Integrated Sensing System for Automotive Applications

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ABSTRACT

The Department of Energy (DOE) Vehicles Group has identified a need for novel multifunctional composite materials and structures for the automotive industry that have the capability to reduce weight and volume as well as costs of "conventional" structural components by performing engineering functions beyond load carrying. As part of this project, Acellent in collaboration with Ford Motor Company is developing a sensing system for use in automotive applications. An advanced sensing system is needed to effectively distinguish impacts between different objects. Information received from the first contact between object and automobile bumper can be used to identify the object for vehicle applications.

This paper will discuss the need and requirements for such a system and provide an overview of the development of a piezoelectric sensor system including the design, development and initial testing of a complete prototype of the system through various tests on bumpers. Acellent's SMART layer sensor design for the bumpers will be discussed along with their manufacturing and installation on the car bumper. The paper will also discuss potential optimization of the sensor locations. Detection algorithms were developed to distinguish between various objects that were used in the impact on the bumper. Additionally key parameters were considered when building the algorithms:

- impact speed,
- bumper stiffness and dimensions,
- object stiffness, mass and size

Testing was conducted using, for example, simulated small animal, stone, wooden board etc. Results from the testing of the complete prototype system for the impact detection for automobile applications will be presented.

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INTRODUCTION

The Department of Energy (DOE) Vehicles Group has identified a need for novel multifunctional composite materials and structures for the automotive industry that have the capability to reduce weight and volume as well as costs of “conventional” structural components by performing engineering functions beyond load carrying. The multifunctionality that couples between structural performance and additional functionalities (e.g., electrical, magnetic, optical, thermal, chemical, biological, etc.) is critical to the growth of artificial intelligence in the automotive industry. Multifunctional structures can sense, diagnose, and adapt to environmental changes with minimum external intervention; allow alternation of shape functionality and mechanical properties on demand; and structural integration of power harvest/storage/transmission capabilities for “self-sustaining” systems. There is currently a need to reduce the demands of the system as a whole, for example for a city car where 98% of the required energy needs is associated with weight, the pedestrian impact sensing system must detect certain contact events occurring on the front bumper of an automobile within a reasonable time and generate the proper response signal to a built-in protection system.

This is of great importance for the safety of pedestrians around the globe, because the number of pedestrians struck and killed by accidents is increasing every year. In the United States, the number of pedestrians struck and killed by accidents is 7388[1] in the year 2021. The growing number of pedestrians killed in accidents is a big concern in recent years. The number of pedestrian deaths increased by 13% from last year, resulting in additional 774 additional lives lost. Therefore it is a very important need that a technology that can accurately determine a pedestrian impact on a vehicle and deploy a safety system for the pedestrian. This research can save lives and ensure pedestrian safety in the United States. The present state-of-the-art detection systems include vision-based methods[1], LiDAR[3-4] (laser beam to measure the distance to objects), the radar-based method[5-6], etc. In the present research, a novel acoustic signal detection-based method was used for impact detection.

Figure 1. SMART Layer sensors

A primary challenge is to design and develop an impact event detection technique that can work efficiently even for complex structures with local property variation. The proposed system utilizes PZT SMART Layer sensors [7-10] to sense the impact signal effectively The SMART Layer is well established in the field and is currently known for its unique ability to provide a large structural coverage for gathering data with its network of sensors/actuators embedded in a layer.

The paper discusses the problem statement and proposed method first. Then the paper discusses the sensor design on the vehicle bumper system. Next, the test setup developed for testing the detection capability and the signal characteristics identification is explained. Then the paper discusses the data collection and analysis from in-house impact tests on the bumper. The paper ends with a summary and conclusions and future work.

PROBLEM STATEMENT

A pedestrian crash sensing system that has the capability to detect any impact event occurring on the front bumper of an automobile within a very short duration and generate the proper response signal to a built-in system needs to be developed. The system should be able to distinguish between impacted objects. The system needs to be able to perform the object classification and initiate the release of the necessary protection mechanism within the time needed per the design requirements.

PROPOSED METHOD

The proposed method continuously records the passive acoustic signals from the sensors installed on the plastic part of the bumper. The system wakes up when the speed of the vehicle is within the defined range for detection The initial defined portion of the signal will be recorded and processed for the object classification. The method calculates the frequency spectrum of the signal and identifies the peak frequency of the signals to classify the objects. The energy of the signals is also studied to classify the objects.

Figure 2. Pedestrian impact on a car

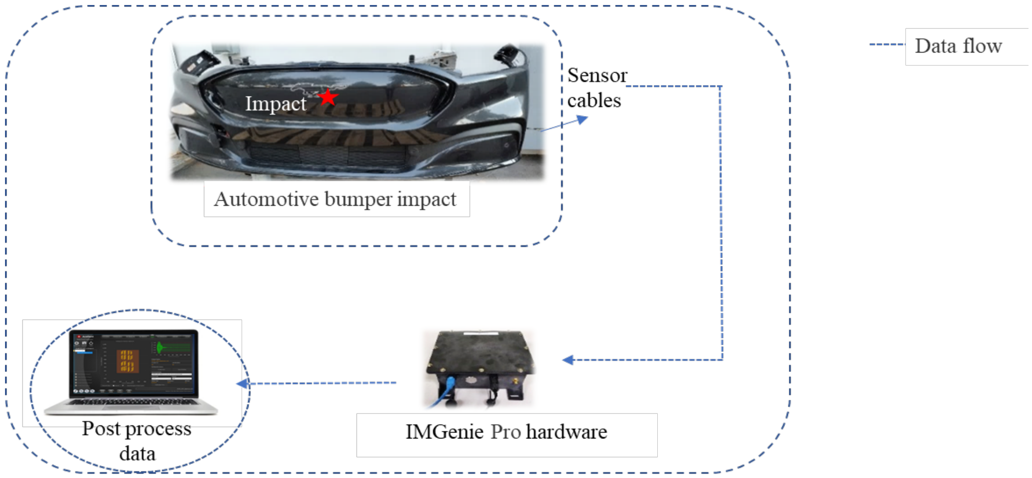


Figure 3. Impact detection system components and data flow

The system is unique with its use of piezoelectric sensors and a novel IMGenie data acquisition system for efficient data collection and processing. In this approach, only the first portion of the signal was used to enable faster impact detection and object classification compared to previous works [11]. Moreover, a novel energy method was also developed and tested in this work.

The system components consist of SMART Layer sensors for sensing the passive signals due to impact, an IMGenie Pro data acquisition system, Cables (Connecting sensor to IMGenie Pro), an Ethernet cable, and a Laptop (For AIM software installation and data processing). A schematic of the system is presented in Figure 3.

SENSOR DESIGN

Acellent designed and installed piezoelectric sensors (PZT) on the plastic part of the bumper (Figure 4). The location and the number of sensors were based on initial testing conducted to determine the signal strength on the bumper. By using multiple PZT sensors, Acellent's pedestrian protection system (PPS) can provide an adequate response for the system. An energy summation circuit can pick up the impact quickly from the sensors, provide sufficient data to the algorithm to discriminate between different types of impacts.

A total of 12 sensors were installed on the plastic bumper, presented in Figure 4 which are required for sufficient data to accurately determination of frequency and energy values and further object classification. The number of sensors was optimized during the testing to minimize the number of sensors and thereby the cost. The PZT sensors were installed on the bumper using two-part Hysol® structure epoxy adhesives. After curing the adhesives, the sensor cables were installed on the single PZT sensors.

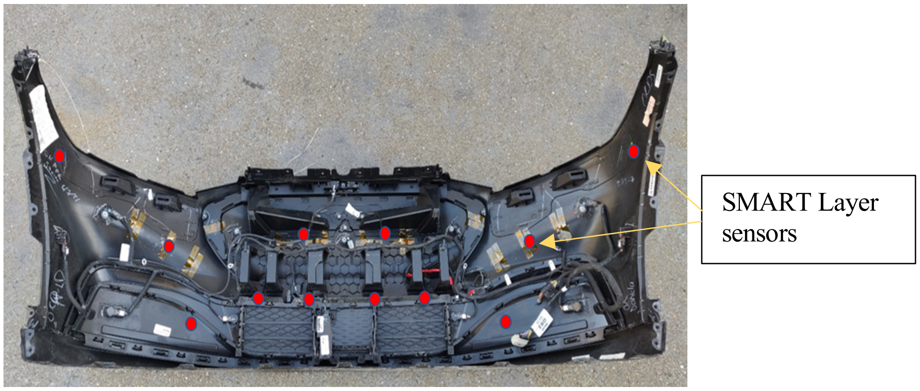


Figure 4. Sensors installed on the bumper

TEST SETUP

To demonstrate the design and sensing system that has the capability to detect impact events occurring on the front bumper of an automobile within the required duration and generate the proper response signal to a built-in protection system, a test set up with vehicle bumper was developed as shown in Figure 5. The bumper consisted of a metal base and a plastic fascia. The bumper metal base was attached firmly to concrete poles using steel U bolts. Using screw fasteners, the bumper plastic part is attached to the bumper metal base.

For simulating some impacts on the bumper, a Hybrid II test dummy leg [11], representing a 50th percentile adult male was used (Figure 5). The dummy leg consists of a steel inner structure wrapped with molded foam flesh. The total length of the leg dummy measures 55 cm. The dummy leg weighs 10 lbs. Size and weight represent the "average" USA adult male population. The range of motion, weights, and centers of gravity were developed from anthropometric studies. The Hybrid II dummy offers repeatable and reproducible impact tests.

Impact experiments on the bumper were performed using several different objects. A fixture was constructed to swing the impact object to impact the bumper. The sensors were installed on the plastic bumper for fast recording of the signals due to the direct impact of the object on the bumper. The sensors were connected to the IMGenie Pro hardware using customized cables and the hardware is connected to the laptop using an Ethernet cable. The recording of the signals is controlled using the AIM software installed on the laptop.

DATA COLLECTION AND ANALYSIS

Several impact tests on the bumper were performed to identify the signal characteristics and develop the software for pedestrian impact detection. The bumper was impacted extensively at different locations and the signals were recorded using the sensors. The bumper was impacted with many different objects such as Hybrid II dummy leg, PVC pipe, a wooden board, a golf club, a wooden dowel rod, a stone, a small animal object, etc. to identify the signals and classify the objects. The impacts were performed several times to identify the signals due to the impact of the objects. Some examples of Hybrid II dummy leg impact signals are shown in Figure 6.

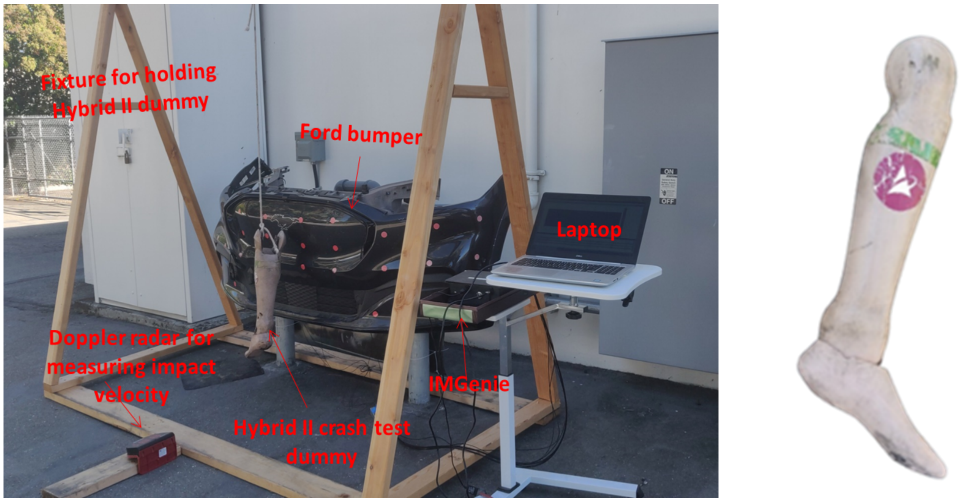


Figure 5. Test setup for bumper testing and Hybird II dummy leg

The main initial part of the signal was analyzed for fast object classification. The signals and the frequency spectrum of the signals were studied to identify the signal characteristics. The frequency spectrum of the object impact signal has a peak at <100Hz. The repeatability of the signals was tested by continuous impact tests and many attempts. The repeatability of the signals and the frequency spectrum were observed.

For identifying the signals due to various non-pedestrian object impacts on the bumper, several impacts on the bumper were applied. The signals due to impacts were recorded using the IMGenie Pro hardware and AIM software. The signal characteristics and the frequency spectrum of the signals were studied. Sample signals due to the impact of different objects on the bumper are presented in Figures 7, 8 & 9. Impact signals due to impact using PVC pipe, wooden board, Golf club, Wooden dowel rod, Stone, and a small animal object are presented. A small animal impact object was created by a leather pouch filled with raw sand [11] as presented in Figure 9. From several trials, the peak frequency due to PVC pipe impact was observed to be between 285 to 363 Hz, and the average value is estimated as 321.35 Hz. The peak frequency due to the wooden dowel rod was identified between 269-363 Hz and the average value is calculated as 320.13 Hz. For the wooden board chunk, the peak frequency between 174-316 Hz was observed and the average value was observed as 264.54 Hz. Golf club impact recorded peak frequency signals between 269 and 395 Hz and an average value of 314.35 was calculated. For the impact tests performed using a stone object, the peak frequency of the signals was identified between 269 to 442 Hz and the average peak frequency is obtained as 358.70 Hz.

A summary of the peak frequency of the frequency spectrum observed for different object impacts is presented the TABLE 1. The peak frequency range and the average peak frequency from many trials for the different object impact signals are presented. The signals due to certain type of impacts using objects in

Figure 7 and Figure 8 were observed to have a peak frequency of the signals between 150-450 kHz range. The signal signature, frequency spectrum, and peak frequency of the signals due to these object impacts were observed to be substantially different compared to Hybrid II dummy leg impact signals.

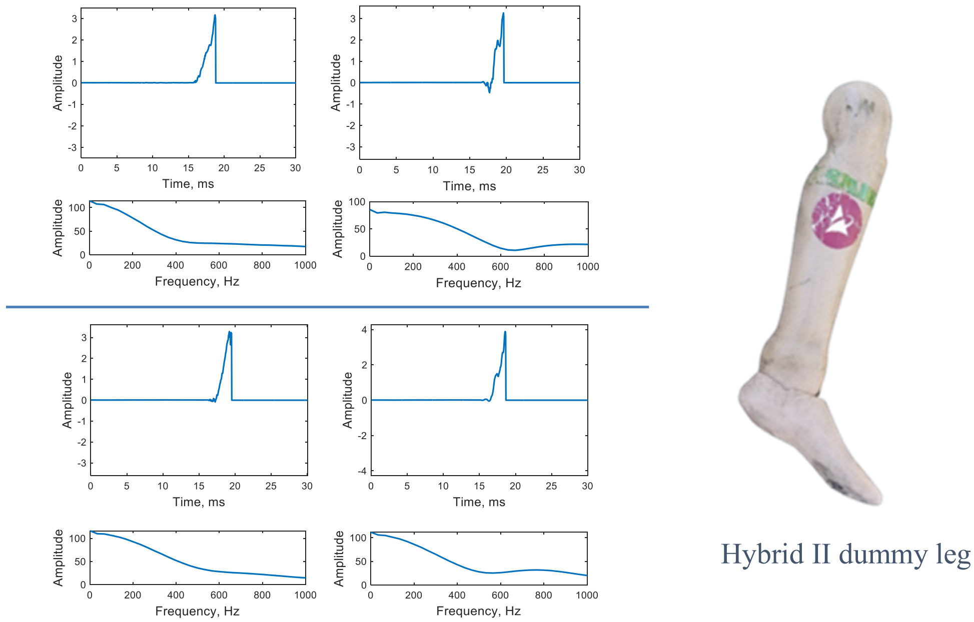
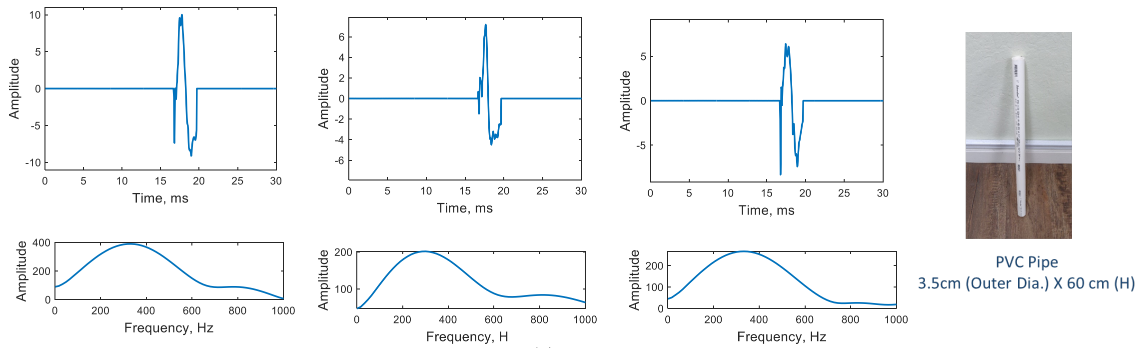


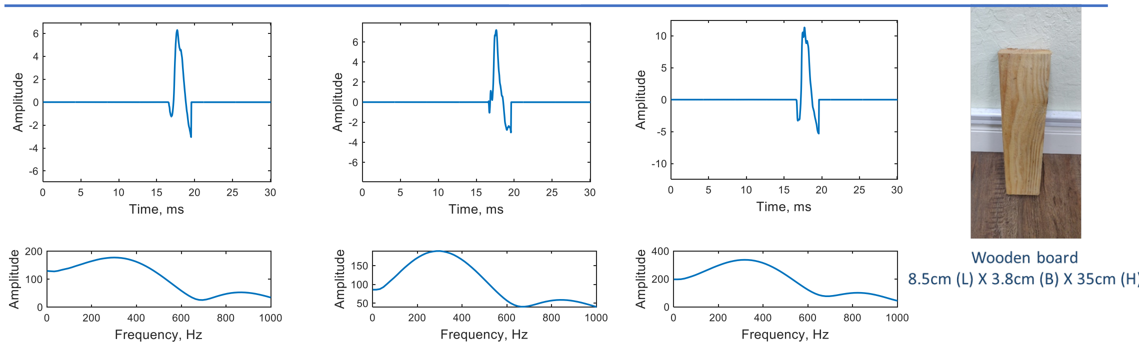
Figure 6. Hybrid II dummy leg impact signals at various trials of impact. The signal signature was observed to be similar for various attempts of impact

From the signals sensed using the sensors, the system was able to discern between dummy leg and other objects. However, the small animal model impact signals were observed to have a signal frequency spectrum similar to dummy leg impact signals. The peak frequency for the Hybrid II dummy leg and the small animal object was observed to be <100Hz. Therefore the dummy leg object and small animal object were observed difficult to classify from the frequency spectrum of the signals.

To classify pedestrian object from the small animal object, a novel signal energy method was developed. In the signal energy method, an additional parameter of energy of the signals was also considered to further distinguish between pedestrian object and small animal object. The energy of the object impact was calculated from the mass (m) and velocity (V) of the impact of the object ($E=1/2mV^2$). The energy of the signals was calculated from the voltage recorded by the sensors (V) and the admittance (Y) of the measuring system [12] ($E=\int YV^2 dv$). The impact energy and signal energy were plotted with respect to the velocity of impact. Then, the impact energy of the objects is plotted to fit the impact signal energy. Assumed loss factors for objects were used for fitting the impact energy with the signal energy data points. The fitted curve is extrapolated up to 50 mph to obtain the energy plots as presented in Figure 10. The representative energy plot for pedestrian object and small animal object at this velocity range showed a higher range of energy values for pedestrian object and a lower energy values for small animal object. Thus the object classification using the impact signals was performed to enhance the ability in distinguishing objects using the three parameters, frequency, the velocity of the vehicle, and signal energy.



(a)



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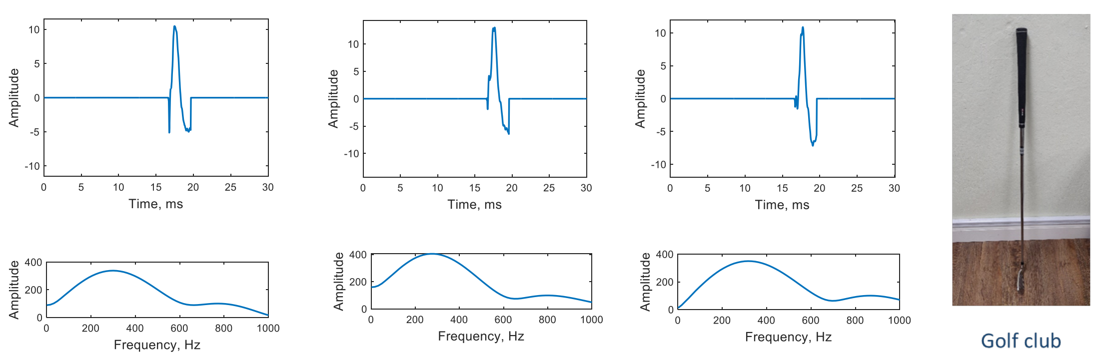
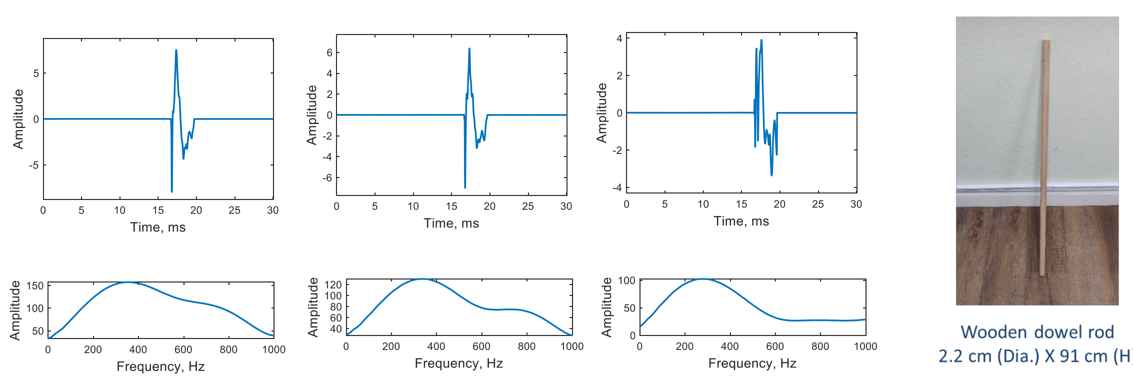


(c)

Figure 7. Impact signals due to PVC pipe, wooden board, and golf club impact



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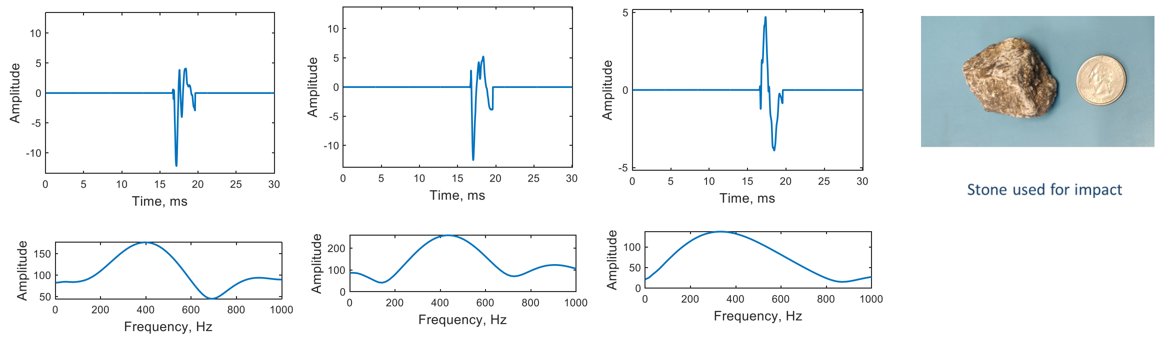

(e)

Figure 8. Impact signals due to a wooden dowel rod and stone impact

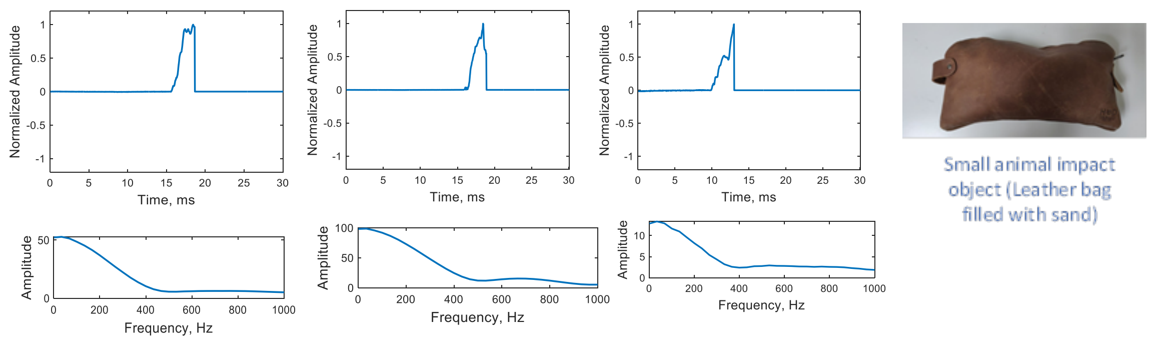

Figure 9. Impact signals due to small animal object impact

TABLE 1 PEAK FREQUENCY DUE TO DIFFERENT OBJECT IMPACTS

Object	Peak Frequency Range
Hybrid II leg	<100 Hz
Small animal object	<100 Hz
PVC pipe	285-363 Hz
Wooden dowel rod	269-363 Hz
Wooden board chunk	174-316 Hz
Golf club	269-395 Hz
Stone	269-442 Hz

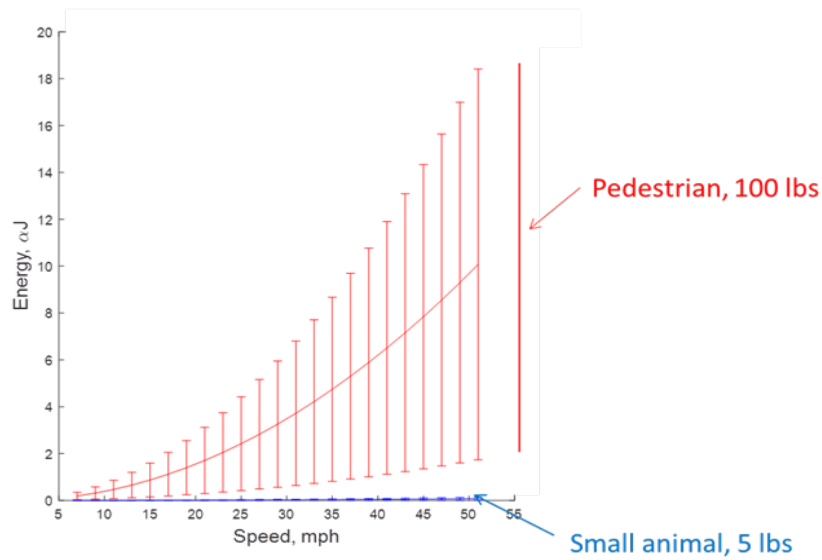

Figure 10. Energy method to distinguish the pedestrian object from small animal

SUMMARY CONCLUSIONS AND FURTHER WORK

A prototype of a pedestrian impact detection system that has the capability to detect and classify any impact events on a bumper of an automobile within a reasonable duration was developed and tested. Initial testing on the bumper was performed to identify the location and the number of sensors for the detection. A test setup was developed to demonstrate the impact-sensing system. The test setup consisted of the bumper, IMGenie Pro Hardware, a laptop installed with AIM software for data recording, cables, a Fixture for holding the test object, and impact objects (Hybrid II dummy leg, small animal model impact object, PVC pipe, wooden board, golf club, wooden dowel rod, etc.). The signals sensed due to various object impacts were recorded by the PWAS sensors. The signal frequency characteristics due to different object impacts were identified from the signals recorded. The peak frequency of signals due to the various objects such as PVC pipe, wooden board, golf club, wooden dowel rod, stone, etc. was observed to be different from the Hybrid II dummy leg impact signals. Similar signal peak frequency characteristics were observed for pedestrian dummy leg and small animal model object impacts. Additional classification of small animal object was achieved by using the developed energy method.

The classification of impact objects was achieved using the first part of the signals for quick response. The signal frequency, impact velocity, and signal energy parameters were studied to classify the objects. In the present work, the impact signal energy at car velocities of interest was obtained by projecting the low-velocity impact signal energies to higher velocities. In the future, controlled high-velocity tests at velocity ranges of interest will be performed to record the signals and obtain the signal energy values at those velocity ranges of impact. Drive tests still needs to be performed and validated to detect system response vehicle system.

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