Gyroscope calibration with the method of simulated identification

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Abstract

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The calibration of Micro-Electro-Mechanical System (MEMS) gyroscopes is important for the application in which an angle is measured. The equipment for the calibration of this sensor is not always available. In this case, the method of simulated identification can be used. Some of the conditions are: using different tracks with saving angular velocity measurements, knowledge of influencing variables with their monitoring, and knowledge of the initial and final states of the angle. Based on this information, an algorithm is designed for the correction of influencing parameters by computer equipment. In our case, offsets, gains, and cross coupling coefficients are calculated for each axis of a sensor ADIS16405BLMZ. The result is an error of up to 0.5°/min of movement. To obtain high accuracy results, it is necessary to reach the conditions which are described in this contribution.

Keywords: simulation; angular velocity; Simpson's rule; MEMS sensors

Nowadays, the science sometimes focuses on tasks in which it is not possible to calibrate sensors non-electrical values in real time for different reasons. The situation is complicated when the measured value is obtained indirectly – by computation and depends on previous states. This one is a typical example of angular displacement measuring and actual data position provided by accelerometers and gyroscopes in strap-down inertial navigations.

The gyroscopes used are mostly derivation ones, therefore it is necessary to calculate the current angle from the angular velocity data by integration. The integration errors increase with an increasing number of samples. Therefore, the sensor has to be precisely calibrated. The offset on the sensor output has the highest influence on the general error of the measured angle.

MATERIAL AND METHODS

The measured angular velocity has to be compensated on the basis of the knowledge of the dependences which affect the operation of gyroscopes. The heading angle is calculated from the angular velocity by integration. The integration is connected with error increasing in time. Therefore, it is important to calibrate and compensate all influences at the highest rate.

The values influencing the angular velocity measurement are described in Eq. (1) (Titterton, Weston 2004):

$$\tilde{\omega}_x = (1 + S_x)\omega_x + M_y\omega_y + M_z\omega_z + B_f + \\ + B_{gx}a_x + B_{gz}a_z + B_{axz}a_y a_z + n_x \qquad (1)$$

where:
$\tilde{\omega}_x$ – compensated angular velocity (°/s)
S_x – scale factor error which can be expressed as a polynomial in ω_x to represent scale-factor non-linearities
M_y, M_z – cross coupling coefficients
ω_y, ω_z – angular velocity of y and z axis (°/s)
B_{f-g} – Earth gravity insensitive bias (°/s)
B_{gx}, B_{gz} – g-sensitive bias coefficients in the axis x and z (s/m)
a_x, a_y, a_z – accelerations in x, y and z axis (m/s^2)
B_{axz} – anisoelastic bias coefficient (s^3/m^2)
n_x – zero mean random bias in the axis x (°/s)

Analogically, it is necessary to compensate the angular velocity measurements in the three axes of the coordinate system.

The identification has generally a double meaning (Ondráček, Janíček 1990):
– knowledge about any object as the object identification,
– ideal identification with more or less different objects – system identification.

Under the term identification we can understand the identification of an idea which has begun with the advent of the computer technology and its aftermath of the system theory genesis. The main part of identification is an identification experiment with characteristic attributes. Its results must be objectivised input data for the identification solution. The next part of the identification consideration is the advisement, the values of which will be determined by the identification experiment and which require the measurement accuracy. The realisation "trial-error" is not acceptable (Ondráček, Janíček 1990).

A simulated identification consists of these steps (Ondráček, Janíček 1990):
– creation of an algorithm and active program of the current task, allowing to determine the correction parameters in the selected limits of the current task solution for the input data,
– the values of the correction parameters will be estimated,
– on the basis of experience and knowledge, intervals will be estimated to show in which range the measured values can be,
– correction in simulation according to the measurement error,
– the analysis of the identification solution and determination of the correction parameters,
– errors calculation for the selected correction parameters,
– analysis of the identification extent of initial and final values.

The input data of identification are the measured angular velocities in the axes x, y, and z. The output is the final heading angle of the inertial sensor in comparison with the initial position in all the three axes of the coordinate system. This is because of the fact that the precise angle cannot be measured in time. The determination of angles is done on the basis of information and is calculated from the gravity vector and magnetic induction vector of the Earth in the final position of a navigation unit. The output parameters are calculated from the differences between the initial and final angles of the measurement in simulation.

We chose the inertial sensor ADIS16405BLMZ (tri-axis inertial sensor with magnetometer) with a digital output developed by Analog Devices (Norwood, USA) for the demonstration of the designed method. It is a tri-axial accelerometer, gyroscope, and magnetometer developed by the Micro-Electro-Mechanical Systems (MEMS) technology. The dynamic range of the gyroscope is ±300 °/s and the initial sensitivity is 0.05 °/s/LSB. The absolute value of the magnetic induction vector is 45.8 μT, and during the measurement its value and direction were constant. The dynamic range of the accelerometer is ±18 g (176.59 m/s^2), and the initial sensitivity is 3.33 mg/LSB (0.03267 m/s^2). Other important parameters are described in the datasheet of the sensor.

We used a unit INU 1.0 designed by ourselves for the measurement data saving, which is based on a 32 bit microprocessor LM3S3748 developed by Texas Instruments Company (Dallas, USA). The measured data are saved on the flash memory of a USB mass storage device. The sample frequency used was 816.6598 Hz. The temperature was also monitored during the measurements. All input data for the sensor are measured at the temperature of 34°C which is important for easy data processing.

The temperature causes the offset fluctuation in MEMS gyroscopes. The effect of temperature on the offset is specified for individual gyroscopes and is considerably non-linear. The temperature effect brings an error into the measurement. ADIS-16405BLMZ contains a temperature sensor for the compensation of the temperature influence on the measured values. The sensor datasheet refers to the temperature dependence of the gyroscope, which is ±40 ppm/K. Non-linearity is up to 0.1% in the full range. The influence of the power supply voltage is minimalized with using a precision voltage regulator. The voltage waveform is watched during the measurements realised currently with the inertial sensor. Therefore, the dependence mentioned is not interesting for our work.

The output samples obtained from MEMS gyroscopes are disturbed by white noise. Let N_i be the i^{th} random variable in the white noise sequence. Each N_i is identically distributed with the mean $E(N_i) = E(N) = 0$ and finite variance $Var(N_i) = Var(N) = \sigma^2$. By the definition of the white sequence $Co_iv(N_i, N_j) = 0$ for all $i \neq j$. The result of using the rectangular rule to integrate the white noise signal ε (t) over a timespan $t = n \times \delta t$ is (Woodman 2007):

$$\int_0^t \varepsilon(\tau)d\tau = \delta t' \sum_{i=1}^{n} N_i \qquad (2)$$

where:
n – number of samples received from the device during the period
$\delta t'$ – time between successive samples

The expected error is:

$$E(\int_0^t \varepsilon(\tau)d\tau) = \delta t' \times n \times E(N) = 0 \qquad (3)$$

and the variance is:

$$Var(\int_0^t \varepsilon(\tau)d\tau) = \delta t^2 \times n \times Var(N) = \delta t \times t \times \sigma^2 \qquad (4)$$

Hence, the noise introduces a zero-mean random walk error into the integrated signal, whose standard deviation (Woodman 2007)

$$\sigma_\theta(t) = \sigma \times \sqrt{\delta \times t} \qquad (5)$$

grows in proportion to the square root of time. Since we are usually interested in how the noise affects the integrated signal, it is common for manufacturers to specify the noise using an angle random walk (ARW) measurement

$$ARW = \sigma_\theta(1) \qquad (6)$$

with units °/sqrt(hour). The random walk is given for the used sensor. The random walk is one of the parameters which cannot be compensated by the designed method. The effect on the accuracy of the measurement is negative.

The angle was calculated according to Simpson's rule with six nodes (Chapra 2002):

$$\alpha_{xn+1} = \alpha_{xn} + \frac{1}{3f}(\omega_{xi-6} + 4\omega_{xi-5} + 2\omega_{xi-4} + 4\omega_{xi-3} + 2\omega_{xi-2} + 4\omega_{xi-1} + \omega_{xi}) \qquad (7)$$

where:
α_{xn+1} – new value of angle in the x axis (°)
α_{xn} – previous value of angle in the x axis (°)
f – sample frequency (Hz)
ω_x – actual sample of angular velocity (°/s)

RESULTS AND DISCUSSION

Fig. 1 illustrates the time waveform of the noise in the individual axes of the gyroscope. On the basis of its distribution, it is possible to determine approximately the offset limits of identification and to speed up the whole calculation. The averages of the individual axes were –0.0447 °/s in the x axis, –0.3754 °/s in the y axis, and 0.151 °/s in the z axis. In simulation, we obtained the offset limits from –0.1 °/s to 0 °/s for the x axis, from –0.45 °/s to –0.3 °/s for the y axis, and from 0.1 °/s to 0.2 °/s for the z axis of the values described. We calculated with 0.001 °/s step for all offsets.

Gain calibration has a condition that the initial and final angles of simulation must be different, namely the more the better. In supposition that the angles should be equal, the simulation results would always have initial values of the calibration parameters for gains in each axis. For all the axes, the limits are in a 5% tolerance, from –0.05 to 0.05 with 0.001 steps. We did not suppose that the deviations in gain would overreach the setup tolerance.

In the next step, we were interested in finding the calibration constants for cross coupling coefficients (M). The developer specifies the accuracy of this parameter being ±0.05°. Based on this description, we set the simulation limits at ±0.0009 with 0.0001 steps for each axis.

We did not pay attention to g-sensitive bias correction. In the case of its inclusion among the calibration parameters, we must ensure the accel-

Table 1. Calibration parameters found

	B	S	$M1$	$M2$
x axis	–0.012	0.002	–0.0002 (y)	0.0001 (z)
y axis	–0.396	0.011	0.0001 (x)	0.0004 (z)
z axis	0.196	0.014	–0.0003 (x)	–0.0001 (y)

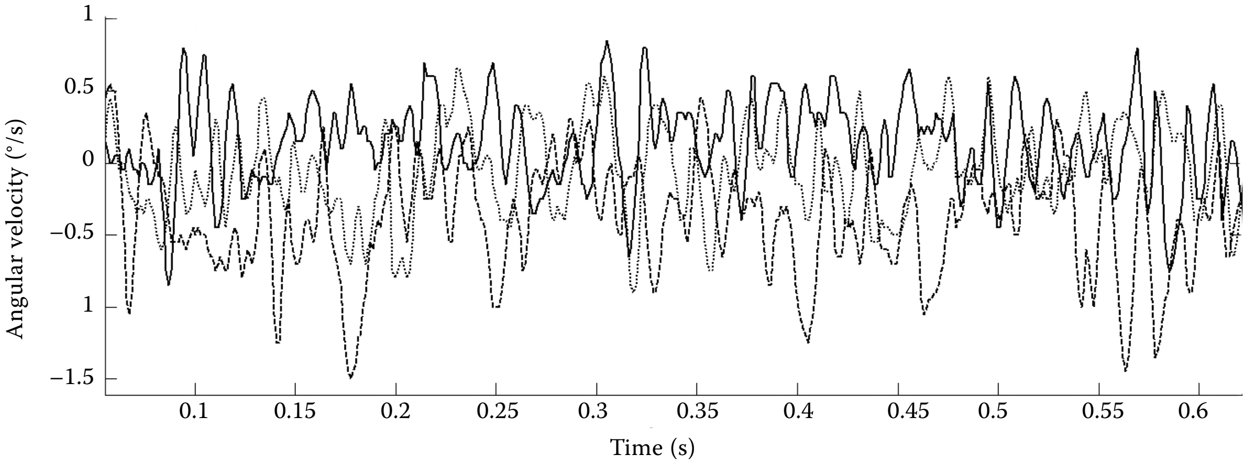

Fig. 1. Angular velocity noise example

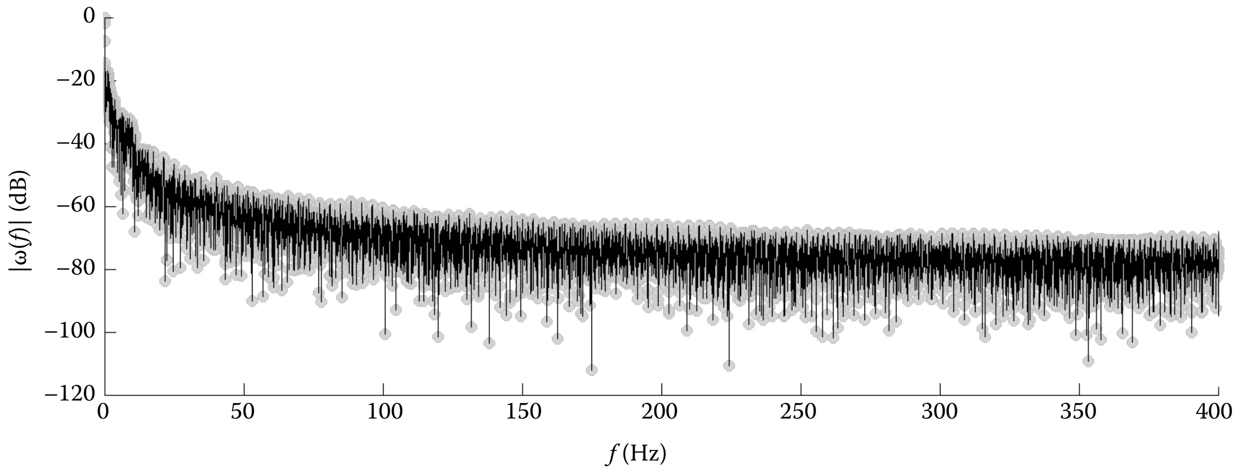

Fig. 2. Fast Fourier Transform (FFT) of angular velocity measurements
$\omega(f)$ – single-sided amplitude spectrum of angular velocity in time; f – frequency

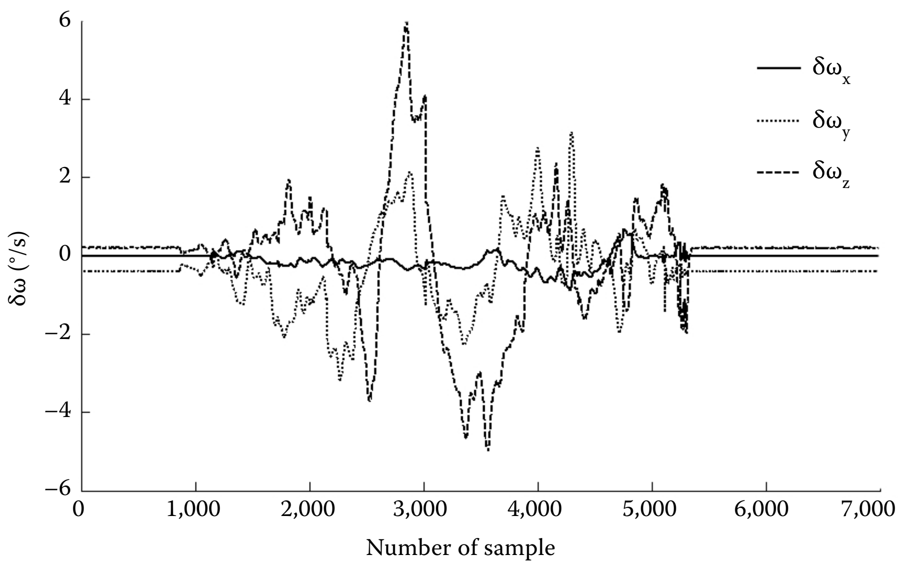

Fig. 3. Difference between angular velocities before and after calibration
$\delta\omega_x$, $\delta\omega_y$, $\delta\omega_z$ – angular velocity difference before and after calibration in axis x, y and z (°/s)

eration values of at least 4 g; otherwise, it is not possible to find precise values of the correction parameters with the method described. For the used sensor, g-sensitive bias is up to 0.05 °/s/g.

With using one waveform, the results may be markedly distorted. As a rule, the results will be more precise with the increasing number of paths. A disadvantage is in an increased complication of the results. In our case, we chose three different time waveforms in the range of 15 seconds. The optimal coefficients were considered to be those with which the sum of deviations in each axis of all waveforms was minimal. In the next step, it is necessary to check the waveforms of angular velocity before simulation if the values do not overreach the dynamic range of the sensor. In the case of the angular velocity waveform limitation, errors would occur in the identification. The resulting correction parameters would be useless. The result of simulation is shown in Table 1.

Fig. 2 proved that the frequency components in the time measurement were deeply below half the sample frequency value. Nyquist-Shannon sampling theorem was thus fulfilled.

The designed algorithm of the described method was created in the Matlab application (MathWorks, Natick, USA). All data are in a data array form. The consequential algorithm for finding optimal correction parameters consists of six nested loops for each axis of the coordinate system. Fig. 3 shows the difference between angular velocities before and after calibration.

CONCLUSION

The main disadvantage of MEMS gyroscope error sources is the error specification in individual sensors. Therefore, each sensor requires an individual approach as regards the calibration and correction. Conventional methods for the calibration of gyroscopes require a special workplace, which is difficult to be available. For the development of simple applications with gyroscopes, the sensors can be calibrated by the described method. A disadvantage is just the time which is necessary for the calculation of the correction parameters. In our case, we have obtained sensor accuracy of up to 0.5° (up to 15° without calibration) during one min in the working time of the device. However, the accuracy has an influence also on the dynamic range of angular velocity where the resolution of the sensor plays an important role.

References

Chapra S.C., 2002. Numerical Methods for Engineers: With Software and Programming Applications. 4th Ed. New York, McGraw-Hill.

Ondráček E., Janíček P., 1990. Výpočtové modely v technickej praxi. [Computational Models in Technical Practice.] Prague, SNTL.

Titterton H.D., Weston J.L., 2004. Strapdown Inertial Navigation Technology, 2nd Ed. Stevenage, Institution of Engineering and Technology.

Woodman O., 2007. An introduction to Inertial Navigation. Technical report No. 696. Cambridge, University of Cambridge.

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