Use of MEMS sensors for data acquisition in crash tests

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Abstract

Crash tests are part of vehicle testing programs that help manufacturers to produce safer cars. Most crash tests use real vehicles instrumented with many sensors that measures speed, forces or accelerations. In tests, the human body, be it pedestrian or vehicle occupant, is replaced with a dummy, also instrumented with sensors. The sensors used today are realized as MEMS (Micro-Electro-Mechanical Systems), with a technology that allow them to be affordable and versatile. Some recommendations regarding vehicle instrumentation for impact tests, including data processing, are included in the SAE J211 standard, where also other descriptions of crash analysis criteria are available. This paper is based on the recommendations given in literature and crash tests performed at Transilvania University of Brasov, using dedicated equipment (with MEMS sensors) from well known suppliers and originally designed.

Introduction

One of the reasons cars are getting safer is the testing program, that includes crash tests. These are destructive tests performed in order to ensure safe design standards in crashworthiness and crash compatibility for vehicles, or automotive systems and components. Nowadays, there are many well known car safety performance assessment programmes, like Euro NCAP (European New Car Assessment Programme) [1], ANCAP (Australasian New Car Assessment Program) [2], NCAP (New Car Assessment Program) created by National Highway Traffic Safety Administration (NHTSA) [3] or JNCAP (Japan New Car Assessment Program), but there are also crash testing programmes performed by research institutes (like DSD - Doctor Steffan Datentechnik) [4] or academic institutions like Monash University Accident Research Centre [6] or Transilvania University of Brasov, Pro-DD Institute (Fig. 1).

There are various types of crash tests:

- frontal impact tests: impacts, at a specified speed, upon a solid concrete wall or a vehicle-vehicle test;
- overlap tests: when only part of the front of the vehicle impacts with a barrier or vehicle;
- side impact tests: usually vehicle-vehicle, when the frontal part of a vehicle at a certain speed colides with lateral part of the other vehicle;
- roll-over tests: testing a car's ability to support itself in a dynamic impact;
- vehicle-pedestrian tests: colision between the front of a vehicle with a dummy [5];
- roadside hardware crash tests: testing the behavior of the vehicle body and airbags when the vehicle colides with guard rails, sign posts, light poles or other lateral obstacles.

Fig. 1. Crash test performed at Transilvania University of Brasov, Pro-DD Institute, in June 2015

A crash test can be simulated using computer models, in order to avoid the high cost of a full-scale crash test. The simulation can help engineers to refine their vehicle, dummy or barrier designs before conducting the live tests. Examples of simulation software used are PC-Crash [4, 7], Virtual Crash [8] and general-purpose multiphysics simulation software packages like LS-Dyna [9].

Data collection and processing

Because the crash tests are very expensive, from each test should be extracted as many data as possible. For this, high-speed data acquisition systems are used, including three-axis accelerometers and speed measuring systems. The sensors should be chosen and installed according to the goal of the test. Standards like SAE J211 [10] are used as recommendation for vehicle instrumentation, for impact tests.

Criteria for crash analysis are described in the report of the Data Processing Vehicle Safety Workgroup [11], for different parts of the dummy (head, neck, chest, extremities), and also additional criteria for measuring and filtering the acceleration values. Data obtained should be filtered before analysis is performed using the recommended criteria. The recommended filtering procedure, according to SAE J211, is using one of four channel frequency classes (CFC) of low-pass filters. As shown in the report related to the design of digital low-pass filters for time-domain recursive filtering of impact acceleration signals [12], "filtering is the most critical phase in the processing of impact signals. Its primary function is to eliminate undesired high-frequency noise that obscures the underlying signature in the signal. The importance of filtering becomes evident when considering that filtering reduces the peaks in the signal and peaks often are used for assessment of protective devices."

The four filters designated by SAE J211 are CFC 60, 180, 600, and 1000. They were derived from analog Butterworth filters whose corner frequency is equal to the CFC designation divided by 0.6. The corner of a filter is defined as the frequency at which the signal loses one half of its power (signal magnitude attenuation is equal to 3 dB).

The filter types and their parameters are listed in Table 1.

Filter type	Filter parameters	
CFC 60	3 dB limit frequency	100 Hz
	Stop damping	-30 dB
	Sampling frequency	at least 600 Hz
CFC 180	3 dB limit frequency	300 Hz
	Stop damping	-30 dB
	Sampling frequency	at least 1800 Hz
CFC 600	3 dB limit frequency	1000 Hz
	Stop damping	-40 dB
	Sampling frequency	at least 6 kHz
CFC 1000	3 dB limit frequency	1650 Hz
	Stop damping	-40 dB
	Sampling frequency	at least 10 kHz

Table 1: Filter types, SAE J211

According to SAE J211, the digital filter that should be used is a 4-channel Butterworth low-pass filter with linear phase.

The filter sequence is described by the difference equation [13]:

$$Y(t) = a_0 \cdot X(t) + a_1 \cdot X(t-1) + a_2 \cdot X(t-2) + b_1 \cdot Y(t-1) + b_2 \cdot Y(t-2) \qquad (1)$$

where the coefficients *a0, a1, a2, b1, b2* are calculated with formulas given in J211, depending by the filter class and sampling frequency.

Typical Test Measurements	Channel Frequency Class (CFC)
Vehicle structural accelerations for use in:	
- total vehicle comparison	60
- collision simulation input	60
- component analysis	600
- integration for velocity	180
Barrier face force	60
Beld restraints system loads	60
Antropomorphic test device:	
- Head accelerations	1000
- Neck forces	1000
- Thorax: spine accelerations	180
- Thorax: sternum accel.	1000
- Lumbar forces	1000
- Pelvis accel./forces	1000
- Femur/Knee/Tibia/Ankle	600
Sled accelerations	60
Steering column loads	600

Table 2: Frequency response classes (from SAE J211)

The selection of a frequency response class depends by application and the expertize of the testing engineer. In order to made valid comparison between different test, it should be used the same frequency response class. The SAE recommendations are listen in Table 2.

The selected frequency class will determine the necessary sampling frequency, according to Table 1.

It is also important in a crash test how the transducers/sensors are mounted. There are differences between the mounting positions for vehicles and dummies, and there are conventions regarding the coordinate systems used as reference. For example, the vehicle coordinate system has the z-axis oriented downward, x-axis directed forward (indicating the vehicle direction of travel forward) and y-axis directed from left to right. To define the dummy coordinate systems, the dummy will be considered as standing erect. For this posture, the y-axis will be directed from its left to right, the z-axis is directed from head to toe, and x-axis is directed forward. So, if the dummy is seating inside the vehicle, the coordinate systems for the sensors mounted in the head or in the chest, will be the same as the coordinate system of the vehicle.

The sensors - what is MEMS

The parameters measured in crash tests are accelerations, forces or displacements. The most used sensors are accelerometers - devices that measure the acceleration in a particular direction. This data can be used to determine the probability of injury. As the acceleration is higher, the probability of injury will be higher. For the parts of the body were established some injury criteria, like HIC (Head Injury Criterion) for head, NIC (Neck Injury Criterion) for neck or VC (Viscous Criterion, or velocity of compression, also called Soft Tissue Criterion) for the chest area [11]. All of these criteria (and others) depends by acceleration.

The acceleration sensors most used today are those manufactured in MEMS technology. MEMS is the abbreviation for Micro-Electro-Mechanical Systems. MEMS is a technology that can be generally defined as miniaturized mechanical and electro-mechanical elements that are made using the techniques of microfabrication [14]. A MEMS accelerometer is integrating an accelerometer and the electronics into a single silicon chip, resulting in a tiny device. The technology used for MEMS manufacturing is similar with that used for integrated circuits, but it is not the same. Some characteristics of MEMS, which make them different by ICs, are: they have 3D complex structure, may have moving parts, may have interface with external media, their functions include biological, chemical, optical, not only electrical.

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, micromachined capacitive or piezoresistive plates sense a change in acceleration from deflection of the plates [15]. One of the first commercial devices using MEMS was the automotive airbag, which is based on an accelerometer. Other automotive applications for MEMS include: antilock braking systems, active suspension, appliance and navigation control systems, vibration monitoring, fuel sensors, noise reduction, rollover detection, seatbelt restraint and tensioning etc. The automotive industry is one of the main drivers for the development of MEMS. However, accelerometers are not just limited to automotive applications.

Equipment and software used

The crash test programmes conducted at Transilvania University include collisions between vehicles, obstacle, pedestrian or two-wheeler, as follows:

- vehicle-vehicle: frontal impact tests; overlap tests, side impact tests, rear impact tests;
- vehicle-obstacle: overlap tests, roll-over tests;
- vehicle-pedestrian: frontal impact tests with dummy;
- vehicle-bicyclist: frontal/overlap impact tests, lateral impact test, with dummy.

Fig. 2. PicDAQ5 Data Acquisition device [16]

One of the devices used to measure accelerations in these crash tests is PicDAQ [16] (Fig. 2 shown the new version of the device). This is a data acquisition platform based on a microcontroller, and with one gyroscope and two accelerometers as input sensors, all of them working on three axes. The recorded accelerations and angular velocities describe the movement. An external sensor can be attached using a cable, for example another accelerometer to measure the impact of the dummy's head when the main unit is installed in the chest. The system can take also data from a GPS receiver, through a serial interface. Only the speed is taken from the GPS receiver, extracted from one of the NMEA 0183 sequences [13]. The two accelerometers have different input ranges: one of them can take accelerations in the range of ± 5 g, and is intended mainly for braking tests, the other can take accelerations in the range of ± 50 g, and is intended for crash tests. The software that accompanies the acquisition device is PocketDaqAnalyzer (Fig. 3).

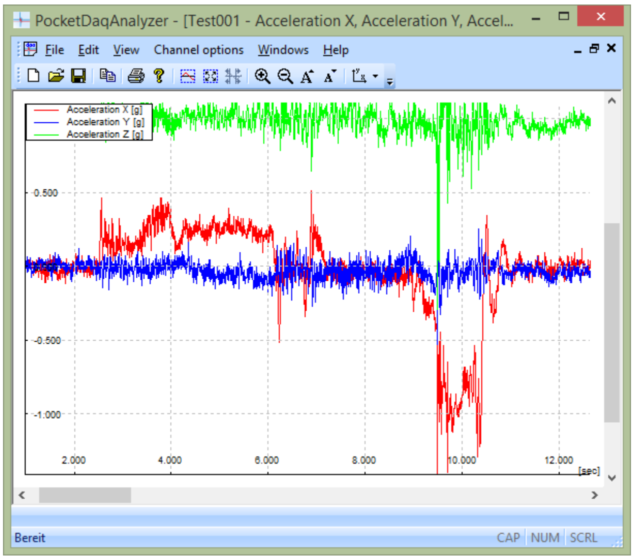
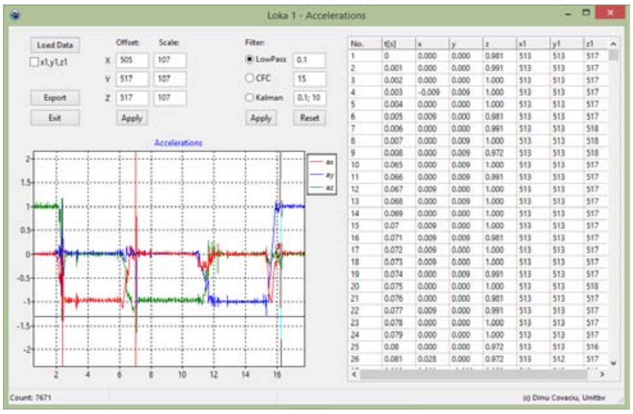


Fig. 3. Screen capture of the PocketDaqAnalyzer software

Fig. 4. PicDAQ on the vehicle floor, with Loka mounted on top of it

Another device used is built in the own laboratory and it was named Loka (shown in Fig. 4 attached to a PicDAQ, as it was used in the tests presented further). It consists in a logger based on the LPC2148 ARM7 microcontroller (Logomatic v2 [17]). Two triaxial accelerometers are connected to the analog input pins of the board: ADXL337 (± 3 g) and ADXL377 (± 200 g) [18]. The calibration and data processing was done with a custom software application (Fig. 5).



☐ x1,y1,z1

	Offset:	Scale:
X	505	107
Y	517	107
Z	517	107

Filter:
● LowPass 0.1
○ CFC 15
○ Kalman 0.1; 10

No.	t[s]	x	y	z	x1	y1	z1
1	0	0.000	0.000	0.981	513	513	517
2	0.001	0.000	0.000	0.991	513	513	517
3	0.002	0.000	0.000	1.000	513	513	517
4	0.003	-0.009	0.009	1.000	513	513	517
5	0.004	0.000	0.000	1.000	513	513	517
6	0.005	0.009	0.000	0.981	513	513	517
7	0.006	0.000	0.000	0.991	513	513	518
8	0.007	0.000	0.009	1.000	513	513	518
9	0.008	0.000	0.009	0.972	513	513	518
10	0.065	0.000	0.009	1.000	513	513	517
11	0.066	0.000	0.009	0.991	513	513	517
12	0.067	0.009	0.000	1.000	513	513	517
13	0.068	0.000	0.009	1.000	513	513	517
14	0.069	0.000	0.000	1.000	513	513	517
15	0.07	0.009	0.000	1.000	513	513	517
16	0.071	0.009	0.009	0.981	513	513	517
17	0.072	0.009	0.000	1.000	513	513	517
18	0.073	0.009	0.000	1.000	513	513	517
19	0.074	0.000	0.009	0.991	513	513	517
20	0.075	0.000	0.000	1.000	513	513	518
21	0.076	0.000	0.000	0.981	513	513	517
22	0.077	0.009	0.000	0.991	513	513	517
23	0.078	0.000	0.000	1.000	513	513	517
24	0.079	0.000	0.000	1.000	513	513	517
25	0.08	0.000	0.000	0.972	513	513	516
26	0.081	0.028	0.000	0.972	513	512	517

Count: 7671

(c) Dinu Covaciu, Unitbv

Fig. 5. Screen capture of the Loka software (calibration)

The "Loka" data acquisition device can log at the same time data through a serial interface, and this may be the signal from a GPS receiver (NMEA 0183 sequences). But in order to use higher sampling rates it was preferred to use an external GPS receiver to log the vehicle speed and direction of travel. The GPS logger used (DL-10) is also one built by authors, with a 10 Hz sampling rate.

Crash test data acquisition

Two tests are presented here: vehicle-bicyclist and vehicle-vehicle (frontal impact). For both tests, the sampling frequency for accelerometers was 1 kHz for the devices mounted on the vehicle body and 5 kHz for the devices installed in the dummies.

For the first crash test, the vehicle which hits the bicycle is equipped with two acceleration logging devices: PicDAQ and Loka, and two DL-10 GPS logger (for data redundancy). The bicyclist dummy is equipped with acceleration logging device (PicDAQ). Only the vehicle data are presented here, because only these are relevant for MEMS devices comparison.

The vehicle speed recorded by both GPS loggers, at impact, is 36.3 km/h (Fig. 6).

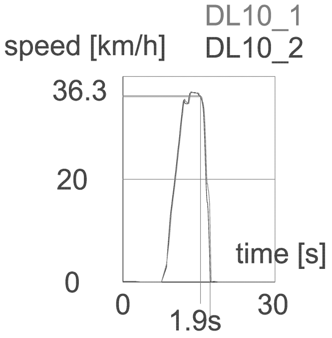


Fig. 6. Vehicle speed measured with 2x DL-10

From the values shown in Fig. 6, results a mean acceleration of about 0.5 g, which is in concordance with the accelerations shown in Fig. 7 (red) and Fig. 8 (blue), where the dominant deceleration value is around 1 g for about 1 second (with a very short pulse going over 1.5 g), and much lower, close to 0, before and after (about another 1 second).

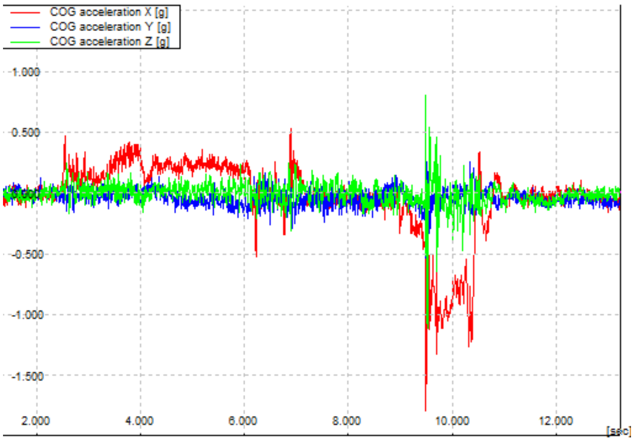


Fig. 7. Accelerations measured on vehicle, PicDAQ

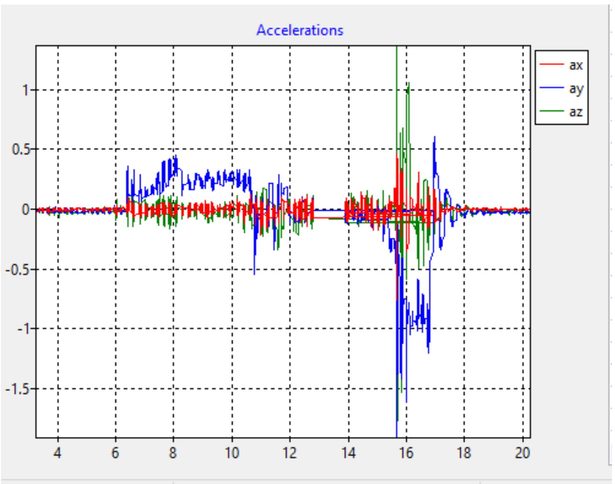


Fig. 8. Accelerations measured on vehicle, Loka

The diagrams in Fig. 7 and Fig. 8 represent the accelerations measured with PicDAQ and Loka, respectively. The Loka device was rotated with 90 degrees, for mounting reasons, and that explains the difference in colors (red versus blue). The graph profiles are very similar. The crash sequence, in time, is about 2 seconds (between 9 to 11 in Fig. 7 and between 15 to 17 in Fig. 8). The sampling rates were 1 kHz and 500 Hz, respectively, and the filtering class are CFC 60 and CFC 30.

Fig. 9. Frontal impact, vehicle-vehicle

For the second test were used two vehicles: a stationary one and a moving one (Fig. 9). Both vehicles were equipped with accelerometers and GPS receivers. On the hitting vehicle (right side of Fig. 9) were installed two accelerometer devices: PicDAQ and Loka, and a DL-10 receiver. On the stationary vehicle was installed a PicDAQ and a DL-10. Inside each vehicle was seated a dummy, with a PicDAQ device inside the chest and an external sensor (also a triaxial accelerometer) in the head.

The vehicle speed recorded by the GPS logger is 30.8 km/h, as shown in Fig. 10 (data processed in GPS/CAD application [19]).

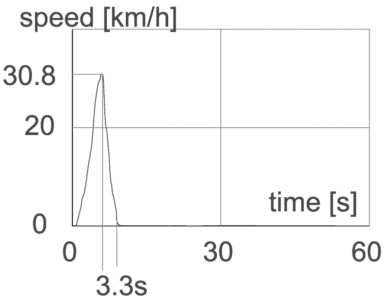


Fig. 10. Vehicle speed measured with DL-10

The time from impact speed to complete stop is much longer than the impact time, because the vehicles were moved together (small accelerations appear also in Fig. 11 after impact). The impact duration is, in fact, about 0.2 sec.

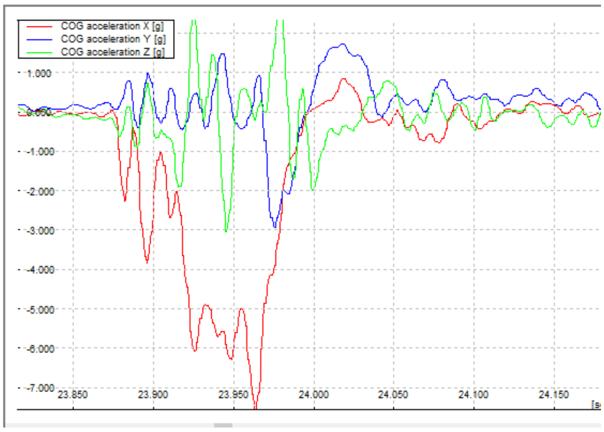


Fig. 11. Accelerations measured on moving vehicle

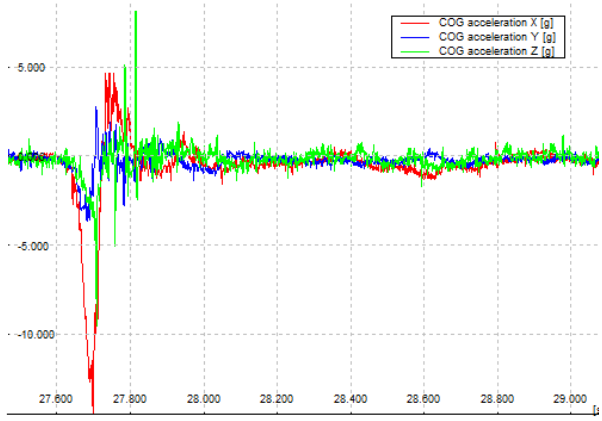


Fig. 12. Accelerations measured in dummy chest, moving vehicle

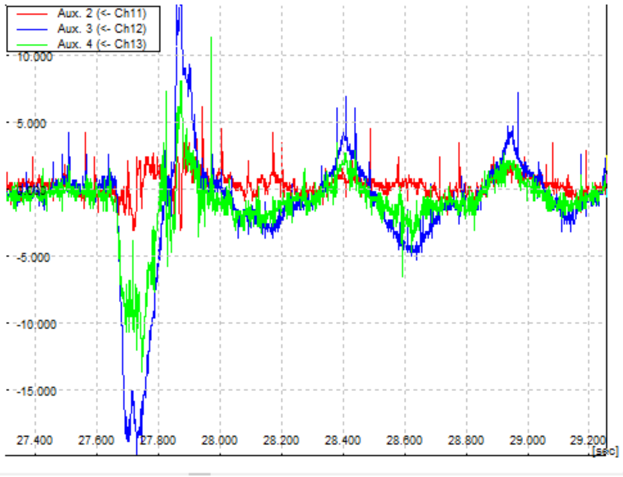


Fig. 13. Accelerations measured in dummy head, moving vehicle

For the moving vehicle, the acceleration diagrams are presented in Fig. 11 for the vehicle body, Fig. 12 for the dummy chest and Fig. 13 for the dummy head (the dummy sitting on the driver's seat). The maximum acceleration measured on x-axis, for vehicle body, is a little over 7 g. For the dummy chest, the accelerations are much higher: about 15 g in x direction, and for the head, the x and z axis movements are in phase, showing the swing of the head.

In this test, the acceleration was to high for the low-accel sensor of Loka, and too small for a good accuracy measurement with the high-accel sensor (± 200 g range). Therefore, data recorded with Loka are not used in the analysis.

The filters used are CFC 60 for vehicle body (1 kHz sampling frequency) and CFC 180 for dummy (5 kHz sampling frequency).

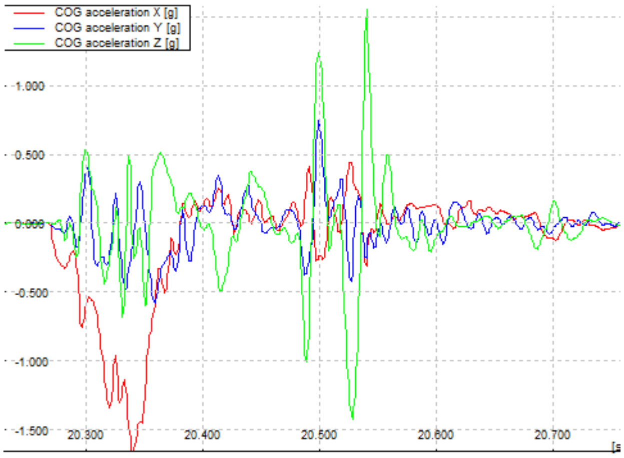


Fig. 14. Accelerations measured on stationary vehicle

For the stationary vehicle, the acceleration diagrams are in Fig. 14 for the vehicle body, Fig. 15 for dummy chest and Fig. 16 for dummy head. It can be noticed the difference in the movements of the dummies in the two vehicles. It has to be mentioned that the red curve in the head acceleration diagrams is for y-axis, blue is for z-axis and green is for x-axis.

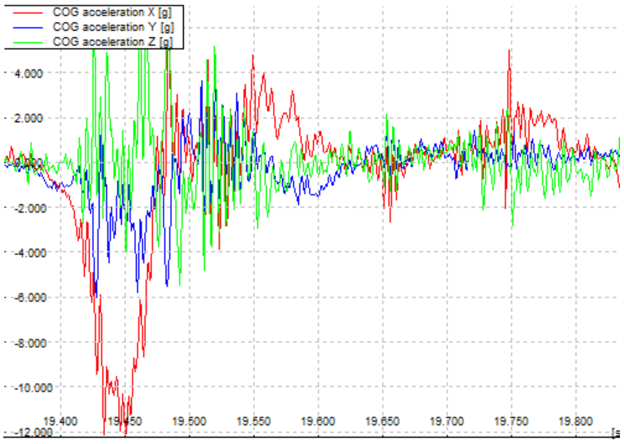


Fig. 15. Accelerations measured in dummy chest, stationary vehicle

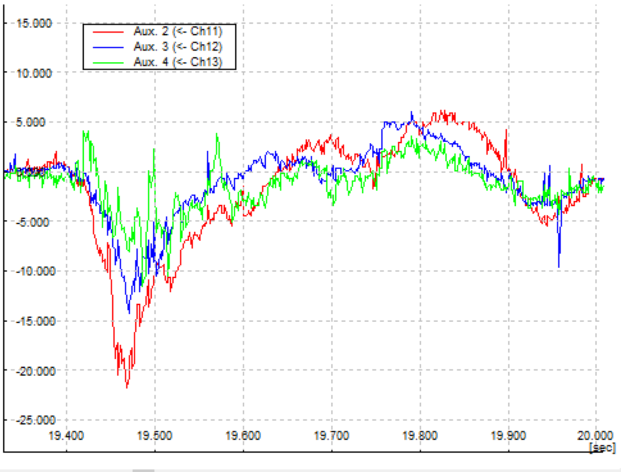


Fig. 16. Accelerations measured in dummy head, stationary vehicle

The filters and sampling frequencies are the same as for the moving vehicle.

The value of acceleration (x-axis) of the vehicle body shows that the vehicle is moving backward, and the variations of the z-axis acceleration indicates a vertical movement - the back of the vehicle is raising and falling back on the ground.

Conclusions

The micro-electro-mechanical systems (MEMS) are to date widely used in many applications; some examples are: identification of free-falling, anti-theft systems, voice recognition, micro-actuators, digital compass, acceleration and tilting measurements. On the modern automotive platforms are implemented many sensor based safety features, such as Electronic Stability Programme (ESP), Tire Pressure Monitoring Systems (TPMS), Advanced Driver Assistance Systems (ADAS), Anti-lock Braking System (ABS), and others. One of the most used application of MEMS in automotive engineering is the acceleration measurement.

Acceleration is an important parameter measured in crash tests, so the MEMS accelerometers are incorporated in specialized data acquisition devices. There are various types of crash tests and the data acquisition equipment should be chosen and/or configures accordingly. An important challenge is to select the appropriate sensor for the measurement to be done - to choose the appropriate measurement range. Then it is important to select the correct sampling frequency, and when processing the data, to choose the appropriate filter. The channel frequency classes used in the test presented in this paper are not all according to the SAE recommendation (Table 2), but are in concordance with the sampling frequency and acceleration values.

The original developed equipment (Loka) gave good results in the first test, similar with the PicDAQ system. It should be also appropriate for measuring accelerations in a stationary vehicle, in a vehicle-vehicle collision. For higher accelerations, like those measured on the hitting vehicle in the second test, another accelerometer have to be added to the device, with a range of ± 50 g or similar. Another further improvement will be the raise of the sampling frequency.

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