

Pressure Based Sensing Approach for Front Impacts

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ABSTRACT

This study demonstrates the use of pressure sensing technology to predict the crash severity of frontal impacts. It presents an investigation of the pressure change in the front structural elements (bumper, crush cans, rails) during crash events. A series of subsystem tests were conducted in the laboratory that represent a typical frontal crash development series and provided empirical data to support the analysis of the concept.

The pressure signal energy at different sensor mounting locations was studied and design concepts were developed for amplifying the pressure signal. In addition, a pressure signal processing methodology was developed that relies on the analysis of the air flow behavior by normalizing and integrating the pressure changes. The processed signal from the pressure sensor is combined with the restraint control module (RCM) signals to define the crash severity, discriminate between the frontal crash modes and deploy the required restraint devices.

A parametric analysis was conducted to study the sensitivity of the factors that might affect the pressure signal. The results demonstrate that the material, thickness, geometry, openings and energy absorbing material are parameters that should be analyzed and optimized.

Improved pressure signals were demonstrated by new system design concepts. The concept of these designs relies on the fluid analysis of air flow in converged, diverged and converged-diverged control volumes and its interface with the dynamic deformation of the surrounding structure. The

initial subsystem test data for these designs showed potential for improvement in the signals and the overall system performance.

This study demonstrates that front pressure sensing concepts have the potential to improve overall system performance. However, more analysis on vehicle level crash testing is needed and algorithms that utilize such concepts are required.

KEY WORDS

Pressure Sensing, Front Crash Performance, Vehicle Collision

INTRODUCTION

Several sensing technology concepts have been investigated and introduced by original equipment manufacturers and their suppliers to further improve crash performance and meet changes in safety regulations. This work investigated the potential to increase the capability of the crash sensor system and enhance the robustness of frontal crash test performance by utilizing pressure sensors to monitor the pressure change in the cavities of the front end vehicle structure.

The pressure sensing concept has already been applied in different fields utilizing sensors (pressure sensors) that measure pressure, force and airflow in various applications, such as, medical equipment, aircraft, engine control and safety control. These sensors convert pressure changes to electrical signals, which can be analyzed and used to control the behavior of other devices. The analysis of pressure sensors is not an objective of this research, however, more information about pressure sensors and their applications can

be found in the literature [1, 2]. One related application to this study is the use of pressure sensing for deploying side airbag systems in side impact crashes. During the last decade several passenger vehicles have been equipped with side pressure sensors mounted in first row door cavity [3, 4, 5, 6]. The pressure sensing concept has also been introduced for pedestrian protection sensing [7], by adding a laterally extending air channel within a block of foam or other crushable medium disposed between a bumper fascia and a rigid beam.

For this study, the primary focus is on the pressure changes within the front structure during a frontal impact. Its registered changes can be processed through mathematical algorithms and the signals can be calibrated against certain criteria to define the deployment conditions of the restraint devices. A summary of the mathematical formulations is presented in the following section.

MATHEMATICAL FORMULATION AND ANALYTICAL ANALYSIS

A frontal impact can result in the compression of the air in the front bumper and rail (crush can) cavities. The fluid (air) mechanics in this system can be analyzed as one-phase flow because the bumper and rails are assumed to have a closed geometrical design with small openings and covered by the fascia, which helps to isolate it from other fluids that might intrude into the monitored control volume. Additionally, the bumper/rail surfaces deform during the crash, which reduces the rate at which the air pressure increases and prevents the compressed air from condensing or reaching a mixed-state. Also, air is typically inviscid, compressible and a calorically ideal gas. The primary variables to study such flow are pressure (p), volume (V), density (ρ), internal energy (e) and temperature (T), and the five governing equations to solve for these independent variables are the continuity, momentum, energy and the ideal gas equations (equations of state and internal energy).

For convenience, some forms of the related governing equations are summarized here, however, more details and analysis can be found in fluid mechanics and gas dynamics literature [8, 9, and 10].

Continuity equation: Mass can be neither created or destroyed

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{V} = 0 \quad (1)$$

Momentum equation: Force equals to time rate of change of momentum

$$\rho \frac{Du}{Dt} = -\frac{\partial p}{\partial x} + \rho f_x \quad (2)$$

$$\rho \frac{Dv}{Dt} = -\frac{\partial p}{\partial y} + \rho f_y \quad (3)$$

$$\rho \frac{Dw}{Dt} = -\frac{\partial p}{\partial z} + \rho f_z \quad (4)$$

Energy equation: Energy can be neither created nor destroyed; it can only change in form.

$$\rho \frac{D(e + V^2/2)}{Dt} = \rho \dot{q} - \nabla \cdot p \vec{V} + \rho (\vec{f} \cdot \vec{V}) \quad (5)$$

Equation of state:

$$p = \rho RT \quad (6)$$

Internal energy:

$$e = c_v T \quad (7)$$

Where, t denotes time, V : Volume, f : Body Forces, u : x-Velocity, v : y-Velocity, w : z-Velocity, $V^2/2$: Kinetic energy per unit mass, C_v : specific heat at constant volume and R is the specific gas constant.

The above equations can be simplified further by introducing more assumptions such as considering the change in the temperature within the bumper/rail assembly to be very small because the required response time for the sensor system in front collisions is very short (less than 50 ms), and the heat transfer is negligible. Thus, the flow is adiabatic.

With these equations and assumptions in mind, the focus was on the empirical data. Relative pressure and its integration were the main terms used in this investigation to quantify the differences between the test results and to assess the potential enhancement to the pressure signal in the sensor system calibration. The raw pressure data was collected with a sampling rate of 12.5 kHz and filtered by a second order Bessel filter. The pressure change was then normalized (P_N) in each time step as in [equation \(8\)](#).

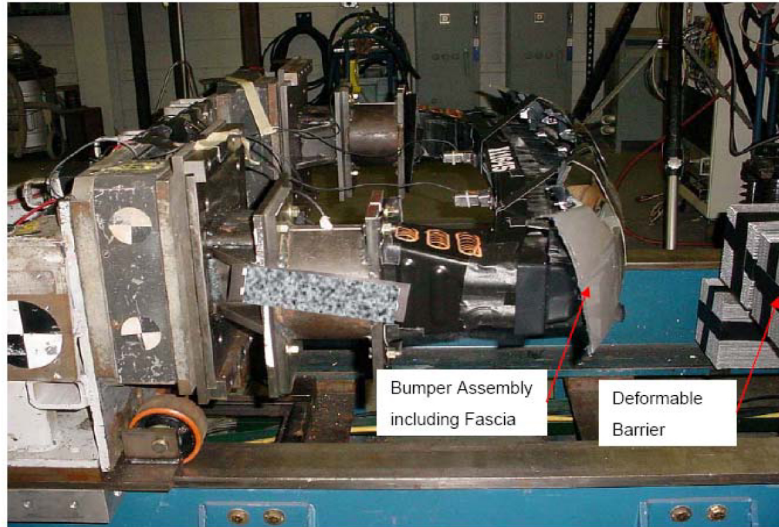


Figure 1. Test setup including the bumper assembly with fascia, energy absorbers and deformable barrier.

$$P_N = \frac{(P_i - P_{ref})}{P_{ref}} 100\% \quad (8)$$

Integrating the normalized pressure change gives an integration term (P_{Int}), which is analogous to acceleration and delta-V terms used throughout the industry.

$$P_{Int}(t) = \int_{t_0}^{t_i} P_N(t) dt \quad (9)$$

Additional mathematical formulations, such as the effects of impact shock waves can be analyzed as future work, but in this study, it is assumed subsonic impact with no effect on the air flow compressibility.

TEST SETUP

The test setup consisted of a subsystem of a front bumper beam and rail (crush cans) mounted to a fixture as shown in [Figure 1](#). The bumper had a rectangular cross section and was closed at both ends and the crush cans were tapered and closed. However, neither the bumper beam nor the crush cans were completely closed due to some holes and openings at the corners. The test sled weight and speed were the variables used to maintain equivalent crash energy and correlation between the laboratory sled tests (subsystem) and barrier tests (full vehicle). The fixture with the bumper/rail assembly was the moving part and the impacted surface was the fixed barrier that was modified to represent a rigid barrier, offset deformable barrier and center pole. The installed data acquisition system recorded data from load cells, accelerometers and five pressure sensors; three of them

mounted at the back surface of the bumper beam and one sensor at the end of each crush can as presented in [Figure 2](#). These sensors were piezoresistive pressure transducers with a range of 15 to 100 psia and 225 mV full scale.

TEST MATRIX AND PARAMETRIC ANALYSIS

The critical factors and their levels used in this study are summarized in [table 1](#). They were defined based on the following design constraints and crash conditions:

1. **Sensor Location:** It was analyzed with five different levels; three locations at the bumper beam (left, center and right) and two at the crush cans. These five locations were chosen to study the variation of the pressure signal in the bumper/rail subsystem, which provided information to optimize the location and the number of sensors for potential future designs.
2. **Impactor (barrier):** Three different impact faces (barrier) were chosen to represent various test conditions; rigid barrier, offset deformable barrier and pole.
3. **Crash Mode:** The frontal crash modes were reconstructed in the laboratory and conducted as follows:
 - a. 90° frontal rigid barrier with five speed levels; 8 mph, 12 mph, 16 mph, 25 mph and 35 mph.
 - b. 30° frontal rigid barrier with two speed levels; 19 mph and 31 mph.
 - c. 40% offset deformable barrier with two speed levels; 25 mph and 40 mph.
 - d. 12" pole with two speed levels; 17 mph and 30 mph.
4. **Air Flow System:** Two bumper/rails subsystems (closed and opened) were tested to analyze the effect of the system

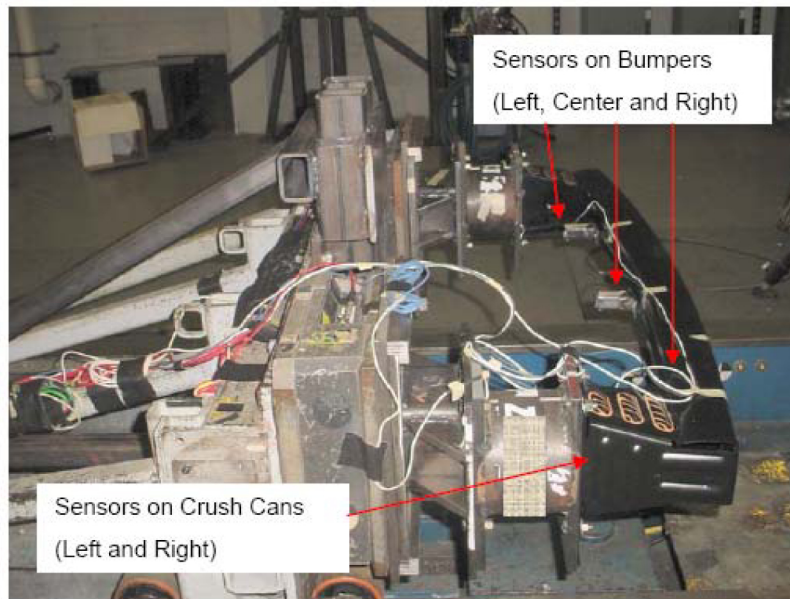


Figure 2. Test setup and mounting location of the pressure sensors

boundary conditions on the air flow and its pressure changes during the different impacts.

5. Pressure Chamber Design: For more understanding of the effect of the geometrical shapes of the pressure system on the pressure signal, the following four air flow design concepts were investigated:

- a.** Converged airflow channels were formed in blocks of soft foam and inserted as nozzles in the front of the sensor port at each location.
- b.** Diverged airflow channels, similar to the converged design, but rotated 180° to function as airflow diffusers.
- c.** Converged-diverged airflow channels using a combination of the previous two concepts and made of a plastic material with rounded convolutes on the surface to minimize any deformation resistance and maximize the response.
- d.** Bumper divider was designed from a 1 mm plate of steel inserted at the middle of the bumper, creating two separate control volumes (left and right).

RESULTS AND DISCUSSION

The first phase of this investigation was intended to define the feasibility of the front pressure sensing concept and the primary factors that affect this approach. This phase included analytical analysis, subsystem testing and full vehicle testing. A summary of the findings is described in the following:

1. Comparison between pressure and acceleration signals was conducted and typical signals are presented in [Figure 3](#). It was observed that the pressure data experiences less noise than the acceleration, which aided in the data processing and

minimized the potential loss of data due to signal clipping or filtering required to eliminate the noise. It was also observed that the pressure signal can be characterized into two zones:

a. Rising pressure (air compression) zone. The pressure signal continuously increased in this zone and had two significant peaks. Given that the deployment time is targeted within this zone, the severity of the crash has to be predicted based on the signal energy in this zone and applied to the deployment thresholds. It was also observed that the pressure signal increases quickly in this zone and can be classified within a short period of time. For all tests conducted in this study, the pressure signal responded less than 5 ms after the time of impact (t_0)

b. Dropping pressure (air leaking) zone. The pressure signal decreases in this zone because of the changes in the boundary conditions and the control surface due to structural deformation. This reverses the signal direction and lowers its magnitude. Typically, this zone doesn't provide as much useful information for the processing of the sensor system.

2. Defining the mounting sensor location is a challenge due to the packaging constraints and desire for a strong and consistent signal. The optimal signal must have high energy, quick response time, and discrimination between the different crash modes. Thus, five sensor locations were investigated using multiple frontal crash modes as shown in [Table 1](#). The findings can be summarized as follows:

a. In perpendicular modes, at all speeds, the time and magnitude of the pressure signal first peak demonstrated the center bumper location had the fastest response, followed by the left and right bumper locations that responded at similar times but with different magnitudes. The rail (crush cans)

Table 1. The investigated factors and their levels

Levels Factors	Level 1					Level 2		Level 3		Level 4		Level 5
Sensing location	Bumper Left Side					Bumper Center		Bumper Right Side		Left Rail		Right Rail
Impactor	Rigid Barrier					Deformable Barrier		10" Pole				
Crash mode	Perpendicular					Angular		Offset		Pole		
	8 mph	12 mph	16 mph	25 mph	35 mph	19 mph	25 mph	25 mph	40 mph	17 mph	30 mph	
Bumper System	Beam only					Beam, energy absorbers and fascia						
System leak	Open System (has production holes, cuts and openings)					Closed System						
Design concept	Converging design					Diverging Design		Converging-Diverging		Bumper Divider		

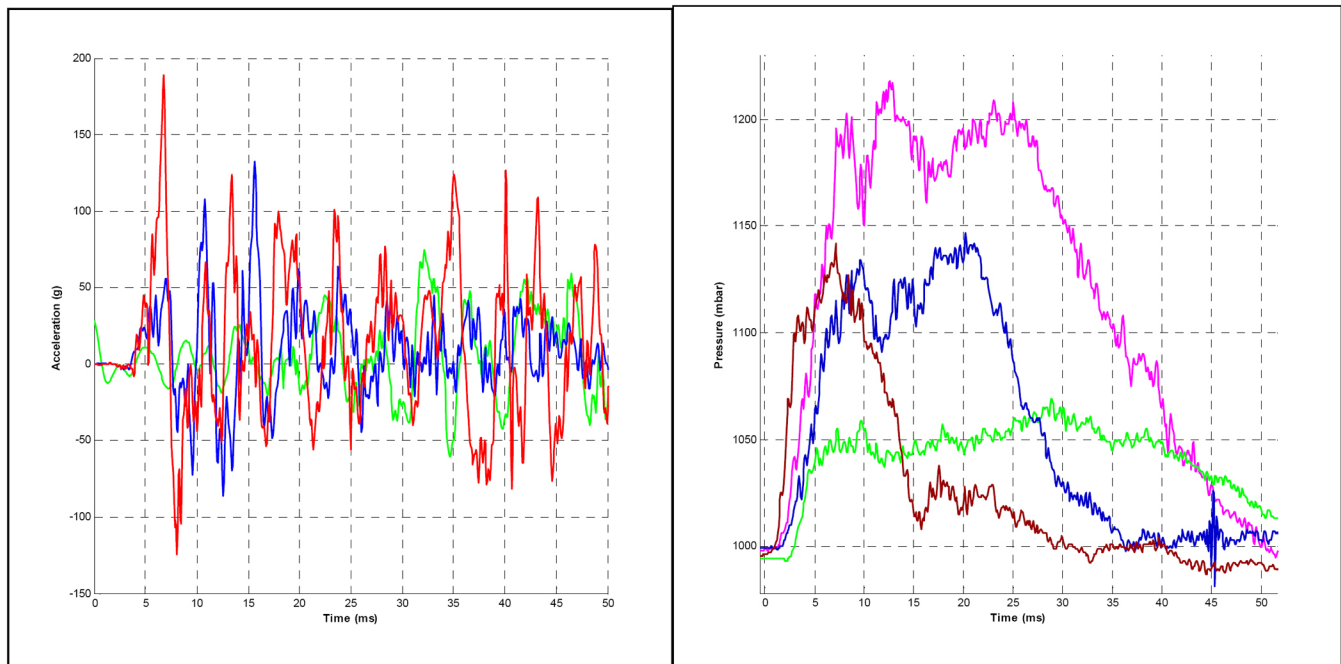


Figure 3. Typical characteristics of acceleration and pressure signals

locations had the slowest response, lagging approximately 2 ms after the bumper. However, it was the opposite for the second peak, where the pressure changed faster in the rails than in the bumper. This could be due to the subsequent axial folding of the rail causing a faster volume rate change. [Figure 4](#) depicts the pressure signal of the five sensors for the 35 mph frontal impact and shows the bumper signal (solid lines)

behavior versus the rail signal (dashed lines). Other frontal tests had similar results.

b. In angular modes, the order of the signal energy from high to low was; bumper impacted side, rail impacted side, bumper center, bumper non impacted side and rail non impacted side. [Figure 5](#) shows the percentage of the pressure change and its integration for the five sensors for the 25 mph 30° rigid barrier right angular impact. In this mode, the first