Detecting Freefall with Low-G Accelerometers

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INTRODUCTION

This application note describes the method of detecting freefall with Freescale's MMA7260Q 3-axis accelerometer. It will cover an overview of the application, the capability of the method, and considerations for developing a freefall detection system. The freefall algorithm was prototyped, tested, and characterized using the TRIAX2 and the STAR board Freescale development tools.

FREEFALL OVERVIEW

Using Freescale Accelerometers, the measurements of static acceleration from gravity and dynamic acceleration, due to a combination of gravity and motion, can be achieved. Freefall is a type of dynamic acceleration. Using the accelerometer to monitor the accelerations of a system, different freefall motions can be detected, called "freefall signatures". We have developed an algorithm to monitor the components of freefall signatures to determine when a freefall condition is met. There are three categories of a fall — linear, rotational, and projectile. A linear fall is defined as a linear translation of an object falling from any orientation, where the orientation does not change during the translation. A rotational fall is defined as a linear translation of an object falling from any orientation, where the orientation changes by the object rotating on an axis. A projectile fall is defined as a planar translation with two dimensions, vertical and horizontal, where the object is essentially thrown in the horizontal direction while falling in the vertical direction. A projectile fall typically ends with a similar signature of a rotational fall.

For a complete freefall solution, the output of accelerations from three axes (x, y, and z) are compared to all possible physical values of the accelerometer during static acceleration, when only gravity is acting on the device at different orientations when the device is not moving. During non-freefall conditions, the x y z coordinates described by the acceleration signals are only a subset of all possible values.

SYSTEM DESIGN

ACCELEROMETER

The MMA7260Q inertial sensor was designed specifically for the consumer products with a small package, low current, low voltage supply, small package, and three sensing axes in one package. The accelerometer is packaged as a low dimension Quad Flat No-Lead (QFN) RoHS compliant package that is 6 x 6 x 1.45 mm to reduce the overall real estate and to accommodate the limited board space available in smart portable electronics with HDD that would benefit from a freefall solution. The MMA7260Q also includes a g-select feature where two inputs control the sensitivity to enable selection of four g-ranges — 1.5g, 2g, 4g, and 6g. This feature enables the freefall application to be implemented by configuring the g-select to 1.5g to monitor freefall conditions with a timer interrupt. When not detecting freefall, other applications can be implemented by the MCU driving the g-select pins to change the g-range of the accelerometer for other application requirements as seen in Figure 1.

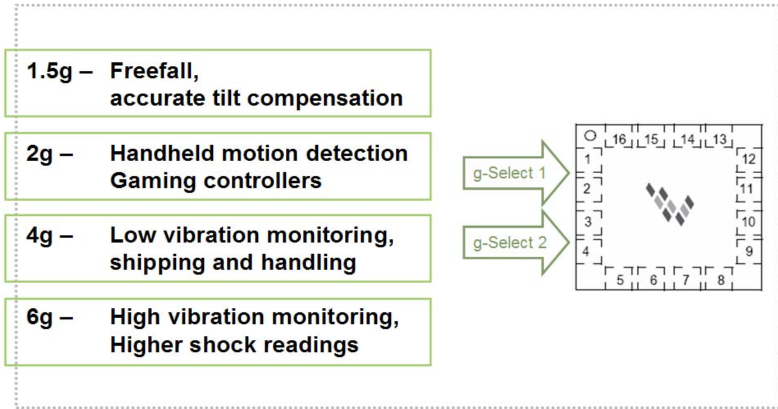


Figure 1. G-Select Enables Multiple Applications with One Accelerometer

MICROCONTROLLER

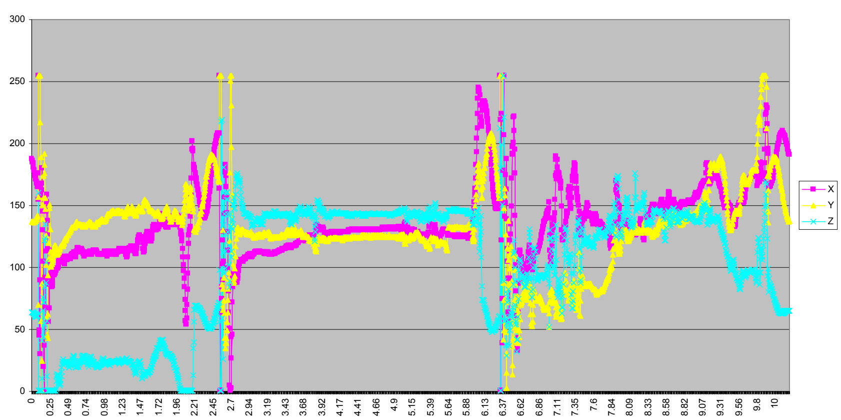
The Freefall detection demo was implemented on a low cost, 8-bit microcontroller with 8K of flash memory. These are the minimum processing requirements for running the freefall detection algorithm and sending a high/low signal to drive an LED or Piezohorn when freefall is detected. This ensures that freefall is quickly and reliably detected because there are no other processes running that may take precedence over the freefall detection algorithm. In most end products, there is a need for more complex MCUs or DSPs. In that case the freefall algorithm can be easily upgrade to one of these processors.

LINEAR FREEFALL

Linear freefall is the simplest of the three identified types of falls. Linear freefall is defined as a drop when the device was not previously moving, so there are no other forces acting on the device. Linear freefall is independent of the original orientation of the device. However, the requirement for linear freefall detection is that the orientation remains during the fall. If there is a dynamic change in the orientation, another freefall algorithm will be needed.

Figure 2. Linear Freefall is Defined as a Linear Translation to Earth's Surface without any Dynamic Change in Orientation

The linear freefall algorithm entails sampling the x-, y-, and z-axis output signals. If the acceleration on all three axes are determined to be at 0g with a predefined margin (i.e., ±5 bits when using an 8-bit ADC), for a set duration of time (5 samples in a row), then we are in a linear freefall condition.



Basic Software Algorithm Parameters

- Resolution of Analog to Digital converter: 8-bit (MC68HC908KX8)
- Accelerometer(s): MMA7260Q
- Processor speed/Sampling Rate: 50 Hz (200 samples per second)
- Averaging: None
- 0g Offset Calibration: YES
- Operating Temperature: approx 25°C

S-FACTOR

At all times, the accelerometer will sense the acceleration of gravity. Depending on the orientation, each axis of the accelerometer will see a range of accelerations from 1g (when the axis is parallel to gravity) to 0g (when the axis is perpendicular to gravity). The S-factor is a way to consider the total acceleration acting on the device at once, acting for all axes combined.

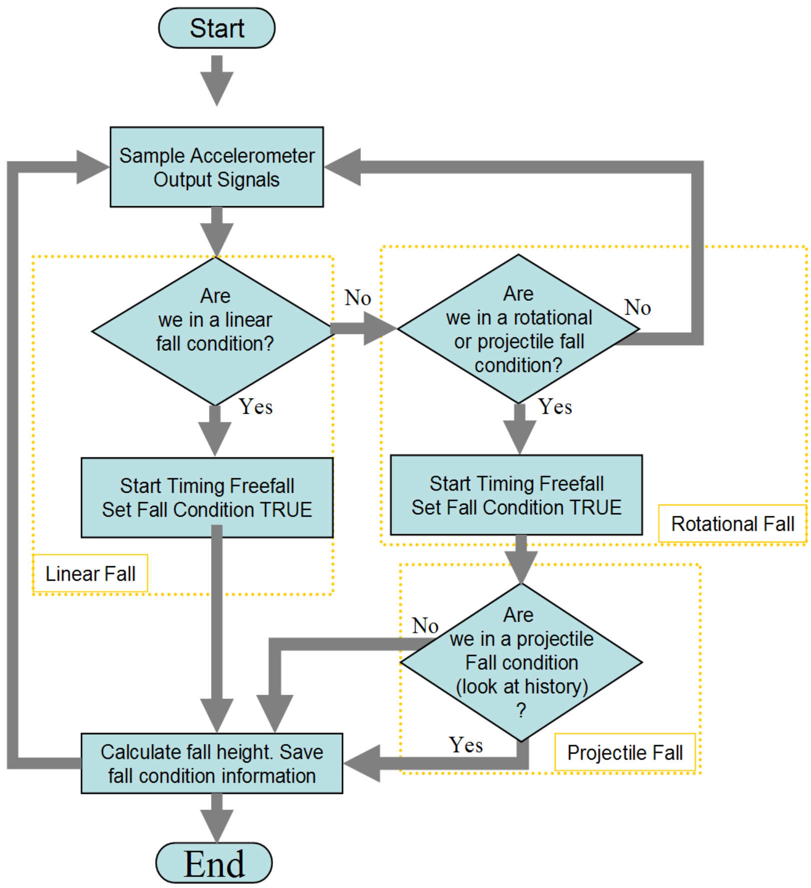
$$Sfactor = \sqrt{Xout^2 + Yout^2 + Zout^2}$$

When the accelerometer is held in any orientation, at least one of the sensing axes will be parallel with the acceleration of gravity. Therefore, at least one of the axes will be more than 0g. For example, when the accelerometer is tilted at an angle, a portion of the acceleration of gravity will be sensed. Therefore, the S-factor will always be equal to 1 when the accelerometer is static.

$$Sfactor = \sqrt{1^2 + 0^2 + 0^2}$$

During freefall, all 3 sensing axes converge to 0g. Since the S-factor is the total acceleration on all axes and all three axes are zero, the S-factor is 0. The S-factor will only be zero when freefall is occurring.

$$Sfactor = \sqrt{0^2 + 0^2 + 0^2}$$



HEIGHT REQUIREMENTS FOR FREEFALL DETECTION

The height requirement for detecting freefall is directly dependent on the sampling rate of the software, the conversion time of the ADC, and the time segment given for sampling the freefall algorithm in the overall system. The freefall demo algorithm samples the data from x, y, and z output signals 256 times and takes the average for a steady value. The conversion of an ATD signal requires between 16 and 17 ADC clock cycles of the MC68HC908KX8 to complete. Conversion time in terms of the number of bus cycles is a function of CGMXCLK frequency, bus frequency, the ADIV prescaler bits, and the ADICLK bit. For example, with a CGMXCLK frequency of 8 MHz, bus frequency of 2 MHz, and fixed ADC clock frequency of 1 MHz, one conversion will take between 16 and 17 μs and there will be 32 bus cycles between each conversion. Therefore, the sample rate would be approximately 60 kHz. However, in most freefall applications, the fall protection mechanism is what takes over 95% of the fall time. For example, in a Hard drive protection application, the actual parking of the drive takes over 60 ms. Therefore, when designing a freefall protection algorithm, the typical height of a fall should be considered in addition to the limitation of the mechanical protection mechanism to determine what is more important in the solution — speed or accuracy.

TIME REQUIREMENTS FOR FREEFALL DETECTION

The time that an object will be in freefall when dropped from a typical drop height is useful for determining the maximum time allowed for the total freefall protection solution. The time required for an object to fall from a specific height is calculated using the kinematic equations of motion. For calculating a distance (height of the fall) with a known acceleration (gravity) from a static height (the initial velocity equals zero), we have the following equation:

$$\begin{aligned} d &= v_i * t + ½ *a*t\text{^}2 \\ &= 0 + ½ *a*t\text{^}2 \end{aligned}$$

Since the distance is the known height of the fall and the acceleration of gravity is a known constant, the time can be calculated from the following translated equation:

$$t^2 = 2d/a$$

$$t = \overline{[(2d)/a]}$$

For example, if the typical height for an application is 700 mm, then the time needed for detecting freefall and protecting the device would be less than 400 ms.

$$\begin{aligned} t &= [(2d)/a] \\ &= [\ (2 \text{ x } 0.070 \text{ m}\ ) / 9.8 \text{ m/s}^2\ ] \\ &= 0.3779 \text{ seconds} \\ &= 400 \text{ ms} \end{aligned}$$

Using this equation a time table can be formed so that the time a device is in freefall can be referenced (see Table 1) along with the time requirement for detecting freefall (see Table 2) to provide an understanding of how much time is available after the detection of freefall before impact occurs.

Table 1. Time in Freefall

Height of Fall (mm)	Time of Fall (ms)
5	31.944
10	45.175
50	101.02
100	142.86
200	202.03
300	247.44
400	285.71
500	319.44
600	349.93
700	377.96
800	404.06
900	428.57
1000	451.75

Table 2. Sampling Rate and Time to Detect Freefall

Sample/s	Samples in Algorithm	S/Sample	Time to Detect Freefall (ms)
200	1	0.005	5
500	1	0.002	2
1000	1	0.001	1
200	10	0.05	50
500	10	0.02	20
1000	10	0.01	10
200	20	0.1	100
500	20	0.04	40
1000	20	0.02	20

The time it takes for a system to detect freefall is directly related to the sampling rate of the system. If the analog to digital converter samples at 200 times per second, as in the Freescale Accelerometer demo board, then the system requires 100 ms before determining a freefall condition. If the system is able to sample at 1000 times per second, then a freefall condition can be detected in 10 ms. Another factor in the time required for freefall detection is the number of samples that are used in the freefall algorithm. For a simple linear freefall algorithm, only one sample is needed to determine freefall. However, to include detection for rotational and projectile freefall and increase the accuracy of freefall detection by looking at the conditions of the device before freefall, more samples may be needed before determining freefall. Table 2 shows the time required to detect freefall at the sampling rate of 200, 500, and 1000 samples per second along with 3 different levels of detection — simple freefall detection using 1 sample to determine freefall, and more complex algorithms which require 10 and 20 samples before determining freefall.

RELIABILITY OF FREEFALL DETECTION

The reliability of freefall is dependent on the algorithm that is used and the calibration of the 0g offset of the device. The variation of the 0g offset for the MMA7260Q is shown in Figure 3. Depending on the range of the ADC bits in the algorithm logic, the reliability will be affected if the system is not calibrated for 0g on all axes. Our freefall solution recommends a 0g calibration for the highest reliability of freefall. As seen from Figure 1, the mean of the X, Y, and Z offset voltages is 1.654, 1.637, and 1.621, respectively. This variation between axes can be hard coded in the software; however, for six sigma reliability, the ranges for each axis would need to be considered.

Distributions

X-offset

Quantiles		
100.0%	maximum	1.7034
99.5%		1.7008
97.5%		1.6878
90.0%		1.6767
75.0%	quartile	1.6665
50.0%	median	1.6542
25.0%	quartile	1.6420
10.0%		1.6309
2.5%		1.6220
0.5%		1.6066
0.0%	minimum	1.6010

Moments	
Mean	1.6545037
Std Dev	0.0173212
Std Err Mean	0.001
upper 95% Mean	1.6564717
lower 95% Mean	1.6525357
N	300

Capability Analysis

Specification	Value	Portion	% Actual
Lower Spec Limit	1.485	Below LSL	0.0000
Upper Spec Limit	1.815	Above USL	0.0000
Spec Target	1.65	Total Outside	0.0000

Overall, Sigma = 0.01732

Capability	Index	Lower CI	Upper CI
CP	3.175	2.921	3.430
CPK	3.089	2.837	3.341
CPM	3.073	2.834	3.312
CPL	3.262		
CPU	3.089		

Portion	Percent	PPM
Below LSL	0.0000	0.0000
Above USL	0.0000	0.0000
Total Outside	0.0000	0.0000

Y-offset

Quantiles		
100.0%	maximum	1.6972
99.5%		1.6922
97.5%		1.6741
90.0%		1.6623
75.0%	quartile	1.6507
50.0%	median	1.6366
25.0%	quartile	1.6242
10.0%		1.6139
2.5%		1.6036
0.5%		1.5917
0.0%	minimum	1.5916

Moments	
Mean	1.6376483
Std Dev	0.0183739
Std Err Mean	0.0010608
upper 95% Mean	1.6397359
lower 95% Mean	1.6355607
N	300

Capability Analysis

Specification	Value	Portion	% Actual
Lower Spec Limit	1.485	Below LSL	0.0000
Upper Spec Limit	1.815	Above USL	0.0000
Spec Target	1.65	Total Outside	0.0000

Overall, Sigma = 0.01837

Capability	Index	Lower CI	Upper CI
CP	2.993	2.753	3.233
CPK	2.769	2.543	2.996
CPM	2.484	2.306	2.663
CPL	2.769		
CPU	3.217		

Portion	Percent	PPM
Below LSL	0.0000	0.0000
Above USL	0.0000	0.0000
Total Outside	0.0000	0.0000

Z-offset

Quantiles		
100.0%	maximum	1.6750
99.5%		1.6720
97.5%		1.6610
90.0%		1.6491
75.0%	quartile	1.6347
50.0%	median	1.6232
25.0%	quartile	1.6074
10.0%		1.5942
2.5%		1.5708
0.5%		1.5656
0.0%	minimum	1.5648

Moments	
Mean	1.6211368
Std Dev	0.0215688
Std Err Mean	0.0012453
upper 95% Mean	1.6235874
lower 95% Mean	1.6186862
N	300

Capability Analysis

Specification	Value	Portion	% Actual
Lower Spec Limit	1.485	Below LSL	0.0000
Upper Spec Limit	1.815	Above USL	0.0000
Spec Target	1.65	Total Outside	0.0000

Overall, Sigma = 0.02157

Capability	Index	Lower CI	Upper CI
CP	2.550	2.346	2.754
CPK	2.104	1.930	2.278
CPM	1.526	1.423	1.630
CPL	2.104		
CPU	2.996		

Portion	Percent	PPM
Below LSL	0.0000	0.0000
Above USL	0.0000	0.0000
Total Outside	0.0000	0.0000

Figure 3. MMA7260Q 0g Offset Data

Another consideration is the operating temperature of the system. The characterization of freefall in this report was completed at room temperature, approximately 25°C. However, during the operation of some consumer electronics, the temperature increased beyond room temperature, so temperature drift may need to be considered. The operating temperature of the MMA7260Q is in the range of -20 to 80°C. Figure 4, Figure 5, and Figure 6 shows the temperature drift of the MMA7260Q in the operating temperature range. The changes in offset are small, so they should not alter the reliability of a freefall solution. However, a system characterization for temperature is still recommended.

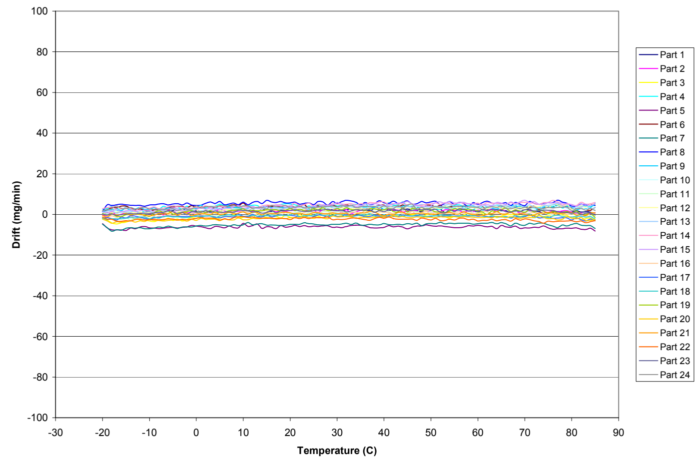


Figure 4. X-Offset Drift Over Temp (mg/min) at V_{DD} = 3.3 V

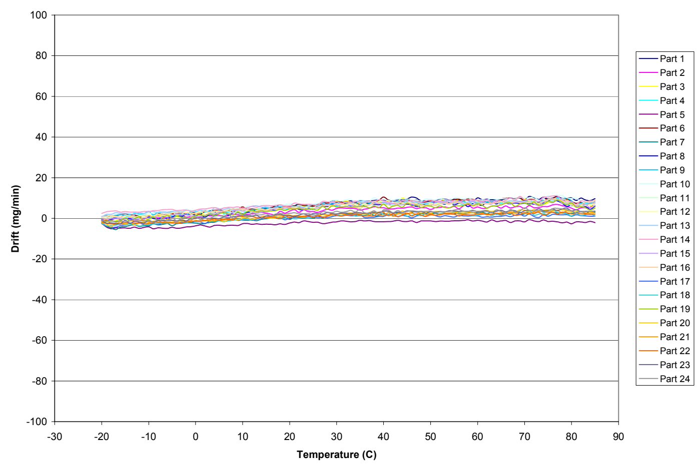


Figure 5. Y-Offset Drift Over Temp (mg/min) at V_{DD} = 3.3 V

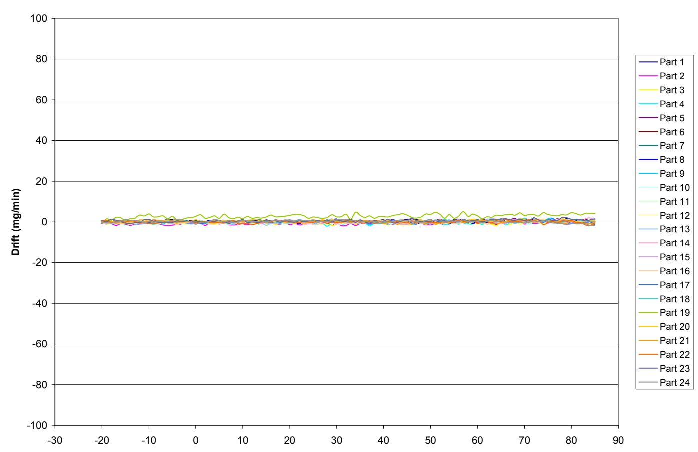


Figure 6. Z-Offset Drift Over Temp (mg/min) at V_{DD} = 3.3 V

SHOCK PROTECTION IN ADDITION TO FREEFALL PROTECTION

Freefall detection is typically used for hard drive protection. However, freefall protection does not include protection from shock, which would not put the device into a freefall mode. Shock includes banging of the product itself, or using an external device to apply shock to the product, or excessive shaking of the product. Shock protection would have to be added in addition to freefall protection to ensure full protection on a hard drive during all types of excessive handing.

Table 3. Testing of the RD3112MMA7260Q

Trial	Orientation	Height of Fall	Freefall Detected
1	X-axis =1g	15 cm	Yes
2	X-axis =1g	10 cm	Yes
3	X-axis =1g	5 cm	Yes
4	Y-axis =1g	15 cm	Yes
5	Y-axis =1g	10 cm	Yes
6	Y-axis =1g	5 cm	Yes
7	Z-axis =1g	15 cm	Yes
8	Z-axis =1g	10 cm	Yes
9	Z-axis =1g	5 cm	Yes
10	X-axis = -1g	15 cm	Yes
11	X-axis = -1g	10 cm	Yes
12	X-axis = -1g	5 cm	Yes
13	Y-axis = -1g	15 cm	Yes
14	Y-axis = -1g	10 cm	Yes
15	Y-axis = -1g	5 cm	Yes
16	Z-axis = -1g	15 cm	Yes
17	Z-axis = -1g	10 cm	Yes
18	Z-axis = -1g	5 cm	Yes

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