Solutions for acceleration measurement in vehicle crash tests

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Abstract. Crash tests are useful for validating computer simulations of road traffic accidents. One of the most important parameters measured is the acceleration. The evolution of acceleration versus time, during a crash test, form a crash pulse. The correctness of the crash pulse determination depends on the data acquisition system used. Recommendations regarding the instrumentation for impact tests are given in standards, which are focused on the use of accelerometers as impact sensors. The goal of this paper is to present the device and software developed by authors for data acquisition and processing. The system includes two accelerometers with different input ranges, a processing unit based on a 32-bit microcontroller and a data logging unit with SD card. Data collected on card, as text files, is processed with a dedicated software running on personal computers. The processing is based on diagrams and includes the digital filters recommended in standards.

1. Introduction
At Transilvania University of Brasov are carried out, every year, crash tests between vehicles, vehicles with pedestrian or cyclist, vehicles with stationary obstacles (pole). The crashes are simulated also using specialized computer programs. The simulation should be as closed as possible to the real crash. By combining the results of computer simulation and crash tests, the young experts learn how to fine tune their software in order to reproduce a crash event. This will help them in reconstruction of real road accidents.

When a vehicle is involved in a collision, there is a crushing of metal, which reduces the speed of the vehicle until the vehicle is stopped or disengages from the vehicle/object. The soft crush of sheet metal produces low deceleration pulses in the vehicle. A hard metal (like structural members of the vehicle frame) produces more resistance, more deceleration, and more energy transfer. When the engine is engaged, it produces a high amplitude spike of deceleration transferred to the vehicle. The series of decelerations, with a duration of over a hundred or more milliseconds of a crash, may be called a crash pulse or deceleration curve [1]. The objective of the vehicle manufacturers is to keep decelerations low in order to minimize occupant injuries. The essence of crashworthiness is the energy management and the control of crash deceleration pulses.

The simulation of a road accident may be based on the evolution of acceleration versus time, during the crash. The crash pulse is characterized by shape, amplitude and duration [2]. The crash pulses used in simulation are obtained from measured acceleration time history, using analytical techniques. The stages of the crash, mentioned above, may depend by the type of vehicles and tests.
2. Data acquisition
A crash test includes instrumentation to measure the time variation of acceleration, force and other parameters.

Vehicles instrumentation and data processing are defined in standards like SAE J211 [3] and ISO 6487 [4]. The standards provide a meaningful comparison of test results from different sources. SAE J211 and ISO 6487 are similar documents published by the two standards organizations and are the main specification documents governing the performance requirements of crash test data acquisition systems [5].

2.1. Data acquisition devices
The standards include the main technical characteristics for accelerometers and parameters of digital filters used for preliminary data processing. The filtering procedure recommended by SAE J211 is to use the Channel Frequency Classes (CFC) of low-pass filters. Filtering is the most critical phase in the processing of impact signals, having the roles of eliminating the high-frequency noise and reducing the peaks in the signal. SAE J211 designate four CFC filters for crash data processing: CFC 60, 180, 600, and 1000 [3]. The CFC filters are derived from analog Butterworth filters that have the corner frequency (the frequency at which the signal loses one half of its power) equal to the CFC designation divided by 0.6 [7]. Selecting the frequency response class appropriate for each application is an important task in preparation of the crash test. The frequency class will determine also the sampling frequency.

The SAE requirements for data acquisition hardware include: a sampling rate of 10 kHz (10000 samples/seconds/channel), 12 bit resolution, and a determination of impact time within ±0.4 msec. The time base should have at least 1/100 seconds resolution - this don't affect the requirement for sampling rate; instead, it means it is possible to use the oversampling technique. Despite the increasing capabilities of sensors, recording media and software, it is not easy to meet all the standard requirements for crash data acquisition.

One of the challenges of the crash-test team from Transilvania University is to develop reliable and cost-affordable data acquisition devices to be used in tests, together with the professional recording devices (a reference device is PicDAQ [8]).

The measurement systems consists in one or more data channels. According to above mentioned standards, a data channel represents "all the instrumentation from, and including, a single transducer (or multiple transducers, the outputs of which are combined in some specified way) to, and including, any analysis procedures that may alter the frequency content or the amplitude content of data" [4]. In other words, a data channel is a combination of a sensor, data acquisition hardware and post-processing software. The combined performance of these components determines the accuracy of the acquired data.

2.2. Acceleration measurement
The first device in a data channel, used to convert a physical quantity to be measured into a second quantity (such as an electrical voltage), is the transducer. The transducers used in crash tests convert a mechanical movement of a sensing mass inside, in electrical voltage. The electronic sensor consists in a transducer to generate the crash signal, a circuitry to process the signal and a means to send out a triggering signal [9]. Although the transducer signal is not restricted to acceleration pulses only, the use of accelerometer dominates in vehicular applications. The most used transducers used in acceleration measurements are MEMS (Micro-Electro-Mechanical Systems) [10]. A MEMS accelerometer is integrating an accelerometer and the electronics into a single silicon chip. The accelerometer is essentially a capacitive or piezoresistive device consisting of a suspended pendulum proof mass/plate assembly. As acceleration acts on the proof mass, micro-machined capacitive or piezoresistive plates sense a change in acceleration from deflection of the plates [11].

The first phase of data processing is inside the transducer. Signals from crashes may contain high amplitude, high frequency components, containing very little useful information. These components
may be reduced by a filter included by the manufacturer at the output of the accelerometer, like a 2-
pole Bessel [12]. However, the accelerometer output does not look like a filtered version of the
acceleration signal, because of signal saturation before the filter.

Depending by the type of output signal, the accelerometers can be digital or analogue. An
important parameter to be considered when choosing the appropriate accelerometer for a certain test is
the input range [7]. This can vary from ±2 g to ±200 g or even more. The accelerometer must be
chosen depending by the expected values to be measured. The impact duration is very short, so the
bandwidth is also important. The frequency response of the sensor is an indication of the sensor's
ability to respond to changes in the measured displacement. Higher bandwidth means that it can be
measured higher frequency motion, and will have an influence on the sampling frequency of the
acquisition device. The MEMS accelerometers usually can have a bandwidth between 0.5 Hz and
1600 Hz (which can be set using external capacitors). In some tests this can be a limitation. Another
parameter is the sensitivity, and depends by the input range and maximum output voltage. For
example, if the input range of the accelerometer is ±5 g, and the output voltage is between 0 and 3.3V,
this means the output resolution is 0.33 V for 1 g. The sensitivity is influenced also by the
temperature.

2.3. Crash Data Logger

Based on MEMS accelerometers, a prototype of a crash data logger (named CDL-01) was built in
laboratory. A simple block diagram of the data acquisition system is shown in Figure 1. There are two
sensors used, one for low accelerations and another one for high accelerations. Both are analog 3-axis
accelerometers, with signal conditioned voltage outputs. The first one is ADXL 337 (manufactured by
Analog Devices [13]), with an input range of ± 3 g. This is to be used especially in accelerating and
braking tests, but can also be useful in vehicle-pedestrian crash tests, mounted on the vehicle. The
second sensor is ADXL 377 (from the same manufacturer), with an input range of ± 200 g. These are
low cost accelerometers, and both have similar limitations in bandwidth and resolution. Bandwidths
can be selected to suit the application, with a range (for ADXL 377) of 0.5 Hz to 1300 Hz for the x-
axis and y-axis and a range of 0.5 Hz to 1000 Hz for the z-axis.

![](image1.png)

**Figure 1.** Basic schematic of the data acquisition system

The acquisition hardware uses the microcontroller AT91SAM3X8E (32 bit, ARM core), that
operates at a frequency of 84 MHz and features up to 512 Kbytes of Flash and up to 100 Kbytes of
SRAM. The microcontroller is installed on an Arduino Due board [14], which allows the use of all
features of the microcontroller, including 12 analog inputs (12 bits).

The data logging module is a logging shield made for Arduino boards: Adafruit Data Logger Shield
[15], with SD card interface, RTC (real time clock) and a prototyping area. An important limitation of
the system is the writing speed of the SD card. This limits the sampling rate of the system to maximum
500 Hz, but the sampling rate may be increased by using the available memory of the microcontroller.
In the available memory is possible to store about 3 seconds of data from 6 channels at a rate of 1 kHz.
More information could be stored if using additional RAM modules.
The source code of the software stored in the microcontroller is written in C++. The tasks of the program are to pre-process raw data taken from the accelerometers, to store data on SD card, to offer a simple user interface (based on buttons and LEDs) and to communicate, through USB interface, with a personal computer (an advanced configuration interface). The main tasks are data pre-processing and storing. When a high acceleration value is measured, the system starts to record next data in the memory, at 1 kHz, as detail information. When the acquisition process is finished, the data from memory are stored also on the SD card. In order to avoid the start of detail acquisition when a false acceleration spike is measured, raw data measured are filtered using a low-pass filter. This filter is used only in real time measurement and is implemented so that a minimum processing time is required. It uses the function:

\[ y(t) = x(t) \cdot \alpha + y(t - 1) \cdot (1 - \alpha) \]  

Equation (1)

where \( y(t) \) is the current calculated (estimated) value, \( y(t-1) \) is the previous calculated value, \( x(t) \) is the current measured value and \( \alpha \) is an attenuation factor between 0 and 1.

The effect of this filter is not saved in the data file; only raw data are saved. The "raw data" represents accelerations measured, expressed as integer numbers that are part of the entire range of the analog input of the acquisition board. As example, a 10 bits input allow values from 0 to 1023. This means the zero level of an accelerometer will be around the value 512. Some sample lines are given in Table 1. In the example it can be seen the small variation of values when vehicle is stationary. The columns X1, Y1, Z1 are for the low-g channels, and X2, Y2, Z2 are for hi-g channels. Obviously, the difference between Z values and the other two axes is equal with \( g \) (gravity acceleration).

| Time | X1  | Y1  | Z1  | X2  | Y2  | Z2  |
|------|-----|-----|-----|-----|-----|-----|
| 0    | 506 | 499 | 612 | 515 | 516 | 519 |
| 3    | 508 | 499 | 612 | 514 | 516 | 519 |
| 5    | 510 | 498 | 612 | 514 | 515 | 519 |
| 7    | 508 | 498 | 613 | 514 | 516 | 519 |
| 9    | 507 | 497 | 614 | 515 | 515 | 520 |
| 11   | 508 | 495 | 613 | 515 | 515 | 518 |
| 13   | 507 | 498 | 614 | 514 | 515 | 519 |

In order to transform raw data to acceleration values, expressed in m/s\(^2\) or g, it is necessary to identify the zero level as exactly as possible, and also a transformation scale (gain), which depends by the sensor resolution. An accurate and simple calibration method is to use two points per axis of interest [6]. When an axis is placed into a +1 g and −1 g field, the measured outputs are as follows:

\[
A_{1g} = A_0 + (1g \cdot Gain) \\
A_{-1g} = A_0 + (-1g \cdot Gain)
\]

Equation (2)

where \( A_0 \) is the zero level of acceleration, or acceleration offset, and \( Gain \) is the transformation scale, which can be calculated from the measured levels of +1g and -1g. An example diagram of a 3-axis accelerometer calibration is shown in Figure 2, and the raw values for 1g/-1g can be identified and extracted from the raw data file (using the time stamp as reference). The gain and offset (zero level) values are then used in post-processing phase.
3. Data processing and results

The tool used for data processing is a dedicated program, developed for the CDL data acquisition system. From the program features, can be mentioned: possibility of data filtering using CFC or simple low-pass filters, display the processed data as diagrams (as shown in Figure 2), selection of the acceleration curves (channels) to be displayed, zoom and pan functions for diagrams, possibility to update the zero level for each channel, export data from the table (calculated) or as raw data as text files.

The user interface of the software is presented in Figure 3. The left side of the interface is covered mainly by the chart area. The size of the chart area is changing when the program window is resized, since the other areas remain constant. So, the chart area will be much bigger when the window is maximized, and is also interactive (a click on the chart will give information about the selected point on diagram).

The digital filter used for crash tests data, as per SAE J211, is CFC (Channel Frequency Classes) filter (which is also a low-pass filter). The basic relation for a CFC filter is:
\[ y(t) = a_0 \cdot x(t) + a_1 \cdot x(t - 1) + a_2 \cdot x(t - 2) + b_1 \cdot y(t - 1) + b_2 \cdot y(t - 2) \quad (3) \]

where the coefficients \(a_0, a_1, a_2, b_1, b_2\) are calculated using the relations available in the standard [3] and many other sources, as [7], and they depend by the filter class and sampling frequency. The \(x\) values represents measured data (current, and two previous values) and \(y\) represents estimated data (two previous values).

3.1. Vehicle-vehicle collision

The prototype of the acquisition device was used in various crash tests, at different speeds. The device was installed with bolts on the vehicle floor, with one axis oriented in the direction of travel. It is not important which axis is aligned with the travel direction, as long as the position of the device is known (the accelerometer axis can also define an angle with the direction of travel, but this will make calculation more complicated).

The crash pulse measured on a stationary vehicle that was impacted by another vehicle is given in Figure 4, using raw and filtered data. The filter used is CFC60. Raw data used are from the Hi-g accelerometer (input range ±200 g).

**Figure 4.** Example crash pulse from a vehicle-vehicle collision: left-unfiltered; right-filtered

**Figure 5.** Example crash pulses from vehicle-vehicle collisions (the moving vehicle)
Two other crash tests given the diagrams shown in Figure 5. There are two different tests, but in both cases the crash data logger was installed on the moving vehicle. The impact speeds were between 35 and 40 km/h.

3.2. Vehicle-pedestrian or vehicle-cyclist collision
Other collision types for which the acquisition device was used are vehicle-pedestrian and vehicle-cyclist. These two types of crash tests are quite similar regarding the accelerations measured on the vehicle. The CDL acquisition device is installed on the vehicle. The raw data used are provided by the low-g accelerometer (input range ±3 g).

![Figure 6. Vehicle-pedestrian collision: vehicle acceleration-left; vehicle speed-right](image1)

![Figure 7. Vehicle-cyclist collision: vehicle acceleration-left; vehicle speed-right](image2)
Resulted diagram, for longitudinal and lateral accelerations (blue and red curves, respectively), is shown in Figure 6. The velocity of the vehicle, measured with a GPS based acquisition device, was about 32 km/h at the moment of impact. The velocity diagram is shown also in Figure 6 (as function of distance).

The diagrams of vehicle-cyclist collision are presented in Figure 7. The vehicle speed at the impact moment was about 35 km/h.

Both acceleration diagrams show the same profile: a short crash pulse, at the time of collision, then the braking sequence, when the driver presses the brake pedal. The maximum value of acceleration during the crash pulse is less than 2 g, which means that the data from the low-g accelerometer should be used.

4. Conclusion

The accelerations of vehicles involved in road accidents differ from an event to another. The crash tests can help the experts to identify the ranges of accelerations that may appear in various collision types. The correct sensors and data acquisition devices used in crash tests depend by the type of collisions. There are also different requirements for the sensors installed on vehicles or dummies.

The sensor characteristics specified in standards are difficult to obtain with cheap accelerometers. However, the shape of a crash pulse can be determined also using low cost devices, with limited bandwidth and resolution.

The original data acquisition device presented in this paper is affordable, easy to use and highly configurable. The dedicated data processing software allows user to generate the crash pulses quick and easy. For additional operation, if needed, the data can be exported to other software, like Excel, as text files.

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