Forty Years of Use and Abuse of Impact Testing: A Practical Guide to Making Good FRF Measurements

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ABSTRACT

Impact testing first came into common use over forty years ago, once the fast Fourier transform (FFT) was commercially available. Over this period of time, implementation of impact testing has evolved but some of the same problems seem to reoccur. This paper documents the practical guidelines that have evolved, along with some practical examples of what happens when the guidelines are not followed, particularly with respect to overload detection and related errors. In particular, the ADC hardware differences are noted and the distortion problem associated with overloads is thoroughly reviewed. Other issues that are discussed include factors that affect force spectrum, impact hammer calibration, double impacting, use, application and correction for exponential windows and understanding how the time truncation causes leakage for a realistic case involving a lightly damped structural system.

KEYWORDS: Impact Test, Hammer Test, Overload, Exponential Window, Double Impact, ADC Issues

1. Introduction

Impact testing and other related transient testing methods have now been utilized for over forty years. Throughout that time, a few general guidelines have evolved regarding how to handle the common problems that arise from using transient signals. The specific problems of a force signal that has a very high peak to RMS characteristic and a response signal that may have similar characteristics but for most applications have signals that do not decay in the observation time window. These attributes contribute to problems with adjusting the frequency content of the Impact excitation and thus the response to the transient excitation, auto-ranging the digital signal processing hardware and software, capturing the peak signals without the distortion that arises if an overload occurs, double impacts by the force hammer and correctly chosen and applied windows on both force and response signals to identify the primary issues. Many of the guidelines were developed in the 1970s and have evolved to the present time without much recognition that the digital signal processing software and hardware has evolved significantly. While the software and hardware evolution has not changed the guidelines, the impact of the changes in hardware and software greatly affects the use of impact testing, particularly with respect to overloads and overload detection. If good frequency response functions (FRFs) are the goal, recognition of these hardware and software changes must be understood.

2. Background

The development of impact testing predates the first commercial Fourier analyzer system. In the mid-1960s, the mathematical properties of the integral and discrete Fourier transform were well known but its applications were limited until the fast Fourier transform (FFT) was developed and published. Much research work had already been done and published information regarding digital signal processing (DSP) and windowing had begun to be available from groups like the US Air Force Research Lab (US-AFRL). The equations for the numerical estimation of FRFs and coherence functions along with most DSP concepts, including windowing, were already known. In the mid-

1960s, the potential use of an impact as an excitation signal was being evaluated at the University of Cincinnati via available equipment.

In the 1966-67 time period, a project to develop a transient testing procedure for measuring frequency response functions was initiated as part of a MS thesis. In this initial effort, an impact hammer was used to excite a machine tool structure, with the measurement of the transient input and response on an FM tape recorder. Tape loops of the transient responses were played into a transfer function analyzer (TFA). The input and response signals were processed by using the tracking filters in the TFA to filter and ratio the response to the input signal, thereby estimating the frequency response between the input signal and the response signal. This method proved to be impractical due to signal-to-noise problems.

At about the same time, a single channel, prototype Real Time Analyzer (RTA), made available by Spectral Dynamics, was used to estimate the response spectrum to an impact on the machine tool structure. This spectrum measurement had good agreement with the response spectrum estimated from the measured FRF using the current test standard, the TFA methodology using analog sinusoidal excitation. Based upon this result, a serious effort was initiated to develop a measurement process which would use the newly developed FFT algorithm to estimate an FRF from the FFTs of the digitized input and response signals.

Once the FFT algorithm was published, a hybrid computer, located in Department of Electrical Engineering at the University of Cincinnati was used to develop a software program which used the analog part of the hybrid computer to digitize the force and the response (accelerometer) signals, recorded on an FM Tape recorder, measured by testing a machine tool base. The digital part of hybrid computer was used to compute FRFs and coherence functions using the FFT algorithm. These measurements were compared to FRF functions measured with the analog TFA equipment with good agreement. Unfortunately, the hybrid computer filled a complete room. As a result, only small test objects could be taken into the computer room to be tested in real time. For large test articles, the measurement data had to be recorded on an AM and/or FM tape recorder and this recorded data were processed with the hybrid computer.

Finally, in the late 1960s and early 1970s, small minicomputer based systems, manufactured by Hewlett Packard and the Time Data Corporation, became available. These systems included analog to digital converters (ADCs) along with the mini-computer and a proprietary software operating system that processed the digitized data with the FFT. These systems were portable and could be located next to the test article, making laboratory and field testing practical. These systems made impact testing possible and practical leading to one of the first publications in 1972 regarding the approach to testing a mechanical structural system [1, 2].

2.1. Impact Testing Development

Impact testing was investigated during the 1970s [1-4], becoming a mainstream testing technique for the experimental analysis of vibration and acoustics. The portability of the excitation established impact testing as a testing method well suited for trouble-shooting vibration and noise problems, including the development of single reference and multi-reference, experimental modal analysis methodologies. The paper by Halvorsen and Brown [5] in Sound and Vibration Magazine in 1978 summarized many of the practical issues associated with impact testing. Most of the issues highlighted in that article (force spectrum characteristics, specialized windows, multiple impacts, overloads and overload detection, etc.) remain the focus of current impact testing technique. The only commonly used method today not reviewed in the article is the use of a pre-trigger which was not available in hardware of that era. However, it is important to understand that the hardware and software technology of the 1970s has changed and those changes make some of the issues even more important with respect to current hardware and software. The next section will document some of those changes.

2.2. Evolution of Impact Testing Hardware/Software

Impact testing hardware and software involves a number of concepts/issues that need to be considered. This includes anti-aliasing filters, the location and purpose of the anti-aliasing filters, the number of bits in the ADC that are available to quantify the amplitude of the time domain signal, the detection of signals that are too large for the input gain chosen (overloads), the location of the detection of the overloads and the number of simultaneous channels.

The year 1980 is chosen as the crossover point where the hardware began moving toward fewer sampling frequencies with fewer analog filters to the design of the current delta-sigma (or sigma-delta) ADC technology with only one sampling frequency and one analog anti-aliasing filter, relying increasingly on digital filtering. By 1980, most hardware systems had added the ability to pre- and post-trigger, the last piece of hardware and software technology that is commonly used in impact testing today.

2.2.1. Historical Impact Testing Hardware/Software (pre-1980)

Figure 1 gives a block diagram of the typical hardware that was used prior to 1980 for each channel of the data acquisition. It is important to note that there were generally not more than four channels of simultaneous data acquisition in the Fourier transform analyzers of this time period. From the first commercial Fourier transform analyzers, the traditional frontend hardware input utilized a user selectable, low-pass filter (LPF) that was placed before the analog gain portion of the ADC to protect against the aliasing error (noted by location A in Figure 1). This filter was not generally part of the Fourier analyzer during this time period and the user had to choose the LPF based upon the Nyquist frequency that would be used in the ADC. The general rule was to choose the cutoff frequency of the LPF around 80 percent of the Nyquist frequency to eliminate the frequency information above the Nyquist frequency, thus avoiding the aliasing error.

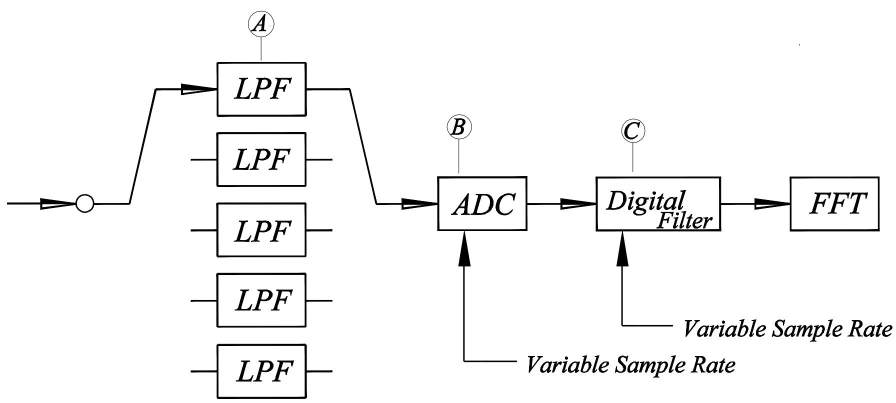

Figure 1. Historical ADC Design

Several design issues are important to note. The analog, anti-aliasing LPF needs to have significant roll-off to prevent the aliasing error based upon the 80 percent, Nyquist frequency rule and the same filter must be applied to all channels of data acquisition to prevent phase mismatch between channels. This requires an instrumentation quality filter to be both adjustable and to have the desirable pass band characteristics. The overload detection was generally a visual indicator on each channel (LED) but the software interface with the hardware rarely provided any feedback to the user. The overload detection circuitry that triggered the visual indicator was in the output of the analog gain section of the ADC or in the input of the digital section of the ADC (location B in Figure 1). The ADC typically had only 10-12 bits together with numerous input gain settings to allow for optimization of the analog signal to the ADC. The digital filter (noted by location C in Figure 1) was limited by the computer performance of the mini-computers available in these data acquisition systems (computer speed, computer word size, computer memory, etc.). For this reason, the digital filter was only used to perform banded frequency analysis within the chosen Nyquist frequency bandwidth.

With respect to impact testing, it is important to note that the analog, anti-aliasing LPF performed a secondary function that is distinctly different in the current ADC design. Since the cutoff frequency of the LPF filter was always set at 80 percent of the desired Nyquist frequency, this filter removed the frequency information (energy) above the Nyquist frequency on every signal before the signal entered the analog gain section of the ADC (at location B). This allowed the input gain to be set according to the signal frequency content that was in the user's frequency band of interest. Note that in the mid 1980's, when DSA manufacturers first integrated the LPF into the frontend, it was not uncommon for the manufacturer to choose a 50% cutoff frequency to protect the quality of the user's data through an additional guard-band.

The high cost of this ADC design had a significant cost per channel that prohibited multiple channel designs. The high cost was a function of both the design of the ADC itself and the requirement for an instrumentation quality filter for each ADC channel.

2.2.2. Current Impact Testing Hardware/Software (post-1995)

Figure 2 gives a block diagram of the typical hardware that is now used for each channel of the data acquisition. The delta-sigma design currently used allows for a digital signal analyzer to have a much lower cost per channel since this design takes advantage of the delta-sigma ADC/DAC design that is widely used throughout many consumer electronics devices (CD and DVD players, HD-TV systems, etc.). The delta-sigma ADC design uses a different process that takes advantage of the bundling of the operations into a single electronics chip along with increased computer speed, computer word size and computer memory to give a superior final result (24 bits) at a much lower cost. This means that more channels can be made available at a lower and lower cost per channel. The changes in the design concept give the same final result but the operation is a bit different.

In Figure 2, the significant difference in the delta-sigma design is the single sampling rate that is required. The ADC is a one-bit ADC with a sampling rate at a very high frequency when compared to structural testing, or even acoustic testing, requirements. The actual sampling rate is often in the 5-10 MHz region, (noted by location B in Figure 2) and is generally chosen at 128 times the *effective sampling rate* associated with the highest *effective Nyquist frequency*. Note that other oversampling rates are used in specialized application areas when the decimated frequency may be chosen to match a particular application need; for example in audio applications where the effective sampling rate is chosen to match the CD audio data rate. As an example, if the highest desired Nyquist frequency is 25 kHz, then the highest effective sampling rate would be 50 kHz. The actual sampling rate would then be 6.4 MHz. The 24 *effective bits* of the delta-sigma ADC, at the highest effective sampling rate, comes via the digital filtering and down-sampling that occurs in the delta-sigma ADC chip beginning with the one bit sampling that occurs at 6.4 MHz. The *user selected Nyquist frequency* is determined by the digital filter characteristics (noted by location C in Figure 2).

The difference in the delta-sigma ADC design that affects impact testing comes from the analog, anti-aliasing LPF that is utilized (noted by location A in Figure 2). Note that the analog, anti-aliasing LPF (at location A) is positioned early in the signal processing and separated from the digital filter that is set by the user selected Nyquist frequency (at location C). In the example cited above, the cutoff frequency of the LPF can be chosen anywhere between 80 percent of the highest effective Nyquist frequency (25 kHz) up to 80 percent of the actual Nyquist frequency (3.2 MHz). Since the digital filter (at location C) removes the high frequency energy in the signal *after* the input gain and quantization, the input gain cannot be optimized as in the historical ADC design. In order to make sure that the characteristics of the LPF do not affect the magnitude and phase characteristics of any data in the frequency range up to the effective Nyquist frequency, vendors will often choose a less aggressive anti-aliasing filter design set at a frequency that is well above the effective Nyquist frequency. This gives an effective anti-aliasing design at a minimum cost per channel.

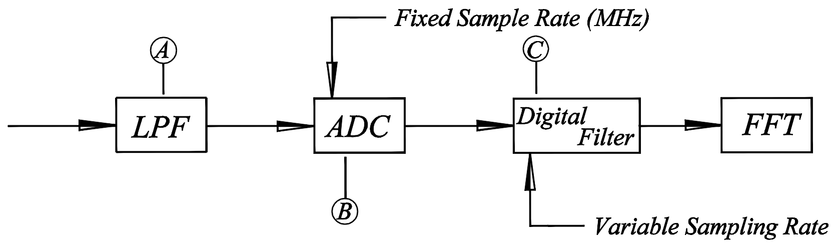

Figure 2: Current ADC Design

Regardless of the oversampling rate, the type of anti-aliasing filter that is used and/or the cutoff frequency chosen by the vendor in a delta-sigma design, the anti-aliasing filter no longer limits the higher frequency energy that may be present in impact testing. At a minimum, this cutoff frequency would be at 80 percent of the highest Nyquist frequency (25 kHz) in a digital signal analyzer. Most structural testing involving impact testing is at 1 kHz or below. While there are no issues involving the aliasing error, the anti-aliasing LPF now allows this high frequency energy from the impact input or response to reach the ADC.

The overload detection in a delta-sigma ADC design occurs at the same location as in the historical ADC design. The overload is detected at the output of the analog gain section of the ADC or in the input of the digital section of the ADC. The problem for impact testing is that the data signals now have energy in the frequency range well above the actual Nyquist frequency desired (100-500 Hz). This means that the analog, input gain on each channel will be set using the higher energy level of the frequency range up to the analog, anti-aliasing LPF. This is distinctly different from the historical ADC design. As an example, the delta-sigma ADC may require that the input gain be set to a plus/minus 10 volt range to satisfy the high frequency characteristics in the data (25 KHz or above) but the final time waveforms may be only a volt or less once the digital filter reduces the data to the desired Nyquist frequency (100 Hz). This means that the choice of the hammer and hammer tip, to limit the frequency content above the desired Nyquist frequency, is critical. This will be discussed further in a later Section concerning auto-ranging, overloads and overload detection.

There are a number of other issues concerning the delta-sigma ADC design that affect impact testing. With the move to a delta-sigma ADC design with 24 *effective bits* (more dynamic range than previous designs), most manufacturers have reduced the number of input gain settings as the number of effective bits in the ADC have increased. Figure 3 summarizes the ADC characteristics of a number of current and past ADC configurations. While the need for fewer input ranges may be true for most steady state testing situations, it is another complication for impact testing since there are fewer input ranges to choose from to avoid the overload problem.

Card	ADC Info	Dynamic Range	Channels Card	Fmax (lowest)	Fmax (highest)	Vmax (lowest)	Vmax (highest)	Number Ranges
HP-35652-A	14-16 bit, conventional	80 dB	1	.195 Hz	51.2 kHz	.0013 V	40 V	46
HP-35652-B	14-16 bit, conventional	75-80 dB	1	.195 Hz	102.4 kHz	.0013 V	40 V	46
HP-35655-A	14-16 bit, conventional	72 dB	8	0.0625 Hz	12.8 kHz	.005 V	10 V	34
HP-35655-B	14-16 bit, conventional	72 dB	4	0.0625 Hz	12.8 kHz	.005 V	10 V	34
Agilent/VTI-1432A	16 bit, delta sigma	80-90 dB	16	10 Hz	23 kHz	0.1 V	10 V	7
Agilent/VTI-1433B	16 bit, delta sigma	74-90 dB	8	0.0954 Hz	76.8 kHz	5 mV	10 V	11
VTI-1435 (1436)	24 bit, delta sigma	112 dB	8 (16)	244 μHz	46 kHz	0.1 V	20 V	8
NI-4462	24 bit, delta sigma	106-110 dB	4	400 Hz	81.92 kHz	0.316 V	42.4 V	6
NI-PXI-4472	24 bit, delta sigma	118-130 dB	8	453.5 Hz	23.2 kHz	10 V	10 V	1
NI-PXIe-4499	24 bit, delta sigma	104 dB	16	435 Hz	92.9 kHz	0.316 V	10 V	4
VTI-EMX-4350	24 bit, delta sigma	125 dB	4	0.864 Hz	270 kHz	0.1 V	20 V	4

Figure 3. ADC Characteristics of Various Current Systems

Other changes that are common in current ADC designs involve a number of trends. Most systems have more channels than previously with 8 to 16 channels very common. More channels means that visual checking of each channel for overload or undesirable characteristics is often overlooked or compromised. To reduce this problem, most overload detection is now integrated with the software so that a hardware overload is communicated to the data acquisition software. This allows for a software auto-ranging algorithm to assist the user in detecting overloads. Current data acquisition designs also offer the ability to pre- and/or post-trigger to make sure that the initial portion of transient signals, like those involved in impact testing, is not missed.

3. Practical Guidelines

There are a number of impact testing guidelines that have evolved that need to be reviewed in light of the hardware and software evolution over the last forty used. In general, the same guidelines still applied but the importance of adherence to the guidelines has changed. The choice of the impact hammer and impact hammer characteristics is still the primary focus but the overload and overload detection issues are maybe more important when trying to make the best impact testing measurement of FRFs. Other concepts/issues that will be quickly reviewed include the application, use and correction of force and impact windows applied to the time domain data, minimizing multiple impacts, being careful with DC voltage shifts and the impact of various background noises on the data.

3.1. Impact Testing Force Spectrum

The factors that affect the force spectrum of the impact hammer are well known, have been thoroughly documented in the past and will only be reviewed briefly in the following discussion. Note, however, that the characteristics of the force spectrum will in general include energy above the user selected Nyquist frequency that is no longer reduced by the anti-aliasing filter of the current, delta-sigma ADC design.

The force spectrum of the impact hammer is controlled by a number of factors. First and foremost, the characteristic of the removable tip used in the impact hammer will define the primary usable force spectrum. A soft tip will spread the applied energy over a longer time period and thus give a lower maximum frequency that can be used. A hard tip will concentrate the applied energy over a shorter time period and thus give a higher maximum frequency. Any characteristic of the impact hammer that affects these pulse characteristics in the time domain will contribute to altering the force spectrum. Common changes are adding mass to the back of the impact hammer, using a "dead-blow" impact hammer (with mass beads inside the impact hammer head), using a larger impact hammer and imparting different velocities with a specific impact hammer will all affect the frequency content. Note that the compliance and surface characteristics of the object that is being impacted will also affect the force spectrum. In particular, a compliant structure with light damping will often make it more difficult to get a single impact. The subject of multiple impacts is discussed in the next Section.

It is important to note that the characteristic of the force spectrum need not be flat in the frequency range of interest as long as a) there is some excitation and b) the structure being tested is essentially linear. An order of magnitude variation in the force spectrum across the frequency range of interest is not uncommon and perfectly acceptable. This is essentially more of a signal to noise ratio (SNR) than anything else. While impact testing can be used for nonlinear system, it is generally not advisable due to the difficulty in getting a repeatable impact. However, for nonlinear systems involving nonlinear damping mechanisms, a single ensemble of an impact and response can be useful for understanding the damping characteristics when a sliding window of data analysis is applied in the time domain.

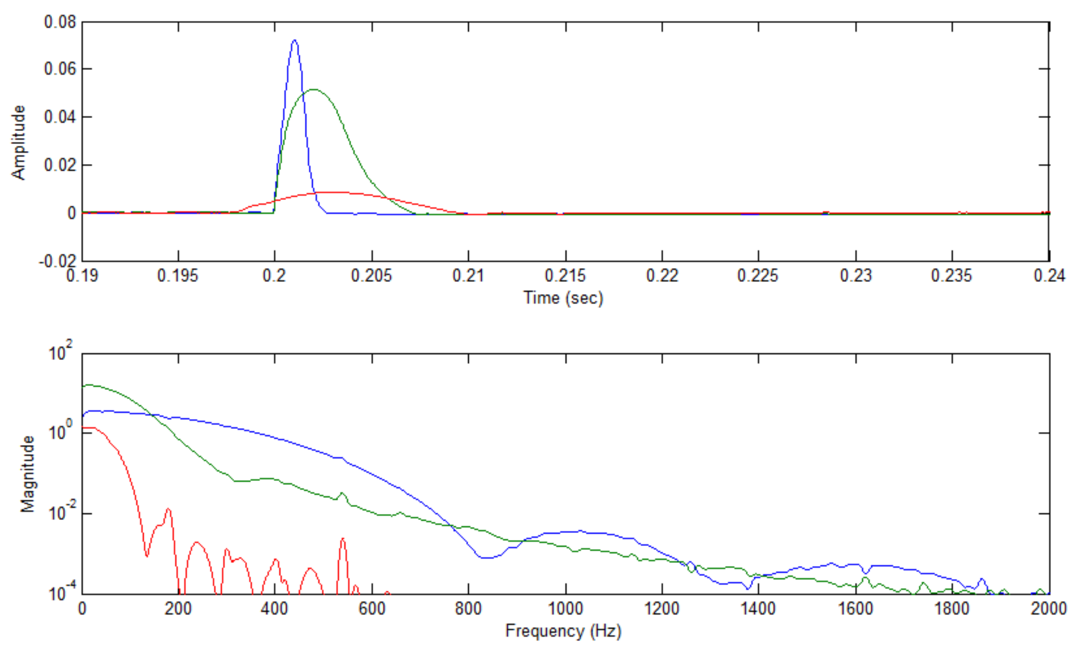

Figure 4: Comparison of Single Impact Energy Distribution

Figure 4 represents the force spectrum for three different hammer tip compliances. Each would have been considered to be suitable for the test object chosen. For this comparison, the same sampling frequency range and input voltage range was chosen for each of the three examples showing the response captured for two different Nyquist frequencies. Based upon Figure 4, it becomes obvious that the informational/energy content that is passed through to the ADC is not limited by the analog LPF and must be removed via the digital filtering process. In addition to the primary energy lobe, significant energy is contained in the signal well above the desired Nyquist frequency.

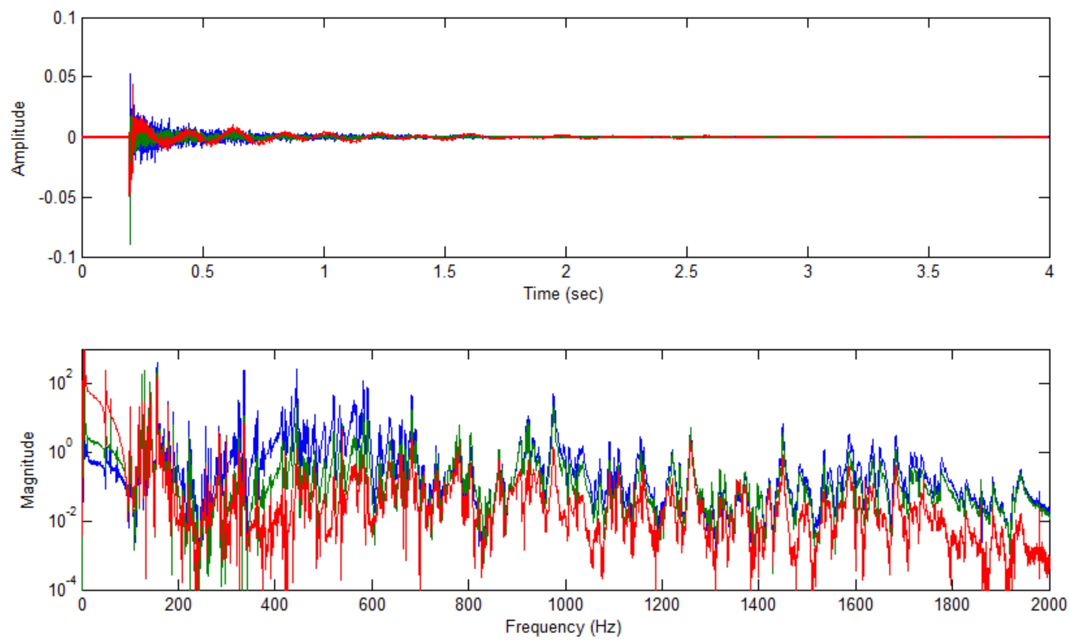

Figure 5: Comparison of Single Response Energy Distribution

As the frequency domain plot in Figure 5 (lower) reveals, the system response includes significant out-of-desired band energy which must be removed by the digital filtering process associated with the user selected Nyquist frequency. However, the voltage range set in the ADC must accommodate this out of band energy. As a result, the use of suitable tip with appropriate compliance and frequency domain characteristics becomes even more critical if optimal sampled/digitized dynamic range data is to be obtained.

3.1.2 Multiple Impacts

From a theoretical viewpoint, multiple impacts can be utilized if the user is very careful and if windows are adjusted appropriately. The practical view, however, is to avoid multiple impacts by previewing the impact and response signals and rejecting any ensembles that show signs of a multiple impact.

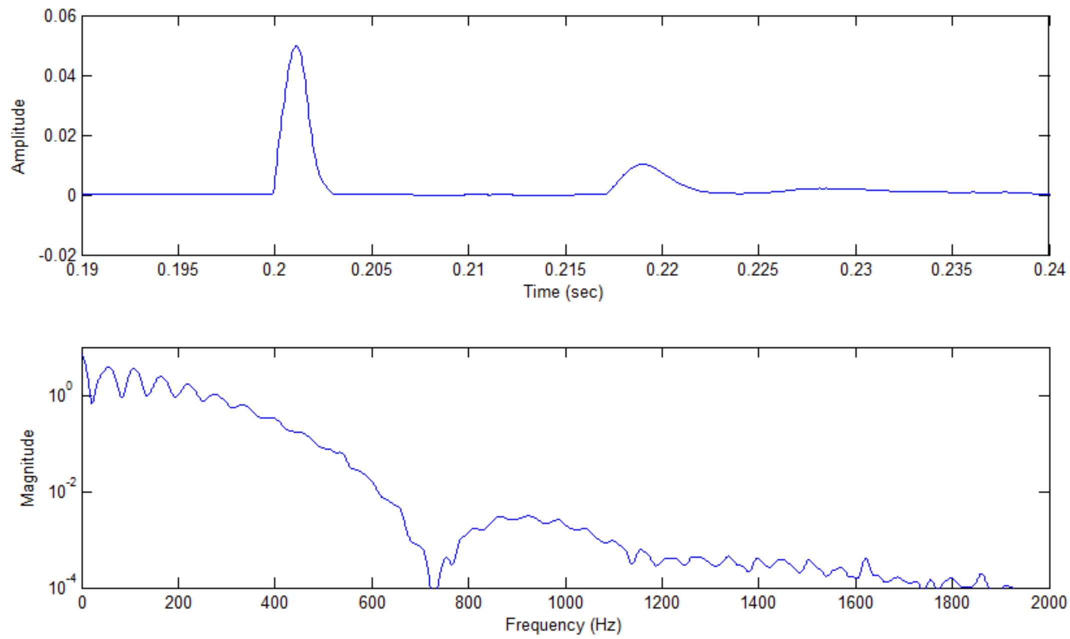

Figure 6: Force Spectrum to Double Impact

Figure 6 shows a typical double impact characteristic in the time and frequency domains for a single ensemble of the force. When double or multiple impacts occur within the acquired data block, zeros in the resulting force spectrum are introduced. In this case, the magnitude ripple or oscillation in the force spectrum is due to the double impact within the block. While the power spectrum (and resulting response spectrum, Figure 7) could theoretically be used in the averaging process, practically, due to leakage, the power spectra are distorted and the ripple effect tends to become visible in the resulting frequency response functions (FRFs). The double impacts manifest themselves as both magnitude and phase distortions in the frequency domain. While no force window was used in this case, the use of a force window when double impacts are present might eliminate the second impact from the measured signal but not from the actual energy that is applied to the structure and not from the response signal.

With respect to the response to a double impact, shown in Figure 7, the deleterious effect is primarily associated with extending the exponentially decaying response in the time domain. This would increase the truncation of the response signal which would directly affect the leakage.

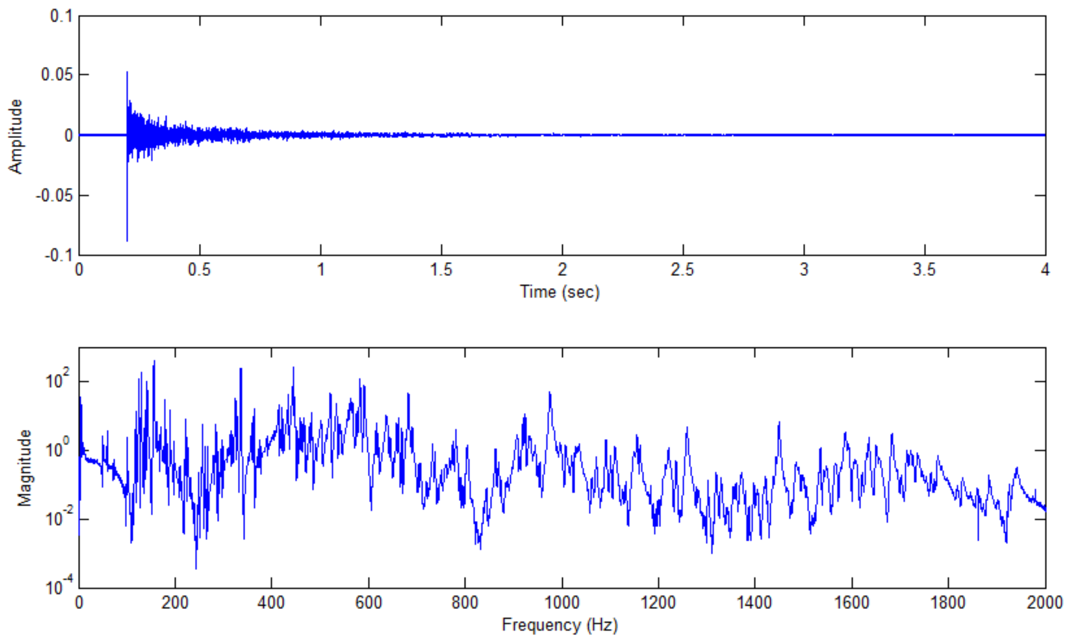

Figure 7: Response Spectrum to Double Impact

3.2. Triggering Issues

It is common to trigger the data acquisition for the impact testing case based upon the characteristic of the force signal. The trigger condition is normally set to a positive voltage and positive slope for the force channel to initiate data acquisition on *all channels*. In order to reduce the possibility of inadvertent triggers to minimal hammer motion and to make sure that all of the force pulse is captured, a pre-trigger is utilized to capture data that happens before the trigger condition is met. If a pre-trigger is utilized, the same pre-trigger should be applied to all channels to avoid the introduction of a time delay between channels and the resulting phase error. The exception to this is when impact testing is used with acoustic response. Based upon different spatial positions of any the microphones, the pre-trigger may need to be different, response channel by response channel, due to the time delays associated with the different distances between the impact location and the microphones.

The top plot in Figure 8 is the force pulse captured with a pre-trigger which in this case is around 0.2 seconds. The amount of the pre-trigger should be kept to a minimum but does not need to be too exact. There are two reasons for this. First of all, the bottom plot of Figure 8 is the impact force after it has been digitally filtered to the user defined Nyquist frequency. Note the oscillation before and after the digitally filtered force. This is part of the energy that should be retained to properly capture the characteristics of the force pulse in the band of interest.

The second reason for allowing the pre-trigger to be longer than the minimum is that this region of the force and response signals is often used for DC offset removal. If a force and/or exponential window will be applied to the data, it is important to remove any DC signal prior to the application of the windows. Otherwise, the window characteristics will distort the DC signal into energy that occurs across the frequency band.

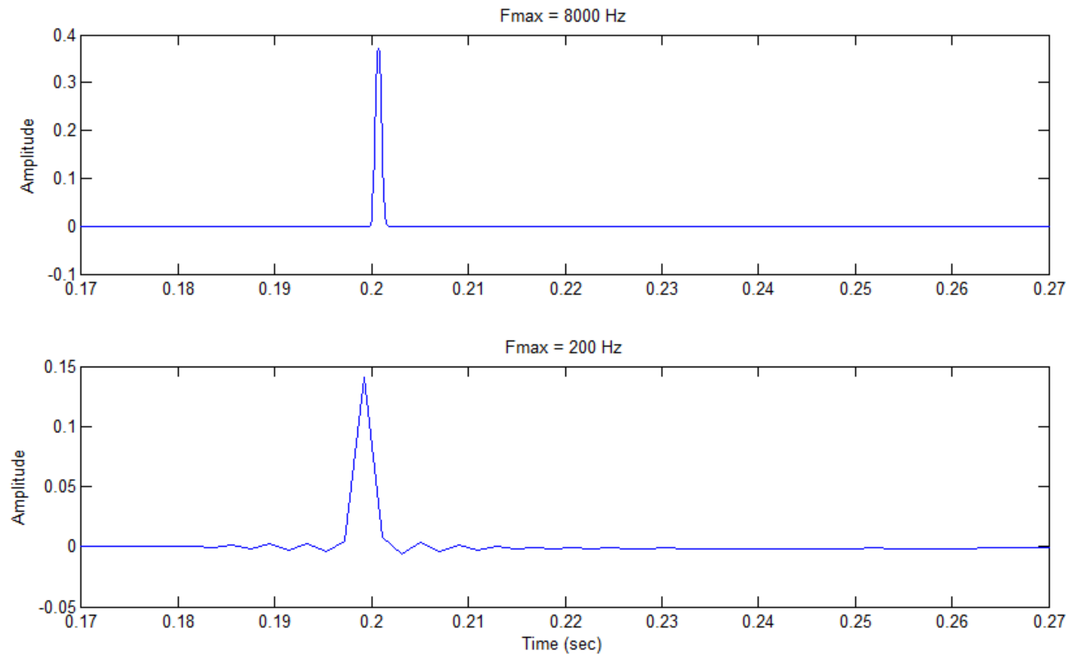

Figure 8: Triggering on the Impact Force – Pre-Triggering

3.2. Overload Issues

The overload problem is one area that has been greatly affected by the delta-sigma ADC design that is now being used in current data acquisition analyzers. Eliminating ensembles that include overloads is one of the most difficult tasks for impact testing with both historical and current data acquisition analyzers. Impact testing generates a high peak to RMS transient input and associated exponentially decaying response signals that may have significant amplitudes in response to the impact. Unless the hammer characteristics and the force spectrum of the hammer are chosen carefully, overloads will occur. Current delta-sigma ADCs no longer limit the frequency content of either signal to the frequency range of interest which contributes to overloads which may be difficult to understand. The difficulty in trapping *near overload* conditions in delta-sigma ADC designs contribute to frequency domain distortion errors that give non-physical FRF data on occasion. This means that relying on the overload detection and auto-ranging algorithms may still allow some significant data errors to occur.

A common pretest procedure, established with the historical ADC design, is to impact at the selected input location and observe the measured time histories of the input and response(s), sampled at a very high Nyquist frequency (essentially setting the digital filter in the current, delta-sigma ADC design to a very high cut-off frequency). In this configuration, the digital signal analyzer is acting as a digital oscilloscope and, with experience, this procedure may make it possible to visually identify some overload conditions. However, in the current, delta-sigma ADC design, it is often difficult to detect the overload visually and it is possible that the hardware and software overload detection will miss the *near overload* condition. This near overload condition may result in a distortion error that can be observed in the resultant FRF data, if the user is carefully watching for it. Unfortunately, the use of larger and larger number of channels in impact testing causes the users to increasing rely on the auto-ranging algorithm and the associated overload detection software and hardware.

However, the current, delta-sigma ADC design makes this overload situation difficult to detect visually. Therefore, users rely on the data acquisition hardware to detect an overload and interact with the software to flag the problem, possibly rejecting the data automatically and/or setting the input gain higher or lower as appropriate. This all begins with the auto-ranging process which will need to be repeated for each time the impact force is moved to a new point. In order to start the auto-ranging and overload detection process, a continuous series of impacts are applied at the input point. This allows the data acquisition to be set to levels that will reduce the potential for overloads. Obviously, during this auto-ranging phase, if a large input occurs, the overload detection hardware allows the data acquisition software to detect the overloads and to reset the input gain on each channel appropriately.

Once the actual measurement cycle begins, if the force channel overloads, then all the channels have to be rejected for that ensemble. If the any of the response channels overload, then the normal procedure is to reject all channels as well. However, if a response channel overloads, then only that ensemble for that channel needs to be rejected. This results in each response channel potentially having a different number of averages. This approach has been evaluated but is rarely implemented as it requires more user interaction.

This potential overload problem is documented in the following figures. Currently, it appears that high frequency overloads (overloads due to energy above the user's frequency range of interest) are causing distortion errors in measured FRFs in most digital data acquisition systems. This phenomenon has been observed in hardware and software systems from more than one vendor.

As an initial example shown in Figure 9, the overload distortion problem can be observed in a typical FRF measurement even when some care is taken in detecting overloads by visually observing the time domain signals. Note the difference in the definition of the anti-resonance noted at location A in the two measurements. More important to note is the phase distortion at location B in the two measurements. The distorted FRF shows a phase loss at the anti-resonance which, physically, should be a phase gain. This was particularly troublesome and notable when trying to work with the characteristics of a physical system in this low frequency region. At first this was thought to be just a graphical plotting mistake involving phase wrapping and unwrapping but this is not the case.

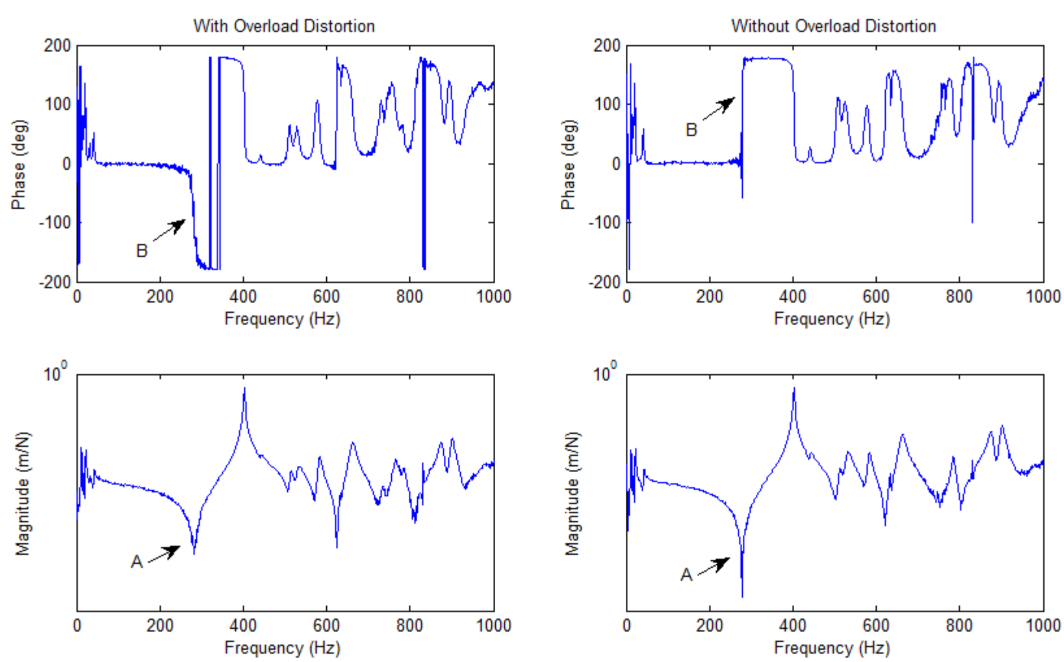

Figure 9: FRF Measurement Exhibiting Overload Distortion

3.2.1. Overload Issues Test Cases

The following figures represent a series of test cases investigating the effect of overload. The data was captured simultaneously by replicating one force (input) channel and one response (output) channel to multiple frontend channels set to different voltage ranges and different frequency spans. Two voltage ranges were chosen, 0.1v and 1.0v, and two frequency spans, 200Hz and 8000Hz. The result is that the four different voltage/span cases for each channel were captured simultaneous.

Figures 10 and 11 represent the time and frequency domain results of the 8000 Hz and 200 Hz spans without overload. The markers A and B on each plot represent the region of the plot that will be emphasized in the following overload figures (Figures 12-17). In many cases, the difference between the overloaded and the non-overloaded measurements will be very slight. In some cases, the difference will only be practically detectable on the full 8000 Hz span. Unfortunately, unless the user explores frequency ranges other than the frequency range of interest, this distortion is not observable. In all FRF cases, only one ensemble is shown to make sure that the resultant distortion is linked to the time domain overload. This results in more noise on the FRF data but clearly shows the distortion in both FRF magnitude and phase.

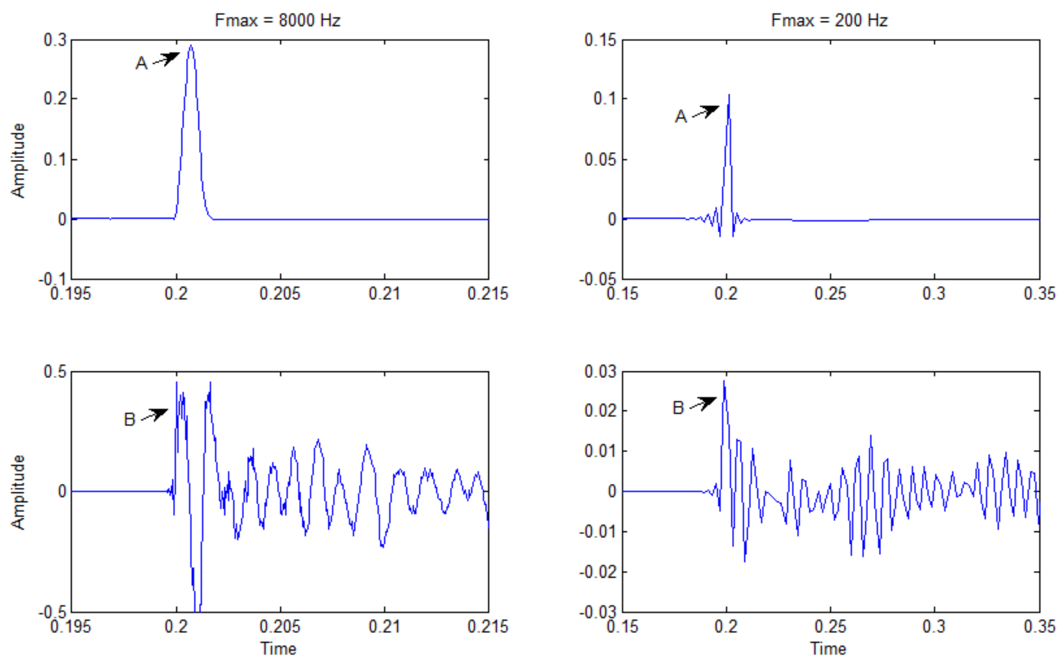

Figure 10: System Input/Response without Overload

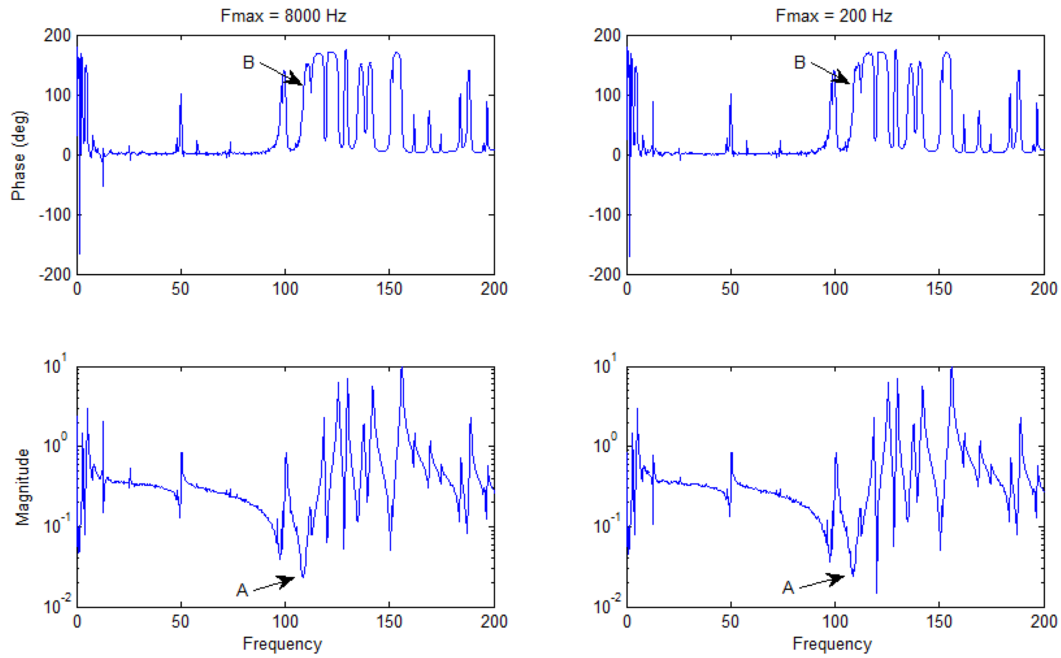

Figure 11: System FRF without Overload

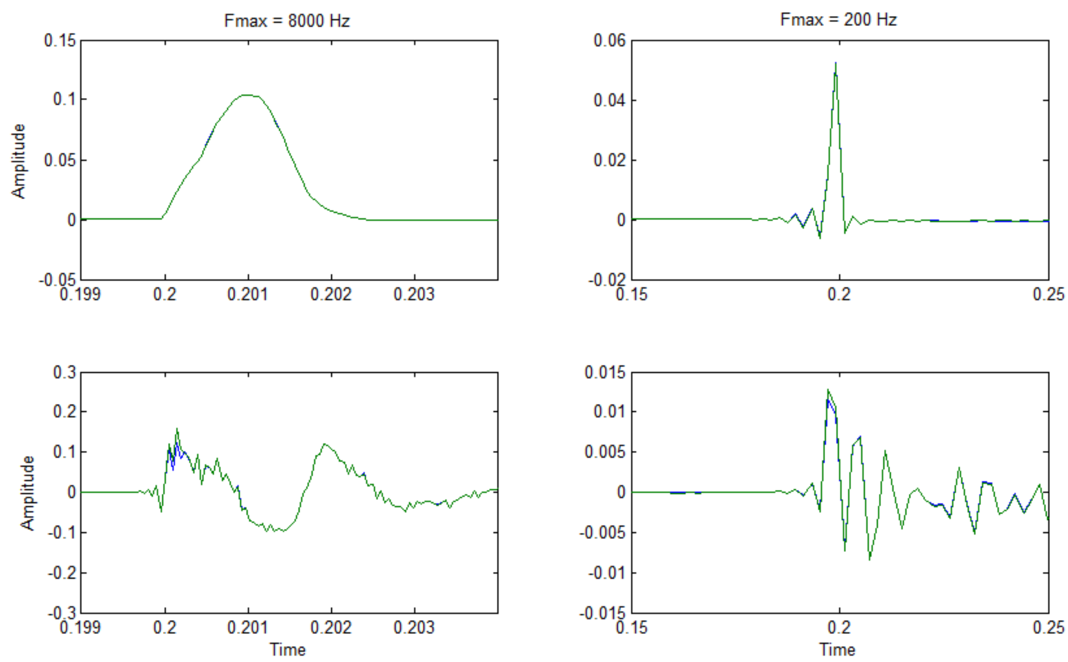

Figure 12: System Input/Output Exhibiting Minimal Overload Distortion

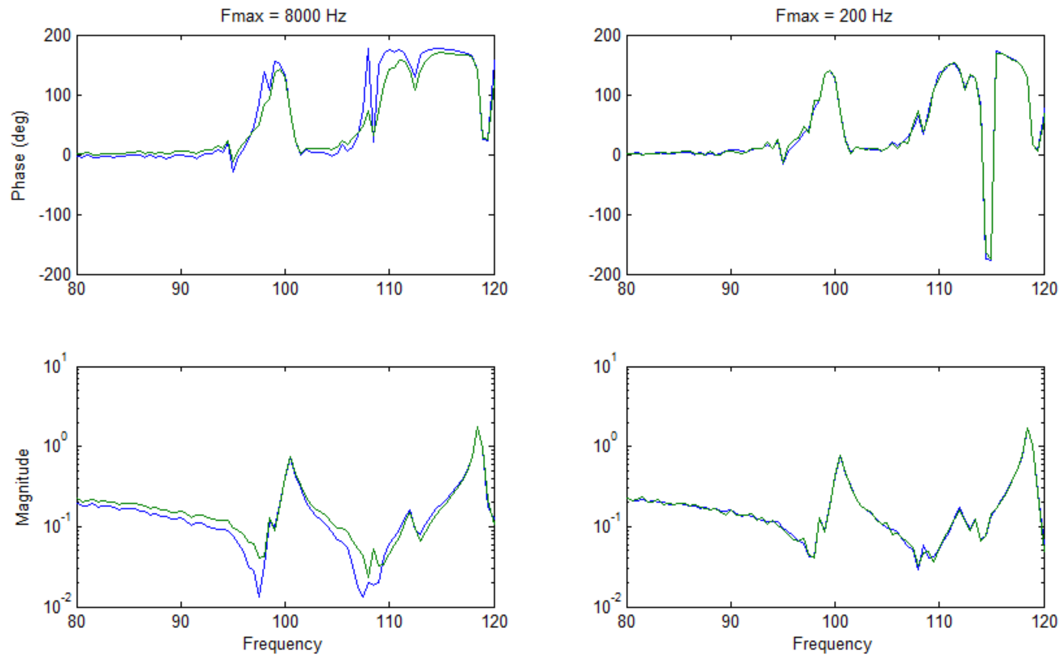

Figure 13: System FRF Exhibiting Minimal Overload Distortion

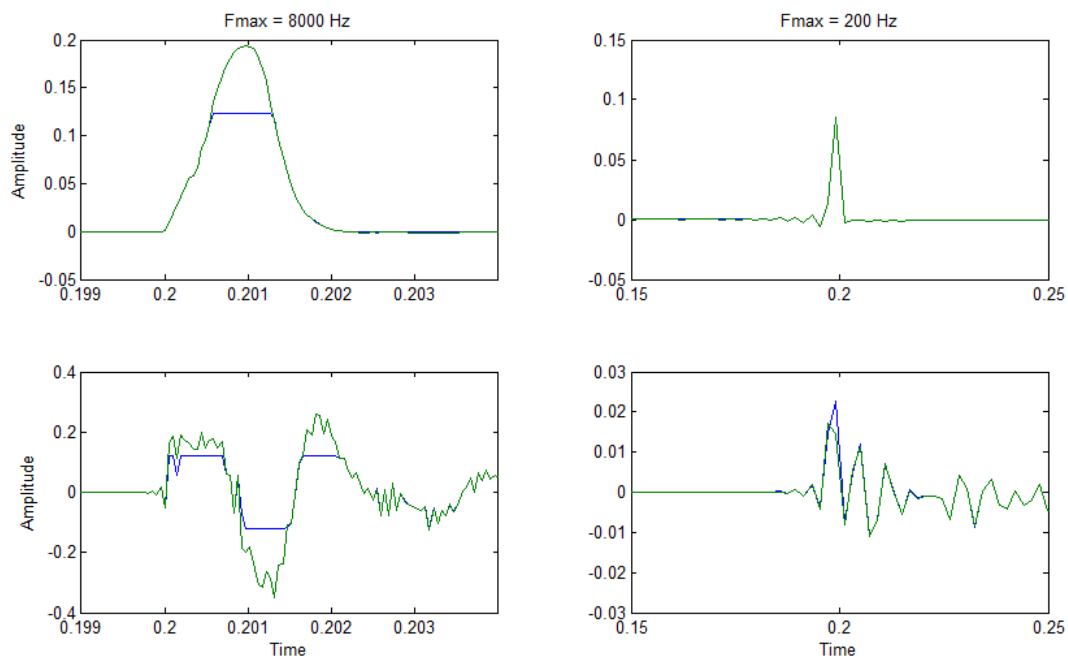

Figure 14: System Input/Output Exhibiting Overload Distortion

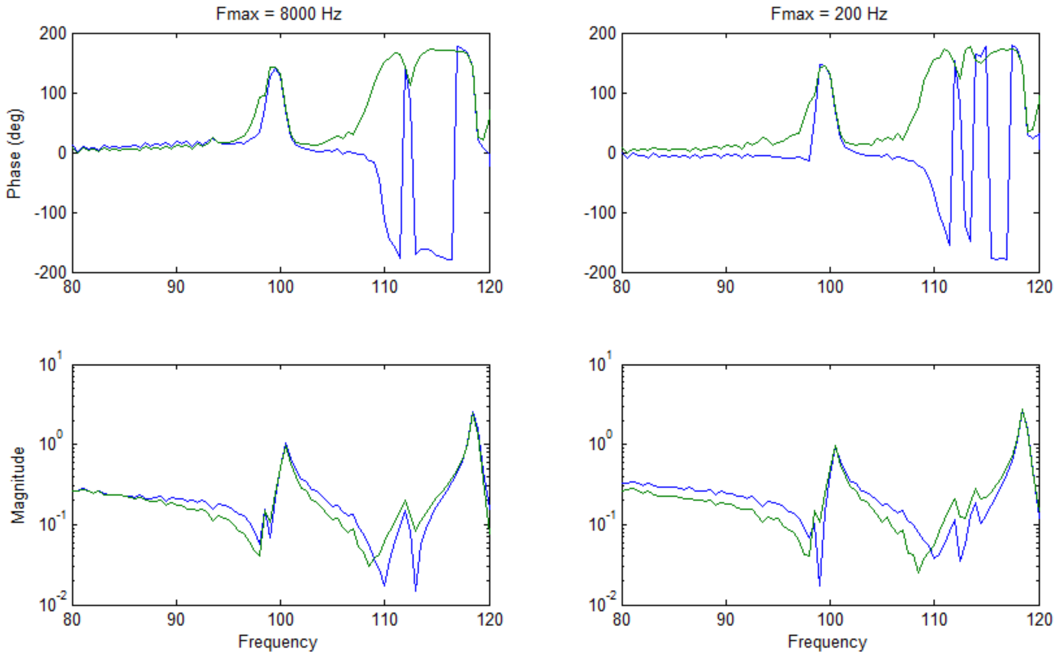

Figure 15: System FRF Exhibiting Overload Distortion

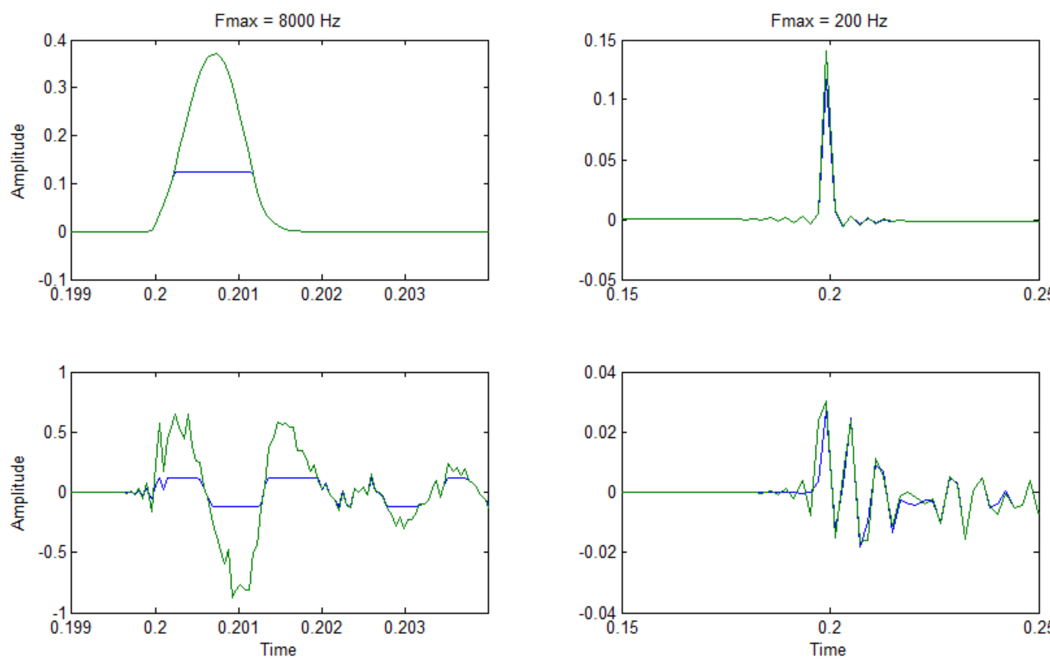

Figure 16: System Input/Output Exhibiting Significant Overload Distortion

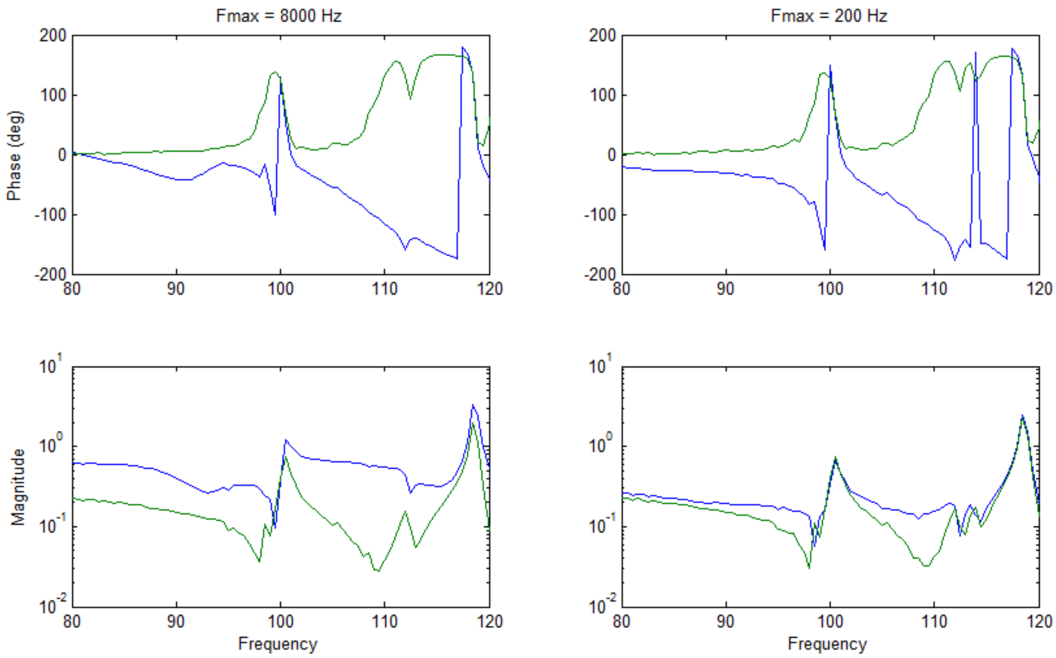

Figure 17: System FRF Exhibiting Significant Overload Distortion

3.4. Impact Hammer Calibration

Current impact hammers involve a load cell that is embedded in the head of the hammer. Even with ideal placement of the load cell, the force that is measured is not exactly the force that enters the structure at the hammer tip. The force measured by the load cell is the force acting across the load cell, which is not equal to the external force acting on the tip of the hammer during the impact.

In order to calibrate an impact hammer, a free-free, rigid mass is impacted with the force vector acting through its center of mass. The external force acting on the mass is equal to external force acting on the hammer tip which is equal to external force acting on the hammer. The force acting on the rigid mass is equal to the mass of calibration mass times is acceleration (Newton's Second Law, $f = ma$). The acceleration of the rigid mass is measured with an accelerometer. The mass line of the (acceleration over force) FRF is equal to the reciprocal of the mass of the calibration mass, in whatever units are desired.

It is common to adjust the hammer tip characteristics to allow for a drop of 10-20 dB (factor of 10-100) in force spectrum magnitude over the frequency range of interest. As long as the structure being tested is linear, this does not pose any problems and minimizes the energy that excites system dynamics above the user's frequency range of interest. This will allow the channels gains to be set as optimally as possible during the auto-ranging procedure.

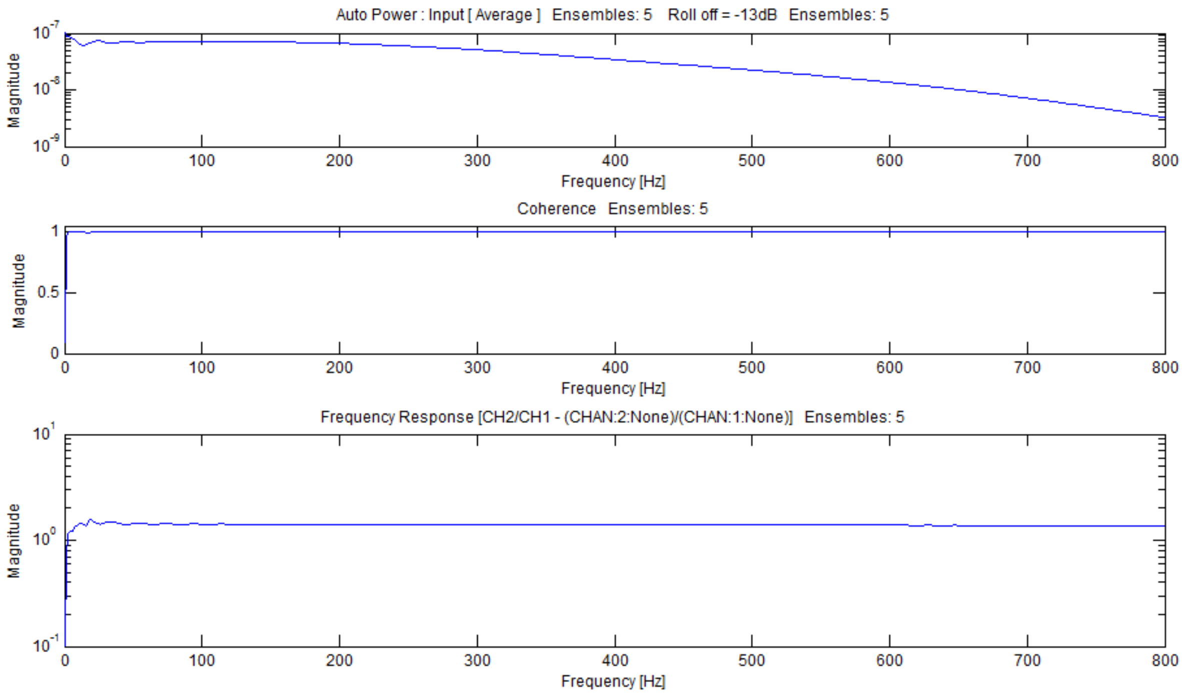

Figure 18: Ratio Calibration Example

If the accelerometer calibration is known (or updated with a separate calibration method), then the true calibration of the force from the impact hammer, at a level that is appropriate for the test involved, can be determined in order to get the correct value for the calibration mass. It should be noted that it is not necessary for the load cell and the accelerometer to be calibrated individually as long the two sensors are always used in pairs (for example, if the testing procedure is to mount the accelerometer at a fixed point of the structure and rove the hammer to points of interest on the structure). While this is a possible approach, it is common practice to first calibrate the accelerometer and then calibrate the hammer with a known calibration mass.

3.4. Force and Response Windows

In the early 70's, the most important signal processing development for impact testing was the development of force and exponential windows. The shift theorem states that multiplying a time function by an exponential function will shift the damping and/or frequency axis in the transformed domain. In other words, the apparent damping of system can be changed in a predictable way, simply by multiplying the unit impulse response measurement of a system by a damped exponential. Inversely, it became apparent that this could be used as a window to eliminate errors due to the time domain truncation of the response signal (leakage) and to improve the signal-to-noise of impact measurements. As result, an exponential window can be applied to both the input force and the output response signal. An additional force window can be applied to the force signal to eliminate noise on the force channel after the impact since this noise is not actual input energy that excites the system being tested. These windows have been documented in a number a references [4-7]. Figure 19 shows an example of the force and response (exponential), time domain windows that are used in impact testing. It should be noted that if an exponential window is applied to the response, the same exponential window must be applied to the force window to allow for the proper damping correction [7].

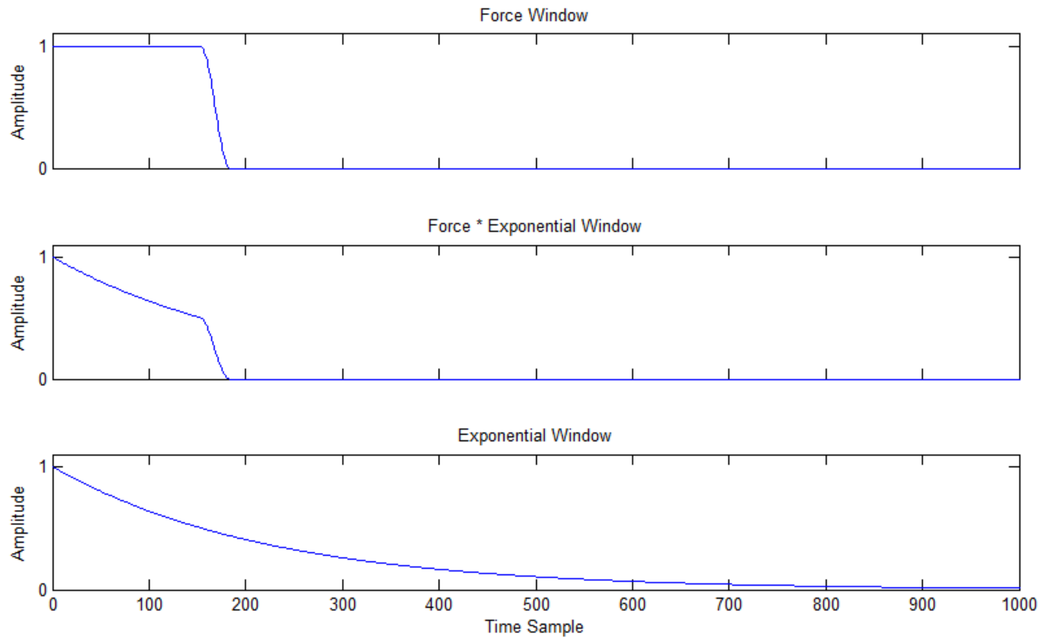

Figure 19: Typical Force and Response Windows

The damping effect of the exponential window can easily be corrected in the frequency domain once the damping is estimated from an FRF. Primarily, the response (exponential) window may add significant damping to the resultant frequency response function. This can only be corrected after the modal damping for each mode is found.

$$h_{pq}(t) = \sum_{r=1}^{2N} A_{pqr}\ e^{\lambda_r t}$$

$$e^{\beta t} h_{pq}(t) = e^{\beta t} \sum_{r=1}^{2N} A_{pqr}\ e^{\lambda_r t}$$

$$e^{\beta t} h_{pq}(t) = \sum_{r=1}^{2N} A_{pqr}\ e^{\beta t} e^{\lambda_r t}$$

$$e^{\beta t} h_{pq}(t) = \sum_{r=1}^{2N} A_{pqr}\ e^{(\lambda_r + \beta) t} = \sum_{r=1}^{2N} A_{pqr}\ e^{\hat{\lambda}_r t}$$

$$\hat{\lambda}_r = \hat{\sigma}_r + j\ \hat{\omega}_r = (\sigma_r + \beta) + j\ \omega_r$$

$$\hat{\sigma}_r = \sigma_r + \beta$$

$$\sigma_r = \hat{\sigma}_r - \beta$$

$$\omega_r = \hat{\omega}_r$$

Note that, while the damping correction of the exponential window is possible, the use of the exponential window for lightly damped systems may cause modal parameter estimation problems when the lightly damped modes are close in frequency. The added numerical damping provided by the exponential window may make it more difficult to identify and estimate the individual frequency and damping values for each mode. If these estimates are inaccurate due to this numerical damping distorting the FRF measurement or there is noise on the data, when the damping correction is applied, the corrected estimate of the damping factor can become slightly positive (physically, a passive structural system must have negative damping factors). This must be recognized as a numerical error and treated accordingly. Since the alternative is an incorrect damping estimate due to the leakage error, this issue is normally considered a reasonable problem to be accommodated.

3.5. Other Common Issues

Another frequent source of error, or loss of measurement quality, which is not related to either DSP or system noise, is an inconsistency in force input location or direction due to either user lapse of attention or extreme difficulty of access to a particular input location. It is not uncommon to have an intermediate measurement result that is clean and then, in the process of looking from the test article to the computer screen and back to the article again, to hit a location or direction close to, but not identical with, the previous averaged ensembles. The result is to average in a data ensemble with slightly different input-output characteristics. Because impact testing generally uses only a few ensembles in its averaging process, the effect upon the computed FRF and Coherence is generally quite dramatic. The anti-resonances tend to fill in and there a general loss of coherence. Figure 20 provides an example of this error where the first three ensembles were hit with a consistent location and direction. Then a fourth ensemble was added which represents a user lapse where a wrong, but nearby, location was hit.

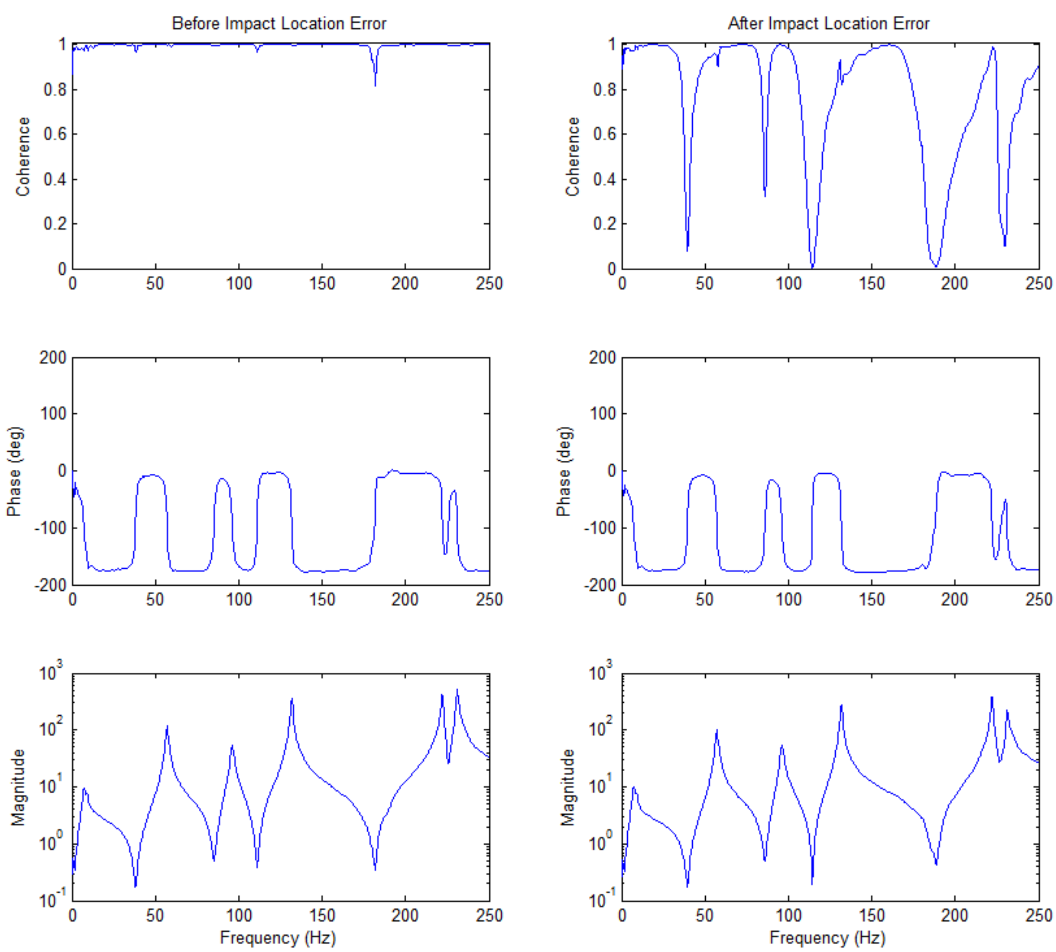

Figure 20: Comparison of FRF/COH before and after Ensemble with Impact Location Error

3.6. Reducing External Noise and Non-Linear Effects

One of the negative aspects of the exponential impact window is that periodic noise (periodic noise with respect to the length of the time domain FFT window) components and/or DC offsets are smeared by the exponential window over a frequency range centered on the frequency of the periodic noise. The DC component and frequency components due to noise (like 60 Hz) that were periodic in the window were filtered by taking the FFT of both the input and response channels and setting the Fourier coefficient of the noise components to the mean values of the adjacent Fourier coefficients. The DC component could be removed by removing the zero frequency Fourier coefficient in this process. The data were then transformed back into the time domain. The force/exponential window could then be applied to the filtered force and response signals. Once pre-triggering was available (around 1980), the DC offset could be determined from the pre-triggered section of the data and removed directly in the time domain by subtracting the offset from the data.

For noise signals which are not periodic in the window, a technique which has been used with some success is to use a full block pre-trigger, process this block for periodic and non-periodic noise components and then generate a time block of noise which can be subtracted from the data block being processed. This must happen before any windows are applied to the impact data. This has been used with some success on rotating systems, particularly large steam turbine generator sets.

However, in many cases the ambient noise in the testing environment is too large and the methods mentioned above cannot be reasonably applied. In this case, one possible solution is to shut down most or all the ambient, environmental noise sources. This technique has been used in a number of industrial situations by conducting the test during a third shift, on the weekend or a holiday.

4. Summary/Conclusions:

Impact testing is an important testing methodology that has evolved over the last forty years. While impact testing appears to be a very simple method, obtaining good FRF measurements, compared to other test methodologies is not trivial. Great attention must be paid to the details, particularly due to the transient nature of the signals. The process begins with force spectrum adjustment via the hammer size and tips and continues through properly pre-triggering and recording the time domain signals, careful inspection of both time and frequency domain data for the possibility of overloads, estimation of FRFs in the presence of ambient noise and finally correcting any damping estimation in response to the application of exponential windows. While many of these issues remain the same with only minor refinement over the last forty years, it is particularly important to recognize the difference in the data acquisition hardware has resulted in the need to pay particular attention to the overload problem.

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