Measurement 75 (2015) 263–272

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Characterization of a fiber optic gyroscope in a measurement while drilling system with the dynamic Allan variance

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ARTICLE INFO

Article history:
Received 1 November 2014
Received in revised form 14 April 2015
Accepted 4 May 2015
Available online 14 June 2015

Keywords:
FOG
Allan variance
DAVAR
Dynamic performances

ABSTRACT

The environment influences Fiber Optic Gyroscopes (FOG) directly. Thus, FOGs in Measurement While Drilling (MWD) system exhibit a non-stationary behavior over time due to strong vibration, high-speed rotation and temperature increasing. Therefore, it is important to introduce a representation that can take the time-varying nature of FOGs' stability into account. The Allan variance is a common and standard method to analyze FOGs, but it cannot be used to analyze the dynamic characteristics. In this effort, a method based on the dynamic Allan variance (DAVAR) was developed. Firstly, the validity of DAVAR was verified by simulated data. Secondly, the FOG working in the harsh environment was characterized by the DAVAR. According to the results, an improved experiment was implemented to verify the practical application of the DAVAR. In addition, a 2-D diagram is used for the first time to illustrate the noise characteristics of FOGs. A 2-D analysis diagram can not only separate and distinguish the stochastic noise term, but also track and reveal the changes in the behavior of FOGs in a clear and intuitive manner. In conclusion, with the new method developed by this paper, the performance of FOGs can be evaluated more comprehensively and effectively.

1. Introductions

The Allan variance was developed by David Allan to characterize the stability of precise clocks and time references [1]. It is a method to analyze the frequency stability in the time domain [2]. The Allan variance has become a standard and typical tool to analyze Fiber Optic Gyroscopes (FOG) since it can identify the stochastic noise in the gyroscope. However, the Allan variance assumes that the FOG's output signal is stationary, and such a condition is only suitable for an ideal signal [3]. In reality, a FOG's signal is non-stationary and can be easily influenced by environment, such as temperature, humidity, radiation and a sudden power failure [4]. FOGs in Measurement While Drilling (MWD) systems work with a high-speed rotation. At the same time, their temperature increases with the drilling depth increasing at a rate of 3 °C/100 m. Additionally, FOGs withstand a strong shock due to the obstruction of stone underground. Thus, it is difficult to characterize FOGs working in MWD. How to judge the performance of FOGs in MWD is crucial.

The dynamic Allan variance (DAVAR) was developed by Galleani and Tavella to characterize the time-varying stability of precise clocks and time references in 2003 [3,5–9]. It is a new method that can track and describe the dynamic characteristics of time series. In 2007, the DAVAR was routinely used to monitor the clocks of the Galileo experimental satellites GIOVE-A and GIOVE-B [10]. In 2009, the fast algorithm and confidence of the DAVAR were researched by Galleani and Tavella [11–14]. In China, it was first applied to FOGs' static data by Li

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http://dx.doi.org/10.1016/j.measurement.2015.05.001
0263-2241/

et al. [15]. Wei and Long put it in application to evaluate Ring Laser Gyro random error [16]. Li and Zhang used it to analyze swing signal in marine FOGs [17,18]. Zhang et al. put it into characterizing stochastic error in FOGs [19]. However, the dynamic performance of FOGs in high-dynamic states has not been researched. Furthermore, to the best of our knowledge, how the FOG noise changes over time in quantity has not been studied before. In this paper, the validation of the DAVAR and the poor performances of the Allan variance for non-stationary noise are discussed. Besides, three sets of experimental data obtained from MWD systems are characterized by the DAVAR. Above all, a 2-D diagram is used for the first time to illustrate the noise characteristics of FOGs.

The present paper is organized as follows. In Section 1, the computation process of the DAVAR is discussed, and the theory of 2-D description for FOG noise is introduced. In Section 2, the validity of the DAVAR is verified by three groups of simulation data. In Section 3, three experiments are carried out with MWD systems. The performance of FOGs in severe environment is characterized by the DAVAR. According to the analysis results, an improved experiment is implemented. The conclusion is reported in Section 4.

2. Dynamic Allan variance

2.1. Dynamic Allan variance

The DAVAR $\sigma_y^2(t,\tau)$ could represent the instantaneous stability of FOGs. It is a 3-D surface that defines the stability of FOGs at a given observation interval τ for a given time t while the Allan variance $\sigma_y^2(\tau)$ is a 2-D representation that gives the stability of FOGs on a given observation interval τ for total time. The computation procedure of the DAVAR can be summarized as follows [10]:

1. Fix analysis point in time at t_1.
2. Obtain the signal $y_T(t_1)$ by truncating the original signal $y(t)$ in an interval of duration T. That is, the length of the truncation widow is T.
3. Estimate the Allan variance $\sigma_y^2(t_1,\tau)$ of $y_T(t_1)$. Enter the Allan variance in a 3-D diagram. τ is the observation interval. t is the analysis time point.
4. Choose another analysis point $t = t_2$ and repeat from step 2. The new truncated signal corresponding to t_2 must overlap the previous one corresponding to t_1.

The procedure is repeated at every instant t. Finally, The results $\sigma_y^2(t,\tau)$ evaluated by the Allan variance at any given time t are represented in a 3-D diagram. For Continuous-Time signals, the DAVAR could be obtained by formulation (1). The detailed computation process can be found in citations [11].

$$\sigma_y^2(t,\tau)=\frac{1}{2\tau^2(T-2\tau)}\int_{t-T/2+\tau}^{t+T/2-\tau}[y(t'+\tau)-2y(t')+y(t'-\tau)]^2dt' \tag{1}$$

2.2. 2-D description for FOG noise terms

Different noise terms appear in different regions of τ which allows easy identification of various random processes existing in the FOGs' signal [4]. If it can be assumed that the existing random processes are all statistically independent, the Allan variance at any given τ can be the sum of Allan variances corresponding to each random processes at the same τ. In other words,

$$\begin{aligned}\sigma^2(\tau) &= \sigma_Q^2(\tau)+\sigma_N^2(\tau)+\sigma_B^2(\tau)+\sigma_K^2(\tau)+\sigma_R^2(\tau)\\ &=\frac{3Q^2}{\tau^2}+\frac{N^2}{\tau}+\frac{2B^2}{\pi}\ln 2+\frac{K^2\tau}{3}+\frac{R^2\tau^2}{2}\end{aligned} \tag{2}$$

where $\sigma_Q^2(\tau)$, $\sigma_N^2(\tau)$, $\sigma_B^2(\tau)$, $\sigma_K^2(\tau)$ and $\sigma_R^2(\tau)$ represent Allan variance of the Quantization noise (Q), Angle random walk (N), Bias instability (B), Rate random walk (K) and Rate ramp (R) respectively. The coefficients Q, N, B, K and R denote the magnitude of every kind noise respectively.

The Allan deviation is the square root of the Allan variance. The Allan deviation could be described as follows [4]:

$$\begin{aligned}\sigma(\tau) &= \sqrt{\sigma^2(\tau)} \approx \sum_{n=-2}^{2} C_n\sqrt{\tau^n}\\ &= \sigma_Q(\tau)+\sigma_N(\tau)+\sigma_B(\tau)+\sigma_K(\tau)+\sigma_R(\tau)\\ &= \frac{\sqrt{3}Q}{\tau}+\frac{N}{\sqrt{\tau}}+\frac{\sqrt{2}B}{\sqrt{\pi}}\sqrt{\ln 2}+\frac{K\sqrt{\tau}}{\sqrt{3}}+\frac{R\tau}{\sqrt{2}}\end{aligned} \tag{3}$$

The terms C_n are the coefficients of the polynomial $\sigma(\tau)$. The relation between $\sigma(\tau)$ and τ is always described using the double logarithmic curve. Fitting the double logarithmic curve $\sigma(\tau)-\tau$ with the least square method, the coefficients Q, N, B, R, and K could be obtained. The coefficients of different noise terms can be given as follows:

$$\begin{aligned}N &= \frac{\sqrt{C_{-1}}}{60}(^\circ/\mathrm{h}^{\frac{1}{2}})\\ K &= 60\sqrt{3C_1}(^\circ/\mathrm{h}^{\frac{3}{2}})\\ B &= \frac{\sqrt{C_0}}{0.664}(^\circ/\mathrm{h})\\ Q &= \frac{10^6\pi\sqrt{C_{-2}}}{180\times 3600\times\sqrt{3}}('')\\ R &= 3600\sqrt{2C_2}(^\circ/\mathrm{h}^2)\end{aligned} \tag{4}$$

The DAVAR consists of the Allan variances at every instant t. Therefore at any given time t, there is

$$\sigma(t,\tau)=\sigma_Q(t,\tau)+\sigma_N(t,\tau)+\sigma_B(t,\tau)+\sigma_K(t,\tau)+\sigma_R(t,\tau) \tag{5}$$

$\sigma(t,\tau)$ is the dynamic Allan deviation (DADEV) which is the square root of the DAVAR. At any given time t, fitting the double logarithmic curve $\sigma(t,\tau)-\tau$ with the least square method, coefficients $Q(t)$, $N(t)$, $B(t)$, $K(t)$ and $R(t)$ at the same given time t can be obtained. As analysis point t moving forward on the timeline, coefficients for the total time are obtained. Putting $Q(t)$, $N(t)$, $B(t)$, $K(t)$ and $R(t)$ in pictures according to the chronological order, the time-varying noise of FOGs could be characterized in a 2-D diagram.