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Digital signal processing for a micromachined vibratory gyroscope based on a three dimensional adaptive filter demodulator

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ABSTRACT

This paper reports a digital controller based on a three dimensional adaptive filter demodulator (AFD) for micromachined vibratory gyroscopes with the goal of eliminating common-mode noise and reducing hardware resources. The least mean square (LMS) adaptive filter, which has advantages of fast convergence speed, lower noise and fewer occupied hardware resources, is adopted to demodulate the vibration velocity of the gyroscope and detect its phase shift. A three dimensional AFD is proposed to eliminate the common-mode noise and quadrature coupling induced by the initial capacitance mismatch. Simulation and experimental results have verified the effectiveness of this method. The measurement results of the digital controlled gyroscope show a zero bias drift of 24.6 °/h and a nonlinearity of 0.1% with the measurement range of ±200°/s.

1. Introduction

Digital signal processing circuits have been widely applied in the control of gyroscopes for their flexibility and insensitivity to environmental parameters [1–3]. According to the principle of micromachined vibratory gyroscopes [4], various control methods have been employed for the drive mode to maintain a stable vibrating velocity [5–9]. In the sense mode, force rebalance control is often used because of the increased dynamic range, improved linearity and better anti-disturbance capability [10–15]. In digital controllers, quadrature demodulation is preferred as it can get the amplitude and phase of the vibration velocity simultaneously [16,17]. Most of these digital demodulators are composed of a multiplier and a low-pass filter, as shown in Fig. 1 [18]. However, the response time, bandwidth and noise level are mainly limited by the filter. To achieve better performance, high-order digital filters can to be used to minimize the influence of the quantization noise, however, much more digital resources are required. Moreover, the phase lag induced by the high-order filters makes the closed-loop controller design difficult. So trade-offs must be made by considering the overall performance.

Zhou et al. adopted adaptive filter as the demodulator instead of the combination of multiplier and low-pass filters [19], and the least mean square (LMS) algorithm was used to realize the demodulation function. The LMS adaptive filter consists of two orthogonal one-order filters, and the coefficients are the demodulation results which can be obtained by enough iterations. Therefore, this method avoids the problem of quantization noise coming from the high-order filters in multiplication demodulation. However, the algorithm cannot handle common-mode noise. Due to the fabrication imperfections, there is always a common-mode noise in the detected signal of gyroscopes, which would induce fluctuations in the output of the LMS demodulator.

In this work, we propose a three dimensional adaptive filter demodulator (AFD) to solve the problem of common-mode noise. In the drive mode, the vibration

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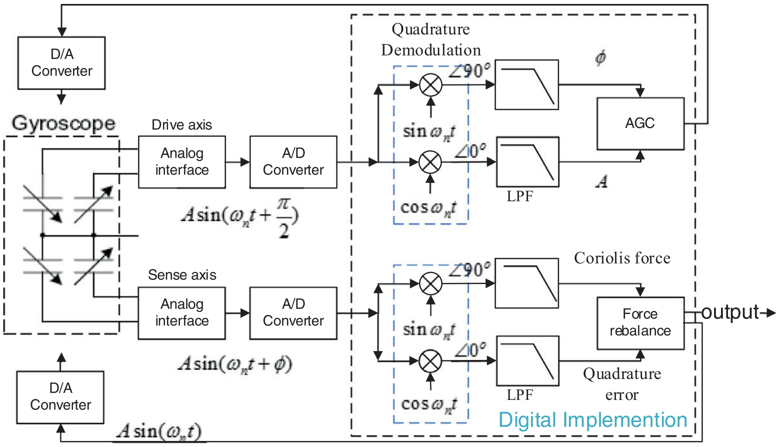

Fig. 1. The digital singal processing scheme of micromachined gyroscopes.

velocity's amplitude and phase are obtained by the three dimensional AFD and controlled separately to keep constant amplitude at resonant frequency. In the sense mode, the three dimensional AFD can eliminate quadrature error and common-mode noise. The structure of the paper is as follows. Section 2states how the adaptive filter realizes the demodulation function, and compares the performances of several demodulation algorithms. Section 3introduces how the AFD is implemented in the gyroscope's sense loop. A three dimensional AFD based on LMS algorithm is proposed to eliminate the quadrature coupling and common-mode noise.

2. Principle of AFD

Usually, an adaptive filter consists of a reference signal, a filter coefficients array and iteration loops based on the adaptive algorithm. The filter generates a predictive value by multiplying the reference signal with the coefficients array. According to the adaptive algorithm, the predictive value approximately equals the input after enough iterations, which is called the 'learning' process, as shown in Fig. 2. When the adaptive filter is used as a demodulator, the reference signal is in the same frequency with the input signal. While the predictive value approaches the input, the filter coefficient approaches the amplitude of the input. When the 'learning' process is finished, the demodulation is realized. By setting the reference as an array including $\cos\omega_n t$ and $\sin\omega_n t$, the function of quadrature demodulation can also be accomplished.

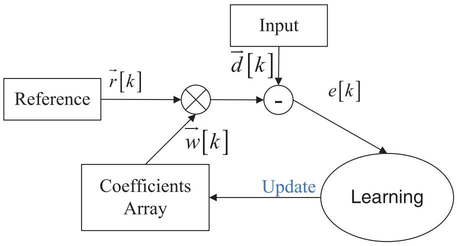

Fig. 2. The structure of an adaptive filter.

The least mean square (LMS), the recursive least square (RLS) and the Kalman filter [20] can all realize the adaptive algorithm in the AFD. Simulations on the quadrature demodulation were carried out by Matlab to compare these adaptive algorithms and multiplication demodulation. The multiplication quadrature demodulator includes one two-order Butterworth low-pass filter in each loop. The input is a sinusoidal wave with the amplitude of 1 V superposed with a Gauss white noise with mean value of 0 V and standard deviation of 0.01 V. Fig. 3 shows that the LMS and the Kalman algorithms have shorter convergence time. The noise of Kalman algorithm is the lowest, as that depicted in Fig. 4. According to the occupied digital hardware resources listed in Table 1, the LMS demodulator has the best hardware efficiency.

Comprehensively considering the convergence speed, noise and hardware realization on FPGA, the LMS algorithm is selected in our controller design, which has the advantages of fast convergence time (wider bandwidth), low noise, better hardware efficiency, and so on.

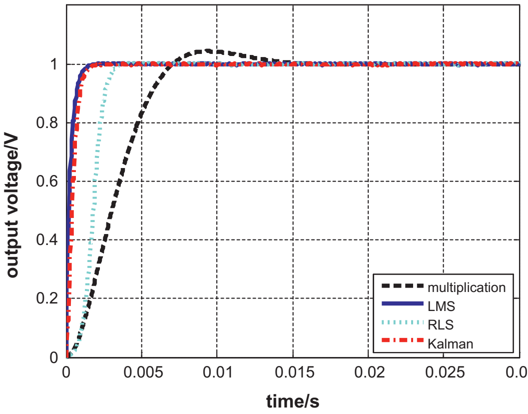

Fig. 3. Simulation results of the convergence time for LMS, RLS, Kalman and multiplication algorithm.