DEVELOPMENT OF CAE SIMULATED CRASH PULSES FOR AIRBAG SENSOR ALGORITHM/CALIBRATION IN FRONTAL IMPACTS

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ABSTRACT

Development of frontal impact airbag sensor algorithms/calibrations requires crash signals, which can be obtained from vehicle crash testing and/or CAE simulations. This paper presents the development of finite element sensor models to generate CAE simulated crash pulses/signals at the sensing location during frontal impacts. These signals will be evaluated for potential used in the airbag sensor algorithm/calibration. The study includes (1) use of the concept of frequency analysis to determine a cut-off frequency for extracting representative signals at the sensor locations for various carlines during frontal crashes, (2) assessment of current CAE capability in the frequency domain to see whether FEA models can predict sensor pulses up to this cut-off frequency, (3) identification of areas for potential further improvements in FEA methods, (4) development of signal processing to remove high frequency noise from CAE simulated pulses, and (5) development of a single quality sensor model. These methodologies are applicable to both car and truck programs. In addition, a single car crash/sensor model will be used to demonstrate generation of simulated sensor signals for calibration in a single-point sensing system. Simulated CAE singles include pulses from various frontal impact modes (fixed barrier at 90° and pole impact) for a spectrum impact velocities ranging from 8 mph to 35 mph. Comparisons between the simulated and test sensor signals will be presented.

INTRODUCTION

Generally speaking, there are two major types of airbag sensor algorithm today: velocity- and acceleration-based algorithms [1,2]. Velocity-based algorithm makes deployment decision based on integration of acceleration (signal) pulses, while acceleration-based algorithm looks for peaks/valleys of acceleration pulses or average of acceleration over a pre-determined interval. The velocity-based algorithm is used more often in dual sensing systems including front crash sensor and compartment sensor. The acceleration-based algorithm is used in most single-point sensing systems. It also requires more accurate CAE crash signatures than the velocity-based algorithm. This algorithm considers all signals, which pass through the filter built in the sensor hardware in calculating all parameters required for fire/non-fire decision-making.

Existing publications on CAE sensor development are scarce in the literature [3,4]. Many sensor algorithm engineers stated that CAE crash signatures were too noisy and/or not accurate enough for use in sensor algorithm development. The conclusion of a study recently reported by Lin et al. [4] also supports this claim. Lack of technology in this area motivates the initial development of CAE simulated crash pulses for airbag sensor algorithm/calibration in frontal impacts. Primary efforts have been directed toward crash and sensor signals analysis of test data and related methods development. Analysis of crash test and CAE pulses for airbag sensor development was made. Further studies of signal frequencies related to airbag sensor issues were also conducted. In addition, technical exchanges with various sensor suppliers were also conducted to understand their respective algorithms and requirements on sensor signals.

Potential CAE application to sensor development requires knowledge of CAE predictive capability in spectral response of crash simulations. A study arrived at a conclusion that FEA was capable of providing accurate crash response prediction of frequency content up to 100~150 Hz. Due to lack of published literature on FEA predictive capability in frequency response of crash simulations, this assessment was considered to be of “preliminary” nature, because the assumptions were primarily based on NVH engineering experiences, practices, and element size/modal shape relationship. Theoretical investigation of the development of techniques for extracting “reliable” high frequency data up to 400 Hz data from crash simulations is urgently needed.

The development of more accurate method(s) for crash simulation frequency response requires fundamental studies of "factors" that may cause degradation of spectral response of or contribute high frequency noises to sensor signals. Such factors may include parameters used in contact routines, rigid linkage, element types/sizes, sampling frequency of analysis recorded, and etc. The spectral fidelity can then be investigated using actual crash/sensor models of good quality. For the application aspect, however, a minimum requirement of 400 Hz frequency content in sensor pulses still remains in demand by most airbag sensor algorithm suppliers. Under such circumstances, a question remains as to whether CAE can still be an enabler in support of airbag sensor development and how. This question needs to be answered, since the development of CAE sensor simulation capability is a necessary step toward sensor applications.

Many difficult tasks in developing frontal impact CAE sensor methodology are challenging. One of the challenges is in the development of **a single model** that is capable of simulating various frontal impact modes including 90 degree fixed barrier, center pole, Thatcham, angular, and etc. Two different crash signatures can be extracted from locations at the front center tunnel. One is on the sheet metal and the other on the ECS (Electronic Control System) module. Most algorithm engineers use the signal from the ECS module for sensor calibrations, and some use the signal from the sheet metal location. No matter which signals the algorithm engineers use, CAE safety engineers should ensure the quality of the signatures at the sheet metal location prior to looking at the waveforms at the ECS module in the FEA sensor models.

Within the current code limitations in RADIOSS that is used in this study, a frontal impact sensor model was developed and validated for low velocity fixed barrier and center pole impacts, and then used for trend predictions of fixed barrier impact at higher velocities, Thatcham, and angular impacts. The CAE pulses obtained from this model are evaluated by sensor suppliers for possible use for airbag sensor calibration. Positive feedbacks from suppliers for application to sensor calibration are extremely promising, and will be potentially realized. Should such a realization happens, this marks a significant milestone in the first time that CAE data are utilized for airbag sensor calibration in the automotive industry. Once the methodology and process are established, extensive use of CAE data in future vehicle programs for sensor calibrations can be visualized.

Another challenge that can be mentioned is that CAE sensor development has to face the sensor calibration/ARS (Advanced Restraint Systems) in the future due to limitation or non-existence of collective crash signatures from testing because of tests reduction or elimination. Advances in improvements over the CAE sensor model quality/accuracy and FEA capability related issues have to be continuously monitored/researched to ensure that simulations from future models are representative of prototype vehicles under impacts. An evaluation metric, which provides the best quality measurement for sensor pulses when compared with referenced and/or target ones in both time and frequency domains, need to be developed. Development of this metric requires changes of out-of-the-box thinking on how this can be linked or integrated with new CAE technology for future airbag sensor calibration and emerging smart restraint systems in ARS.

This paper presents the development of finite element sensor models to generate CAE simulated crash pulses/signals at the sensing location during frontal impacts. These signals will be used in the airbag sensor algorithm/calibration to help achieve costly prototype test reduction. The methodologies include (1) use of the concept of frequency analysis to determine a cut-off frequency for extracting representative signals at the sensor locations for various carlines during frontal crashes, (2) assessment of current CAE capability in the frequency domain to see whether FEA models can predict sensor pulses up to this cut-off frequency, (3) identification of areas for potential further improvements in FEA methods, (4) development of signal processing to remove high frequency noise from CAE simulated pulses, and (5) development of sensor modeling guidelines. These methodologies are applicable to both car and truck programs. Each of the afore-mentioned methodologies is presented, and conclusions are drawn at the end of the paper.

CRASH PULSE CHARACTERIZATION

Development of sensor algorithms for frontal impacts requires crash signals, which can be obtained from vehicle crash testing and/or CAE simulations. Vehicle testing includes barrier, pole and car-to-car impact tests. Test vehicles are instrumented to provide vehicle acceleration/ deceleration data that are experienced in the passenger compartment. Such acceleration-time histories are normally used as a forcing function input to occupant kinematics simulation models for assessing occupant injury, and

also used as a signal for air bag sensing algorithm development.

Generally in vehicle crash tests, accelerometers are mounted at various locations, such as the rocker panels at the base of the B-pillar, behind the bumper, shock tower, dash location, and tunnel area, etc. for deceleration measurements. In the analysis of vehicle frontal impacts, it is customary to use the vehicle longitudinal component of acceleration from underneath the B-pillar, located in an undeformed area of the vehicle occupant compartment. Historically, acceleration pulses obtained from some of the above locations are used for air bag distributed sensing system development. Currently, an air bag single point sensing activation requirement depends largely on signals measurement using an accelerometer at the tunnel or dash location. In general, the deceleration-time history is a superposition of a spectrum of frequencies representing the instrumentation noises, elastic-plastic vibrations, structural collapse, and engine/accessories interactions as they impact one another. An unfiltered or raw deceleration-time history provides little information of value. In order to better utilize crash data, techniques for characterizing the deceleration pulse with various degrees of approximations have been developed and reviewed by Chou and Lim [5]. One method is resort to use of the concept of frequency with spectrum analysis. In this study, crash pulses obtained from “B”-pillar are used for signal identification. The method is generic and applicable to analysis of signals obtained from other locations.

Basically, a crash signal carries essential backbone information, which is needed for air bag sensing algorithm development. Depending on their sensing strategy, some air bag sensor engineers may require this information at a higher frequency than others. The question is then raised to what should the frequency content of this backbone curve be. To derive this basic information, a technique developed by Chou and Lim [5] can be used to determine the cut-off frequency in characterizing a crash sensor signal. Once this cut-off frequency is determined, one would ask, "can CAE model predict crash sensor pulses up to this cut-off frequency?"

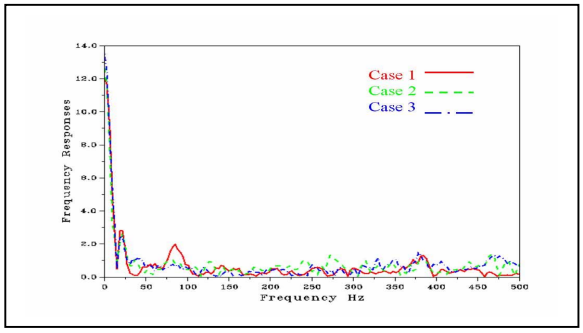
Data Analysis

The methodology developed by Chou and Lim [5] is applied to studying frequency characteristics of various crash sensor pulses obtained from cars and trucks. Data, measured at the “B”-pillar rocker location, from vehicle crashes impacted perpendicularly against a fixed barrier at 31 mph were selected to study the frequency characteristics of their respective pulses. Based on the afore-mentioned approach, it is to choose a frequency band that is not only deterministic, but also suitable for signal identification. The frequency bands at filter classes SAE 60, 180, 300, and 600 are used in this study.

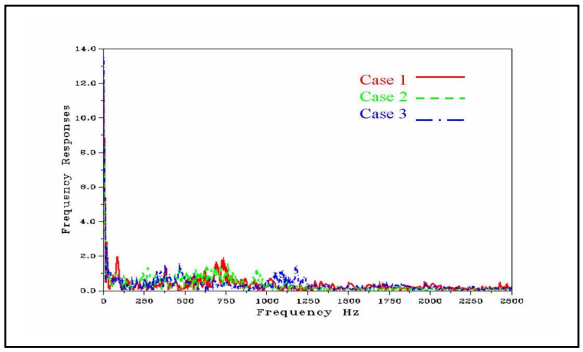
Frequency domain

Original crash test data contain frequencies up to 4000 Hz (or beyond), which will be referred to as the “raw” data in this study. When the first 40 msec data are transformed from the time domain into the frequency domain, the spectra of these tests are shown in Figure 1, where Figure 1(b) shows the frequency response (spectrum) as a function of frequency up to 2500 Hz, while Figure 1(a) depicts the same data up to 500 Hz. The crash pulses studied have similar frequency contents up to 300 Hz. Generally speaking, results indicate that the low frequency band (up to 50 Hz) dominates the crash pulse, as evidenced by the first excitation shown in Figure 1.

Based on results shown in Figure 1, various “potential” cut-off frequencies can be chosen. These are 100 Hz, 300 Hz, 500 Hz and 1000 Hz. The corresponding filter classes are then Class 60, Class 180, Class 300 and Class 600, respectively. These filter classes are then applied to the original data for reconstructing crash pulses.



(a)



(b)

Figure 1. Frequency responses (amplitude)

Time domain

As an example, the reconstructed pulses using Classes 60, 180, 300 and 600 are compared with original deceleration traces as shown in Figures 2-5, respectively. They indicate that the reconstructed pulses not only smooth away the high frequency signals, but also follow closely the peaks and valleys of the original curves.

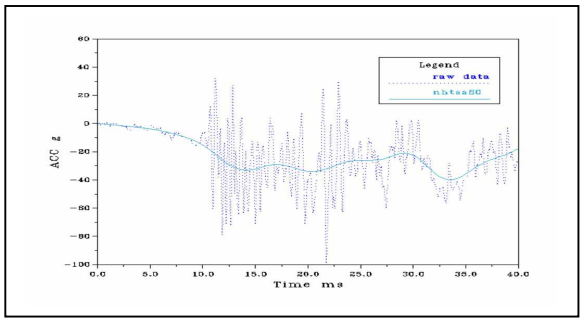


Figure 2. Comparison of raw data wrt. filtered data using Class 60 class

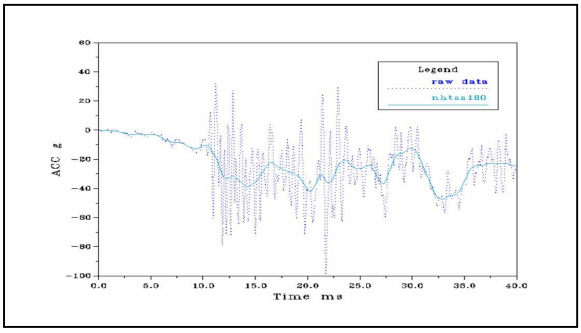


Figure 3. Comparison of raw data wrt. filtered data using Class 180 class

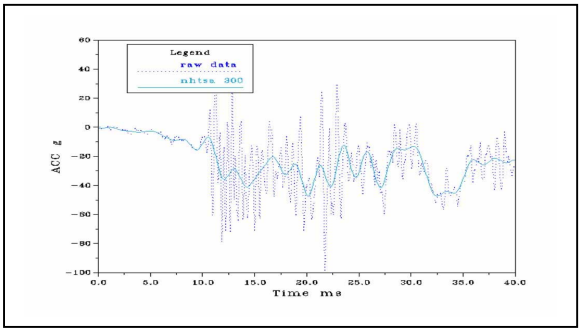


Figure 4. Comparison of raw data wrt. filtered data using Class 300 class

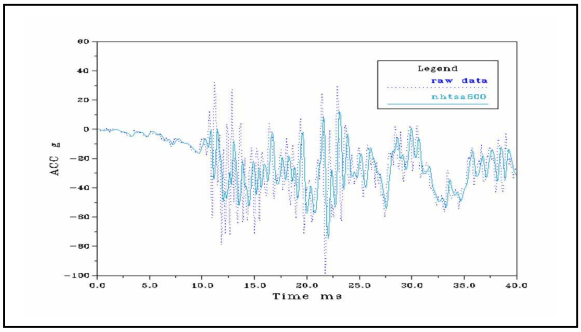


Figure 5. Comparison of raw data wrt. filtered data using Class 600 class

Integrations of the original and the reconstructed pulses yield the velocity and the displacement time histories as compared in Figures 6 and 7, respectively. A desired cut-off frequency can be chosen by comparing the velocity and displacement time histories between the original and the reconstructed pulses depending on the degree of accuracy at an engineer's disposal.

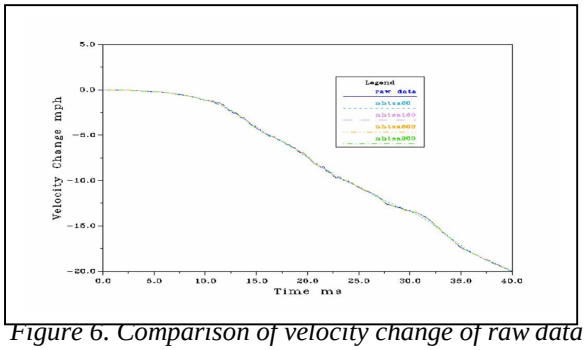


Figure 6. Comparison of velocity change of raw data wrt. filtered data

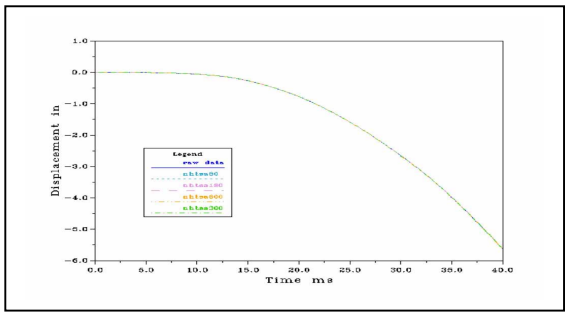
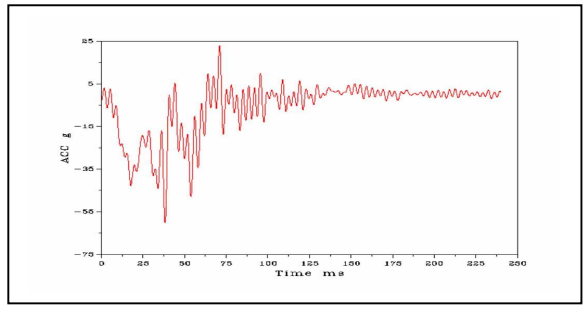


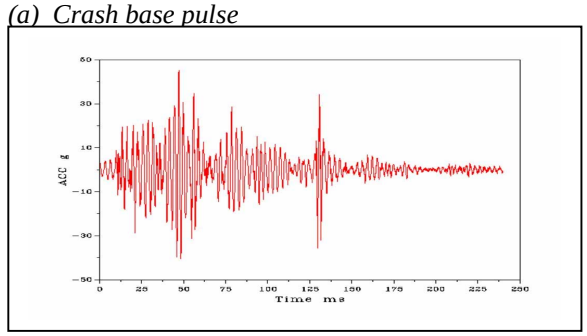
Figure 7. Comparison of displacement of raw data wrt. filtered data

Should the reconstructed curve be considered as the "backbone" characteristic of the signal, then the original curve can be splitted into two parts: "crash base pulse" and "shock or noise" as shown in Figure 8 (a) & 8 (b). Basic properties of these two parts become apparent when they are integrated. An integration of the crash base pulse results in a total velocity change, which equals to the sum of the impact and rebound velocities. The resulting velocity of the "shock" pulse, when integrated, becomes zero. These can be seen from the integrated results shown in Figure 8 (c).

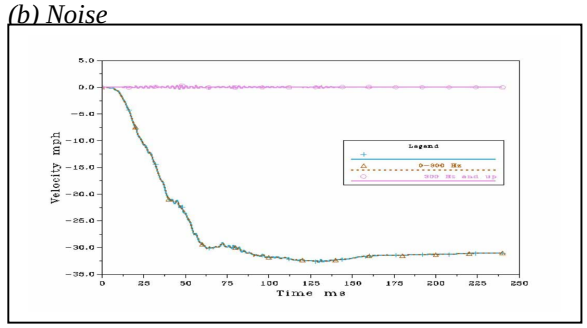
The reconstructed curves for the original crash pulse are plotted in Figures 9 (a) and 9 (b) for the filter Classes 180 and 600, respectively. Results obtained from both filter classes show that peaks and valleys are attenuated more in Class 180 than in Class 600 as expected.



(a) Crash base pulse

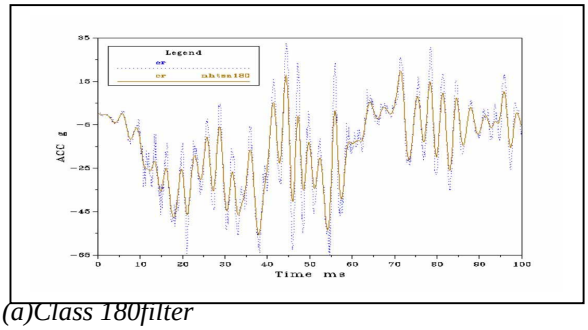


(b) Noise

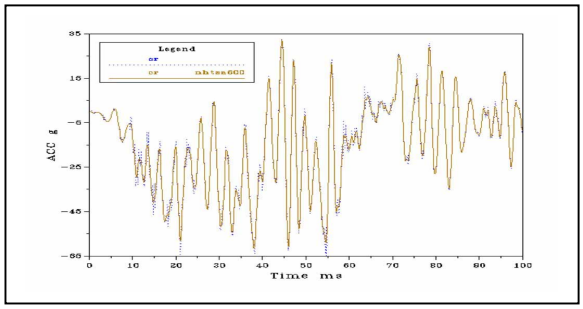


(c) Integrations

Figure 8 Base pulse, noise and its integrations



(a)Class 180filter



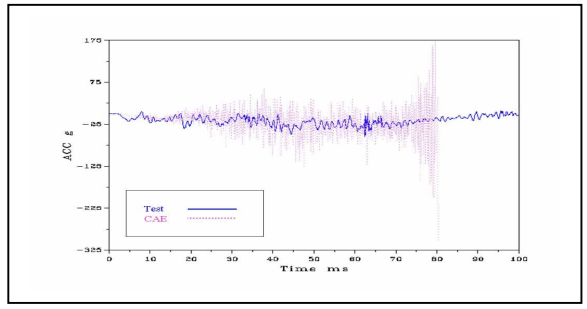
(b) Class 600 filter

Figure 9. Comparison of reconstructed pulses with original one using Class 180 and Class 600 filters

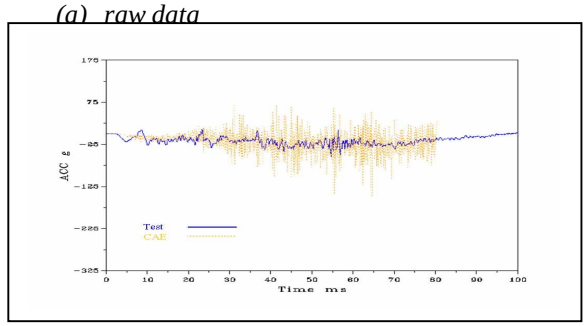
FEA MODELING STUDY

Three car and truck FEA models are used to address CAE capability/predictability related issues. These models were compared with data from 90 degree frontal crash tests with a fixed barrier at 31 mph. To obtain the simulated crash signal at the sensor location, the signal is monitored at a single node representing the sensor location. The simulated results are compared in Figures 10 to 14. To compare predicted results with the test data for these models, both the unfiltered (raw) data and Class 180 filtered data are used for comparisons as shown in these figures. Figures 12 and 14 are the frequency spectra of the CAE generated signals from the car and truck models, respectively.

Results shown in Figures 10 and 12 reveal that the CAE predictions exhibit higher frequency noise signals than the test data. The bandwidth of the noise roughly ranges from 500 Hz to 6500 Hz as shown in Figures 12 and 14 for both models. It is again confirmed by observing that frequency responses from spectrum analysis of the model predictions and the test data are in favorable agreement up to 300 Hz. When both the CAE and test data are filtered using Class 180 filter, the car and CAE results are in much better agreement with their respective test data as shown in Figures 11 and 13 (b), respectively.



(a) raw data



(b) Class 180 filter

Figure 10. Comparison of FEA with test results for car

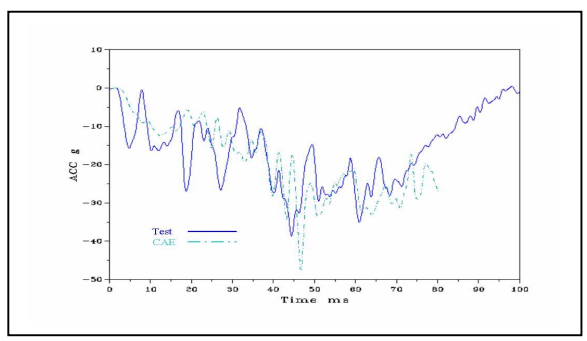
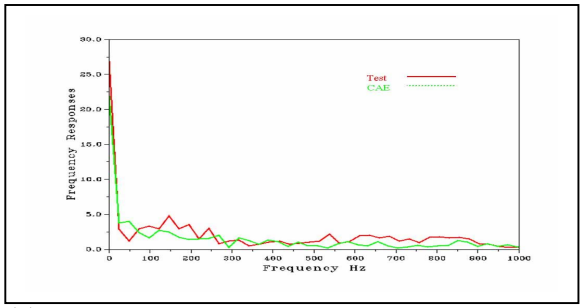
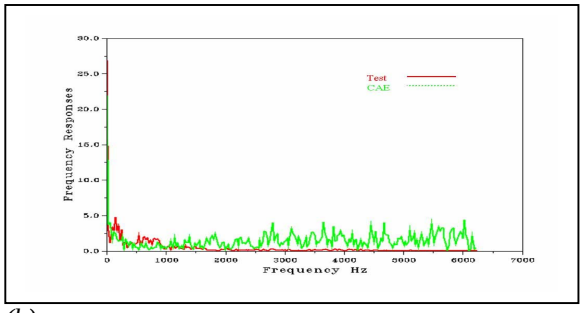


Figure 11. Comparison of FEA and test results in Class 180 filter for car

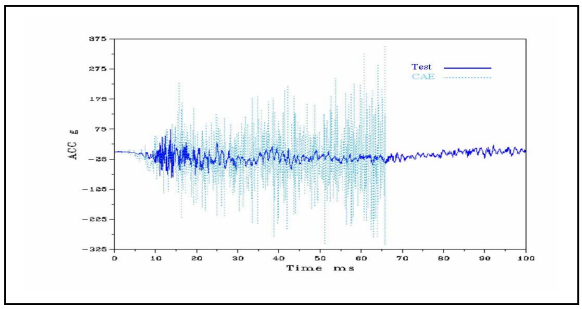


(a)

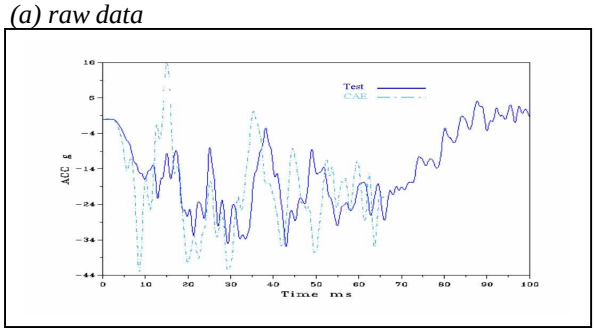


(b)

Figure 12. Comparison of FEA and test results in frequency domain - Car

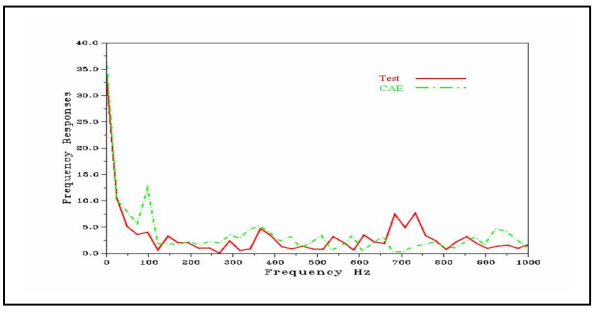


(a) raw data

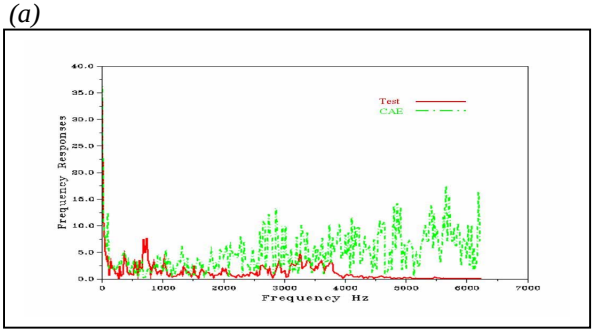


(b) Class 180 filter

Figure 13. Comparison of FEA with test results for truck



(a)



(b)

Figure 14. Comparison of FEA with test results in frequency domain for truck

Although comparisons between CAE predictions and crash test data presented above show good correlations for overall (entire) pulses, still there is room for CAE improvement. Referring to Figure 11, for example, the responses between CAE prediction and test result from the onset to approximately 15 msec is poorly correlated. This is particularly true if a signal is filtered at a lower cut-off frequency, say 60 Hz. The improvement over the CAE capability in predicting early crash response is urgently needed. Crash signals occurring at this early stage play an important role in setting strategy for sensor algorithm development. This portion of crash signal affects calculation of delta velocity and average velocity, etc. To improve predictability of CAE models in this area, emphases should be placed on more detailed modeling of bumper and front-end subsystem with local deformation, and material modeling needs.

Crash sensor development requires crash signals, which can be obtained, form either tests

and/or CAE simulations if FEA models are capable of doing.

I) Tests:

Historically, sensor development is largely dependent of tests data obtained from a matrix of crash testing on a variety of crash modes. These data are then used by suppliers to develop their respective airbag crash sensor algorithms. In the past, the bandwidth requirement on these data varies from supplier to supplier, depending on their algorithm and/or intention of usage. It is learned later that a 400 Hz bandwidth low pass filter has been used in airbag crash sensor algorithm applications by many sensor suppliers. Therefore, 400 Hz filter has been accepted as a minimum frequency requirement contained in crash pulses for the sensor calibration based on data prototype testing and/or CAE model predictions. An analysis of crash signals for sensor development described above has shown that the base crash signal, closely representing the vehicular crash behavior, is about 300 Hz. Therefore, the 400 Hz bandwidth indeed covers the representative signals in the pulse for sensor algorithm development.

A series of airbag crash sensor simulations was performed by supplier's simulators using their respective calibrated algorithms. Selected crash pulses of center line tunnel at dash have been filtered to 300 Hz, 100 Hz and 60 Hz along with the original 4000 Hz data were provided to four different suppliers. Crash pulses selected were from different car lines and crash modes. The results concluded that: 300 Hz pulses are good enough for air bag sensor calibration regardless vehicle structure or weight.

II) CAE Simulations:

CAE driven design has been a key emphasis in the automotive industry aiming at shortening the program development time and minimizing the number of tests. If the 300 Hz signal data are required, then: a question is raised as to whether CAE simulations can provide accurate/reliable crash signals up to 300 Hz? To answer this question requires understanding of predictive capability of CAE codes, which are used in simulating crash signals.

There are two issues, frequency content and pulse accuracy, in current safety CAE practices. The frequency content is related to the high frequency extracted from CAE simulation that represents physical responses with minimum numerical noises. However, this should not be confused with accuracy issue in low frequency range, which is primarily resulted from improper modeling practices.

Due to lack of studies of frequency response of non-linear FE systems, a preliminary study based on NVH experience, the current CAE modeling practices enables accurate prediction of frequency content up to 100-150 Hz. Further increase of frequency content will required much finer model which is unpractical due to limitation of computer resource.

AREAS FOR FURTHER DEVELOPMENT AND/OR IMPROVEMENTS

The above discussion indicates that suppliers need 300 Hz pulses for their sensor algorithm simulation, while CAE models having capability in producing accurate signals containing frequency in the range of 100-150 Hz. Figure 15 shows this assessment along a frequency axis, where Zone 1 represents the frequency range that FEA is feasible, but requiring accuracy improvement, Zones 2 and 3 represent frequency ranges that FEA is tractable with difficulty, and out of questions, respectively. At the first glance, one feels that CAE probably cannot help much in sensor development due to existence of this gap.

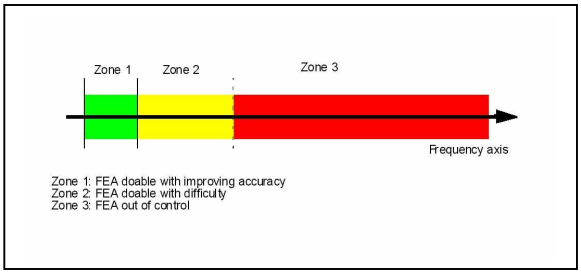


Figure 15. Distribution of FEA capability in various frequency ranges

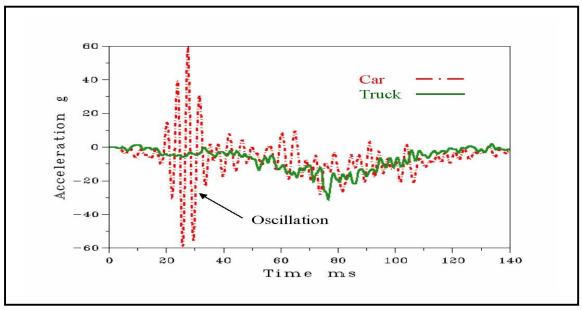
Potential solutions can be adapted to fill this gap are:

1) Development of new CAE methodology other than current FE approach to satisfy sensor needs.
2) Conducting full vehicle tests.
3) Understanding sensor suppliers' process of sensor calibration and proposing alternative methods to restrict frequency content requirement within the current CAE capability.

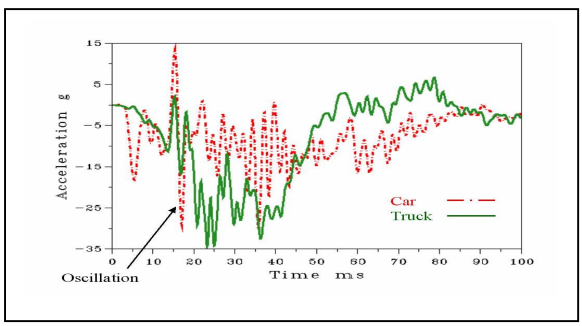
New CAE methodology is a long-term development that may require involvement of code developers, and full vehicle tests are too expensive and time consuming to conduct. The third solution is technically feasible and can be potentially achieved.

Comparison of Test Pulses with Results From Sensor Simulations

Crash data analyzed in the airbag sensor simulation are obtained from tests of trucks and passenger cars. Figs. 16 (a) and 16 (b) show comparison of the 300Hz crash pulses between car and truck obtained from the center pole impact and frontal barrier impact, respectively.



(a) Pole impact case



(b) frontal barrier impact case

Figure 16. Comparison of the pulses between car and truck with 300 Hz filter

Signals affect the performance of airbag sensor algorithms. If the algorithm is an acceleration-based scheme, characteristics of a crash signal, such as the degree of oscillation, magnitude and duration of a pulse are very important parameters that affect determination of airbag triggering time. The high amplitude of acceleration signals affects greatly the triggering time. Sensitivity study of how oscillation of crash pulses affect determination of triggering time does not exist. This area requires further investigation.

Analysis of crash data showed that the first peak in the frequency response is important for distinguishing the signal between the fire and non-fire cases. Airbag crash sensor algorithm tends to catch high frequency signals if the algorithm has been calibrated using pulses containing signals up to 300 Hz. If the frequency of a pulse is dominated below 100 Hz, the firing time is found to be not frequency sensitive.

Studies of crash pulses based on suppliers' algorithms indicated that some crash pulses from one platform may work well using the low frequency content data, while some pulses from the other platform may need high frequency data for determining the triggering time. Therefore, airbag sensor crash pulse characteristics need to be evaluated in the frequency domain prior to being forwarded to sensor suppliers.

Assessment of Frequency Content of Simulated CAE Results

After analyzing the sensor test signals, the CAE generated signals need to be assessed also in order to understand their behavior in the frequency domain. Comparisons show that CAE simulation results filtered at 300 Hz do have relatively higher frequency noise than test pulses, particularly during the period when major impacts occur. In addition to improper connections in models, numerical schemes, contact algorithms, and rigid-body link options in the codes may also contribute to this.

Reviewing general signal process in crash sensor unit and analyzing many sensor signals from cars and trucks using sensor simulators lead to conclusions that 300 Hz pulses are needed for current algorithms. CAE simulation results filtered at 300 Hz do have high frequency noise when compared with test pulses as studies indicated. This is the area where technology needs to be developed for improvement. It should be mentioned that CAE analysis should focus on developing quality sensor models that well correlated in the low frequency range for better simulations and predictions of the sensor signals of 100-150 Hz frequency. It is believed that only those pulses obtained from quality and correlated sensor models can be used to calibrate the algorithms for predicting accurate airbag firing times at the low velocity and pole impact conditions. A remark on test variation vs. CAE accuracy is worthy noting. The variations of test-to-test exist, but cannot be estimated based on very limited tests data. A well-developed algorithm should have a provision that copes with those variations. Therefore, it is not necessary that CAE simulated pulses correlate with test counterpart peak-by-peak. However, CAE simulated results should fall within the test-to-test variation corridor in low frequency range. The

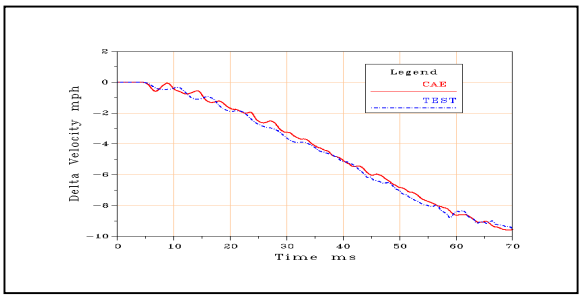
accuracy of some CAE sensor pulses still need to and can be improved. Since many discrepancies between CAE and test pulses in low speed are not attributed by frequency content, but by engineer's experiences in understanding crash vehicle performance, modeling, and CAE software capabilities.

DEVELOPMENT OF NON-FEA TOOLS TO IMPROVE CAE SIMULATED PULSES

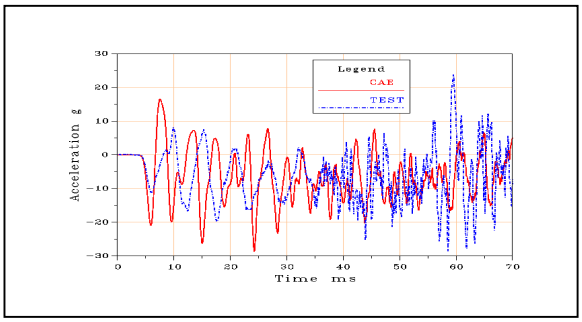
CAE crash waveforms in raw data are frequently requested for use in the airbag sensor development. However, containment of high frequency noises in CAE waveforms precludes them from being accepted and used in sensor algorithm applications. In fact, it is extremely difficult to control these high frequency noises by FEA modeling techniques, because most of them are generated through numerical algorithms built in crash codes, such as contact algorithms, rigid walls, hourglasses, material laws and so forth. In order to use CAE waveforms for airbag sensor algorithm calibration, raw data in these waveforms provided to the algorithm engineers should be compatible to actual test waveforms as much as possible. Therefore, signal processing should be used to further improve CAE high frequency noise.

A SINGLE QUALITY SENSOR MODEL

A single quality FEA sensor model is needed for controlling the quality of CAE waveforms. This model is developed for multiple frontal impact mode simulations are an essential step in the sensor development/ implementation process. To develop a quality model requires the skill and experience of safety analysts who are proficiency in FEA codes and understanding of physical phenomena of vehicle crashes. In addition, they need to make quality check that all weights, geometries, components/parts, linkages/connections, materials and so forth, are correct. This is the first step to ensure that the CAE waveforms generated from the quality model will satisfy the minimum requirements for the sensor calibration purpose. Some examples using a single sensor/crash model in frontal barrier and pole impact simulations are shown in Figures 17-20. The figures display both the velocity- and acceleration-time histories for these cases, exhibiting very good correlation between the simulated and test results, particularly at the early impact stage.

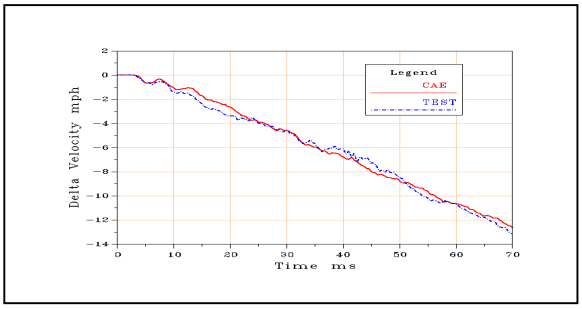


(a) velocity time histories

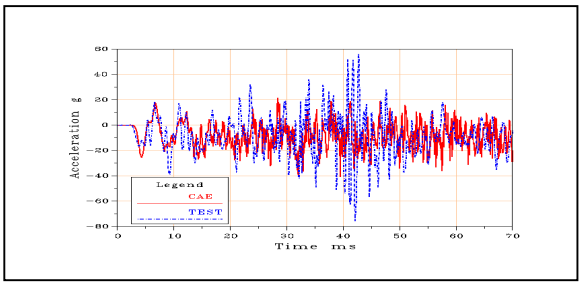


(b) acceleration time histories

Figure 17. Comparison of CAE and test data for 8 mph frontal barrier

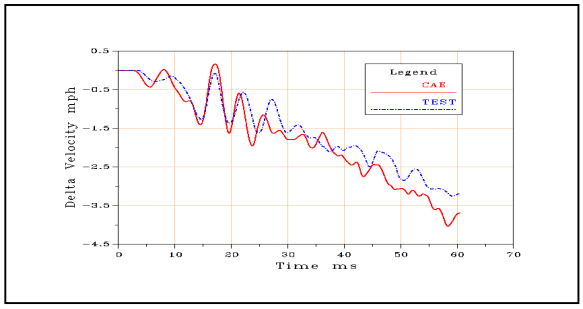


(a) velocity time histories

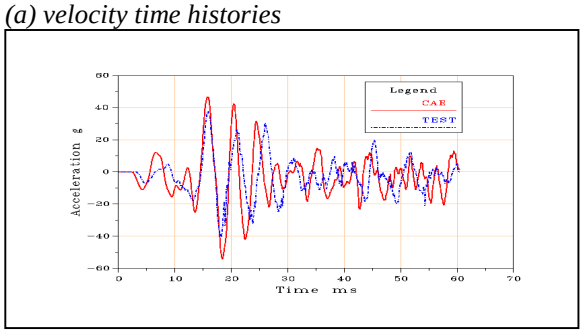


(b) acceleration time histories

Figure 18. Comparison of CAE and test data for 14 mph frontal barrier

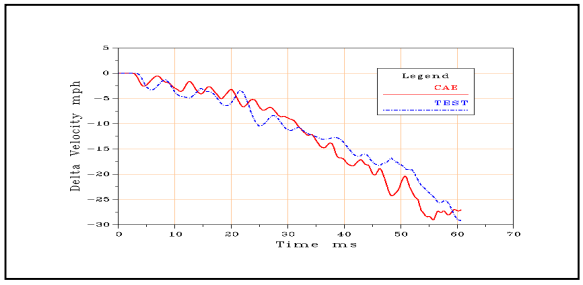


(a) velocity time histories

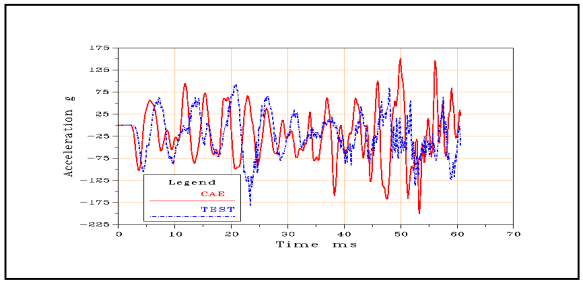


(b) acceleration time histories

Figure 19. Comparison of CAE and test data for 19 mph rigid pole



(a) velocity time histories



(b) acceleration time histories

Figure 20. Comparison of CAE and test data for 35 mph frontal barrier

CONCLUSIONS

The concept of frequency analysis is to extract a simple but representative signal that is experienced by a vehicle during a crash for sensor development Based on signals from cars and trucks, a cut-off frequency of 300 Hz using Class 180 filter is found to give accurate representation of signals for these crashing vehicles.

Crash signal predictions from FEA models compare fairly well with test data when both filtered using SAE Class 180 filter. This filter type is ideal for signal identification as well as for CAE correlation at low frequency range. Analysis indicates that low frequency band in signal dominates the crash behavior, while high frequency band in a signal is highly unpredictable.

A general signal process in airbag sensor unit and the effect of low and high frequency range on the algorithms are discussed. The discussion leads to identification of a need to develop a method, which can be used to evaluate airbag sensor crash pulses in frequency domain.

Further, Most FEA models were built for high velocity impact analysis in either evaluation of structural crash performance or prediction of occupant injury. CAE crash waveforms contain high energy noisy and are not accurate enough for airbag sensor algorithm calibration. These waveforms need to and can be improved using a non-FEA model.

Finally, a single quality sensor model is demonstred. Development of such a model requires discipline, experience, and strong crash analysis background of CAE analysts in order to make virtual crash pulses become reality in prototype reduction applications.

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