Error Minimization of Sensor Pulse Signal Delay-Time Measurements

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Abstract – Measurement of delay-time (arrival-time) of pulse signals from various sensors (optical detectors, radiation detectors, etc.) have important applications in many scientific and technical fields. Ultimate goal in all measurements is to determine pulse arrival-time with minimum error, which depends on signal parameters as well as on discriminator circuit parameters.

I. Introduction

Pulse arrival-time measurements are of significant importance in many scientific and technical areas, such as: laser and radar ranging, altimetry and profilometry; optoelectronic distance and dimension measurements; characterization of optical communication and telemetry systems; nuclear spectroscopy and fluorescence life-time spectroscopy, etc.

The measurement chain contains the following parts: sensor (detector), electronic preamplifier of pulse signal from sensor, signal processing circuits, and timing discriminator. Pulse signal from sensor is supposed to be stochastic, i.e. it exhibits amplitude and rise-time statistical variations and it is accompanied with noise. The role of signal preamplifier and processing circuits is to assure maximum signal-to-noise ratio, necessary to achieve minimum timing error depending on applied method of discrimination

Timing discriminator circuits, that are usually used, are based on three basic principles of pulse time discriminations: (1) discrimination on leading-edge of the original signal, (2) discrimination on zero-crossing of constant fraction of transformed signal, and (3) discrimination on zero-crossing of integrated constant fraction of original signal, using step-recovery (charge storage) diode as an almost perfect integrator and charge zero-crossing discriminator (charge-balanced) discriminator. Fig. 1. shows principles of operation of all three discriminators.

Assuming stochastic character of the measuring process, we measure probability distribution function (pdf) of time interval between zero-time reference and moment of starting pulse from timing discriminator, and this time-interval represents pulse arrival-time, in accordance with relation:

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$$T_d^{'} = T_d + T_m \tag{1}$$

where: T_d is true delay-time, T_m is discrimination time and $T_d^{'}$ is measured delay-time. From (1) it follows:

$$\sigma^2_{T_d^{'}} = \sigma^2_{T_d} + \sigma^2_{T_m} \tag{2}$$

If T_d is deterministic, error of pulse delay-time is determined by the error of discrimination time.

From time distribution function we calculate mean value and standard deviation (error) of measured arrival-time. Used measurement instrumentation belongs to class of stochastic time analyzers, originaly introduced in nuclear spectroscopy [1] .

We will analyze the influence of pulse amplitude and rise-time variations, noise effect and energy (charge) sensitivity of discriminator triggering on the over-all timing resolution for three mentioned types of discriminators.

To obtain simple and transparent analytic expressions, usable for comparison of circuit characteristics comparison with adequate accuracy, it is assumed that the pulse signal at the input of timing discriminator has linear rise in time.

II. Timing Error Analysis

A. Influence of Amplitude and Rise-Time Variations

Assuming that the signal at the discriminator input can be expressed as $s(t) = A \cdot x(t)$, where A is the amplitude and $x(t)$ represents its shape, following conditions for discrimination should be satisfied:

$$s(T_m) = A \cdot x(T_m) = d \tag{3}$$

for <u>leading edge discriminator</u>,

$$A\left[f \cdot x(T_m) - x(T_m - t_d)\right] = 0 \tag{4}$$

for <u>constant-fraction discriminator</u>, and

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$$A\int_0^{T_m}[x(t)-k\cdot x(t-t_d)]dt=0 \qquad (5)$$

for charge balanced discriminator,

where: d is a discrimination level, T_m is time point of discrimination, t_d is delay of original signal, f is used fraction of signal used in constant-fraction discriminator, $k=1/f$ is amplification factor of reversed signal used in charge balanced discriminator.

It could be shown from expressions (3) to (5) that, for linear rise of pulse, amplitude and rise-time variations affect only leading-edge discriminator [2, 3]. If these variations are statistically independent, relative timing error is:

$$\left(\frac{\sigma_{T_m}}{T_R}\right)^2=\left(\frac{d}{A}\right)^2\left[\left(\frac{\sigma_{T_R}}{T_R}\right)^2+\left(\frac{\sigma_A}{A}\right)^2\right] \qquad (6)$$

where: T_R is pulse rise-time, and σ_{T_m}, σ_{T_R}, and σ_A, are standard deviations of timing moment, pulse rise-time and pulse amplitude, respectively.

B. Energy (Charge) Sensitivity of Discriminator Triggering

Effect of energy (charge) sensitivity is known in two-state switching circuits. because they need some amount of energy (charge) at the input, to be switched, causing delay of output pulse regarding the time point of ideal discrimination of input pulse.

This effect, however, is not present in charge-balanced discriminator, based on switching properties of step-recovery diode, which stops conducting the current very sharply when the diode extracting charge becomes equal to previously injected one. In this manner diode acts as almost ideal current integrator and charge discriminator [4, 5].

Calculations of timing error of leading-edge discriminator (LED) and constant-fraction discriminator (CFD) are based on Fig. 2. Expression (7) summarizes the results of calculations:

$$\left(\frac{\sigma_{T_m}}{T_R}\right)^2=\frac{\sigma_E}{E} \qquad (7)$$

for both leading-edge and constant fraction discriminators,

where: $E=\frac{A\cdot T_R}{2}$, and $\sigma_E=\frac{\Delta s\cdot\Delta T}{2}\cdot\alpha$.

$\alpha \ll 1$.

Contribution of energy sensitivity of triggering on timing error was omited in many analysis. Expression (7) shows that this effect is important.

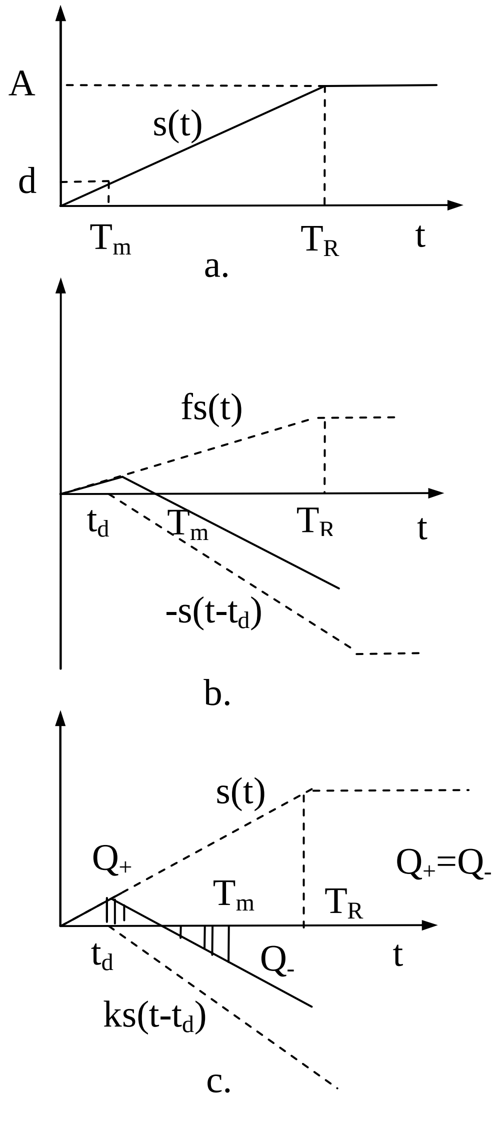

Fig. 1 Principles of timing: a. LED, b. CFD, c. CBD

C. Noise Effect on Timing Error

Analysis of the noise effect was done under assumptions of linear signal leading edge and white Gaussian noise at the discriminator input.

Because the noise from preamplifier is not white, due to the summing effect of series (voltage) noise and parallel (current) noise of the detector-preamplifier circuit, “whitening filter” as the part of optimum, or quasi-optimum filter, was used, so the noise at the discriminator input is white one [6] .

Given the noise standard deviation σ_n, the standard deviation of timing error

$$\sigma_{T_m} = \frac{\sigma_n}{\left| s'(T_m) \right|} \tag{8}$$

where $s'(T_m)$ is first derivative of the signal at the point of time discrimination T_m.

Using expression (8), we can express relative (normalized) standard deviations of timing error for all three discrimination circuits:

$$\frac{\sigma_{T_m}}{T_R} = \frac{\sigma_n}{A} \tag{9}$$

for <u>leading edge discriminator</u> (LED):

$$\frac{\sigma_{T_m}}{T_R} = \frac{\sqrt{1+f^2}}{1-f} \cdot \frac{\sigma_n}{A} \tag{10}$$

for <u>constant-fraction discriminator</u> (CFD), and

$$\frac{\sigma_{T_m}}{T_R} = m \cdot \frac{\sqrt{1+f^2}}{1-f} \cdot \frac{\sigma_n}{A} \tag{11}$$

for <u>charge-balanced discriminator</u> (CBD),

where: σ_n is a variance of white noise at the discriminator input, $m = T_m / T_R$ and $f = 1/k$.

Expressions (5) to (7) and (9) to (11) are basis for estimation of the influence of signal parameters on timing error for different discriminator circuits.

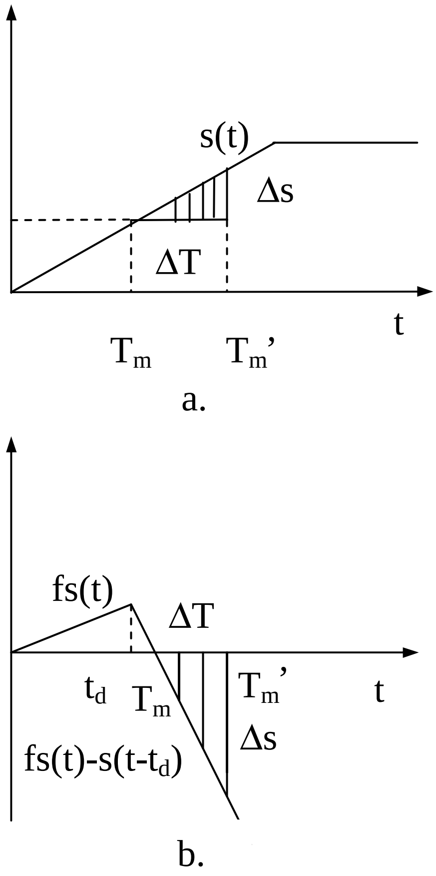

Fig. 2 Energy (charge) sensitivity of triggering

III. DISCUSSION

On the basis of obtained theoretical results quantitative calculation of contribution of all disturbing effects to overall timing error was made using the accessible or estimated data.

TABLE I shows results of estimated relative timing-error (normalized to pulse rise-time) for three discriminator configurations. Parameters of pulse signal and discriminators are chosen as much as close to realistic.

In according to data from TABLE 1 following conclusions could be made:

1. The pulse amplitude and rise-time variation of 1 to 10 percents gives contribution to timing-error in leading-edge discriminator of about 0.1 to 1 percent of pulse rise-time. The influence of charge sensitivity is about order of magnitude higher, as well as the noise effect.
2. Constant-fraction discriminator is not affected by amplitude and rise-time variations, while it shows similar sensitivity on effects of charge-sensitivity and noise. In comparison to LED it is slightly worse regarding noise.

TABLE I

ESTIMATED RELATIVE TIMING ERRORS

$$f = 0.2 \;\; k = 0.5 \;\; m = 0.1 \;\; d/A = 0.1$$

σ_{T_m/T_R}	$\frac{\sigma_A}{A} = \frac{\sigma_{T_R}}{T_R}$ 10^{-2}-10^{-1}	$\frac{\sigma_E}{E}$ 10^{-3}-10^{-2}	$\frac{\sigma_n}{A}$ 10^{-2}-10^{-1}
LED	$1.4 \cdot 10^{-3}$-$1.4 \cdot 10^{-2}$	$3.2 \cdot 10^{-2}$-10^{-1}	10^{-2}-10^{-1}
CFD	0	$3.2 \cdot 10^{-2}$-10^{-1}	$1.3 \cdot 10^{-2}$-$1.3 \cdot 10^{-1}$
CBD	0	0	$1.3 \cdot 10^{-3}$-$1.3 \cdot 10^{-2}$

3. Charge-balanced discriminator is significantly less sensitive on noise than other two discriminators, while it is not sensitive to other parameter variations considered. Results of measurements show that the standard deviation of timing error was 120 ps, 220 ps, and 350 ps for input pulse rise-times of 100 ns, 200 ns and 500 ns, respectively, with amplitude dynamics of 15:1. Calculated relative timing-error was 10^{-3}, which is in good accordance to data from Table 1. Method of measurements was described with more details in [4] and [5].

IV. Conclusion

Results of the analysis of all factors affecting the measurements of pulse delay-time (arrival-time) gives us useful basis for quantitative estimation of influence of signal and discriminator parameters on overall timing-error. It would help in further optimization of methods and circuits to minimize the measurement error, especially in analysis with actual pulse signal shape.

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