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Spectral and Allan deviation analyses of offset, drift and low-frequency noise cancellation schemes in measurements

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***Abstract*—This work presents an analysis of the noise-shaping effect of offset, drift and low-frequency noise cancellation schemes in measurements. The analysis is carried out in the spectral domain by means of signal processing techniques and the Allan deviation is employed to quantify the achievable resolution or the type A uncertainty component and to compare a number of cancellation schemes.**

***Index Terms*—Measurement uncertainty, noise, 1/f noise, noise shaping**

I. Introduction

When measuring a low-level signal, offsets and drifts affecting the measuring system can significantly bias the measurement result. In addition, low-frequency noise processes with slowly decaying correlations (e.g. $1/f$ noise processes) can fundamentally limit the resolution of the measuring system and the type A measurement uncertainty component. For these reasons, researchers from a variety of fields have developed over the years devices, techniques and measuring schemes that cancel or reduce to acceptable levels the effects of offset, drift and low-frequency noise. Some of these techniques were analyzed in [1], [2] but, to the authors' knowledge, the noise shaping effect has not yet been investigated in a way suitable for metrological purposes and for the prediction of the measurement uncertainty. The purpose of this work is to undertake such an investigation, by means of signal processing techniques and by employing the Allan deviation to quantify the achievable resolution or the type A uncertainty component and to compare different schemes [3]–[5].

II. Theoretical analysis

To eliminate or reduce offset, drift and low-frequency noise, a number of measurement techniques exploit a mechanism similar to that used by lock-in amplifiers [6]: the measurand is first modulated according to a periodic pattern, then processed and finally demodulated. There are several possible modulation patterns; each phase of the modulation is commonly labeled with a symbol. For instance, common patterns are (see e.g. [2]) A0 (e.g. on/off) and AB or ABBA (e.g. with polarity reversal). Intermediate processing typically involves amplification, continuous-time integration (continuous-time moving average), sampling, discrete-time integration (discrete-time moving average), decimation. For instance, Fig. 1 reports the the timing sequence of an AB or A0 pattern: T is the duration of a modulation phase (e.g. the A phase); τ_0 is the integration time; T_S is the sampling period and $\tau_1 = NT_\mathrm{S}$ is the recording time of N averaged samples. Dead times are represented by light colors, whereas integration times are represented by darker colors. The dead time $T - \tau_1$ allows a measuring system to settle after each change in the modulation phase; the dead time $T_\mathrm{S} - \tau_0$ is the time required for the sampling operation.

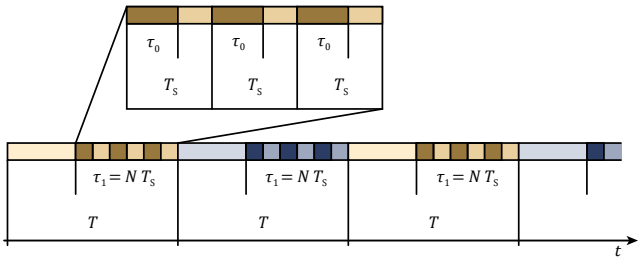


Fig. 1. Example timing sequence required for a two-phase measurement pattern (AB or A0).

The entire process can be rigorously analyzed from a signal processing perspective. In fact, each operation performed on the signal (integration, sampling, and averaging) corresponds to an operation on the signal spectrum.

Let $X(t)$ be the random process representing the modulated measurand, possibly affected by noise, with two-sided spectral density function (power spectrum) $S_X(f)$, $-\infty < f < \infty$. The integration of $X(t)$ over a time τ_0 corresponds to a low-pass filter with power transfer function $|H_1(f)|^2 = \sin^2(\pi f \tau_0)/(\pi f \tau_0)^2$. Sampling, performed with period T_S, results in a periodization of the filtered spectrum with period $1/T_S$. The discrete moving-average over N samples corresponds to a low-pass filter with power transfer function $|H_2(f)|^2 = \sin^2(\pi f T_S N)/(N^2 \sin^2(\pi f T_S))$. The decimation corresponds to a periodization of the spectrum with period $1/(NT_S)$ [7]. The final step consists of demodulation followed by another decimation. Demodulation corresponds to a high-pass filter with power transfer function $|H_3(f)|^2$, whose specific form depends on the modulation pattern employed (e.g. for the AB pattern, $|H_3(f)|^2 = \sin^2(\pi f T)$, for the A0 pattern, $|H_3(f)|^2 = 4\sin^2(\pi f T)$, and for the ABBA pattern, $|H_3(f)|^2 = 4\cos^2(\pi f T)\sin^4(\pi f T)$). It is exactly this high-pass filter that cancels the offset and reduces the drift and the low-frequency noise affecting $X(t)$. The subsequent decimation periodizes the spectrum with period $1/(MT)$, where MT is the period of the modulating pattern. The output

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after the last decimation step is a discrete-time process Y_r, r integer, whose power spectrum can be written as

$$S_Y(f) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} \sum_{k=-\infty}^{+\infty} \left| H_1\left(f - \frac{k}{T_S} + \frac{n}{NT_S} + \frac{m}{MT}\right)\right|^2 \times \left| H_2\left(f + \frac{n}{NT_S} + \frac{m}{MT}\right)\right|^2 \left| H_3\left(f + \frac{m}{MT}\right)\right|^2 \times S_X\left(f - \frac{k}{T_S} + \frac{n}{NT_S} + \frac{m}{MT}\right). \quad (1)$$

This expression allows one to determine the Allan variance of Y_r at the averaging times $\tau_{2,j} = 2^{j-1}MT$, $j = 1, 2, \ldots$, as [8]

$$\sigma_Y^2(\tau_{2,j}) = 2 \int_{-1/(2MT)}^{1/(2MT)} \frac{\sin^4(\pi f 2^{j-1} MT)}{2^{2(j-1)} \sin^2(\pi f MT)} S_Y(f)\, \mathrm{d}f \quad (2)$$

III. Numerical Example

The spectrum $S_X(f)$ can be frequently approximated by a superposition of power-law processes $S_X(f) \approx \sum_\alpha h_\alpha f^\alpha$. As an example of application, let us consider a superposition of white and flicker noise with spectrum $S_X(f) = h_0 + h_{-1}/f$, with $h_0 \approx (10\,\mathrm{nV}/\sqrt{\mathrm{Hz}})^2/2$ and $h_{-1}/h_0 \approx 100\,\mathrm{Hz}$, and a measurement process analogous to the one illustrated in Sec. II, with $T = 20\,\mathrm{s}$, $\tau_0 = 1\,\mathrm{s}$, $T_S = 2\,\mathrm{s}$ and $\tau_1 = 10\,\mathrm{s}$. The chosen values of h_0 and h_{-1} are typical values for the input-referred voltage noise of an operational amplifier. Fig. 2 reports the results of the analysis in the spectral domain: the input spectrum $S_X(f)$ is represented by a solid blue line; the other three dashed lines correspond to $S_Y(f)$ relative to A0, AB and ABBA patterns. The solid lines around the center represent the portions of the spectra between the Nyquist frequencies $-1/(2MT)$ and $1/(2MT)$. The corresponding Allan deviations are shown as solid lines in Fig. 3, together with the one corresponding to $S_X(f)$ (solid blue line). It can be observed that the measurement patterns whiten the noise, allowing the Allan deviation to decrease below the input flicker floor level. The dotted lines in Fig. 3 represent the same operations performed on pure white noise $S_X(f) = h_0$, together with the Allan deviation of the unfiltered white noise $S_X(f)$ (blue dotted trace). On pure white noise, the measurement patterns can introduce a penalty compared to simple averaging and sampling without dead times: a first penalty that raises the spectrum is introduced by the aliasing caused by the sampling with dead times (a factor of two penalty in the example of Fig. 3), and a second penalty of a factor of two is introduced by the A0 pattern due to the statistical cost of this [2].

IV. Conclusions

The analysis briefly summarized herewith shows the noise shaping effect of offset, drift and low-frequency noise cancellation schemes in measurements, and allows one to predict the resolution or the type A uncertainty component in a measurement employing these schemes. This analysis will be completed by considering general modulation patterns and with a validation against experimental results.

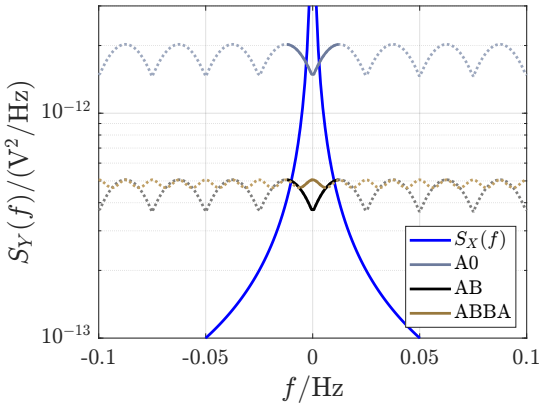


Fig. 2. Example spectra $S_X(f) = h_0 + h_{-1}/f$ and the corresponding $S_Y(f)$ for different modulation patterns, according to the sequence of Fig. 1.

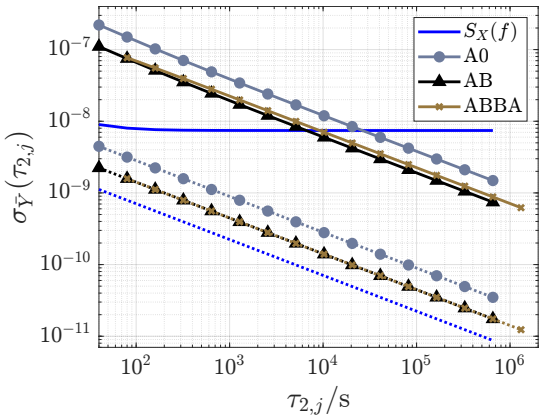


Fig. 3. Allan deviations from $S_X(f)$ as in Fig. 2 (solid lines). Allan deviations from $S_X(f) = h_0$ (dotted lines) with the same measuring patterns, together with the Allan deviation of $S_X(f)$ (blue dotted trace).

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