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Non-Stationary Noise Analysis of Magnetic Sensors using Allan Variance

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The presented paper describes methodology for the non-stationary noise analysis of the magnetic sensors' data using the dynamic Allan variance. The methodology was developed for the characterization of clock behavior. In the article the theory is applied for the magnetic sensors noise analysis and verified by the simulations and experiments. Results of the data analysis are graphically presented and statistically evaluated and prove the correctness of the initial hypothesis and confirm suitability of the dynamic Allan variance approach for magnetic sensors with the non-stationary noise behavior.

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1. Introduction

The Allan variance is a method of analyzing a sequence of the data in the time domain and can also be used to determine the noise types in a system as a function of the averaging time even in cases, which cannot be adequately handled with a classical statistical approach. The Allan variance provides, directly, magnitude versus time separation, which in the form of a log–log plot allows the different noise and drift types to be readily identified by the slopes of the different plot regions. We proved that the theory is very well applicable also for magnetic sensors [1], which become nowadays together with accelerometers and gyroscopes a common part of the inertial measurement units.

However, the Allan variance is the most common time domain measure of the frequency stability and several versions of it that provide for example better statistical confidence or can better distinguish noise types have been developed, there is still a problem with the determination of those output data series, which exhibit non stationary behavior over time, for example due to the interference, disturbances or temperature changes. Therefore during the noise analysis it is necessary to consider the dynamic characteristics and time-varying nature of the noise stability.

2. Theory

The Allan variance (AVAR) provides magnitude versus averaging time which in the form of a 2D log–log plot allows identification of the different noise types by the slopes of the different plot regions [2]. In case of the dynamic Allan variance (DAVAR) that was developed for the characterization of the space clock behavior [3] the observation interval τ and a given time t, the Allan variance σ_A of the sensor output signal marked as x has to be considered and the DAVAR can be calculated as

$$\sigma_A^2(t,\tau) = \frac{1}{2\tau^2(T-2\tau)} \times \int_{t-T/2+\tau}^{t+T/2-\tau} \left(x(t'+\tau) - 2x(t') + x(t'-\tau)\right)^2 \, \mathrm{d}t'. \quad (2.1)$$

The procedure of the DAVAR calculation is therefore based on the sequential analysis of the measured signal in the analysis time point t with the length of the window T. The result of the procedure can be visualized in a 3D plot.

According to the Allan variance analysis, generally there are five main error sources existing in inertial sensors: quantization noise (Q), random walk (N), bias instability (flicker noise) (B), angular rate random walk (K) and ramp noise (R) with the corresponding Allan variances

$$\sigma_T^2(t,\tau) = \sigma_Q^2(t,\tau) + \sigma_N^2(t,\tau) + \sigma_B^2(t,\tau) + \sigma_K^2(t,\tau) + \sigma_R^2(t,\tau). \quad (2.2)$$

The methodology was applied also for gyroscope testing [4], but the noise parameters of these stochastic errors overviewed in Table I can be very effectively used also for the quantification of the magnetic sensors noise.

TABLE I

Stochastic error sources in inertial sensors.

Noise type	Parameter	$\sigma^2(\tau)$
white or quantization noise	Q	$3Q^2/\tau^2$
random walk	N	N^2/τ
bias instability	B	$2B^2 \ln 2/\pi$
rate random walk	K	$K^2\tau/3$
ramp noise	R	$R^2\tau^2/2$

3. Simulations

For the theoretical principles of the DAVAR methodology verification three simulation models consisting of 10^6 samples using the 1 kHz sampling frequency were created. The first model with the simulated sensor output

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x_1 served as the verification model with modeled white noise with the noise amplitude of 2 nT, but without non-stationary processes. The second model with the sensor output marked as x_2 copied the x_1 signal in its first half until the 500 s and then a "step" with the white noise amplitude of 6 nT was modeled. This situation can occur in case of magnetic sensors utilization for example due to the problems with power supply, turning on of electrical appliances or movement of objects made from magnetic materials in the sensor proximity. The third model contained a continuously increasing signal designated as x_3 with the noise amplitude changing in the range from 0 to 2 nT and it can represent for example output sensor signal without the temperature compensation in the environment with increasing temperature.

In Fig. 1 Allan variances σ_A of all three simulated models are visualized in the conventional 2D log–log plots. It can be seen that slopes of the calculated AVAR are in all cases equal to "–1", which corresponds to the simulated white or quantization noise that is dominant in the whole frequency range. The calculated AVAR differs only in the noise parameter amplitude.

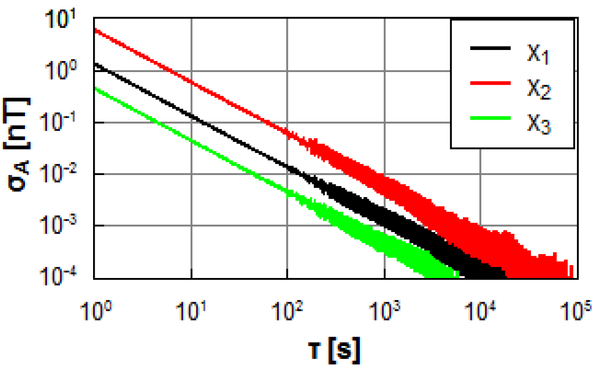

Fig. 1. AVAR calculated for the simulated white noise (x_1), white noise with the "step" (x_2) and with the increasing white noise (x_3).

However, we have no information about the non-stationary processes in the sensor output signal. That is the reason why the DAVAR analysis is reasonable. In Figs. 2–4 results of the three simulated models are shown in the 3D plots.

In Fig. 2 we can see that the slope remains the same in the whole time period as expected and corresponds to the simulated white noise, which refers to the stationary noise behavior and the noise parameter Q is constant. In Fig. 3 the simulated "step" in the middle of the simulated data set after 500 s can be clearly seen. The noise parameter Q in this case also changes its amplitude in the "step" time just according to the simulation. In the third simulated case in Fig. 4 we can see that the magnitude of the DAVAR continuously increases with the time and the noise parameter Q in this case increases linearly.

The simulation results confirmed that the DAVAR methodology is convenient for the time-varying signal analysis and revealing of the non-stationary processes.

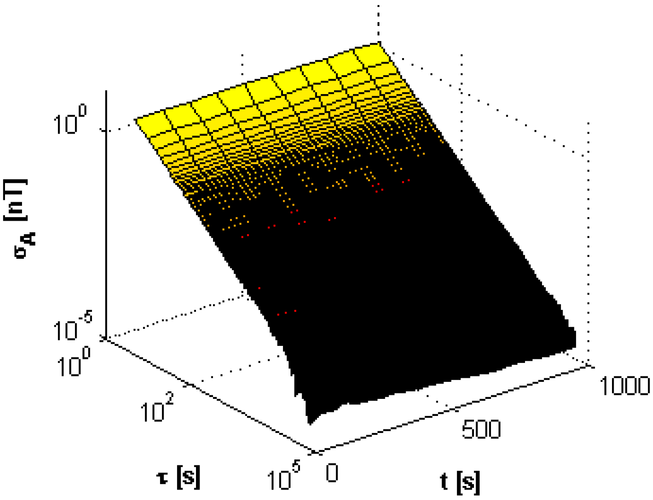

Fig. 2. DAVAR calculated for the simulated white noise (x_1).

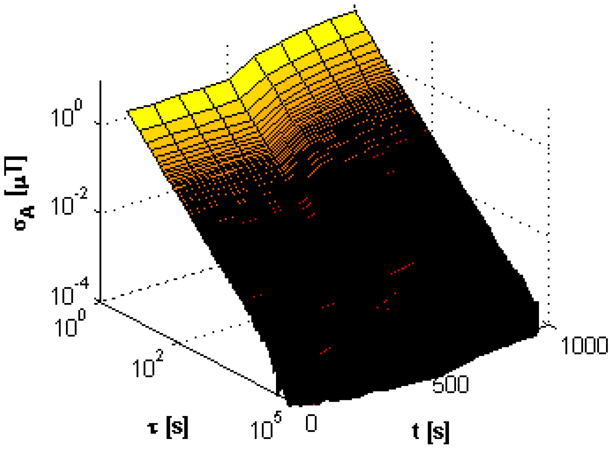

Fig. 3. DAVAR calculated for the simulated white noise with the "step" (x_2).

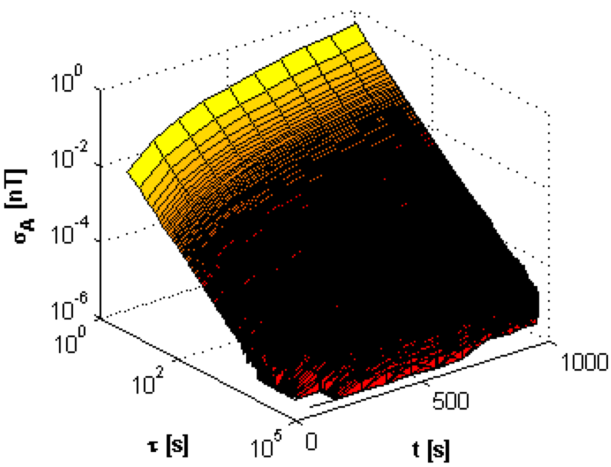

Fig. 4. DAVAR calculated for the simulated white noise with the increasing noise amplitude (x_3).

4. Experiments and results

Measurements were performed using the VEMA 040 series magnetometer, which is a 4-channel magnetometer with the Complex Programmable Logical Device (CPLD) controlled electronics developed at our Department [5]. Sampling frequency during the measurement was 1 kHz.

In case of the experimental measurements two data sets were compared. The sensor signal marked as x_r represents unfiltered reference signal and the sensor signal designated as x_m represents a non-stationary sensor signal, in which the transformer load was switched on near the sensor in three time intervals — after 1, 6, and 8.5 min — with the 1 min duration and with the standard deviation changing from 52 nT to 483 nT when the load was switched on. Comparison of the AVARs of the both signals is shown in Fig. 5. From the calculated characteristics we can see that for lower averaging time until the 10^3 s the white or quantisation noise is dominant. Then the slope changes to the random walk due to the inherent instability in the sensor output in case of the x_r signal. A very similar trend we can observe also in the case of the non-stationary x_m with negligible differences of the slopes caused by the peaks during the turning on of the transformer load, but the significant difference can be seen similarly to the performed simulations only in the amplitudes. Oscillations in the AVAR characteristics are caused by the 50 Hz industrial frequency and its harmonics.

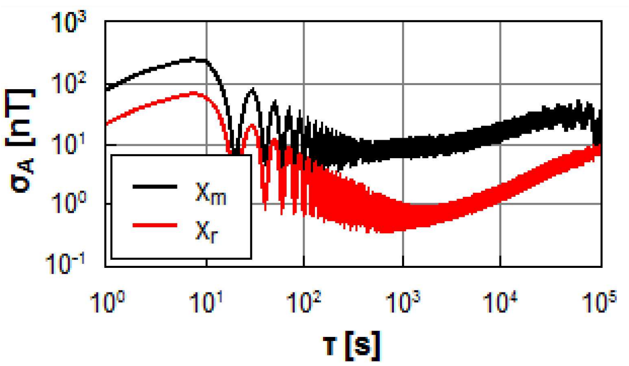

Fig. 5. AVAR calculated for the reference (x_r) and non-stationary (x_m) signal.

However about the in time changing behavior of the noise we get information only using the DAVAR analysis, results of which are shown in Fig. 6. In regard to the above mentioned dominant noise types the analysis of the noise type parameters also confirmed that the white noise parameter Q changes from 24.07 to 138 nT, which is caused by the peak during the turning on of the transformer load and the random walk parameter N varies from 7.22 to 41.42 nT $\mathrm{s}^{-1/2}$ during the "steps" caused by the transformer load. Other noise parameters remained constant without significant changes.

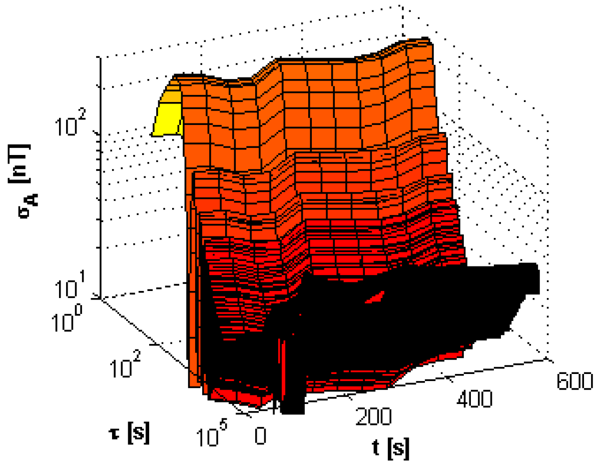

Fig. 6. DAVAR calculated for the measured non-stationary signal (x_m).

5. Conclusions

The statistical methodology of the noise analysis based on the Allan variance in comparison to other conventional statistical methods has several significant advantages — there is no need of any transformation and according to the IEEE recommendation it is one of the preferred methods for the noise type of inertial sensors (accelerometers and gyroscopes) identification. The presented dynamic Allan variance methodology can be furthermore very effectively used for the non-stationary processes of the magnetic sensor channel identification, which was proved by the simulations and also the experimental results.

Acknowledgments

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