Analysis of the noise parameters of quad structure of MEMS angular rate sensors

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Abstract – **The current paper discusses the analysis of the noise parameters of quad sensor structure of angular rate sensors in comparison to the same parameters of the single sensors. It is shown that the signal processing of quad gyroscopes may result to the improved noise parameters of the whole structure. The Allan variance method is used to calculate the bias instability, rate random walk and angle random walk according to the curve slope.**

Keywords – **Quad sensor structure, MEMS, Allan variance**

INTRODUCTION

Inertial sensors, gyroscopes and accelerometers are widely applied. The sensor noises, bias variations, drifts and scale factor instabilities are the main error sources which cause the accuracy degradation of the modern navigation systems especially based on low cost MEMS inertial sensors. Two main parameters representing the quality of inertial sensors are the angle random walk and the bias instability for gyroscopes. These two parameters may be obtained by the Allan variance (AV) method [1-3] or by power spectral density (PSD) [4-6].

The PSD is the most commonly used representation of the spectral decomposition of a time series. It is a powerful tool for analyzing or characterizing data and stochastic modeling. The PSD, or spectrum analysis, is also better suited for analyzing periodic or aperiodic signals than other methods.

Allan Variance (AV) is a simple and efficient method for verifying and modeling these errors by representing the root mean square (RMS) random drift error as a function of averaging time. The AV can be used to determine the characteristics of different random processes. The details of the AV and how it is applied to the frequency and time metrology can be found in the literatures e.g. [7]. The most attractive feature of AV is its ability to sort out various noise components by the slopes on the root AV (Allan deviation) plot provided the different noise mechanisms are reasonably separated in the frequency and time domain

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The current paper discusses the noise parameters of the quad sensor structure, build by four identical digital output inertial sensors with synchronization inputs and microcontroller to compare the error values according to the single sensor using AV method.

SYSTEM DESCRIPTION

The inertial measurement systems consists of four identical MEMS inertial sensors MPU-6000 [8], which are placed in such way that each two sensors have one common axis and two opposite axes (Figure 1) [9]. The proposed quad sensor structure is based on MPU-6000 MEMS sensors which combines a 3-axis gyroscope, 3-axis accelerometer, and a Digital Motion Processor™ (DMP). One of the most important special feature of the selected MEMS sensors is the FSYNC (Frame synchronization) input, which may be used to start the measurement process. The sync signal connected to the FSYNC pin may support image, video and GPS synchronization. The system synchronization is carried out by the multiple output clock generator. The MPU-6000 inertial sensor has external clock inputs of 32.768kHz or 19.2MHz, but the first one is too slow to obtain high speed measurements. Therefore the 19.2MHz oscillator is connected to the crystal oscillator interface of the clock generator. It is based on the Ultra-low Jitter LVCMOS Fanout Buffer/Level Translator LMK00105 [10] with 5 ultra low jitter clocks from a differential, single ended or crystal input. The four of these 5 clocks are used in the quad sensor structure to ensure the sensors synchronization and the fifth one is connected to the microcontroller clock input (Figure 1).

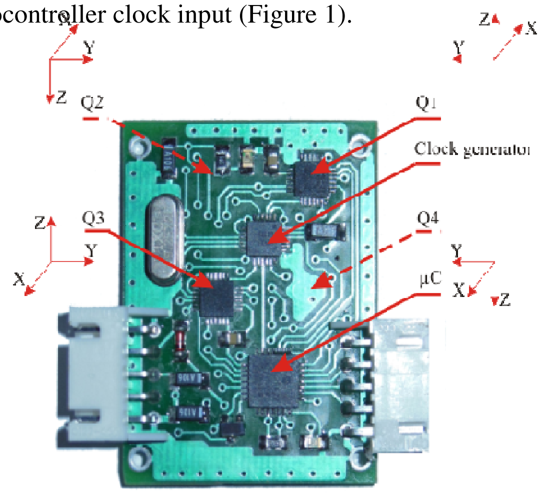

Figure 1. Measurement system design

The synchronous mode is distinguished with simultaneous sampling of the signal for all four sensors. This mode is realized by a simultaneous activation of the FSYNC inputs of the MEMS sensors. This action is possible because all FSYNC inputs are connected to the same port (PORTA) of the microcontroller and only one instruction is required to set all PORTA outputs simultaneously.

Two of the inertial sensors (Q1 and Q3) are placed on the top plate of PCB, while the other pair of the inertial sensors (Q2 and Q4) are placed on the bottom plate. The inertial sensor pairs (Q1-Q3) and (Q2-Q4) are connected to the different hardware based I^2C based ports of the microcontroller type PIC18F25K22 (μC). This allows reading the inertial data from two sensor pairs simultaneously.

EXPERIMENTAL RESULTS

The experimental data are obtained and processed in the MATLAB environment. The sensor update time is set to 1 kHz (accelerometers and gyroscopes) while the sampling frequency is set to 100Hz due to the limited time to transfer the inertial data to PC via RS232 interface. The system reads the XYZ linear and angular accelerations and temperature (14 bytes) from each sensor and sends the data to PC. The total amount of transferred data is equal to 57 bytes per one time sample (4 sensors multiplied by 14 bytes per sensor plus 1 SYNC byte). The measurement time is set to 2 hours.

The errors in typical inertial sensors include white noise, quantization noise, white rate noise, correlated (Markov) random drift, bias instability (1/f or flicker rate), flicker rate ramp (ramp instability), and random rate ramp. The AV method is used to analyze the bias instability, rate random walk and angle random walk of the quad sensor structure and the single sensors.

TABLE 1. Allan variance for X axis for single sensor and quad sensor structure

Error type	X gyro axis		Curve slope	Units
	Sensor #1 Sensor #2 Sensor #3 Sensor #4	Quad sensor structure		
Bias instability $B=\frac{\sigma(f_0)}{0.664}$	$7,22.10^{-3}$ $6,47.10^{-3}$ $7,37.10^{-3}$ $6,32.10^{-3}$	$1,65.10^{-3}$	0	deg/s
Rate random walk $K=\sigma(3)$	$1,7.10^{-3}$ $9,0.10^{-4}$ - $1,0.10^{-3}$	$1,2.10^{-4}$	+1/2	$\frac{deg/s}{\sqrt{s}}$
Angle random walk $N=\sigma(1)$	$2,3.10^{-2}$ $2,8.10^{-2}$ $2,2.10^{-2}$ $2,4.10^{-2}$	$1,2.10^{-2}$	-1/2	$\frac{deg}{\sqrt{s}}$

TABLE 2. Allan variance for Y axis for single sensor and quad sensor structure

Error type	Y gyro axis		Curve slope	Units
	Sensor #1 Sensor #2 Sensor #3 Sensor #4	Quad sensor structure		
Bias instability $B=\frac{\sigma(f_0)}{0.664}$	$7,37.10^{-3}$ $8,28.10^{-3}$ $6,92.10^{-3}$ $8,88.10^{-3}$	$2,4.10^{-3}$	0	deg/s
Rate random walk $K=\sigma(3)$	$1,8.10^{-3}$ $2,1.10^{-3}$ - $2,2.10^{-3}$	$2,0.10^{-4}$	+1/2	$\frac{deg/s}{\sqrt{s}}$
Angle random walk $N=\sigma(1)$	$2,2.10^{-2}$ $2,5.10^{-2}$ $2,3.10^{-2}$ $2,5.10^{-2}$	$1,3.10^{-2}$	-1/2	$\frac{deg}{\sqrt{s}}$

TABLE 3. Allan variance for Z axis for single sensor and quad sensor structure

Error type	Z gyro axis		Curve slope	Units
	Sensor #1 Sensor #2 Sensor #3 Sensor #4	Quad sensor structure		
Bias instability $B=\frac{\sigma(f_0)}{0.664}$	$7,22.10^{-3}$ $6,92.10^{-3}$ $7,22.10^{-3}$ $6,32.10^{-3}$	$1,65.10^{-3}$	0	deg/s
Rate random walk $K=\sigma(3)$	$1,6.10^{-3}$ $1,0.10^{-3}$ $1,3.10^{-3}$ $1,0.10^{-3}$	$1,2.10^{-4}$	+1/2	$\frac{deg/s}{\sqrt{s}}$
Angle random walk $N=\sigma(1)$	$2,3.10^{-2}$ $2,6.10^{-2}$ $2,2.10^{-2}$ $2,5.10^{-2}$	$1,2.10^{-2}$	-1/2	$\frac{deg}{\sqrt{s}}$

The resulting angular accelerations of the quad sensor structure are calculated according to the equations:

$$G_{x,q}=\frac{G_1+G_2-G_3-G_4}{4}+G_x$$
$$G_{y,q}=\frac{G_1+G_2-G_3-G_4}{4}+G_y, \quad (1)$$
$$G_{z,q}=\frac{G_1+G_2-G_3-G_4}{4}+G_z$$

where $G_{x,q}$, $G_{y,q}$, $G_{z,q}$ – angular rate of the structure, G_i – bias of the *i*-th sensor, G_x, G_y, G_z – angular rate

The AV parameters are calculated for each axis angular rate of the single sensor and the resulting angular rate for the quad sensor structure according to the equation (1) and the results are shown at Table 1, Table 2 and Table 3 for the X, Y and Z angular rate respectively. It is clearly visible that all values of the quad sensor structure are lower than the corresponding noise parameter of the single sensor. The bias value is also less than the single sensor value and theoretically may be reduced to zero according to the equation (1) because the bias values are summed with the opposite sign of the different sensors.

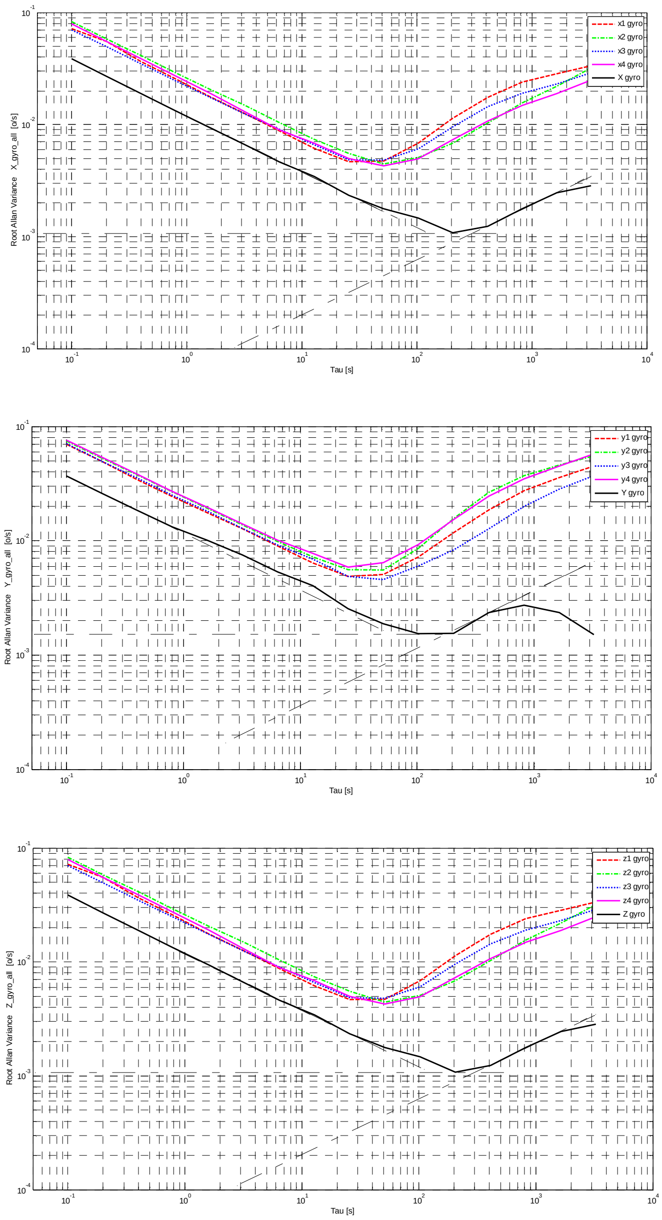

Figure 2. Allan deviation plot for all axes

The Figure 2 represents the AV plots for all axes of the single sensor and the quad sensor structure. The graphics shows that the noise components are lower for all values of the time cluster.

CONCLUSION

The Allan-variance method presented in this paper allows a systematic characterization of the various random errors contained in the output data of the inertial sensor. By performing a simple operation on the entire length of data, a characteristic curve is obtained whose inspection facilitates the determination of the different types and magnitude of error terms existing in the inertial sensors.

It is shown by this method that the quad sensor structure is distinguished with better noise parameters (rate random walk, angle random walk and bias instability) in comparison with the single MEMS gyroscopes. If the structure is manufactured as a single chip it may be used in many different applications like free-fall detection, precise tracking, kinetic measurements, tilt measurements, vehicle vibration monitoring, etc.

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