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Adaptive Kalman filtering based on higher-order statistical analysis for digitalized silicon microgyroscope

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ABSTRACT

In order to reduce the noise level of a silicon microgyroscope (SMG) digital system, a filter based on the theory of Kalman filter algorithm is designed. The performance of a Kalman filter depends on the proper model identification and parameter estimation. The method of higher-order statistical theoretical analysis is used to obtain the statistical properties of the gyroscope random signal. By modifying the conventional Kalman filter as adaptive Kalman filter, the filtering performance is enhanced. The filter is programmed in the Field Programmable Gate Array (FPGA) soft-core of the silicon microgyroscope digital system, based on SOPC (System-on-a-Programmable-Chip) technology. The effect of the filter is evaluated by Allan variance analysis. It is shown that noise characteristics such as quantization noise and angular random walk are obviously lowered compared with the original signal. In this way, by making use of ARMA (Auto Regression Moving Average) modeling results, a method of designing adaptive Kalman filter on digitalized SMG system is implemented.

1. Introduction

Silicon MEMS gyroscope offers revolutionary improvements in cost, size, and robustness relative to fiber-optic and spinning mass technologies. It is suitable for mass production and is widely used to commercial and military application [1].In recent years, the issues on digitally controlled MEMS microgyroscope systems based on FPGA (Field-programmable Gate Arrays) have been discussed in depth. This technology provides superior precision and robustness against environment interference. It also ensures the reversibility of both algorithms and control parameters of the system and allow for in-situation programming and calibration of the MEMS microgyroscope [2–4]. Although combined with FPGA based digital control circuit, traditional FIR or IIR filters still have disadvantages of storage space consumption and unable to suppress the in-band signal noise component [5]. The random error of the micromachined gyroscope can be modeled by time-series data analysis and reduced by Kalman filtering according to statistical characteristics [6,7].

Kalman filtering algorithm has been widely used in different areas of signal processing since proposed in 1960 [8], including fiber optic gyroscope, GPS navigation and accelerometer [9–11]. With the applications in these related fields, Kalman filter is expected to achieve satisfactory performance on the digitalized SMG system. The realization of a Kalman filter relies on an ARMA model that established according to the time series samples from the signals.

Generally, the conventional method of second-order statistical analysis can be used to identify the model category and estimate the parameters of the ARMA model, but

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various noise sources exist in the digitalized SMG system, which will make the output signal mixed with non-Gaussian random noise. To deal with such problem, the method of higher-order statistical analysis is applied, which has advantages of suppressing non-Gaussian noise, especially in the fields of detecting and characterizing non-linearities in time series, and extracting new classification features from signals [12]. To decide which of these two methods should be used in the final parameter estimation, a simulation is designed in this paper to compare the estimation precision.

Considering the possible time-varying noise characteristics of digitalized SMG system output signal, the conventional Kalman algorithm is replaced by an adaptive Kalman filter [13]. Concerning FPGA programming and algorithm complexity, the proper solution is to take advantage of the SOPC technology and embed a soft-core in the FPGA chip, where the adaptive Kalman filtering algorithm is realized [14].

The digitalized SMG control circuit and signal processing modules are also embedded in the same FPGA chip. The structure of the system will be discussed in the following sections. To evaluate the performance of this kind of filter, the comparison technique by Allan variance analysis is applied. By comparing them with the noise level coefficients of the filtered signal, we can evaluate the performance of the adaptive Kalman filter in this work.

The rest of the paper is organized in 5 sections: in Section 2 the structure of the SMG and its circuitry will be presented. In Section 3 the estimation precision is compared between the second-order statistical analysis method and the higher-order statistical analysis method, and then the category identification and parameter estimation of the ARMA model is carried on, through the obtained sampled sequence and the estimation method chosen. Section 4 shows how to realize the filter in the digitalized SMG system, and presents some details and corresponding parameters. The Allan variance analysis is also conducted in this section. Finally, the paper is concluded in Section 5.

2. The structure of the SMG system

In this section, the structure and workflow of the digitalized SMG system along with some of its essential components are presented. Previous work has prepared us a set of digitalized SMG system based on FPGA [15]. The structure of the digitalized SMG system based on SOPC technology can be described in Fig. 1.

A capacitive silicon micromachined gyroscope is used in this experiment. The designed z-axis gyroscope is a fully decoupled single proof mass gyroscope. It is a two-layer structure which mainly consists of the drive mode components, the sense mode components, the proof mass, the damping elements and the glass substrate etc. The details of the gyroscope including its packaging, comb figures, coupling and decoupling springs are also displayed in Fig. 1(c), and the corresponding parameters of the gyroscope are summarized in Table 1. The modal simulation results of the gyroscope are shown in Fig. 1(a) and (b). Its mode-matched natural frequencies in drive and sense modes are 3032.3 Hz and 3033.9 Hz, respectively. The gyroscope is fabricated by SOG (silicon-on-glass) process. The upper layer of the gyroscope is the silicon structure ICP etched through the single crystal silicon bulk micromachining, while the lower layer is the glass substrate which is anodic bonded with the silicon structure.

The schematic diagram of digitalized SMG system is shown in Fig. 2. The signals of changing capacitance in drive and sense modes are both converted to electric signal before processed by the A/D converter. Auto gain control (AGC) section is used to maintain the amplitude of the drive mode, and least mean square demodulation (LMSD) is used in the sense mode. Apart from the modules mentioned above, some other parts are also essential to the system, such as the phase-locked loop (PLL) and FIR low-pass filters, all these modules are realized by programmable logic units in the FPGA chip. The detailed working principle has been introduced in our previous work [15].

A new improvement is embedded in that a customized NIOS soft-core is connected with the Verilog programmed sections using the Avalon Bus. A novel adaptive Kalman filtering is realized by programming in the soft-core and its output signal is packed by several groups of 5-bit width hexadecimal numbers.

After the filtering, the data is transferred to the host computer through the UART sending program, in the format of our designed protocol.

The GUI program on the host computer can plot the original output signals and the results of adaptive Kalman filter in real-time. After the signal acquisition process, two groups of data before and after filtering can be saved on the host computer for further Allan variance analysis.

3. Establishment of ARMA model and the realization of adaptive Kalman filter

The work flow diagram of the adaptive Kalman filter in this work is shown in Fig. 3. Our main aim is to obtain the statistical characteristic of the original signal in an applicable Kalman Filter. Since here ARMA model is used to describe the sequence, the parameters evaluation should be conducted for state estimation in the Kalman filter. First, the parameter evaluation method should be chosen between second-order statistical analysis and higher-order statistical analysis by simulation. The higher-order statistical analysis is especially suitable for non-Gaussian noise, thus the signal sequence is examined through the bispectrum analysis to judge whether the signal is truly non-Gaussian random and necessary to use higher-order statistical analysis. Second, the ARMA model category and specific parameter coefficients should be identified according to the time sequence theory, the minimum length of sample sequence decided to satisfy the evaluation precision under different noise condition simulation. Besides, the residual sequence will be calculated to derive the category, orders, and model parameters of the gyroscope output sequence. Third, after the higher-order statistical analysis algorithm is determined and the estimated