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Practical Circuits and Interface Techniques for MEMS Accelerometers with Quasi-Digital Output

Sergey Y. YURISH
Institute of Computer Sciences and Technologies, National University Lviv Polytechnic,
Bandera str., 12, 79013 Lviv, UA
Phone: +380502280003, fax: +380 32 2971641
E-mail: syurish@mail.lviv.ua

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Abstract: The application specific paper describes a practical circuits and interface techniques for quasi-digital MEMS accelerometers. This design approach is based on the Universal Frequency-to-Digital Converter (UFDC-1) working well with any frequency-time domain sensors. Such design approach lets significantly simplify the design process, reduce time-to-market and production price and produce data acquisition and sensor systems with high metrological performances. Practical examples of direct interfacing of quasi-digital accelerometers to the UFDC-1 are given.

Keywords: universal frequency-to-digital converter, quasi-digital output, MEMS accelerometers, PWM, duty-cycle, UFDC-1.

1. Introduction

The measurement of acceleration or its derivatives such as vibration, shock, tilt, inclination, etc. has become very wide used in different applications. Accelerometers with frequency output are known since the beginning of 60^{th} [1]. The past decade MEMS accelerometers began to become commonplace in the market. There are many manufacturers producing digital or quasi-digital output single IC chip accelerometers [2]. The surface micromachined products provide the sensing element and the signal conditioning circuitry on the chip, and require only a few external components. Some manufactures have taken this approach one step further by converting the analog output into a quasi-digital format such as duty-cycle, frequency or pulse-modulated signal (PWM). This does not only lift the burden of designing of the fairly complex analog circuitry for the sensor, but also reduces the cost and the board area [3]. Main features of quasi-digital accelerometers from different manufacturers are shown in Table 1.

Table.1. *Quasi-digital accelerometers performances.*

Device	Number of Axis	Range	Sensitivity Accuracy (%)	Max Bandwidth (kHz)
Analog Devices				
ADXL202	2	± 2 g	± 16	6
ADXL210	2	± 10 g	± 20	6
ADXL213	2	± 1.2 g	± 10	2.5
Honeywell				
RBA500	N/A	± 70 g	N/A	> 0.4
SA500	N/A	± 80 g	N/A	> 1
Kionix				
KXG20	2	± 2 g	N/A	< 0.5
MEMSIC, Inc.				
MXD2125	2	± 2 g	± 12.5	> 0.16
Silicon Designs, Inc.				
1010	2	± 2 g ...± 200 g	N/A	0...2

N/A – no available information

Very often such accelerometers are called "digital" accelerometers but really they should be called "quasi-digital" because of they have duty-cycle or PWM outputs. They can be directly interfacing to modern microcontrollers but duty-cycle and pulse width measurements with high resolution are not trivial tasks. A designer must take into account many factors or so-called program-dependent or software-related effects [4-6] that influence on the conversion error, for example, the error due to delay of reaction to interruption and error of shift in time of the response for interruption. Very often, these components exceed the quantization error. In order to simplify a design process of digital sensors and sensor systems and reduce time-to-market, the Universal Frequency-to-Digital Converter (UFDC-1) can be used [7].

2. MEMS Accelerometers to UFDC-1 Interfacing

2.1 *Analog Devices*' Quasi-Digital Accelerometers

Analog Devices manufacturers three models of dual axis MEMS accelerometers ADXL202, ADXL210 and ADXL213 with duty-cycle modulated outputs.

The ADXL202E is a low-cost, low-power, complete 2-axis accelerometer with a measurement range of ±2 *g*. The ADXL202 can measure both dynamic acceleration (e.g., vibration) and static acceleration (e.g., gravity). The outputs are Duty-Cycle Modulated (DCM) signals whose duty-cycles (ratio of pulse width to period) are proportional to the acceleration in each of the two sensitive axes (Figure 1). These outputs may be measured directly with the UFDC, requiring no A/D converter or glue logic. The DCM period $T2$ is adjustable from 0.5 ms to 10 ms via a single resistor (R_{SET}) by choosing a value between 100 kΩ and 2 MΩ. As outlined in the data sheet, the nominal duty-cycle output of the ADXL202 is 50% at 0 g and 12.5% duty-cycle change per *g*. Therefore to calculate acceleration from the duty- cycle:

$$Acceleration\ (g) = \frac{(T1/T2) - 50\%}{12.5\%} \qquad (1)$$

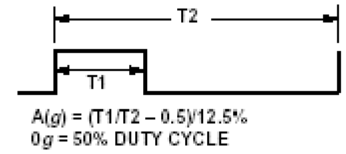

Fig.1. *ADXL202 output signal.*

If the 0 *g* duty-cycle output of the ADXL202 is other than 50 %, and/or the duty-cycle changes more or less than 12.5 % per *g*, the acceleration calculation will be inaccurate. In practice, the 0 *g* output and the sensitivity of the ADXL202 vary somewhat from device to device (see the data sheet for details). So, this formula can only be used for low accuracy measurements. For higher accuracy measurements, the actual offset and scale values must be substituted. Two simple methods of calibration to find the actual offset and scale values are described in [8].

Note that while *T2* is nominally constant, it does change over temperature and contains some jitter. For systems that do not require resolutions of better than 100 mg, *T2* may be measured only once. For more accurate measurements, several *T2* measurements should be made and averaged. The average should be updated periodically to account for *T2* drift over temperature [8].

The bandwidth of the ADXL202 may be set from 0.01 Hz to 6 kHz via capacitors C_X and C_Y. The functional block diagram is shown in Figure 2.

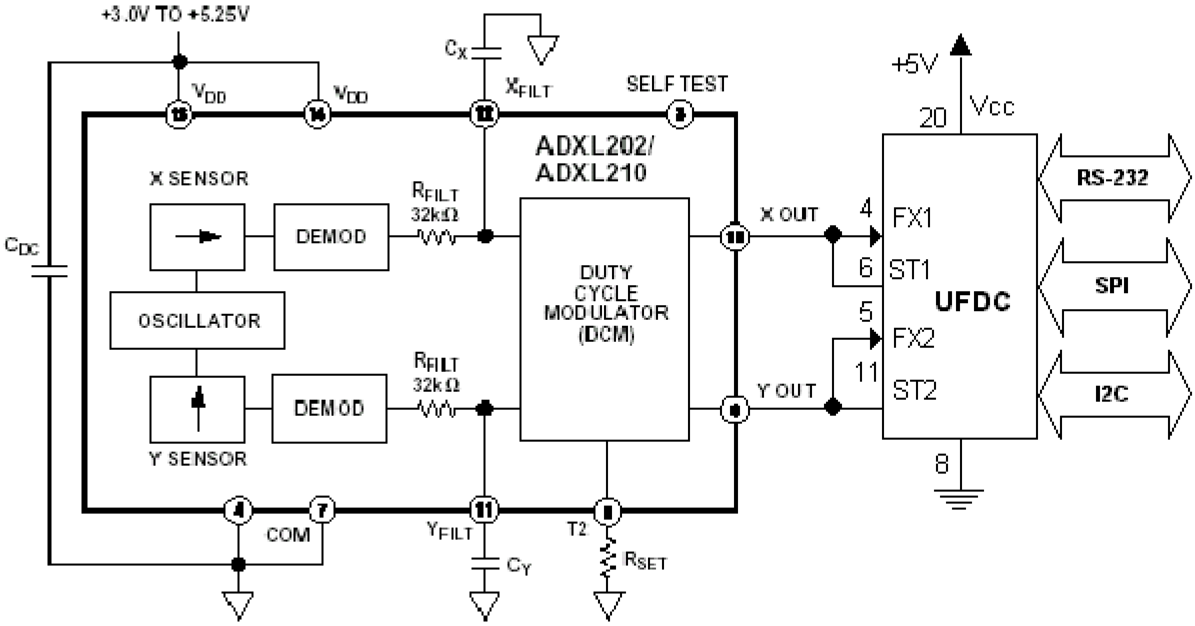

Fig. 2. *ADXL202 to UFDC interfacing functional diagram.*

In order to choose right values of external components for ADXL202, the Interactive Design Tools - *Accelerometers: ADXL202 Calculator* is recommended for the use [9], taking into account high metrological UFDC's performances [7] especially related to the duty-cycle output and acquisition rate. The screen of Interactive Design Tools is shown in Figure 3.

The ADXL210 is a low cost, ±10 g, dual-axis accelerometer with a digital output, all on a single monolithic IC. The ADXL210 will measure accelerations with a full-scale range of ±10g, making it suitable for tilt measurement. It is an improved, smaller version of the ADXL210.

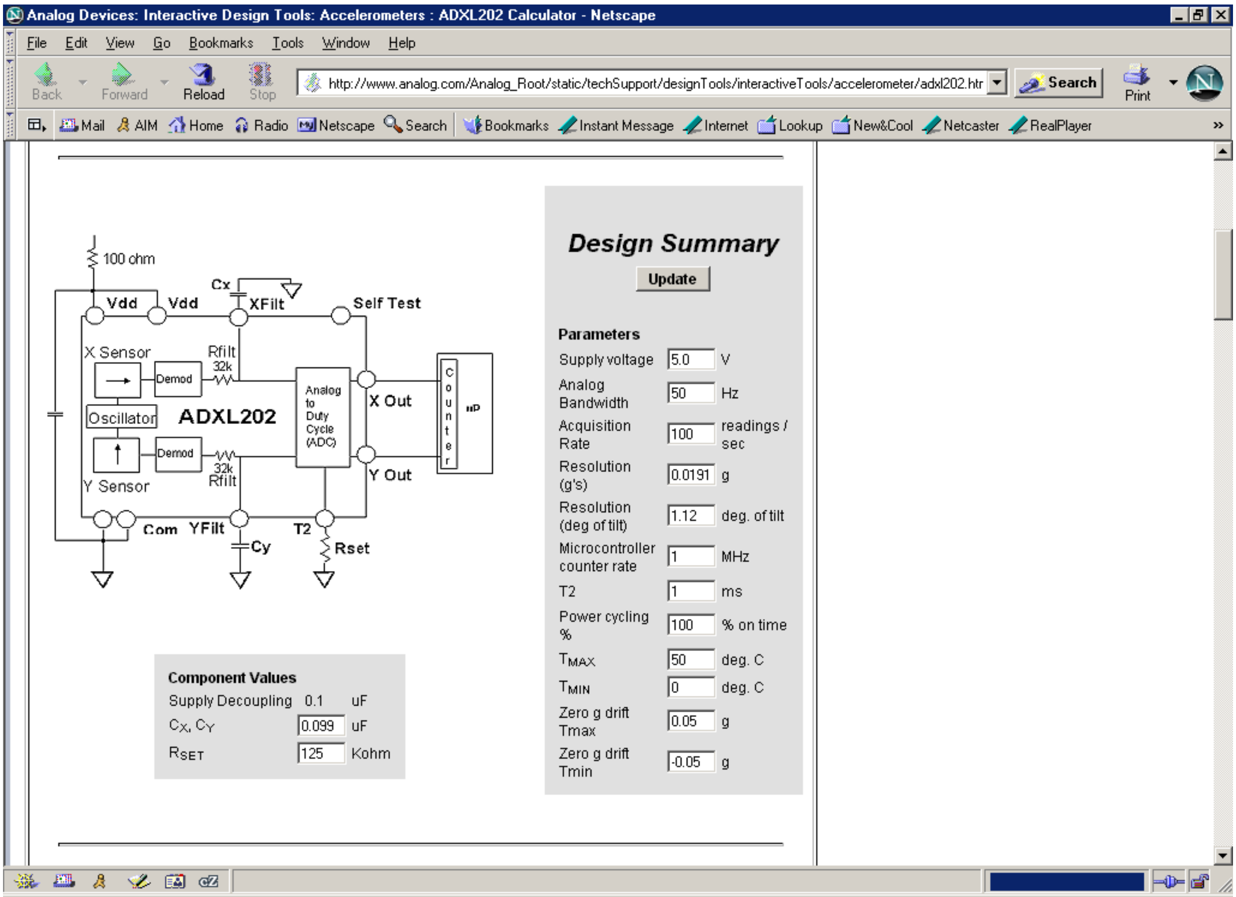

Fig.3. *Interactive Design Tools -Accelerometers: ADXL202 Calculator.*

The ADXL210 to UFDC interfacing functional diagram is shown in Figure 4. In order to calculate acceleration from the duty-cycle the following equation should be used:

$$Acceleration\ (g) = \frac{(T1/T2 - 0.5)}{4\%} \qquad (2)$$

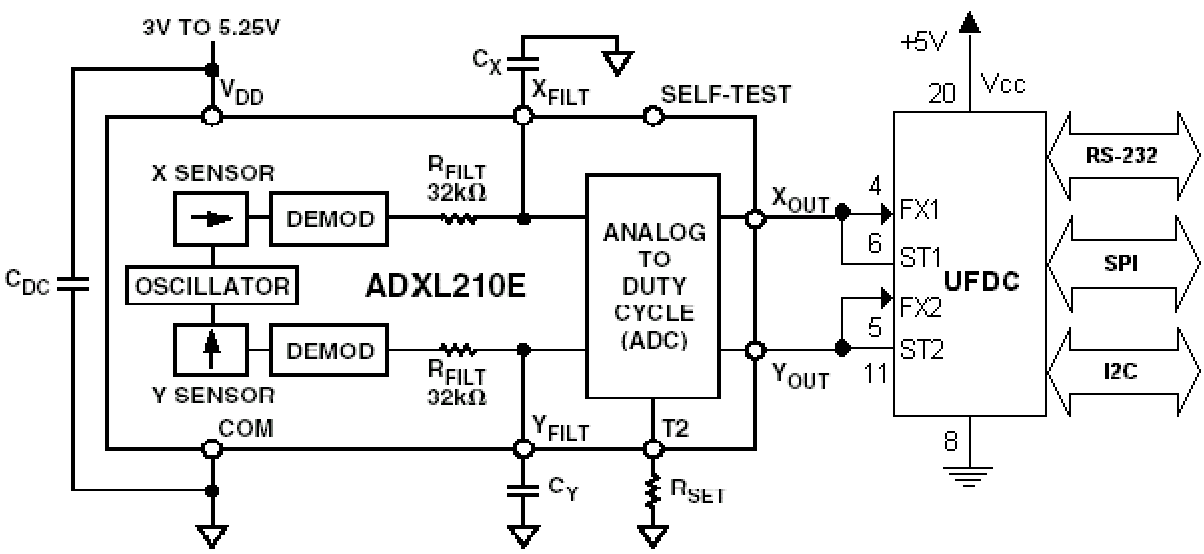

Fig. 4. *ADXL210 to UFDC interfacing functional diagram.*

The ADXL213 is a precision, low power, complete dual axis accelerometer with signal conditioned, duty-cycle modulated outputs, all on a single monolithic IC. The ADXL213 measures acceleration with a full-scale range of ±1.2 g (typical). The ADXL213 can measure both dynamic acceleration (e.g. vibration) and static acceleration (e.g. gravity).

The outputs are quasi-digital signals whose duty-cycles (ratio of pulse width to period) are proportional to acceleration (30%/g). The duty-cycle outputs can be directly measured by the UFDC without an A/D converter or glue logic.

The ADXL213 greatly improves upon the ADXL202 in two critical specifications: zero-g stability over temperature, and sensitivity accuracy. Bandwidths of 0.5 Hz to 250 Hz may be selected to suit the application.

The acceleration can be calculated according to the following formula:

$$Acceleration\ (g) = \frac{(T1/T2 - 0.5)}{30\%} \tag{3}$$

The ADXL210 to UFDC interfacing functional diagram is shown in Figure 4.

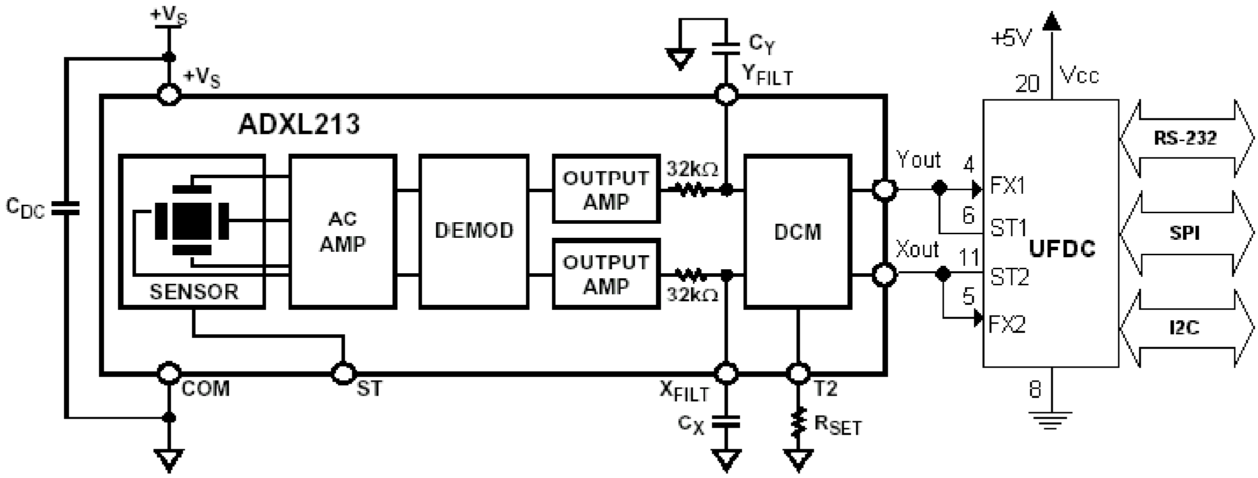

Fig. 5. *ADXL213 to UFDC interfacing functional diagram.*

In case of use of two accelerometer's axis as it is shown in Figure 2, 4, 5 the custom design of UFDC should be ordered [7] because of standard version of the UFDC-1 in its 2nd channel can measure only period. The custom design lets also to have readings in *g*, in other words the custom designed UFDC can calculate acceleration according to equations (1), (2) or (3). In case of standard UFDC-1 applications, the calculation should be done by a master microcontroller or PC. This is very suitable for portable data acquisition systems and multisensors systems design using bus capabilities of the UFDC-1.

2.2 *Kionix's* Quasi-Digital Accelerometer

Kionix silicon micromachined linear accelerometers consist of a sensor element and an ASIC [10]. The sensor element functions on the principle of differential capacitance. Acceleration causes displacement of a silicon structure resulting in a change in capacitance. An ASIC, using a standard

CMOS manufacturing process, detects and transforms changes in capacitance into a duty-cycle signal, which is proportional to acceleration. Output is in the form of a pulse width modulated duty-cycle signal offering broad application and design flexibility. The acceleration can be calculated according to the following equation:

$$Acceleration\ (g) = \frac{(T1/T2 - 0.5)}{20\%} \quad (4)$$

The 0 *g* condition corresponds to 50% of duty-cycle (T1 /T2 = 0.5). The application schematic is shown in Figure 6. Outputs *X* (pin 8) and *Y* (pin 9) should be connected to the UFDC by the same manner as it is shown in Figures 2, 4 and 5.

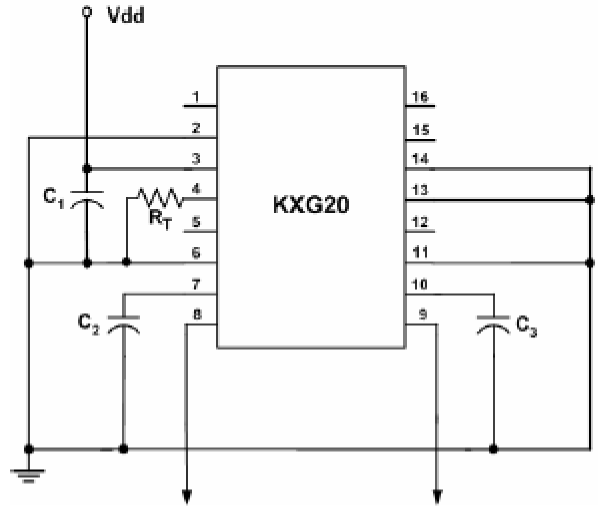

Fig. 6. *Application schematic of KXG-20 accelerometer.*

External capacitors *C2* and *C3* are used to set the -3dB filter point for each sensor output. In a typical application, the desired bandwidth will be determined by the fastest signal needing to be measured. It is recommend to use 0.1 µF for decoupling capacitor *C1*. In order to calculate the *C2* and *C3* for the sensor the following equation should be used:

$$C2 = C3 = \frac{1}{2\pi \cdot 32000\, f_{BW}}, \quad (5)$$

where f_{BW} is the sensor bandwidth frequency needed in application (typically from 10 Hz to 1500 Hz).

To set the digital output, data rate R_T can be calculated with this formula:

$$R_T = \frac{437 \cdot 10^6}{f_{PWM} \cdot V_{dd}}, \quad (6)$$

where f_{PWM} is the frequency of digital output data rate (from 100 to 2000 Hz). $f_{PWM} = 1/T2$.

The custom design consideration for this model of accelerometer is the same as considered above for quasi-digital accelerometers from *Analog Devices*.

2.3 Other Quasi-Digital Accelerometers

Other quasi-digital accelerometers, first of all RBA500 and SA500 frequency output accelerometers from *Honeywell* and some series of accelerometers (inclinometers) from *Rieker Electronics, Inc*. also can be directly interfacing to the UFDC [2]. The acceleration in *Honeywell's* devices is measured as a function of the frequency difference between two vibrating quartz beams. Accelerometers from *Rieker Electronics, Inc*. are available with pulse-width or frequency- modulated outputs.

Dual axis CMOS accelerometers from *MEMSIC, Inc.,* for example*,* MXD2125GL/HL/ML/NL provide two digital outputs that are set to 50% duty-cycle at zero *g* acceleration. The outputs are digital with duty-cycles (ratio of pulse width to period) that are proportional to acceleration [11]. The duty-cycle outputs can be directly interfaced to the UFDC. The acceleration can be calculated according to the equation (4). The MXD2125GL/HL/ML/NL has two PWM duty-cycle outputs (x,y). The acceleration is proportional to the ratio T1/T2. The zero *g* output is set to 50% duty-cycle and the sensitivity scale factor is set to 20 % duty-cycle change per *g*. These nominal values are affected by the initial tolerance of the device including zero *g* offset error and sensitivity error. This device is offered from the factory programmed to either a 10ms period (100 Hz) or a 2.5ms period (400 Hz).

The noise level is one determinant of accelerometer resolution. The second relates to the measurement resolution of the UFDC when decoding the duty-cycle output. The actual resolution of the acceleration signal is limited by the time resolution of the UFDC used to decode the duty-cycle. Taking into account the high resolution of the UFDC, accelerometer's noise floor may set the lower limit on the resolution.

The Model 1010 from *Silicon Designs, Inc*. is a low-cost, integrated accelerometer for use in zero to medium frequency instrumentation applications. It produces a digital pulse train in which the density of pulses (number of pulses per second) is proportional to applied acceleration. It requires a single +5V power supply and a TTL/CMOS level clock of 100 kHz - 1 MHz [12]. The output is ratiometric to the clock frequency and independent of the power supply voltage. Two forms of digital signals are provided for direct interfacing to the UFDC.

Due to its standard CMOS technology the UFDC can be easy embedded by manufacturers into its accelerometers in order to produce really digital single IC chip device with high metrological performances, wide functional and communication capabilities.

3. Acceleration to Frequency Circuits

Low cost monolithic accelerometers with voltage output may be paired with a circuit whose output changes with frequency (V/F) to provide a TTL level frequency output. The UFDC can be easily convert frequency to digital and sent down a long transmission to compute the applied acceleration by master microcontroller or PC.

A high performance acceleration-to-frequency circuit can be built based on analog accelerometers ADXL05 and voltage-to-frequency converter AD654 from *Analog Devices* [13]. An ADXL05, accelerometer directly converts any applied acceleration into an analog output voltage which then controls the output frequency of an AD654 low cost voltage-to-frequency converter IC.

One of the most popular applications of accelerometers is in tilt/inclination measurement. An accelerometer uses the force of gravity as an input to determine the inclination angle of an object. ADXL05 accelerometer can be also connected to a low cost CMOS 555 timer to provide a frequency output. Such solution can be used for frequency output accelerometer tilt sensor design [13].

A pulse width modulated (PWM) outputs very suitable for remote sensing and noisy environments can be obtained from analog signal with the help of analog or discrete circuit solutions [14, 15].

4. Conclusions

The described practical circuits and interface techniques for quasi-digital accelerometers based on the Universal Frequency-to-Digital Converter UFDC-1 lets significantly simplify the design process, reduce time-to-market and production of data acquisition and sensor systems with high metrological performances.

In comparison with the direct microcontroller interfacing the proposed approach also lets to eliminate many design problems connected with the microcontroller choice, its programming and additional error components due to so-called program-dependent or software-related effects.

A voltage output of popular analog accelerometers can be also easy converted to noise resistance frequency or duty-cycle output signal and then to be interfacing directly to the UFDC.

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