Three-Axis Electronic Collision Sensor for Airborne Application

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Abstract - This paper discusses the design and implementation of a low cost three-axis electronic collision sensor for airborne application. The primary function of collision sensor is to continuously monitor the flying situation of air vehicle, and to engage the ELT system in the case of crash accident occurs. The core component of the collision sensor is the MEMS accelerometers. The data acquisition, reduction, and crash determination are accomplished using a low cost PIC microcontroller. The crash condition is determined based on vehicle acceleration and variation of velocity. A backup Li-Ion battery is incorporated into the system to prevent power shout down. A drop test is also developed and performed to investigate the characteristics of impact accelerations.

Key word : Accelerometer, Collision sensor, Microcontroller, Drop test

I. INTRODUCTION

With the flourishing development of the aviation technologies in the last century, aviation electronic technologies are reaching a new stage too. This greatly improves flight safety for traveling in the air. Although lots of avionics devices are designed to assist the air crew, unavoidably, flight accident still happened occasionally. Among flight safety associated avionics, some of them are designed to prevent the occurrence of flight accident, such as Traffic Alert & Collision Avoidance System (TCAS) and Ground Proximity Warning System (GPWS) etc., [1]. These devices will alert the pilot for dangerous flight situation and provide recommendations for proper actions to avoid flight accident. Some of the avionics equipments are designed for accident investigations, such as Flight Data Recorder (FDR) and Cockpit Voice Recorder (CVR) etc., [1]. These equipments are essential for accident investigations. We will recover the facts before the occurrence of the accident and possibly resolve the cause of the accident from the recorded data. Even though the avionics systems are designed to provide a comfortable and safety flight, the hidden fatal crisis is that the accident rate of flight can not be perfectly reduced to zero. Therefore, some systems are designed to provide the information of the accident location to help and reduce the search and rescue time for possible survivals. FDR and CVR system will automatically transmit beacon signal in the event of flight accident occurred. The rescuer then can find the aircraft wreck from the beacon signal. However, transmission range of the beacon signal is limited. Find the wreck based on the beacon has certain difficulties. Therefore, equip with an Emergency Locator Transmitter (ELT) system becomes a necessary requirement for the modern aircrafts [2]. The ELT system transmits the location message to the Search and Rescue (SAR) center through satellite system. This will continue to be the trend for the future development of the locator transmitter systems.

In June 2004, FAA had formally announced that all of the jet airlines have to equip with the EELT (Enhanced Emergency Locator Transmitter, 406 MHz) system, which is the second generation ELT system, to improve rescue capability. In addition to that, The international COSPAS-SARSAT systems will no longer process the emergency signal transmitted by the first generation ELT (121.5 MHz) system after 2009 [2,3]. After that date, the first generation ELT systems operating on the lower frequency will only be detected by ground-based receivers.

Collision sensor is one of the core elements of the ELT system. The primary function of collision sensor is to continuously monitor the flying situation of air vehicle, and to wake up the ELT system in the case of crash accident occurs. Once initiated, the ELT system will continuously transmit the position of the aircraft through satellite system. That will greatly reduce the search time and will increase the chance to rescue the survivals.

For most applications, we may only need single axis or dual axes collision sensors to sense the longitudinal and/or vertical axes accelerations. That, however, will not cover all of the possible crash conditions. This paper discusses the design and implementation of a low cost three-axis electronic collision sensor to sense all of the possible crash accidents. The basic requirements for the collision sensor are adopted from the specification ED-62 [4] published by the EUROCAE (The European organization for civil aviation equipment).

II. SYSTEM REQUIREMENT

The collision sensor detects an aircraft crash and provides the stimuli to automatically initiate ELT transmission. The primary function of collision sensor is to continuously monitor the flying situation of air vehicle, to determine the crash occurrence and to engage the ELT system in the case of crash accident occurs. Besides, the collision sensor incorporates a built-in-test function to ensure the system integrity during operation. In normal operating condition, the aircraft power line powers the collision sensor. In case of aircraft power line shut down, its own rechargeable Li-Ion battery will continuously power the collision sensor.

The simplest way to determine the crash accident is to monitor the aircraft acceleration and its velocity changes. Since the velocity change can be computed from aircraft acceleration, apparently the core element of the collision sensor is the accelerometer. The functional block diagram of the collision sensor is depicted in Figure 1 with brief explanation below.

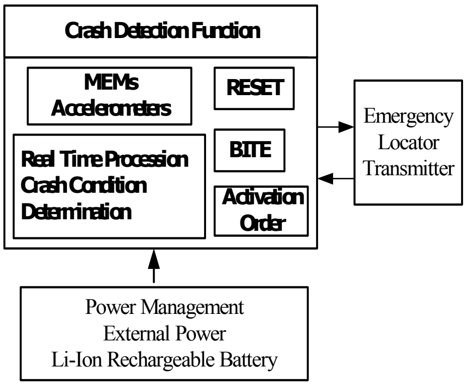

Figure 1. Basic functions of a collision sensor

(1) Accelerometer : To simplify the design and reduce the volume and weight of the collision sensor, the MEMS technology based accelerometers are considered adequate for this particular application. The MEMS accelerometer ADXL210E from Analog Device is selected for this design. The ADXL210E device is a two-axis accelerometer with both analog and digital outputs on a monolithic IC. Each axis will measure acceleration of a full scale range of $\pm 10g$ [5]. To provide three axes measurement, two ADXL210E accelerometers are used in this design.

(2) Real time processing : The real time processing function provides the real time measurement and computation of the sensor data and determines the occurrence of the crash accident. The processing unit shall be fast enough to ensure instantaneous beacon activation. It is desired that the processing time plus the switch time shall be less than 50ms.

(3) Built-In-Test (BIT) : The built-in-test function continuously monitors the sensor health to ensure the system integrity during operation. If the collision sensor has an internal failure in normal flight situation, the BIT function shall immediately provide a NOGO information to activate an aural or visual failure alert.

(4) Beacon activation order : In normal situation, the Beacon activation order will remain at logic state 0 (0 V). Once the crash accident is determined the Beacon activation order will be switched to logic 1 (5 V), and will stay in its position permanently and only the reset function can change its logic state back to 0.

We will use both analog and digital output signals from the accelerometer for design comparisons. The low cost PIC micro-controller, with built-in A/D converters, is selected as the core processor to perform the data acquisition, reduction, and crash determination.

III. CRASH CONDITION

The crash accident is determined from the measured vehicle acceleration and the computed velocity change. Crash accident is declared if the vehicle acceleration is greater than a predetermined threshold G_{TH} and the velocity change is greater than predetermined threshold $\Delta v_{\min}$ respectively. To avoid false activation, both conditions must be occurred simultaneously for crash accident activation. Determination of the thresholds G_{TH} and $\Delta v_{\min}$ depend on the aircraft type and the location where sensor is installed. NASA Langley Research Center had conducted a series of full-scale aircraft and rotorcraft crash testing and simulations [6]. The results clearly show that we will encounter high impact accelerations at crash instant. This, however, is not suitable for determining the threshold value. Instead, we will use heavy landing condition as the guide to select G_{TH} . Heavy landing for most of the commercial aircrafts ranges from 1.7g to 2.0g. In this design $G_{\mathrm{TH}} = 2.3 \pm 0.3g$ and $\Delta v_{\min} = 1.4 \pm 10\%$ m/s are selected. Response curve of the collision sensor is shown in Figure 3. The collision sensor must activate the ELT system in the area above the response curve shown in Figure 2 and must not activate ELT in the area below the response curve.

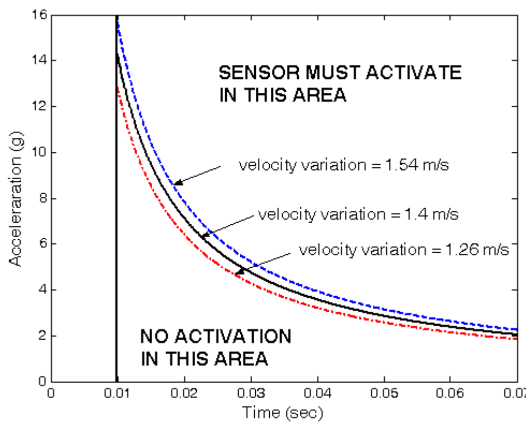

Figure 2. Collision sensor response curve

IV. SYSTEM DESIGN CONSIDERATION

Based on the requirements discussed in sections 2 and 3, we come up with the system block diagram of the collision sensor as shown in Figure 3. Major parts of the system include two ADXL210E MEMS accelerometers perpendicularly arranged to sense 3-axis accelerations, a PIC microcontroller with built-in A/D converters to perform the data acquisition, reduction, and crash determination, and a power management circuitry to ensure proper operation of the system. MEMS accelerometer is the core of the collision sensor system. We will briefly discuss it in the next section. Power management portion monitors the condition of the supply power from aircraft power system. In the event of power shortage, the backup rechargeable Li-ion battery will automatically power the collision sensor to ensure proper operation of the system. Power management basically contains a power converter and a charging/discharging circuitry for the Li-ion battery. The power converter receives power from aircraft power line and converts to a voltage level (5V) that in turn powers the collision sensor. The charging/discharging circuitry monitors the status of the Li-ion battery. In normal condition, the battery is charged to its full capacity and will power the collision sensor when power shutdown occurs. This, however, is limited to 10 minutes (in our design) if aircraft is grounded to prevent from using up the battery power.

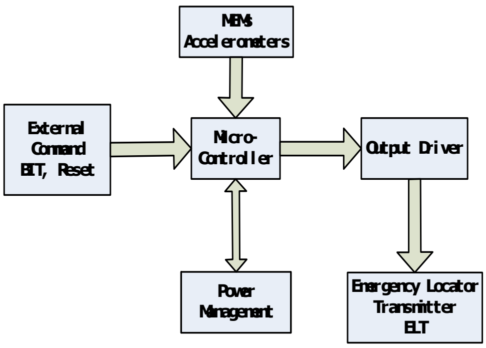

Figure 3. Collision sensor system block diagram

Another important design consideration is the crash condition determination. The three axes acceleration signals are directly measured from the two mutual perpendicularly arranged dual axes MEMS accelerometers. Denote the acceleration along the X, Y, and Z-axis as G_X, G_Y, and G_Z, we compute the resulting acceleration from

$$G = \sqrt{{G_X}^2 + {G_Y}^2 + G_Z^2} \quad (1)$$

Velocity changes are computed from the integral of the acceleration signals. There are several ways to compute the integrals. We use Simpson's rule in this design. Once the acceleration G greater than the threshold G_{TH} is assured, we start to compute velocity changes by using the following Simpson's rule [7]

$$\delta v(k) = 9.81 \times \frac{\Delta T}{3}\left[G(k-2) + 4G(k-1) + G(k)\right] \text{ m/s} \quad (2)$$

where k is the index of the sampling instant, ΔT is the sample time period. In this algorithm, we need three sampled data to compute the velocity change that covers a length of $2\Delta T$ time span. The total velocity change is obtained by accumulating δv as $\Delta v = \sum \delta v$. The crash condition determination flow chart is shown in Figure 4.

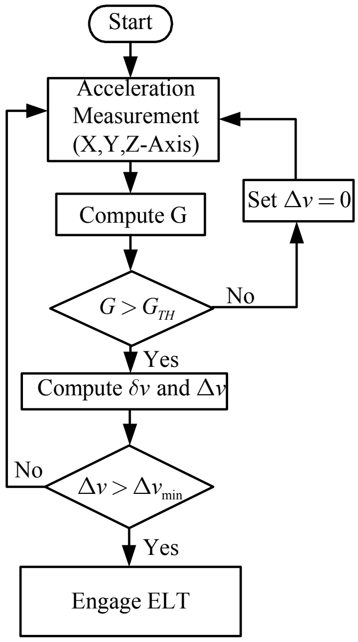

Figure 4. Crash condition determination flow chart

V. ADXL210 MEMS ACCELEROMETER

The ADXL210E is a complete dual-axis acceleration measurement system on a single monolithic IC chip. It contains a polysilicon surface-micromachined sensor and signal conditioning circuitry to implement an open loop acceleration measurement architecture. Details of the ADXL210E characteristics are provided in the Analog Device ADXL210E data sheet [5]. The ADXL210E is capable of measuring dynamic accelerations (such as vibration) and static accelerations (such as gravity) at both positive and negative direction for up to $\pm 10g$ full-scale ranges. Typical applications include tilt sensing, alarms and motion detections, computer peripherals, vehicle securities, etc. The ADXL210E provides both analog voltage outputs and digital signal outputs. The analog output voltage and the duty cycle of the digital output signal are proportional to the acceleration. The functional block diagram of the ADXL210 is shown in Figure 5.

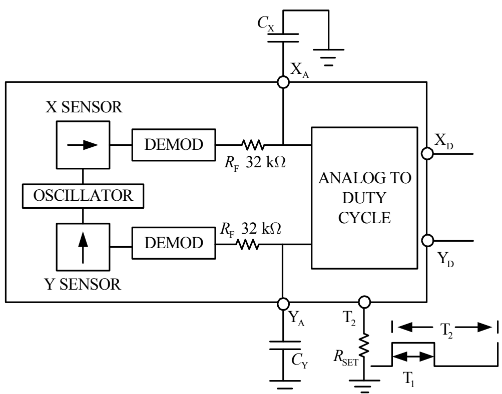

Figure 5. ADXL210E MEMS accelerometer [5]

As shown in Figure 5, designer can add a capacitor at the analog output pin (X_A , Y_A) to limit the signal bandwidth of the measurement. This filtering will improve measuring resolution and help prevent aliasing effect. The 3 dB bandwidth is

$$f_{BW} = \frac{1}{2\pi R_F C} \quad (3)$$

where $R_F = 32\ \mathrm{k}\Omega$ and C is the capacitor C_X at X_A or C_Y at Y_A . The period of a complete cycle (T_2) is determined through a single resistor R_{SET} , which can be set between 0.5 ms and 10 ms. The equation for the period is

$$T_2 = \frac{R_{SET}\Omega}{125\ \mathrm{M}\Omega} \quad (4)$$

The nominal digital output is 50% duty cycle at $0\ g$ and the scale factor is 4% duty cycle change per g .

VI. DROP TEST

In order to gain the inside characteristics of the acceleration variations at crash instant, a drop test is developed and performed using the collision sensor itself. The results will be used to determine the bandwidth requirement, which in turn will be used to compute the filter capacitor value at the analog outputs. The major works of the drop test include the designs on the collision sensor side and the designs on the data receiving side. The designs on the collision sensor side include the hardware design, software design, interface design, and data transfer. The designs on the data receiving side include the data acquisition (on LABVIEW environment), data reduction, and data analysis. In addition to obtaining the spectrum distribution of the crash acceleration signal, we also intent to gain some information about the crash signal obtained from digital and analog outputs at the same instant. Figure 6 shows the picture of the prototype of the collision sensor used for the drop test. During test, the collision sensor freely dropped from about 75 cm height to the floor. We recorded all three axes acceleration information from both analog and digital outputs for the complete dropping process. The resulting accelerations are then computed. Figure 7 depicts the construction of the drop test.

Figure 6. Prototype of the collision sensor

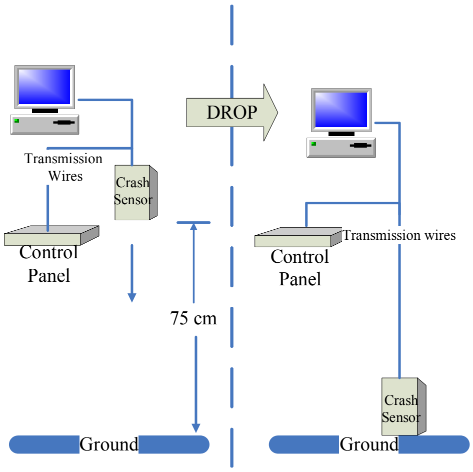

Figure 7. Construction of the drop test

The measured accelerations are denoted as $G_X(n)$, $G_Y(n)$, and $G_Z(n)$ for X-,Y-,and Z-axis respectively. The resulting acceleration is then computed from

$$G(n) = \sqrt{G_X{}^2(n) + G_Y{}^2(n) + G_Z^2(n)} \quad (5)$$

In order to understand the spectrum distribution of the acceleration signal $G(n)$, we can perform discrete time Fourier transforms [8] on the signal to obtain the frequency domain signal $G_F(k)$ as

$$G_F(k) = \sum_{n=0}^{N-1} G(n) e^{-j(2\pi/N)nk} \ ;\ k = 0,1,\ldots,N-1 \quad (6)$$

where N is the number of the sampling data. Time domain signal $G(n)$ can be recovered from $G_F(k)$ by performing the inverse discrete time Fourier transforms. That is

$$G(n) = \frac{1}{N} \sum_{k=0}^{N-1} G_F(k) e^{j(2\pi/N)nk} \ ;\ n = 0,1,\ldots,N-1 \quad (7)$$

In this experiment, we set the measuring signal bandwidth to 100 Hz. We believe 100 Hz is high enough to cover the characteristics of the crash acceleration signals. By estimating the time required for data acquisition and signal procession, we set the sampling frequency f_s to 238 Hz and a total of 300 data points are recorded. The total record period is about 1.25 sec which covers the complete drop test process. Figure 8 shows the results from analog outputs include the three axis acceleration signals G_X , G_Y , G_Z , and the resulting acceleration G . The results from digital outputs are shown in Figure 9. Comparison of the analog and digital outputs is shown in Figure 10. The results show that the measured data from analog and digital outputs are quite consistence under this test condition. From the results, it is clear that 0 g is measured at X and Y-axes, while 1 G is measured at Z-axis before sensor is dropped to the floor. At the instant of the sensor is freely dropped, the outputs from all axes are 0 g. All the outputs remain at 0 g until the moment that the sensor hit the floor. After the sensor hit the floor, it bounced for several times. After that, the collision sensor backs to its steady condition. And X and Y outputs read 0 g, and Z outputs read 1

G again. After we perform the digital Fourier transform to these measured data, the spectrum distributions are shown in Figures 11 and 12. Again the results are consistence for analog and digital outputs.

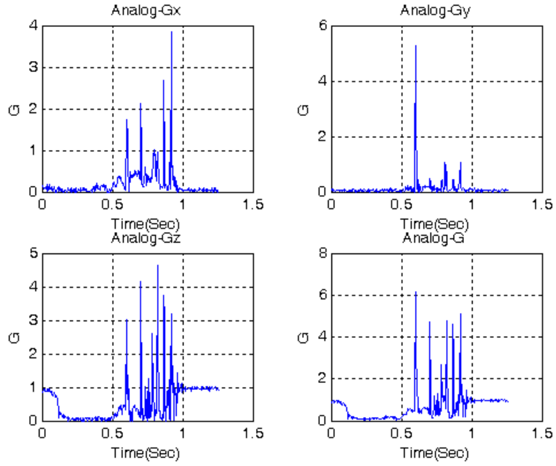

Figure 8 : Acceleration signals from analog outputs

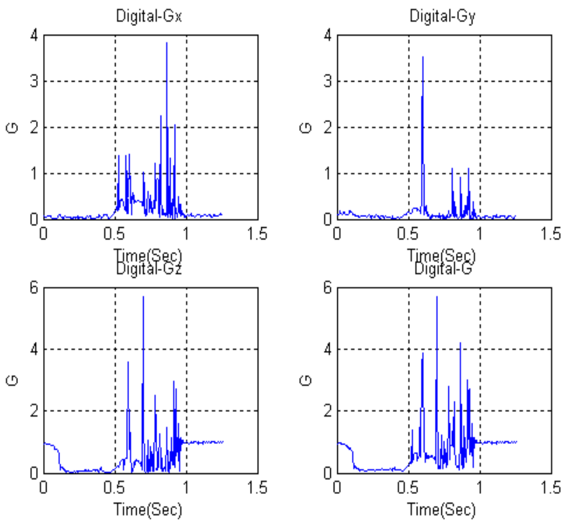

Figure 9 : Acceleration signals from digital outputs

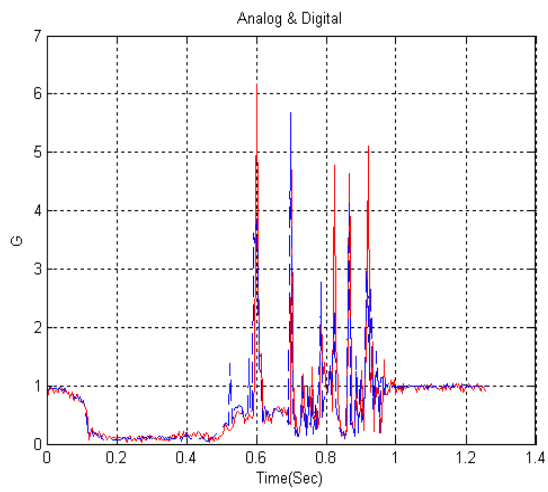

Figure 10. Comparison of the acceleration signals between analog and digital outputs.

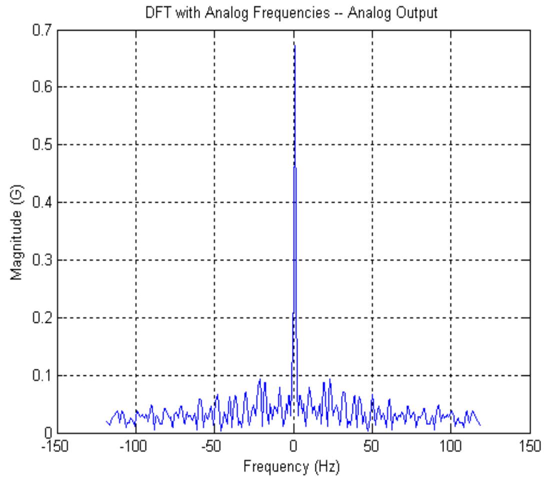

Figure 11. Spectrum distribution of the acceleration signal from analog output.

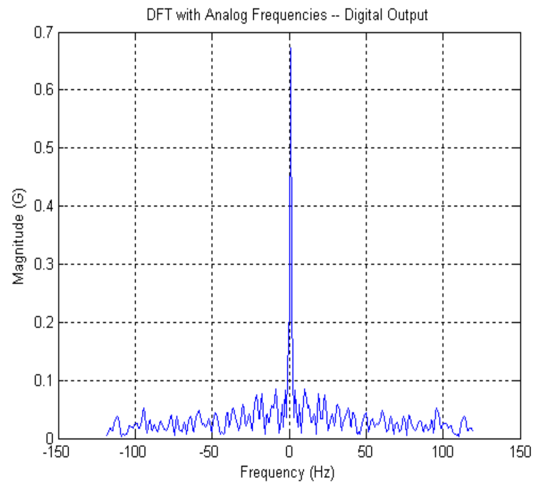

Figure 12. Spectrum distribution of the acceleration signal from digital output.

VII. CONCLUSION

In this paper we summarize the design and implementation of a low cost three-axis electronic collision sensor using MEMs accelerometers. We use acceleration and velocity variation signals to determine the condition of crash accident. Crash accident is declared if the acceleration and velocity variation exceed certain thresholds. The thresholds depend on aircraft type and installation location of the collision sensor.

In this design, we investigate both digital and analog outputs from MEMs accelerometers. Analog and digital outputs basically provide consistent and reliable results. However, we have to be careful in selecting the duty cycle period T_2 when measuring a high frequency signals. We could totally mix up the acceleration signal if we set T_2 too long. For properly selecting the length T_2, we have to be familiar with the characteristics of the signal that we are measuring. On the other side, using digital output will simplify the hardware interfaces. Using analog or digital output of the accelerometer depends on particular consideration and applications. For the application discussed in this paper, we feel comfortable for using both analog and digital outputs.

Finally, from the results of the drop test, we confirmed that the most of the energy is centralized in low frequency range. Therefore, we set the 3-dB bandwidth for the collision sensor design to be 50 Hz. We believe that will cover most of the high frequency components of the crash signal and be adequate for our application.

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