

ACCUMULATED JITTER MEASUREMENT OF STANDARD CLOCK OSCILLATORS

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Abstract

Long term instability of frequency and phase fluctuations of the clock signal are significant source of the measurement error in the precise time-interval measurement systems. In this paper the problem of clock signal instability, fluctuations caused by accumulated clock jitter and their influence on the precision of the time-interval measurement system implemented in the programmable CMOS FPGA devices are discussed. The presented method enables jitter characterization of the reference-clock. Moreover, the time-interval-error in the range up to several milliseconds can be easily and quickly calculated using only two parameters obtained during the calibration process. The described method can be applied in measurement instruments with a precise time-base.

Keywords: time-interval error, jitter, time-interval measuring module, phase fluctuations.

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1. Introduction

High resolution Time Interval Measurement Systems (TIMS) can be applied in experimental physics or telecommunication. The precision of such systems is determined by the standard clock signal. Standard clock phase fluctuations and long-term frequency instability depend on the type of the oscillator and other environmental factors such as: temperature, vibration, supply voltage fluctuation, noise.

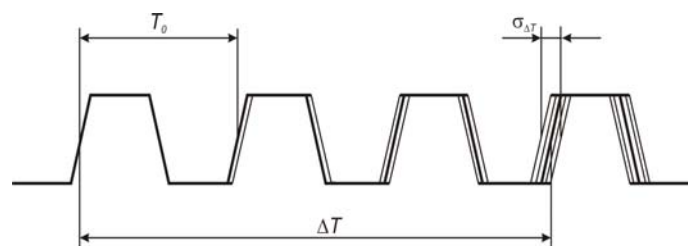


Fig.1. Long-term accumulated clock jitter.

Usually, an oscillator can be characterized by phase noise or jitter [1]. The phase noise is used in the frequency domain and is defined as deviation of the main frequency, while jitter is used in the time domain and is defined as deviations of clock or data signal edges from expected slope lines. Various degrees of correlation occur between following errors of time transition of the clock signal. Long term accumulated jitter is shown in Fig. 1 (in case of deep correlation). This diagram shows main reason of errors in TIMS.

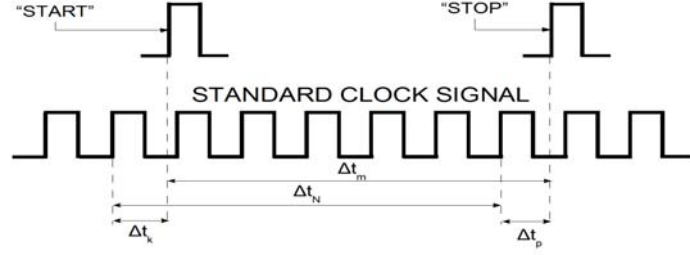


Fig. 2. Time interval measuring method.

A typical diagram of time interval measurement is shown in Fig. 2. This diagram shows that in order to measure the time-interval Δt_m , the measuring module should measure three time intervals:

- Δt_p - between the stop pulse rise transition and clock rise transition,
- Δt_k - between the start pulse rise transition and clock rise transition,
- Δt_N - which consists of the integer number N of standard clock periods ($\Delta t_N = NT_0$).

The result of time-interval measurement will be given as

$$\Delta t_m = \Delta t_N + \Delta t_p - \Delta t_k = \Delta t_p - \Delta t_k + NT_0. \quad (1)$$

The precision of TIMS depends on the precision of interpolators that measure the phase shifts Δt_p and Δt_k , and the accumulated jitter of the clock [2,3] that produces a significant time-interval error TIE [4,5,6]. For this reason the jitter parameters of the clock, which will be employed in the TIMS, are very important [7].

The motivation to this paper was the fact that high resolution TIMS can be used both in clock characterization and in TIE estimation or prediction. Fortunately, this goal can be easily achieved after small modification of a time-interval measurement. First of all, the resolution of the TIMS should be higher than 100 ps and double-pulse resolution should be higher than 10 ns to enable clock characterization up to a frequency of 100 MHz. Moreover, for such application, the TIMS should contain two independent standard oscillators of the same type and frequency. The measurement module adapted in clock characterization is described in section three.

2. Theoretical analysis

Time intervals Δt_N , $N > 0$ between the initial and N -th transition of the oscillator can be treated as a random variable and written as

$$\Delta t_N = NT_0 + \sum_{n=1}^N \varepsilon_n, \quad (2)$$

where ε_n is the fluctuation (random variable) of the n -th oscillator period and T_0 is its nominal value. Assuming that fluctuations have normal distribution, the probability density function of time intervals Δt_N (*pdf*) can be written as

$$pdf(\Delta t_N) = \frac{1}{\sqrt{2\pi}\sigma_{\Delta t_N}} \exp\left(-\frac{(\Delta t_N - NT_0)^2}{2\sigma_{\Delta t_N}^2}\right), \quad (3)$$

where $pdf(\Delta t_N)$ is a Gaussian distribution, $\sigma_{\Delta t_N}$ is a standard deviation of Δt_N . Standard deviation depends on the correlation degree of fluctuations ε_n . When there is no correlation between fluctuations, the time-interval variance of the N -th time interval can be written as

$$\sigma_{\Delta N}^2 = \sigma_{\Delta 1}^2 + \dots + \sigma_{\Delta 1}^2 = N\sigma_{\Delta 1}^2, \quad (4)$$

where $\sigma_{\Delta 1}^2$ is a variance of time-interval that equals T_0 .

When correlation occurs, the standard deviation of N -th time-interval can be written as

$$\sigma_{\Delta N} \leq \sigma_{\Delta 1} + \dots + \sigma_{\Delta 1} = N\sigma_{\Delta 1}. \quad (5)$$

The range of the variance value is given by

$$N\sigma_{\Delta 1}^2 \leq \sigma_{\Delta N}^2 \leq N^2\sigma_{\Delta 1}^2. \quad (6)$$

The time-interval standard deviation strongly depends on the number N of oscillator cycles [4]. The maximum of the probability density function for N oscillator cycles is given by

$$pdf(NT_0) = \frac{1}{\sqrt{2\pi}\sigma_{\Delta N}} = cN^{-a/2}. \quad (7)$$

Parameters a and c enable to estimate a standard deviation $\sigma_{\Delta N}$ as shown below

$$\sigma_{\Delta N} = \frac{N^{a/2}}{c\sqrt{2\pi}}. \quad (8)$$

Parameter a depends on the correlation between oscillator period fluctuations and c depends on period stability. Having obtained these parameters, the standard deviation of TIE for longer time-intervals can be simply extrapolated. It is important because indirect measurements of standard deviation might take a long time and would request a lot of data (time-stamps). The block diagram of the new method which enables measurements of parameters a and c is shown in Fig. 3. The procedure described below can be applied when the standard oscillator variance is not known.

A TIMS measures time intervals between the start pulse rising edge and each rising edges of another oscillator signal. In such way, during a single measurement, the time intervals for all values of N can be collected. After an appropriate number of such measurements it is possible to calculate the standard deviation of each time interval for any value of N . Standard oscillators A1 and A2 are system reference clocks. Standard oscillator A2 is of the same type as main oscillator A1. It has been assumed that both oscillator parameters: frequency and jitter are exactly the same. In practice the frequencies of oscillators A1 and A2 are a little bit different [9]. Oscillator A2 is used only during the calibration process.

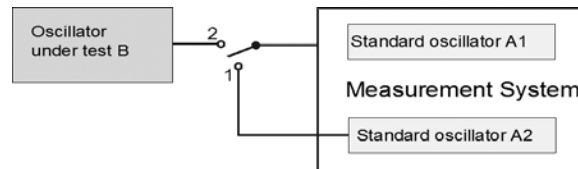


Fig. 3. Steps of the measurement method (calibration).

Two steps of measurements must be done to determine the standard oscillator variance. The first step is to connect oscillator A2 that is built-in measurement system generator to the trigger input (switch in position 1). This step is done for calibration purposes. Standard oscillator A2 has the same parameters as oscillator A1 (standard deviation $\sigma_{A1} = \sigma_{A2}$), so

$$\sigma_{A1} = \frac{1}{\sqrt{2}} \sigma_{A1+A2}, \quad (9)$$

where σ_{A1+A2} is the standard deviation obtained during the calibration process.

The calibration allows to find the parameters of standard oscillator A1. In order to find the standard deviation of external oscillator B (switch in position 2), the following formula can be used

$$\sigma_B = \sqrt{\sigma_{B+A1}^2 - \sigma_{A1}^2}, \quad (10)$$

where σ_{B+A1}^2 is the standard deviation obtained during the test of oscillator B.

It is possible to calculate the standard deviation for any time-interval which consists of B clock periods by using equation (8) and the procedure described above.

3. Time-interval measurement module

The high resolution time interval measurement module (TIMM) implemented in FPGA structure consists of: tapped delay line, data registers, clock counter, code converters, control unit and memory [6]. The block diagram of the TIMM is shown in Fig. 4.

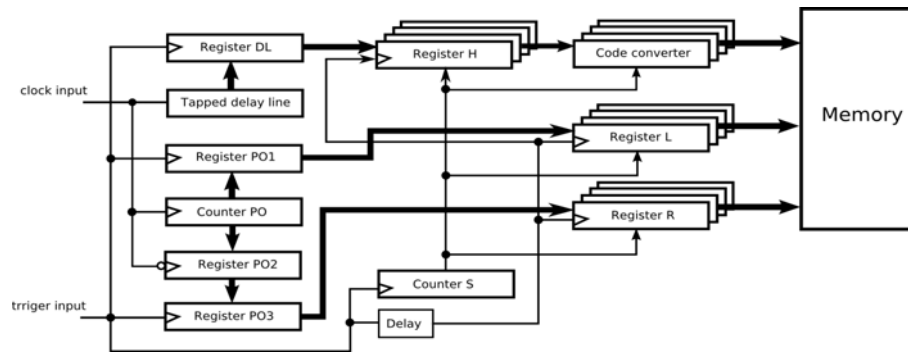


Fig. 4. Block Diagram of the TIMM implemented inside the FPGA structure.

In this system, time-intervals between the trigger pulse and each of the clock transitions applied to the input are precisely measured using tapped delay lines and are collected in the memory. A number of standard clock periods N between two events is measured using one pair of Counter PO and Register PO2. These elements work alternatively because each of them needs some time (in this case about 2 ns) to settle the output data after increment. PO1 and PO3 are auxiliary registers, where the number of standard clock periods N between two events are stored. The time needed for data conversion is equal to 36 ns but the minimal time between trigger transitions, when a 100 MHz clock signal is fed to the trigger input, is equal to 10 ns. This problem has been solved by increasing the number of code converters to four. Counter S enables to choose an appropriate block.

The double-pulse resolution can be adjusted to 5 ns by increasing the number of blocks. In this way it is possible to collect the time-stamps of oscillator periods even when the oscillator frequency is higher than 100 MHz. This system should have a clock of high stability and a tapped delay line with high resolution. The TIMM can be implemented in a single FPGA regular structure. A tapped delay line with high resolution is implemented in the FPGA device using very fast arithmetical carry connections between slices, which are fine basic elements of the FPGA structure. In this case, the resolution of the tapped delay line is about 70 ps (In

Virtex-II Pro) and, as shown in equation (1), the phase shift can be measured with this resolution.

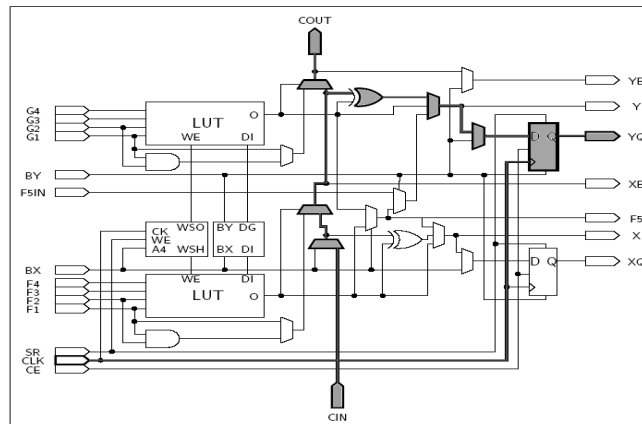


Fig. 5. Using arithmetical carry chain of FPGA slice for single delay element implementation (VIRTEX).

The TIMM resolution can be improved up to 50 ps by using Virtex 4 FPGA device. The diagram of a single delay line element of high resolution TIMM, which is built using a carry chain, is shown in Fig. 5. A similar resolution of the measurement system can be obtained by implementation of time-to-digital converter modules into different FPGA devices [5].

4. Experimental results

The process of the oscillator investigation consists of two steps: calibration and measurement. During the calibration phase, standard oscillators A1 and A2, manufactured by Epson (PC-4395G) are used. These elements operate at frequency of 100 MHz. Successive time intervals have been measured and the results of such measurements are shown in Fig. 6 and Fig. 7.

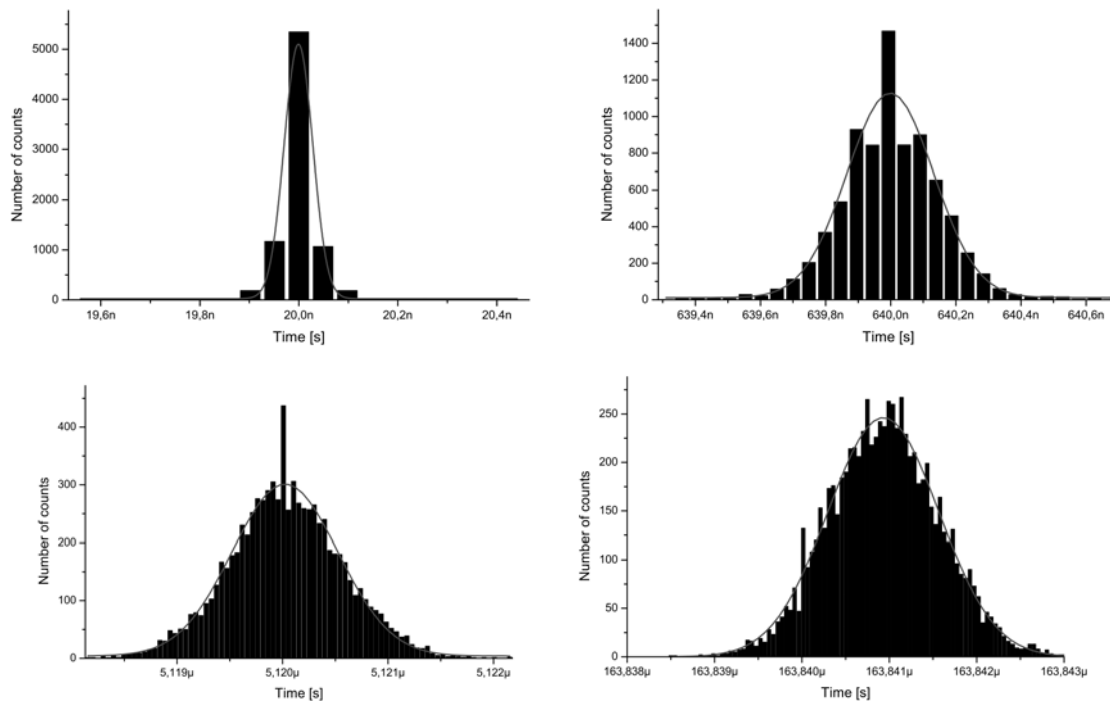


Fig. 6. Histogram of time-intervals fluctuations.

Time-intervals between clock events are measured and the maximal values of the Gaussian function related to each clock event are calculated. The result of such operation is shown in Fig. 7a. Using equation (7) parameters a and c can be obtained.

The histograms of time-interval fluctuations obtained for chosen clock events are shown in Fig. 6. These histograms enable to obtain the characteristic shown in Fig. 7a. Using equation (9), the standard deviation $\sigma_{\Delta TN}$ for any time-interval can be calculated as it is shown in Fig. 7b.

If the signal which is fed to the trigger input of the TIMM comes from a different oscillator than a standard one, the standard deviation of the appropriate time-interval can be calculated using equation (10). The result of such test is shown in Fig. 8. The tested oscillator was manufactured by C-MAC (CFPS-73B) and was of 100 MHz main frequency.

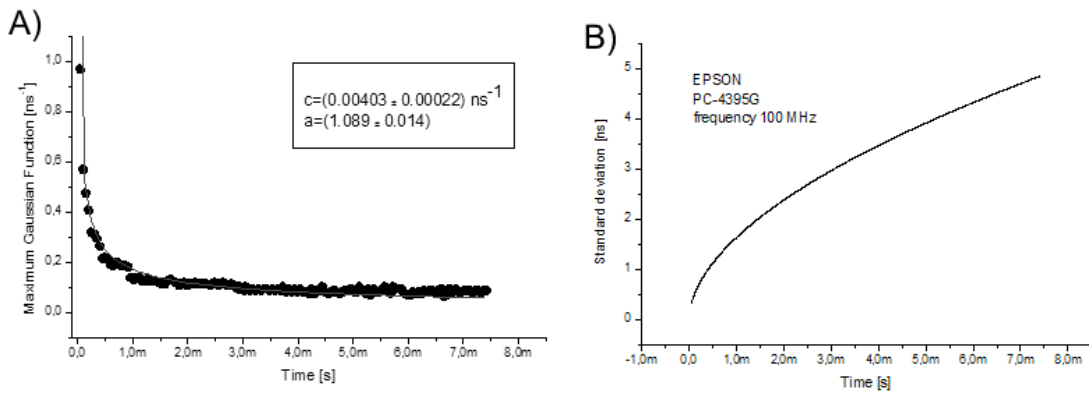


Fig. 7. Results of time interval measurements for the same oscillators: A) maximum Gaussian function with respect to the measured time interval, B) standard deviation with respect to the measured time interval.

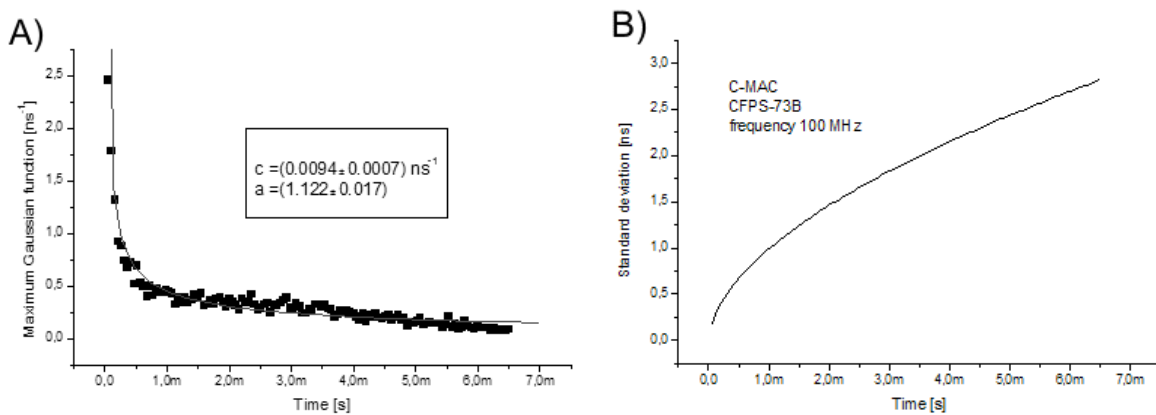


Fig. 8. Results of time interval measurements for different oscillators: A) maximum Gaussian function with respect to the measured time interval, B) standard deviation with respect to the measured time interval.

This model gives good results in the range from several nanoseconds to several milliseconds for the oscillators without a PLL. If the PLL is applied, the range of application will be limited to 200 microseconds. If the range of interest is wide, this system can be also applied but its model will be more complicated [8].

In Fig. 9, there are results of measurements for a PLL clock and the fitting curve. Parameters derived from fitting have the values: $a = 1,29$ and $c = 0,44 \mu s$. The total TIE for

others ranges of time-interval can be estimated by using equation (8). It should be pointed out that phase fluctuations of the reference standard clock built in the TIMS have also an influence on the measured standard deviation. Fortunately, the standard deviation of the reference standard clock can be determined in the calibration process [9].

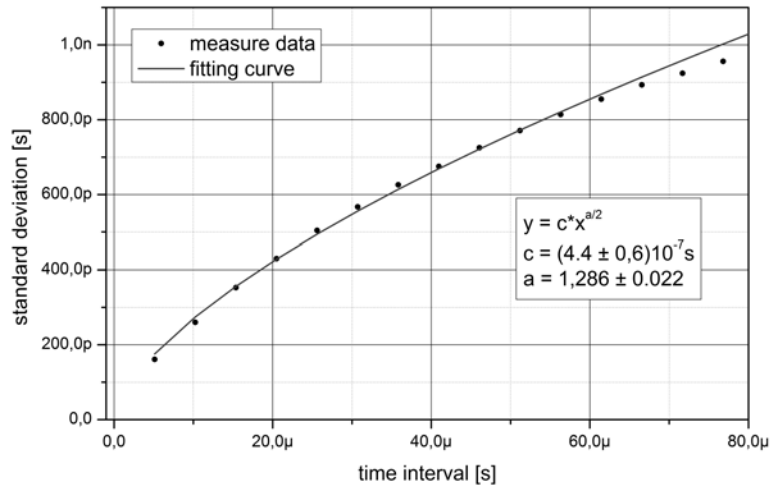


Fig. 9. Standard deviation for a PLL clock oscillator with fitting curve.

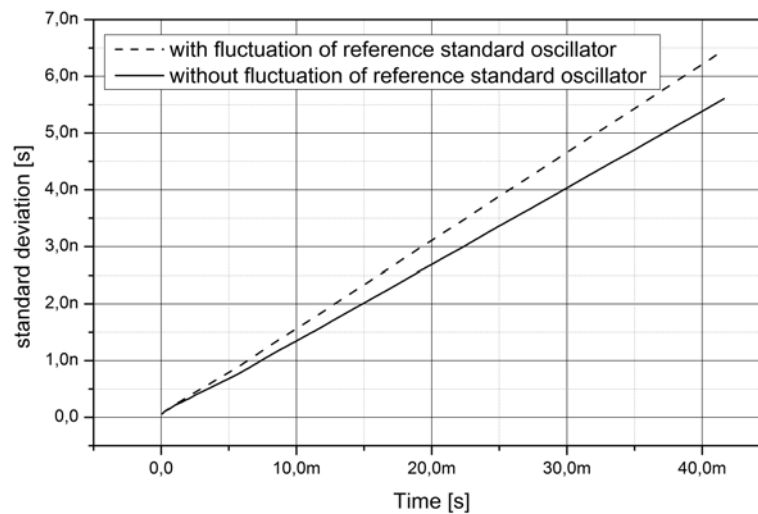


Fig. 10. Standard deviation of the quartz oscillator Jauch 0 100.0-JO75-B-3.3.1.

Standard deviation as function of time obtained using the described TIMS for quartz oscillator Jauch 100MHz is shown in Fig. 10. The characteristic of oscillator standard deviation allow to estimate TIE for any time-interval.

5. Summary and conclusions

Implementation of TIMM in a single FPGA structure allows to improve the resolution, increase the scale of system integration and decrease the influence of external factors. For a short time-interval the range of accumulated phase fluctuations of the clock signal can be described by only two parameters which can be easily measured by the TIMS with high resolution. These parameters enable to estimate the time-interval error caused by the reference clock in many measurement systems with a time-base. The new method of jitter

characterization enables to predict the time-interval-error, which is a very significant parameter for measurement systems, data transmission systems and many other systems where standard oscillator application for time base set-up is necessary. It should be pointed out that only two parameters describe the fluctuations of an oscillator up to several milliseconds. Fortunately, the typical range of the measuring cycle for many systems is similar.

Acknowledgments

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