MEASUREMENT OF TIME BASE CHARACTERISTICS OF HIGH RESOLUTION DIGITIZERS

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Abstract − The paper is focused on time base frequency measurement of high resolution digitizers with resolution up to 16 bits without an external output of the time base signal.

Keywords: frequency measurement, sine wave fit, zero crossing method.

1. INTRODUCTION

Quality of a digitizer depends not only on a good analogue-to-digital (A/D) converter, but also on the design of other circuits in its measuring system that can affect the process of digitization (sampling and quantization) of an analogue signal. The process of sampling, particularly, depends on the quality of the time base.

Basic characteristics of a real digitizer, such as fractional frequency deviation, frequency stability and phase noise, are evaluated using standard methods of measurement of a sine wave oscillator signal. This requires from the particular digitizer to provide an external output of the signal from its time base. However, most oscilloscopes and cheaper digitizers in the form of USB modules, PCI cards and PXI modules do not have an external connector available. This makes the measurement of their frequency, frequency stability or phase directly via a counter and a frequency etalon unavailable.

The only feasible solution is to sample a reference signal (e.g. a signal from a frequency standard, whose precision and frequency stability are known to be markedly better than those of the time base being evaluated) by standard means, that is to send this reference signal to an analogue input, digitize it and assess the sought values from the measured samples using the techniques of digital signal processing.

Sampling methods of frequency measurement are already theoretically well elaborated. Their deployment in practice, however, requires a certain experience as well as verifying by measurement in the particular conditions.

2. THEORETICAL BACKGROUND

Time base signal can be considered stationary (or quasi-stationary) and having a constant frequency (at least for the time interval of sampling). If this is established, several methods of signal processing in the time or the frequency domains can be utilised to determine the instantaneous frequency.

2.1. Zero crossing method.

This is the basic method of determining frequency (or period) in the time domain. Time interval between two signals with an equal slope (i.e. with the same sign of the signal derivative) crossing zero designates the period of the measured signal. Measurement uncertainty of the instantaneous frequency when using this method depends on the signal distortion, noise and the ratio of the digitizer sampling frequency to the signal frequency.

Several modified versions are used in practice (see [1] to [3]):

Zero crossing with filtration (ZCRF) method utilizes a preliminary digital filtration through a FIR or an IIR low-pass filter, which minimizes the distortion and noise of the real sine wave signal.

Zero crossing with regression (ZCRR) method increases the precision with regression lines (curves in general) near the zero crossings in order to minimize the sine wave signal distortion caused by an additive noise or higher harmonic spectrum components.

Integrated zero crossing (IZC) method, in which the signal is integrated and its expected value is discarded before processing with the ZCR algorithm.

2.2. Best fitting sine wave method

This method is used in dynamic testing of A/D converters and digitizers with a sine wave signal. An ideal sine wave is fitted to the measured samples according to the 'least squares criteria' (i.e. sum of the squares of the deviations of the measured signal and the reconstructed signal is minimal). For details, see IEEE Std 1057-2007 [4] and article [5].

2.3. Spectrum analysis method

The basic method of frequency measurement in the frequency domain is the calculation of frequency spectrum of a sampled periodic signal using the discrete Fourier transform (DFT), in practice using one of the fast Fourier transform (FFT) algorithms. Signal frequency corresponds to the frequency of the fundamental harmonic component of the signal. The method is also used in dynamic testing of A/D converters and digitizers with a sine wave signal. For details, see standard [4], Par. 4.5 Discrete Fourier transform (DFT).

3. ALGORITHMS FOR DETERMINATION OF FREQUENCY OF TIME BASES

Out of the methods mentioned in Chap. 2 only the processing methods in the time domain will be further elaborated. Algorithms used are specified below. Algorithms were deployed in programs written in C and MATLAB languages.

3.1. Zero crossing method.

Two algorithms were chosen for the tests: ZCRR and ZCRF. Signal for the latter algorithm was filtrated using a moving average of d/4 (where d is the number of samples from each period). Both algorithms were programmed as scripts in the MATLAB environment.

3.2. Best fitting sine wave method

Two different algorithms were used for the calculation. The first algorithm is described in the IEEE Std 1057-2007 standard (see [4], Par. 4.6 Sinewave testing and fitting, and Annex A.2 Algorithm for four-parameter least squares fit to sinewave data using matrix operations). Algorithm was programmed in C language.

The second algorithm was implemented in the MATLAB environment using the *nlinfit()* function. Use of this function is illustrated in the following example:

Table 1. Use of the function *nlinfit()* for sine wave fitting.

```
function [Parameters] = sine_fit(t, x, InitialParameters)

% 4-parameter sine fit with initial parameters option
%
% Syntax:
% [Parameters] = sine_fit(x, y, [InitialParameters])
%
% struct Parameters = InitialParameters =
%           [Offset, Amplitude, Phase, Frequency]

% Evaluate arguments

InitialParameters = NaN(1,4);
InitialParameters(1) = median(x);
InitialParameters(2) = mean(minmax(x));
InitialParameters(3) = 0;
[tmp,pos]=findpeaks(smooth(x,10));
InitialParameters(4)=1/max(diff(t(pos)));

eval('f =  @(InitialParameters,timeval) InitialParameters(1)
        + InitialParameters(2) * sin( InitialParameters(3)
        + 2*pi* InitialParameters(4) * timeval );')

[Parameters] = nlinfit(t,x,f,InitialParameters);
End
```

4. MEASUREMENT SYSTEM

A block diagram of the system for measuring time base characteristics of digitizers is shown in Fig. 1. At the core of the system is the highly stable and precise rubidium (Rb) frequency standard FS725 (manufactured by Stanford Research Systems) synchronised by the GPS signal with long-term frequency stability in the order of magnitude of 1.10^{-12}. The standard is continuously calibrated with the National time and frequency standard located in the Institute of Photonics and Electronics of the Czech Academy of Sciences. While the nominal output frequency of the Rb generator of 10 MHz is efficient for synchronization of other instruments, it is generally not suitable for digitizer testing. Lower frequencies needed for the test were generated by a HP33120 waveform generator phase synchronised with the Rb generator.
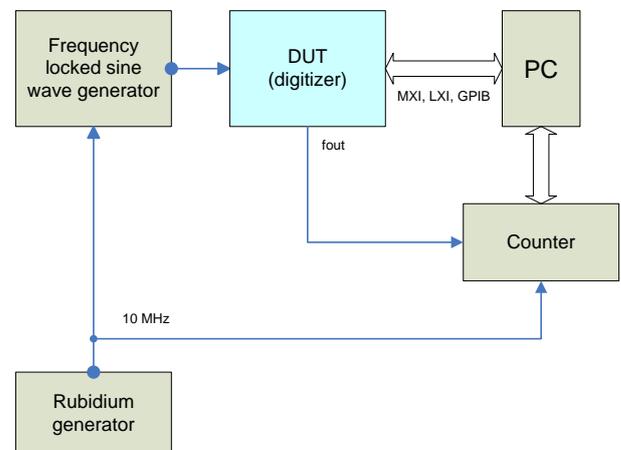

Fig 1. Measurement setup

System is also capable of a direct measurement of the digitizer time base frequency in the case, when the tested digitizer is equipped with an external connector for signal output from an internal oscillator (i.e. timebase oscillator). Direct measurements can be used for a verification of the digital methods. SR620 counter (manufactured by Stanford Research System) was utilised for such measurements.

Software for controlling the measurement and transferring the data to PC for further processing was designed at Faculty of Electrical Engineering CTU in Prague. Currently available are programs for the measurement of National Instruments PXI digitizers (including PXI-5122 a PXI-5922 models), Agilent LXI digitizer (model L4534A) and TELEDYNE/LECROY oscilloscope (model HDO 6104).

Measured data was processed using the aforementioned algorithms written in C language (in the LabWindows/CVI development environment) and functions and scripts of the MATLAB environment. Documentation in the form of M-Files can be found in App. 1 of the research report [6].

5. MEASUREMENT RESULTS

Testing measurements were carried out on a National Instruments PXI-5122 digitizer (14-bit resolution, Fig 2), an Agilent L4534A digitizer (16-bit resolution) and on a model HDO6104 TELEDYNE/LECROY oscilloscope (12-bit resolution, Fig 3). In all cases, an external output for a direct time base frequency measurement was also available. Values acquired directly were used for a comparison with the results of measurements of sampling methods described in Par. 2 and 3. Complete results can be found in App. 2 of the report [6].
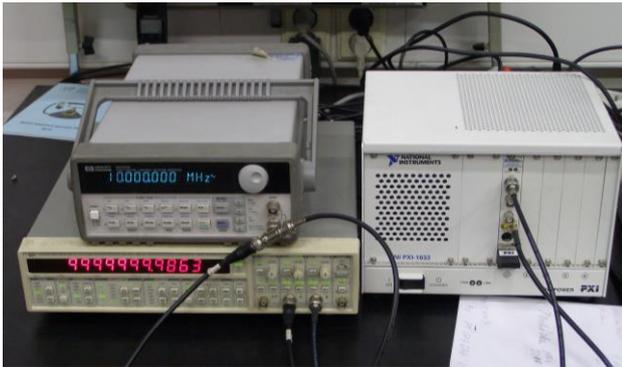

Fig 2. System for measurement of PXI digitizers

Test signal frequency f_{IN} was selected from the range of 1 to 101 kHz, sampling speed was set to 10 MSa/s and total number of samples was 1 MSa.

For the PXI-5122 module the directly measured value of fractional frequency deviation was -15.10 ppm (Table 1), for the L4534A digitizer the value of -2.02 ppm (Table 2), and for the HDO6104 oscilloscope the value of just -0.07 ppm (Table 3). Measurement uncertainty was lower than 0.001 ppm.
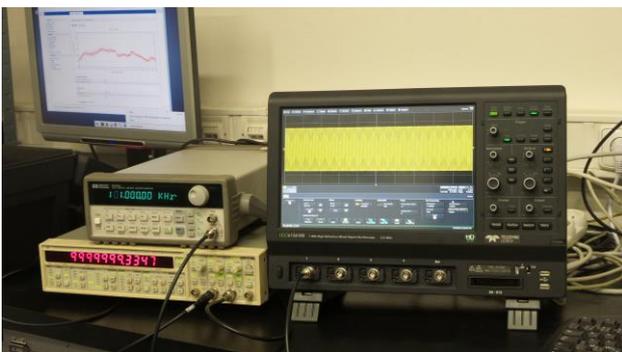

Fig 3. System for measurement of digital oscilloscopes

Extended testing of the individual methods and algorithms was therefore performed on the HDO6104 oscilloscope, as it had proved to have the highest quality time base.

The best results were obtained from the best fitting sine wave method (with both tested algorithms performing equally), where the error of fractional frequency deviation was less than 0.1 ppm. Weaker performance was shown by the ZCR method with moving average filtration, where the error was approximately 0.13 ppm. Significantly worse were the results of the ZCRR method without filtration, where the fractional frequency deviation error reached to 0.5 ppm.

Table 1. Measurement with NI PXI-5122

f_{IN} [kHz]	Fractional Frequency Deviation [ppm]		
	Sine Fit	ZCRF	Counter
1	-15.06	-15.04	-15.10
1.01	-15.07	-15.22	-15.10
3.333	-15.18	-15.21	-15.10
10	-15.10	-15.11	-15.10
10.1	-15.11	-15.12	-15.10
33.333	-15.17	-15.15	-15.10
100	-15.13	-15.12	-15.10
101	-15.15	-15.14	-15.10

Table 2. Measurement with Agilent L4534A

f_{IN} [kHz]	Fractional Frequency Deviation [ppm]		
	Sine Fit	ZCRF	Counter
1	-1.98	-2.72	-2.02
1.01	-2.02	-1.57	-2.02
3.333	-2.01	-2.05	-2.02
10	-2.02	-1.90	-2.02
10.1	-2.03	-2.05	-2.02
33.333	-2.02	-1.87	-2.02
100	-2.02	-1.98	-2.02
101	-2.02	-2.05	-2.02

Table 3. Measurement with TELEDYNE/LECROY HDO6104

f_{IN} [kHz]	Fractional Frequency Deviation [ppm]		
	Sine Fit	ZCRF	Counter
1	-0.10	3.44	-0.07
1.01	0.03	-0.20	-0.07
3.333	-0.03	0.08	-0.07
10	-0.10	-0.02	-0.07
10.1	-0.09	-0.24	-0.07
33.333	-0.10	-0.20	-0.07
100	-0.12	-0.16	-0.07
101	-0.05	-0.11	-0.07

Comment:

Results were acquired using a statistical processing of repeated measurements in accordance with the requirements stated in [4] and [5]. That applies to e.g. optimal choice of test input signal frequency, digitizer sampling frequency and the number of measured samples. Measurement uncertainty may be affected not only by the calculation precision of the algorithms (considering the A/D converter resolution – see [6]), but also by the specific design of the digitizer and its actual technical parameters (aperture uncertainty, number of ENOB bits, or the SNR/SINAD signal-to-noise ratio – see [4] and Fig. 4).
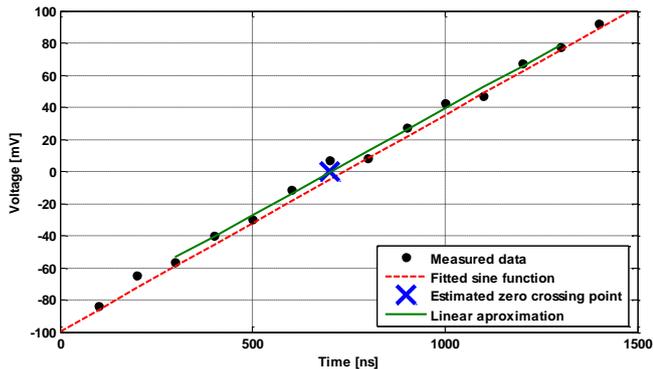

Fig 4. Zero crossing detail, f_{IN} = 3.333 kHz

6. CONCLUSIONS

Based on the measurements carried out, it can be established that the sampling methods are viable for determination of the time base frequency of digitizers without an external output of the time base signal. Best results were measured with the sine wave fit test method. This corroborates the recommendations in the IEEE standard [4].

It was also proved that the attainable measurement accuracy of fractional frequency deviation is in the order of 0.01 ppm (in measurement time interval of 0.1 to 10 s). The method is viable even for measurements of long-term frequency stability for time intervals longer than 100 s.

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