CRASH TYPE DISTINCTION USING STRUCTURE-BORNE SOUND SENSING

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ABSTRACT

Current crash sensing systems are normally based on acceleration sensing. Therefore, the deceleration pulses affecting the car's body are used to apply the firing thresholds of the restraint systems. A new kind of crash sensing consists of measuring high frequent chassis vibration regarding frequencies up to 20 kHz: crash sensing based on structure-borne sound (SBS). The main benefit of this technology will be to support the common deceleration-based crash detection in crash type distinction during the early crash phase. To be able to use the acquired data in a physically reasonable way, the events causing SBS during crash important to know.

In the proceeding of the study, the events occurring during a crash are interpreted as shock excitations of different impulse lengths that can be divided into hard and soft events. Valuable results from a multitude of component crash tests on a drop tower test stand are transferred to vehicle crashes in serial development. The applicability of crash separation criteria is examined. The crash type distinction of hard/soft crashes based on structural vibration sensing is the main idea to support the differentiation of hard no fire tests and soft must fire tests. The study shows that shock excitation of the vehicle structure is the most important cause of high frequent vibration signals acquired during vehicle crashes.

The article deals with the usage of high frequent structural vibration in the range up to 20 kHz for crash detection. The understanding of the vehicle being a structure under linear elastic shock excitation leads to a physically plausible usage of the signals for crash type distinction.

INTRODUCTION

Today, architectures of current crash detection systems, used to activate passive safety restraint systems, are based on processing data of a multitude of sensors distributed in the vehicle. This is needed to fulfil the high and complex requirements of legislation, consumer and insurance organisations. For frontal collision detection, mainly acceleration sensors are used to process the deceleration of the vehicle's structure and its velocity reduction during the crash. Figure 1 shows a symbolic representation of a current sensor architecture consisting of acceleration sensors mounted at the vehicle's central position and at four satellite positions (one at each B-pillar and two at the front of the vehicle).

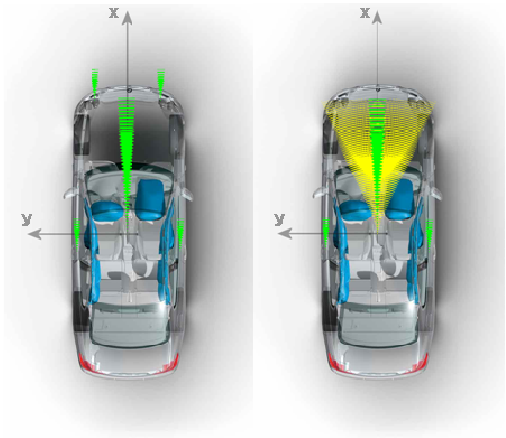

Figure 1. Sensor architectures for frontal collision detection showing symbolic representations with current (left) and reduced number of satellite sensors including an additional structure-borne sound sensor (right).

The performance of the frontal satellites strongly depends on their mounting position, which leads to a high effort during development [1]. Replacing them by a more innovative technology like SBS sensing at the central sensor position using a special sound sensor is preferable. On the right side of Figure 1, a possible sensor architecture is represented that only provides two satellite positions at the B-pillars and a single central position including both, current acceleration sensor and SBS sensor.

Separation of Hard and Soft Crash Types

Basically, the main task in crash detection is the distinction of must fire and no fire cases. While in must fire cases at least one restraint system (e.g. seat belt retractor or air bag) has to be activated, no restraint system must be activated during the whole crash for no fire cases. A particular challenge is the distinction of so called hard or soft crash types. The crash type is defined by the over all crash stiffness not only depending on the front end stiffness of the own vehicle, but also on the stiffness, position and

orientation of the barrier or the crash partner. The higher the crash stiffness, the harder the crash. Examples for hard crash tests are:

- AZT (**A**llianz **Z**entrum für **T**echnik) crash repair test: frontal offset crash with 40 % overlap against a rigid barrier, vehicle speed 15-16 kph, no fire [2]
- USNCAP (**US N**ew **C**ar **A**ssessment **P**rogram): frontal crash 100 % overlap against a rigid barrier, vehicle speed 56 kph, must fire [3]

Important examples for soft crash types are the ODB tests (**O**ffset **D**eformable **B**arrier):

- Euro NCAP (**Euro**pean **N**ew **C**ar **A**ssessment): frontal offset crash with 40 % overlap against a deformable barrier, vehicle speed 64 kph, must fire [4]
- FMVSS 208 (**F**ederal **M**otor **V**ehicle **S**afety **S**tandard): see Euro NCAP, but: vehicle speed 40 kph [5]

In the following, the ODB 40 kph will be treated as the typical representative of the soft crash type. As described below, the distinction between the ODB 40 kph and the AZT is very challenging.

During a hard impact, the velocity reduction begins early and proceeds relatively quickly. During a soft impact, even at high vehicle speed, the velocity reduction occurs much more delayed. In the TTF (TTF: **T**ime **T**o **F**ire < 30-40 ms) zone, the velocity reduction level for slow hard crash tests corresponds to the velocity reduction of much faster soft crash types. Based on this single criteria, the distinction of soft must fire tests (ODB) and hard no fire tests is not possible.
Figure 2 shows that a clear distinction based on the detected velocity reduction is not possible before 80th millisecond.
The additional information of SBS that can be measured in the central position allows a better recognition of the actual impact characteristics. Knowing the impact characteristic can be used to support the classical acceleration-based fire logic by using a hard-soft-classification. In addition to the vehicle's deceleration in x- and y-direction and dependent on the chosen algorithm concept, the crash type is an important factor for activating the restraint systems in the required time range. The following paragraph describes the data processing of SBS signals as it is implemented by sensor manufacturer to allow the usage of SBS in a crash detection algorithm.

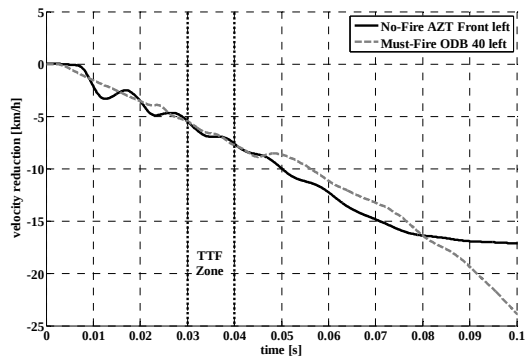

Figure 2. Velocity reduction for AZT and ODB, trigger: $t = 0 = t_0$.

STRUCTURE-BORNE SOUND – MEASUREMENT AND DATA ANALYSIS

SBS is defined as elastic waves in a frequency range between 16 Hz and 20 kHz, propagation in solid structures [6]. SBS signals are commonly measured using high frequency acceleration sensors. To avoid aliasing effects in the relevant frequency range up to 20 kHz, the sampling frequency must be chosen to have at least twice the highest interesting frequency [7]. Such a highly resolved raw signal, however, is not applicable for serial utilization because of the required bus loads and computational demands. Instead, a data reduction is processed so that the signals can be transferred using a standard sampling rate. Therefore, a band pass filter extracts the signal of the interesting frequency range. Based on this high frequent signal, the envelope is created by rectification followed by a final low pass filter procedure. The resulting signal can be sampled at a lower rate depending on the chosen low pass frequency while the content of the relevant information is preserved. The integrative characteristic of the envelope processed on a frequency band is similar to the generation of a windowed RMS (**R**oot **M**ean **S**quare) value. Although the envelope basically can be realized using analogue electric components, digital signal processing of high resolution reference sensors is highly recommended using sampling frequencies of at least 40 kHz. The transferability between the reference signals and the occurring signals of a series production sensor in a central position must be guaranteed. Here, a detailed knowledge of the properties of serial and reference sensors is very important. In addition, the transfer path between these both sensors must not change, especially not during a crash. In this regard, SBS sensing is very sensitive to variation. In the field of low frequency acceleration sensing, individual transfer functions are determined to map both, the reference signals and the series production sensor signals for the application of the crash detection algorithms. The algorithm development can therefore be realized

using only reference signals. Signals of sensors for serial production are only considered in the final development of the vehicle to confirm the system's performance. This demand also applies on SBS sensing. The satisfiability of this demand, however, highly depends on the position, integration and sensor type of the reference sensors. An important aspect for being capable to use SBS signals in a reasonable way is to understand the effects that cause SBS emission. The processes that lead to a SBS emission during a vehicle crash are described in the following.

Structure-Borne Sound Excitation in Case of a Vehicle Crash

Earlier works on material research describe sound emission during plastic deformation of metallic structures. The sound emission is caused by various effects like dislocation movement within the crystal lattice and is usually observed in the ultrasonic frequency range (>20 kHz) [1], [8]. Beside the continuous sound emission in case of plastic deformation of metal, the impact characteristic of a crash has been identified as important factor in the frequency range up to 20 kHz. The impact characteristic is mainly defined by the shock excitation of the vehicle structure. The excited spectral distribution depends on the shock duration and the pulse shape. A long soft impact produces a spectral response in a lower frequency range. Short hard impacts additionally generate a higher amount of high frequency content [7], [9].
Figure 3 schematically shows two impact forces of different stiffness. The impulse area *A* is equivalent to the integrated impact force and is identical for both shocks. Only the duration of the impulse τ separates both shocks in hard with $\tau = \tau_1$ and soft with $\tau = \tau_2$.

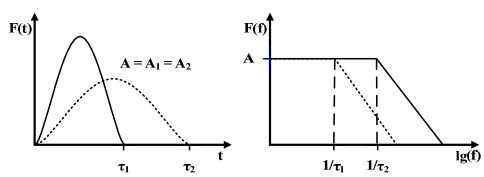

Figure 3. Shock impulses over time (left) and corresponding spectral distribution (right) according to [9].

This corresponds to an experiment in which, for example, a ball drops from a constant height on two surfaces of different hardness. The measured signal is the force applied from the ball onto the surface. Each of both impulses of equivalent area generates a force spectrum that can be estimated by the method described in [9]. There, it is explained that amplitudes are constant for low frequency domains when varying the impulse duration, but for high frequencies, they decrease in the majority of practical cases with -40 dB/frequency decade beginning at a critical frequency defined by:

$$f_{s,i} = 1/\tau_i \qquad (1).$$

This characteristic spectral distribution does not vary in case of identical stiffness conditions but different impulse height since the impulse duration is not influenced. Here, only the spectral amplitude rises. The shock impulse excites all resonance frequencies of the structure inside the spectrum. The general relation between time and frequency domain is described by the Fourier integral:

$$F(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \check{F}(\omega) e^{j\omega t} d\omega ;$$

$$\check{F}(\omega) = \int_{-\infty}^{\infty} F(t) e^{-j\omega t} dt \qquad (2).$$

In case of a vehicle crash the characteristic of the shock impulse is indeed very complex. The example mentioned above describes the ideal case of an elastic shock. During a crash, instead, plastic deformation usually occurs which principally has a spreading influence on the impulse shape. But it can be shown that there still remain shock excitations exciting the structure of the vehicle.
To analyze these excitation processes under a high amount of reproducibility, the SBS generation is observed in component crash tests on a drop tower test stand. The crash proceedings can be isolated and observed in detail thanks to a strongly reduced complexity of the used structure. Only crash-relevant body components that are important for the impact excitation in the early crash phase are used: the bumper cross member with its deformation elements (crash boxes) and the frontal part of the longitudinal beam (Figure 4).

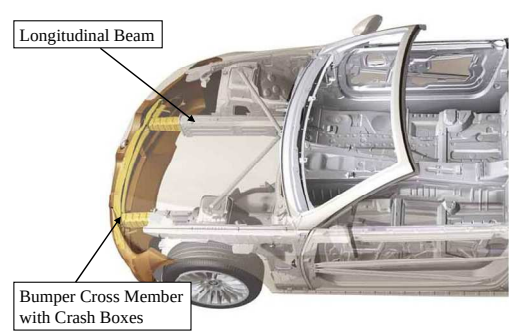

Figure 4. Frontal structure of a BMW 3 Series Convertible.

The tests are realized in AZT configuration with the structural components mounted vertically on the floor. The impact is generated by a rigid metallic barrier falling onto the structure with a partial overlap of 40 %. Two barrier types are considered for these tests: the older barrier with an angle of 0° as well as the newer testing configuration [2] using a barrier with an angle of 10°.

The impact velocity is varied to evaluate the velocity influence, too. The following representation of the test results consists of the analysis of two different serial bumper systems. They mainly differ in the junction between the different parts of the bumper cross member as well as the junction to the longitudinal beam (Figure 5).

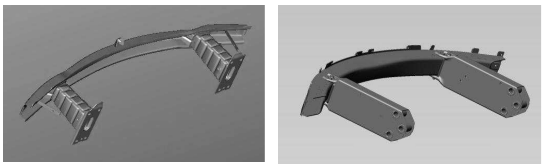

Figure 5. Different bumper systems with a welded cross member and longitudinal screw connection (left) and lateral screw connections within the cross member and longitudinal beam (right).

The left structure is characterized by the solid welded connection between the cross member and the crash boxes and the screw connection between the crash box and the longitudinal beam. These two solid and force-transferring connections lead to a high degree of reproducibility which is especially needed for SBS generation analysis.
In case of the right structure instead, the lateral screw connections cause influences in the SBS excitation due to a clearance passage within the screw joint. Such clearance passages induce glitches that have a strong influence on the variance of the measured signals. The clearance cannot be eliminated completely in the vehicle mounting. Therefore, the influence of a clearance passage is examined as well at the drop tower test bench.

Results

An acceleration sensor mounted on the dropping mass delivers data of the deceleration that is applied on the mass during the crash. The measured deceleration is proportional to the force integrated over the contact area of both structures. A small sampling rate does not allow the exact spectral analysis according to equation (2). but a qualitative analysis of the deceleration progress gives valuable insights on the deformation processes of the early crash phase. Two main deformation phases can be identified using the test configuration with 0° barrier angle. Both deformation phases, as described later, are each linked to an initial shock event. The first contact of the barrier causes a bending of the cross member which already dissipates a certain amount of energy. The force applied on the section of the crash box still is small. The duration of this phase is only a few milliseconds. The following compression of the crash box leads to a significant rise of the deceleration.
Because of its inclination, the 10° barrier touches down to the crash box much more directly which leads to a lack of the initial bending of the cross member. The deceleration of the mass increases more quickly.
Figure 6 shows the deceleration of the drop tower barrier for AZT configurations with barrier angles of 0° and 10°. The representation of the three measurements performed allows a statement about the variance of the test. All curves are very close to each other and only in the later proceeding of the test they differ lightly. The reproducibility of both, the test and the deformation process of the welded structure, is very high. All following explanations are referring to the black mean signal.
At the beginning, the abrupt rise of the mass deceleration is obvious for the 10° barrier. The decrease towards local minima represents the folding process, the deformation of the crash box. In the bottom figure the two deformation phases of the 0° barrier test can be identified. A shock precedes both deformation processes and leads to a short impulse excitation of the structure. Although the deceleration signals of the drop tower mass are strongly low pass filtered these impulses can be recognized in the measurement as short deviations of the curve's shape. These passages are mainly responsible for the SBS excitation and are marked with arrows in the figure below.

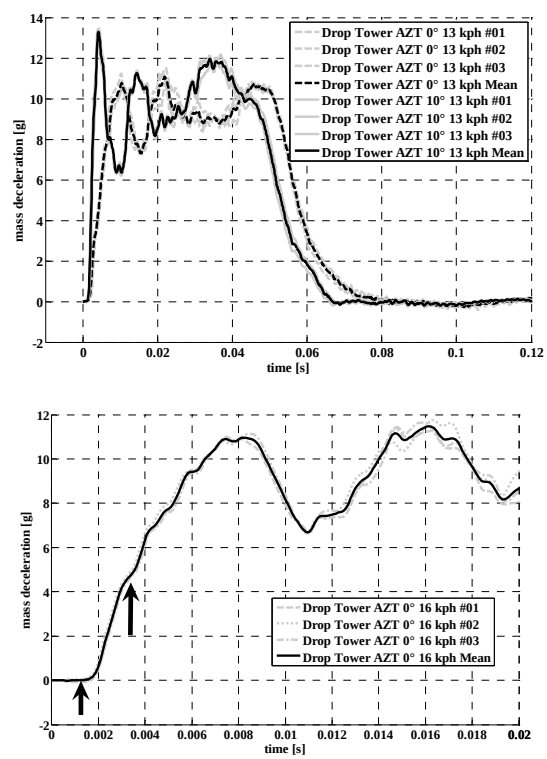

Figure 6. Measured deceleration of the barrier for 0° and 10° AZT drop tower test at 13 kph (above), 0° AZT drop tower test at 16 kph zoom 0-20 ms (below).

Because of their broad-band spectral characteristics, these shocks act as emission source for high

frequency SBS in the domain up to 20 kHz. Figure 7 shows the corresponding SBS envelope together with the view of the deformation of the bumper structure of three 16 kph 0° barrier tests. The variance of the measurements is shown by the illustration of three tests of the same configuration with their mean signal. The existing time offset of 1-2 ms compared to the mass deceleration is due to minimal asynchronies in trigger time stamps of both measurements. The SBS signal was measured on the longitudinal beam in a distance of 100 mm away from the flange. In comparison with the deceleration signal, the importance of shock excitation to the generation of SBS signals becomes obvious. At the 2nd millisecond, the initial contact between the barrier and the cross member has generated the first SBS peak. The following bending of the cross member does not affect the generation of additional SBS. The envelope amplitude slightly decreases. When the crash box is hit by the barrier (about 5th millisecond) the major part of SBS is measured (see central view in Figure 7).

The beginning folding process is generally accompanied by decreasing SBS amplitudes even though the force deviation causes further SBS excitation. The shift between longitudinal pressure load and the buckling of the crash box generates new impulses. But the isolated analysis of these secondary processes is hardly feasible. In the proceeding of the deformation, different excitation processes superpose, single events are difficult to separate.

A detailed analysis of the processes generating SBS requires a high degree of reproducibility. This is the case for the examples just mentioned before. Unlike, connection joints presenting a possible clearance passage have a much higher influence on the SBS generation than the shock excitation during the deformation of the crash box mentioned before. Clearance passages represent very short shocks that generate a high amount of high frequent SBS. The reproducibility of the SBS measurements is massively decreased compared to clearance-free structure parts. Lateral connections, like the screw connection in Figure 5 on the right are defined as connections having their axis orientated perpendicularly to the longitudinal axis of the vehicle. Here, the friction force affected within the connection is overcome very quickly, even at very low collision speeds. The parts slip through the connection which is followed by a very strong shock that is affected directly to the vehicle's body via the longitudinal beam. The procedure can generate a multitude of SBS signal produced by the deformation of clearance-free parts (Figure 8).

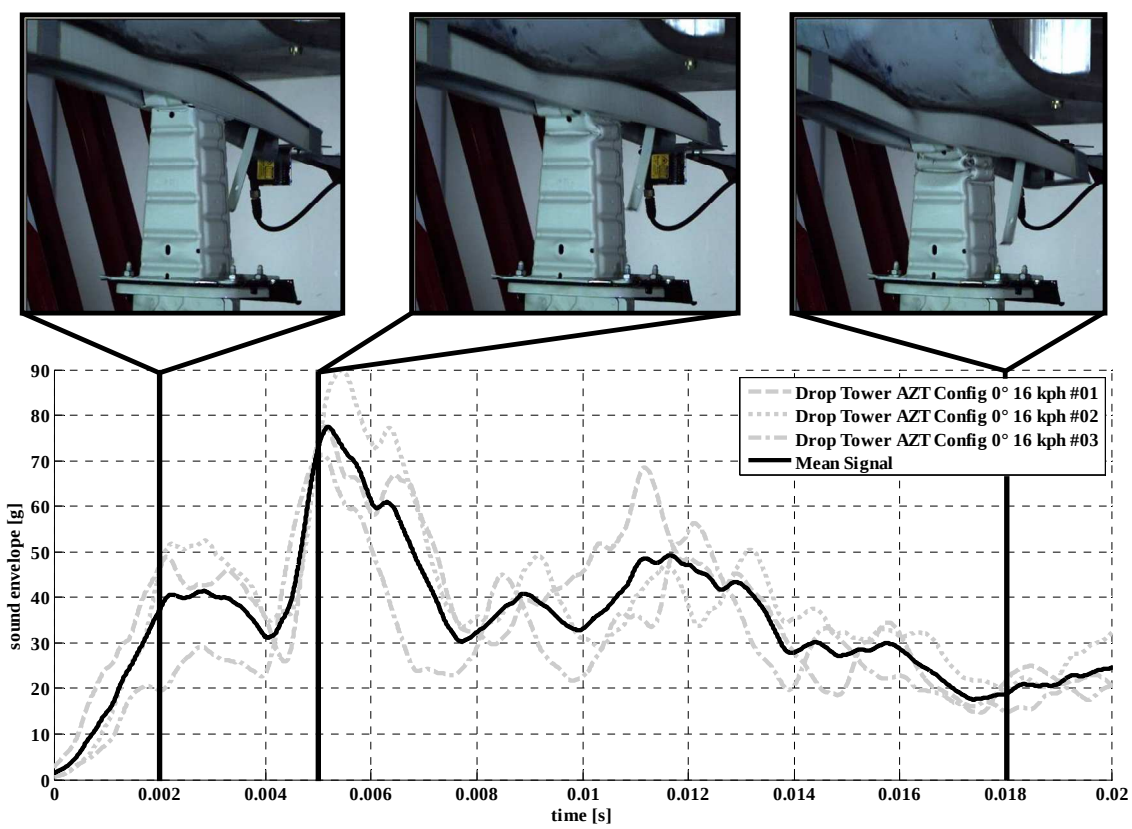

Figure 7. View of the deformation with measured SBS signal for three equal tests (black solid line corresponds to the mean signal).

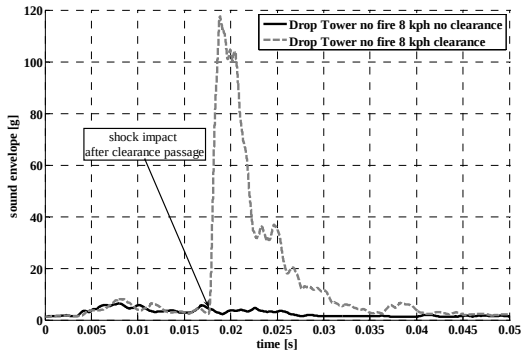

Figure 8. SBS signal measured at the longitudinal beam in a low speed drop tower test with (dotted line) and without clearance passage (solid line).

Such deviations in signal amplitude reaching an order of magnitude of much more than 500 % cannot be processed reasonably in a crash detection algorithm. Tests with clearance-free connections of the structural parts have shown that SBS envelope amplitudes in peaks can vary about ±50 % of the mean signal. Clearance-free connections like welding and longitudinal screw connections are recommended in order to avoid too high signal deviations. The resultant consequences of clearance passing for crash detection systems cannot be fixed at this point. But most algorithm concepts will not be able to handle such signal deviations.
In the following paragraph, it is described how the physical principle behind the SBS generation by shock excitation can be used in a crash detection system and what the restrictions are to be aware of.

Resulting Consequences on the Crash Detection Algorithm

For the classical acceleration-based crash detection, the influence of clearance passages is not proven yet. It was shown that clearance passage, dependent on the constructive realization of the bumper systems, will lead to a highly increased signal variation. Crash detection criteria purely based on amplitude processing of high frequent SBS signals cannot necessarily be used to discriminate must fire and no fire crash cases. The AZT, defined as hard no fire, produces high SBS amplitudes and then, can reach magnitudes of must fire crash tests. High ODB signals with coexistent low AZT signals could not be observed. In Figure 9, the measurements of three typical frontal crash tests are shown for a small vehicle having welded connections between the cross member and the crash boxes as well as clearance-free longitudinal screw connections between the crash boxes and the longitudinal beam.

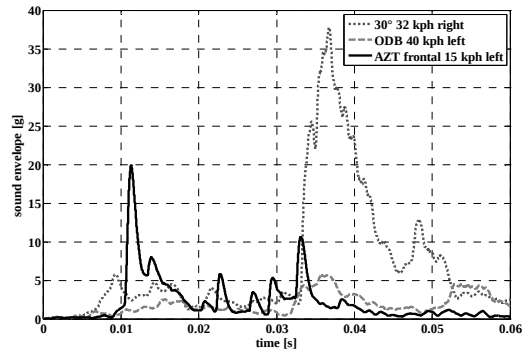

Figure 9. SBS signal examples of typical crash tests, measured in the central position.

The chosen examples are very important for the crash type separation:

- AZT representing the hard no fire test
- ODB 40 kph and an angular test (30°, 32 kph) representing the soft must fire tests in the early crash phase ($t < 30$ ms)

The crash stiffness of the ODB is mainly characterized by the energy dissipation of the deformable barrier. The barrier prevents the occurrence of shock impulses by its own deformation. The generation of great magnitudes of SBS signal is not possible.
In the case of the 30° angular crash, the resulting crash stiffness is reduced in the early crash phase due to the inclined force input. On the other hand, body parts, e.g. mud guard wings, soften the impulse by their deformation. Further more, a much more important fact is that the force input is not orientated directly in direction of the longitudinal beam. The resulting bending of the structural components in the first 30 ms generates relatively low SBS signals even if the barrier is not deformable. The high SBS amplitudes of the AZT are very interesting since they are remarkably higher than the must fire signals in the relevant time range of 30 ms.
This fact can be used to separate AZT from ODB by a hard/soft distinction criterion. This offers the possibility to separate soft must fire crashes and hard no fire tests at an early point. In combination with the classical acceleration-based crash detection, the hard/soft distinction can help to fulfil current and future requirements on passive restraint systems. A first algorithm concept can be described as a simple regulation of the fire threshold $f_{\Delta v}$ giving the *fire* decision. This threshold still is processed on the velocity reduction Δv measured by the classical acceleration-based crash sensors. On the one hand, $f_{\Delta v}$ is increased when hard impacts are registered. This means that hard impacts require an increased velocity reduction in the same time period. On the other hand, $f_{\Delta v}$ is decreased for soft

impacts to become more sensitive for soft must fire decisions. The following expression describes the relations in a simple generic and abstracted way:

$$fire = \begin{cases} 1 \text{ if } \Delta v \geq f_{\Delta v} \cdot h \\ 0 \text{ else} \end{cases}$$

with:

$$h = \begin{cases} = 1 \text{ if no information} \\ > 1 \text{ if hard positive} \\ < 1 \text{ if soft positive} \end{cases} \qquad (3).$$

CONCLUSION

Structure-Borne Sound (SBS) sensing in the field of crash detection mainly applies on a crash type distinction of hard and soft crash scenarios. Therefore, the shock waves that are generated during the crash and travelling through the vehicle structure are very important. The vehicle's resonant frequencies are excited by short impulses that depend on the stiffness of the crash. To be capable to use the SBS signals the relations that lead to SBS excitation are essential to know. In addition to sound emission in the ultrasonic range due to plastic deformation of metallic structures, highly dynamic impact shocks produce a great amount of SBS in the frequency domain up to 20 kHz.
Hard impulses (e.g. AZT) generate high frequencies while soft impacts (e.g. ODB) usually don't in the early crash phase.
Clearance passage and the following disturbing impulse increase the signal variance significantly and must be avoided for not provoking false decisions in the crash detection logic.

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