Calibration of MEMS Accelerometer Based on Kalman Filter and the Improved Six Position Method

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Abstract —The measurement precision of Micro Electronic Mechanical System (MEMS) accelerometer are influenced by zero drift, scale factor and installation error. In order to increase the measurement accuracy of the MEMS accelerometer, an improved calibration method is proposed on the basis of traditional six position method. The raw measurements of the MEMS accelerometer not divided by the scale factor are filtered by the Kalman Filter first, then the filtered values of six positions are calibrated to obtain the error model of MEMS accelerometer. The error model is verified by the experiments, and the results show that the measurement precision of the calibrated MEMS accelerometer is increased to 0.0066 m/s^2 from the uncalibrated 0.2646 m/s^2, and the measurement precision of pitch calculated by the calibrated MEMS accelerometer is increased to 0.145 degree. It has been verified that error model based on Kalman Filter and improved six location method are feasible and effective. Therefore, this error model can be very valuable in promoting MEMS accelerometer to be widely used in engineering field.

Index Terms—MEMS accelerometer, Installation error, Kalman Filter, Six position method, Calibration

I. INTRODUCTION

Compared with the traditional inertial device, Micro Electronic Mechanical System (MEMS) have advantages of low power dissipation, small size, low cost, high reliability, strongly anti-vibration and impact resistance and so on [1]-[4], it is widely used in oil drilling, aviation, navigation, automotive electronics, industrial control, consumer electronics, and other fields [5]-[7]. But, the installation error, zero bias and scale factor affect the measuring accuracy of MEMS accelerometer, so that the application of MEMS accelerometer was limited [8]-[9]. As one of the core components of inertial measurement unit [10]-[11], it is necessary to calibrate MEMS accelerometer by establishing an effective error model.

In 2009, Yongyuan Qin *et al.* did a calibration and compensation of the installation error of the MEMS accelerometer by the traditional six position method and took the actual output values divided by the scale factor as the research object [12]. In 2012, Xiaochun Wang and others did a calibration of the MEMS accelerometer in the whole temperature range and also took the actual output values of the MEMS accelerometer as the research object [13]. However, in practical engineering applications, the scale factor of MEMS accelerometer is often not a fixed value, if it is not compensated, it will cause error of the actual output value of MEMS accelerometer and lead to the inaccuracy of the calibration model. Therefore, an improved six position method for MEMS accelerometer calibration was adopted in our research, in which, the attitude indicator based on the MEMS inertia sensor was used for taking the measurement. The calibration scheme takes the raw data of MEMS accelerometer as the processed object in order to avoid inaccuracy caused by the unfixed scale factor. Usually, there are two types of calibration schemes: one is to establish different error calibration models in every temperature range by using the six position method; another is to establish an unified error calibration model in the whole temperature range by using the six position method. Considering about the constraint of the engineering application, this paper adopts the second calibration method. In order to reduce the influence of Gaussian noise, the raw data of MEMS accelerometer are filtered by using the Kalman Filter [14] first; and then, combined with the improved six position method, the error model of MEMS accelerometer is calibrated. The related experiments show that MEMS accelerometer can get a better compensation effect after calibration and meets accuracy requirements for the engineering applications, such as navigation, logging, gradiograph and so on.

The advantages of this calibration model also include small amount of calculation, operation-simple, ease of implementation and high precision, etc.

The rest of this paper is structured as follows. Section II presents output model of MEMS accelerometer. Section III introduces the principle of Kalman Filter and the improved six position method in detail. Section IV introduces calculation of calibration coefficient in error model of MEMS accelerometer in detail. Experimental results and discussion are provided in Section V. Finally, Section VI summarizes the paper.

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II. MEMS Accelerometer Output Model

In a stationary state, the X axis's output model of MEMS accelerometer is expressed, as follows:

$$A_x = a_{x0} + K_{ax} \times a_x + K_{ax1} \times a_x^{\,2} + K_{ax2} \times a_x \times a'_x \qquad (1)$$

where A_x is raw output value of the MEMS accelerometer, its unit is mV; a_{x0} is raw zero drift of MEMS accelerometer, its unit is mV; K_{ax} is the scale factor, its unit is mV/(m/s^2); K_{ax1} is the quadratic nonlinear coefficient, its unit is the mV/(m/s^2)^2; K_{ax2} is the cross-coupling coefficient, its unit is the mV/(m/s^2)^2; a_x is the output value in parallel with MEMS accelerometer input axis, its unit is m/s^2; a'_x is the vertical output value with MEMS accelerometer input axis, its unit is m/s^2. For MEMS accelerometer itself, the errors caused by the third and last terms of equation 1 are less than 5 ‰, so the third and last terms of equation 1 can be removed while dealing with accelerometer output values. Therefore, the accepted output model of MEMS accelerometer can be described as follows:

$$A_x = a_{x0} + K_{ax} \times a_x \qquad (2)$$

The original six position method is used in calibrating the MEMS accelerometer output value a_x . For better performance of MEMS accelerometers, K_{ax} should be a fixed value, but in practical application, it is often not a constant value which leads to inaccurate MEMS accelerometer output value. Consequently causes the error of the MEMS accelerometer output value calibrated by the traditional six position method. Based on this, an improved six position method is proposed to calibrate the raw output value A_x of MEMS accelerometer.

III. Calibration Algorithm

A. *The Principle of Kalman Filter*

The Kalman Filter is an optimal estimation method under the criterion of minimizing the sum of absolute errors. It has advantages of small amount of computations, strong real-time capability, and can constantly revise estimation value of the future motion state to improve the estimation precision considering real-time and robustness requirements by using the actual motion parameters [15].

The Kalman Filter of state equation and measurement equation are as follows respectively:

$$\mathbf{X}_i = \mathbf{B}\mathbf{X}_{i-1} + \mathbf{W}_i \qquad (3)$$

$$\mathbf{Z}_i = \mathbf{H}\mathbf{X}_i + \mathbf{V}_i \qquad (4)$$

where $\mathbf{B}$ is the 3×3 state transfer matrix, $\mathbf{H}$ is 3×3 the measurement matrix, i is the i time, $\mathbf{X}_i$ is system state at the time of i , $\mathbf{W}_i$ and $\mathbf{V}_i$ are the state and measurement matrix of noise respectively, $\mathbf{Z}_i$ is the 3×1 matrix and includes the measurement values of triaxial MEMS accelerometer.

The prediction equation of state vector:

$$\hat{\mathbf{X}}_{i|i-1} = \mathbf{B}\hat{\mathbf{X}}_{i-1|i-1} \qquad (5)$$

State vector covariance matrix prediction:

$$\mathbf{P}_{i|i-1} = \mathbf{B}\mathbf{P}_{i-1|i-1}\mathbf{B}^T + \mathbf{Q} \qquad (6)$$

The state vector updating equation:

$$\hat{\mathbf{X}}_{i|i} = \hat{\mathbf{X}}_{i|i-1} + \mathbf{G}_i(\mathbf{Z}_i - \mathbf{H}\hat{\mathbf{X}}_{i|i-1}) \qquad (7)$$

The covariance updating equation of state vector:

$$\mathbf{P}_{i|i} = (\mathbf{I} - \mathbf{G}_i\mathbf{H})\mathbf{P}_{i|i-1} \qquad (8)$$

Gain matrix of the Kalman Filter:

$$\mathbf{G}_i = \mathbf{P}_{i|i-1}\mathbf{H}^T(\mathbf{H}\mathbf{P}_{i|i-1}\mathbf{H}^T + \mathbf{R})^{-1} \qquad (9)$$

where $\mathbf{Q}$ and $\mathbf{R}$ are unrelated white noise, $\hat{\mathbf{X}}_{i-1|i-1}$ is the optimal result of previous state, $\hat{\mathbf{X}}_{i|i-1}$ is a predictive state of MEMS accelerometer, and $\hat{\mathbf{X}}_{i|i}$ is an estimated status of MEMS accelerometer at time of i , $\mathbf{P}_{i|i-1}$ is the predictive error covariance corresponding to $\hat{\mathbf{X}}_{i|i-1}$, $\mathbf{P}_{i|i}$ is the estimation error covariance, $\mathbf{G}_i$ is the Gain matrix, $\mathbf{I}$ is the 3×3 unit matrix.

B. *The Principle of the Improved Six Position Method*

After analyzing the X axis' output model of MEMS accelerometer, the installation error model of inertial measurement units based on triaxial MEMS accelerometer is expressed as follows:

$$\begin{bmatrix} A_x \\ A_y \\ A_z \end{bmatrix} = \begin{bmatrix} a_{x0} \\ a_{y0} \\ a_{z0} \end{bmatrix} + \begin{bmatrix} K_{ax} & S_{ax1} & S_{ax2} \\ S_{ay1} & K_{ay} & S_{ay2} \\ S_{az1} & S_{az2} & K_{az} \end{bmatrix} \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} \qquad (10)$$

where A_x, A_y and A_z are the original measurements of the triaxial MEMS accelerometer , and the unit is mV; a_{x0} , a_{y0} and a_{z0} are the original zero drifts of the triaxial MEMS accelerometer respectively, and the unit is mV; S_{ax1} , S_{ax2} , S_{ay1} , S_{ax2} , S_{az1} and S_{az2} are installation error coefficients of the MEMS accelerometer; K_{ax} , K_{ay} and K_{az} are scale factor of the MEMS accelerometer. Therefore, the error model of MEMS accelerometer considering actual output value can be written as shown in equation 11:

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} K_{ax} & S_{ax1} & S_{ax2} \\ S_{ay1} & K_{ay} & S_{ay2} \\ S_{az1} & S_{az2} & K_{az} \end{bmatrix}^{-1} \begin{bmatrix} A_x - a_{x0} \\ A_y - a_{y0} \\ A_z - a_{z0} \end{bmatrix} \qquad (11)$$

Different from the traditional six position method which used the actual output values of MEMS accelerometer divided by the scale factor as the processed object, the improved six position method used original output values not divided by the scale factor as the processed object.

IV. Calibration of Improved Six Position Method

A. Experimental Platform

As shown in Fig. 1, the attitude indicator based on MEMS sensor was independently designed and developed in our laboratory, which include triaxial MEMS accelerometer, triaxial MEMS gyroscope, triaxial magnetometer and a barometer. Its size is 34.4 mm × 32.6 mm × 15.7 mm, bias stability is less than 1 degree/h, static measuring accuracy is 0.2 degree, and dynamic measurement accuracy is 0.5 degree. Compared with the other attitude indicator, the volume was reduced under the condition that the measuring accuracy was not decreased. The designed attitude indicator is in the leading domestic level, and it has been applied in firefighter location so far. 902E-1 biaxial electric turntable was produced by Beijing Aviation Precision Machinery Research Center, its accuracy of revolutions is 1×10^{-3}($\pm0.01^o$/s ～ $\pm100^o$/s), and angular position accuracy is 5″. The turntable provides two functions: one is to provide the reference position when placing the MEMS accelerometer in six positions; and another is to provide a validation platform of calibration results.

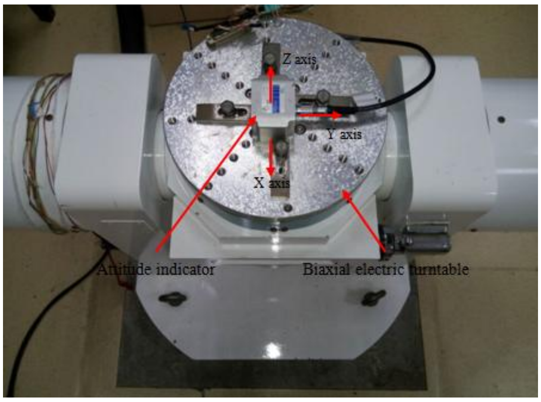


Fig. 1. Experimental platform

B. Calibration Scheme of the Improved Six Position Method

For obtaining the calibration coefficients of error model of MEMS accelerometer, the chosen six positions are shown in Table I.

TABLE I: SIX POSITION ORIENTATION OF MEMS ACCELEROMETER AND THE AXIS OF THE GRAVITATIONAL ACCELERATION

Position	Axis orientation			Gravity /g		
	X Axis	Y Axis	Z Axis	*X* Axis	*Y* Axis	*Z* Axis
1	ground	east	south	1	0	0
2	sky	north	west	-1	0	0
3	west	ground	south	0	1	0
4	north	sky	east	0	-1	0
5	south	west	ground	0	0	1
6	east	north	sky	0	0	-1

Respectively, MEMS accelerometer's three sensitive axis X, Y, Z were vertically placed at the turntable's surface up and down, "up" means that sensitve axis of MEMS accelerometer point to "sky", and "down" means that sensitive axis of MEMS accelerometer point to "groud", namely the center of earth. Table I shows the MEMS accelerometer's six positions and each axis's acceleration of gravity.

MEMS accelerometer calibration process is as follows:

- Place the attitude indicator axial direction vertically onto the turntable central axis;
- Turn on the power of the attitude indicator, and the preheating time is about 30 minutes;
- Regulate the turntable to ensure that MEMS accelerometer are respectively placed at the first, second, ..., six positions shown in Table I, and collect 1500 groups of data of each axis at each position;
- Filter out the Gaussian noise of triaxial MEMS accelerometer at each position, and take average of the filtered values, as the raw output value.

X axis raw output values of six positions of MEMS accelerometer can be respectively presented as follows:

$$\begin{cases} A_{x1} = a_{x0} + K_{ax}, A_{x2} = a_{x0} - K_{ax}, \\ A_{x3} = a_{x0} + S_{ax1}, A_{x4} = a_{x0} - S_{ax1}, \\ A_{x5} = a_{x0} + S_{ax2}, A_{x6} = a_{x0} - S_{ax2} \end{cases} \tag{12}$$

Y axis raw output values of six positions of MEMS accelerometer can be respectively presented as follows:

$$\begin{cases} A_{y1} = a_{y0} + S_{ay1}, A_{y2} = a_{y0} - S_{ay1}, \\ A_{y3} = a_{y0} + K_{ay}, A_{y4} = a_{y0} - K_{ay}, \\ A_{y5} = a_{y0} + S_{ay2}, A_{y6} = a_{y0} - S_{ay2} \end{cases} \tag{13}$$

Z axis raw output values of six positions of MEMS accelerometer can be respectively presented as follows:

$$\begin{cases} A_{z1} = a_{z0} + S_{az1}, A_{z2} = a_{z0} - S_{az1}, \\ A_{z3} = a_{z0} + S_{az2}, A_{z4} = a_{z0} - S_{az2}, \\ A_{z5} = a_{z0} + K_{az}, A_{z6} = a_{z0} - K_{az} \end{cases} \tag{14}$$

With (12), *X* axis' corresponding coefficients of MEMS accelerometer in the calibration model are obtained, as follows.

$$\begin{cases} a_{x0} = \dfrac{A_{x1} + A_{x2} + A_{x3} + A_{x4} + A_{x5} + A_{x6}}{6}, \\ K_{ax} = \dfrac{A_{x1} - A_{x2}}{2}, \\ S_{ax1} = \dfrac{A_{x3} - A_{x4}}{2}, \\ S_{ax2} = \dfrac{A_{x5} - A_{x6}}{2} \end{cases} \tag{15}$$

With (13), *Y* axis' corresponding coefficients of MEMS accelerometer in the calibration model are obtained, as follows.

$$\begin{cases} a_{y0} = \dfrac{A_{y1} + A_{y2} + A_{y3} + A_{y4} + A_{y5} + A_{y6}}{6}, \\ S_{ay1} = \dfrac{A_{y1} - A_{y2}}{2}, \\ K_{ay} = \dfrac{A_{y3} - A_{y4}}{2}, \\ S_{ay2} = \dfrac{A_{y5} - A_{y6}}{2} \end{cases} \tag{16}$$

With (14), Z axis' corresponding coefficients of MEMS accelerometer in the calibration model are obtained, as follows.

$$\begin{cases} a_{z0} = \dfrac{A_{z1} + A_{z2} + A_{z3} + A_{z4} + A_{z5} + A_{z6}}{6}, \\ S_{az1} = \dfrac{A_{z1} - A_{z2}}{2}, \\ S_{az2} = \dfrac{A_{z3} - A_{z4}}{2}, \\ K_{az} = \dfrac{A_{z5} - A_{z6}}{2} \end{cases} \tag{17}$$

C. Calculation of Calibration Coefficients

In order to reduce the influence of random noise on the MEMS accelerometers' original data, we smooth the original data of MEMS accelerometer by using Kalman Filter. The 1500 groups of raw data of MEMS accelerometer are collected and filtered at each position.

By averaging over the filtered original values of triaxial MEMS accelerometer respectively, the six positions' output values of triaxial MEMS accelerometer are obtained, as shown in the Table II.

TABLE II: THE AXIS OUTPUT VALUES OF MEMS ACCELEROMETER

Position	X axis (mV)	Y axis (mV)	Z axis (mV)
1	623.2727	-14.1387	-1.29067
2	-656.297	-10.3787	-15.4807
3	-8.90067	637.2373	-11.7007
4	-18.67	-657.565	-1.75267
5	-20.4347	-5.6	640.8233
6	-10.9193	-22.5593	-654.715

By combining (15), (16) and (17), X, Y, Z axis zero drift and calibration coefficients of MEMS accelerometer can be obtained, as shown in Table III.

TABLE III: AXIS OF MEMS ACCELEROMETER OF ZERO BIAS AND CALIBRATION COEFFICIENT

Sensitive axis	Zero drift (mV)	Calibration coefficient
X		$K_{ax} = 0.01531604$
	a_{x0} = -16.32488888	S_{ax1} = -0.00011468
		S_{ax2} = 0.00011399
Y		K_{ay} = 0.01513557
	a_{y0} = -12.16733333	S_{ay1} = 4.66691e-05
		S_{ay2} = -0.00019779
Z		K_{az} = 0.01512607
	a_{z0} = -7.35277777	S_{az1} = -0.00016739
		S_{az2} = 0.00011747

Therefore, the installation error model of MEMS accelerometer of attitude indicator can be described as follows.

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} 0.01531604 & -0.00011468 & 0.00011399 \\ 4.66691308\text{e-}05 & 0.01513557 & -0.00019779 \\ -0.00016739 & 0.00011747 & 0.01512607 \end{bmatrix} \times \begin{bmatrix} A_x + 16.32488888 \\ A_y + 12.16733333 \\ A_z + 7.35277777 \end{bmatrix} \tag{18}$$

V. RESULTS AND DISCUSSION

A. Calibration Verification Process

Equation 18 is utilized to process the original measurements of MEMS accelerometer for verifying the feasibility and effectiveness of the calibration model. The flow diagram of calibration and verification process is shown in Fig. 2.

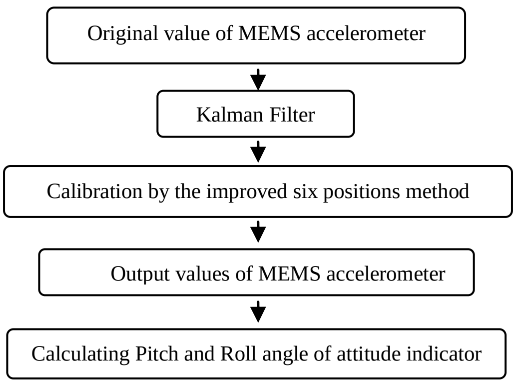
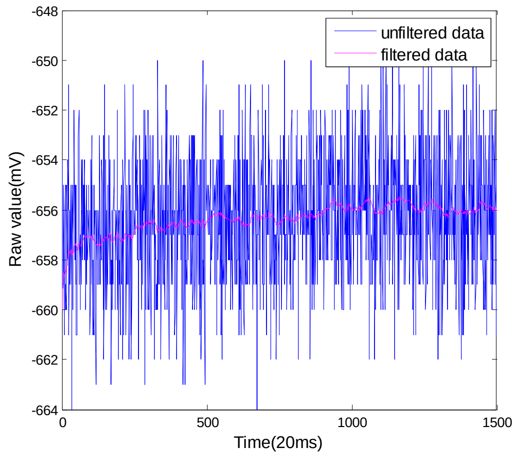


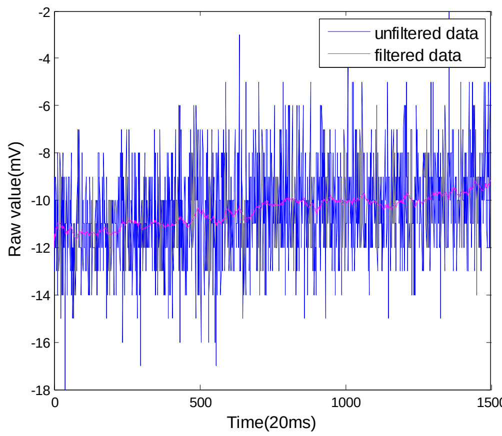
Fig. 2. Flow diagram

B. Analysis of Experimental Results

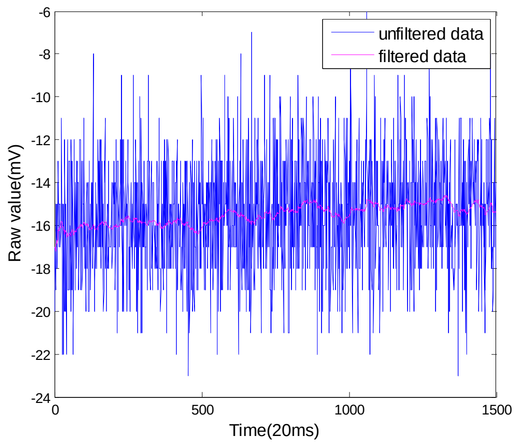
Place the X sensitive axis of MEMS accelerometer vertically onto the biaxial electric turntable and collect the original data; First, a number of collected original data are smoothed by the Kalman Filter, then the smoothed data are plugged into the error model of MEMS accelerometer, and finally, compare the uncalibrated and calibrated results. The unfiltered and filtered original values of MEMS accelerometer are shown in Fig. 3. MEMS accelerometer values calibrated by the improved six position method are shown in Fig. 4.



(a) Unfiltered and filtered values of X axis



(b) Unfiltered and filtered values of Y axis



(c) Unfiltered and filtered values of Z axis

Fig. 3. (a) Unfiltered and filtered values of X axis, (b) Unfiltered and filtered values of Y axis, (c) Unfiltered and filtered values of Z axis

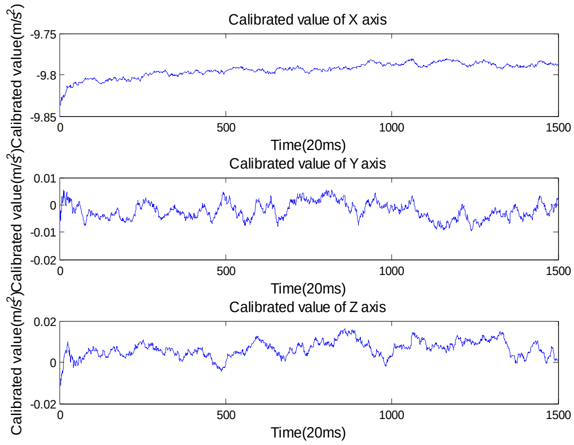


Fig. 4. The calibrated values of X axis, Y axis, and Z axis of MEMS accelerometer

In the paper, because chosen sample rate of MEMS accelerometer is 50 Hz and collected raw data are 1500 groups, 20 ms is chosen as the horizontal axis of Fig. 3 and Fig. 4.

As it can be seen from Fig. 3, filtering effect of X axis, Y axis and Z axis are very obvious. Raw data of MEMS accelerometer are seriously influenced by the Gaussian noise, then the filtered values of MEMS accelerometer become smooth. But because of the influence of the temperature, the values of MEMS accelerometer present a slow rising tendency. Considering raw data of MEMS accelerometer as processed object, the paper didn't adopt temperature compensation.

As it can be seen from Fig. 4, the calibrated values of X axis, Y axis, and Z axis of MEMS accelerometer are relatively stable, their variation range are very small. With the accumulation of time, the calibrated values of MEMS accelerometer show very little change because the values of MEMS accelerometer are influenced by temperature.

When X sensitive axis of MEMS accelerometer is placed onto the turntable plane, uncalibrated accelerometer values and calibrated accelerometer values by traditional six position method and improved six position method are shown in Table IV.

TABLE IV: UNCALIBRATED AND CALIBRATED OUTPUT VALUES OF MEMS ACCELEROMETER

Sensing axis	Uncalibrated accelerometer value (m/s^2)	Accelerometer value calibrated by traditional six position method (m/s^2)	Accelerometer value calibrated by improved six position method (m/s^2)
X	-9.3757	-9.8685	-9.8041
Y	-0.1483	-0.1260	-0.0021
Z	-0.2212	-0.1143	0.0137

As it can be seen from Table IV, uncalibrated values of X, Y and Z axis are -9.3757 m/s^2, -0.1483 m/s^2 and -0.2212 m/s^2 respectively, and its (Mean Absolute Error) MAE is 0.2646; Compared with traditional six position method, the MAE of MEMS accelerometer calibrated by the improved six position method is reduced to 0.0066 from 0.1029. The results show that the improved six position calibration method has an obvious improved effect.

When attitude indicator is in the static condition, accelerometer output values can be used for calculating its Pitching angle and Roll angle, so this can be used for testing the calibration effect of error model of MEMS accelerometer. Taking the Pitch angle as an example, attitude indicator was controlled by the turntable to ensure Pitch angle placed at position of 60 degree, as the reference value. The Pitch angles calculated by the uncalibrated and calibrated MEMS accelerometer output values are respectively shown in Fig. 5.

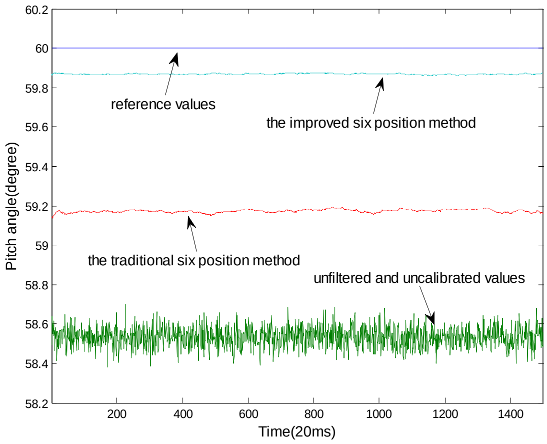


Fig. 5. Pitch angle calculated by uncalibrated MEMS accelerometer, and MEMS accelerometer calibrated by the traditional six position method and the improved six position method

As it can be seen from Fig. 5, after MEMS accelerometer is calibrated by the improved six position method, Pitch angle calculated by MEMS accelerometer is closer to the reference value, and the MAE is about 0.145 degree; after MEMS accelerometer is calibrated by the traditional six position method, MAE of Pitch angle calculated by MEMS accelerometer is about 0.822 degree; but for the unfiltered and uncalibrated MEMS accelerometer value, MAE of Pitch angle is about 1.44 degree. So the feasibility and the accuracy of calibration scheme are verified.

VI. CONCLUSION

As the measurement precision of MEMS accelerometer are mainly influenced by zero bias, scale factor and installation error, the error model based on Kalman Filter and improved six position method is proposed to calibrate the MEMS accelerometer. Firstly, six positions' raw data of MEMS accelerometer is respectively filtered by using Kalman Filter, which can reduce the influence of Gaussian noise; secondly, by averaging over the filtered original values of triaxial MEMS accelerometer respectively, the six positions' output values of triaxial MEMS accelerometer are obtained; finally, combined with the improved six position method, the calibration of error model is obtained to overcome the traditional six position method's error caused by the unfixed scale factor. The experiments show that the calibrated output values of MEMS accelerometer are closer to the actual values, and the precision of pitch calculated by the calibrated MEMS accelerometer is reduced to 0.145 degree. It has been verified that error model based on Kalman Filter and improved six position method is feasible and effective. With advantages of simple calculation, operation-simple, easy implementation, high precision and so on, calibration model can be very valuable in promoting MEMS accelerometer widely used in engineering field.

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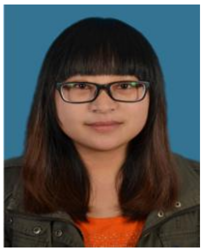

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