

Chapter 2

Vibration Test Setup

This chapter describes the test setup of the locomotive cab that was studied throughout this research. First, the cab configuration and its installation at the Advanced Vehicle Dynamics Laboratory at Virginia Tech are discussed. Next, the actuation system used for emulating the vibration inputs to the cab is described. This is followed by a description of the data acquisition system and the data analysis techniques that were used.

2.1 Cab Configuration

The plan view and side view of the locomotive cab that was tested throughout this research are shown in Fig. 2.1 and 2.2, respectively.

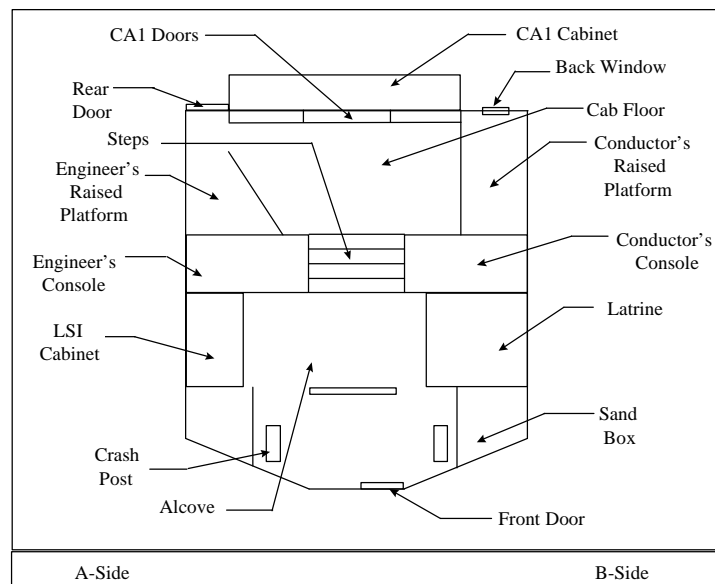


Figure 2.1 Plan View of Locomotive Cab

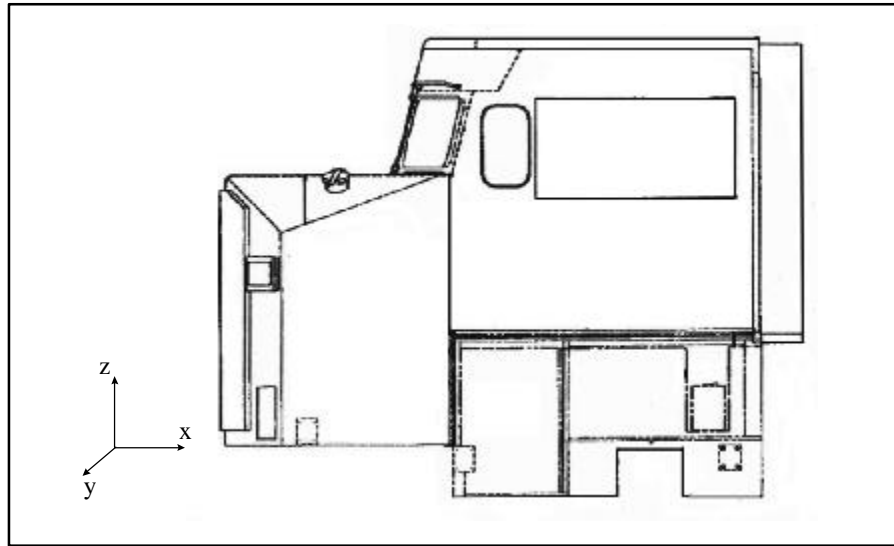


Figure 2.2 Side View of Locomotive Cab

The entire structure weighs approximately 22,000 lb and the dimensions were 16-ft long, 10-ft wide, and 10-ft high. The cab front section, known as the "nose cab," is constructed predominantly from 0.375-in steel. Inside the front door there is a small area containing the crash posts, which are large steel post structures used to support a head-on collision with another locomotive or a very large object. An internal door is used to separate the immediate entrance area from the remainder of the cab, which provides better sound and temperature isolation. Beyond the internal door, a lavatory is located to the right and a rack for mounting electronic equipment (called an LSI rack) is located to the left. The test cab did not include any of the electronic equipment that is normally installed in the LSI racks or elsewhere in the cab. Most of the internal cabinetry is made of 0.0625-in sheet metal or molded plastic.

The area between the lavatory and LSI racks is called the "alcove." This area leads to a set of three steps that connect the alcove to the operator cab, which is located approximately two feet above the alcove floor. Immediately to the right and left of the steps are located the conductor's and engineer's consoles, respectively. Each console consists of a plastic counter

top, communication equipment, and LED displays for running the locomotive. Several large side windows and a windshield surround the operator cab. The back wall of the cab consists of a small door that leads to a walkway (not included in our test cab), an electronic cabinet (called CA1) that is separated from the cab by a tri-fold door, and a small window. The cab floor is made of 0.125-in sheet steel that is plug-welded to a tubular substructure. This structure is the skeleton of the area that is located directly underneath the operator cab. This area (called the "air brake cab") houses the air brake and HVAC equipment. A foam rubber mat of approximately 0.25-inch thickness is glued to the cab floor to provide cushion (for operator comfort) and damping effect for vibrations. The engineer's and conductor's seats are located on a raised structure to the right and left of the operator cab. The roof of the cab is made of thin-gauge steel with supports placed at approximately every 16 inches. A thin damping material is installed between the supports to reduce vibrations of the roof plate.

As previously mentioned, the area beneath the cab is the air-brake compartment. Plumbing, air conditioner, ducts, and various other components are located in this compartment. This equipment was not included in our test cab, but weights were included to emulate the affects of the actual equipment. The air-brake compartment is constructed with 4-in x 4-in box tubing in a rectangular configuration. The air brake compartment and the front cab structure are welded to the sill plate, which is constructed of a 1-in thick plate spanning the cab length and width. The sill plate is in turn welded to I-Beams (sills), which are the main support.

2.2 Cab Installation

The cab is placed on four Goodyear airbags, model # 1B14-350, in the configuration shown in Fig. 2.3. Each airbags 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. 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.

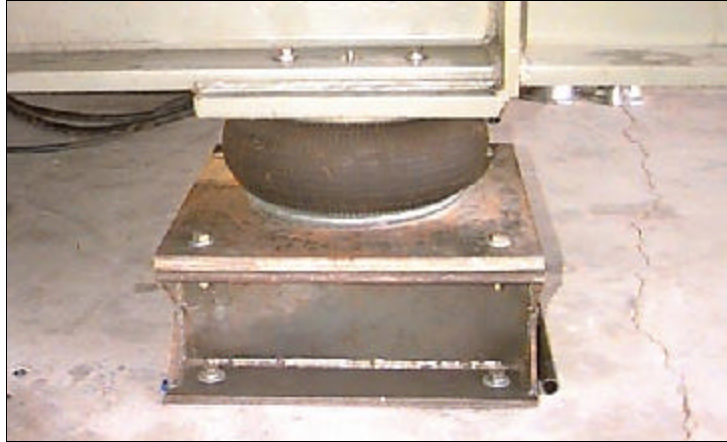


Figure 2.3 Goodyear Airbag Installation

2.3 Actuation System

In order 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 is manufactured by Material Testing System (MTS). A hydraulic power supply, model # 502.020, similar to the one shown in Fig. 2.4, was used to provide fluid to the manifold at a rate of six gallons per minute (gpm) and with 3000 psi pressure. This pump was used because it supplied the required rate and was available for our use. A model 263 hydraulic service manifold, shown in Fig. 2.5, 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.

A hydraulic actuator, as shown in Fig. 2.6, with a force capacity of 2000 lb. was used to shake the cab. The MT 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.

The hydraulic system is controlled by an MTS model 407 controller, shown in Fig. 2.7. 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.

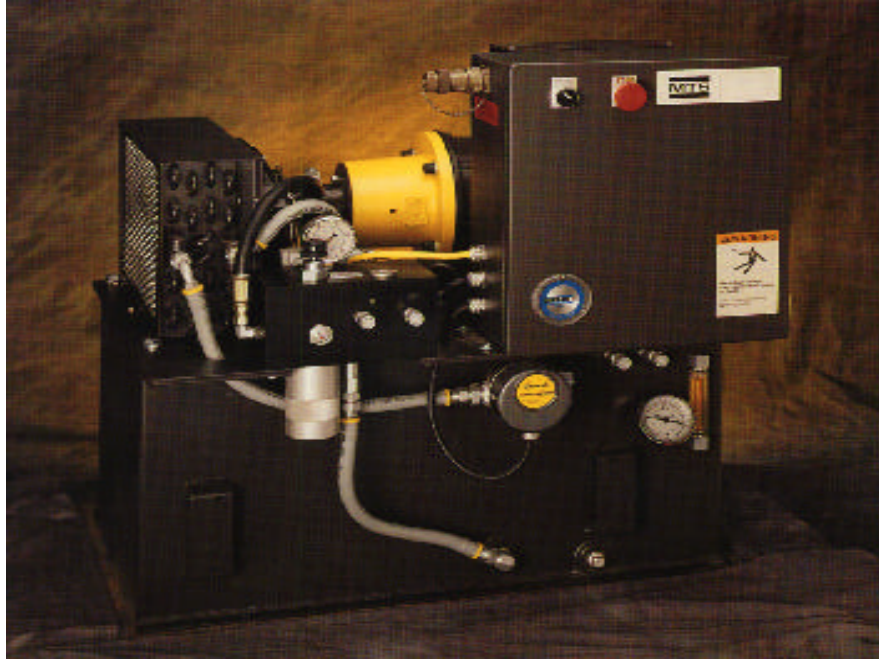


Figure 2.4 MTS 506 Series Hydraulic Power Supply [28]



Figure 2.5 MTS 263 Hydraulic Service Manifold [29]

2.4 Actuator Setup

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 vibration energy flow 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. 2.8, the hydraulic actuator is mounted between the lab floor and a short, heavy needle beam that is added to the sill structure.

The actuator is solidly bolted to the floor and the cab such that it is not subjected to any free play in extension or compression. The swivel ends of the actuator accommodate any misalignment that may exist between the top and bottom installation. Therefore, the force applied to the cab will be in a purely vertical direction.

To determine the most suitable location for the load input, the actuator was tested at the four corners of the cab, near the attachments to the sill. At each corner, the response of the cab to the input was evaluated in terms of how efficiently the cab was excited by the actuator and how well the cab responded to emulated field data. This analysis indicated that the B-Side, aft attachment would be the most suitable location for exciting the cab. At this location, we were able to excite the cab fairly efficiently and the interior noise and vibration closely resembled actual field measurements. This was determined by comparing the data with the BBN data. BBN was a company that GETS hired to test the cab for noise and vibration levels.

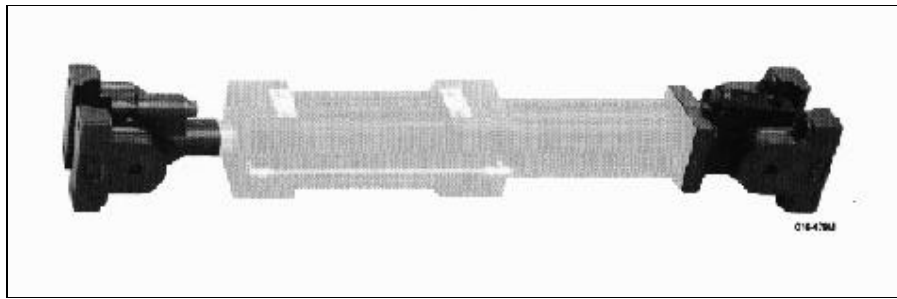


Figure 2.6 MTS 249 Actuator with Swivel Ends [30]



Figure 2.7 MTS Model 407 Servo Hydraulic Controller [31]

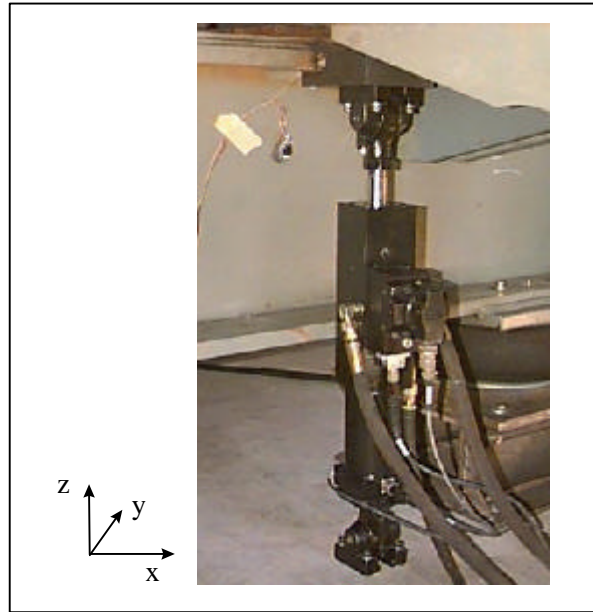


Figure 2.8 Actuator Installation on the Locomotive Cab

2.5 Excitation Input

The next step involves determining what type of signal is needed. The cab is excited with various types of input, including random, pink signal, and pure-tone input. The random excitation provides nearly the same effect as the field input, while the pure tone is used to find the cab response at individual frequencies. The sine random input combines the effect of random and pure tone input to emulate the peaks that are observed in field data, such as the peak at 35.0 Hz due to the second harmonics of the diesel engine. In each case, the intensity is properly adjusted to duplicate the noise and vibration levels observed in field operation.

2.6 Data Acquisition System

The data acquisition system used for vibration measurements consisted of accelerometers, a data acquisition system, and an HP workstation. The accelerometers, shown in Fig. 2.9, were provided by PCB Piezotronics, Inc. [36]. The accelerometer, model number 333A, has a voltage sensitivity of 100 mV/g, along with a measurement range of ± 50 g peak. The accelerometers are capable of taking measurements in the frequency range of 1-1000 Hz. The accelerometers were mounted to the cab using either single axial or tri-axial mount blocks with hot glue. The requirement for using hot glue is for the application temperature to be below 250 ° F. Figure 2.9 shows a tri-axial setup for the accelerometers.

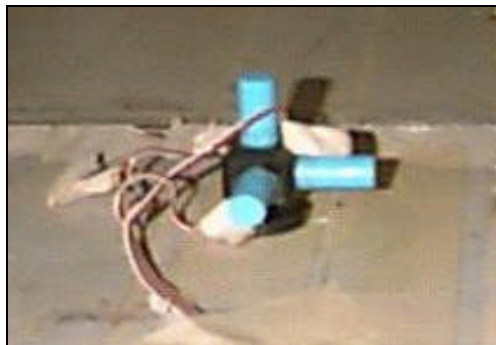
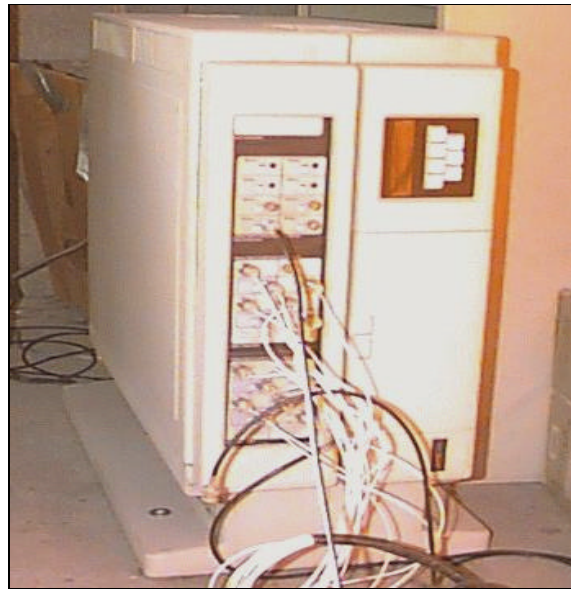


Figure 2.9 PCB Accelerometers Used for Vibration Measurements

An HP Series 300 workstation and a Zonic 7000 data acquisition system are depicted in Figs. 2.10 (a) and (b), respectively, were used to acquire, filter, and store the data. The Zonic 7000 data acquisition system is suited for applications in multi-channel real-time signal processing, multi-shaker modal analysis, acoustic analysis, and structural analysis. The signal processing capabilities provide 4-1000 parallel data acquisition channels, built-in 120 dB/octave anti-aliasing filters, variable FFT block size up to 8K, swept sine, and order tracking. All of these capabilities allow for frequency analysis ranges up to 150KHz, real-time analysis rates to 20 kHz, and linear spectrum, power spectrum, auto spectrum, cross spectrum, frequency response function (FRF), and coherence measurements.



(a)



(b)

Figure 2.10 (a) HP Workstation and (b) Zonic 7000 Data Acquisition

2.7 Data Analysis

The Zonic data acquisition system is set up such that it computes the auto spectrum, FRF, and coherence of the acceleration measurements. The Zonic system, however, can be set up to reduce the data to many other forms depending on the testing need. 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

$$G_{xx} = \frac{2}{k} \sum_{k=1}^k X_k^*(f) X_k(f) \quad (2.1)$$

where $X_k^*(\omega)$ indicates the complex conjugate of $X_k(\omega)$. The constant k 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 the 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 1 Hz frequency bandwidth yields power spectral density (PSD), which is a good indication of the energy across the frequency spectrum.

The spectrums that will be described in the following chapters are in a different form than shown above. The square root of the auto spectrum was taken in order to have the units in terms of *g*, *in*, and *lb*. The spectrum is defined as

$$spectrum = \sqrt{\frac{1}{n} \sum_{i=1}^n X_i^* X_i} \quad (2.2)$$

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

$$H(\omega) = \frac{G_{yx}}{G_{xx}} \quad (2.3)$$

where G_{xx} is as defined in Equation (2.1.) and G_{xy} indicates the cross spectrum defined as

$$G_{xy} = \frac{2}{k} \sum_{k=1}^k X_k^*(f) Y_k(f) \quad (2.4)$$

where $Y_k(\omega)$ is the discrete Fourier transform of the output. The resemblance between the cross spectrum in Equation (2.4) and the auto spectrum in Equation (2.1) 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 Equation (2.3) 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 true cab. The non-linearities come 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

$$g^2 = \frac{G_{xy} G_{yx}}{G_{xx} G_{yy}} \quad (2.5)$$

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 Equation (2.5) are as defined in Equations (2.1) and (2.3). 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

For the locomotive cab, the coherence values were generally poor due to the highly non-linear structure. Coherence should have a value above 0.90 to be “good” for comparisons. Figure 2.11 shows a sample of the coherence measurements. We monitored the coherence values only to determine gross errors in our measurements.

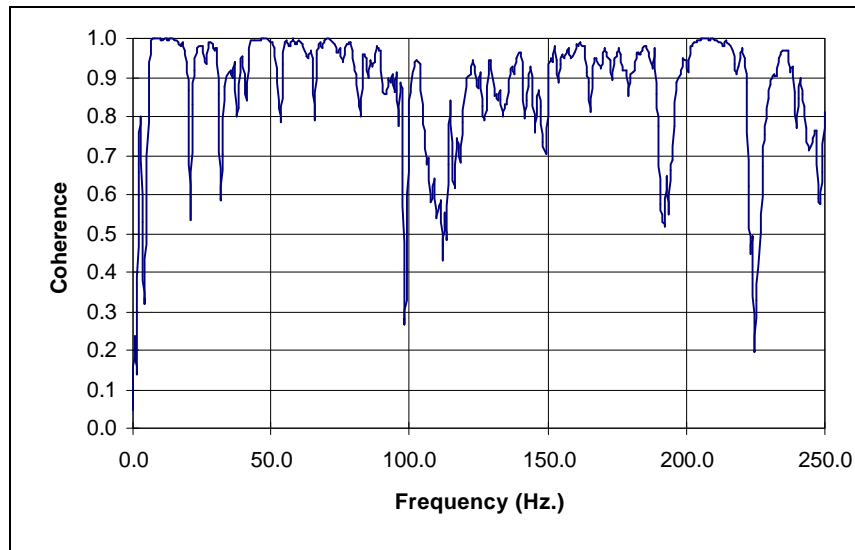


Figure 2.11 Coherence Plot Center Lower Floor

In analyzing the data in the following chapters, the input force and displacement spectrums will be needed. The assumptions made will be directly due to the input to the

system. The input force and displacement spectrums show that the input was constant. This allows us to assume that the input is not placing any resonance into the output. There is a point in question with the 50 Hz region. This may cause the resonance to be shifted. Figures 2.12 and 2.13 show the input force and displacement spectrums.

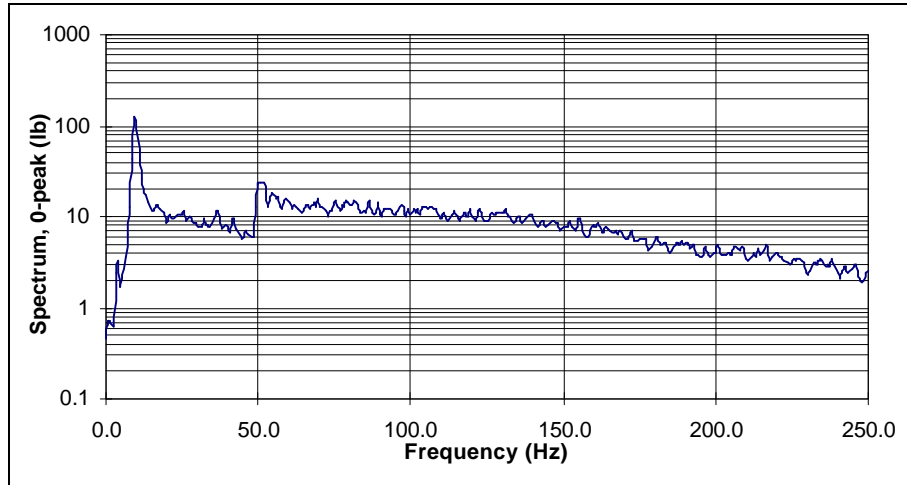


Figure 2.12 Force Plot from the Actuator

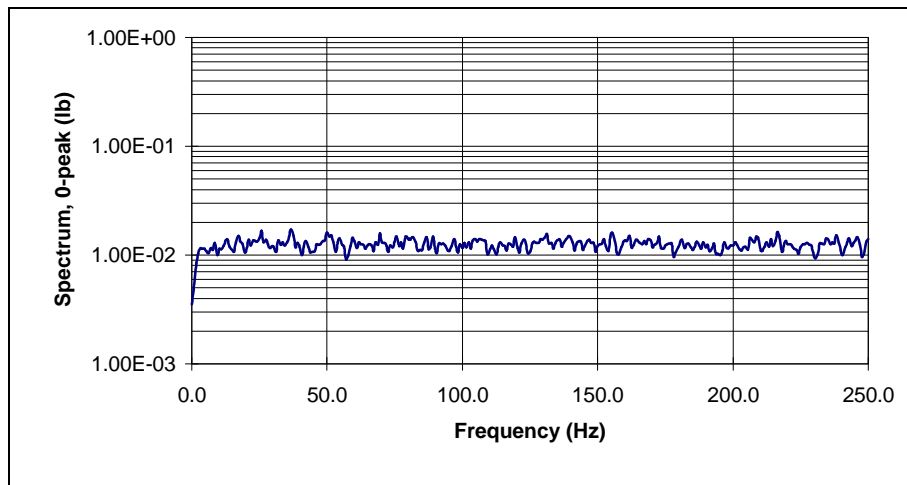


Figure 2.13 Displacement Plot from the Actuator

The system noise level was found in order to determine how the noise affects the data. The noise level is found by running a test where data was collected without any input from the actuator. Therefore, it represents the true noise level of the transducers and data acquisition system. The maximum system dynamic range is computed according to the maximum range of accelerometers and the amplifier gain, i.e.,

maximum accelerometer dynamic range: 10 g or 1000 mV

amplifier gain: 10

maximum system dynamic: 100 g or 10,000 mV

Figures 2.14 and 2.15 show the noise level baseline in g's and mV's, respectively.

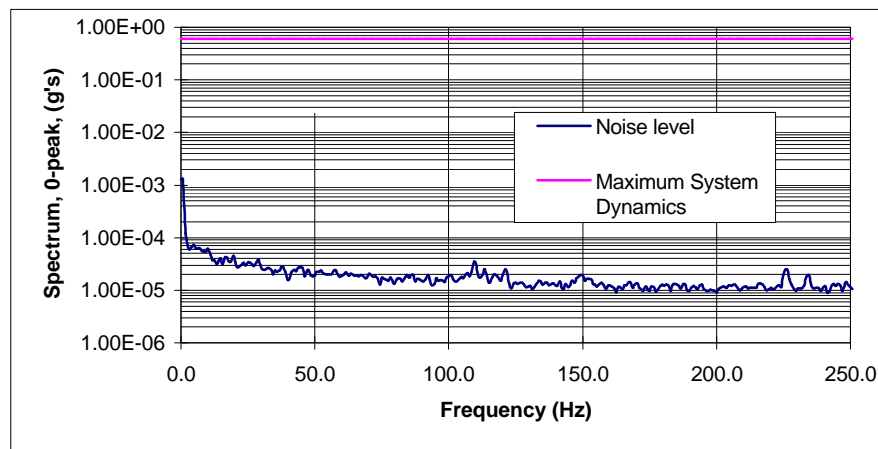


Figure 2.14 Noise Level Baseline Compared to Maximum System Dynamics in g's

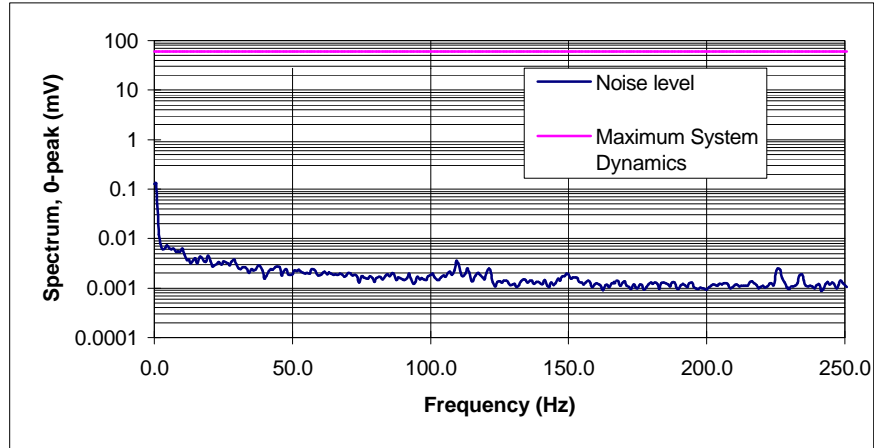


Figure 2.15 Noise Level Baseline Compared to Maximum System Dynamics in mV's

The noise floor was taken from Fig. 2.14 as $4.0e-05$. This value was found by taking the highest peak in the spectrum. The peak due to the dc participation was neglected. All tests run with values in this range will be neglected due to the contamination content of the electronics. The vibration levels observed to this point have been above the $e-3$ value for this reason the electronic contamination has not effected any tests.