Freescale Semiconductor
Application Note

AN4069
Rev 0, 09/2010

Energy Efficient Solutions by Freescale

Offset Calibration of the MMA8451, 2, 3Q

by: Kimberly Tuck
Applications Engineer

1.0 Introduction

Various sources of error in an accelerometer need to be understood and, in some cases, compensated before use. Understanding these sources of errors can be as important as understanding how the accelerometer operates within an application. One of the leading sources of error in an accelerometer is attributed to the 0g-offset or bias error, which is defined as *"the difference between the measured value of the sensor from the true zero value"*.

Accelerometers are "trimmed" for offset and sensitivity in the factory by adjusting the offset trim codes and gain by using factory programmable registers within the part. Accelerometers are trimmed within a narrow test target in the manufacturing process to calibrate out these sources of error within the devices. Ultimately, the accuracy of the test station and its ability to calibrate determine how well the devices are initially calibrated during the manufacturing process.

End users then solder the accelerometers onto a PCB upon which various mechanical strains are produced:

- On the package from mounting the part to the PCB
- From the PCB mount holes or screws
- From other components placed close to the sensor

Such conditions can cause further offset or shifts. Other sources of shifts can also occur due to temperature changes and aging. All of these sources of errors may cause the accelerometer to appear to be tilted or rotated relative to the zero reference point. Re-calibration after the sensor has been PCB-mounted may be needed for other reasons as well. For example, an application may need to change the zero (0) reference point if the zero (0) position in a tilt application is always at a 15° angle, thus considering this the new "zero" position. These re-calibrations add to the end product manufacturing cost (by adding additional steps to assembly). Accordingly, the benefit of re-calibration will have to be weighed against these added costs.

TABLE OF CONTENTS

1.1 Key Words

Accelerometer, Calibration, 0g-offset, Bias Error, Trim, Offset Trim, Sensor, Sensitivity, Zero Reference Point, Tilt Application, AN3447, XYZ Registers, LSB.

freescale Xtrinsic

1.2 Summary

A. The 0g offset and sensitivity errors can be significant sources of error for applications requiring high accuracy. Due to these potential sources of errors, attention and care should be taken to calibrate the MMA845 1, 2, 3Q.

B. The calibration values will be stored in the device until the power is removed (requiring the calibration process to be performed every time the device is powered up).

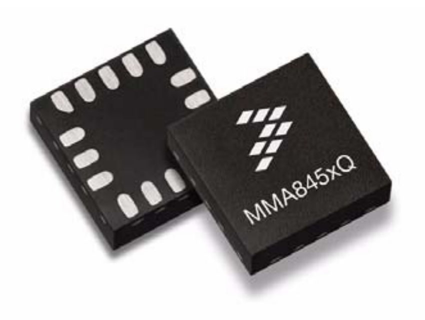
C. The trade-off of the cost of this extra manufacturing step should be considered depending on the application requirements.

D. For applications requiring low accuracy tilt, or applications interested in AC measurements only, calibration may not be necessary.

2.0 MMA8451, 2, 3Q Consumer 3-axis Accelerometer 3 x 3 x 1 mm

The MMA8451, 2, 3Q has a selectable dynamic range of ±2g, ±4g, ±8g. The device has 8 different output data rates, selectable high pass filter cut-off frequencies, and high pass filtered data. The available resolution of the data and the embedded features is dependant on the specific device.

Note: The MMA8450Q has a different memory map and has a slightly different pin-out configuration.



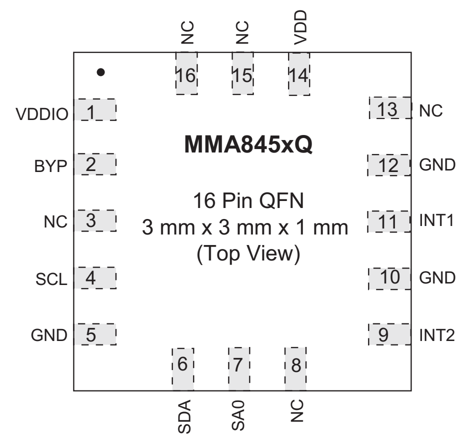


Figure 1. MMA8451, 2, 3Q Consumer 3-axis Accelerometer 3 x 3 x 1 mm

2.1 Output Data, Sample Rates and Dynamic Ranges of all Three Products

2.1.1 MMA8451Q

1. **14-bit data**
   2g (4096 counts/g = 0.25 mg/LSB) **4g** (2048 counts/g = 0.5 mg/LSB) **8g** (1024 counts/g = 1 mg/LSB)
2. **8-bit data**
   2g (64 counts/g = 15.6 mg/LSB) **4g** (32 counts/g = 31.25 mg/LSB) **8g** (16 counts/g = 62.5 mg/LSB)
3. **Embedded 32 sample FIFO (MMA8451Q)**

2.1.2 MMA8452Q

1. **12-bit data**
   2g (1024 counts/g = 1 mg/LSB) **4g** (512 counts/g = 2 mg/LSB) **8g** (256 counts/g = 3.9 mg/LSB)
2. **8-bit data**
   2g (64 counts/g = 15.6 mg/LSB) **4g** (32 counts/g = 31.25 mg/LSB) **8g** (16 counts/g = 62.5 mg/LSB)

2.1.3 MMA8453Q Note: No HPF Data

1. **10-bit data**
   2g (256 counts/g = 3.9 mg/LSB) **4g** (128 counts/g = 7.8 mg/LSB) **8g** (64 counts/g = 15.6 mg/LSB)
2. **8-bit data**
   2g (64 counts/g = 15.6 mg/LSB) **4g** (32 counts/g = 31.25 mg/LSB) **8g** (16 counts/g = 62.5 mg/LSB)

2.2 Application Notes for the MMA8451, 2, 3Q

The following is a list of all the application notes available for the MMA8451, 2, 3Q:

- **AN4068**, *Embedded Orientation Detection Using the MMA8451, 2, 3Q*
- **AN4069, *Offset Calibration of the MMA8451, 2, 3Q***
- **AN4070**, *Motion and Freefall Detection Using the MMA8451, 2, 3Q*
- **AN4071**, *High Pass Filtered Data and Functions Using the MMA8451, 2,3Q*
- **AN4072**, *MMA8451, 2, 3Q Single/Double and Directional Tap Detection*
- **AN4073**, *Using the 32 Sample First In First Out (FIFO) in the MMA8451Q*
- **AN4074**, *Auto-Wake/Sleep Using the MMA8451, 2, 3Q*
- **AN4075**, *How Many Bits are Enough? The Trade-off Between High Resolution and Low Power Using Oversampling Modes*
- **AN4076**, *Data Manipulation and Basic Settings of the MMA8451, 2, 3Q*
- **AN4077**, *MMA8451, 2, 3Q Design Checklist and Board Mounting Guidelines*

3.0 Methods of Calibrating

A few different methods of calibrating the accelerometer are discussed in Freescale application note AN3447, which may be helpful to review. Typically, either an end user wants to do a quick calibration with minimal amount of effort to correct the bias error, or, alternately, wants to put in more care to account for both bias and sensitivity errors in order to calibrate out these sources of error for the most accurate reading. These two methods are presented in the following sections.

3.1 Simple Offset Calibration Method

With no offset error, and when in the ideal zero (0) reference position, the accelerometer will read 0g. Regarding the sensor, it is important to understand what the (zero) 0g reading represents. Since the MMA845 1, 2, 3Q is a digital part, the 0g reading will depend on how the output has been scaled. First, it is important to understand how to read the output values from the accelerometer. That is,

- In the MMA845 1, 2, 3Q, the digital 0g reading will be 0x00
- Negative values are in 2's complement format coming out of the XYZ registers. Therefore, a value of 4095 corresponds to -1 counts as a 12 digit number, 16383 corresponds to -1 as a 14-bit number and 1023 corresponds to -1 as a 10-bit number.

Typical procedure:

- Set the accelerometer in the flat position.
- Record the value for X and Y at 0g and Z at +1g
- Per the known device sensitivity, calculate the 0g value for Z by subtracting the 1g acceleration output from the known sensitivity

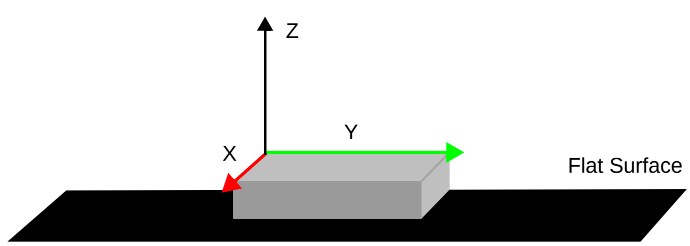


Figure 2. Accelerometer Calibration Set-up

3.1.1 Computing Calibrated Values

This technique requires the values to be read while the device is in one position, therefore, requiring minimal effort. The calibrated values are computed as follows:

$$Calx = -1\ ax$$
$$Caly = -1\ ay$$
$$Calz = S - az$$

where ax, ay and az are the 0g offset acceleration readings measured on the x, y and z axes, respectively.

Note: "S" refers to the sensitivity of the device.

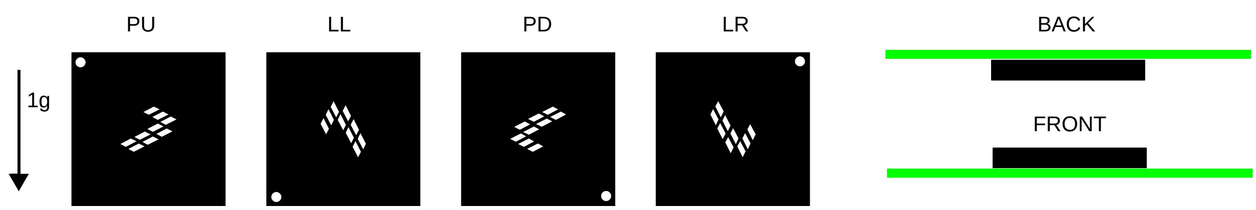
The calibrated values are added to the current acceleration reading in the device.

$$X = Current\ ax + Calx$$
$$Y = Current\ ay + Caly$$
$$Y = Current\ az + Calz$$

3.2 More Accurate Calibration Method: Offset and Sensitivity

To increase accuracy, more characterization of the part must be performed in all six positions in order to calibrate out both the offset and the sensitivity errors. Note the following procedure.

1. Place the accelerometer on a flat surface.
2. Record the offset values for all directions of the sensor by recording the offset on all 6 faces.
3. After recording offset values for all six positions, determine the sensitivities and offsets for each axis.
4. Calculate offsets by taking the average of all four (4) 0g positions (Figure 3), or
5. Take the midpoint reading of the -1g and +1g reading for each axis (as indicated in AN3447)



6 Positions	Portrait Up	Landscape Left	Portrait Down	Landscape Right	Front	Back
X	0g	-1g	0g	+1g	0g	0g
Y	-1g	0g	+1g	0g	0g	0g
Z	0g	0g	0g	0g	+1g	-1g

Figure 3. Offset Values on All Six Faces

The following are the sensitivity calculations for each axis:

$$0g_x = \frac{(PU_x + PD_x + Front_x + Back_x)}{4}$$

$$0g_y = \frac{(LL_y + LR_y + Front_y + Back_y)}{4}$$

$$0g_z = \frac{(PU_z + LL_z + PD_z + LR_z)}{4}$$

The calibration values are recorded as follows:

Calx = -0gx

Caly = -0gy

Calz = -0gz

4.0 Calibration Procedure for the MMA8451, 2, 3Q

In the MMA845 1, 2, 3Q there are three 8-bit (volatile) offset registers for storing the calibration values, at one register per axis. When the offsets are stored in these registers the values will be added to the X, Y, and Z output of the device automatically until the device is powered off. When the device is powered off, these values will be lost. Note: In order to avoid re-programming for offset, store the calibration values in memory on the processor or MCU. One LSB in the offset register corresponds to 2 mg. The offset register is an 8 bit 2's complement number. Therefore the maximum calibration that can be stored is ±256 mg. There are three (3) sensitivity ranges in each device since there are three dynamic ranges (2g, 4g and 8g). It will be necessary to correlate the output data knowing the offset registers are 2 mg per 1 LSB.

4.1 Calibrating the MMA8451Q (14-bit Data)

4.1.1 Calibration from 2g Mode

If the calibration is done reading in 2g mode (0.25 mg/count) then every value will be **divided by 8** when storing it in the calibration registers. One (1) count in the calibration register corresponds to 8 counts from the output data. For example if the offset result is -12 counts then the value would be 12/8 = 1.5 counts. The value to be stored is therefore +1 count or +2 counts to shift the offset to zero. This is 1 or 2 as a 2's complement number stored in the calibration register.

4.1.2 Calibration from 4g Mode

If the calibration is done reading in 4g mode (0.5 mg/count) then every value will be **divided by 4** when storing it in the calibration registers. One (1) count in the calibration register corresponds to 4 counts from the output data. For example if the offset result is 9 counts from the output data then 9/4 = 2.25. The value to be stored is -2, which is 254 as a 2's complement number stored in the calibration register.

4.1.3 Calibration from 8g Mode

If calibrating from 8g mode, **1 count in the calibration register corresponds to 2 counts from the output data.** If the 0g offset for the X-axis is 5 counts then the value to be stored in the calibration register is -5/2 counts. This could be stored as either 254 or 253 in the offset registers.

4.2 Calibrating the MMA8452Q (12-bit Data)

4.2.1 Calibration from 2g Mode

If calibration is done from the 2g mode then **1 count in the calibration register corresponds to 2 counts from the output data.** The output data is **divided by 2** when storing it in the calibration registers.

4.2.2 Calibration from 4g Mode

If the calibration is done reading in 4g mode (2 mg/count) then **1 count in the calibration register corresponds to 1 count from the output data.**

4.2.3 Calibration from 8g Mode

If the calibration is done reading in 8g mode (3.9 mg/count) then every value will be **multiplied by 2** when storing it in the calibration registers. For example if the offset result is 2 counts then the value would be -2 x 2 = -4 counts. The value to be stored is therefore -4 counts to shift the offset to zero. This is 252 as a 2's complement number stored in the calibration register.

4.3 Calibrating the MMA8453Q (10-bit Data)

4.3.1 Calibration from 2g Mode

If calibration is done on the MMA8453Q from 2g range (3.9 mg/count) then 1 count of output data corresponds to 2 counts in the calibration register. Every output count will be **multiplied by 2** before going into the calibration register. If the 0g offset for the X-axis is -5 counts from the output data in 2g mode then this corresponds to +5 counts x 2 = 10 counts. The value to be stored in the calibration register is +10 counts to shift the value to zero. This is a 2's complement value of 10 stored in the 8 bit calibration register.

4.3.2 Calibration from 4g Mode

If the calibration is done reading in 4g mode (7.8 mg/count) then every count will be **multiplied by 4** before going into the calibration registers. One count of the output data corresponds to 4 counts in the calibration register.

4.3.3 Calibration from 8g Mode

If the calibration is done reading in 8g mode (15.6 mg/count) then every value will be **multiplied by 8** before storing it in the calibration registers. One count of the output data corresponds to 8 counts in the calibration register.

Advisory: It is best to read the data at 1.56 Hz Output Data Rate (ODR) with the LNOISE bit in Register 0x2A set. Also if the device can be put in High Resolution Mode (Register 0x2B) this can improve the accuracy of the reading as well. This is the highest resolution possible for the device. The accuracy of the calibration is within ±2mg.

5.0 Auto-Calibration Example Procedure

In the following example routine, the board will remain flat and will take readings, where X would ideally read 0g, Y would read 0g, and Z would be at +1g. The device goes into active mode to read out the new XYZ values and then goes into standby mode to write the updated calibration values.

Note: Hold the board flat so that X and Y are in the 0g field and Z is in the 1g field.

```
MMA845x_Standby();
     /*
     **  Configure sensor for:
     **    - Sleep Mode Poll Rate of 50Hz (20ms)
     **    - Low Noise Bit Set
     **    - System Output Data Rate of 1.56Hz (640ms)
     **    - Full Scale of +/-2g
     **    - High Resolution Mode MODS1 bit set
     */
IIC_RegWrite(SlaveAddressIIC, CTRL_REG1, ASLP_RATE_20MS+LNOISE_MASK+DATA_RATE_640MS);
IIC_RegWrite(SlaveAddressIIC, XYZ_DATA_CFG_REG, FULL_SCALE_2G);
IIC_RegWrite(SlaveAddressIIC, CTRL_REG2, MODS1_MASK);


/*
     **  Set the Calibration variables to zero
*/
signed int X_cal=0;
signed int Y_cal=0;
signed int Z_cal=0;

/*
**   Clear the Calibration Register
*/
IIC_RegWrite(SlaveAddressIIC, OFF_X_REG, 0x00);
IIC_RegWrite(SlaveAddressIIC, OFF_Y_REG, 0x00);
IIC_RegWrite(SlaveAddressIIC, OFF_Z_REG, 0x00);

/*
**   Go into the Active Mode
*/
MMA845x_Active();

/*
**   Delay time to change from Standby to Active before taking a reading
**   at 1.56Hz (2/ODR + 1ms delay timing)

Delay(1300ms_delay);

IIC_RegReadN(SlaveAddressIIC, OUT_X_MSB_REG, 6, &value[0]);
x_value.Byte.hi = value[0];
x_value.Byte.lo = value[1];
y_value.Byte.hi = value[2];
```

```
y_value.Byte.lo = value[3];
z_value.Byte.hi = value[4];
z_value.Byte.lo = value[5];


     switch (deviceID)
     {

            case 1:
            /**
            **   Calculations for the 14-bit MMA8451Q device calibration
            */

            PrintXYZdec14(); //Print out the XYZ values in signed counts
            SCI_putCRLF(); //New Line, Left Justify

            if (x_value.Byte.hi> 0x7F)
            {
            x_value.Word= (~x_value.Word +1)>>2;
            X_cal= X_cal + x_value.Word/8;
            }
            else
            {
            X_cal= X_cal + ((~x_value.Word+1)>>2)/8;
            }
            if (y_value.Byte.hi> 0x7F)
            {
            y_value.Word= (~y_value.Word +1)>>2;
            Y_cal= Y_cal + y_value.Word/8;
            }
            else
            {
            Y_cal= Y_cal + ((~y_value.Word+1)>>2)/8;
            }
            if (z_value.Byte.hi> 0x7F)
            {
            z_value.Word= (~z_value.Word +1)>>2;
            Z_cal+=(4096 + z_value.Word)/8;
            }
            else
            {
                Z_cal+=(int)(4096- (z_value.Word>>2))/8;
                if (Z_cal<0)
                {
                Z_cal+=256;
                }
            }
            break; // End of MMA8451Q case

            case 2:
            /*
            **   Calculations for the 12-bit MMA8452Q device calibration
            */

            PrintXYZdec12();
            SCI_putCRLF();

            if (x_value.Byte.hi> 0x7F)
            {
```

```
x_value.Word= (~x_value.Word +1)>>4;
X_cal= X_cal + x_value.Word/2;
}
else
{
X_cal= X_cal + ((~x_value.Word+1)>>4)/2;
}
if (y_value.Byte.hi> 0x7F)
{
y_value.Word= (~y_value.Word +1)>>4;
Y_cal= Y_cal + y_value.Word/2;
}
else
{
Y_cal= Y_cal + ((~y_value.Word+1)>>4)/2;
}
if (z_value.Byte.hi> 0x7F)
{
z_value.Word= (~z_value.Word +1)>>4;
Z_cal+=(1024 + z_value.Word)/2;
}
else
{
    Z_cal+=(int)(1024- (z_value.Word>>4))/2;
    if (Z_cal<0)
    {
    Z_cal+=256;
    }
}
break; // End of MMA8452Q case

case 3:
/*
**   Calculations for the 10-bit MMA8453Q device calibration
*/

PrintXYZdec10();
SCI_putCRLF();

if (x_value.Byte.hi> 0x7F)
{
x_value.Word= (~x_value.Word +1)>>6;
X_cal= X_cal + (x_value.Word)*2;
}
else
{
X_cal= X_cal + ((~x_value.Word+1)>>6)*2;
}
if (y_value.Byte.hi> 0x7F)
{
y_value.Word= (~y_value.Word +1)>>6;
Y_cal= Y_cal + (y_value.Word) *2;
}
else
{
Y_cal= Y_cal + ((~y_value.Word+1)>>6)/2;
}
if (z_value.Byte.hi> 0x7F)
{
```

```
            z_value.Word= (~z_value.Word +1)>>6;
            Z_cal+=(256 + z_value.Word)*2;
            }
            else
            {
                Z_cal+=(256- (z_value.Word>>6))*2;
                if (Z_cal<0)
                {
                Z_cal+=256;
                }
            }
            break; // End of MMA8453Q case

 }  //End of switch statement

      /*
      ** Go to Standby mode and write the Calibration values into the registers
      */
            MMA845x_Standby();
            IIC_RegWrite(SlaveAddressIIC, OFF_X_REG, (byte)X_cal);
            IIC_RegWrite(SlaveAddressIIC, OFF_Y_REG, (byte)Y_cal);
            IIC_RegWrite(SlaveAddressIIC, OFF_Z_REG, (byte)Z_cal);
            MMA845x_Active();
```

How to Reach Us:

Home Page:
www.freescale.com

Web Support:
http://www.freescale.com/support

USA/Europe or Locations Not Listed:
Freescale Semiconductor, Inc.
Technical Information Center, EL516
2100 East Elliot Road
Tempe, Arizona 85284
1-800-521-6274 or +1-480-768-2130
www.freescale.com/support

Europe, Middle East, and Africa:
Freescale Halbleiter Deutschland GmbH
Technical Information Center
Schatzbogen 7
81829 Muenchen, Germany
+44 1296 380 456 (English)
+46 8 52200080 (English)
+49 89 92103 559 (German)
+33 1 69 35 48 48 (French)
www.freescale.com/support

Japan:
Freescale Semiconductor Japan Ltd.
Headquarters
ARCO Tower 15F
1-8-1, Shimo-Meguro, Meguro-ku,
Tokyo 153-0064
Japan
0120 191014 or +81 3 5437 9125
support.japan@freescale.com

Asia/Pacific:
Freescale Semiconductor China Ltd.
Exchange Building 23F
No. 118 Jianguo Road
Chaoyang District
Beijing 100022
China
+86 10 5879 8000
support.asia@freescale.com

For Literature Requests Only:
Freescale Semiconductor Literature Distribution Center
1-800-441-2447 or +1-303-675-2140
Fax: +1-303-675-2150
LDCForFreescaleSemiconductor@hibbertgroup.com

freescale™ semiconductor

AN4069
Rev. 0
09/2010