An Integrated Measurement to Road Vibration Simulation System

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Abstract

This paper presents an integrated system approach to measurement, compensation and replication of vibrations for product testing. Important issues such as data verification, compensation techniques, the effects of DC offset and physical shaker limits are discussed and a case study is presented for vibrations measured on a Jeep, compensated, and replicated on an electrodynamic shaker.

Introduction

Vibration tests are commonly used to design or qualify products such as electronics, auto parts, and consumer goods, and ensure they can withstand transportation and normal use or occasional vibration shocks. Many vibration tests specify random, sine, or classic shock vibration profiles. These produce vibrations from mathematically parameterized models and result in very predictive and consistent results. However it can be argued that the vibrations observed in the real world are not like any of these. For example many products will survive low level random vibrations for a long period of time, but if the test is started with a shock that moves the parts out of the designed location, then the same random vibrations can cause damage in a short time. For this reason, many manufacturers prefer to use simulated real world vibrations in a laboratory environment to test their products. This is most commonly used in the auto industry.

Simulation of real world vibrations requires the integration of many complex tools. The process is illustrated in Figure 1. The data must be acquired using a portable recording device. Sensor conditioning is often difficult in the field. Without real-time analysis tools it is unknown whether or not the desired vibration characteristics have been captured until the data is returned to the lab. Before the data can be used for simulation , it must be compensated to conform to the physical limits of the shaker and account for DC offset and other factors. Simulation is typically executed using a mechanical shaker. Finally the accuracy of the simulated vibration must be evaluation.

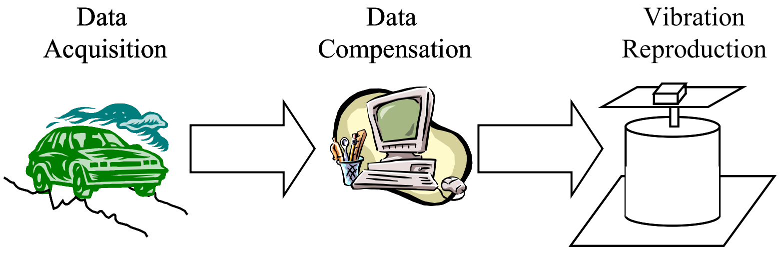


Figure 1. Simulation of measured vibrations requires data acquisition, data compensation, and reproduction with a mechanical shaker

This process is simplified if an integrated system is used that addresses the complexities in a single software environment, using high quality data acquisition, real-time signal processing, and vibration shaker control. This paper illustrates how such a system can be used in an automobile road noise reproduction test case.

Data Acquisition

The first step in simulating real world vibrations is capturing the vibration events. For this study the focus was vehicle suspension vibrations from typical road conditions. A 2000 Jeep Wrangler (Figure 2) was driven at various speeds over reflective road bumps, on a dirt road, and over speed bumps. Acceleration from a 10 mv/g PCB U352C67 accelerometer was recorded at 12,000 samples per second for various time lengths. The time record was streamed to disk and the frequency spectra was computed using a Dactron Photon Dynamic Signal Analyzer and viewed in real time on a laptop (Figure 3) to ensure that the recorded signals met the needs of the study.

Figure 2. Vibration levels from Jeep suspension were measured at various speeds over reflective road bumps, on a dirt road, and over speed bumps.

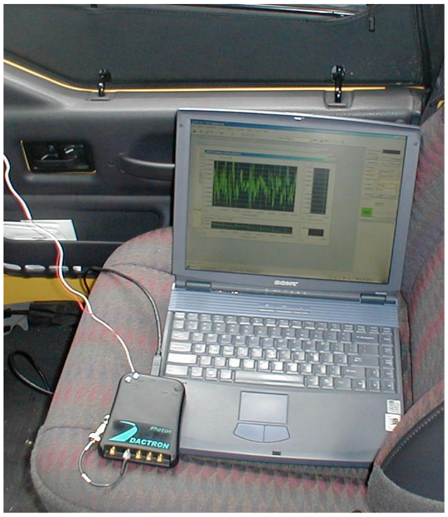


Figure 3. Portable DSA streamed data to disk and displayed real-time spectral and time data to ensure the recorded signals me the needs of the study.

Monitoring the data in real-time is important to ensure that the vibration characteristics of interest are captured during measurement. This also indicates that the sensor and wiring are intact during the field measurement. The time and frequency levels were monitored in real time as the data was streamed to disk simultaneously.

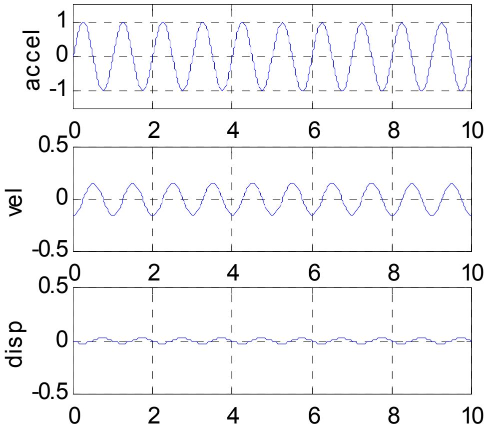
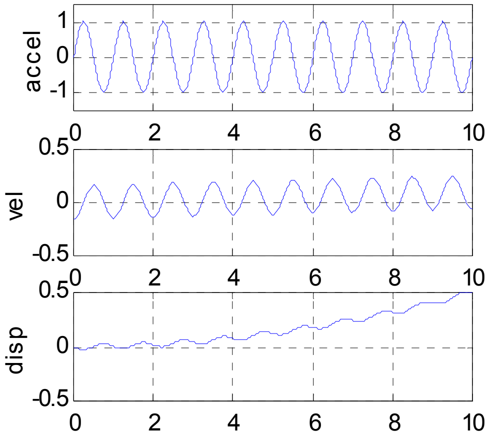
Data Compensation

Data compensation is required before the measured vibration signals can be simulated. Various factors must be considered in this compensation. These include the shaker physical limits, frequency content, DC offset and drift.

The first factor to consider is the physical limitations of the mechanical shaker that will be used to replicate the vibrations. Electro-dynamic shakers typically have a stroke length on approximately 1 inch or less depending on the size. Hydraulic shakers can have significantly larger stroke. Both types of shakers also have velocity and acceleration limitations. With these limitation, not all vibrations measured in the real world can be simulated in the lab.

The next factor to consider is the frequency content of the vibration signal. A measured signal can contain significant low frequency energy due to large displacements from road contours and hills, and vehicle dynamics such as roll, pitch and yaw. These vibrations are typically below 1 or 2 Hz and may have large displacement levels that are beyond the shaker limits. In many cases these low frequency vibrations are not of interest and can be removed without significantly changing the nature of the vibrations.

DC offset and drift will also affect the vibration reproduction. If there is any finite DC offset as a result of calibration or thermal drift then the displacement will exhibit a trend that will exceed the shaker limits. This is a fundamental result of mathematics. The vibrations are typically measured in the acceleration domain. The velocity and displacement are the first and second integral of the acceleration signal. To illustrate this point, Figure 5a shows a sine wave (accel) with no offset and the first and second integral (vel and disp). Also shown is the symbolic equation that represents these graphs (neglecting the constants of integration). The displacement graph has zero mean and is perfectly suitable for vibration replication on a shaker. Figure 5b shows the same sine wave with a 1% DC offset in the acceleration plot. The effects in the velocity and displacement are dramatic even with this small offset. Furthermore, the magnitude of the final value offset will grow with time as shown by the symbolic equations below the figure. These results are commonly exhibited in measured data because all measurements will have some finite DC offset.

	
$a(t) = Sin(2\pi * t)$ $v(t) = -\frac{1}{2\pi} Cos(2\pi * t)$ $d(t) = -\frac{1}{4\pi^2} Sin(2\pi * t)$	$a(t) = Sin(2\pi * t) + 0.01$ $v(t) = -\frac{1}{2\pi} Cos(2\pi * t) + 0.01t$ $d(t) = -\frac{1}{4\pi^2} Sin(2\pi * t) + 001t^2$
Figur 5a. Sine wave (accel) with no DC offset and first and second integral (vel and disp) .	*Figure 5b. Sine wave (accel) with 1% DC offset and first and second integral (vel and disp) which exhibit large trends.*

Below is a typical vibration result from the Jeep road test. Figure 6 shows acceleration, velocity, displacement and the auto spectrum of the time record. The acceleration shows several pulses as large as 6 g. The auto spectrum shows significant energy below 1 Hz and as a result of this and possible DC offset and thermal drift there is significant trending in the displacement. The red lines in the displacement graph show the shaker physical limits. This signal must be compensated before it can be used to replicate the vibrations on a shaker.

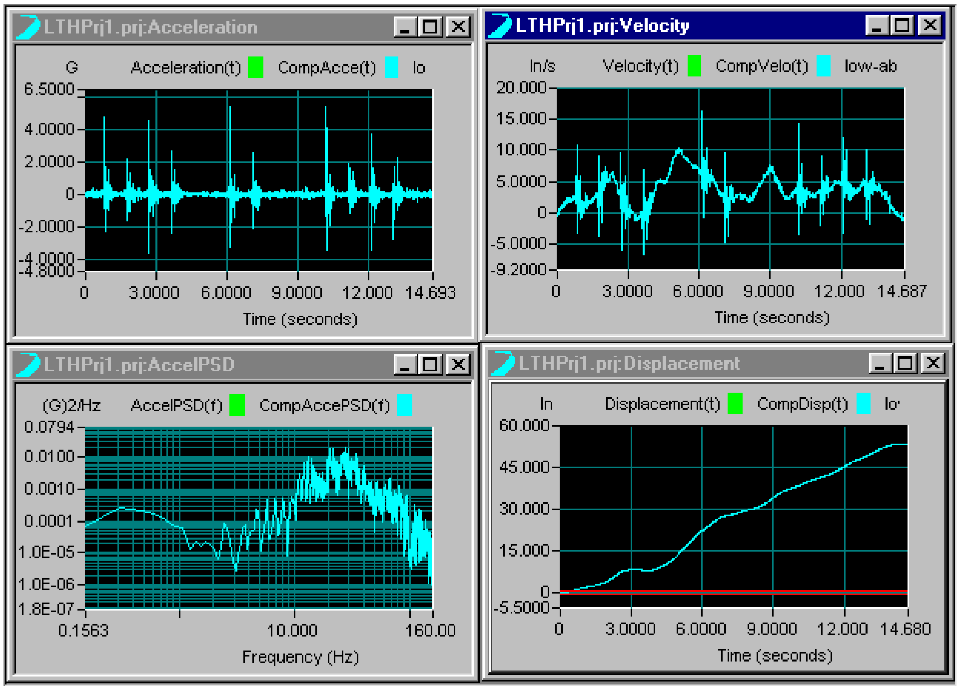


Figure 6. Acceleration, velocity, displacement and auto spectrum of the original recorded Jeep road test vibration.

The Dactron LTH editor software was used to compensate the signal offline on a PC computer. This software provides the compensation techniques necessary to prepare a signal for vibration replication. The data file was directly read by the software. The first step was to apply a high pass filter to remove the low frequency energy below 1 Hz. Figure 7 shows the results after the compensation with the original signal in green and the compensated signal in blue. There is little change in the acceleration signal, but the velocity signal now appears to have a zero mean. The results of the high pass filter can be seen clearly in the auto spectrum plot. There is still an unacceptable trend in the displacement plot.

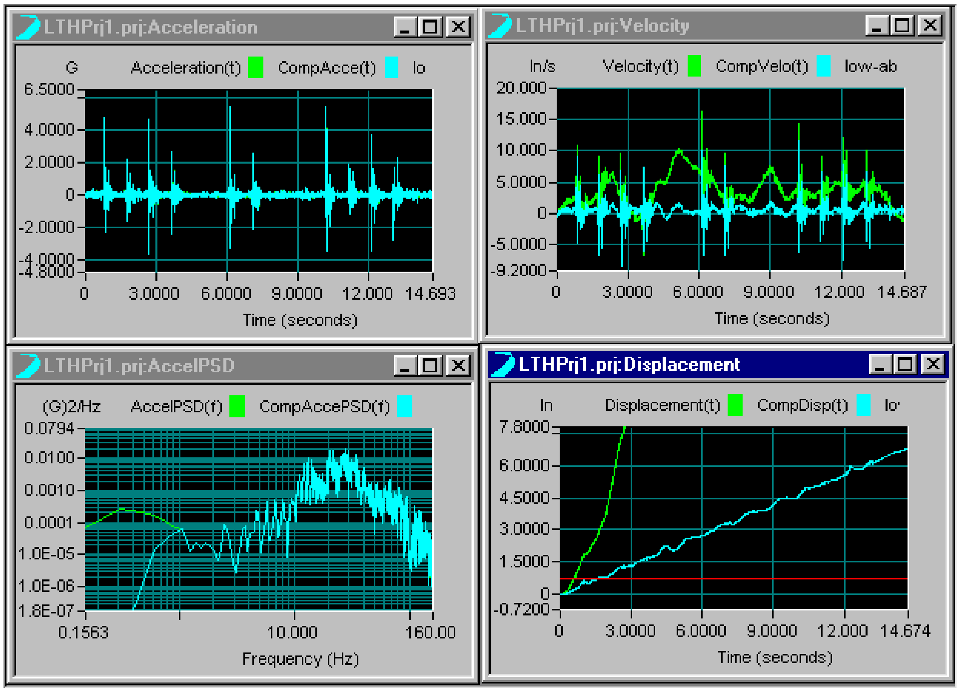


Figure 7. Acceleration, velocity, displacement and auto spectrum after 1 Hz high pass filter compensation.

The next step is to remove the trend in the displacement. The software includes an algorithm to remove displacement trend (velocity offset). Figure 8 shows the results after this compensation. Finally the displacement falls within the shaker limits and the compensated signal can be used for vibration replication.

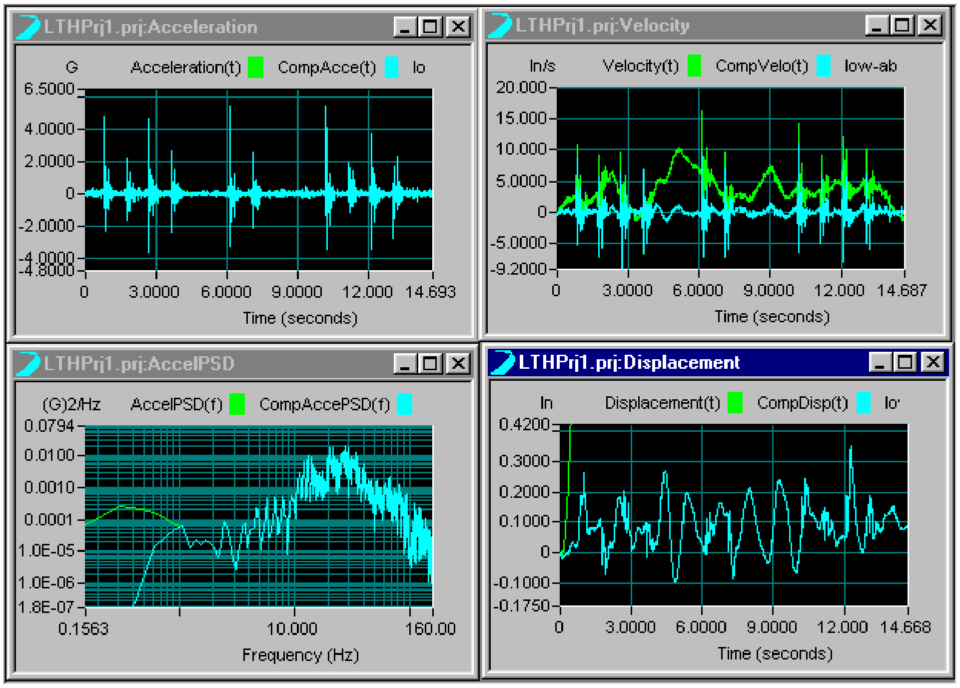


Figure 8. Acceleration, velocity, displacement and auto spectrum after displacement trand (velocity offset) remove compensation.

The steps used for this study are typical for most measured data. Typically the signal must be compensated using a high pass filter, then the displacement or velocity trend must be removed. During this process some engineering judgment must be used because every compensation technique alters the nature of the data to some extent. A good check is to compare the compensated acceleration to the original acceleration. This is shown in Figure 9 for one of the pulse events and very little difference is visible between the two signals.

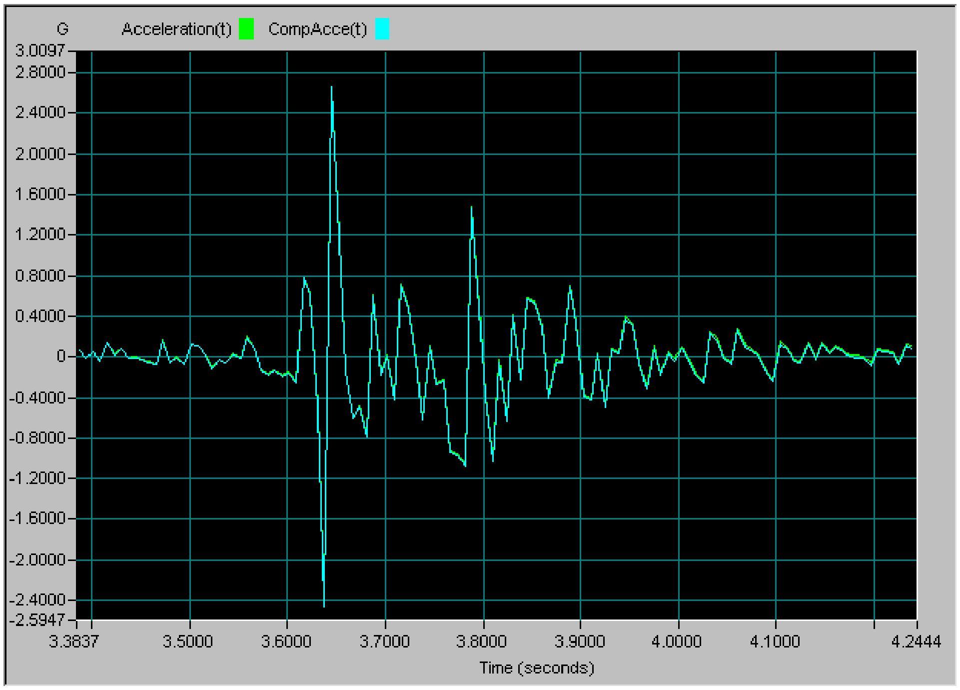


Figure 9. Comparison of original and compensated acceleration signals showing very little difference after the compensation.

Vibration Replication

After the original measured signal is compensated it can then be used for vibration replication on a shaker. The Dactron Shaker Control software uses closed loop feedback control to drive and monitor the response of the shaker as the test is conducted. A Dactron Laser Shaker Controller, an LDS V400 shaker, a LDS PA100E power amplifier, a PCB U352C67 accelerometer with a PCB 482A17 signal conditioner were used for the vibration test (Figure 10). For this case study the shaker was run with nothing on the shaker since the focus was only to verify that the vibration signal could be replicated accurately.

Figure 10. Dactron Shaker Controller, LDS V400 and amplifier used to replicate vibrations.

The Dactron Shaker Control software uses a unique control algorithm that results in precise control even in the presence of changes in dynamic over the length of time of the test. Other shaker control systems implement the control by first measuring the frequency response function of the system, then, based on the target profile and measured frequency response function (FRF), the user iteratively computes the drive signal. The drive signal is then saved to the disk after it is developed. During the test, the drive signal is simply re-played. The disadvantages of this approach are that it is very time-consuming to develop the long drive signal because usually iterative processing is applied. Also during the test, the control system can not respond to any system change. This is essentially an open-loop control technique.

The Dactron Shaker Control system uses a non-cyclic convolution algorithm which continuously computes the drive signal based on system transfer characteristics (Inverse FRF) and target profile. The Inverse FRF can be calculated and stored before the test started, and can be updated adaptively during the test. The advantage of Dactron's approach is that it is a true close-loop control algorithm. The control accuracy is much higher than the "open-loop" approach. .It does not require a pre-computed drive signal. The drive signal is computed based on current system characteristics in the run time. Also, the user can choose different frequency resolution to make the compromise between control accuracy and the responsiveness of the control engine. Also the adaptive rate can be adjusted by the user, from 0% to 50%

The non-cyclic convolution algorithm implemented is illustrated in Figure 11. First the long profile is divided into small blocks. Then based on continuous acceleration measurements, the H inverse function which measures the system dynamics is adaptively computed as the test progresses. The profile blocks and the H inverse functions are then convolved, and the resulting blocks are then combined by overlapping the output blocks.

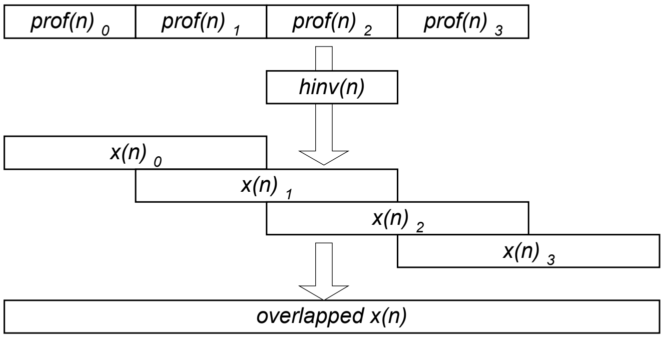
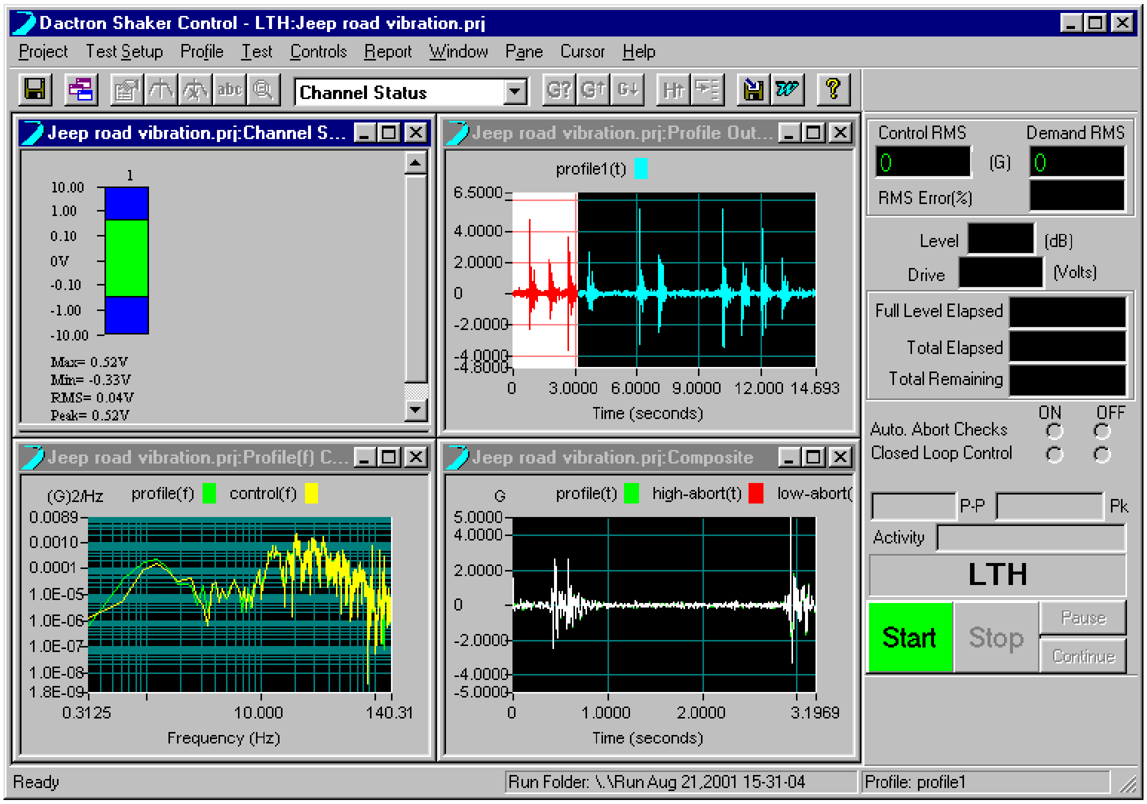


Figure 11. Non-cyclic convolution algorithm used in the Dactron Shaker Control software for vibration replication

The shaker control software interface (Figure 12) provides control and status of the test. The entire time waveform is shown with the current time block in white. A display shows each time block and the associated auto spectrum and compares the profile with the control signal.



Max= 0.52V
Min= -0.33V
RMS= 0.04V
Peak= 0.52V

Ready

Run Folder: \.\Run Aug 21,2001 15-31-04

Profile: profile1

Figure 12. Dactron Shaker Control software user interface.

The waveform was accurately replicated as shown from a comparison of a portion of the profile and the measured control in Figure 13. The error computed by the absolute value of the difference between the profile and the control is shown for a larger section of the profile in Figure 14.

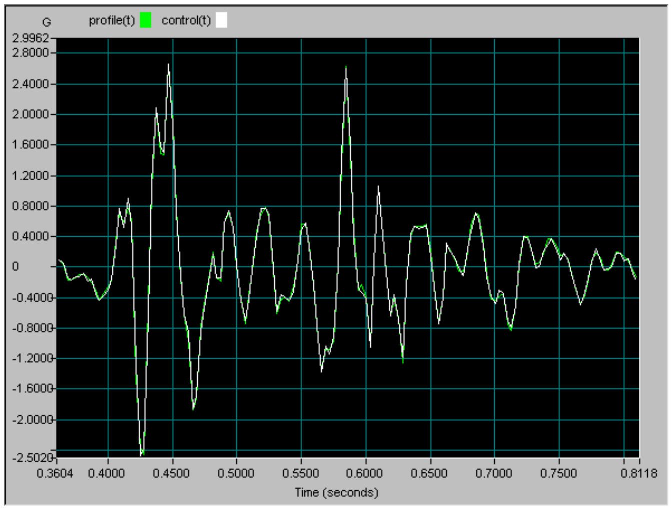


Figure 13. Comparison of Profile and measured control signal from vibration replication.

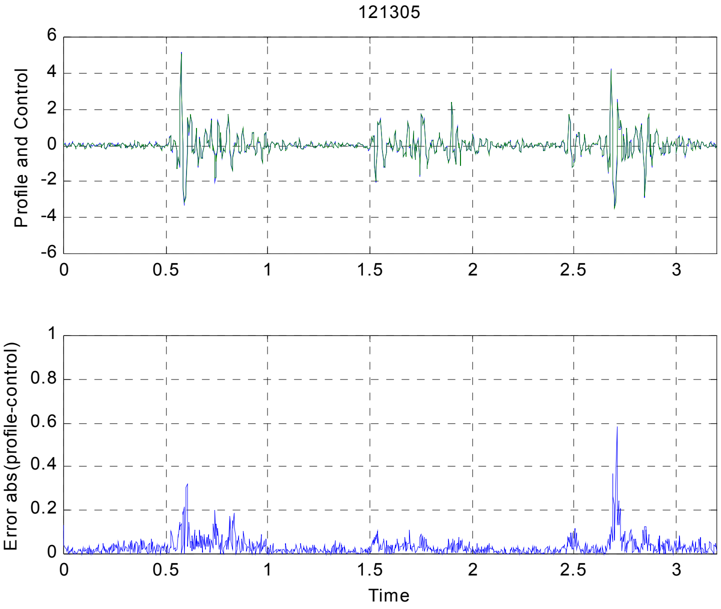


Figure 14. Error between profile and control signals computed by absolute value of profile minus control.

Conclusions

This paper presents the results of an integrated measurement, compensation, and vibration replication system. The importance of real-time signal analysis during measurement to ensure that the event of interest is captured was discussed. The need for signal compensation and methods were presented. Finally an advanced adaptive control strategy was presented and demonstrated to produce accurate control on a controller and electro dynamic shaker system. A case study was presented in which vibrations from a Jeep suspension were measured, compensated and replicated on an electro-dynamic shaker.