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A Fast Pulse Oscilloscope Calibration System

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Abstract ***- A system is described for calibrating high-bandwidth oscilloscopes using pulse signals. The fast pulse oscilloscope calibration system (FPOCS) is to be used to determine the step response parameters for digitizing oscilloscopes having bandwidths of ~20 GHz. The system can provide measurement traceability to standards maintained at the U. S. National Institute of Standards and Technology (NIST). It is comprised of fast electrical step generation hardware, a personal computer (PC) and software, and a reference waveform, i.e., a data file containing an estimate of the step generator output signal. The reference waveform is produced by prior measurement by NIST of the step generator output signal (calibration step signal). When the FPOCS is in use, the calibration step signal is applied to the device under test, which is an oscilloscope sampling channel. The measured step waveform is corrected for timebase errors, then the reference waveform is deconvolved from it. The results are impulse, step, and frequency response estimates, and their associated parameters (e.g., transition duration, transition amplitude, -3 dB bandwidth) and uncertainties. The system and its components are described, and preliminary test results are presented.***

I. INTRODUCTION

A system is being developed to calibrate high-bandwidth equivalent-time digitizing oscilloscopes using pulse signals, to determine oscilloscope performance parameters such as transition duration (risetime) and bandwidth. The system allows calibration of such oscilloscopes at the laboratory of the user, with direct traceability to standards maintained at NIST.

Fast pulse test signals are often used to characterize the dynamic time-domain performance of oscilloscopes, digitizers, and other data acquisition devices [1-4]. If an applied test signal is close to an ideal step, then certain performance parameters of an oscilloscope can be derived from its response to that signal. Such parameters include transition duration, overshoot, settling, etc. [5]. The step response can also be used to determine the oscilloscope frequency response and related frequency-domain parameters: bandwidth, gain flatness, etc [6,7].

The FPOCS will meet requirements for testing high-bandwidth (20 GHz) equivalent-time sampling oscilloscopes. These oscilloscopes typically have one or more sampling heads or plug-ins. Each sampling head has one or two sampling channels. The testing will determine transition duration and other dynamic parameters of the sampling channels.

The FPOCS includes fast electrical step generation hardware, that produces the calibration step signal used to test the sampling channels. The hardware is also the transfer standard that provides direct measurement traceability [8] of pulse parameter estimates to NIST [9] (or possibly to another standards laboratory, e.g., [10]).

Other researchers have described pulse measurement systems that include correction of timebase errors, deconvolution, etc. [2,11]. The key features of FPOCS include: (i) hardware capable of creating step signals having short transition duration, low jitter, and sufficient stability to be used as a transfer standard between the user and NIST; (ii) novel parameter estimation, timebase correction, and deconvolution algorithms; and (iii) analyses of parameter uncertainties.

II. ARCHITECTURE

A. Hardware

The FPOCS step generation hardware consists of a precision step generator, a trigger generator, a delay

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network, an attenuator, and cables. The components are all commercially available, and were selected to meet the triggering requirements of the precision step generator, to provide stability and flexibility, and to minimize jitter [12]. The step generation hardware serves as the transfer standard to provide traceability to standards at NIST. It will be sent to NIST periodically for measurement [2,9]. NIST will return the step generation hardware to the customer with a reference waveform (a data file containing the NIST discrete-time estimate of the calibration step signal).

Figure 1 shows a schematic of the FPOCS hardware setup for step response tests. The trigger generator creates a square wave having a 150 ps transition duration and variable repetition rate and duty cycle. The repetition rate used here is 100 kHz, with 50% duty cycle. The trigger generator output is connected to the delay line input. The delay line has two outputs; one output is connected, via an attenuator, to the trigger input of the oscilloscope under test. The attenuator is needed to reduce the amplitude of that signal to within the range allowable for the oscilloscope trigger input. The other delay line output, which is delayed by 56 ns relative to the first output, is connected to the trigger input of the precision step generator. The precision step generator produces the calibration step signal, that has 0.25 V amplitude, 10%-90% transition duration of ~15 ps, low short-term jitter (σ < 1.2 ps) and good settling and stability characteristics. The step generator has a remote head attached by an umbilical to its main unit. The remote head and umbilical allow the calibration step signal to be applied directly to the input of the oscilloscope (sampling channel) under test, without intervening cables that would degrade the signal.

For timebase characterization, the sinewave test hardware consists of a stable microwave synthesizer, a microwave power splitter, optional attenuators, and low-loss cables. The synthesizer output is connected to the power splitter input. One power splitter output is connected to the oscilloscope sampling channel, possibly via attenuators to avoid overvoltages. The other splitter output is connected to the oscilloscope trigger input. In this setup, the sinewave frequency is limited by the maximum input frequency of the oscilloscope trigger (e.g., 10 GHz).

B. Software

The FPOCS software is menu-driven. The graphical user interface allows the user to navigate the tree-like menu structure simply by pointing and clicking. The major software menus correspond to the major tasks required for pulse calibration of oscilloscope sampling channels: setup, data acquisition, timebase characterization, deconvolution, parameter estimation, etc. Help menus can be called up by the user, providing documentation and guidance. Measurement data and other data are stored in formatted ASCII data files. The data files include extensive header and footer information about the data and about the hardware setup at the time of acquisition, to allow easy reference and archiving.

The FPOCS software was developed using a commercial graphical software application. It requires a PC-compatible microcomputer with at least 24 megabytes of RAM, 1024x768 video resolution, and an IEEE-488 bus interface.

III. USE OF THE FPOCS

A. Setup and Data Acquisition

The primary task of the data acquisition menu is to acquire measurements of the calibration step signal, so as to characterize the oscilloscope sampling channel, but it can

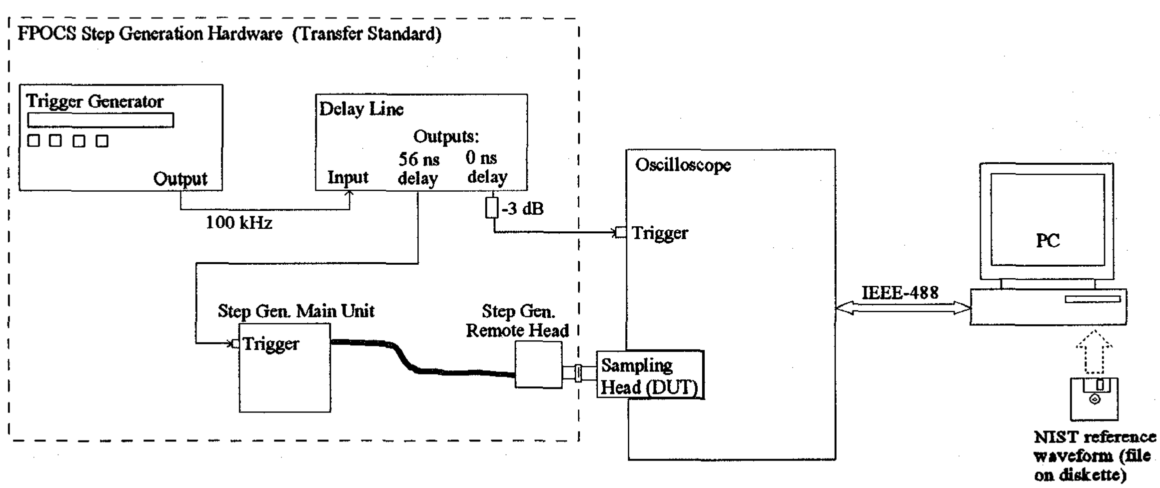

Fig. 1. Hardware setup for step response testing.

also be used for general waveform acqusition. To measure the response of the oscilloscope sampling channel to the calibration step signal, the user connects the hardware and the oscilloscope as instructed by the software help menus, and as shown in Fig. 1. For calibration data, a waveform epoch of 2.048 ns is used, with a record length of 1024 samples. This epoch is a tradeoff between sample resolution and duration of the time epoch. To apply the waveform deconvolution algorithm (Sec. III.D) properly, the time epoch must be sufficiently long for essentially complete settling of the waveform at its ends [13].

The oscilloscope samples the calibration step signal, and multiple acquired waveforms are averaged. The resulting waveform is transferred via IEEE-488 bus to the PC. To minimize timebase drift, the user should immediately characterize the oscilloscope timebase at the settings used to acquire the waveform (Sec. III.C). The waveform pulse parameters are determined as described below. Finally, the waveform is stored in an annotated ASCII data file.

B. Pulse Parameter Calculation

The software uses a newly-developed histogramming method [14] to calculate the state levels for step-like waveforms. This histogramming method adaptively determines the number of histogram bins to use, so as to jointly optimize both resolution (bin width) and statistical accuracy (the number of counts per bin). From the determined state levels, the software calculates pulse parameters, such as transition duration, according to the definitions in IEEE standards [5,15]. Transition duration is calculated using linear interpolation between sample points. Undershoot and overshoot are calculated from the waveform local minimum and maximum, respectively.

C. Timebase Characterization and Correction

The timebase of the oscilloscope is naturally imperfect, resulting in data samples that are not taken at exactly the nominal times, and thus a measured waveform that is nonlinearly distorted [16,17]. For proper sampling channel characterization, timebase errors should be corrected. Transition duration estimates are particularly susceptible to timebase errors [18]. It is also good practice to correct the data as much as possible, particularly before applying deconvolution, which can amplify small errors.

To minimize drift problems, the timebase should be characterized just after a calibration step waveform is acquired. The built-in timebase auto-calibration of the oscilloscope, if any, should be used just before data acquisition, to minimize the timebase errors, then turned off during data acquisition and timebase characterization.

Software menus and algorithms are being developed for characterizing the oscilloscope timebase and for correcting the measured waveforms for timebase errors. The FPOCS timebase characterization menu employs an iterated sinefit analysis method [19], in which sinewaves of multiple frequencies and phases are acquired. This analysis method allows separation of errors due to sinewave harmonics from timebase errors. It is the latest in a series of developments in the field of timebase characterization [1,5,16-20].

The algorithm for correcting timebase errors is under development; it will employ a polynomial fit method to interpolate, from the measured waveform and the timebase estimate, what the properly (uniformly) sampled waveform should be. Earlier researchers have also used spline interpolation [11]. The correction method requires careful validation, particularly to show that it can properly correct step-like waveforms.

D. Deconvolution of the reference waveform

To correct for the nonidealities of the calibration step signal, an estimate of it, the reference waveform, is deconvolved (e.g., [2]) from the measured waveform. Assume that the sampling channel under test is a linear time-invariant system followed by an ideal sampler (for now, neglecting noise, jitter, timebase errors, and nonlinearity). Then the measured waveform, $s_m[n]$, is the sampled convolution of the calibration step signal, $s_{cal}(t)$, with the channel impulse response, $h(t)$:

$$s_m[n] = \int_{-\infty}^{+\infty} s_{cal}(nT-\tau)\,h(\tau)\,d\tau, \quad n=0,1,2,..,N-1 \qquad (1)$$

where T is the nominal sampling interval (e.g., 2 ps) and N is the number of samples (e.g., 1024). If $s_{cal}(t)$ were an ideal step, $s_m[n]$ would be the true discrete-time (DT) step response of the channel, and it could be used directly to determine the impulse response, frequency response, and the performance parameters of the channel. Since $s_{cal}(t)$ is not an ideal step, we want to undo the convolution of Eq. (1), i.e., deconvolve $s_{cal}(t)$ from $s_m[n]$, to determine $h(t)$. Two key problems with the deconvolution are that (i) $s_{cal}(t)$ is not known by the user, and (ii) a direct deconvolution of Eq. (1) is ill-posed and thus highly sensitive to measurement noise and errors in $s_m[n]$.

The first problem is solved by use of the reference waveform. The reference waveform, $s_r[n]$, is a a sufficiently accurate DT estimate of $s_{cal}(t)$, determined by a prior measurement by NIST of the calibration step signal.
The second problem is solved by employing a deconvolution algorithm that regularizes the solution using a filter, to avoid

excessive noise-induced errors. The FPOCS uses an iterative, model-based algorithm [21,22].

The deconvolution algorithm operates in the frequency domain, using discrete Fourier transforms (DFTs). Like $s_m[n]$, the reference waveform $s_r[n]$ also has N samples, with sample interval T. In order to convert the step-like waveforms $s_m[n]$ and $s_r[n]$ into the frequency domain, they are first forced to be duration limited by extending them with their mirrored versions, following the Nahman-Gans technique [23], to make the 2N-sample extended signals $y_m[n]$ and $y_r[n]$, respectively. The DFTs of these extended signals are $Y_m[k]$ and $Y_r[k]$, respectively.

The main deconvolution equation is then

$$\hat{H}_{ech}[k] = \frac{Y_m[k]}{Y_r[k]} \cdot R[k], \tag{2}$$

where $\hat{H}_{ech}[k]$ is a preliminary result, R[k] is the parametric regularization filter, and k = 0, 1, 2, .., 2N-1. The filter R[k] is iteratively determined to minimize a model-based approximation of the root sum of squares of the estimation error, optimizing the tradeoff between noisy and biased estimates [21,22].

The estimated DT impulse response of the sampling channel, $\hat{h}_{ch}[n]$, is the inverse DFT of $\hat{H}_{ech}[k]$, after the removal of the Nahman-Gans extension. This estimated impulse response is numerically integrated to give the estimated DT step response of the sampling channel, $\hat{s}_{ch}[n]$. The pulse parameter algorithm described above is then used to estimate the channel performance parameters, such as transition duration. The waveforms $\hat{h}_{ch}[n]$ and $\hat{s}_{ch}[n]$ are stored in annotated ASCII data files.

E. Jitter

It has been shown that averaging together of jittered acquisitions of a signal results in a lowpass filtering effect, with the filter impulse response being equal to the probability density function (PDF) of the jitter. If the averaged jitter has a significant filtering effect on a measured waveform, this impulse response can be estimated and deconvolved from the waveform [24].

Our measurements of the jitter of the FPOCS plus that of oscilloscopes under test have shown the combined jitter to to have a probability density function that is approximately Gaussian, with a standard deviation of less than 1.2 ps. Thus the filter that is equivalent to the lowpass filtering of the jitter would have a transition duration of less than 3.1 ps, which when combined with the ~15 ps transition duration of the channel under test, in a root-sum-of-squares sense, is of minor importance (~2%). The filtering effect of the jitter is therefore included in the uncertainties, but is not deconvolved. The effects of the random component of the averaged jitter are determined by statistical means.

F. Frequency Response Calculation

The FPOCS estimates the frequency response of the sampling channel under test from the DFT of its impulse response estimate, or from the DFT of the discrete-time differentiation of its step response estimate. The -3 dB bandwidth of the sampling channel is estimated by interpolation of this DFT.

G. Uncertainties

We are developing sample-by-sample uncertainties for the estimated step and impulse response waveforms (e.g., [25]). A simpler problem is to determine uncertainties for pulse parameters. For example, the most widely used time-domain parameter calculated by the FPOCS is transition duration (TD); a typical estimated value for 10%-90% TD is 15 ps. For 10%-90% TD, given current results, our preliminary values for the major FPOCS uncertainty components evaluated by other than statistical means (i.e., Type B [26]) are as follows:

a. Step generator signal variation and drift: ± 0.5 ps
b. Timebase errors (if uncorrected): ± 1.0 ps
c. Jitter filtering effect: (-0.3 ps, 0.0 ps)
d. NIST reference step waveform: (-1.0 ps, +2.2 ps)
e. FPOCS deconvolution errors: (-1.3 ps, +1.0 ps)
f. Parameter estimation: ±0.2 ps

The (Type A) uncertainties are evaluated by statistical means. Preliminary measurements have provided a typical value for the Type A uncertainties for transition duration:

$$u_A = \frac{0.2 \text{ ps}}{\sqrt{\text{no. of repeated measurements}}} \tag{3}$$

Combining the uncertainties in quadrature (by root sum of squares) gives a combined standard uncertainty of (-2.0 ps, +2.7 ps). Multiplying by a coverage factor of 1.96 gives preliminary expanded uncertainties of approximately (-3.9 ps, +5.3 ps), for a confidence level of 95%. This uncertainty analysis and analyses for other parameter estimates are still in development.

III. PRELIMINARY RESULTS

Tests have been made to validate the performance of the FPOCS system, by comparing its estimates of transition duration to those in the calibration certificates provided by the sampling head manufacturer. FPOCS test results are shown in Fig. 2, for eight sampling channels (of four two-channel sampling heads). Immediately prior to the test, the sampling channel gains and the oscilloscope timebase were calibrated using the built-in calibration features of the oscilloscope. The calibration features were then turned off during the test. The measured waveforms were highly averaged. Corrections for timebase errors were not applied. The tests were made at a temperature of 23° C ± 1° C.

Figure 2 shows that the FPOCS transition duration estimates (solid squares) and manufacturer calibrations (diamonds) agree very well, except those for channel 7. For channel 7, the estimates by FPOCS and by the manufacturer differ by 2.3 ps. The source of the difference has not been determined. The FPOCS positive and negative uncertainties are shown by the hollow squares, and the manufacturer's uncertainties are shown by the hollow triangles.

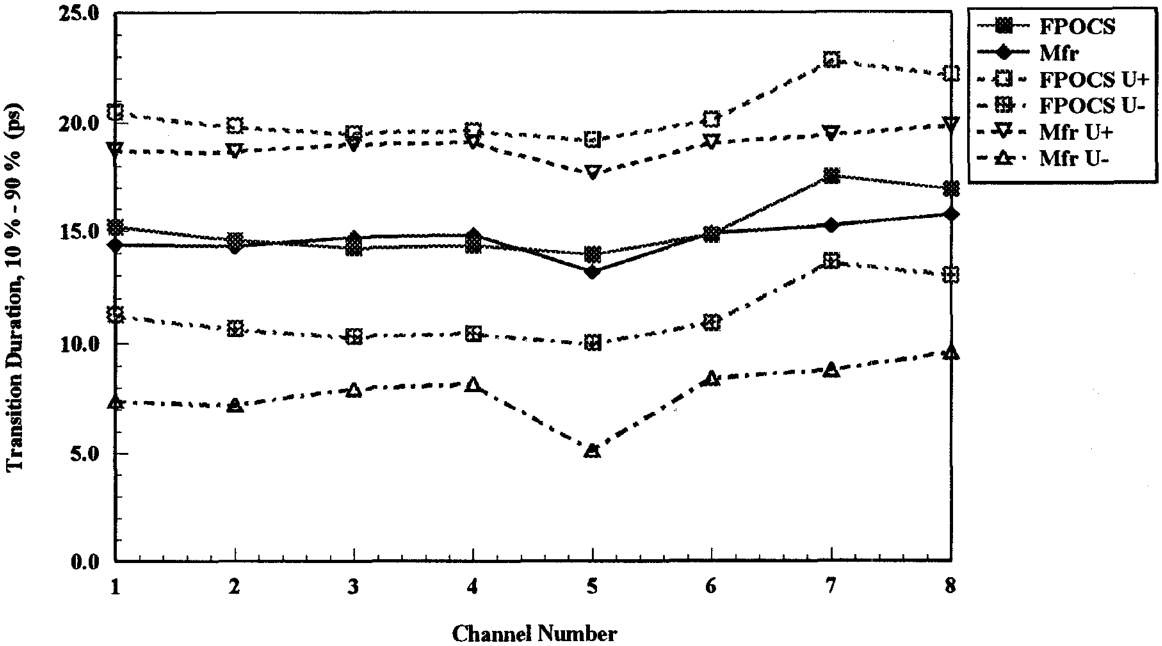

Fig. 2. Preliminary FPOCS test results and uncertainties for transition duration, with manufacturer's calibration results and uncertainties.

IV. CONCLUSIONS

The FPOCS is being developed for providing the traceable calibration of 20-GHz oscilloscope sampling channels using pulse signals. It is PC-based and includes precision step generation hardware, novel algorithms for parameter estimation, timebase correction, reference step deconvolution, and uncertainty analyses. Preliminary tests show good agreement between the FPOCS results and the manufacturer calibrations for 10% - 90% transition duration of oscilloscope sampling channels.

V. ACKNOWLEDGEMENTS

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