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Waveform measurement using synchronous digital averaging: Design principles of accurate instruments

Alexander N. Kalashnikov *

School of Electrical and Electronic Engineering, The University of Nottingham, University Park, Nottingham NG7 2RD, UK

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ABSTRACT

Averaging is frequently employed for waveform measurements in order to reduce the additive noise, but it becomes inaccurate if the averaged records are not coherent. This incoherence can be reduced if the waveform excitations and its acquisitions are clocked from the same source enabling synchronous digital averaging (SDA). Various aspects of an SDA instrument design are discussed in this paper: Architectures that perform averaging "on the fly"; impact of the master clock instability on the remaining incoherence; design of the mixed signal excitation stage; practical limitations on the number of averages, and how remaining incoherence of separate records is reduced as a result of averaging. Theoretical considerations are complemented by experimental results that show good agreement.

1. Introduction

Averaging aims to reduce uncertainty of measurements that are scattered independently around the same true sought-after value by using their mean value. There are various arguments that this value presents "the best estimate of a single number physical quantity, derived from several measurements of equal reliability" [1, p. 27]. Averaging applies to a set of randomly distributed values, x_l, and estimates the true value $\hat{x}$ as

$$\hat{x} = \frac{1}{L}\sum_{l=1}^{L} x_l, \tag{1}$$

where L is the number of measurements available. This estimate is a random variable itself and its variance equals to

$$\mathrm{Var}(\hat{x}) = \mathrm{Var}\left(\sum_{l=1}^{L}\frac{x_l}{L}\right) = \sum_{l=1}^{L}\left(\frac{\sigma}{L}\right)^2 = \frac{\sigma^2}{L} = \frac{\mathrm{Var}(x_i)}{L}. \tag{2}$$

Eq. (2) shows L-fold decrease in the variance of the estimate of the true value (that is related to the measurement uncertainty) compared to any single raw datum.

In many cases separate measurements for averaging can be taken independently and regardless of time (e.g., measurements of a width of a metal bar). On the contrary, waveform measurements require determining signal amplitudes at specific times. Therefore, averaging of waveforms must use repetitive instances of notionally the same waveform.

The acquisition of a single waveform is usually triggered by a comparator when the waveform of interest crosses a particular level.

After the trigger event, analogue oscilloscopes start a ramp pulse for the horizontal deflection of a cathode ray tube's electron beam. The beam is deflected vertically by the waveform of interest. When the ramp pulse ends, the process is repeated, and repetitive beam trajectories form an image that is averaged by the human eye. This image is used for measurements with an accuracy of about 5% at best [2]. This measurement technique is applicable when the signal of interest is produced by a free oscillation circuit, or can be excited at will (as in remote sensing [3]).

* Tel.: +44 115 84 66355; fax: +44 115 9515616.
E-mail address: alexander.kalashnikov@nottingham.ac.uk

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Analogue averaging of a steady signal with additive noise can be implemented by charging storage capacitors at different instants, and averaging their charge by connecting them in parallel [4].

Digital storage oscilloscopes (DSOs) can improve the above accuracy by over an order of magnitude if they employ analogue-to-digital converters of 8 or more bits. After the trigger event, the DSO takes a required number of samples. These samples can be perpetually stored or displayed without a need for the repetition of the waveform, and used for accurate measurements [2]. Averaging in DSOs is used for reduction of the influence of the additive noise, using several, notionally the same, waveforms of interest distorted by incoherent noises [5–7].

As the signal of interest is asynchronous to the DSO's analogue-to-digital converter (ADC) clock, the time interval between the trigger event (when sampling should start ideally) and the following ADC clock (when sampling actually starts) is random within one ADC clock interval. This randomness leads to slight incoherence among the acquired waveforms.

Frame jitter (random displacements of *all* samples in any particular record to the same extent) differs from the timing jitter that is a random shift of any *single* sample in any record due to the ADC clock instability and its aperture jitter [8, Section II]. Fig. 1 shows the effect of the frame jitter on the result of averaging for a sine wave burst (see also Fig. 3 [6]). The adverse effect here increases if the signal frequency increases. It was shown that the variance of the frame jitter itself could be reduced by increasing the sampling frequency that requires more expensive instruments, but a more convenient way to initiate this is to derive the ADC and excitation clocks from the same source [8].

Waveform averaging represents a standard procedure for many applications. For example, ultrasonic non-destructive evaluation (NDE) instruments routinely employ the number of averages in excess of 100–1000 [9].

Synchronous digital averaging (SDA) involves averaging of digital data combined with the synchronous record acquisition. The present paper discusses various aspects of the design of a measurement instrument for synchronous digital averaging including:

- Hardware and software architectures for the instrument (Section 2).
- Practical limitations on the number of averages (Section 2).
- How the timing jitter of the ADC sampling contributes to the remaining frame jitter from both the excitation and the acquisition sides of the instrument (Section 3).
- To what extent this remaining frame jitter is reduced as the result of averaging (Section 3).
- How to design a mixed signal excitation driver to reduce its induced frame jitter (Section 5).

Verifying experimental results are considered in Section 4. Some discussion is presented in Sections 6 and 7 concludes the paper.

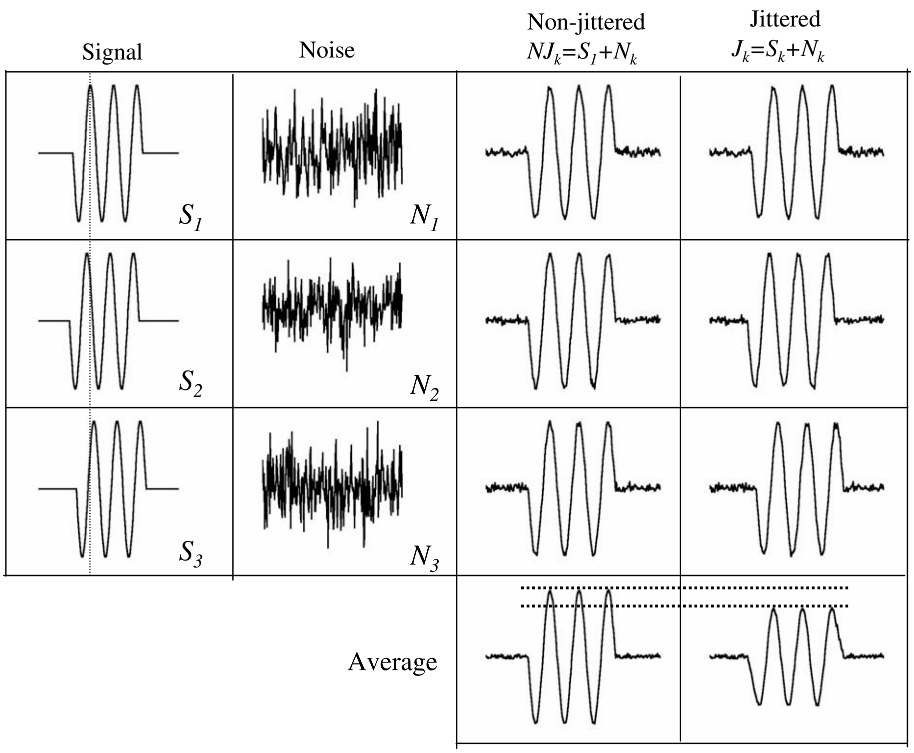

Fig. 1. Illustration of the frame jitter influence on averaging (S_2 and S_3 represent jittered – shifted in the time domain – copies of S_1).