The hardware circuit design in gyroscope detection system combined with SDM

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Abstract. The open-loop detection of Silicon micro-gyroscope always has a low bandwidth and a small dynamic range, and is sensitive with manufacturing errors. So this paper has studied the application of sigma-delta modulator in the closed-loop detection circuit of silicon gyroscope, and has put forward a preliminary hardware solution. Finally get a model of closed-loop detection system for gyro which can reach a signal-to-noise ratio index to 108.5 db, meeting the initial design specifications: resolution of 0.001 ° / s and range of±200 ° / s. And in the aspect of hardware circuit, we have finished the interface circuit, including pre-amplifier circuit, the AD conversion module and the feedback module.

Keywords: silicon micro-gyroscope; sigma delta modulator; closed-loop detection; signal-to-noise ratio; hardware circuit.

1 Introduction

This study set the band-pass Sigma-Delta modulator (SDM) for the silicon micro gyroscope (SMG) as the research object, focusing on the design method of the electromechanical SDM for silicon micro gyroscope detection circuit, providing the methods and techniques for further ASIC and mass production.

At present, the closed-loop detection circuit adopting band-pass SDM for silicon micro gyroscope is mostly designed on the continuous time domain in domestic, the design of continuous time SDM is complex and the circuit parameters can’t be modified then, unable to meet the requirements of ASIC and mass production. However the technology of electromechanical SDM abroad is kept as a secret. So it is necessary to carry out the research for the electromechanical SDM. This research aims to the resolution and range of SMG, to study the method of establishment for closed-loop structure and obtaining of the closed-loop parameters. Finally simulated the structure and parameters, and it is verified that the structure and parameters can satisfy the demands of expected design specifications, thus verified the accuracy of the method. And at the same time, we have put forward a hardware solution to implement the design.

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2 Structure and working principle of SMG

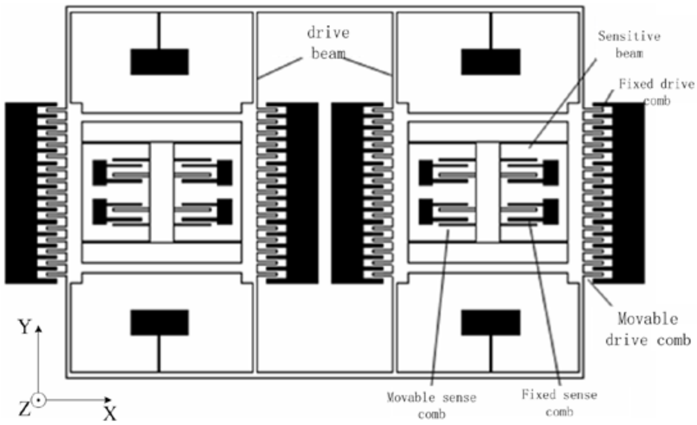

Figure 1. Sketch of silicon micro-gyroscope's structure

The studied SMG structure in the paper is shown in Fig.1, which is a typical Z-axis Coriolis-gyro. X-axis is its drive axis, which constitutes the oscillation loop with the interface circuit, and then provides reference signal which will generates Coriolis force in Y-axis. Y-axis is its sense axis. The input angular rate in the Z-axis direction will generate a Coriolis force combined with the reference signal in X-axis ,and then it can lead to the change of the capacitance between two sense plates, finally generate a couple of differential output current from the two sense plates.

3. Modeling of SDM closed-loop detection for SMG

3.1 Discretization of sense mode in SMG

In the aspect of dynamic domain, as shown in fig.1, the sense mode of SMG can be regarded as a second-order system combined with mass - spring - damper and the transfer function can be expressed as follows:

$$H_s(s) = \frac{1/m}{s^2+\frac{w_d}{Q_y}s+w_d^2} \tag{1}$$

So we can get the discrete model of the transfer function by the Z transform:

$$DH_S(z) = \frac{zw_dT}{z^2-2zcosw_dT+1} \tag{2}$$

Make $\lambda = 2 - 2\cos(\omega_d T_s)$, so the sense model of SMG can be expressed in the discrete domain as below:

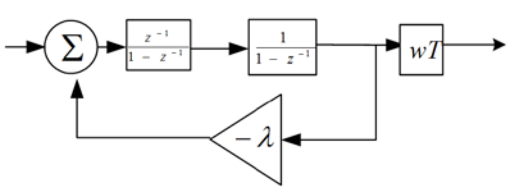

Figure 2. The discrete sense model of SMG

3.2 The structure of SDM modulator

SDM is also called noise reshaping modulator, combined with integrators and a quantizer. The orders of SDM are determined by the number of the integrators, the more integrators, the better performance of noise shaping, but on the contrary it will lead to the instability of the system. Below is the basic structure of a first-order SDM in discrete time, and represents a integrator. The advantages of the SDM modulator is that it can make the signal and the quantization noise have a different transfer function through the loop structure, so as to suppress the quantization noise and preserve the original useful signal.

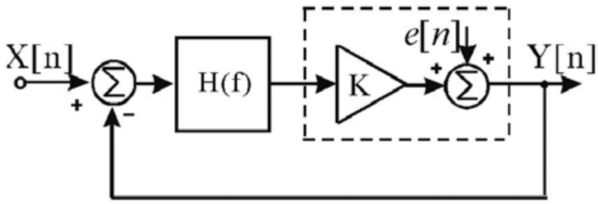

Figure 3. First-order SDM

3.3 Modeling of electromechanical SDM

The figure below is a schematic view of electromechanical SDM closed-loop detection system, including gyro sensitive structure, capacitance / voltage (C / V) conversion circuit in SMG, analog to digital converter (ADC), digital resonance and a quantizer. The platform uses FPGA to implement digital processing in the dashed box in Figure 3, including the digital resonator and a quantizer. It is very convenient to modify the parameters of resonator by the PC to the FPGA, so as to optimize the system.

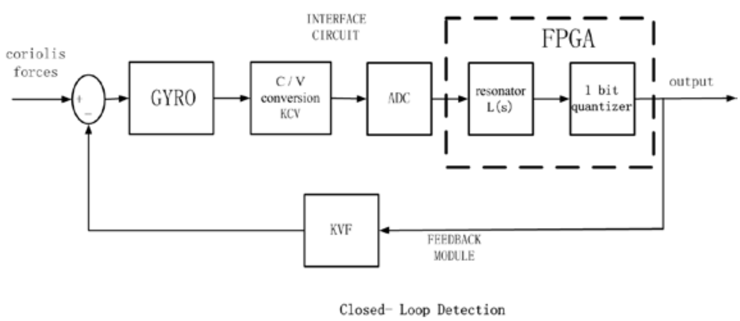

Figure 4. Model of electromechanical SDM

4 The design of the analog circuits

After the modeling of electromechanical SDM of SMG, then first designed the analog circuit part, including the pre-amplifier circuit, the ADC conversion module and the feedback module.

4.1 Pre-amplifier circuit

For the closed-loop detection system, the output current of the gyro will be much smaller compared to that in open-loop, so here we added a secondary op-amp circuit, to make the output current matching the ADC detection range. Specific circuit diagram is show as follows:

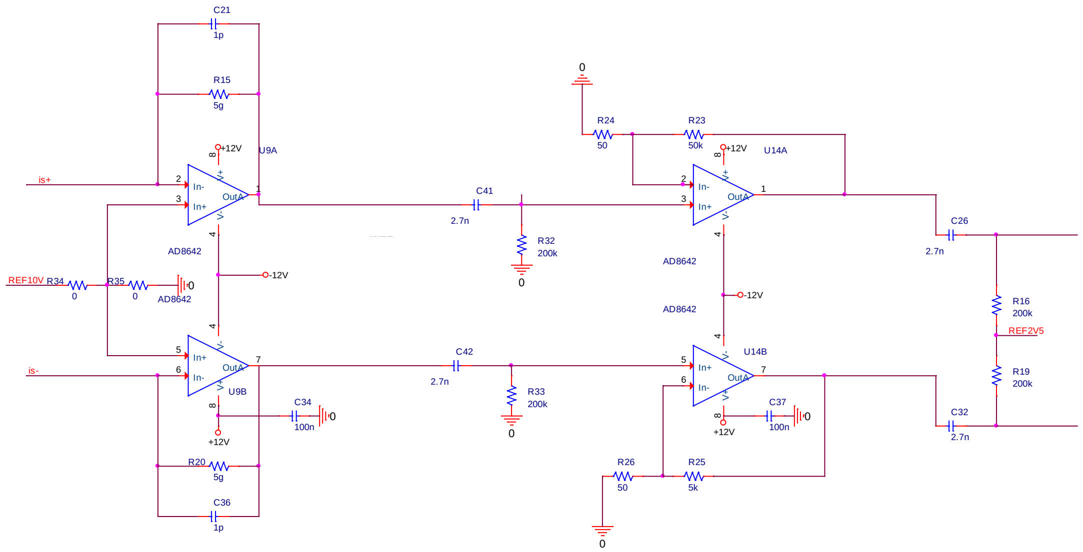

Figure 5. Pre-amplifier circuit module

In simulink it shows the output current of the gyro is roughly about $10^{-10}A$, and then we do the time domain simulation in Pspice software, can get the final output is close to the ADC detection range, which can guarantee the highest sampling precision of the ADC.

4.2 The ADC sampling module

We adopted AD7690 (18 bits) module to do the sampling and quantization for the output of the pre-amplifier circuit, and the communication protocol between FPGA is SPI communication, according to the datasheet we designed the circuit diagram as follows:

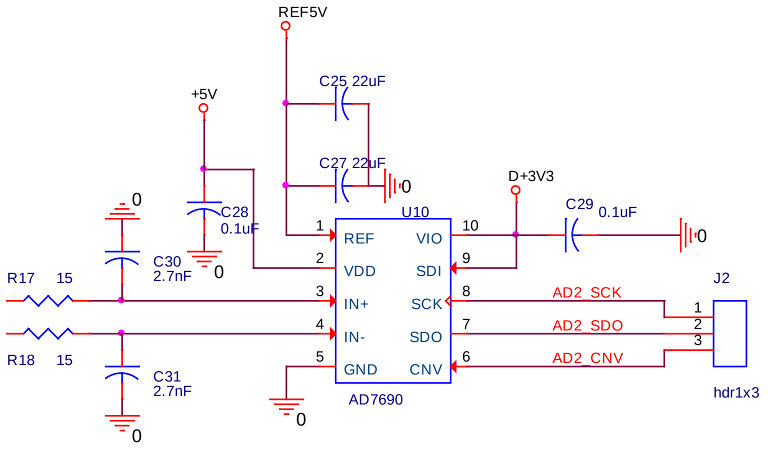

Figure 6. ADC sampling module

4.3 Feedback module

Here we use ADG713 module to feedback, which is a switch can control the output of vsa+ and vsa- at different moment. If the output of 1bit quantizer is greater than 0 , the circuit module can make the vsa+(connected to positive feedback plate in SMG) linked to high level vsaREF and the vsa-

(connected to positive feedback plate in SMG)linked to the ground. And on the contrary, if less than 0, vsa+ linked to GND, vsa- linked to vsaREF. So as to provide the feedback force to balance the Coriolis force.

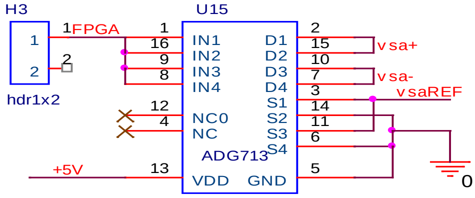

Figure 7. Feedback module

5 The design of the digital circuits

By now we have finished the design of interface circuit , and then the next step is to design the digital part of the system .A key part of the whole digital system is the selection of SDM loop and the obtaining of the loop parameters.

It has a very mature approach to design a discrete-time SDM[11-12] in the discrete domain. Now the first we need to do is obtain the discrete parameters adapted to the gyro detection circuit ,combines the parameters of SMG and the design specifications.

A first order SDM modulator is composed of an integrator and a DAC feedback , and a higher order SDM modulator is composed of more integrators, making it possible to a further shaping of quantization noise. The SDM structure can be designed as two different forms : distributed feedback structure or distributed feed-forward structure. And in the actual circuit ,force feedback is adopted feedback point can only be set at the input of the gyro, so it is more reasonable to adopt the distributed feed-forward structure(CRFF) shown in figure 8:

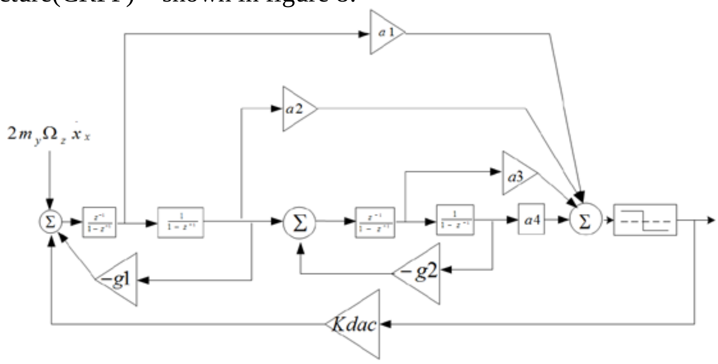

Figure 8. Distributed feed-forward structure

The transfer function for the first two integrators with feedback:

$$\frac{z^{-1}}{z^{-2}-(2-g1)z^{-1}+1} \tag{3}$$

The equation (2) shows that the resonant frequency of SMG is w_d , so when $g1=\lambda=2-2\cos(\omega_d T_s)$, the first two discrete SDM integrators with local feedback can be replaced by the discrete-time model of sense mode in SMG, and now the poles of the system is on the resonant frequency w_d of SMG, reaching the band-pass characteristics of the system.

Design specifications: resolution of 0.001 ° / s, range of ±200 ° / s. Because the output noise of the detection system determines the resolution, it has the formula:

$$SNR_{min} = 20\,log\left(\frac{200}{0.001}\right) = 106dB \tag{4}$$

From the discussion above and the actual parameters of the SMG, we can obtain the following design parameters and initial conditions:

Input frequency of the signal is 6K, the order is set as a fourth-order, OSR is initially set to 256, the initial bandwidth is set to 200HZ, band gain Hinf = 1.3, the form of 'CRFF'. And we can be obtained g1 coefficient is $2-2\cos(\omega_d T_s)$ in advance.

Then use discrete SDM design tool(DSToolbox) to make the design of the discrete SDM with different OSR, it can be improved that when OSR=512,the system can satisfy the demand of SNR, then use the design tool to get the feed-forward coefficient a(a1,a2,a3,a4). To leave more margin of the input and prevent instability at the critical point, we set the input as the 0.7 times of the full-scale (corresponds to actual ± 200 ° / s), then analyze the spectrum output and draw the noise transfer function (NTF) and signal transfer function(STF) in figure 9:

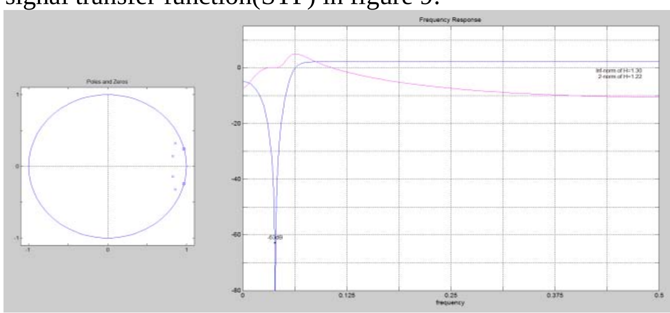

Figure 9. Poles and zeros of NTF and the amplitude-frequency curve of STF, NTF

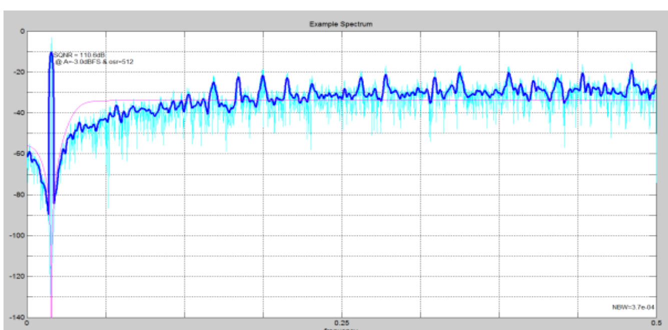

Figure 10. PSD (power spectrum density) of the output

From the fig.9 and fig.10 above it can be seen that the poles of the system are all located within the unit circle, so the system is stable. And we also can see the zeros of the system is located in the conjugate complex roots on the unit circle, which is the resonant frequency of the gyro. Then we leave some margin for the input, set the input to -3dB (0.7 times of the full-scale) ,and at last reached a SNR of 110.6dB.

And now we have completed the SDM design in the discrete time, and it should be realized in reality, so we need to convert the discrete time SDM to electromechanical SDM. The method can be expressed as follows:

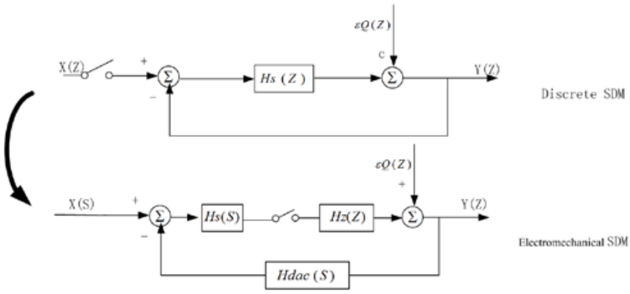

Figure 11. Conversion from discrete time SDM to electromechanical SDM

The principle of the conversion is to ensure that they both have the same noise transfer function, which is they have the same noise suppression effect. So we only need to make sure that the open loop transfer function is equal, which is expressed below:

$$H_S(Z) = Z\{H_S(S).H_{dac}(S)\}.H_Z(Z) \tag{5}$$

$H_S(Z)$ is the second-order system of SMG. In addition the output of the DAC is regarded as a CT model, so the output model is a sample holder, and the Laplace transform expression is:

$$H_{dac}(S) = \frac{1-e^{-ST}}{S} \tag{6}$$

The transfer function ($H_S(Z)$) has been determined by DSToolbox in the discrete SDM already, so we just need to implement the digital processing section $H_Z(Z)$ in FPGA then.

6 The simulation

And then we can establish the actual electromechanical SDM model in simulink in the figure 12, in which the gyro structure is expressed in S domain.

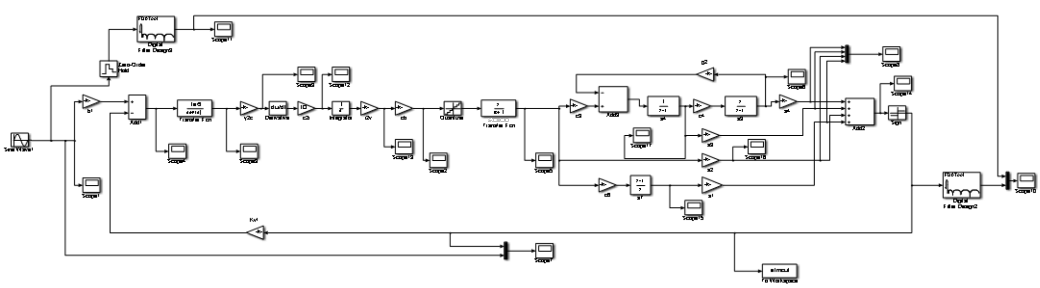

Figure 12. The simulation of the actual electromechanical SDM model in Simulink

Then add the actual coefficient of the gyro detection circuit to the system ,and give it a full input of 200 ° / s (corresponding to the input of 0.7 in discrete model).Then analyse the output of the quantizer output, obtain the PSD of the output, shown in figure 13:

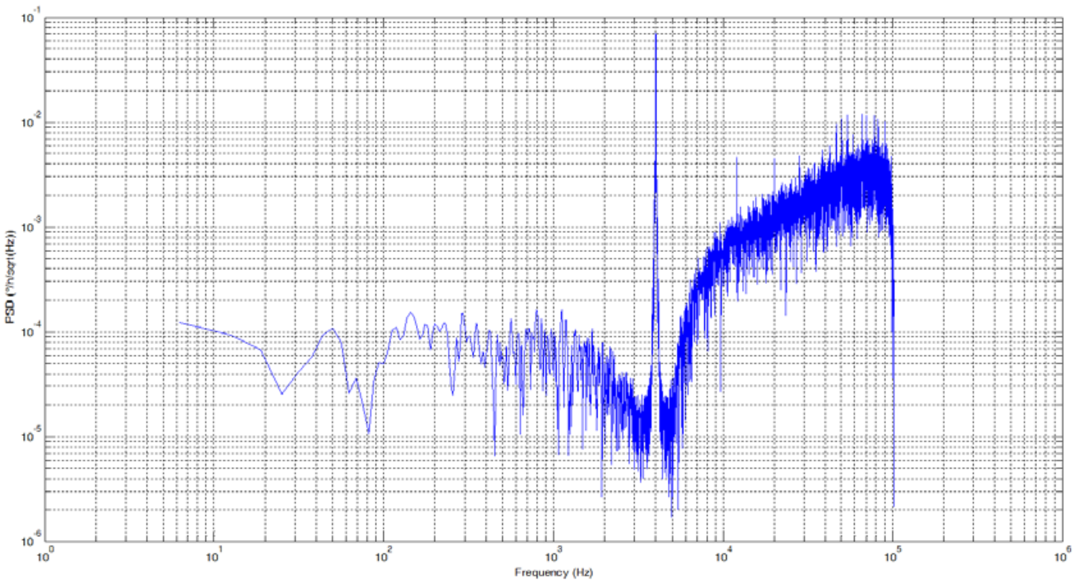

Figure 13. Spectrum of the quantizer output in simulink

From the output spectrum, we can see it has a maximum amplitude at the resonance frequency, which is the representative of the input signal amplitude. At a time, the quantization noise has been pushed away from the resonant frequency band, achieve the purpose of the noise removal and greatly reducing the quantization noise, so as to enhance the signal-to-noise ratio within the bandwidth.

Then we use matlab to calculate the signal-to-noise ratio, it can reach a value of 108.5 dB, meeting the requirements, verified the method in design of electromechanical SDM for SMG.

Acknowledgement

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