Chapter 3

Vibration Test Setup

The test setup of the locomotive cab is described in this chapter. First, the cab configuration and its installation at the Advanced Vehicle Dynamics Laboratory of Virginia Tech are discussed, followed by the actuation system used for emulating the vibration inputs to the cab. Finally, a description of the data acquisition system, as well as the data analysis techniques, is given.

3.1 Cab Configuration

The side view and plan view of the locomotive cab that was tested throughout the research are shown in Figs. 3.1 and 3.2, respectively.

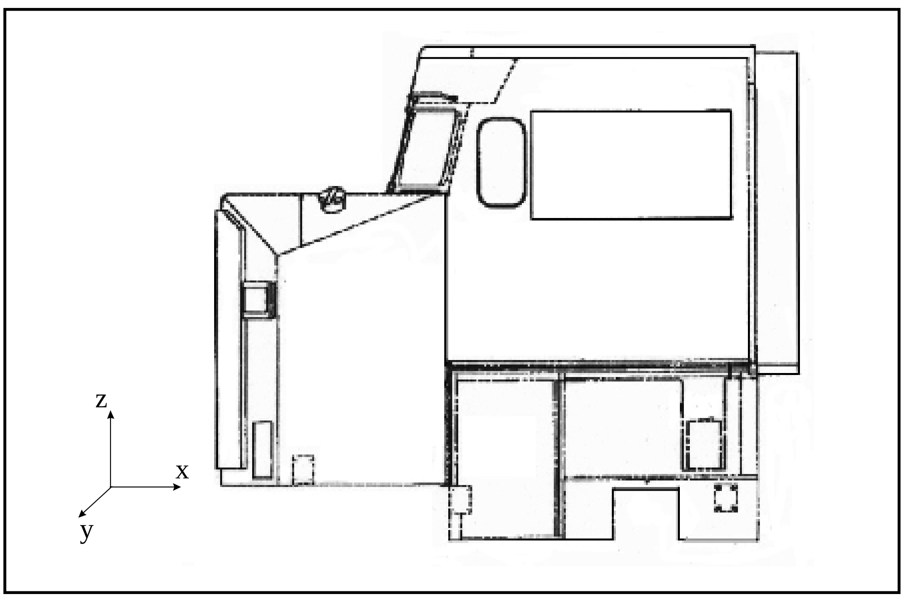


Figure 3.1 Side View of Locomotive Cab

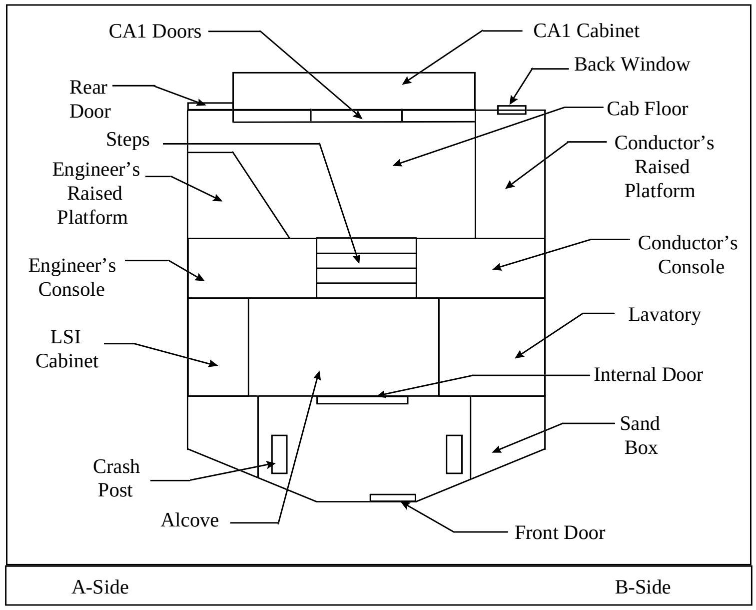


Figure 3.2 Plan View of Locomotive Cab

The overall dimensions of the cab, which weighs approximately 22,000 lb, are 16ft long, 10ft wide, and 10ft high. The cab exterior is constructed primarily of steel, with the front section, known as the "nose cab," having the thickest layer (0.375 in). At the front door of the cab, two large steel post structures, called the crash posts, are located to protect the crew in a head-on collision. The crash posts also help to decrease the amount of roll that is experienced inside the cab. Adjacent to the crash posts is an internal door that is used to separate the immediate entrance area from the remainder of the cab. An added advantage to the internal door is better sound and temperature isolation. Past the internal door is an electronic cabinet, better known as the LSI rack, that is used to store electronic equipment; this structure was not included in the test cab.

A lavatory is separated from the electronic cabinet by a small area, which is referred to as the alcove. The operator cab floor, approximately two feet above the lavatory and LSI rack, is connected to the alcove area by three steps. Immediately to the right and left of the steps are located the conductor's and engineer's consoles. Both consoles consist of vital communication equipment and LED displays for running the locomotive and are connected to raised platforms with seat attachments for the engineer and conductor. Directly opposite the engineer's console is a rear door that enables access to the remainder of the locomotive through a walkway. Adjacent to the rear door, which is on the back wall of the cab, is an electronic cabinet and back window. The cabinet, referred to as the CA1 cabinet, is separated from the cab by a three-fold door and a small window. All electronics that would normally by housed in the cabinet were not included in the test cab.

To provide more comfort and cushioning for the engineer and conductor and to decrease the level of vibration inside the cab, the cab floor has a mat of approximately 0.25-in thickness glued to it. An air-brake cab is located directly below the 0.125-in sheet metal cab floor. This area houses the air brake and HVAC equipment. Although equipment such as the air conditioner, ducts, and plumbing was not located in the air-brake cab, weights were used to account for them.

Finally, the front of the cab and the air brake compartment are both welded to sill plates, constructed of a 1-in thick steel, spanning the cab length and width. The plates, in turn, are welded to the I-beam sills that are used as the main supports for the entire locomotive.

The cab is placed on four Goodyear airbags, model #1B14-350, in the configuration shown in Fig. 3.3. Each airbag is rated for a 10,500-lb. static load. Airbags are used to isolate the cab from the floor and simulate actual installation of the locomotive cab. The natural frequency for the cab system is in the range of 1-2 Hz. The airbags are bolted to the sill and the lab floor to ensure that the cab does not slide across the floor when it is shaken.

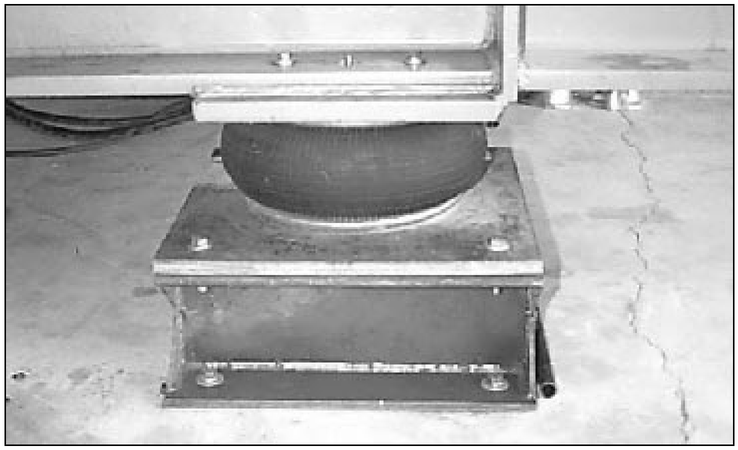


Figure 3.3 Goodyear Airbag Installation

In order to reduce interior noise and vibration, previous studies on the cab revealed soft-mounting as the best approach. Originally, the cab was welded to the sill structure at the front and at four needle beams that are connected to the sill. To soft-mount the cab, it was cut from the sill structure along the welded joints. Once the cab was completely separated from the sill, proper modifications were made to accommodate elastomeric pads, (Fig. 3.4), at four base locations and two crash posts. The mounting of the cab was performed such that, if necessary, the cab could be hard-mounted again by using steel plates in place of the elastomeric mounts.

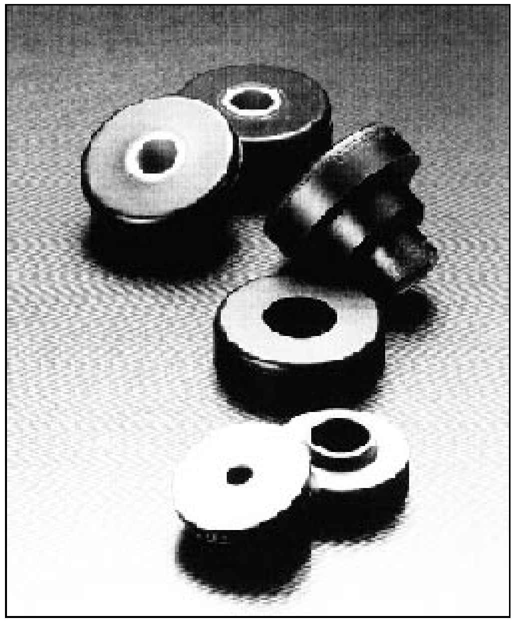


Figure 3.4 Typical Elastomeric Mounts after Lord Corp. [16]

3.2 Actuation System

To simulate the vibration input in the field, the cab was excited with a hydraulic actuation system consisting of a hydraulic pump, manifold, and actuator. The hydraulic system, including the pump, manifold, and actuator is manufactured by Material Testing System (MTS). A hydraulic pump, model #502.020, similar to the one shown in Fig. 3.5, was used to provide fluid to the manifold at a rate of six gallons per minute (gpm) and with 3000 psi pressure.

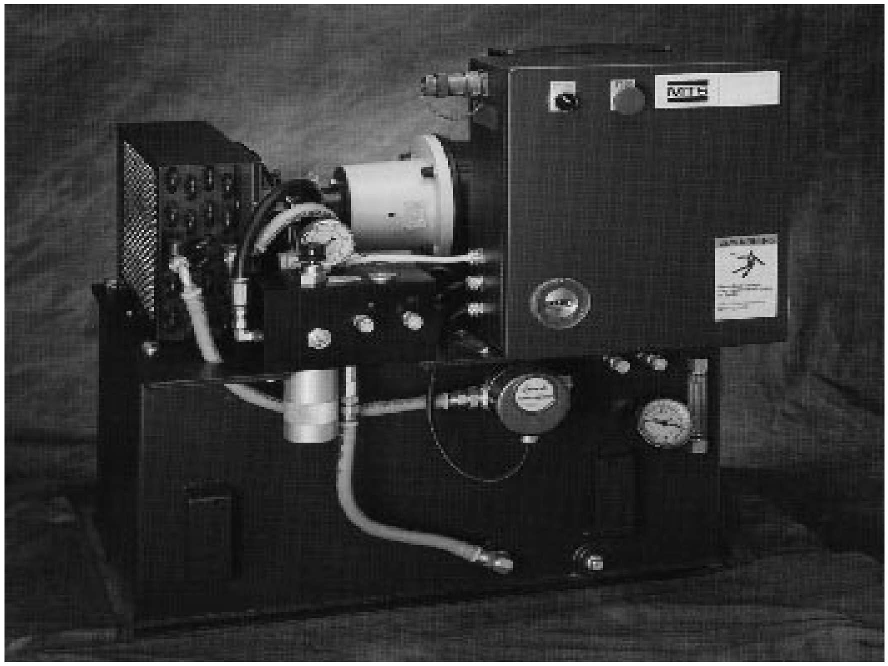


Figure 3.5 MTS 506 Series Hydraulic Power Supply after MTS [17]

A model 263 hydraulic service manifold, shown in Fig. 3.6, was used to interface the hydraulic supply to the actuator. The primary roll of the manifold is to regulate the hydraulic pressure and flow to the actuator. A regulated flow is needed to ensure proper dynamic response of the hydraulic actuator at the higher frequencies required for this testing.

Figure 3.6 MTS 263 Hydraulic Service Manifold after MTS [18]

A hydraulic actuator, as shown in Fig. 3.7, with a force capacity of 2000 lb., was used to shake the cab. The MTS 249 actuator used in our tests has a rod diameter of 1.25 in, and two swivel ends to eliminate lateral loading of the actuator. The actuator is equipped with an internal load cell and linear velocity displacement transducer (LVDT) for measuring force and displacement, respectively.

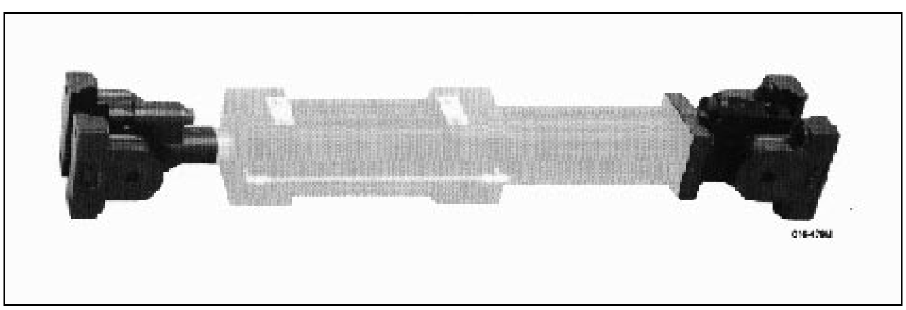


Figure 3.7 MTS 249 Actuator with Swivel Ends after MTS [19]

The hydraulic system is controlled by an MTS model 407 controller, shown in Fig. 3.8. This controller is a single-channel, digitally supervised servo controller that provides complete control of the servo-hydraulic actuator. The controller can be used to prescribe a given displacement or actuation force at the actuator.

Figure 3.8 MTS Model 407 Servo Hydraulic Controller after MTS [20]

The hydraulic actuator is mounted to the cab at locations near the actual attachments of the cab to the sill structure. These locations were chosen to more closely emulate the flow of the vibration energy from the sill (to which the vibration sources such as the diesel engine and locomotive accessories are mounted) to the cab. As shown in Fig. 3.9, the hydraulic actuator is mounted between the lab floor and a short, heavy needle beam that is added to the sill structure.

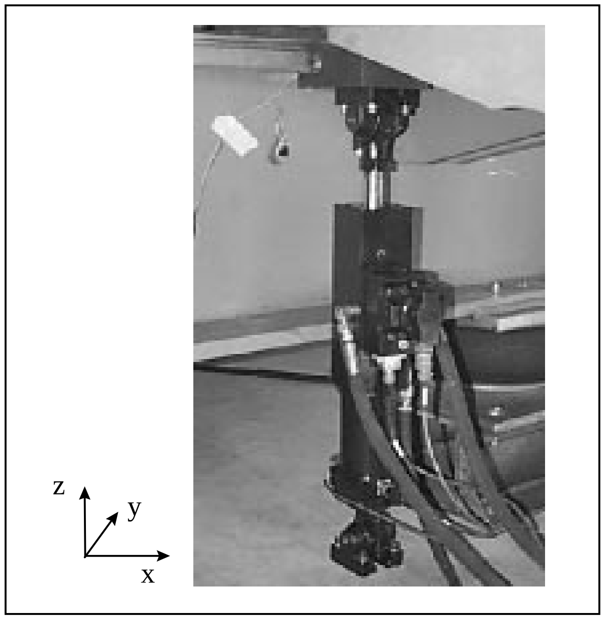


Figure 3.9 Actuator Installation on the Locomotive Cab

3.3 Data Acquisition System

The data acquisition system used for vibration measurement consisted of PCB accelerometers/signal conditioner, a Sony DAT recorder, a HP analyzer, and a personal computer. An overall representation of the data acquisition system in flow chart format is shown in Fig. 3.10.

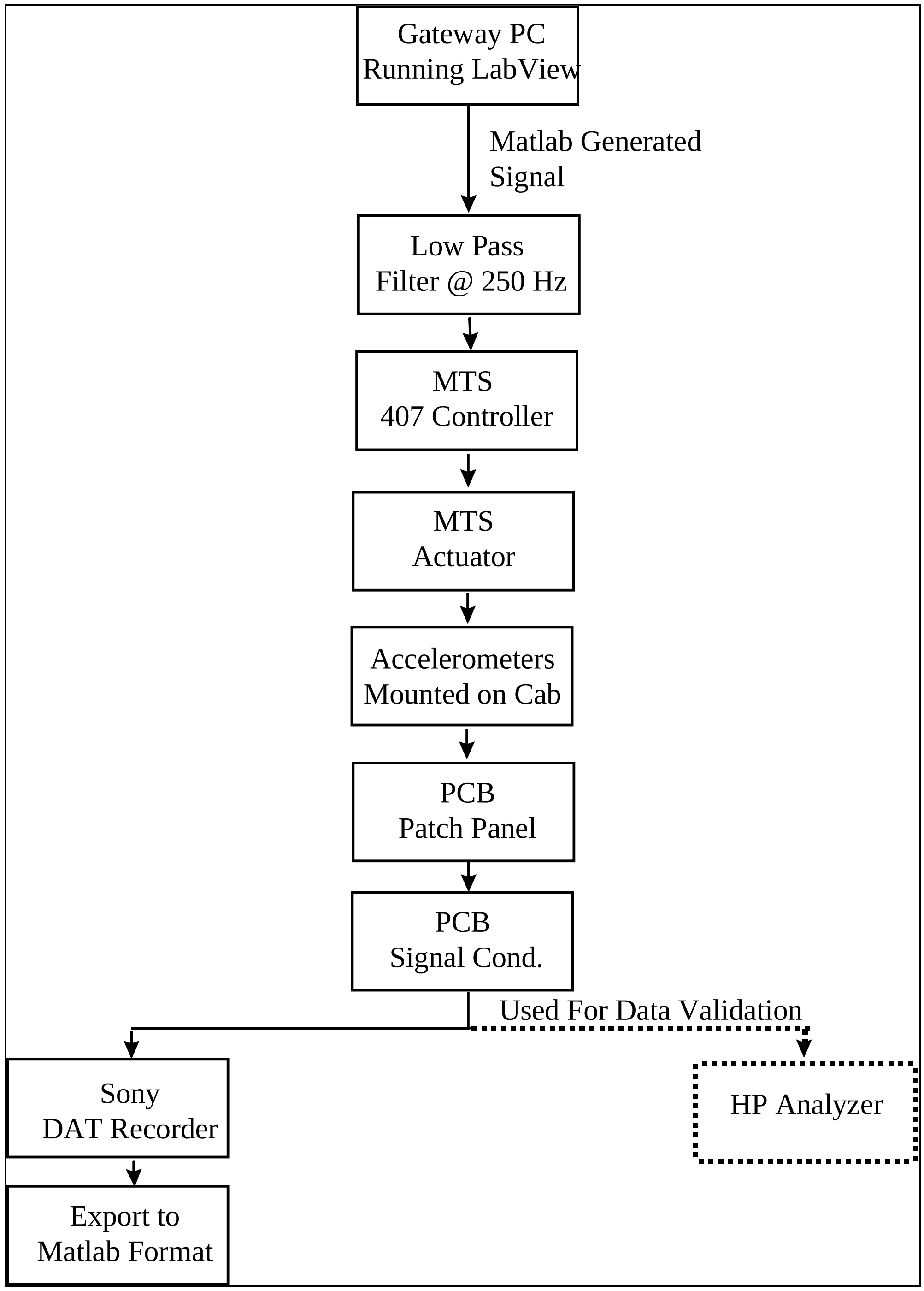


Figure 3.10 Data Acquisition Flow Chart

The flow chart begins with the generation of the excitation input in Matlab. The generated signal is used by Labview [21] to export an external signal to the MTS 407 controller after it is filtered at 250 Hz. Using the external signal, the controller drives the actuator to introduce energy into the cab. Next, accelerometers are used to capture acceleration data at various locations on and inside the cab. The acceleration signal is sent through a patch panel to a PCB signal conditioner, where the signal is amplified. Sampling as well as digital filtering of the data is completed by a Sony DAT recorder. Finally, by using software that was developed specifically for the DAT recorder, the data is converted and saved into Matlab format.

PCB Piezotronics, Inc. [22] provided the model 333A accelerometers, which are shown in Fig. 3.11 mounted to the cab on a tri-axial mount block. The accelerometer has a voltage sensitivity of 100 mV/g, along with a measurement range of ±50 g peak. The overall frequency range that the accelerometers were capable of measuring is 1-1000 Hz.

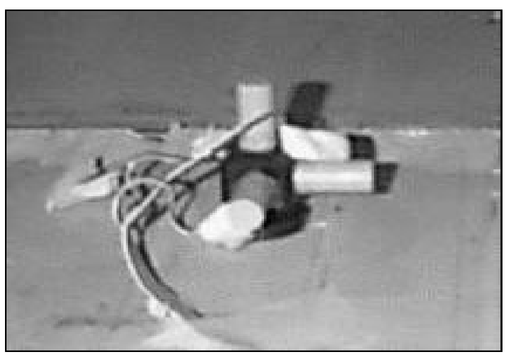


Figure 3.11 PCB Accelerometers Used for Vibration Measurements

The accelerometer signal had to be conditioned and amplified before any processing was done. A model 584 signal conditioner (Fig. 3.12) from PCB was used to condition the acceleration data. The conditioner was capable of monitoring 16 channels of data at one time, as well as providing a gain range of 1 to 100.

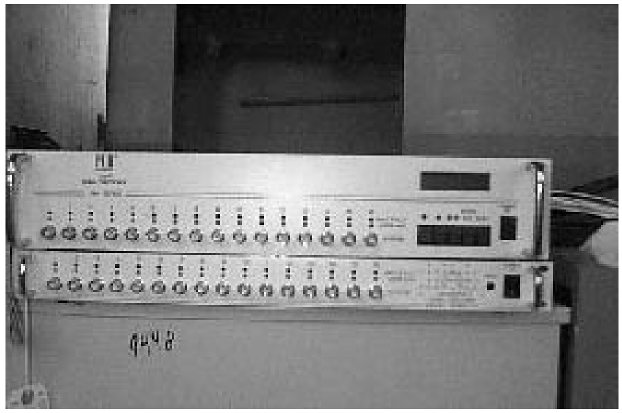


Figure 3.12 PCB Signal Conditioner Used for Vibration Measurements

A Hewlett Packard 35665A two-channel spectrum analyzer, shown in Fig. 3.13, was used to collect frequency-domain data such as FFTs, PSDs, and frequency response functions. The analyzer was used in conjunction with the data acquisition system for validation purposes.

Figure 3.13 HP 35665A Spectrum Analyzer

A PC-series DAT recorder, model PC216Ax, by Sony Precision Technology America was used to acquire and filter the data as shown in Fig. 3.14 [23].

Figure 3.14 Sony DAT Recorder

The 16-channel double-speed recorder equipped with anti-aliasing filters is suited for applications in multi-channel real-time signal processing, multi-shaker modal analysis, acoustic analysis, and structural analysis. Analog and digital data can be captured on Digital Audio Tapes (DAT), which later can be transferred onto a personal computer or another storage device directly through a parallel port in various formats, using a frequency range of up to 20kHz. Due to its compact and lightweight size along with its low power consumption, the recorder becomes a useful tool for all types of experimentation.

3.4 Accelerometer Locations

The PCB accelerometers were used to collect vibration data on the outside and inside of the cab structure in a hard and soft-mounted configuration. The locations of the accelerometers for collecting data on the cab are shown, along with their coordinates, in Fig. 3.15 and Table. 3.1.

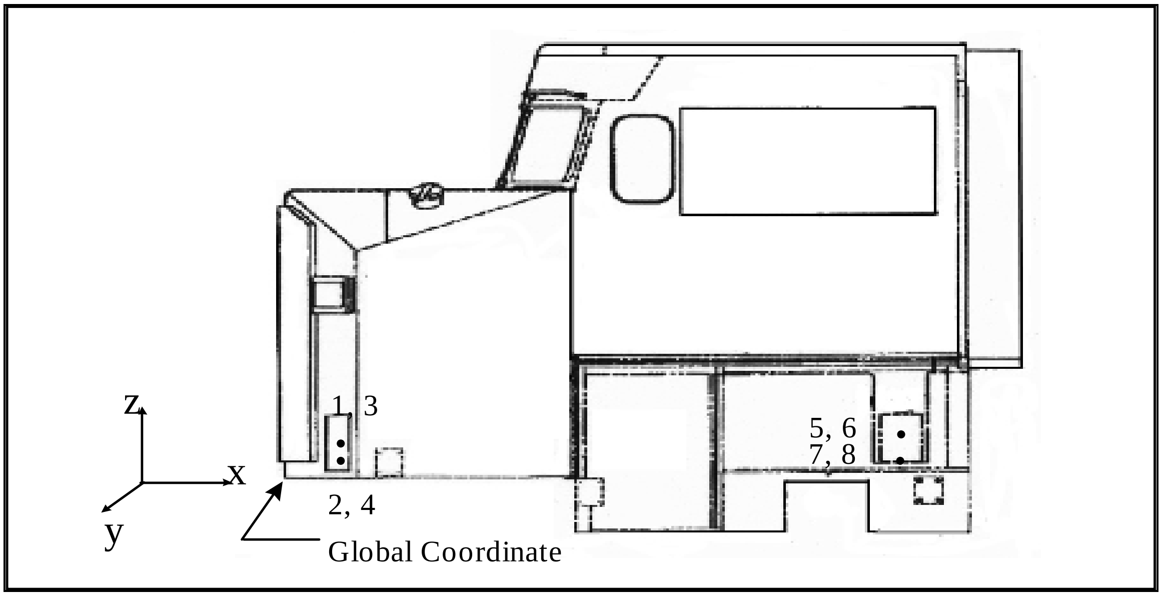


Figure 3.15 Accelerometer Locations for External Cab Testing

Table 3.1 Coordinates of Accelerometers for External Testing

Location	X (in)	Y (in)	Z (in)	Axis
1	11.75	-46.75	9.5	+Z
2	11.75	-46.75	7.5	+Z
3	11.75	46.75	9.5	+Z
4	11.75	46.75	7.5	+Z
5	91.125	-46.75	7.25	+Z
6	91.125	46.75	7.25	+Z
7	91.125	-46.75	4.25	+Z
8	91.125	46.75	4.25	+Z

The eight locations where data was collected consist of four locations on the cab structure, and four locations on the sill. This arrangement allowed us to measure the vibration input to the mounts as well as the transmissibility of the mounts. The coordinates, shown in Table 3.1, of the accelerometers are based on the global coordinate point shown in Fig 3.16.

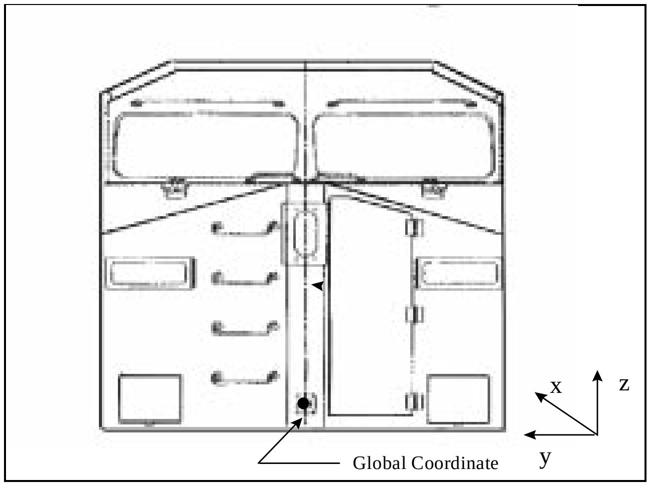


Figure 3.16 Global Coordinate System

Once acceleration data was collected for the locations outside the cab, experiments were run to collect data at locations within the cab. The locations of the accelerometers within the cab were on the conductor table, cab floor, CA1 cabinet door, and on the floor opposite the lavatory door. The locations of the accelerometers inside the cab, along with their coordinate points, are shown in Fig. 3.17 and Table 3.2.

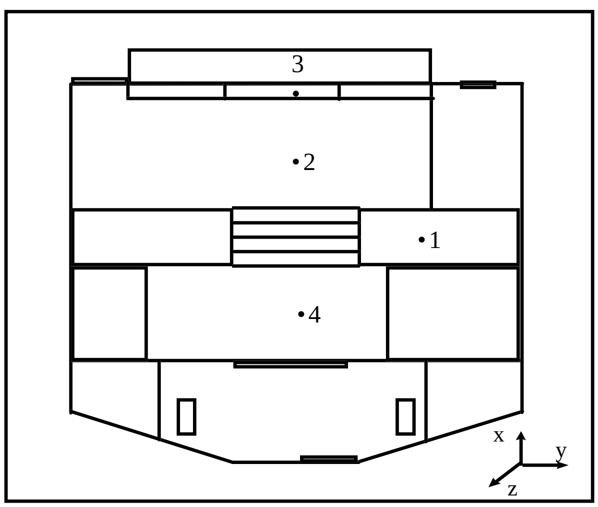


Figure 3.17 Accelerometer Locations for Interior Cab Testing

Table 3.2 Coordinates of Accelerometers for Internal Testing

Location	X (in)	Y (in)	Z (in)	Axis
1	51.25	34.75	68	+Z
2	76.25	0	37.5	+Z
3	111.75	0	68	-X
4	31.25	0	9.5	+Z

Chapters 5 and 6 will discuss the data collected at locations outside and inside the cab, respectively, along with a comparison between the predictions of the model and actual test results for these points.

3.5 Data Analysis

To analyze acceleration data collected by the Sony DAT recorder in MATLAB and to compare its results to those of a HP analyzer, the Sony recorder software was used to convert the analog data into digital format. Next, a program in MATLAB was generated to process the data into the necessary format. A flow chart of the program is shown in Fig. 3.18.

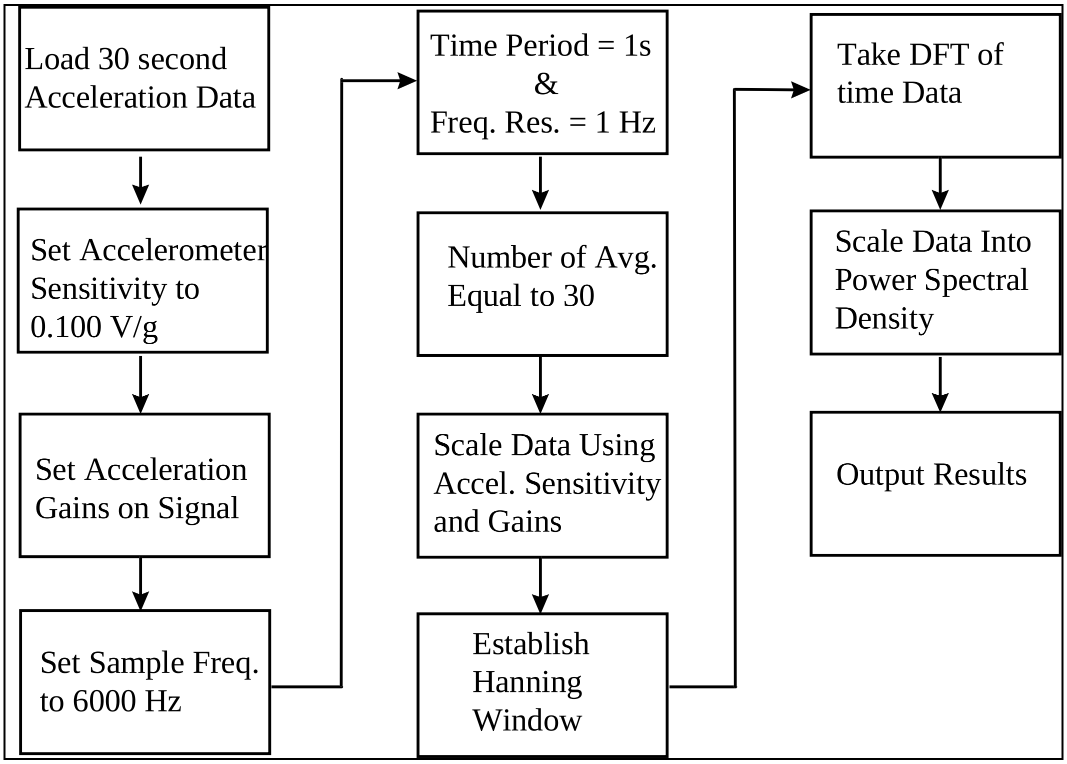


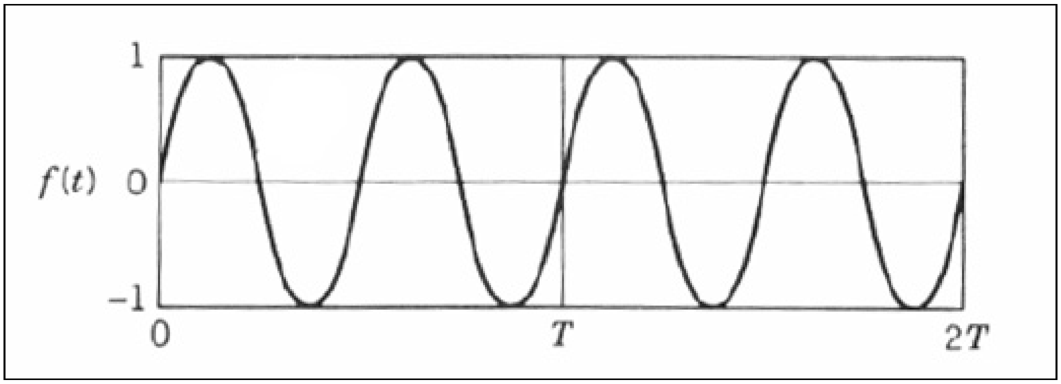
Figure 3.18 Data Analysis Flow Chart

First, the acceleration data from the DAT recorder is loaded into MATLAB in matrix format. Next, the transducer sensitivity, as well as the acceleration gains, are set to their appropriate values so that they can later be applied to scale the data. A sampling rate of 6000 Hz is used to sample the data in order to match the sampling rate used by the recorder. The number of averages is set equal to thirty so that the noise level is minimized. It was possible to complete thirty averages of the signal because a thirty-second data file having a period of one second was used. Next, a Discrete Fourier Transform (DFT) of the time data is taken in order to convert it into frequency domain. A Hanning window, discussed in further detail in section 3.5.1, is applied to the time data to establish periodicity while the DFT is taken. Finally, the magnitude of the DFT spectrum data is squared and normalized to a 1Hz frequency bandwidth to yield Power

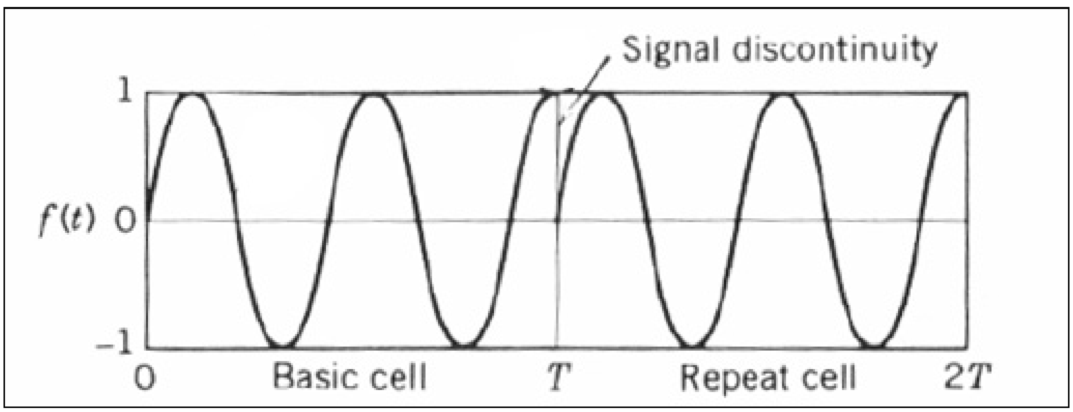
Spectral Density (PSD). The results of this analysis can then be output for data analysis or comparison with another analyzer.

3.5.1 Hanning Window

A Hanning window was applied by the MATLAB-generated program to the input signal of each experiment to force the signal to be periodic and to prevent leakage. Leakage can occur when a signal is not periodic within an analysis period, *T*. A periodic signal is defined as having a continuous magnitude and slope at the beginning and end of a time period *T*. To illustrate mismatching of signal ends, consider the situation shown in Fig. 3.19, where two analysis periods, each of length *T*, are shown. Sinusoidal signal (a) fits precisely with period *T* so that it has a continuous magnitude and slope at the beginning and the end. By fitting perfectly within period *T*, the repeat cell is identical to that in the basic cell. However, the lower plot, (b), shows a signal discontinuity between the magnitudes and slopes at the beginning and the end of time period *T*.



(a)



(b)

Figure 3.19 (a) Periodic Sinusoid (b) Non-Periodic Sinusoid

Assuming that the repeat cell is the same as the basic cell, the signal shown will be analyzed instead of a periodic sinusoid. This discontinuity in magnitude and slope will cause additional frequency components to be calculated in the frequency spectrum, which in turn can cause leakage. The shape that is applied to the input signal by the Hanning weighting filter is shown in Fig. 3.20.

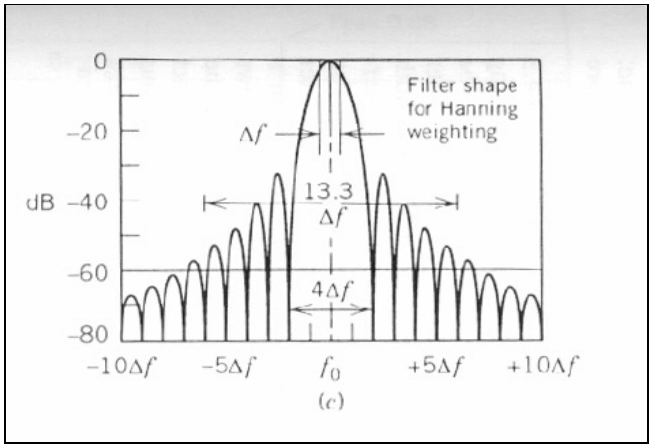


Figure 3.20 Digital Filter Characteristics for Hanning Window after McConnell [24]

Applying this window to an input signal will effectively cause the input to be periodic. Although other windowing filters, such as Hamming, Kaiser-Bessel, and Flat Top, could have been applied to the input signal, the Hanning window was used for its ability to accurately define frequency content of a signal.

3.6 Data Analysis Theory

The Hewlett Packard analyzer, Sony DAT recorder, and Matlab were set up to compute the auto spectrum, FRF, and coherence measurements. Depending on the testing needs, the data acquisition system could be set up to reduce the data to many other forms. This section will describe each of the measures that were selected for the data analysis.

The auto spectrum (also known as auto power spectrum) of a discrete frequency spectrum, such as $X_k(\omega)$, is defined as

$$G_{xx} = \frac{2}{k}\sum_{k=1}^{n} X_k^*(f)X_k(f) \tag{3.1}$$

where $X_k^*(\omega)$ indicates the complex conjugate of $X_k(\omega)$. The constant n denotes the size of $X_k(\omega)$, and the factor 2 is used for a single-sided auto spectrum. The units of the auto spectrum are $(\text{Volts})^2$, which can be transformed to proper engineering units using the calibration factor of a transducer. Auto spectrum is a real number, and as such provides information only about the magnitude of the frequency spectrum. No phase information can be gained from the auto spectrum. Normalizing auto spectrum data to a 1Hz frequency bandwidth yields power spectral density (PSD), which gives a good indication of the energy across the frequency spectrum.

In some instances, the spectrums are defined in a different form than that shown above. The square root of the auto spectrum is taken in order to have the units in terms of *g*, *in*, and *lb*. This spectrum is defined as

$$spectrum = \sqrt{\frac{1}{n}\sum_{i=1}^{n} X_i^* X_i} \tag{3.2}$$

Another measure that is considered for the data analysis is the FRF. This provides the ratio between output and input, which is defined as

$$\mathrm{H}(\omega) = \frac{\mathrm{G}_{\mathrm{xy}}}{\mathrm{G}_{\mathrm{xx}}} \tag{3.3}$$

where G_{xx} is as defined in Eq. (3.1), and G_{xy} indicates the cross spectrum defined as

$$G_{xy} = \frac{2}{k}\sum_{k=1}^{k} X_k^*(f) Y_k(f) \tag{3.4}$$

where $Y_k(f)$ is the discrete Fourier transform of the output. The resemblance between the cross spectrum in Eq. (3.4) and the auto spectrum in Eq. (3.1) is obvious. The cross spectrum provides a measure of the mutual power between the output and input signals across the frequency spectrum. Cross spectrum is commonly used to analyze the phase relationship between two signals (in this case, output relative to the input).

The frequency response function (FRF) in Eq. (3.3) is a complex quantity, and as such contains both phase and magnitude information. It must, however, be mentioned that FRF works well for linear systems. For nonlinear systems, FRF does not necessarily provide accurate information. As will be discussed in later sections, for the data analysis, FRF provided limited information due to high non-linearities of the locomotive cab. The non-linearities result from the cab having a complex structure. Each part of the structure has an effect on the other. This causes problems in deciphering where the dominant inputs are located.

The last measure that was considered for the data analysis was coherence. The coherence function, defined as

$$\gamma^2 = \frac{G_{xy} G_{yx}}{G_{xx} G_{yy}} \tag{3.5}$$

is a measure of the causality between the input and output of a system as a function of frequency. The auto spectrum and cross spectrum measures in Eq. (3.5) are as defined in Eq. (3.1) and Eq. (3.3). Coherence gives the percentage of the measured output power signal that is due to the measured input power signal at each frequency. A coherence value of unity indicates that there is perfect causality between output and input, i.e., output is completely caused by the input. If the coherence is less than one, then one of the following conditions could exist:

1. There is an unmeasured input in the system
2. There are non-linearities in the measured signal
3. The output or input signal-to-noise ratio is low
4. There is leakage due to a non-periodic signal

To date there has not been a systematic way to determine the source and magnitude of uncorrelated content contaminating measurements. A study by Cobb and Mitchell [25] presents a systematic procedure using a three-channel measurement technology to determine the sources and magnitudes of measurement noise. This study demonstrates how having low coherence measurements from an experiment does not necessarily signify non-useful data.