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Shaker Excitation

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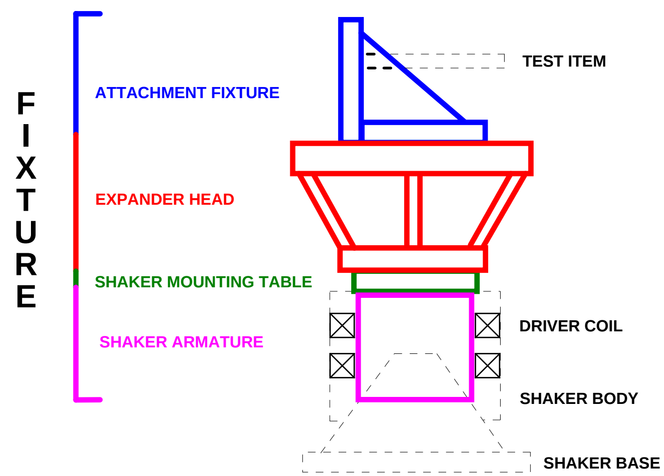
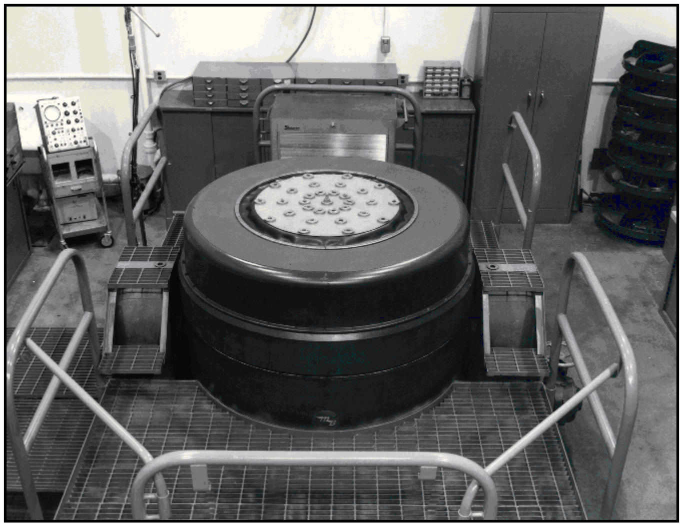
Objectives of this lecture:

- Overview some shaker excitation techniques commonly employed in modal testing
- Review deterministic and non-deterministic methods
- Present excitation techniques that have developed from a historical standpoint
- Present some MIMO testing information

Vibration Shaker Qualification vs Modal Shaker

Many people are familiar with vibration shakers used for qualification of equipment where specific loading is applied to replicate the actual operating environment.

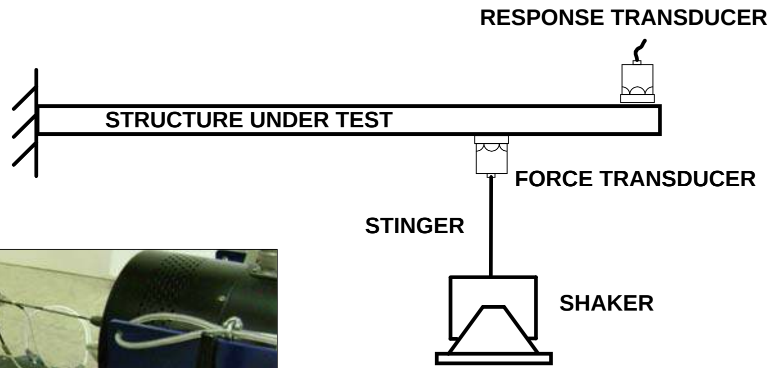




This is a much different testing technique than what is done for modal testing (where high loads are not applied to the structure)

Shaker Excitation for Modal Testing

Excitation device is attached to the structure using a long rod called a "stinger" or "quill"



Its purpose is to provide input along the shaker excitation axis with essentially no excitation of the other directions

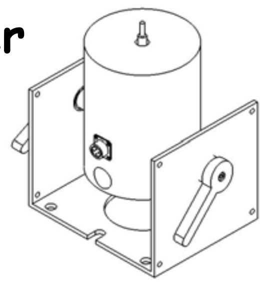
It is also intended to be flexible enough to not provide any stiffness to the other directions

The force gage is always mounted on the structure side of the quill

NOT ON THE SHAKER SIDE

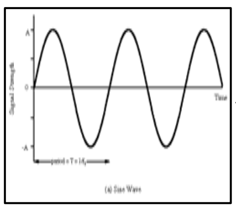
Excitation Configuration

Shaker

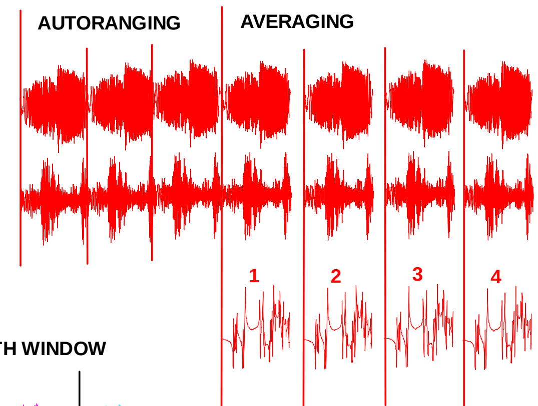


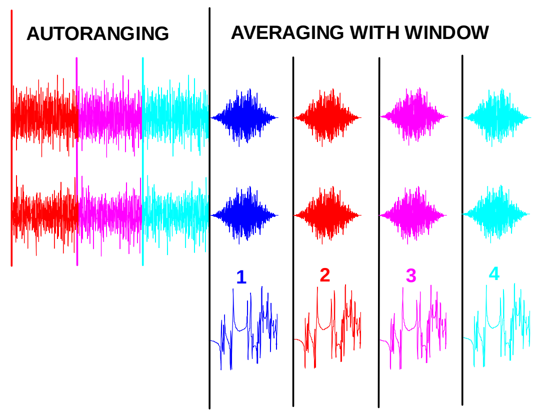
Stinger → force sensor → structure

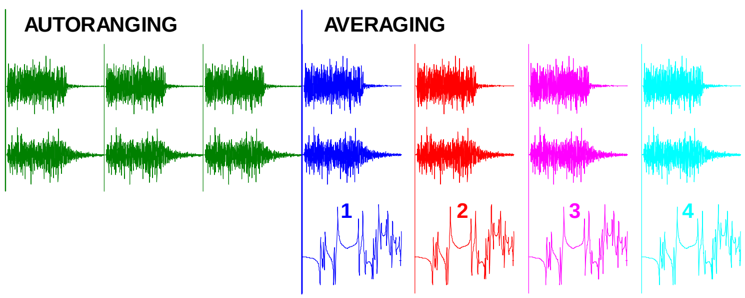
Test Signal
-random
-burst Random
-pseudo-random
-periodic-random
-Chirp



→ Power Amplifier ↑ (to Shaker)



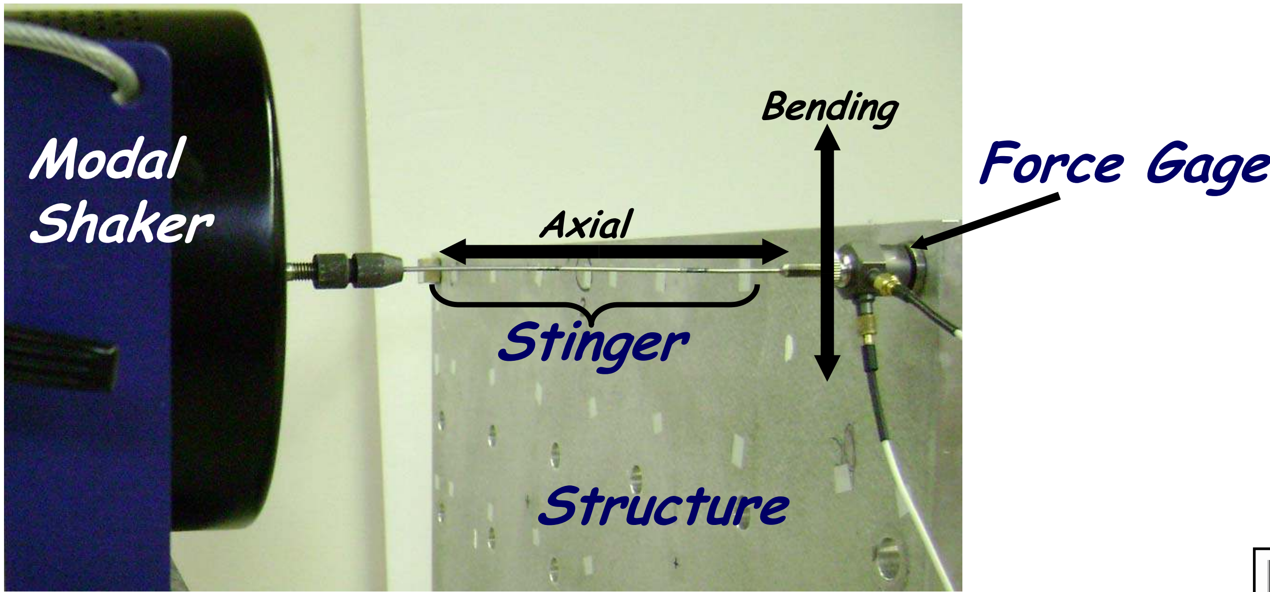




Reason for Stinger

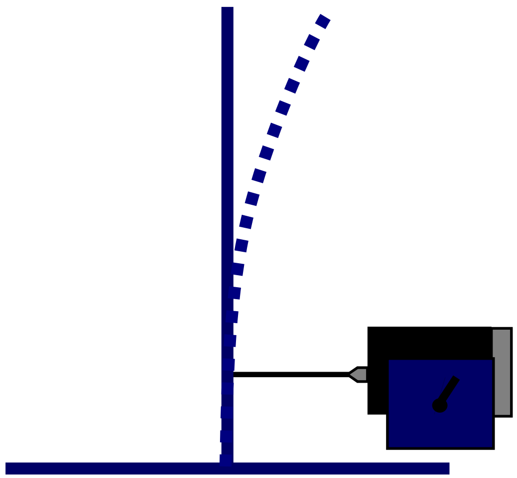
Purpose of Stinger

- Decouple shaker from test structure
- Force transducer between stinger and structure decouple forces acting in the axial direction only
- Forces acting in any other direction will be unaccounted for creating error in the measurements

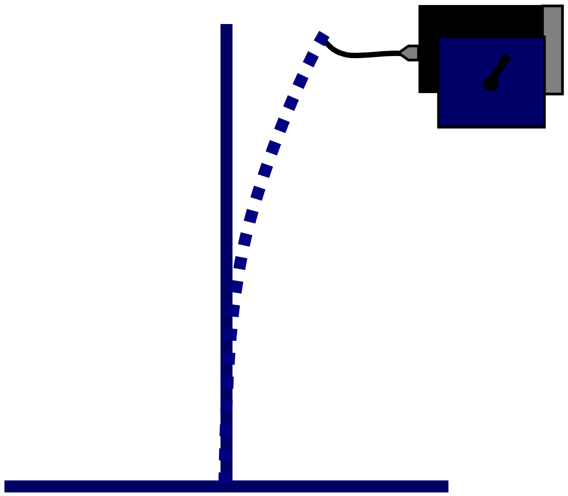


Possible Problems with Stinger

- *Suspect increase in stiffness when stinger is at higher location*

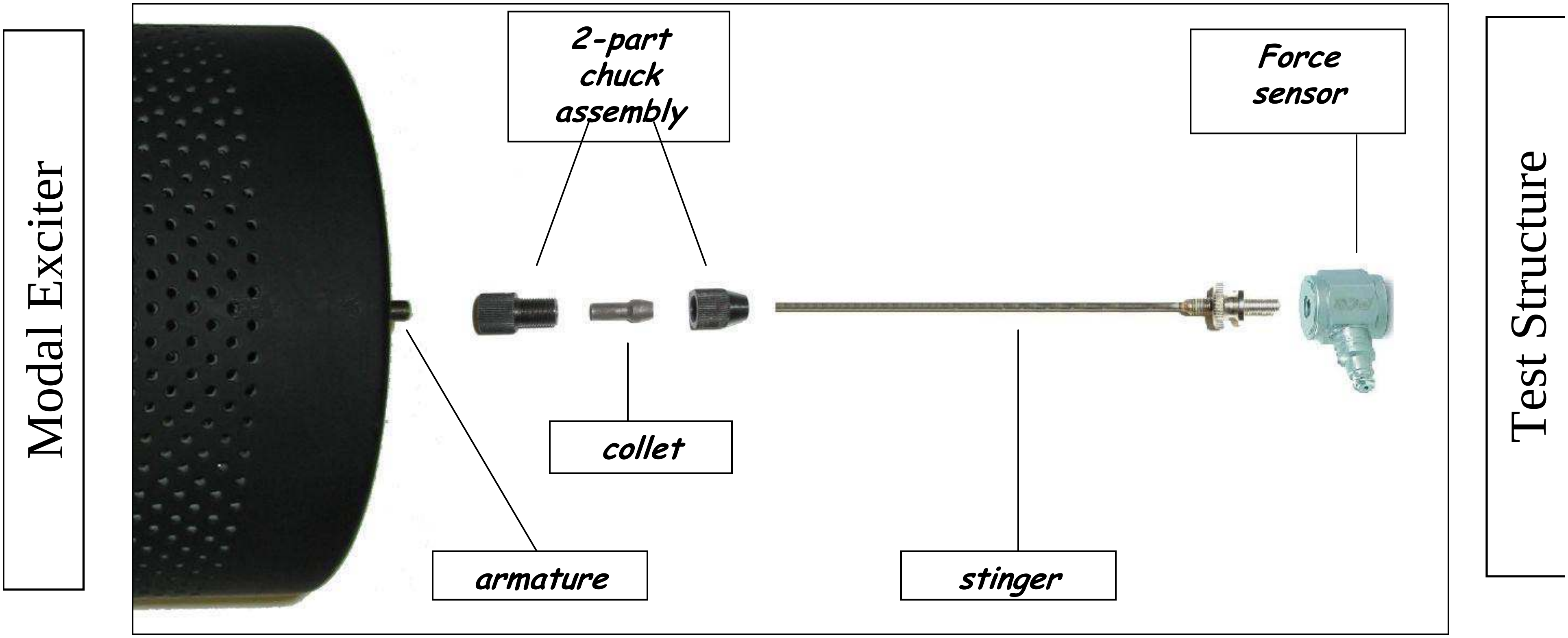


Axial stiffness

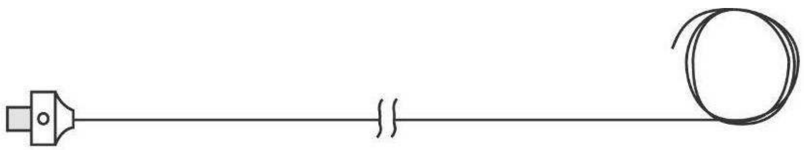


Axial and bending stiffness

Stinger Configuration with Through Hole Shaker



Common Stingers



Piano wire

Modal stinger

Threaded metal rod

Threaded nylon rod

Common Stingers

Types of Stingers Available

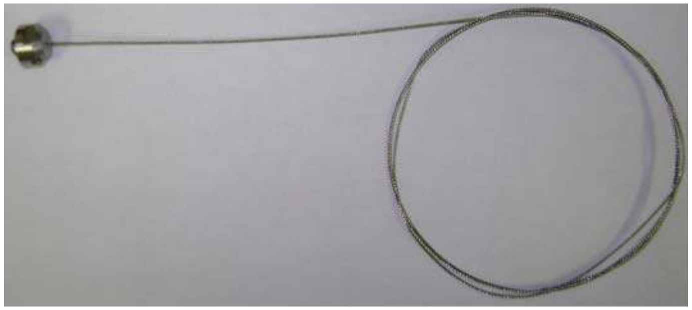
- Drill Rod

- Threaded Rod

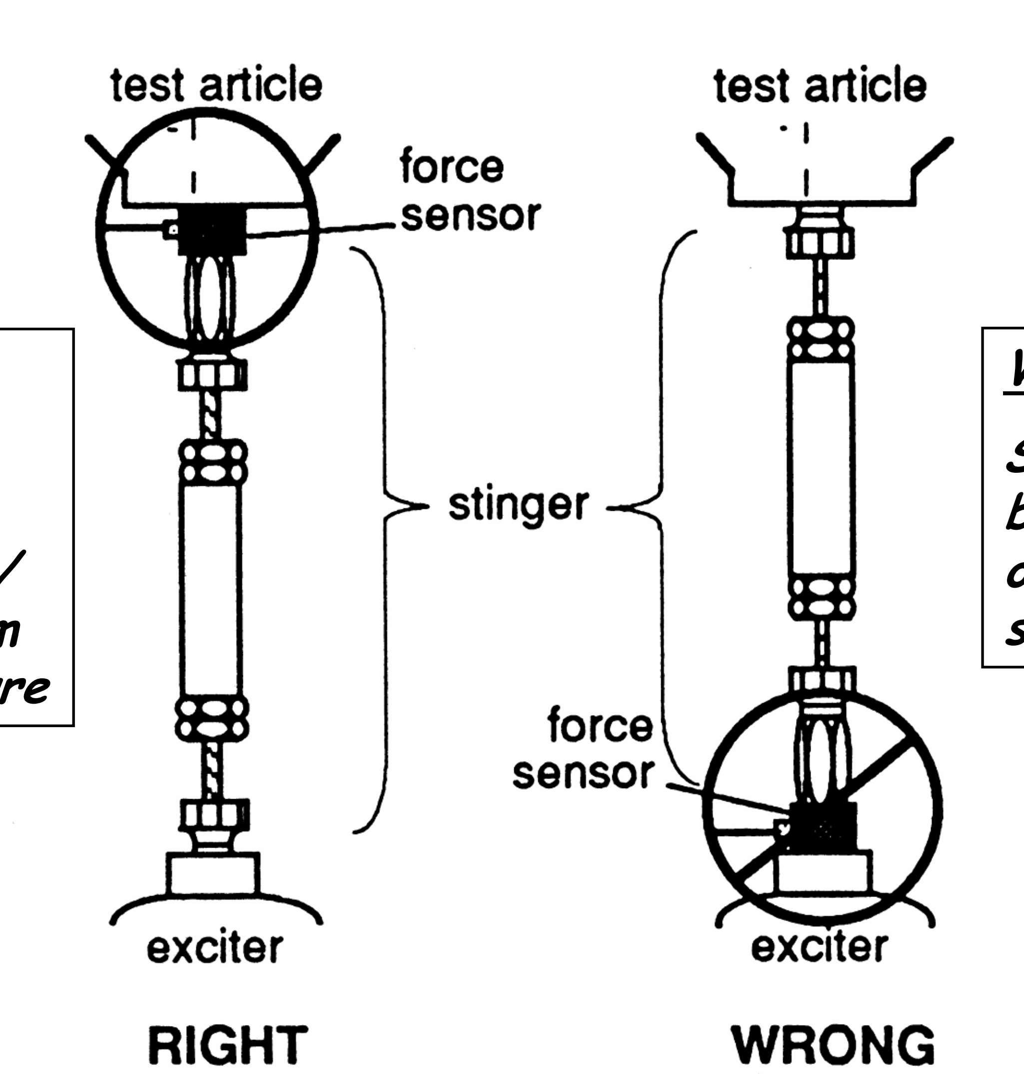
Metal

Nylon

- Piano Wire
  - Axial stiffness provided through a preload on wire
  - Essentially no lateral stiffness
  - Requires shaker and test fixture to be fixed



Shaker Excitation



CORRECT

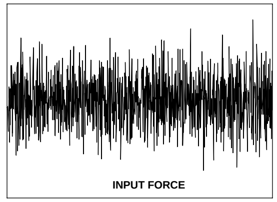
Force gage "divorces" the stinger/ shaker from the structure

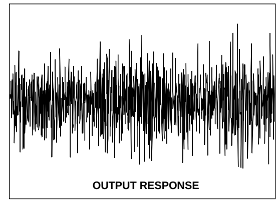
WRONG

Stinger becomes part of the test structure

The Overall Measurement Process

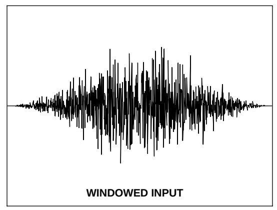
INPUT

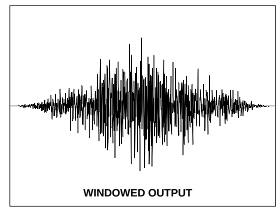




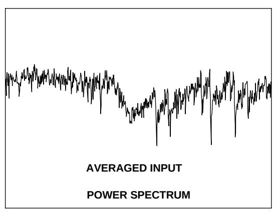
OUTPUT

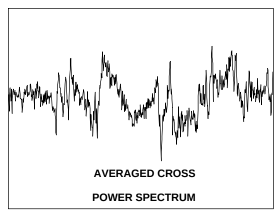
WINDOWED SIGNAL

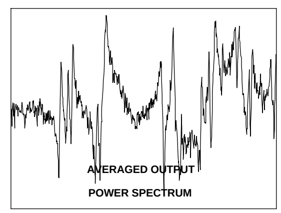




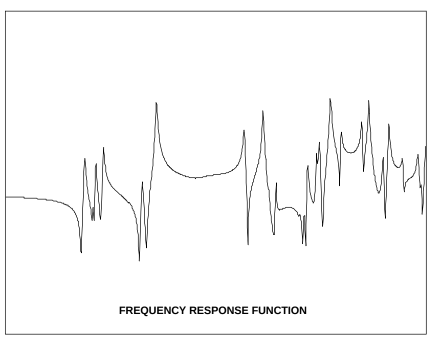
AVERAGED INPUT, OUTPUT AND CROSS SPECTRA

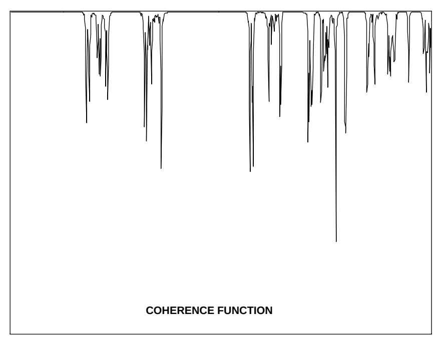






COMPUTED FREQUENCY RESPONSE FUNCTION AND COHERENCE

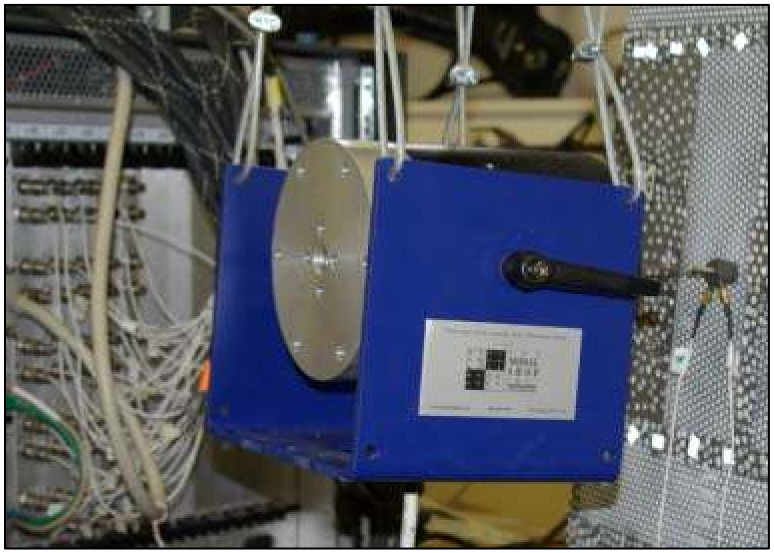




Signal Types

Excitation techniques can be broken down into two categories:

- ***Deterministic Signals***
- ***Non-Deterministic (Random) Signals***



Signal Types - Deterministic

Deterministic Signals

- conform to a particular mathematical relationship
- can be described exactly at any instant in time
- response of the system can also be exactly defined if the system character is known
- swept sine, sine chirp, digital stepped sine are examples

Signal Types – Non-Deterministic

Non-Deterministic (Random) Signals

- do not conform to a particular mathematical relationship
- can not be described exactly at any instant in time
- described by some statistical character of the signal
- generally have varying amplitude, phase and frequency content at any point in time
- pure random, periodic random, burst random are examples

Signal Types – Deterministic vs Non-Deterministic

Good for IDENTIFICATION of system linearity

Deterministic Signals

- conform to a particular mathematical relationship
- can be described exactly at any instant in time
- response of the system can also be exactly defined if the system character is known
- examples :swept sine, sine chirp, digital stepped sine

Good for LINEARIZATION of slight nonlinearities

Non-Deterministic (Random) Signals

- do not conform to a particular mathematical relationship
- can not be described exactly at any instant in time
- described by some statistical character of the signal
- generally have varying amplitude, phase and frequency content at any point in time
- examples: pure random, periodic random, burst random

Excitation Signal Characteristics

- RMS to Peak
- Signal to Noise
- Distortion
- Test Time
- Controlled Frequency Content
- Controlled Amplitude Content
- Removes Distortion Content
- Characterizes Non Linearites

Summary Excitation Signal Characteristics

Excitation Signal Characteristics							
	Steady State Sine	Pure Random	Pseudo Random	Random	Periodic Chirp	Impact	Burst Random
Minimize Leakage	No	No	Yes	Yes	Yes	Yes	Yes
Signal-to-Noise Ratio	Very High	Fair	Fair	Fair	High	Low	Fair
RMS-to-Peak Ratio	High	Fair	Fair	Fair	High	Low	Fair
Test Measurement Time	Very Long	Good	Very Short	Fair	Fair	Very Short	Very Short
Controlled Frequency Content	Yes	Yes *	Yes *	Yes *	Yes *	No	Yes *
Controlled Amplitude Content	Yes	No	Yes *	No	Yes *	No	No
Removes Distortion	No	Yes	No	Yes	No	No	Yes
Characterize Nonlinearity	Yes	No	No	No	Yes	No	No

* Special Hardware Required

Ref: University of Cincinnati

Remarks on General Excitation Characteristics

The complete solution of a forced harmonic excitation will result in two parts of the response
- transient part which decays with time and
- the steady state part of the response

$$\ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n^2 x = \frac{F_0}{m}\sin\omega t$$

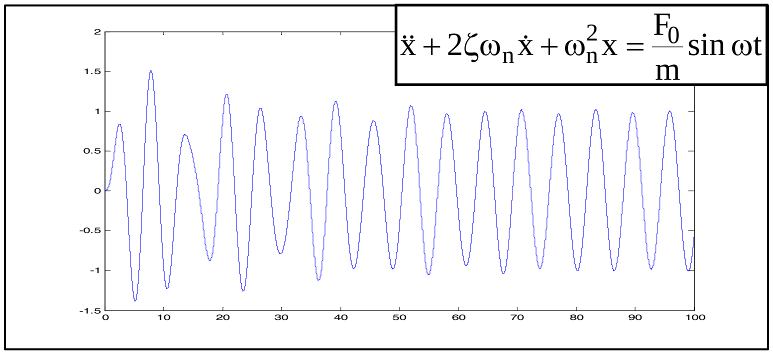
$$x(t) = \frac{F_0}{k}\frac{\sin(\omega t - \phi)}{\sqrt{\left(1-\left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(2\zeta\left(\frac{\omega}{\omega_n}\right)\right)^2}}$$

Steady State

$$+ X_1 e^{-\zeta\omega_n t}\sin\left(\sqrt{1-\zeta^2}\,\omega_n t + \phi_1\right)$$

Transient

Remarks on General Excitation Characteristics



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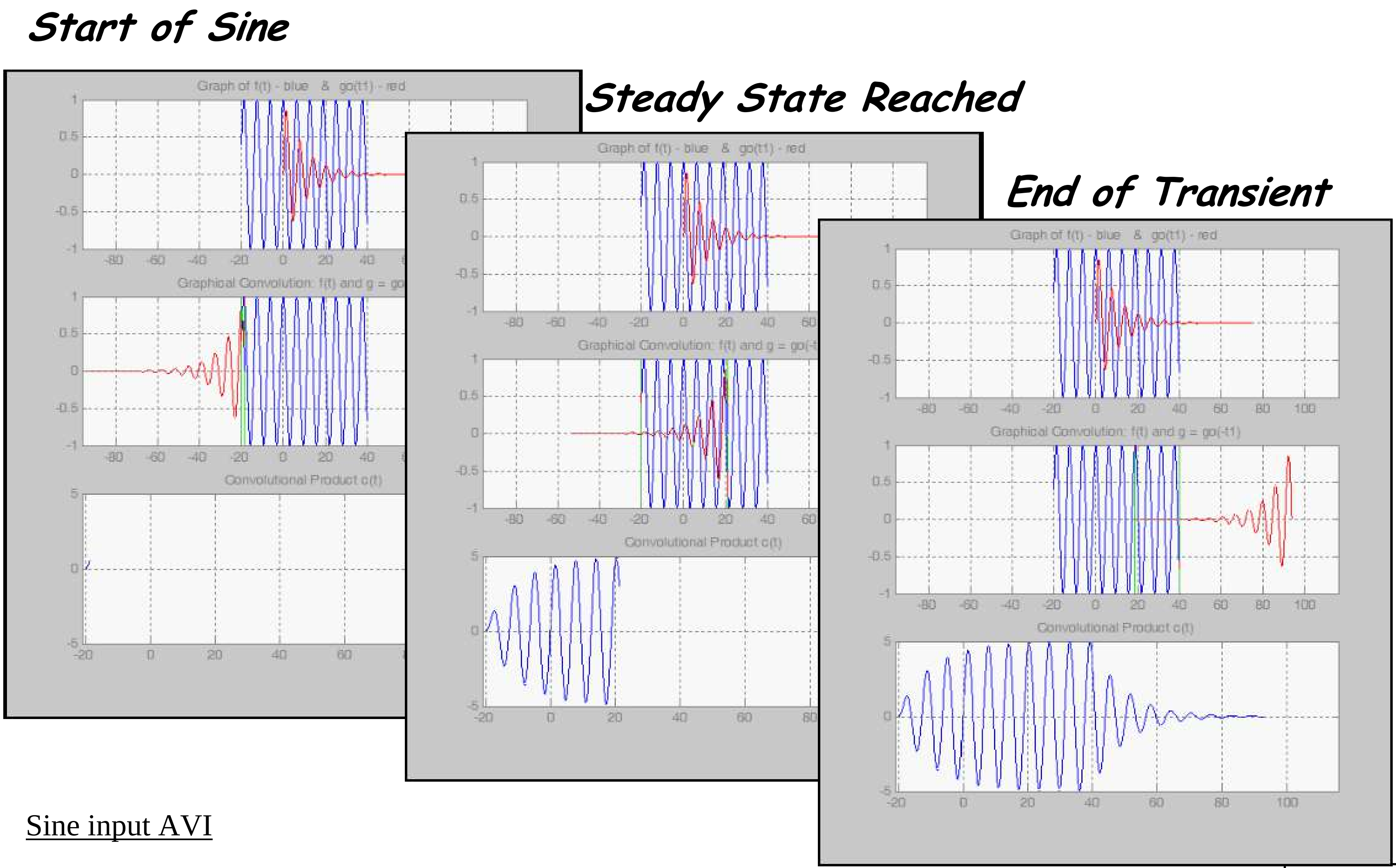
Steady State

$$+ X_1 e^{-\zeta\omega_n t} \sin\left(\sqrt{1-\zeta^2}\,\omega_n t + \phi_1\right)$$

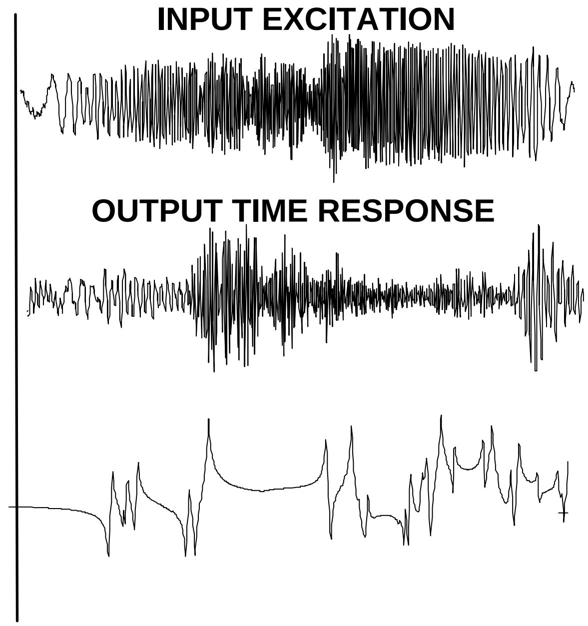
Transient

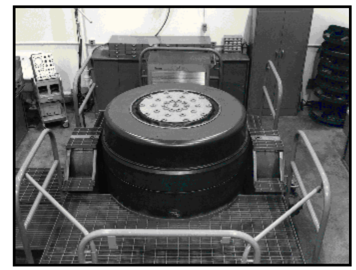
Vibrations – Convolution for SDOF Sine Excitation



Sine input AVI

Swept Sine Excitation





Slowly changing sine signal sweeping from one frequency to another frequency

Analog Slow Swept Sine Excitation

A slowly changing sine output sweeping from one frequency to another frequency

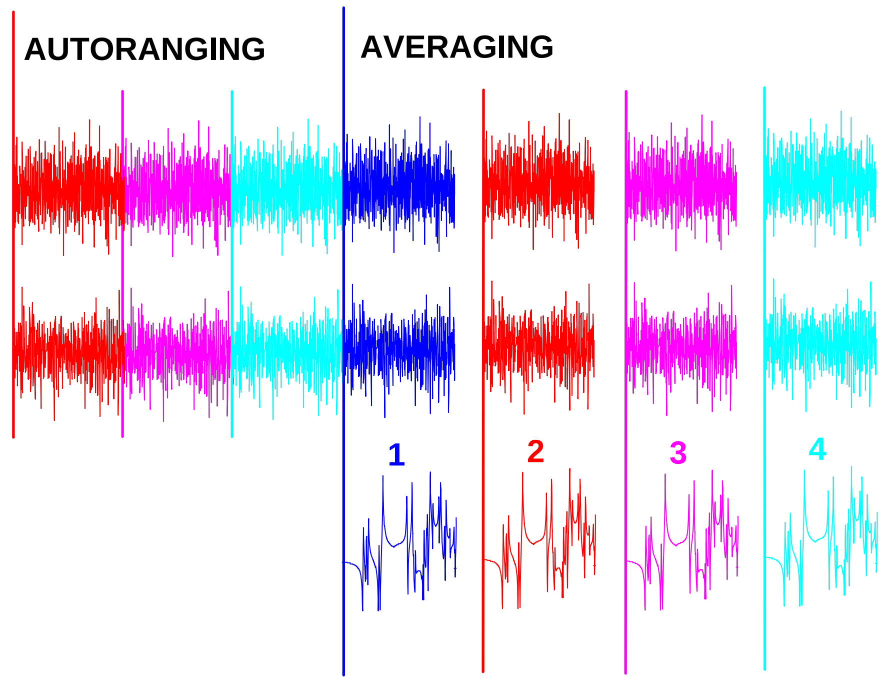
ADVANTAGES

- *best peak to RMS level*
- *best signal to noise ratio*
- *good for nonlinear characterization*
- *widely accepted and understood*

DISADVANTAGES

- *slowest of all test methods*
- *leakage is a problem*
- *does not take advantage of speed of FFT process*

Random Excitation



An ergodic, stationary signal with Gaussian probability distribution. Typically, has frequency content at all frequencies.

Random Excitation

An ergodic, stationary signal with Gaussian probability distribution. Typically, has frequency content at all frequencies.

ADVANTAGES

- gives a good linear approximation for a system with slight non-linearities
- relatively fast
- relatively good general purpose excitation

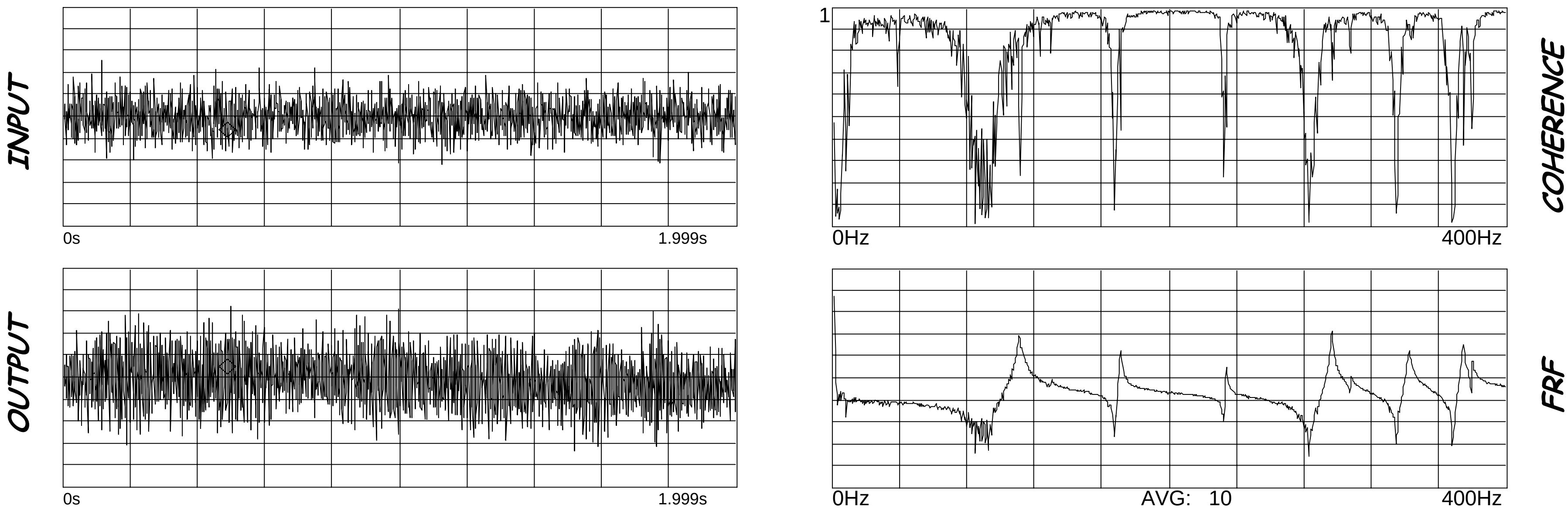
DISADVANTAGES

- leakage is a very serious problem
- FRFs are generally distorted due to leakage

Random Excitation

Time signal

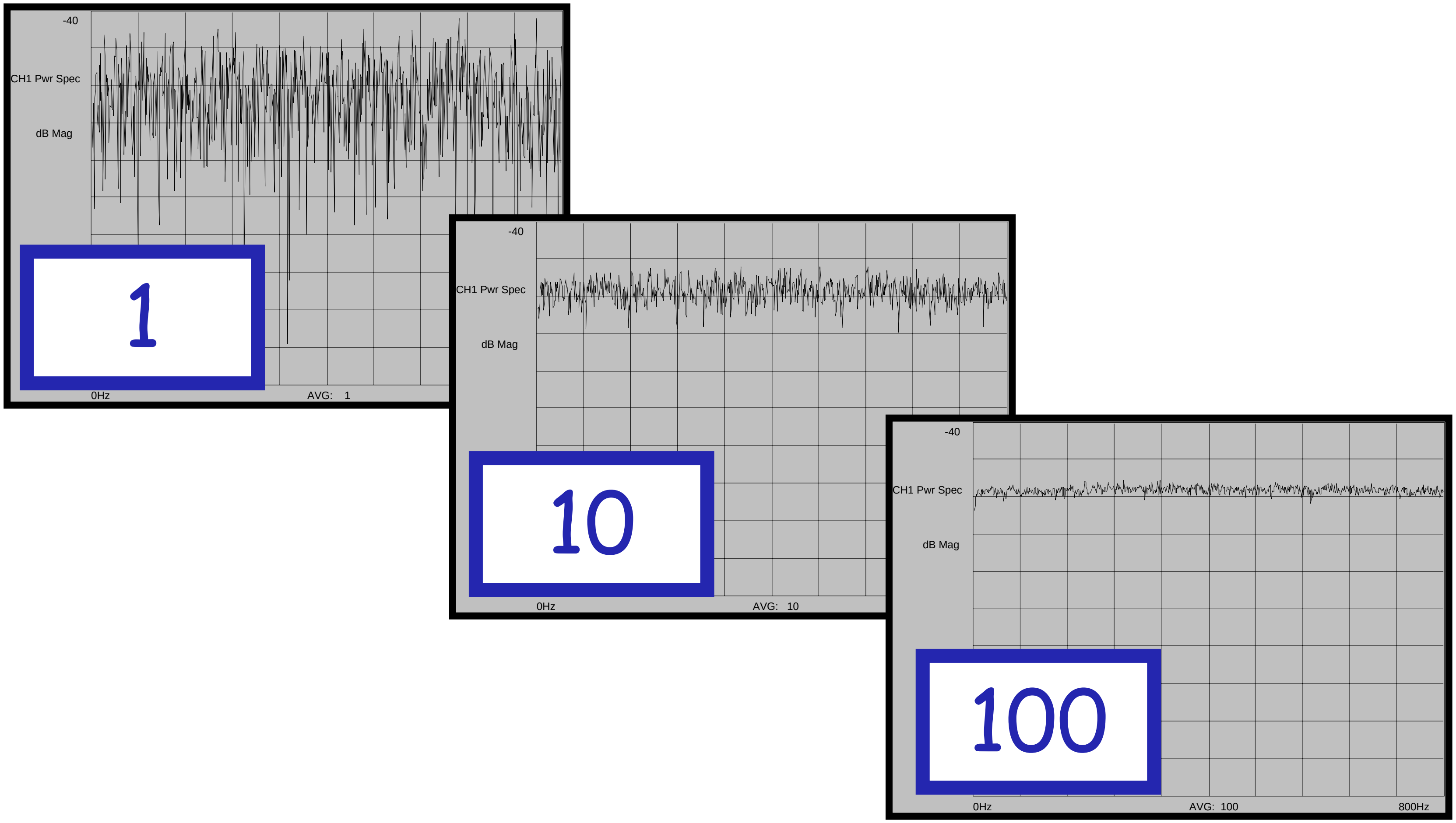
Frequency Signal



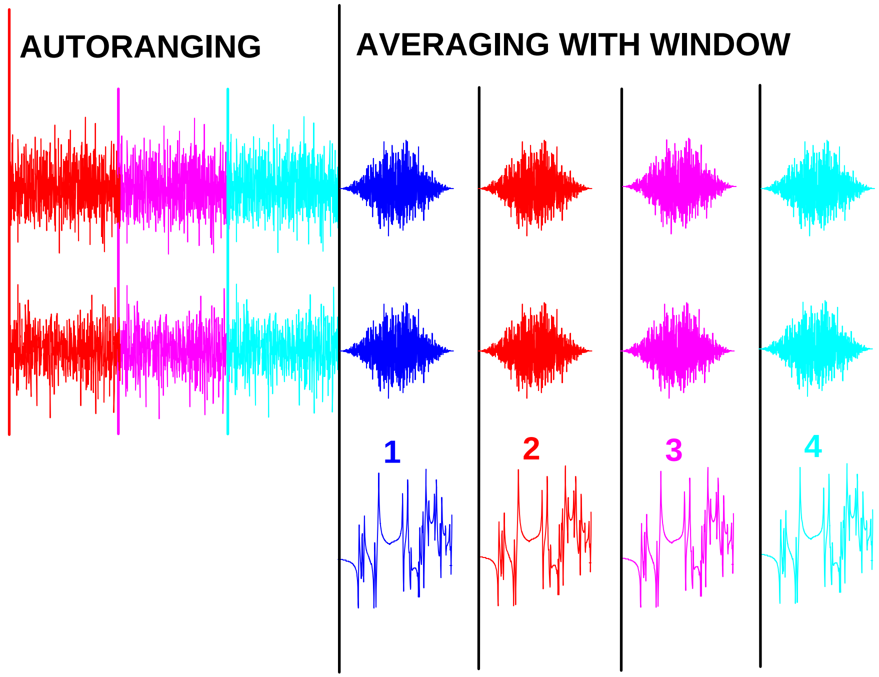
Notice that the coherence is very poor at all frequencies

Random Excitation

Effects of averaging



Random Excitation with Hanning Window



An ergodic, stationary signal with Gaussian probability distribution. Typically, has frequency content at all frequencies.

Random Excitation with Hanning Window

An ergodic, stationary signal with Gaussian probability distributio
Typically, has frequency content at all frequencies.

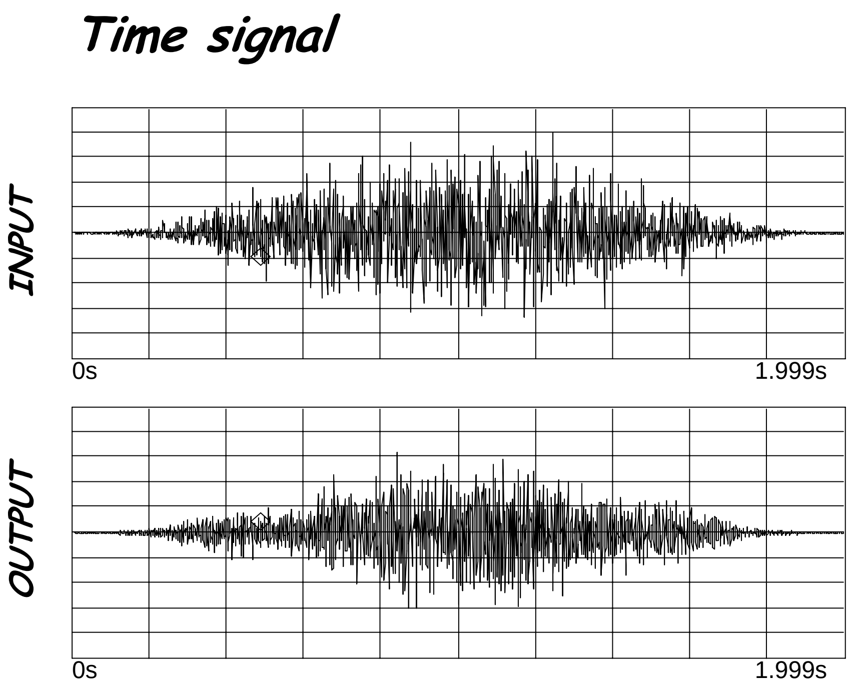
ADVANTAGES

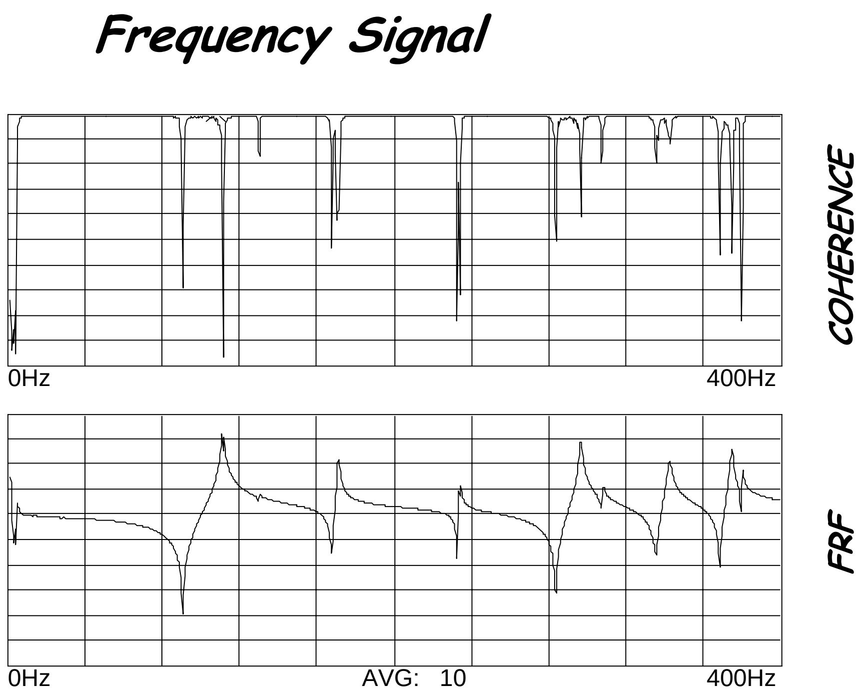
- *gives a good linear approximation for a system with slight non-linearities*
- *relatively fast*
- *overlap processing can be used*
- *relatively good general purpose excitation*

DISADVANTAGES

- *even with windows applied to the measurement leakage is a very serious problem*
- *FRFs are generally distorted due to leakage with (significant distortion at the peaks)*
- *excessive averaging necessary to reduce variance on data*

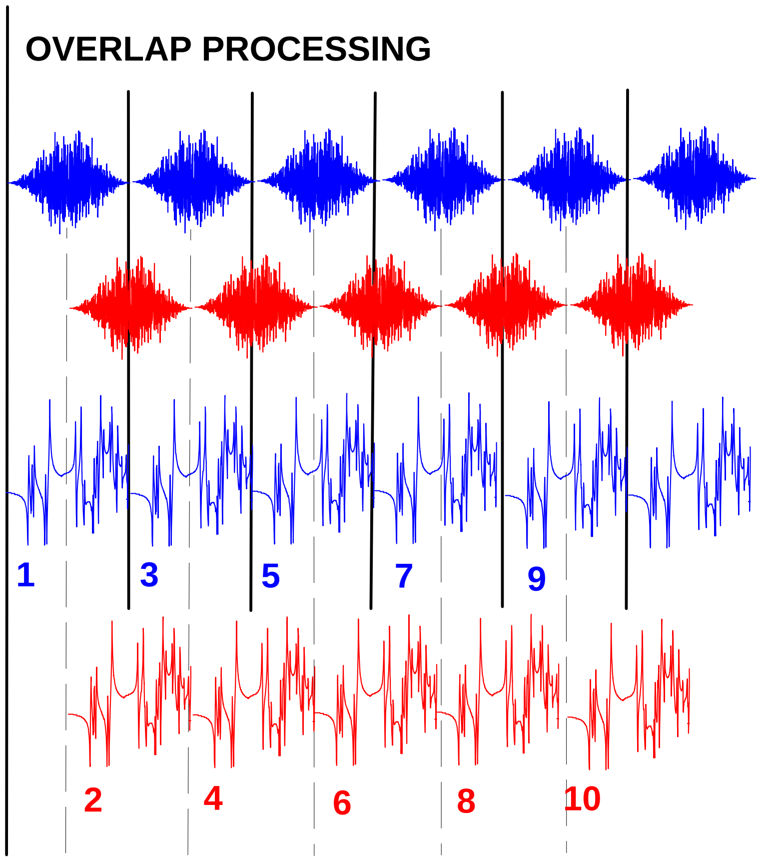
Random Excitation with Hanning Window





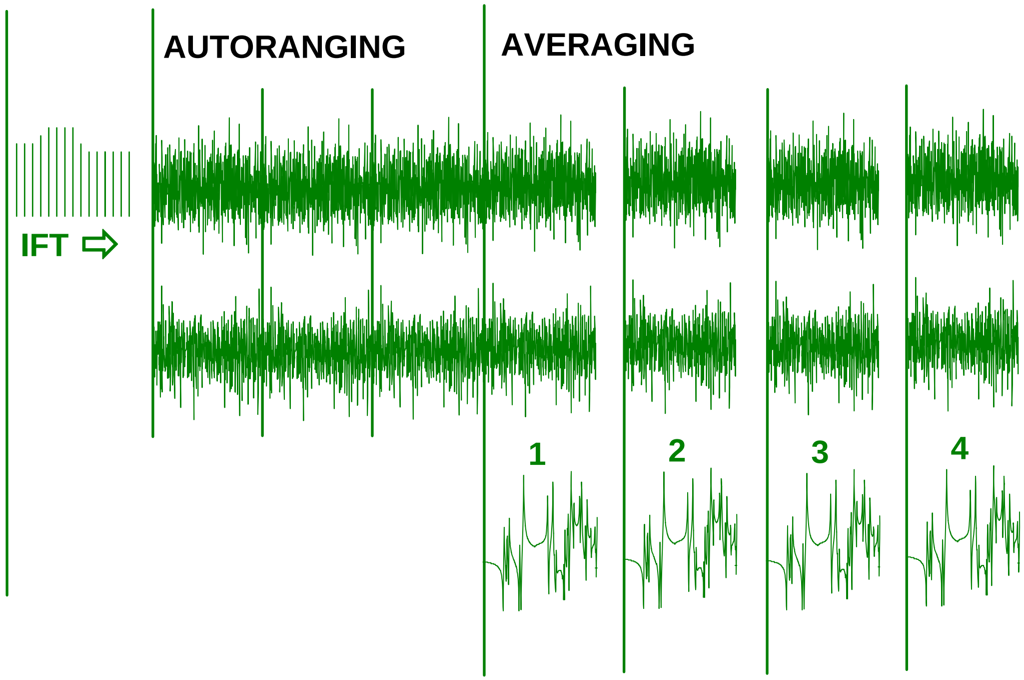
Notice that the coherence is very poor at resonant frequencies

Random Excitation with Overlap Processing



- *used to reduce test time with pure random excitations*
- *Hanning window tends to weight the first and last quarter of the time block to zero and this data is not effectively used in the normal averaging process*
- *effectively uses the portion of the block that has been heavily weighted to zero*
- *overlap processing allows for almost twice as many averages with the same data when fifty percent overlap is used*

Pseudo Random Excitation



An ergodic, stationary signal consisting of only integer multiples of the FFT frequency increment. Signal has constant amplitude with varying phase. Note that the transient part of the signal must decay and steady state response achieved before measurements are taken to assure leakage free FRF.

Pseudo Random Excitation

An ergodic, stationary signal consisting of only integer multiples of the FFT frequency increment.
Signal has constant amplitude with varying phase.

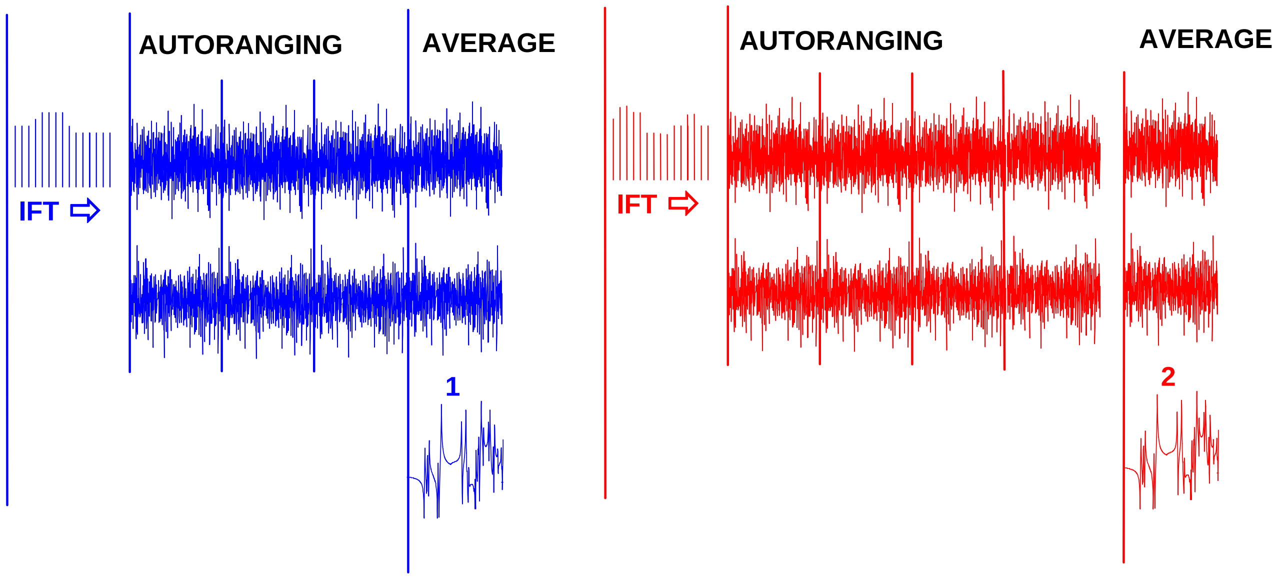
ADVANTAGES

- *always periodic in the sample interval*
- *relatively fast*
- *fewer averages than random*
- *frequency spectrum is shapeable*

DISADVANTAGES

- *sensitive to nonlinearities*
- *same excitation is used for each average*

Periodic Random Excitation



An ergodic, stationary signal consisting of only integer multiples of the FFT frequency increment. Signal has varying amplitude with varying phase. Note that the transient part of the signal must decay and steady state response achieved before measurements are taken to assure leakage free FRF.

Periodic Random Excitation

An ergodic, stationary signal consisting of only integer multiples of the FFT frequency increment. Signal has varying amplitude with varying phase.

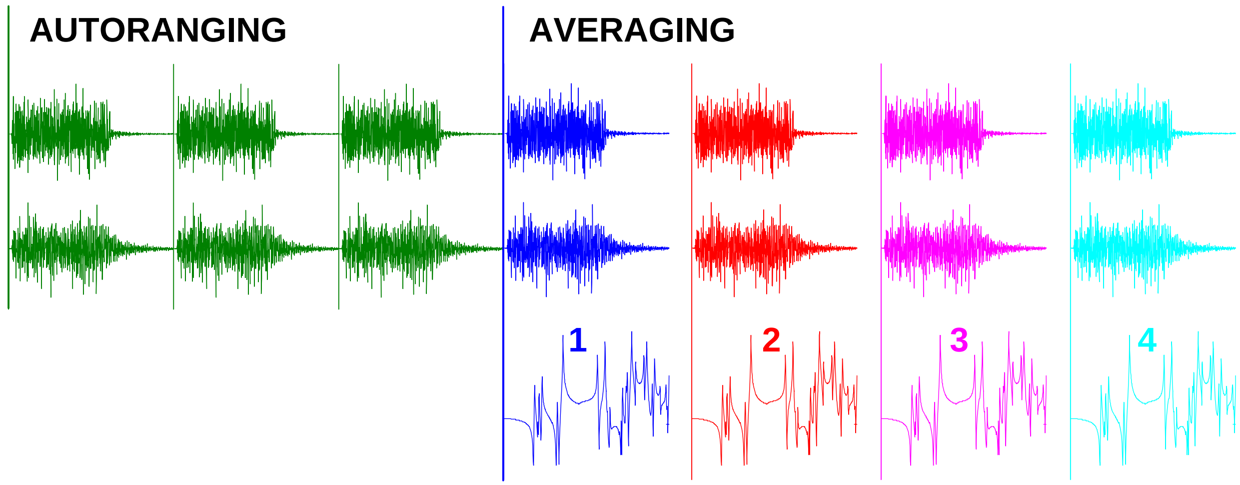
ADVANTAGES

- ***always periodic in the sample interval***
- ***frequency spectrum is shapable***
- ***determines a very good linear approximation of the FRF since leakage is minimized***

DISADVANTAGES

- ***a different signal is generated for each measurement***
- ***longest of all excitation techniques except swept sine***

Burst Random Excitation



Current ~ force
Voltage ~ velocity

A random excitation that exists over only a portion of the data block (typically 50% to 70%).

NOTE: Voltage mode amplifier necessary
- creates back emf effect to dampen response at end of burst

Burst Random Excitation

A random excitation that exists over only a portion of the data block (typically 50% to 70%)

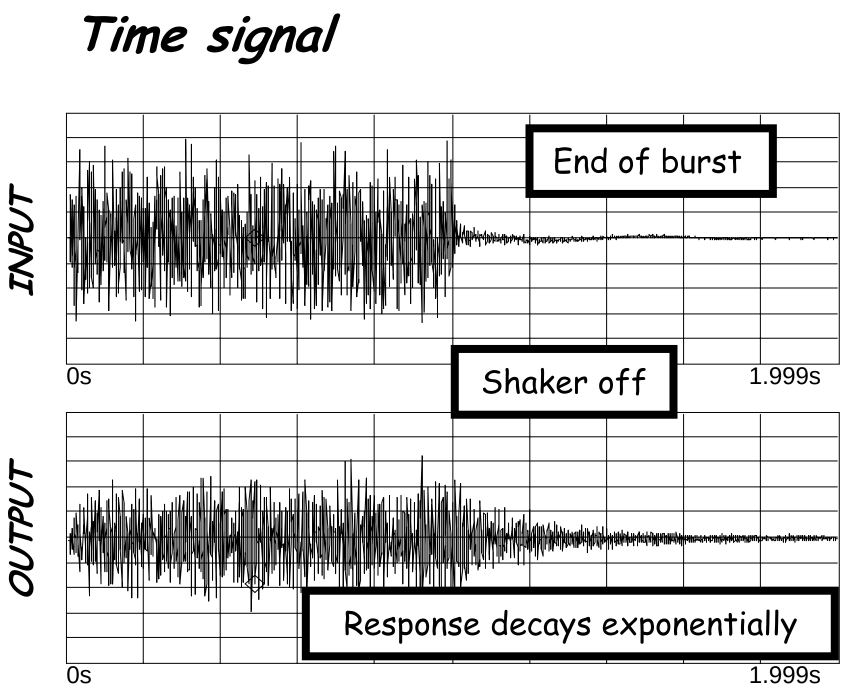
ADVANTAGES

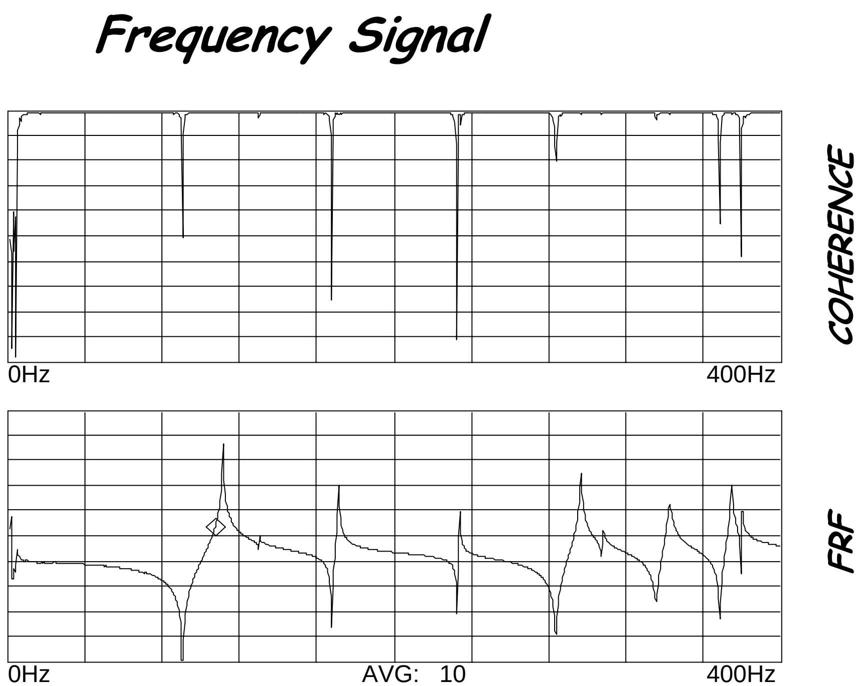
- *has all the advantages of random excitation*
- *the function is self-windowing*
- *no leakage*

DISADVANTAGES

- *if response does not die out within on sample interval, then leakage is a problem*

Burst Random Excitation

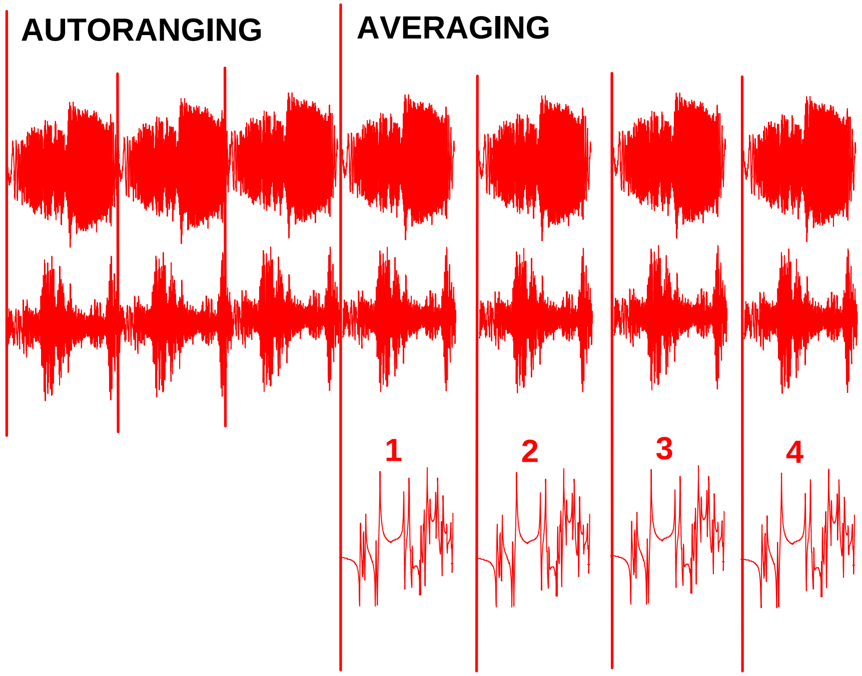




Notice that the coherence is very good even at resonant frequencies

Notice the sharpness of the resonances and measurement quality.

Sine Chirp Excitation



A very fast swept sine signal that starts and stops within one sample interval of the FFT analyzer

Sine Chirp Excitation

A very fast swept sine signal that starts and stops within one sample interval of the FFT analyzer

ADVANTAGES

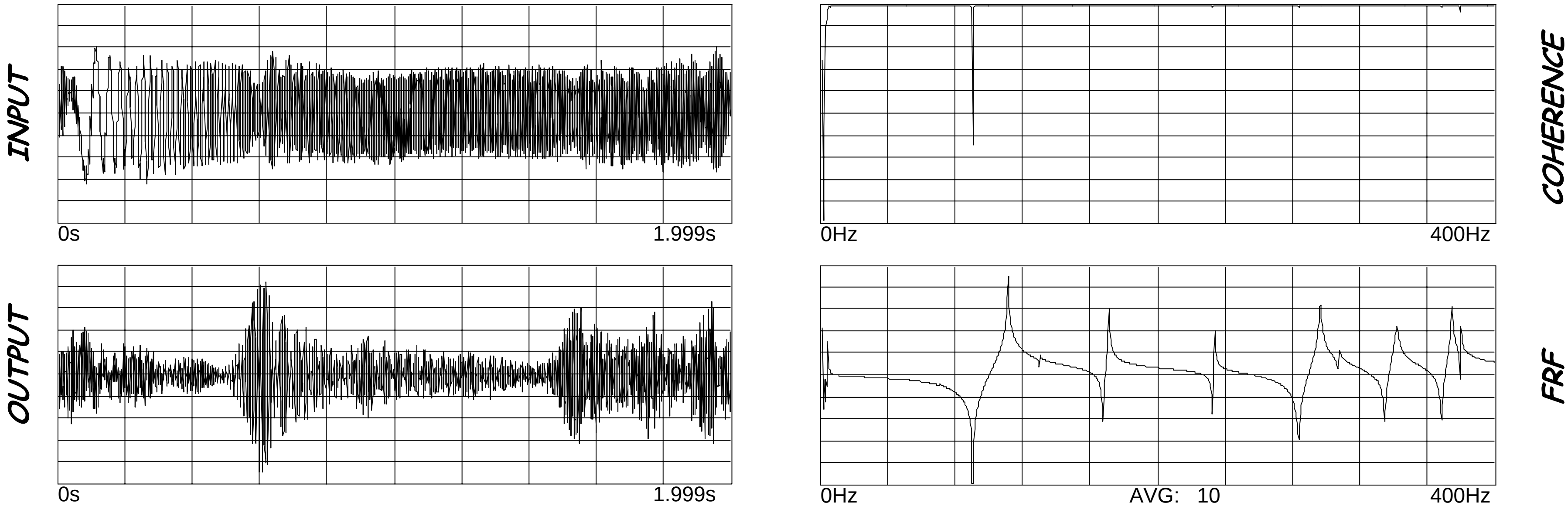
- *has all the same advantages as swept sine*
- *self windowing function*
- *good for nonlinear characterization*

DISADVANTAGES

- *nonlinearities will not be averaged out*

Sine Chirp Excitation

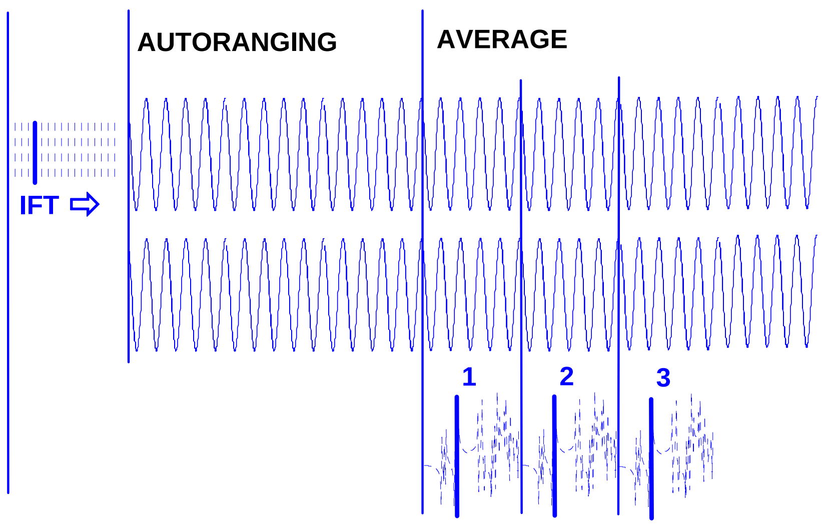
Time signal | **Frequency Signal**

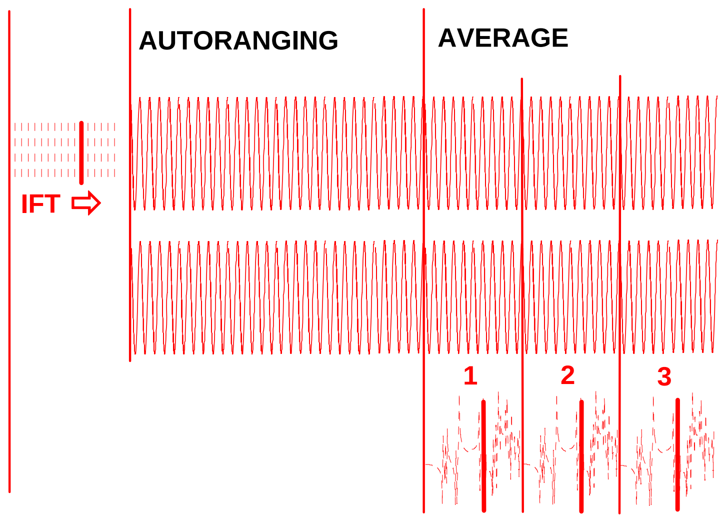


Notice that the coherence is very good.

Notice the sharpness of the resonances and measurement quality.

Digital Stepped Sine Excitation





Sine waves are generated at discrete frequencies which correspond to the digital values of the FFT analyzer for the frequency resolution available. The system is excited with a single sine wave and steady state response measured. Once one spectral line is obtained, the next digital frequency is acquired until all frequencies have been measured.

Digital Stepped Sine Excitation

Sine waves are generated at discrete frequencies which correspond to the digital values of the FFT analyzer for the frequency resolution available. The system is excited with a single sine wave and the steady state response is measured. Once one spectral line is obtained, the next digital frequency is acquired until all frequencies have been measured.

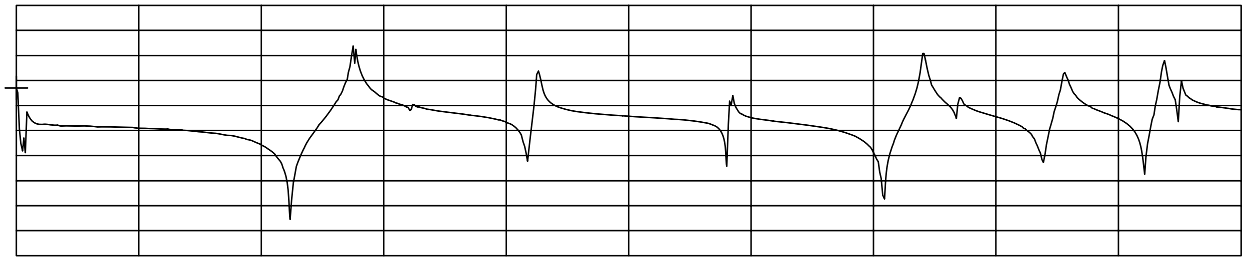
ADVANTAGES

- ***excellent peak to RMS level***
- ***excellent signal to noise ratio***
- ***good for nonlinear characterization***
- ***leakage free measurements obtained***

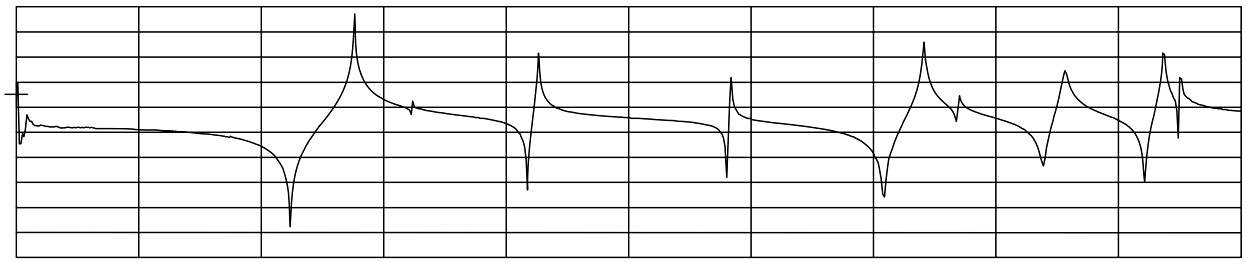
DISADVANTAGES

- ***slowest of all test methods***

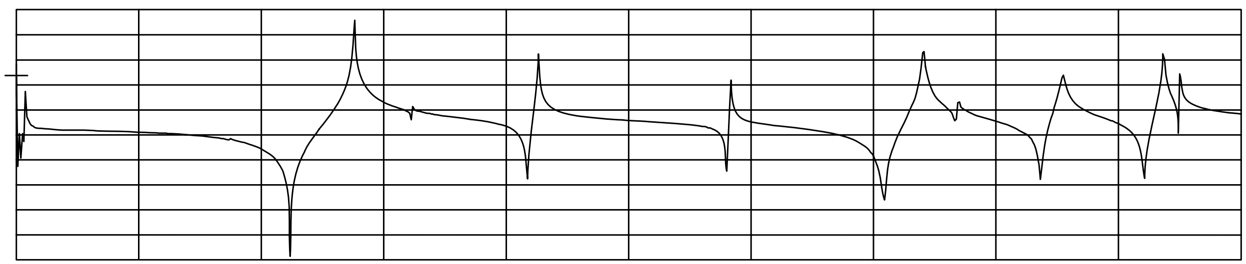
Comparison - Random/Hann, Burst Random, Chirp



RANDOM

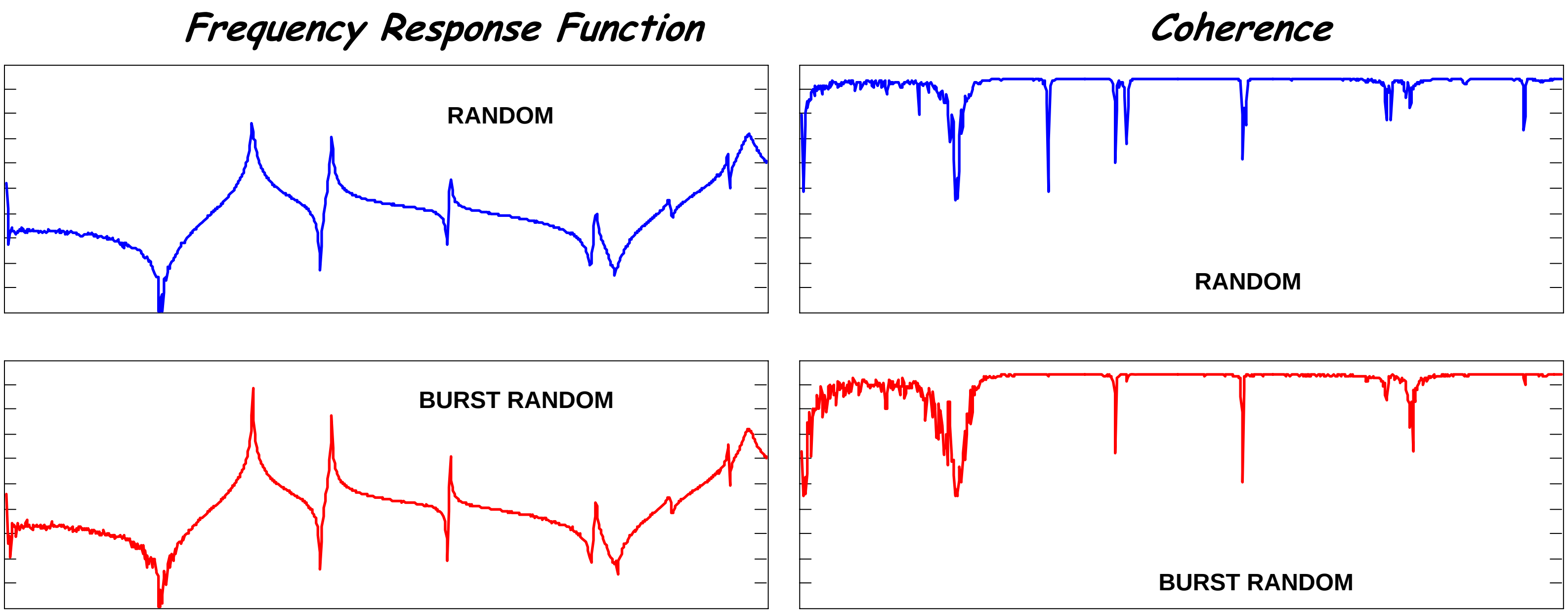


BURST RANDOM



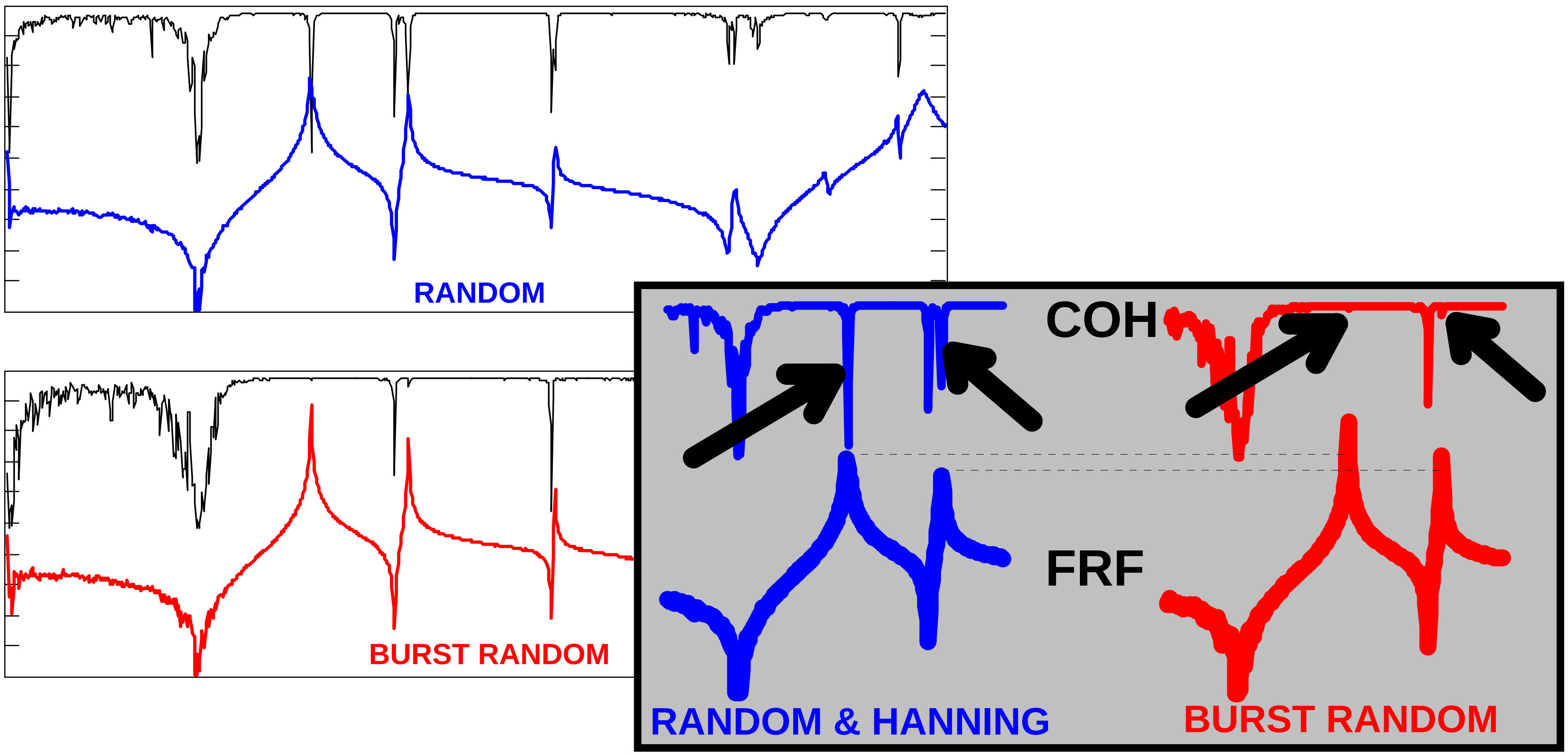
SINE CHIRP

Random with Hanning Window vs Burst Random

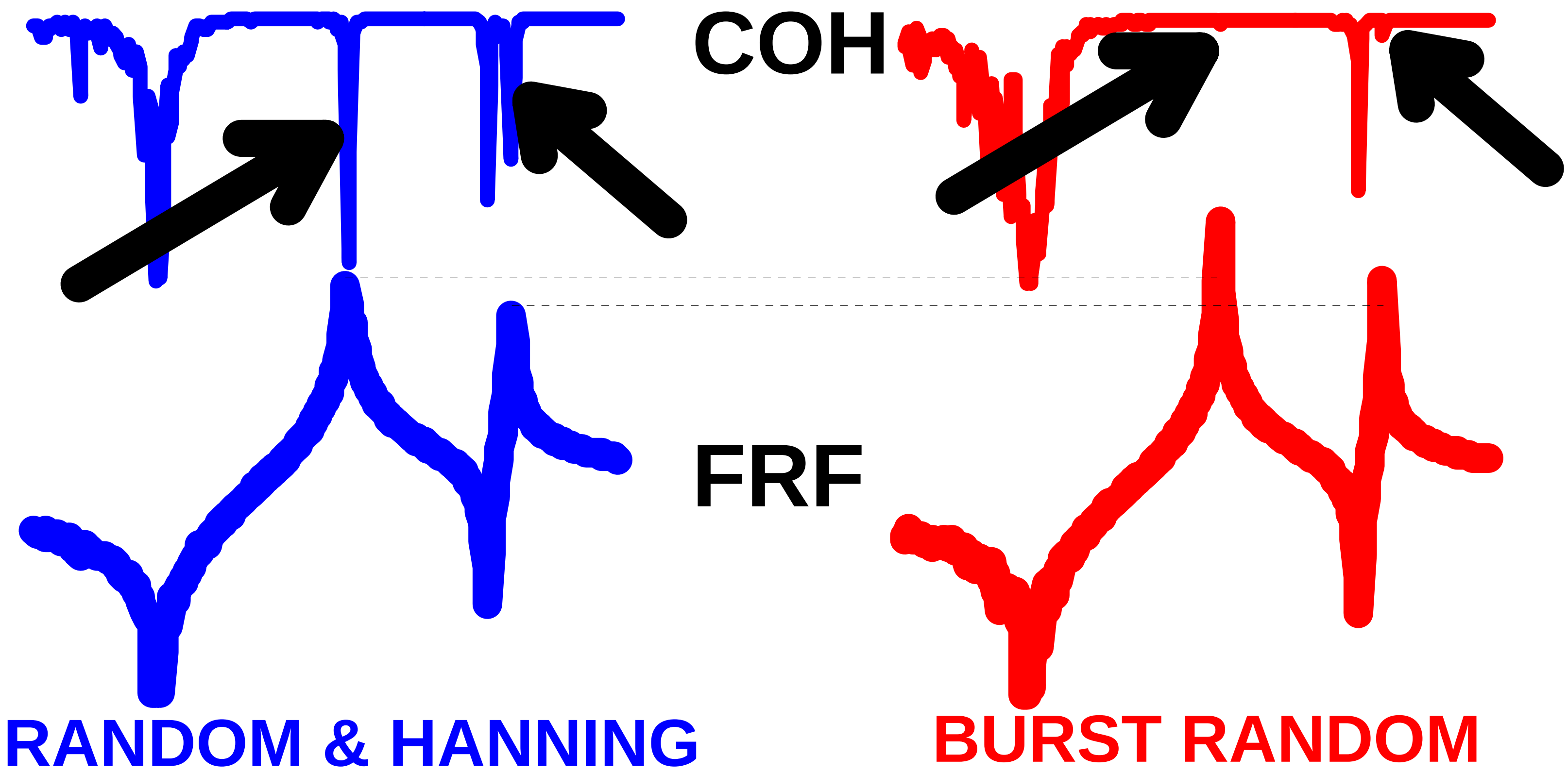


When comparing the measurement with random and burst random, notice that the random excitation peaks are lower and appear to be more heavily damped when compared to the burst random. - also notice the coherence improvement at the resonant peaks.

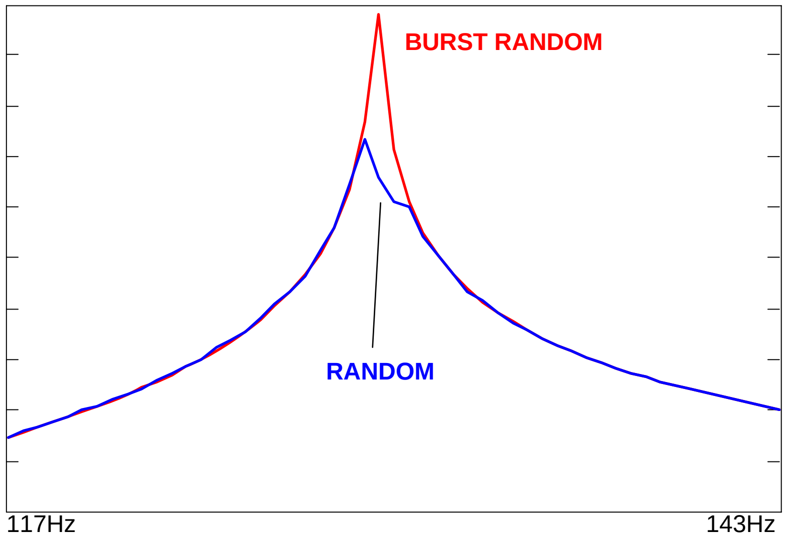
Random with Hanning Window vs Burst Random



Random with Hanning Window vs Burst Random

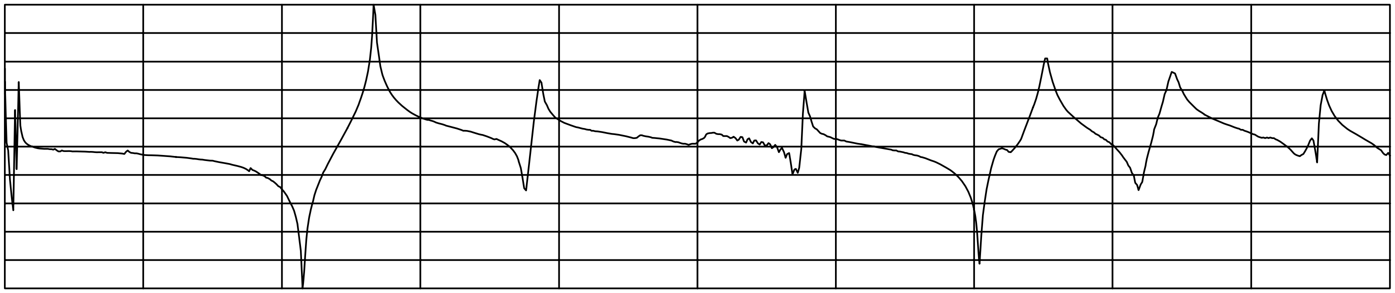


Random with Hanning Window vs Burst Random

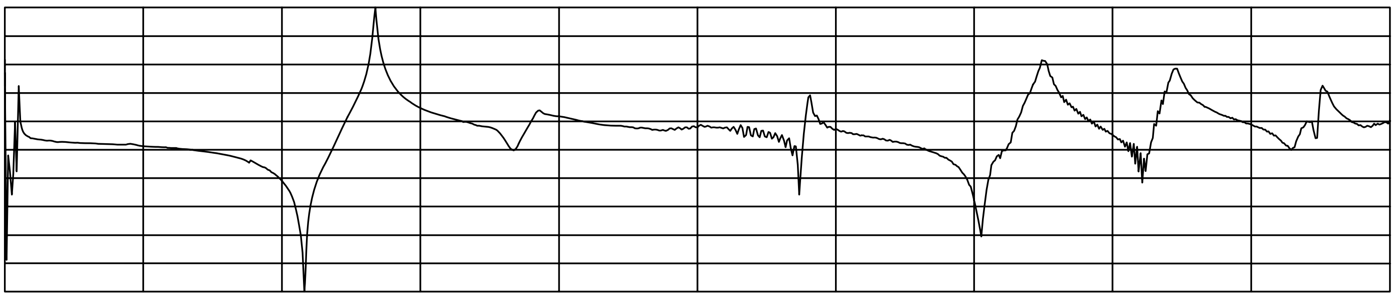


- *Windows will always have an effect on the measured FRF even when the same window is applied to both input and output signals*
- *There will always be a distortion at the peak and the appearance of higher damping*
- *Windows always, always, always, ... distort data!!!*

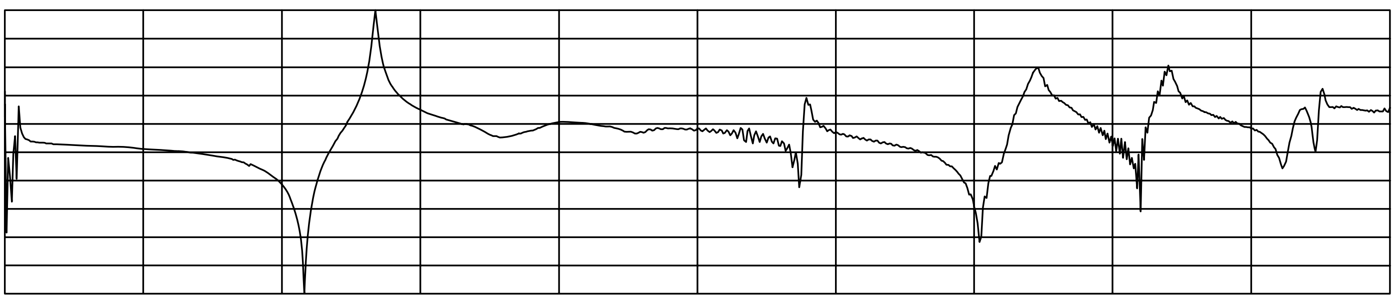
Linearity Check with Sine Chirp Excitation



ONE FORCE UNIT



FIVE FORCE UNITS



TEN FORCE UNITS

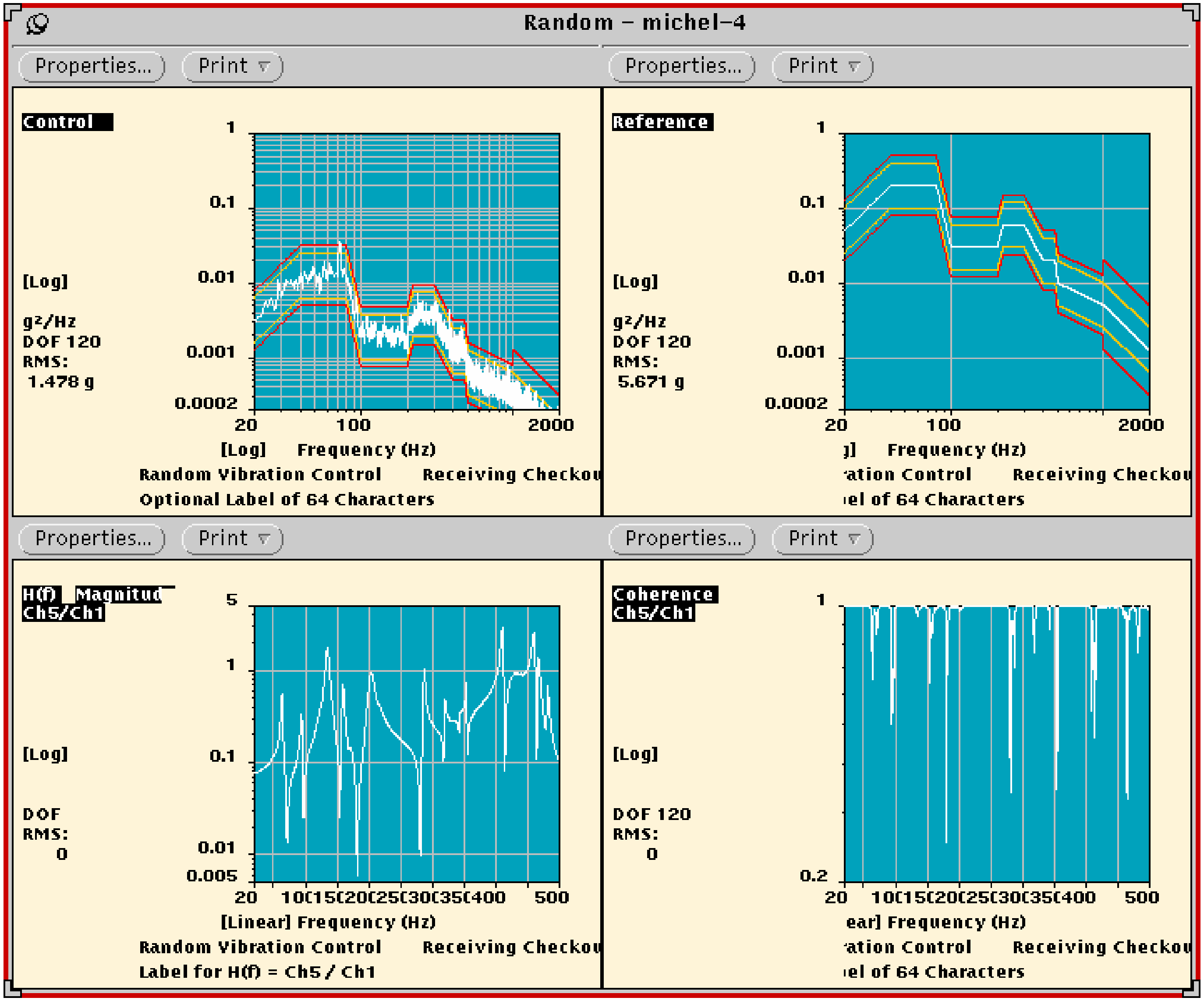
Shaped Spectrum

S H A P E D S P E C T R U M   E X C I T A T I O N

Uncontrolled broadband excitation techniques are used for most modal testing performed today. However, the relatively flat excitation spectrum causes a wide variation in the response accelerometers. This may be a problem when tesing sensitive equipment.

A shaped spectrum, that is contolled, provides an input level that complements the response of the system. This provides a better usage of the ADC since wide variations in level over the frequency range of interest are minimized.

Shaped Spectrum



Multiple Input Multiple Output Shaker Testing

Multiple Input Shaker Excitation

Objectives of this lecture:

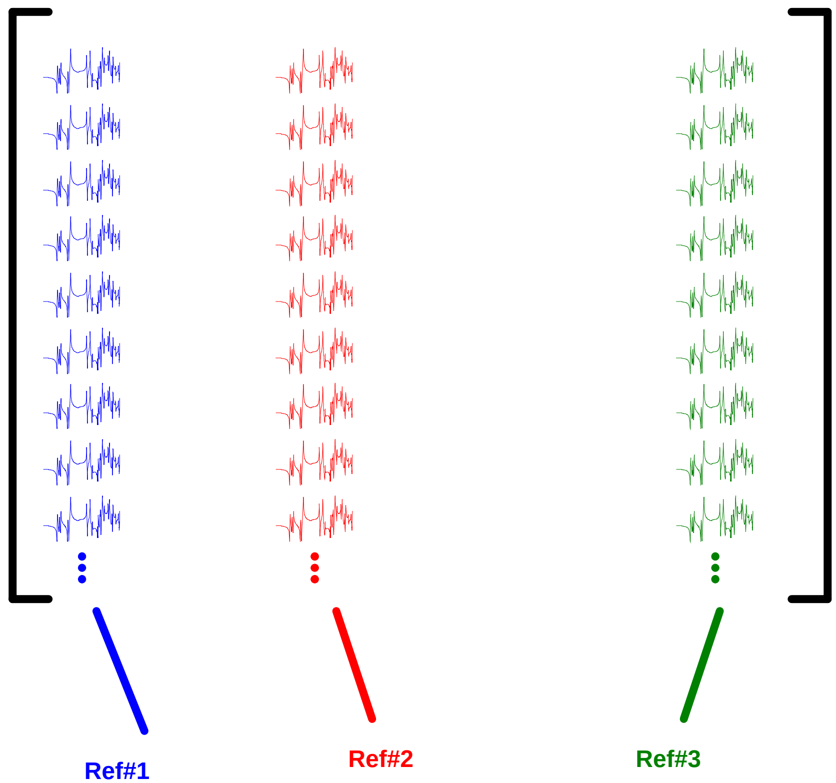
- Discuss several practical aspects of multiple input multiple output shaker testing
- Discuss some tools commonly used in MIMO testing

Multiple Input Shaker Excitation

- *Provide a more even distribution of energy*
- *Simultaneously excite all modes of interest*
- *Multiple columns of FRF matrix acquired*
- *More consistent data is collected*
- *Same test time as SISO case*

Excitation Considerations - MIMO

Multiple referenced FRFs are obtained from MIMO test



Energy is distributed better throughout the structure making better measurements possible

Multiple Input Multiple Output Shaker Testing

$$[G_{XF}] = [H][G_{FF}]$$

$$[H] = \begin{bmatrix} H_{11} & H_{12} & \cdots & H_{1,Ni} \\ H_{21} & H_{22} & \cdots & H_{2,Ni} \\ \vdots & \vdots & & \vdots \\ H_{No,1} & H_{No,2} & \cdots & H_{No,Ni} \end{bmatrix}$$

Measurements are developed in a similar fashion to the single input single output case but using a matrix formulation

where

$$[H] = [G_{XF}][G_{FF}]^{-1}$$

No - number of outputs
Ni - number of inputs

MIMO Testing - Principal Component Analysis

Check for independent shaker inputs. Perform a SVD on the input shaker matrix commonly called Principal Component Analysis

$$[G_{FF}] = [U][S][V]^T$$

The singular values of the SVD should produce large singular values at all frequencies for all shaker excitations. This indicates that the shaker excitation are linearly independent and inversion is possible

Multiple and Partial Coherence

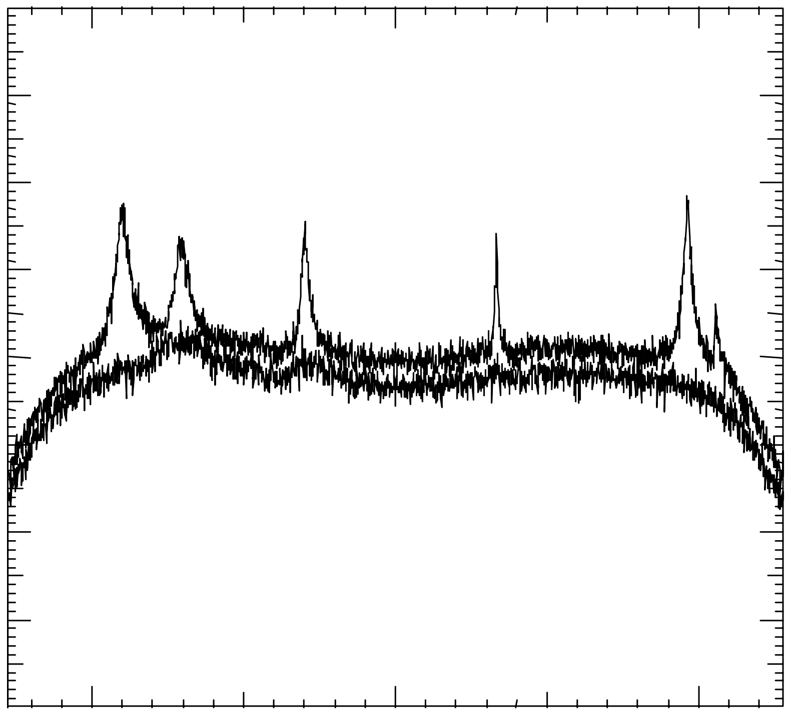
Two additional coherence functions are needed:

Multiple coherence defines how much of the output signal is linearly related to all of the measured input signals. It is very similar to the ordinary coherence of the single input case.

Partial coherence relates how much of the measured output signal is linearly related to one of the measured input signal with the effects of the other measured input signals removed. All of the partial coherences sum together to form the multiple coherence.

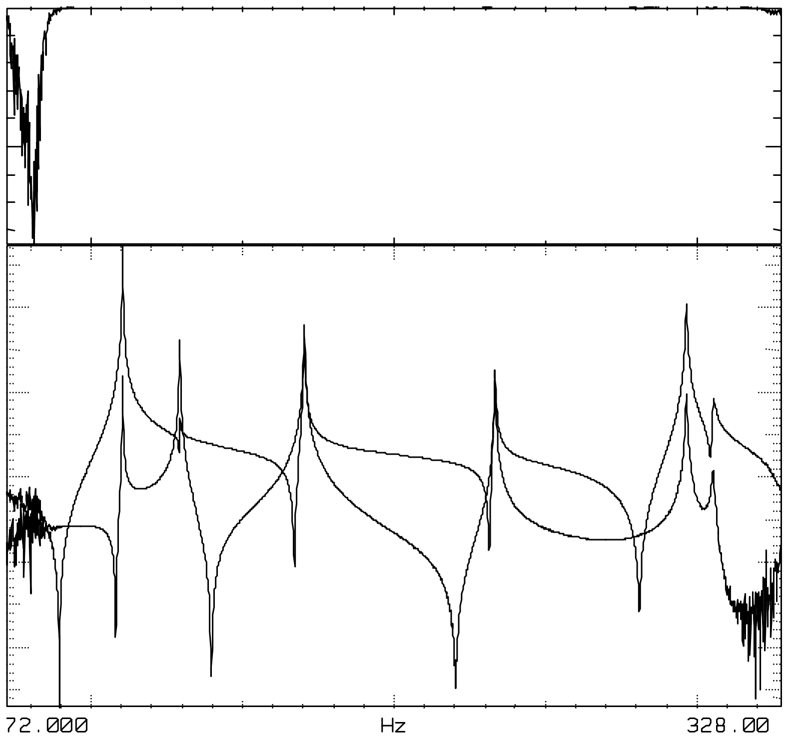
Principal Component Analysis

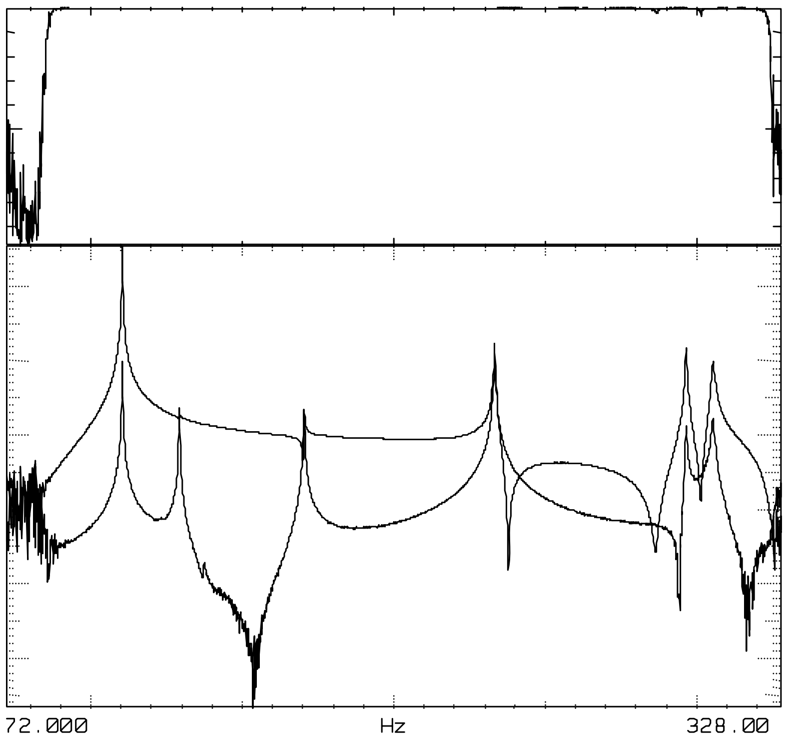
Check for shaker linear independence



MIMO FRF and Multiple Coherence

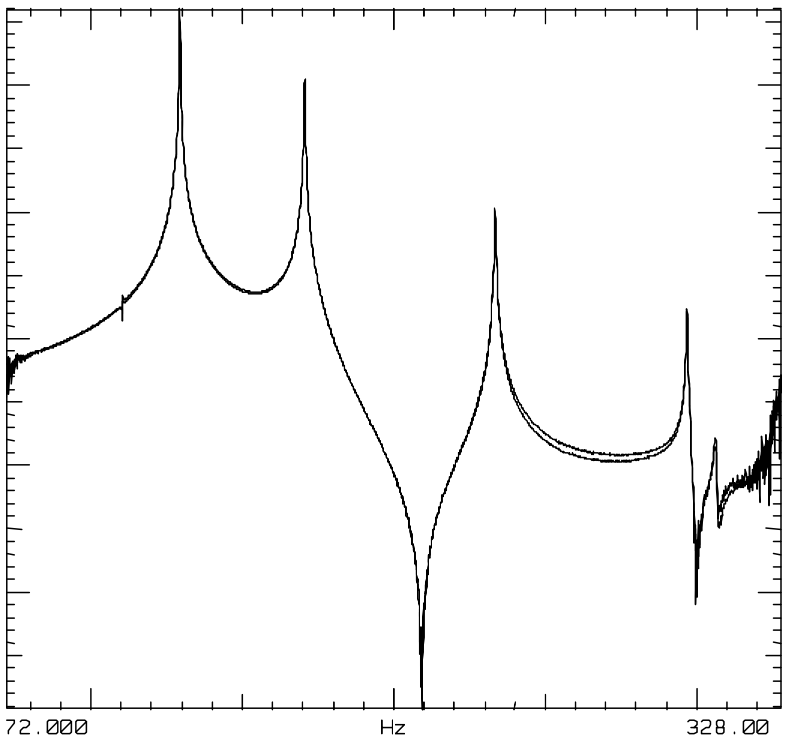
Typical MIMO measurements acquired



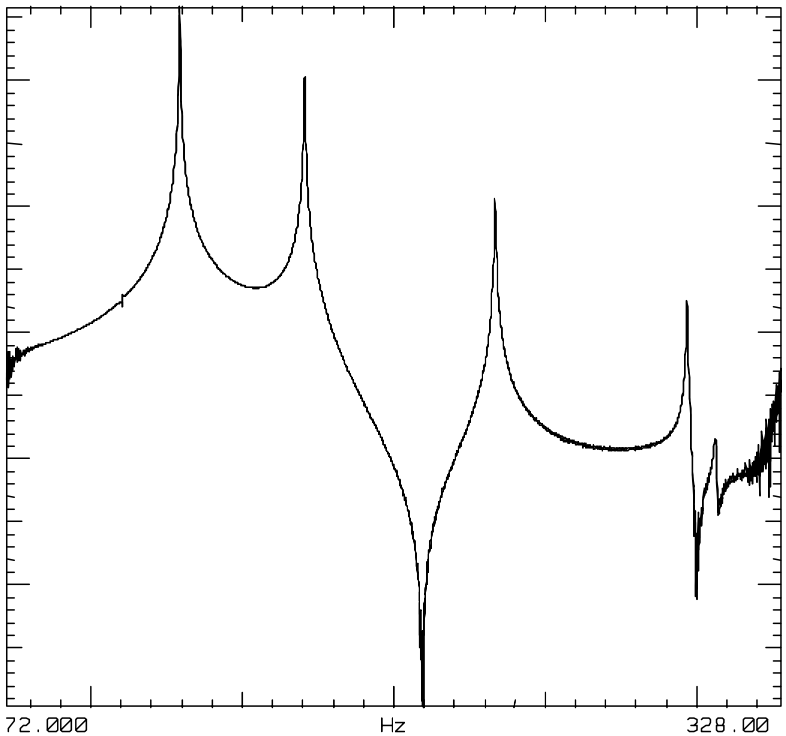


SISO vs MIMO FRF

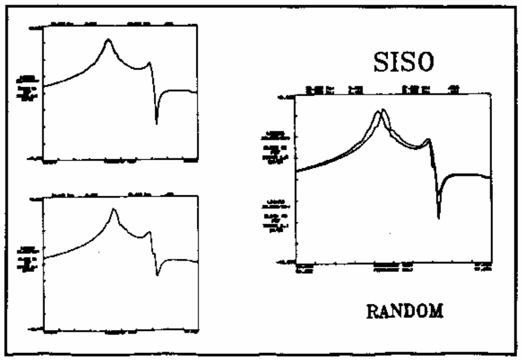
SISO FRF

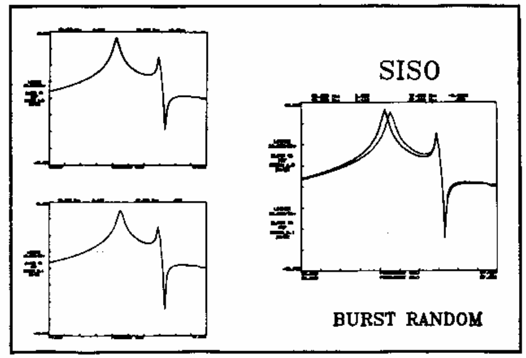


MIMO FRF



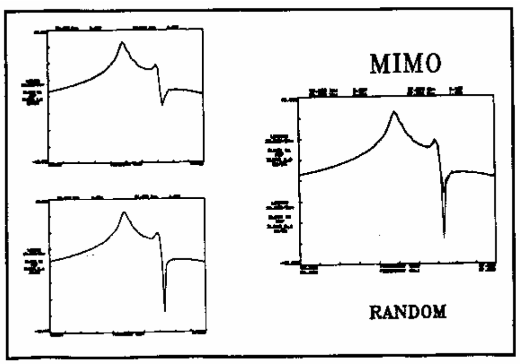
Blue Frame -SISO vs MIMO -Reciprocity Checks

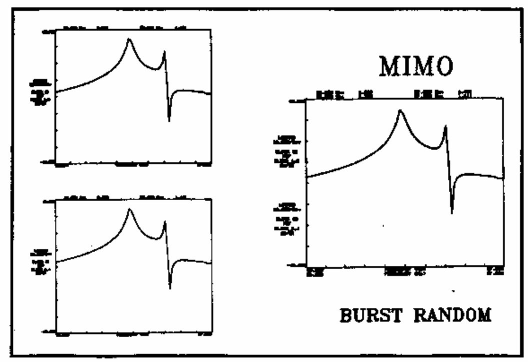




RANDOM WITH WINDOW **BURST RANDOM**

SINGLE INPUT SINGLE OUTPUT TESTING

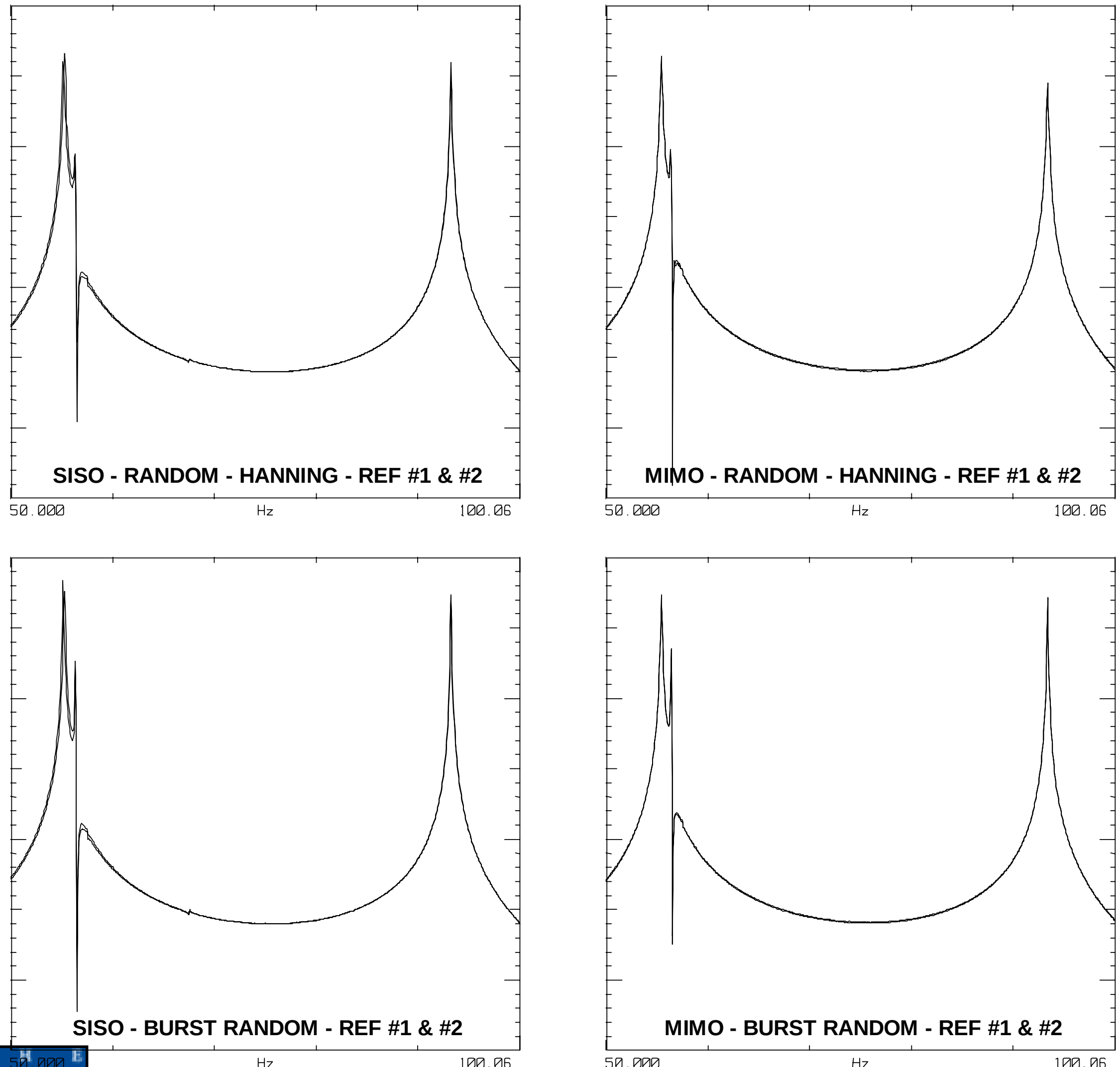




RANDOM WITH WINDOW **BURST RANDOM**

MULTIPLE INPUT MULTIPLE OUTPUT TESTING

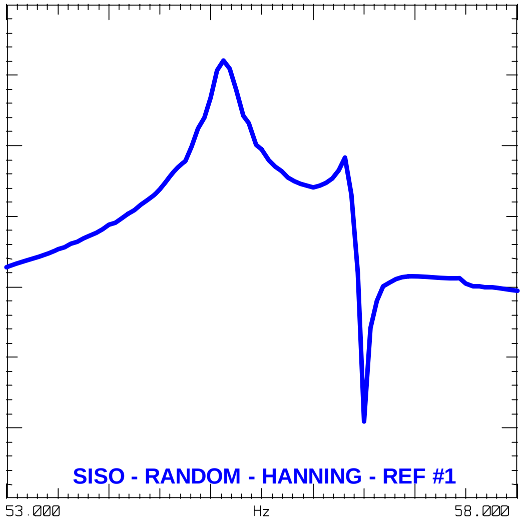
Blue Frame -SISO vs MIMO -Reciprocity Checks

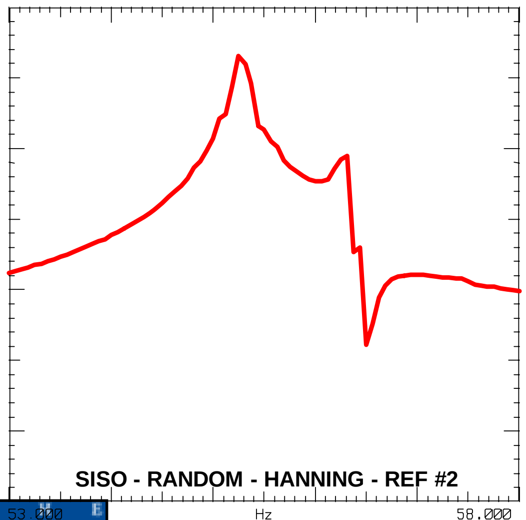


FRFs look reasonably similar

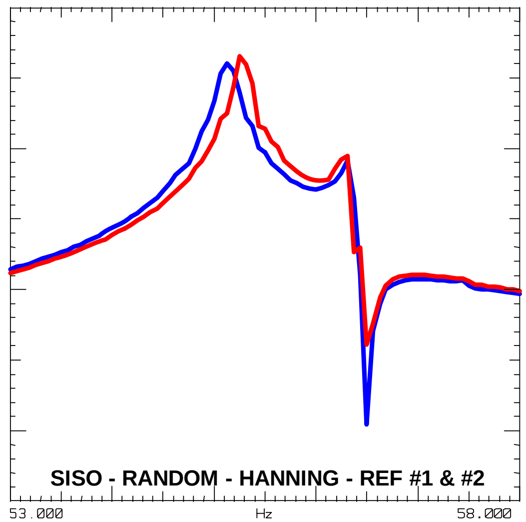
but take a closer look

Blue Frame -SISO vs MIMO -Reciprocity Checks





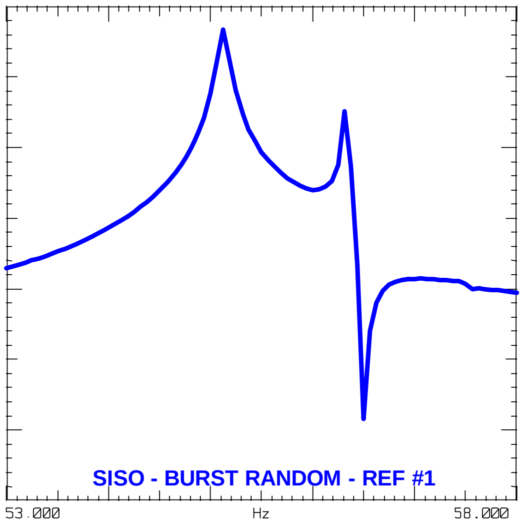
SISO

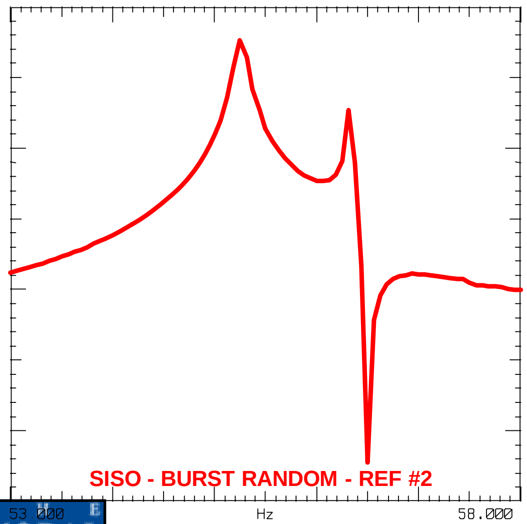


Notice the variance on the FRF measured and the peak shifting

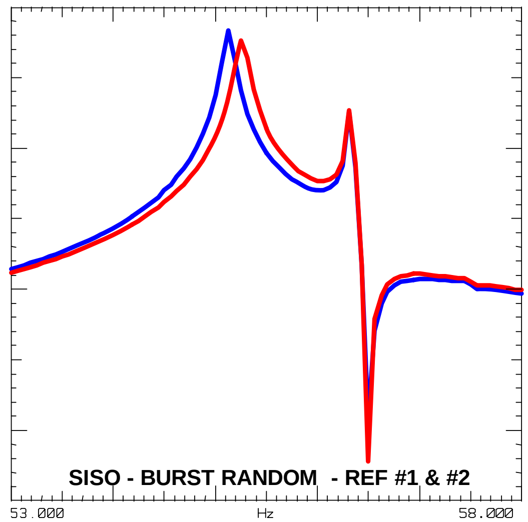
RANDOM
HANNING

Blue Frame -SISO vs MIMO -Reciprocity Checks





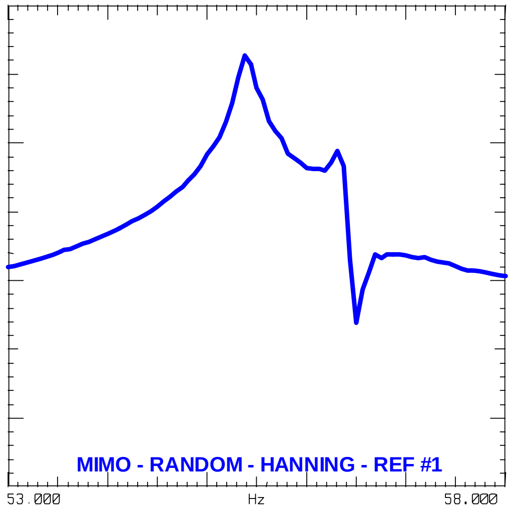
SISO

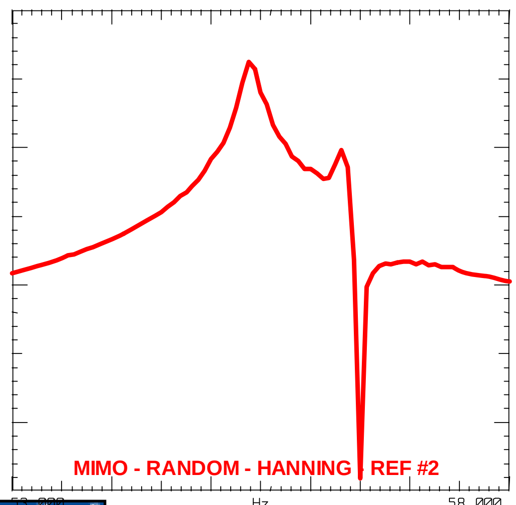


BURST RANDOM

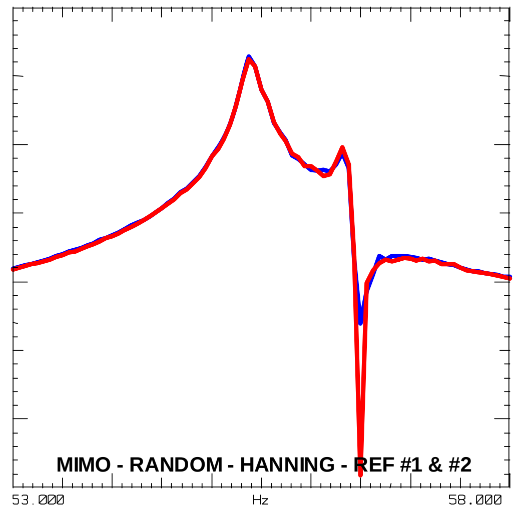
Burst random improves the data but the peaks of the FRFs do not remain the same when single shaker testing is performed

Blue Frame -SISO vs MIMO -Reciprocity Checks





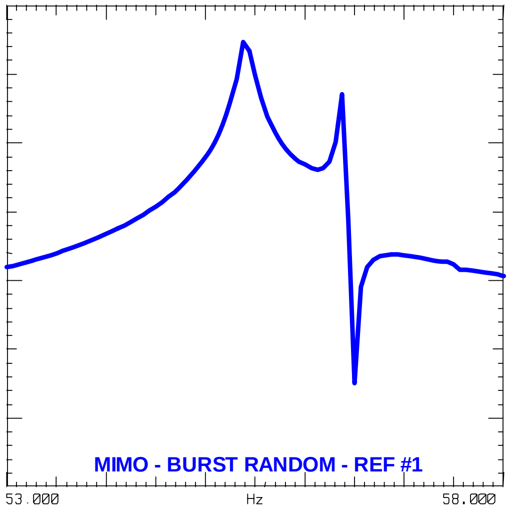
MIMO

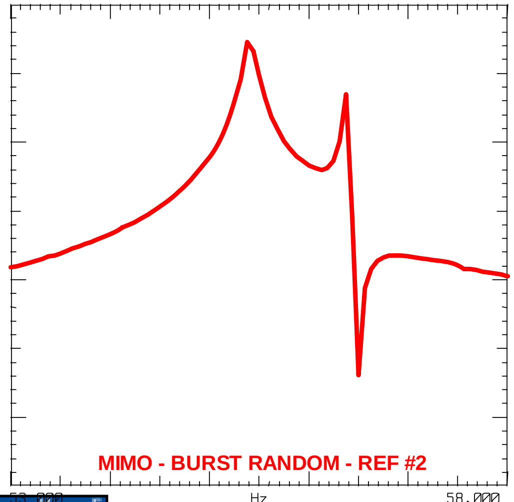


RANDOM HANNING

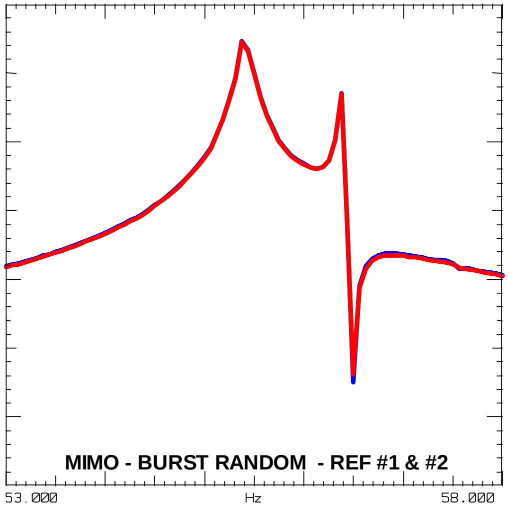
MIMO random improves the consistency but there are other differences that can be seen at the anti-resonance

Blue Frame -SISO vs MIMO -Reciprocity Checks





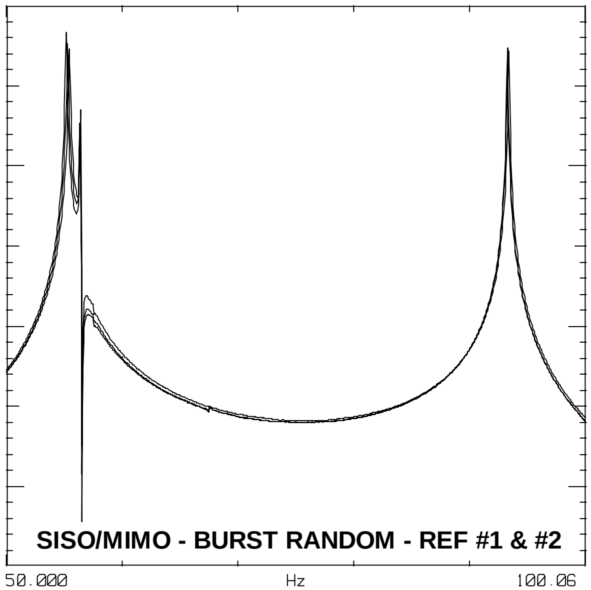
M I M O

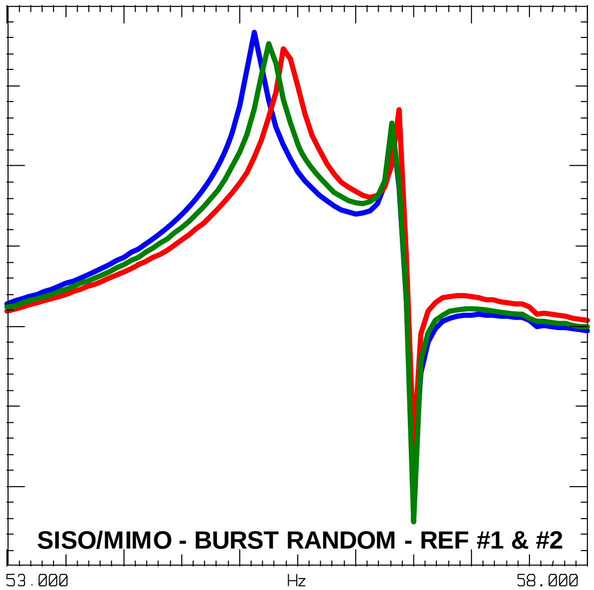


MIMO burst random improves the data in all respects

BURST RANDOM

Blue Frame -SISO vs MIMO -Reciprocity Checks

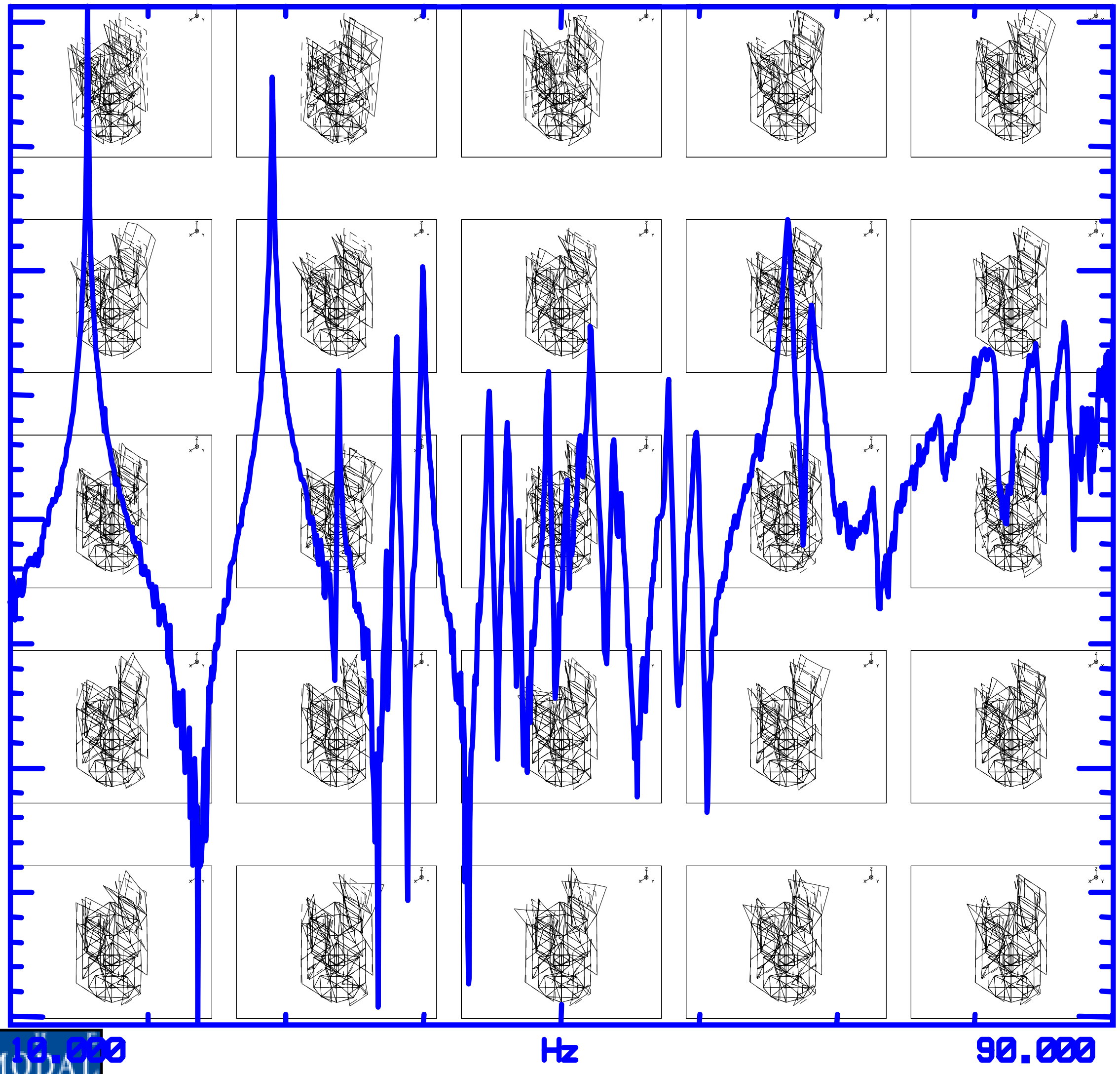




The peaks are definitely shifted relative to the SISO and MIMO data

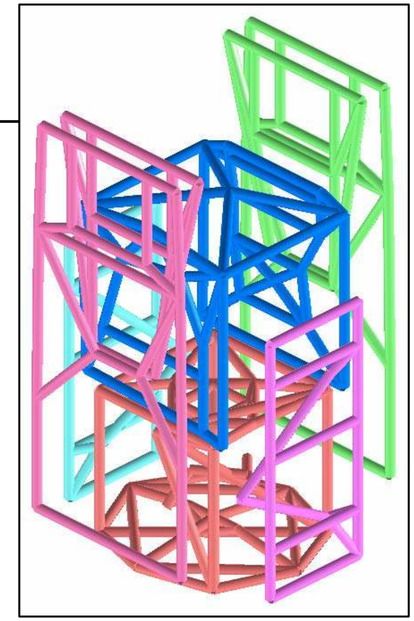
But which is the actual mode ???

Excitation Considerations - MIMO

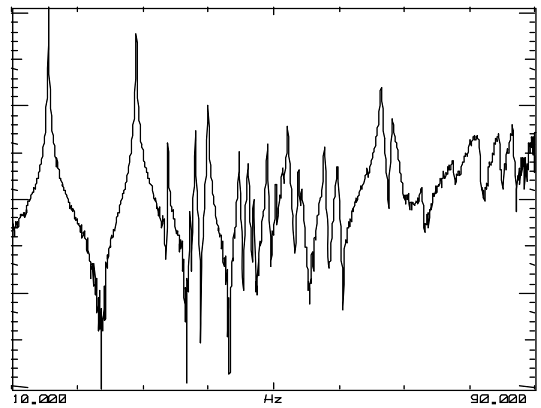


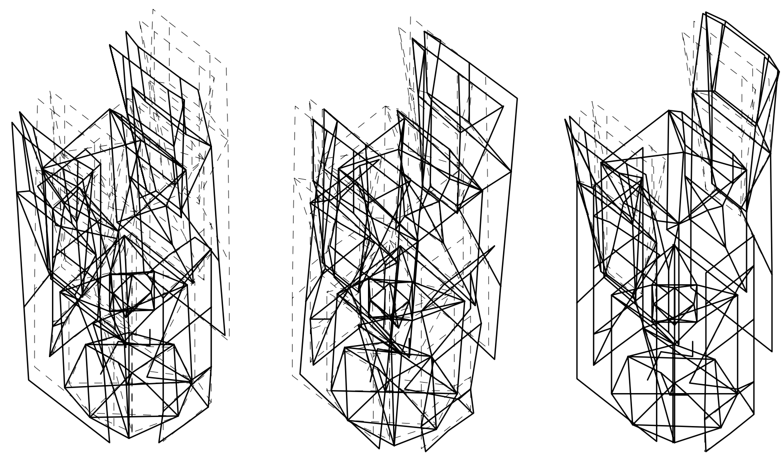
Large or complicated structures require special attention

Excitation Considerations - MIMO



Multiple shakers are needed in order to adequately shaker the structure with sufficient energy to be able to make good measurements for FRF estimation



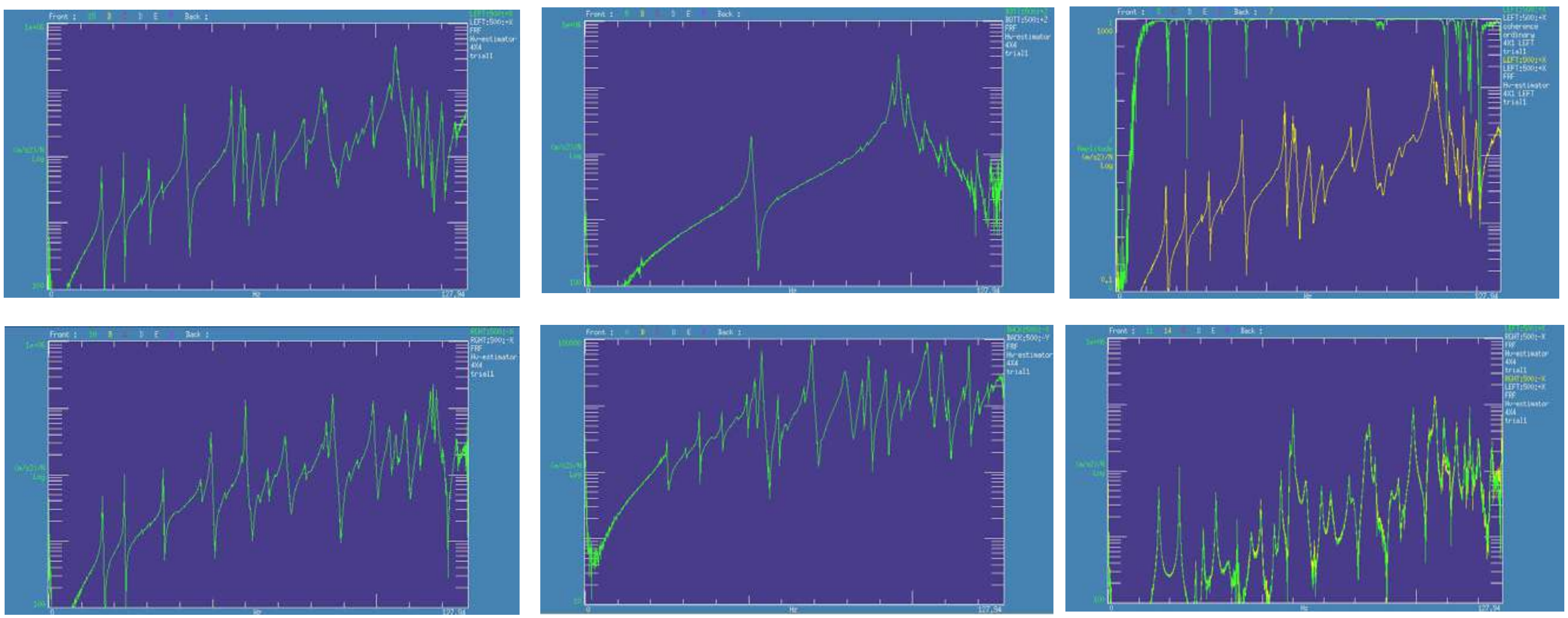


Excitation Considerations - MIMO

Flimsy Dryer Cabinet requires special attention when measuring frequency response functions for modal testing. Extremely lightweight structures are very difficult to test and obtain quality FRFs

Excitation Considerations - MIMO

Measurements on the same structure can show tremendously different modal densities depending on the location of the measurement



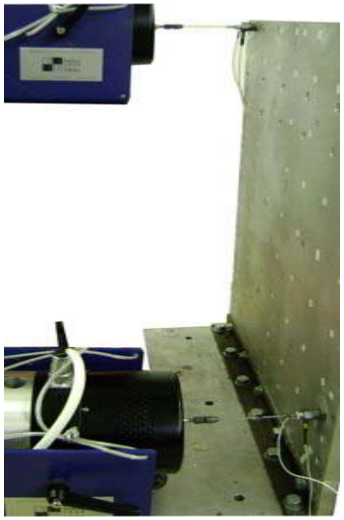
Things no one ever told me !!!

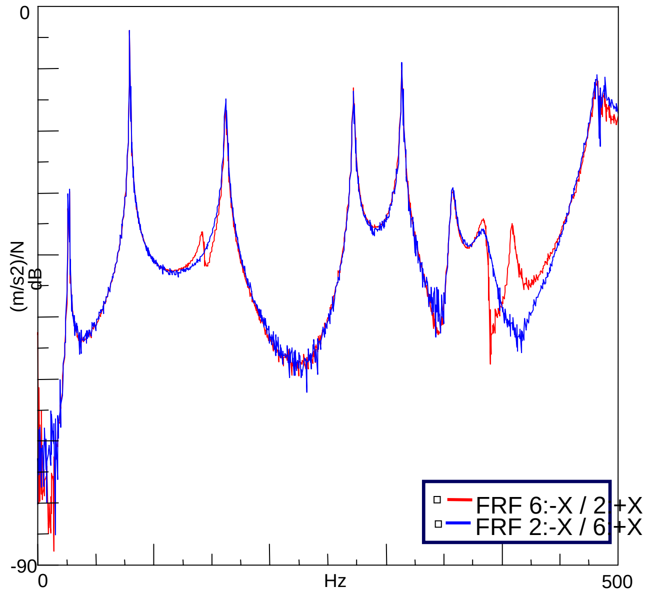
Shaker testing is very powerful but there are many issues that must be understood.

Some of these are identified on the next pages

Reciprocity

Even on simple structures, reciprocity can be a problem but not due to the structure

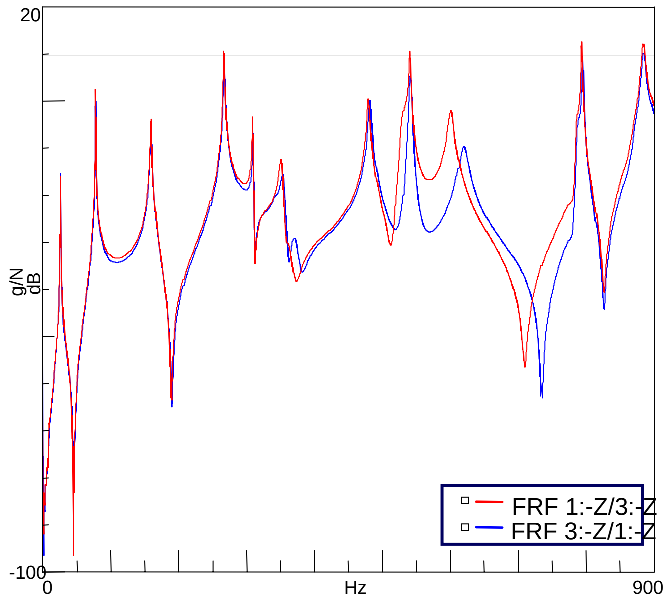


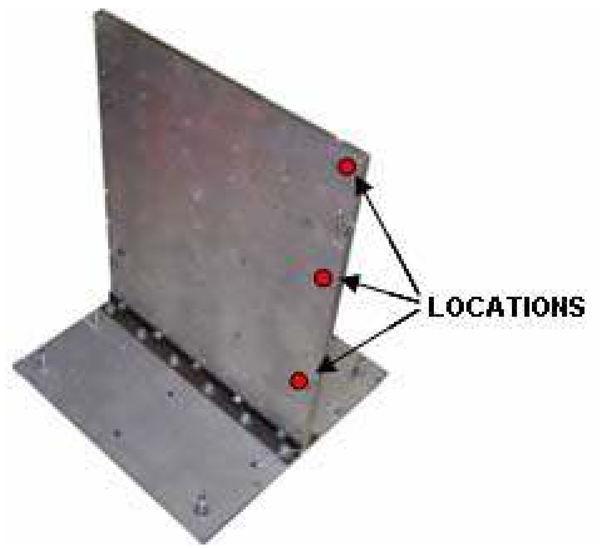


Here is an example of a stinger flexibility due to rotation effects – the upper portion of the structure has a rotational effect

Reciprocity – SISO FRF Measurements

Using SISO, several measurements were made at different locations as shown

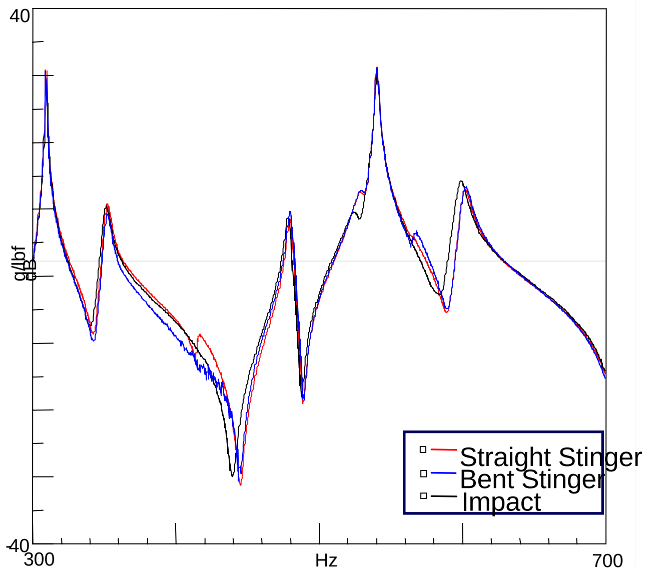


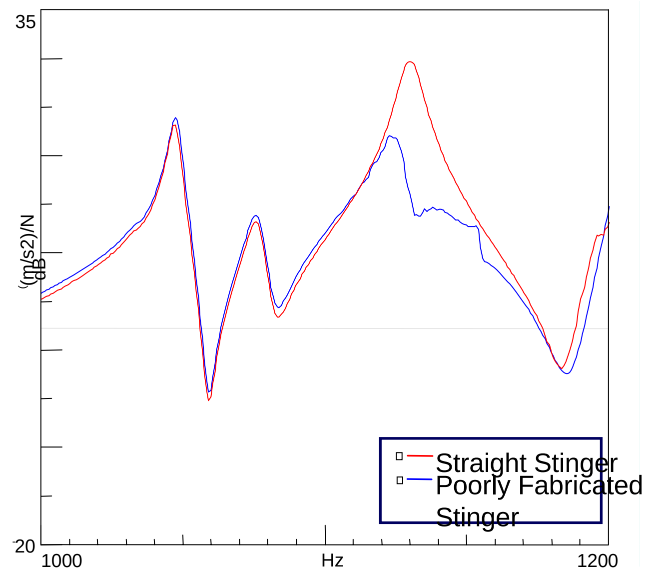


While only a few sample measurements are shown, there is an effect of the shaker location on the structure and the rotational stinger effect.

Stinger Alignment or Damaged Stinger

An incorrectly aligned stinger or a poorly fabricated stinger can ruin a test

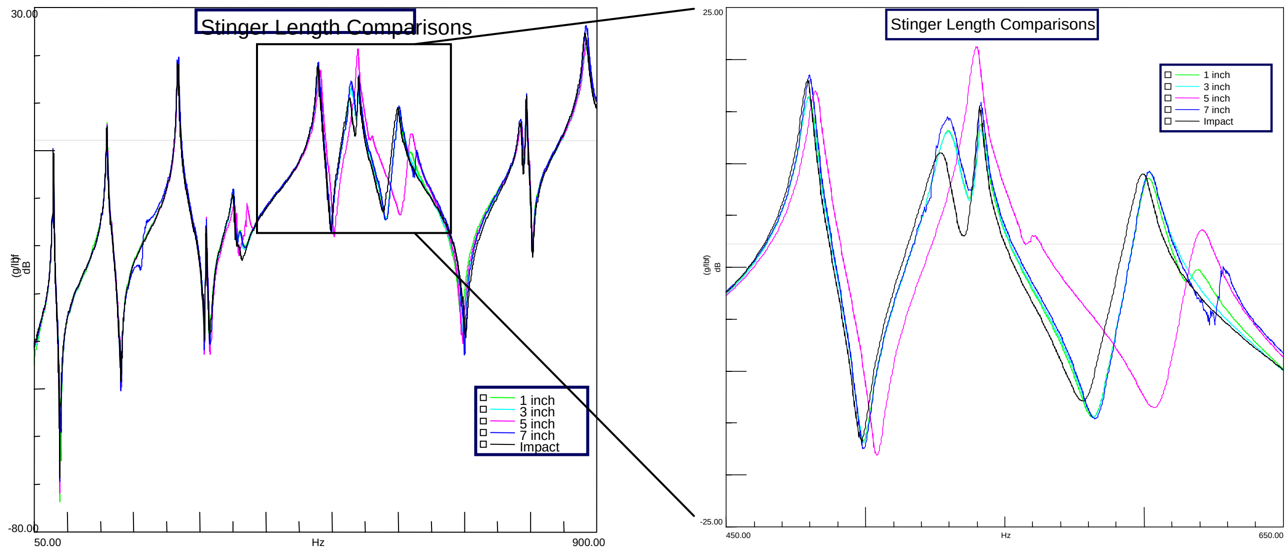




Here are two examples of the effect on an FRF measurement due to these problems

Stinger Length

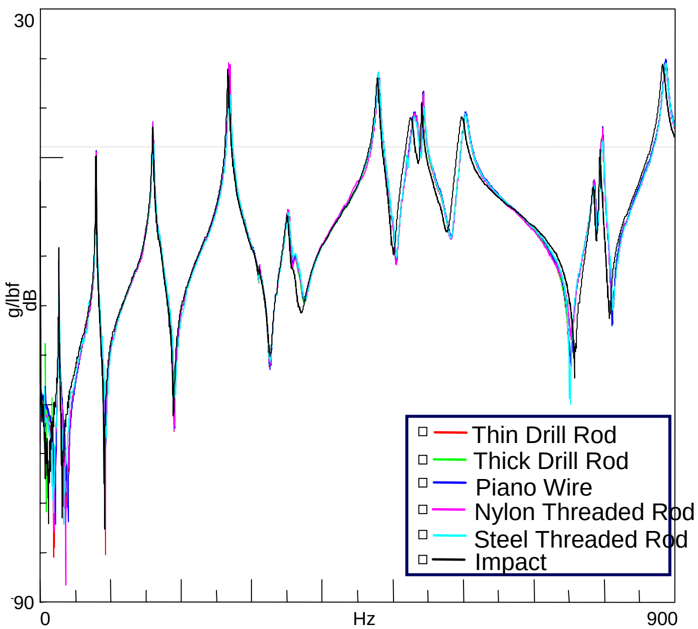
The length of the stinger can also have an impact on the measured response.

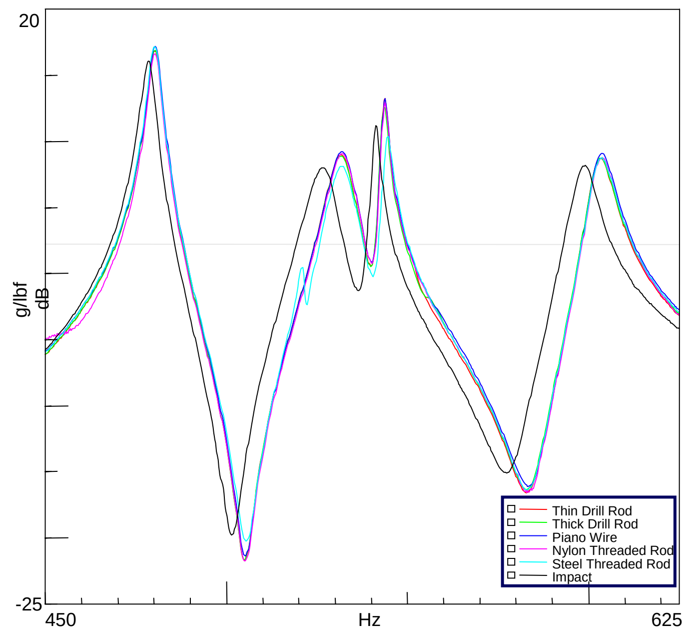


Too short a stinger will have higher lateral stiffness and too long a stinger will have flexibility

Stinger Type

There are many different stinger types





There can be an effect due to these differences

IMAC 27 - Orlando, FL - 2009

Shaker Excitation

Peter Avitabile
UMASS Lowell

Marco Peres
The Modal Shop