter for the Freshman

Abstract

This is the second in a planned series of papers addressing jitter analysis education in the Electrical Engineering Technology (EET) curriculum. The first paper, "A Jitter Education: Finding a Place for Jitter Analysis in the EET Curriculum," described the basic types of jitter and the underlying causes, jitter measurements and displays (two related but distinctly different topics), and proposed how to incorporate jitter analysis into a four-year EET curriculum. The focus of this installment is how to introduce the subject of timing jitter to a first-year EET student.

The basics of jitter are reviewed briefly: types of jitter, its measurement, how the measurements can be displayed, and the measurement tools. Then, topics are proposed for teaching a first-year student. These topics include

- the difference between jitter and wander,
- the difference between random and deterministic jitter,
- types of deterministic jitter,
- types of jitter measurements, and
- what a digital storage oscilloscope (DSO) is and why it is required for jitter analysis (instead of an older analog oscilloscope).

The amount of material presented is fairly small, intended for insertion into an existing lesson plan (e.g., a few PowerPoint slides). The public web site URL is included, so that the interested reader can download a sample lesson outline and associated PowerPoint slides.

Introduction

For the purpose of this paper, timing jitter is defined as "the phenomenon seen when a digital waveform's transition appears before or after the expected time."[1] When jitter displaces the signal's transition so much that it happens in an adjacent clock cycle, the result is a data error on the bus. Because of the high speeds and compact designs of today's systems, jitter that used to be negligible is now very significant, and can prevent a system from working correctly.[1] Today's designers need the ability to analyze jitter, trace its root cause(s), and mitigate or eliminate the cause(s).

In order to effectively analyze jitter, one must understand its nature, the various measurements, how those measurements can be displayed, and the tools used to do the measurement and display. The first section provides a brief review of these jitter topics. For a more detailed discussion, see the first paper in this series and its source references.[1]

The premise of this series of papers is that it is preferable to teach jitter analysis a little at a time, in several courses, as students progress through their undergraduate curriculum. Given that approach, several topics are appropriate to work into one or more first-year courses, in order to lay a foundation for a more in-depth treatment in later years. The basis for this discussion will be the Electrical and Computer Engineering Technology (ECET) curriculum at Purdue's College of Technology. Jitter analysis fits within Purdue's ECET program objective outcome 3.1: Analyze, design, and implement electronic systems using control, communication, computer, or power systems. This background information is described in section two.

Section three is the heart of the paper. It covers the proposed topics and suggests when to teach them to first-year ECET students.

Section four is a short overview of the "roadmap" of topics to teach in subsequent years. These topics will be covered in more depth by later papers.

The conclusion gives a brief recap of the proposed subjects to be taught in a first-year curriculum, along with the web URL where interested parties may download sample instructional materials.

Jitter Basics

There are two broad categories of jitter: random and deterministic. Random jitter (RJ) has a gaussian distribution with respect to time and is, therefore, unbounded. Some level of random jitter will always be present in a real system. Deterministic jitter (DJ), which has a bounded probability distribution, has several subcategories, and is generally caused by events over which the designer has at least some control. Examples of DJ include duty cycle distortion, periodic jitter, and intersymbol interference, each with its own root cause(s). The key to controlling these causal events is to first isolate the different types of jitter and trace each back to its source.

There are three primary jitter measurements.[2] Period jitter measures the time of each cycle in a waveform (not the same as periodic jitter, which is a type of jitter, not a measurement). Cycle-cycle jitter is the period difference between two adjacent clock cycles. Finally, time interval error (TIE) is the difference between the ideal and actual transitions of a signal.

Jitter can be displayed in several different ways. The histogram is a familiar technique for those wishing to view it as a probability distribution function. The trend waveform is a plot of jitter magnitude versus time. When displayed on the same plot with waveforms of interest, it can be used to correlate waveform events with jitter characteristics occurring at the same points in time. A third technique for viewing jitter measurements is the spectral display, which plots jitter magnitude on the vertical axis vs. frequency on the horizontal axis (i.e., a Fourier transform). It can be very useful for identifying sources of interference at known frequencies, such as a clock or high speed bus. A fourth method is the eye diagram, which is a great pictorial to show the size of a bus's data valid window, in both voltage and time. Finally, the bathtub curve, produced by a bit error ratio tester (BERT), is an indirect way of characterizing jitter.

Tools that can be used to measure timing jitter include the real time oscilloscope, sampling oscilloscope, logic analyzer, time interval analyzer, phase noise analyzer, and bit error ratio tester. The real time oscilloscope is by far the most ubiquitous of these, in both industry and academia, because of its general purpose utility and relatively low cost. Moreover, its frequent use by (Purdue) freshmen and sophomore ECET students makes it the perfect basis for introducing early concepts of jitter analysis.

Purdue ECET Freshman Digital Sequence

The first two years of Purdue's ECET plan of study includes a sequence of four analog electronics courses that runs in parallel with a sequence of three digital electronics courses. A first-semester student following this plan of study has two three-hour labs each week: one for the analog course and one for the digital course. The real-time oscilloscope is used in each course, so the freshman student has a reasonable understanding of how to use one by the end of the first semester.

The first digital electronics course covers such subjects as numbering systems, combinational logic, simple sequential logic, circuit construction, testing, troubleshooting, and an introduction to a hardware description language and programmable logic devices. A student exiting this course should have a basic understanding of digital waveforms, positive- and negative-going transitions, and simple timing issues.

Among the topics in the second-semester digital electronics course is an introduction to the digital storage oscilloscope (DSO), including the subjects of sampling and aliasing. After covering these topics, the freshman ECET student is ready to learn a few of the basics of timing jitter, which will build a foundation for more in-depth coverage in later courses.

Jitter Topics for Freshmen

The logical place to begin the discussion of jitter is with its definition (variation of a transition from its expected time), which is easy to understand in the context of a digital timing waveform. A related topic worth mentioning at the outset is wander, which could be described as "slow" jitter. It is possible for the timing of some systems to drift slowly over time, which is called wander. The cutoff to separate jitter from wander is 10 Hz. Time variations greater than 10 Hz are considered jitter, while variations of less than 10 Hz are defined to be wander.[3]

The next step is to explain the difference between random and deterministic jitter (RJ and DJ). At this point, it is not important to understand the statistical concepts of variance, standard deviation, probability distribution function, etc. One can intuitively understand the difference between an event that is random and one that is deterministic. The latter is the type of jitter over which the designer generally has more control, which is not a difficult concept to grasp. For the first-year student, these concepts are enough.

Once DJ has been introduced, the stage is set to introduce its different types: duty cycle distortion (DCD), intersymbol interference (ISI), and periodic jitter (PJ). The key to understanding each type is its underlying cause(s). Although these topics will be reviewed again later in the curriculum for the purpose of reinforcement, the Purdue freshman, at this point, already has the foundation in place to comprehend DCD, ISI, and PJ.

DCD can be caused by an incorrect threshold voltage or asymmetric edge rates. Threshold voltages are covered in both the analog and digital sequences. Op amp comparators are analyzed in the first-semester analog course, including trip voltages. Integrated-circuit logic families are covered in the second-semester digital course (a few weeks before jitter). This includes high- and low-level input and output voltage specifications. Likewise, rise and fall times are also covered in both the analog and digital sequences. So, the student is ready to comprehend DCD.

ISI is caused by bandwidth limitations on the transmitting medium (e.g., a copper trace on a printed circuit board). Although frequency filtering, frequency spectrum, and radio frequency transmission are not covered during the first-year curriculum, they are not required to grasp ISI, because capacitance and inductance are taught in the first-year analog electronics courses. An understanding of RC and RL switching circuits is a sufficient framework. Indeed, teaching ISI provides a link between RC and RL switching theory and real world application, a key motivating factor for most students that serves to improve retention and reinforce the previous material.

PJ is caused by electromagnetic interference (EMI). Electromagnetic fields are discussed early in the second-semester analog course when teaching inductance and transformers. With this background, it only takes a small amount of instruction to explain how two fields can interfere with each other and create periodic jitter on an electronic bus.

The introduction to jitter would not be complete without discussion of the different ways to measure it. The three basic jitter measurements are period jitter, cycle-cycle jitter, and time interval error.[2] (Note the distinction between periodic jitter, which is a type of jitter, and period jitter, which is a jitter measurement.) The essence of each can be clearly taught using a sample waveform.

Figure 1 shows seven cycles of a signal based on a 10-MHz clock, the period of each cycle, and the peak-peak period jitter calculation for this waveform. Although other statistical calculations can be done (average, rms, variance, standard deviation), they are not appropriate for most freshman students, and will be saved for future courses. This figure and a couple minutes of explanation are sufficient to describe the period jitter measurement to a first-year student.

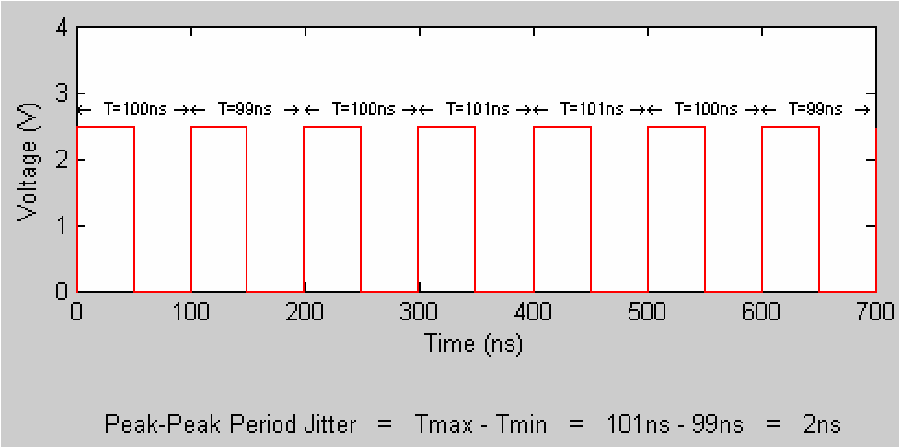

Figure 1: Period Jitter Measurement

Figure 2 shows the same seven-cycle waveform and period measurements as Figure 1, but with cycle-cycle jitter (CCJ) calculations. The CCJ calculation is very straightforward:

$$CCJ_n = T_n - T_{n-1}.$$

There is a closely related measurement called N-cycle jitter that measures the jitter between nonadjacent clock cycles. For instance, 2-cycle jitter would be calculated as $2CJ_n = T_n - T_{n-2}$; 3-cycle jitter is $3CJ_n = T_n - T_{n-3}$; etc. One should probably mention that further statistical computations are appropriate on CCJ and N-cycle jitter measurements, but an in-depth treatment is not possible at this point.

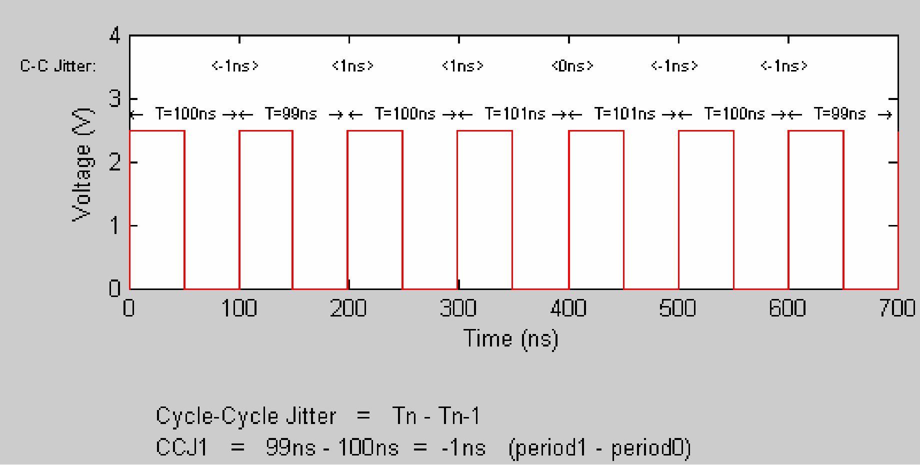

Figure 2: Cycle-Cycle Jitter Measurement.

The third jitter measurement is called time interval error (TIE). The key difference with TIE is a comparison to an ideal clock, which implies some sort of clock recovery mechanism. While clock recovery techniques are well beyond the typical first-year student, the concept of an ideal clock is very intuitive, and is sufficient for a simple understanding of TIE. Figure 3 shows the same signal waveform as Figures 1 and 2, with the addition of the 10-MHz recovered clock waveform and the time, relative to the start of the trace, of the transitions. It is this point that is most relevant here, because one of the prime values of TIE is that it shows the <u>cumulative</u> effect of jitter, which is not possible with period jitter and cycle-cycle jitter measurements. Also, along with the recovered clock waveform, it would be reasonable to define unit interval.

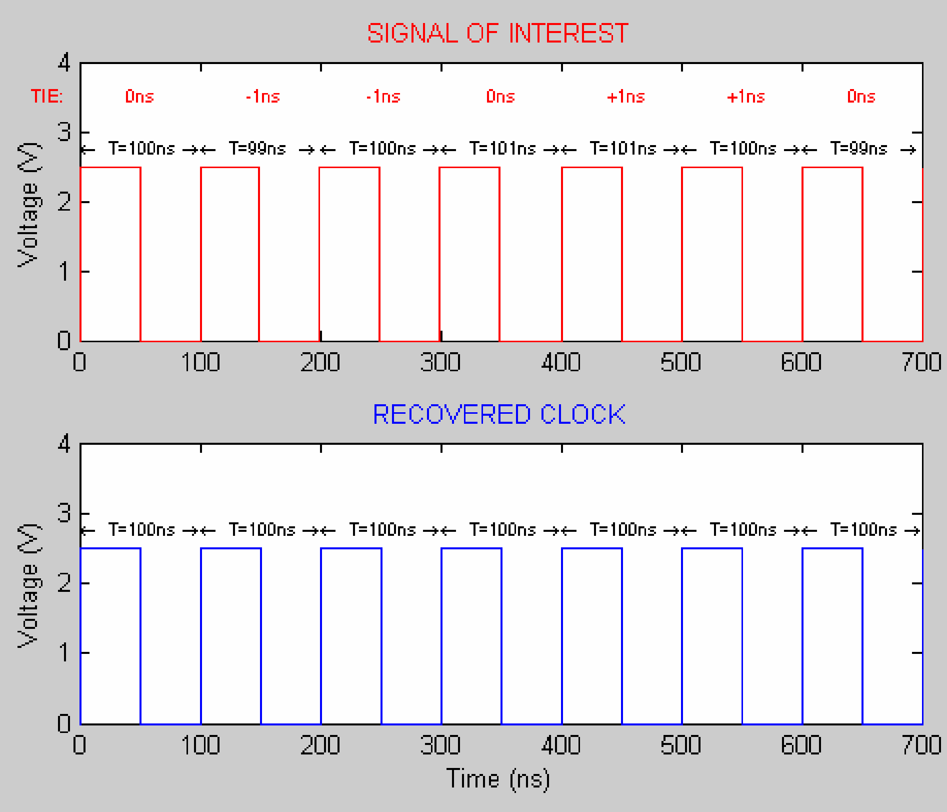

Figure 3: Time Interval Error

That wraps up the topics about jitter itself, but there is one more related subject that should be covered here: the utility of a digital storage oscilloscope (DSO). Timing jitter is characterized with statistics, which means fairly large data sets are required for analysis. DSOs are perfect for this role because they capture data that can be downloaded and analyzed. In many cases today, they do the analysis as they capture the data. Since the concept of sampling has already been covered, this is the right time to discuss what a DSO is and why its capture and storage capability is critical to jitter analysis.

Jitter Topics for Later Years

The subject matter listed above is merely an introduction to jitter, but it lays a foundation for a more thorough understanding. The ultimate goal is the ability to analyze and troubleshoot jitter, so that the graduating engineer can trace jitter to its root cause(s), eliminate or mitigate it (them), and thereby improve the performance of the overall system. Subsequent topics to be covered include the benefit(s) of bus encoding, other test instruments that can be used to measure timing jitter, the probability and statistics necessary to characterize it, the ways to display it and benefits of each, DSO-based jitter analysis software, and how to use a DSO to isolate different types of jitter and identify underlying causes.

Conclusion

While timing jitter analysis is a complex subject, several topics are simple enough to introduce to first-year ECET students at Purdue University. These topics include jitter vs. wander, RJ and DJ, the different types of DJ, types of jitter measurements, and why a DSO is so valuable to measure and characterize it. Introducing this material in the first year builds a foundation for success as more challenging subjects are introduced in later years.

As this material is developed, the plan is to post it on a public web site for download by interested instructors. The PowerPoint lesson slides are largely complete as of this writing, and will be followed by sample exam/quiz questions. The web site URL is http://web.ics.purdue.edu/~glhardin/jitter.

Finally, a follow-up paper is planned that will assess how well students grasp the introductory material on jitter analysis, and whether the instructional material should be modified to improve student comprehension.

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[1] Harding, G. L. (2005). A Jitter Education: Finding a Place for Jitter Analysis in the EET Curriculum [CD-ROM]. *2005 Annual Conference Proceedings, American Society for Engineering Education.*
[2] Tektronix, Inc. (2003, October) *Understanding and Characterizing Timing Jitter* (Primer #55W-16146-1).
[3] Kurpis, G., Booth, C., et. al. (1993). *The New IEEE Standard Dictionary of Electrical and Electronics Terms*, (5th edition). New York: The Institute of Electrical and Electronics Engineers, Inc.