Verification & Validation of Physics-Based Models for Blast Applications

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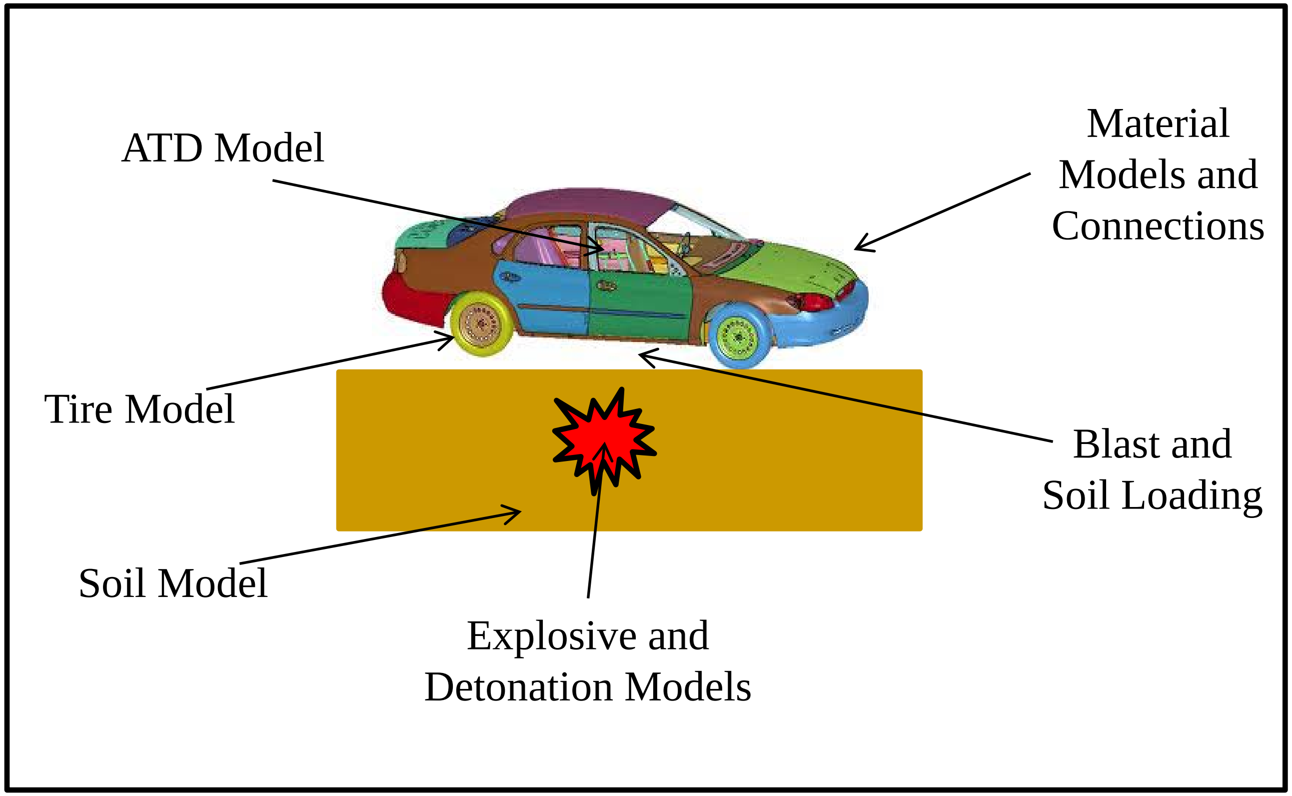
Introduction/Overview

Purpose: Evaluate various survivability scenarios in terms of structural response and personnel injury to buried detonations

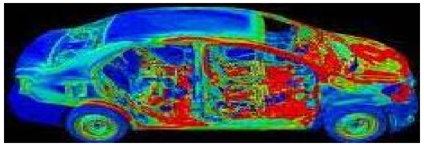
- Predict test events
- Interpolate between test events and support LFT&E planning
- Extrapolate to support survivability decisions and understand theater events

V&V used to answer:

- Is there confidence in the model?
- Is the model credible?
- Is the model fit for the intended use?



Simulation Process



Vehicle

Meshed Model

Vehicle Response

Tech data package
CAD drawing
Scans

Solve conservation equations (mass, momentum, energy)
EOS
Constitutive models

V&V Process

Verify
- Meshed model accurately represents production vehicle
- Fundamental level of physics is captured

Validate
-Fundamental physics by independently predicting simple experiments
-Simulation output by comparing to live fire and theater data

Verification

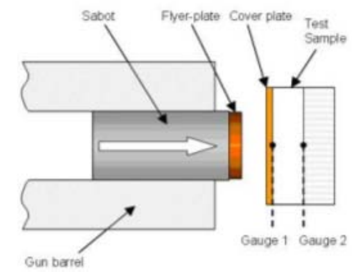
- *Did I build the thing right?*
- Ensures implemented model and its associated data accurately represent the developer's conceptual description and specification
- Verification of
  - Physics Based Models
  - Vehicle Models

Verification: Physics Based Models

Physics based models should be verified at the fundamental level, each verified independently

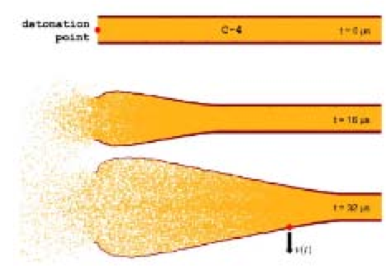
Soil Verification

- Quasi-static material characterization
- Heave tests
- Flyer plate test (high strain rate response)



Explosive Verification

- JWL EOS
- Cylinder test



Verification: Vehicle

Vehicle

Tech data package
CAD drawing
Scans
Technical knowledge
Manufacturing knowledge

Verify meshed model accurately represents production vehicle

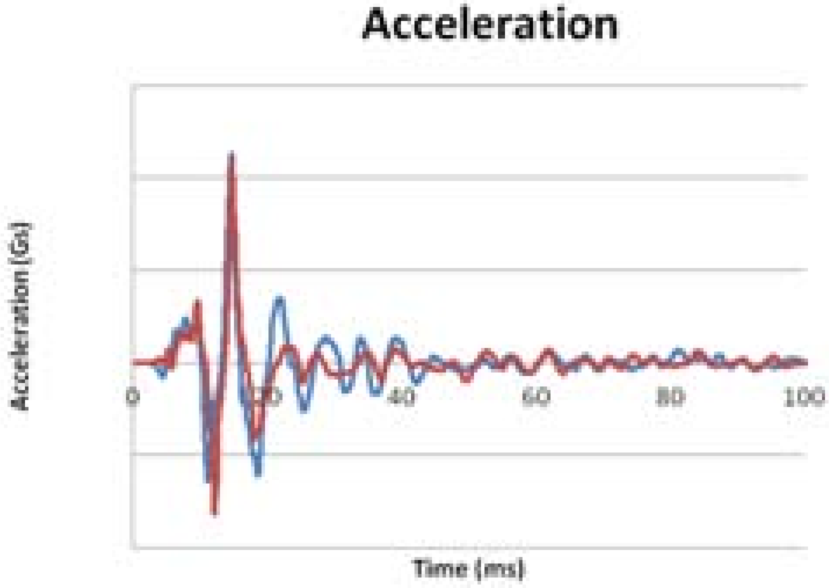
Meshed Model

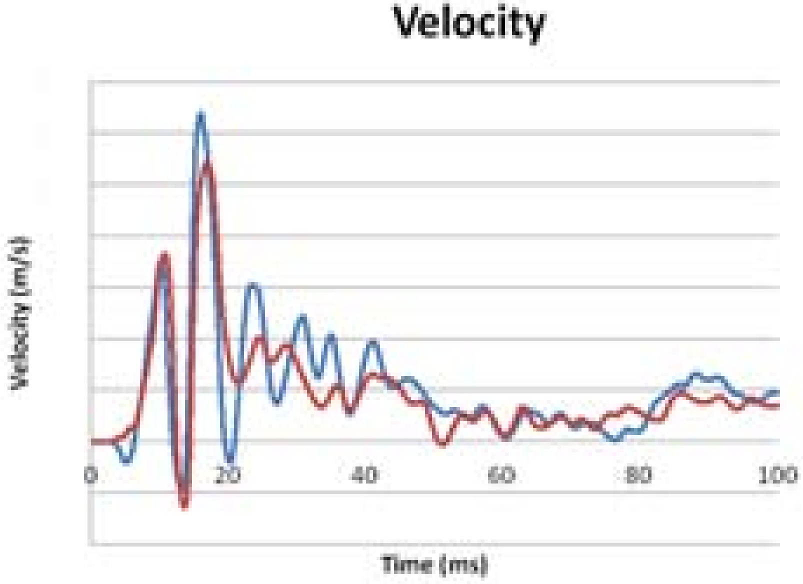
Vehicle Verification

- Compare model to production vehicle
  - Gross vehicle weight
  - Dimensions
  - Center of gravity
  - Materials
  - Correctness and completeness of parts and internal equipment
- Is there enough detail?
  - Internal components
  - Connections: bolts, welds

Validation

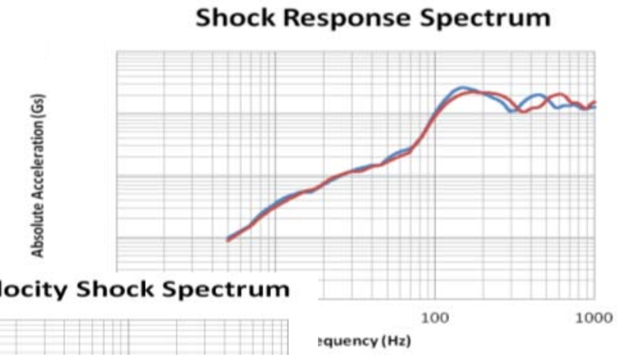
- *Did I build the right thing?*
- Validation determines the degree to which a model or simulation accurately represents the real world from the perspective of the intended uses
- Commonly used Validation Metrics
  - Vehicle damage
  - Acceleration, velocity, and displacement time histories
  - Frequency response

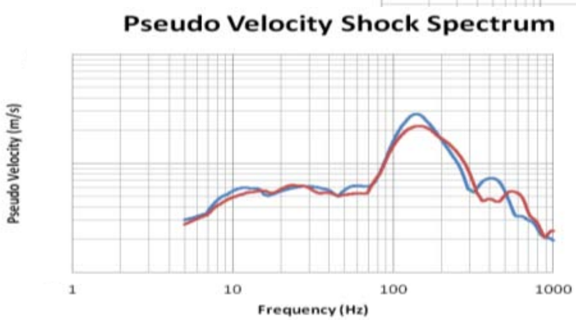




Validation Metrics in the Frequency Domain

- Important to match response in the frequency domain as well as the time domain
  - Matching frequencies reveals how well the model represents reality:
    - Geometry, boundary conditions, and material properties
  - Matching frequency gives an additional level of confidence
- Several options for comparing a signal's frequency response
  - Shock Response Spectrum (SRS)
  - Pseudo Velocity Shock Spectrum (PVSS)
  - Modal Analysis





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Mathematical Background

- Solution to the differential equation governing the motion of a mechanical system subjected to loading from a ballistic event is expressed in terms of a Fourier series

$$A_n(t)Sin(2\pi t\omega_n + \phi_n)$$

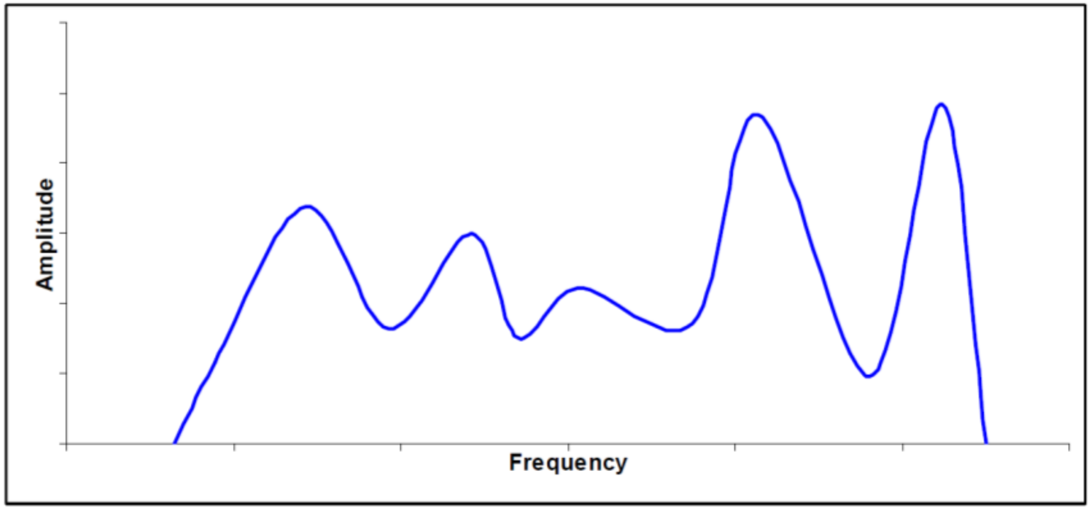
- t is time, $A_n(t)$ is the time-varying amplitude, ω is the nth-term frequency, and ϕ is the nth-term phase angle

Mathematical Background

- Fourier transform
- Takes the function g(t) in the time domain and converts it to the function G(f) in the frequency domain

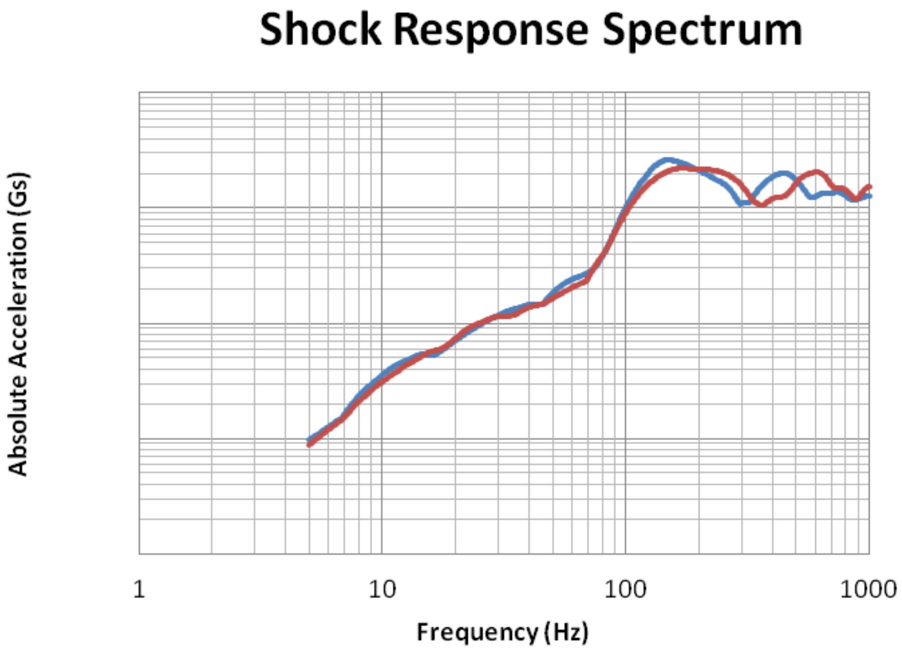
$$G(f) = \int_{-\infty}^{+\infty} g(t) e^{-i2\pi ft} dt \qquad G(f_k) = \sum_{n=1}^{N-1} g(t_n) e^{-i2\pi \frac{k}{N} n}$$

- A plot of |G| or $|G|^2$ vs frequency is called the spectrum



Validation Metrics in the Frequency Domain

- Shock Response Spectrum (SRS)
  - Treats acceleration as input to single degree of freedom mass spring damper systems with various natural frequencies
  - Response represents peak accelerative response



*Damping Factor Q = 10 used

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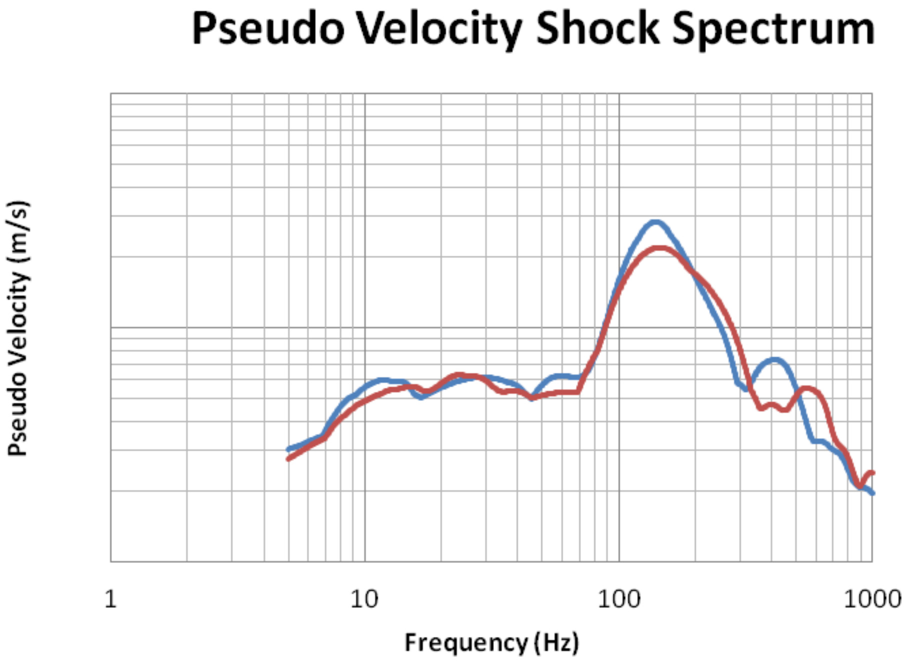
Validation Metrics in the Frequency Domain

- Pseudo Velocity Shock Spectrum (PVSS)
  - Similar to the SRS, except peak velocity of each SDOF system is plotted



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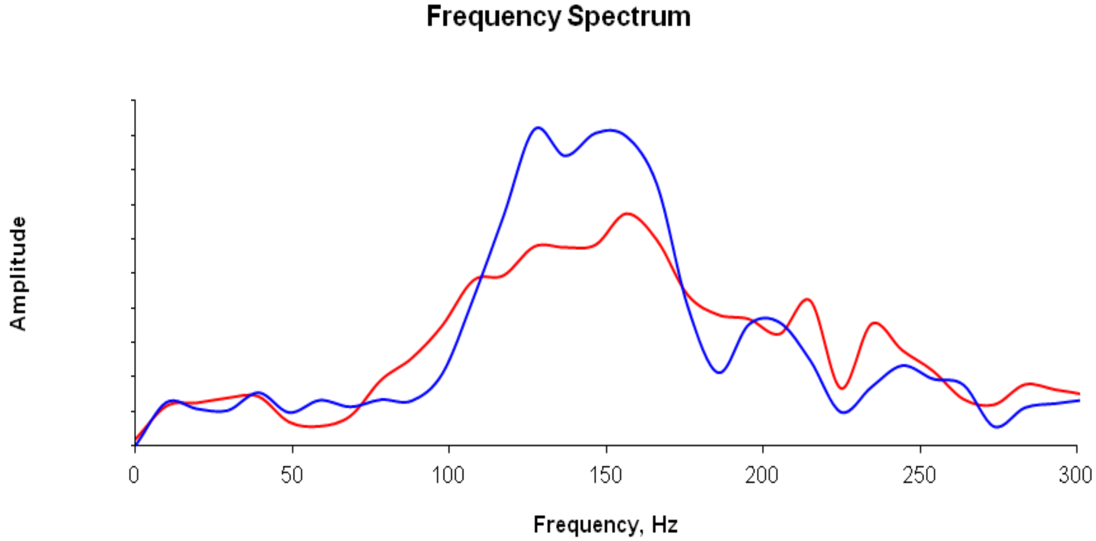
Why Modal Analysis?

- SRS and PVSS
  - Might get the right answer for the wrong reason(s)
  - Summary statistics
  - No way to directly compare test to test or test to simulation
- Modal Analysis
  - Comparison of test data and simulation output is not in how well summary statistics match up, but in how well the constituent parts match up.
  - Comparison between the fundamental mathematical properties of the approximate solution to the differential equation from the simulation and the fundamental mathematical properties of the measured test data

Modal Analysis

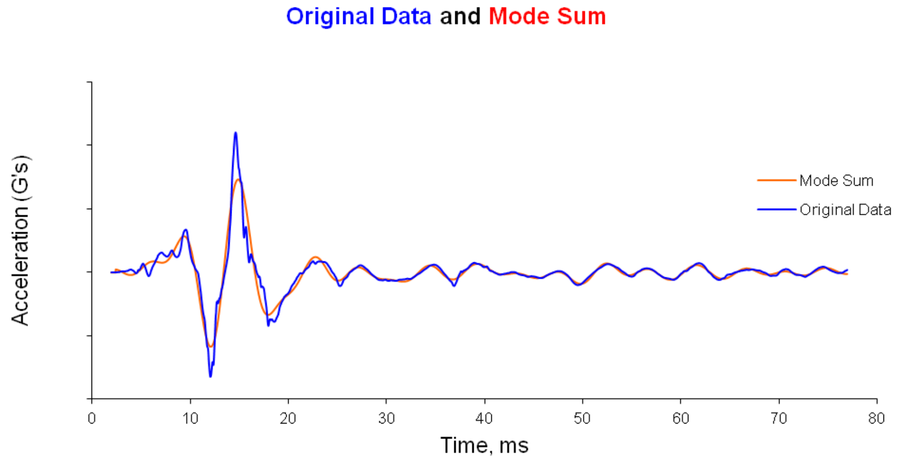
- Alternate look at frequency content
  - Determine modal frequencies, then isolate corresponding modes
  - Modal frequencies found by performing a discrete Fourier Transform on the time series of interest – shown below
  - Regions of frequency content that most strongly influence vehicle response chosen for isolation
  - Table of regions and corresponding frequency ranges shown on right

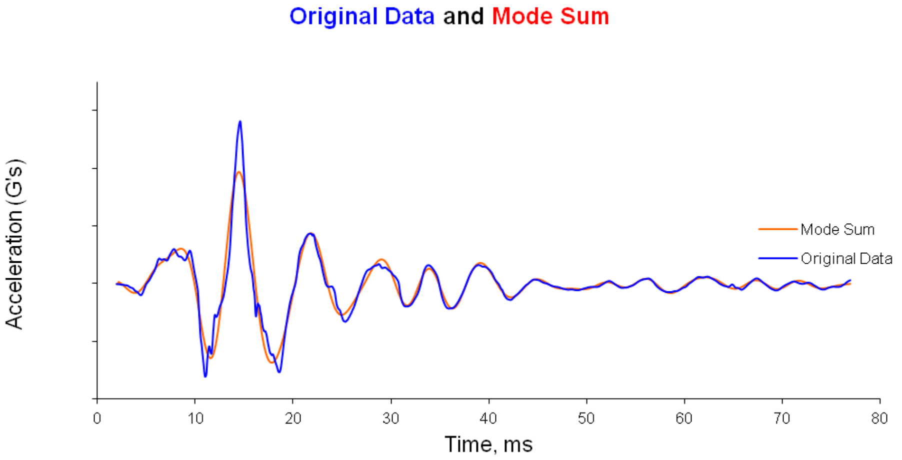


Region	Red	Blue
1	0-59	0-88
2	59-137	88-137
3	137-205	137-186
4	205-225	186-225
5	225-273	225-273

Modal Analysis

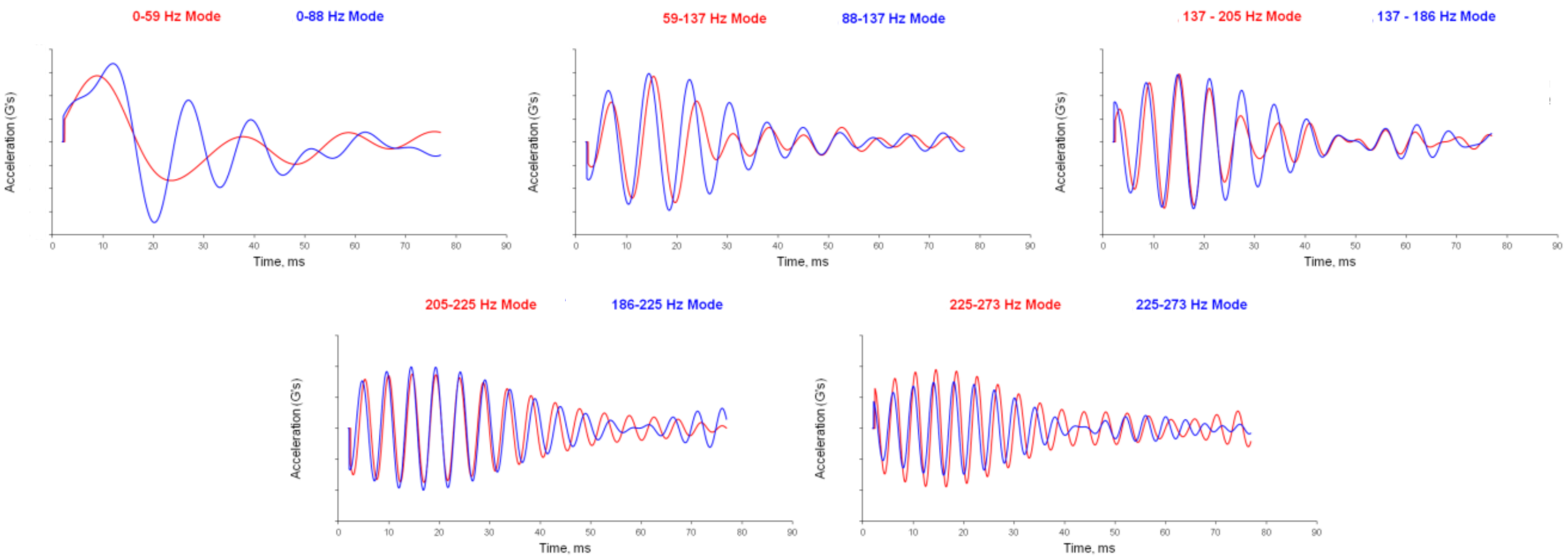
- Sufficient frequency content?
  - Removed all but the first 273 Hz of information
  - Do these modes faithfully represent the original signal?
  - Original Data vs. Mode Sum shown for both test events below
    - Effect similar to that of a low-pass filter





Modal Analysis

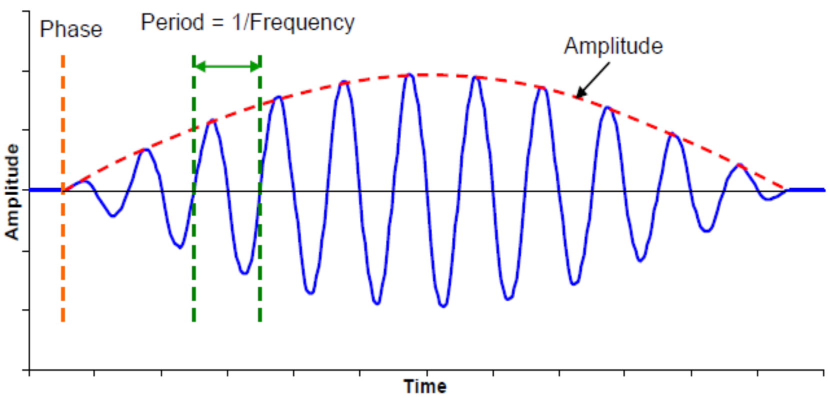
- Isolation via Filter, Transform back to Time Domain
  - Band-pass filters applied to each peak of interest
  - Filter must have very steep roll-off characteristics with minimum ripple in the pass bands and stop bands
  - Isolated spectral bands then individually transformed back into time domain, where they have sine wave-like characteristics



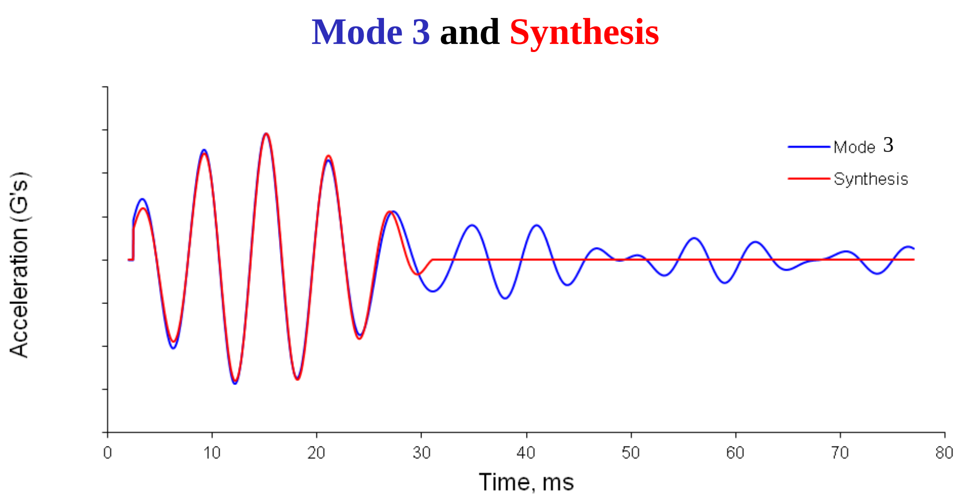
- Representing Modes with an Equation
  - Modes shown were each sums of the close frequencies in that spectral band
  - Goal: find a damped sine wave that approximates the mode, and has the form of Y() and looks like the figure below

$$Y = \sum_{n=1}^{5} A_n * \sin 2\pi \cdot F_n \cdot (T - T0_n) * \sin(2\pi \cdot W_n \cdot (T - ST_n) + \text{Phase}_n)$$

  - Finding the equation entails choosing W_n, Phase_n, A_n, F_n, and $T0_n$, and lining up the sine wave with the modal response
  - Call this the "synthesized equation"



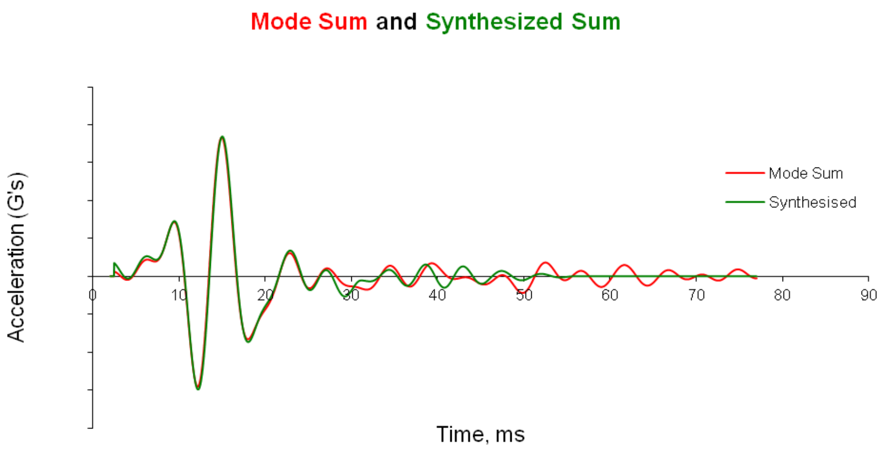
- Representing Modes with an Equation, cont.
  - Example of a mode and the corresponding synthesized equation shown below
  - Red represents best attempt to match the mode with a damped wave
  - Beyond the first 30 ms, the data is of lower amplitude and is of less interest – tends to be eliminated
    - Other synthesized equations incorporate up to the first 50 ms of the mode

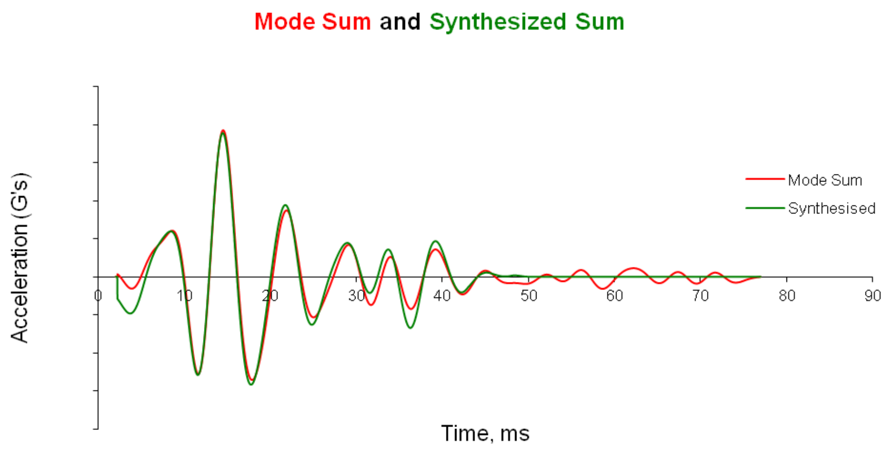


	Region 3
Range (Hz)	137-205
A (gs)	292.7
F (Hz)	15.63
T0 (sec)	-0.001
W (Hz)	167
Phase (Ra)	0.785
ST (sec)	0.002425
ET (sec)	0.031025
Start (msec)	-1
Duration (msec)	32
Amp Adj	1

Modal Analysis

- Modal equations added
  - The five modal equations added together will approximate the mode sum, which in turn approximates the original time series data
- Mode Sum and Synthesized Sum
  - First 50 ms lines up very well





Modal Analysis for Validation

Comparison Process

1) Isolate the first several terms of the time series for the test data and for the simulation output

2) Compare the frequency spectra and decide which frequency ranges are to be isolated

3) Isolate those frequency ranges in both data sets and compare the terms for frequency, phase, and amplitude content.

4) Derive the equations for the components of both the simulation output and the test data to compare the three parameters and understand how close they are to actual terms of the Fourier series and to one another.

Modal Analysis for Validation

Comparison Process Continued

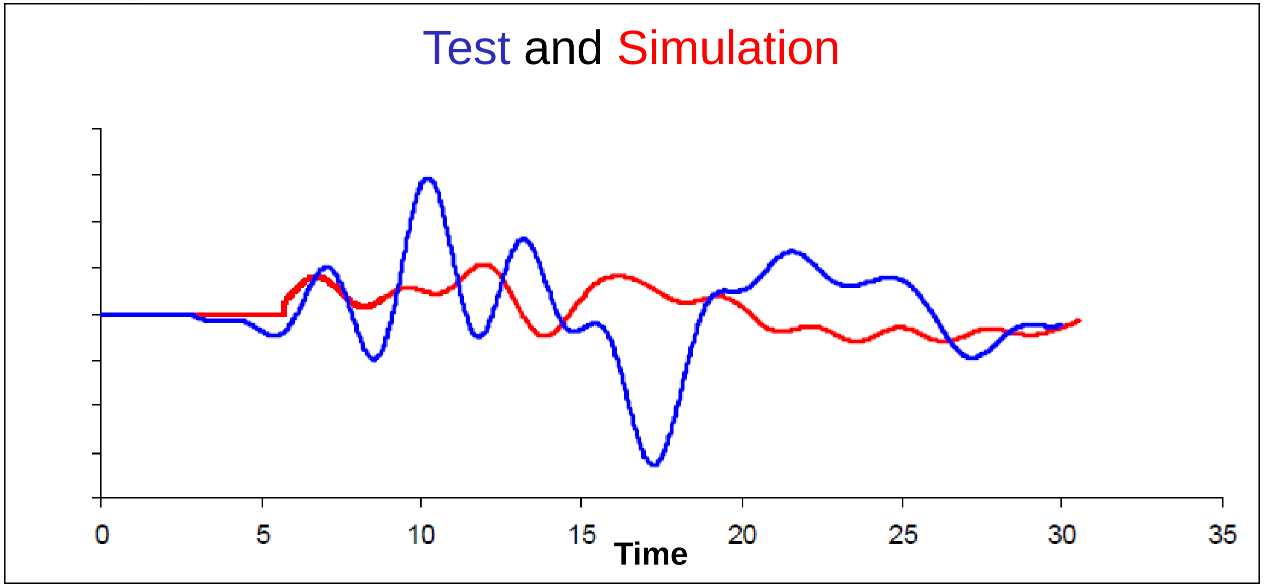
(5) Amplitude- and phase-adjust the components of the simulation output, if and as necessary, to match those of the test data;

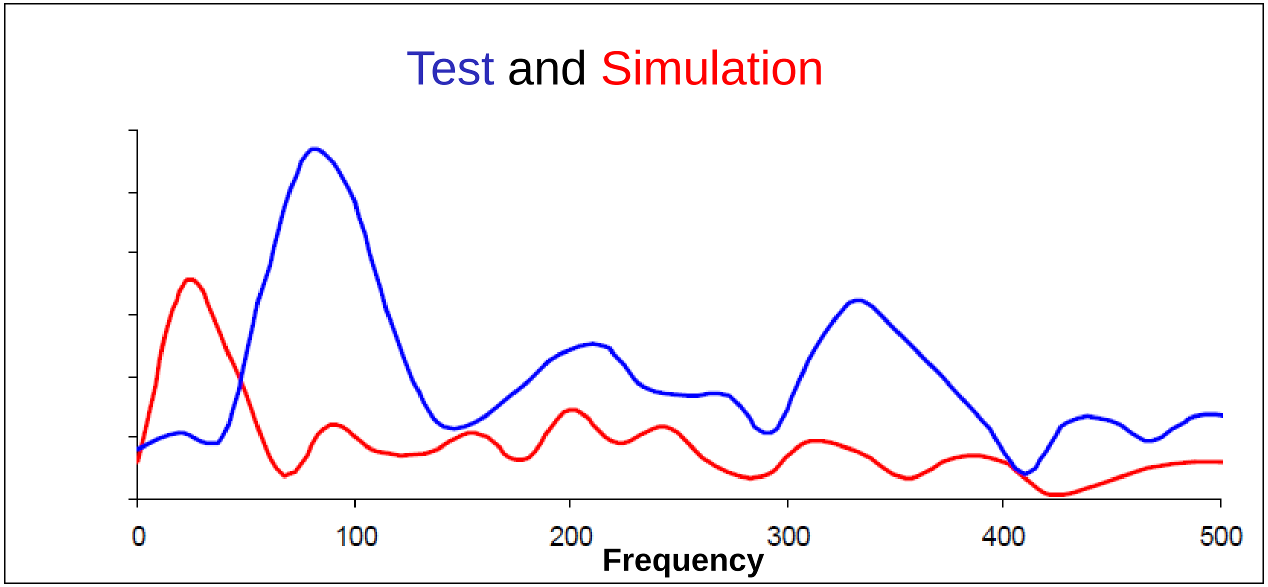
(6) Compare the sums of the resulting components for curve shape and timing (phasing).

Modal Analysis for Validation

- Good agreement in frequency content indicates a good understanding of the geometric and material properties of the system.
- Good agreement in phasing indicates a good understanding of the relative timing of the events and the path through the structure from the point of application of the force to the analytical point.
- Good agreement in amplitude indicates a good understanding of the system damping and the presence of the considerable luck (that is, the test event happened to produce the same force as was assumed in the FEM simulation).

Example: Modal Analysis Validation





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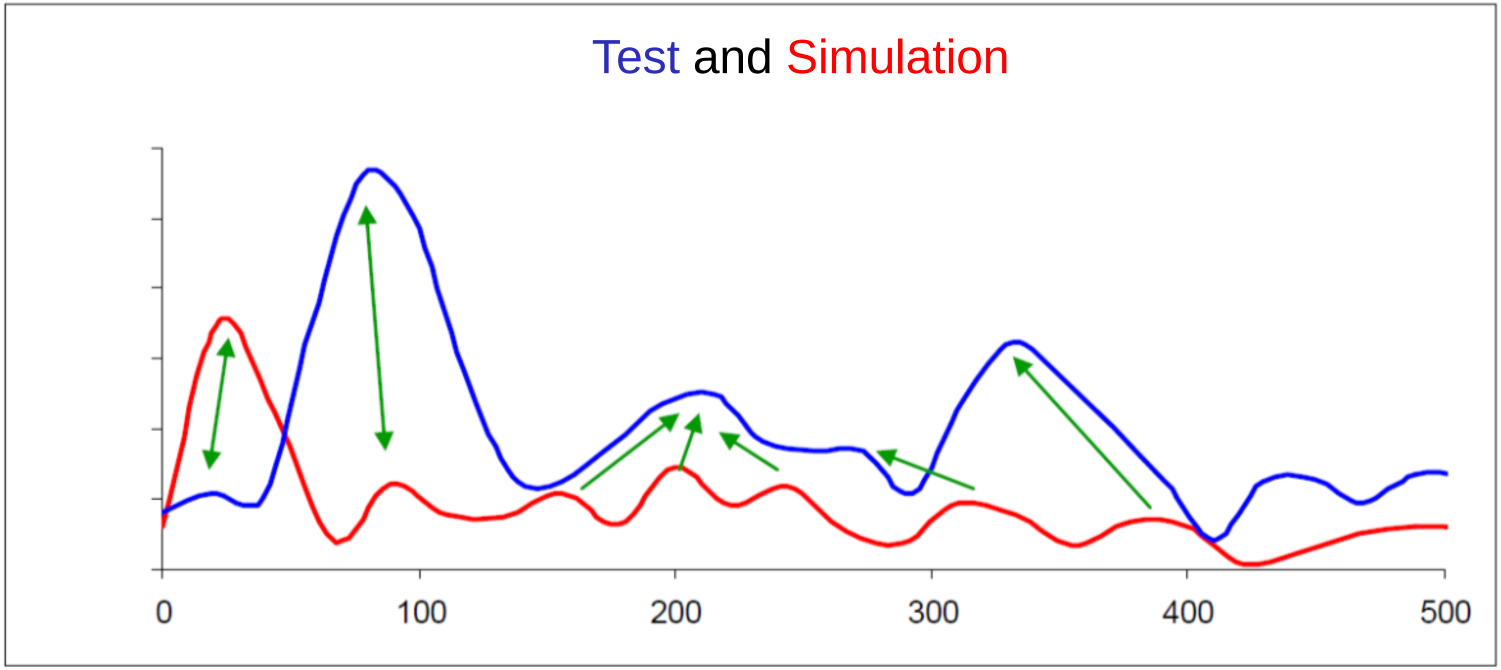
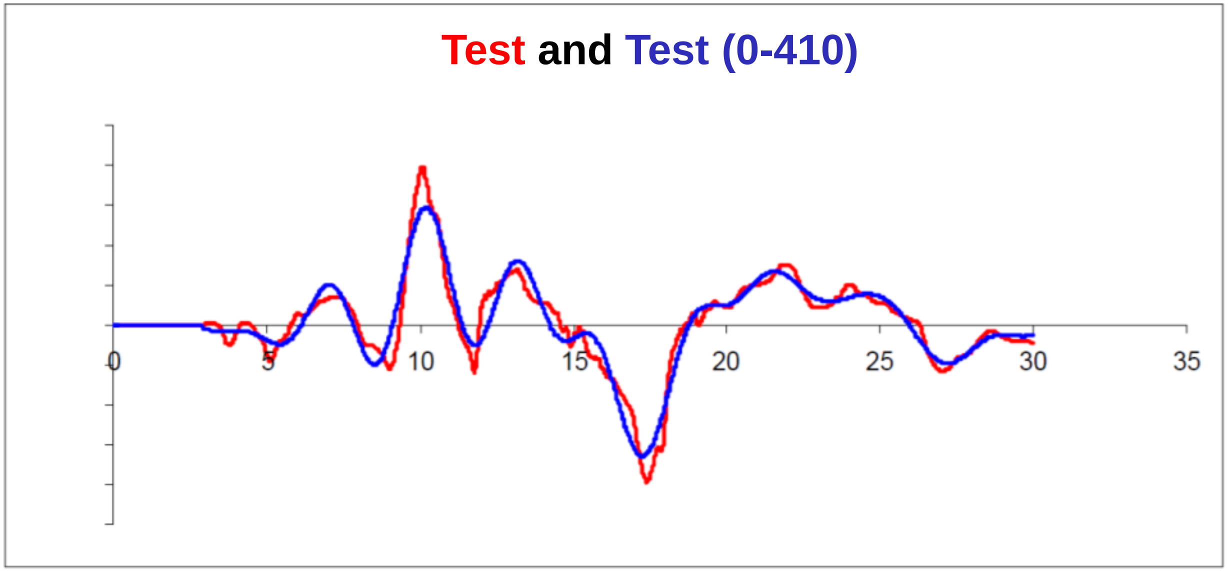
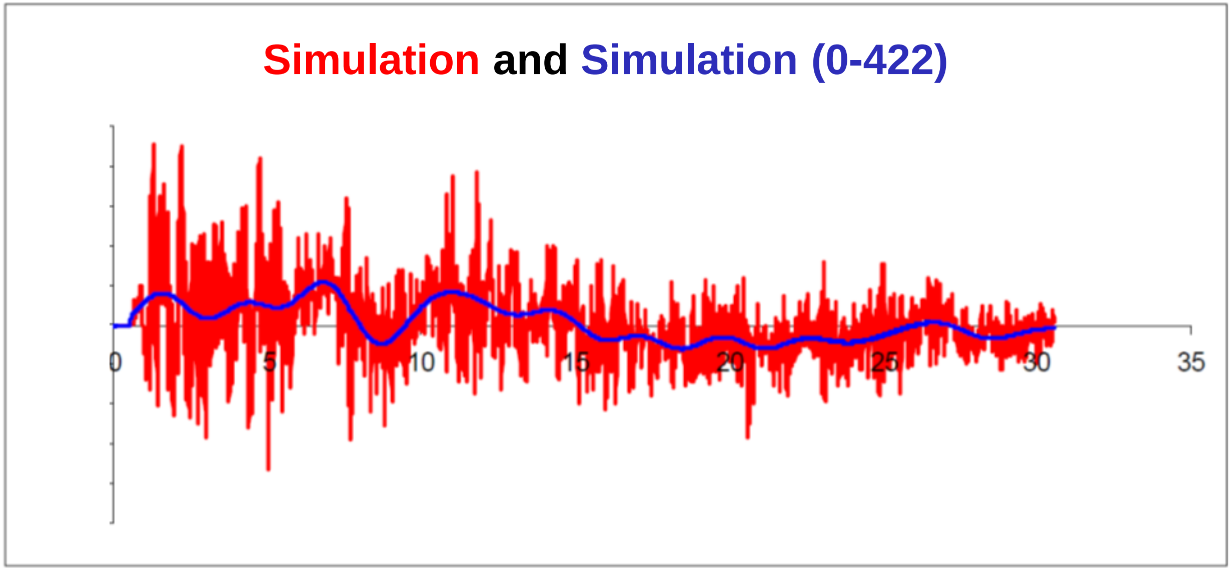
Example: Modal Analysis Validation



Regions	Test	Sim	Sim Adj
1	0-39	0-67	0-67
2	39-156	67-133	67-133
3	156-254	133-178	133-289
4	254-293	178-222	289-355
5	293-410	222-289	355-422
6		289-355	
7		355-422	

Example: Modal Analysis Validation





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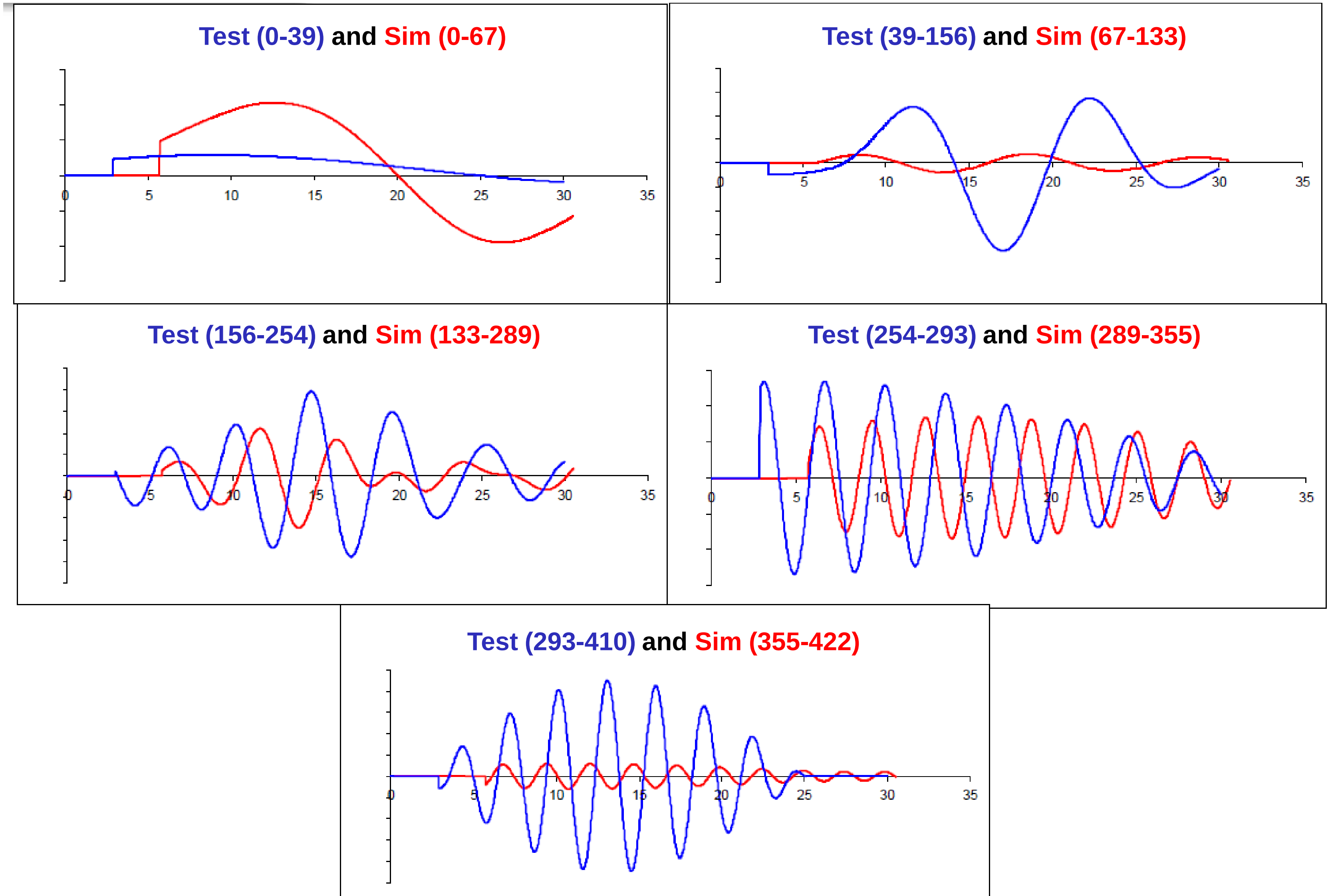
Example: Modal Analysis Validation

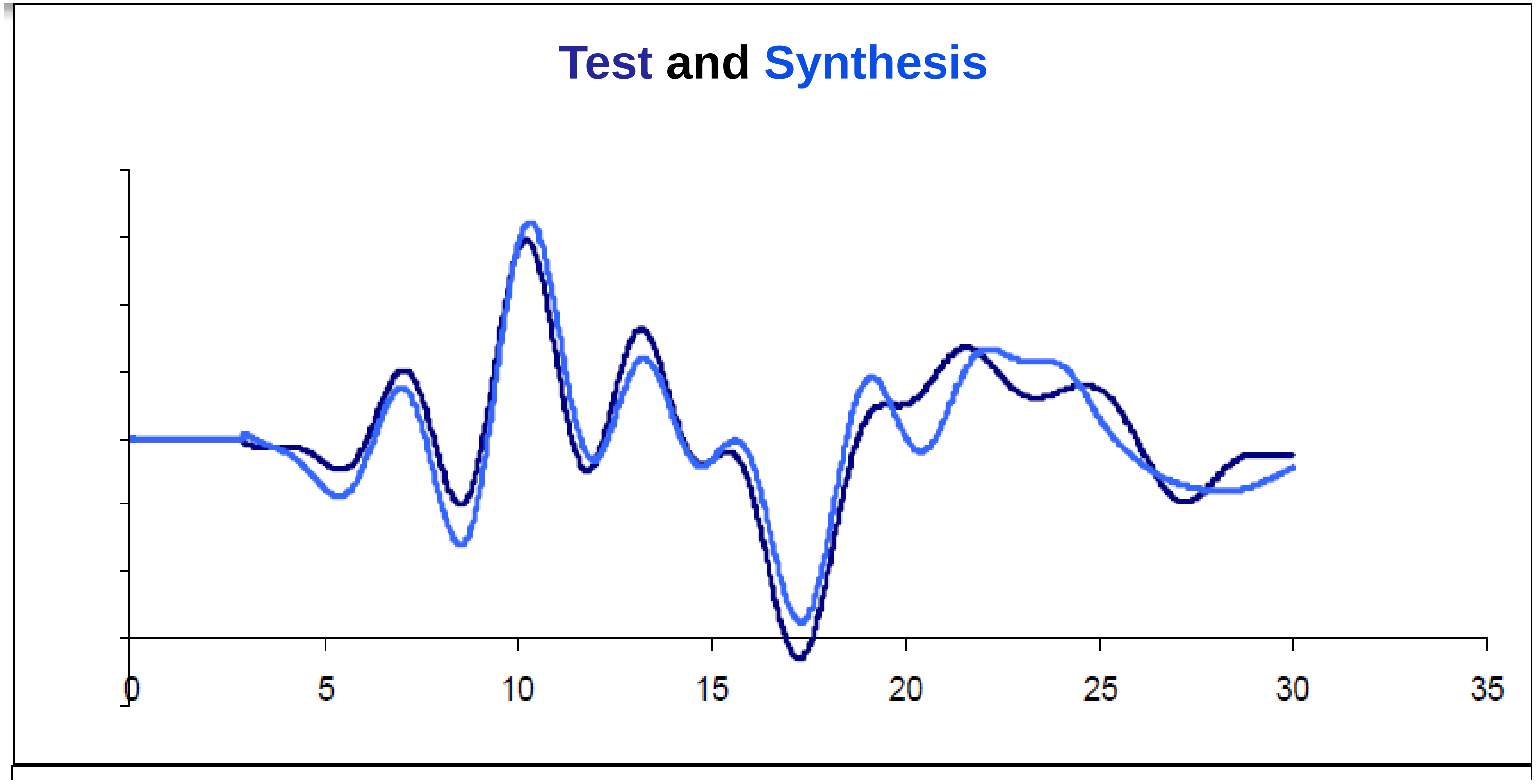


Example: Modal Analysis Validation

$$Y = \sum_{n=1}^{5} A_n*Sin(2Pi*F_n*(T-T0_n))*Sin(2Pi*W_n*(T-ST_n)+Phase_n)$$

SIM	0-67	67-133	133-289	289-355	355-422
A (gs)	102.652	38.471	110.466	33.793	29.446
F (Hz)	7.14857	9.61538	33.3333	11.3636	12.5
T0 (sec)	-0.02	-0.017	0	-0.012	-0.014
W (Hz)	35	97	200	320	383
Phase (Ra)	0.087266	6.25416	0.69813	0.34906	5.28459
ST(sec)	0.000055	0.00055	0.00055	0.00055	0.00055
ET (sec)	0.030536	0.030536	0.015004	0.030536	0.026004
Start (msec)	-20	0	0	-12	-14
Duration (msec)	70	15	15	44	40
Amp Adj	1	1	1	1	1
Rev Amp Adj	0.35	5	1.7	1.4	5
Test	0-39	39-156	156-254	254-293	293-410
A (gs)	31.66	274.081	196.984	53.637	225.739
F (Hz)	10	14.28571	20	11.11111	21.73913
T0 (sec)	-0.01	0	0.001	-0.015	0.002
W (Hz)	14	87	230	285	340
Phase (Ra)	1.29154	3.31613	3.14159	0.69813	4.90018
ST(sec)	0.002875	0.002875	0.002875	0.002875	0.002875
ET (sec)	0.03	0.03	0.026025	0.03	0.025025
Start (msec)	-10	0	1	-15	2
Duration (msec)	50	35	25	45	23
Amp Adj	1.1	1	1	1	1

Example: Modal Analysis Validation



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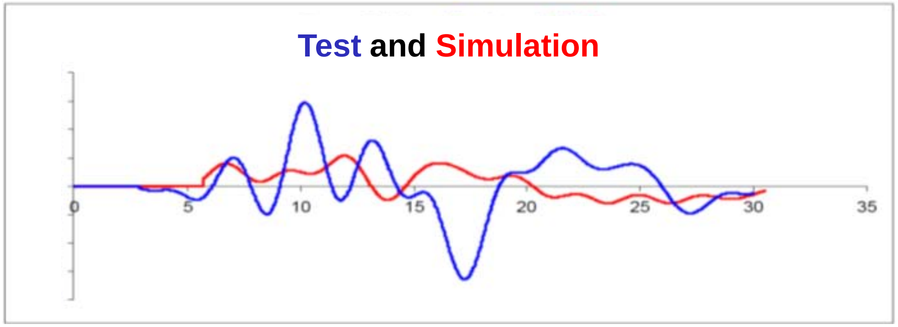
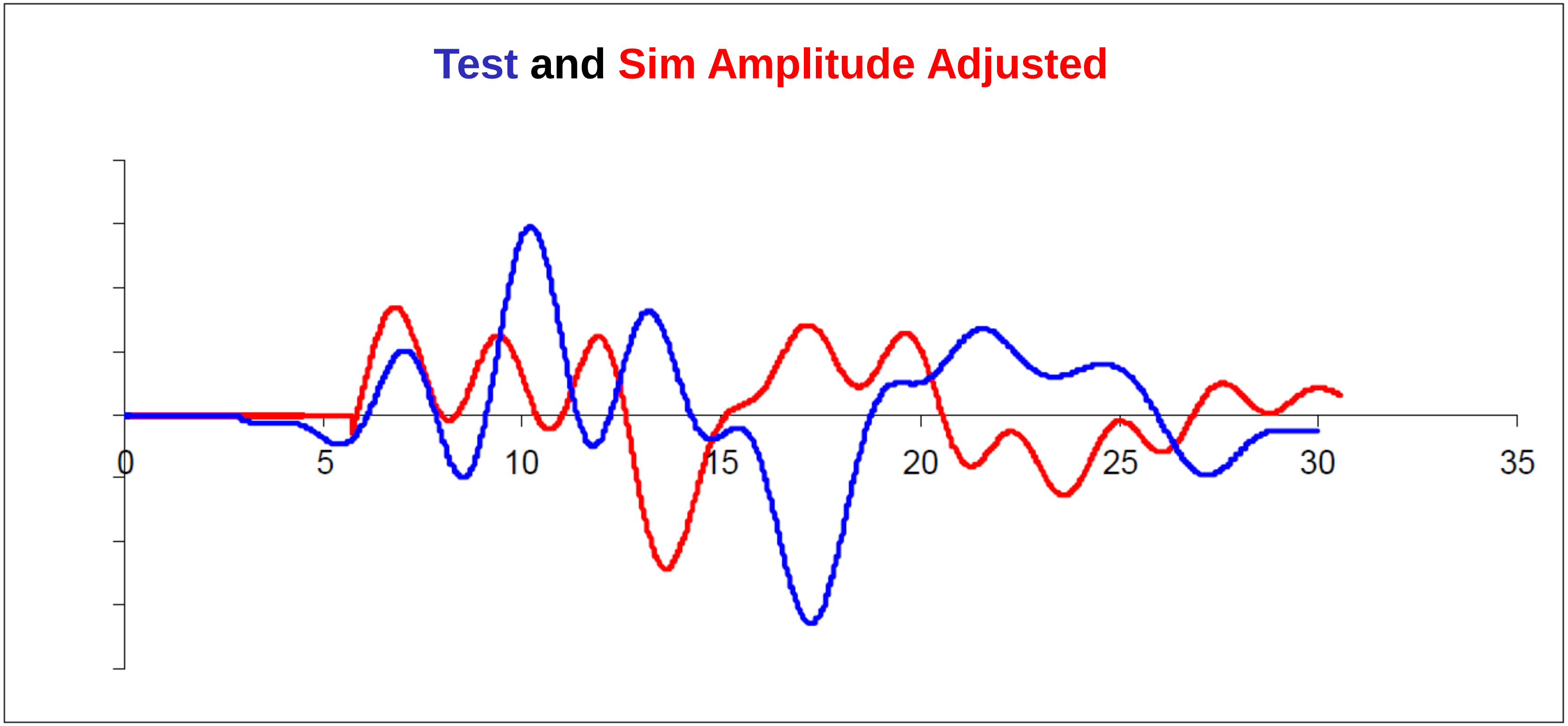


	0-67	67-133	133-289	289-355	355-422
Amp Adj	0.35	5	1.7	1.4	5



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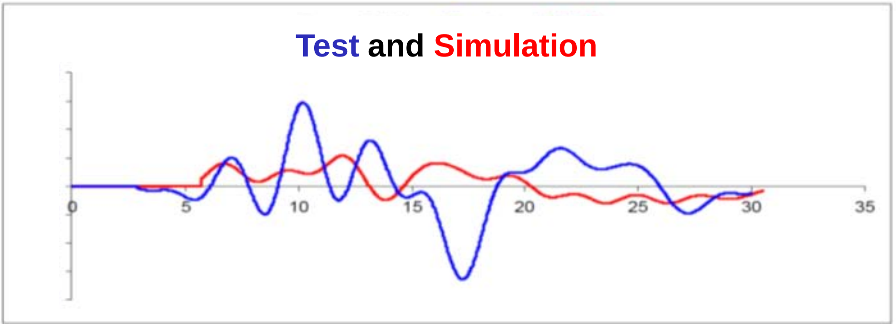

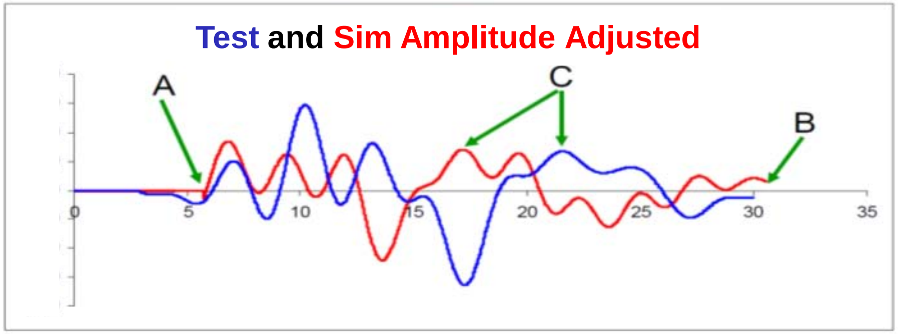

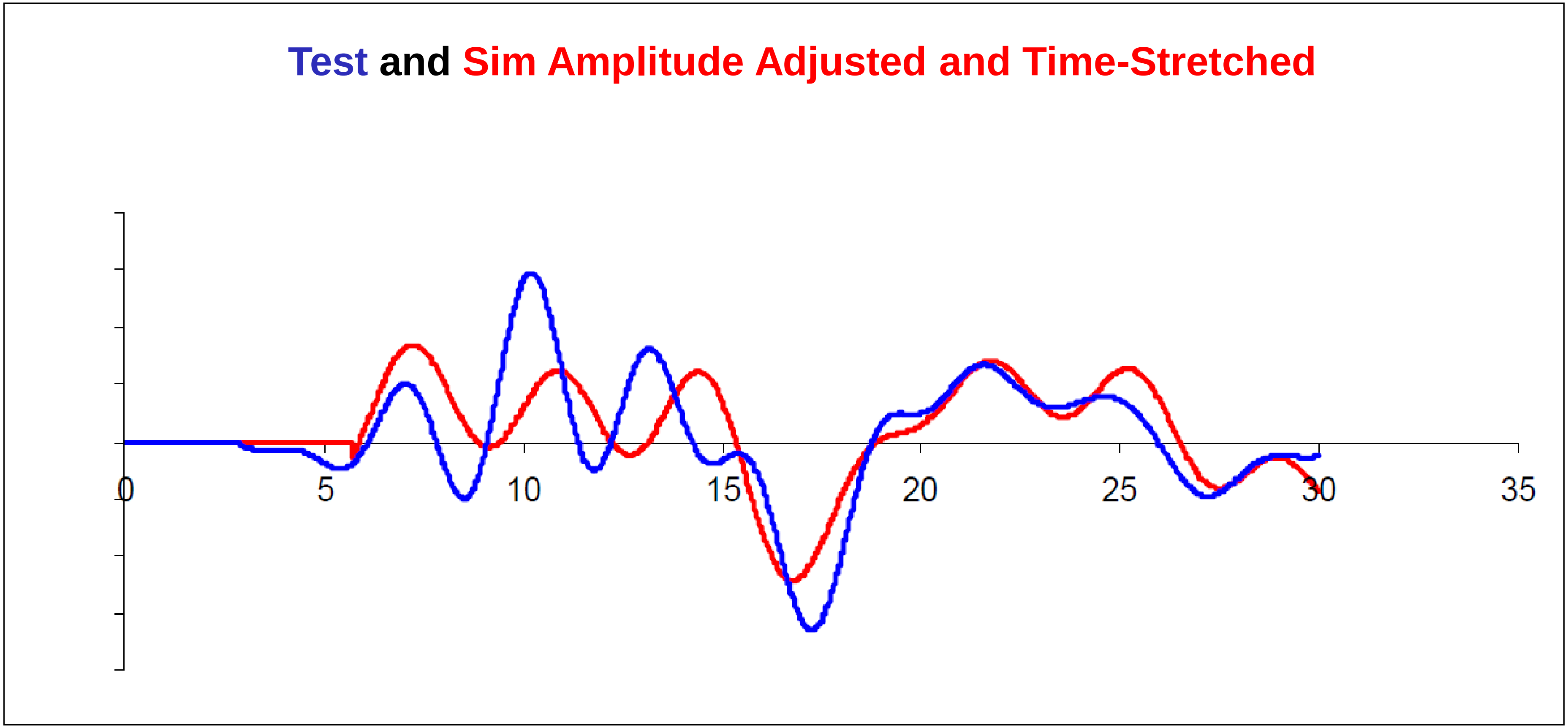

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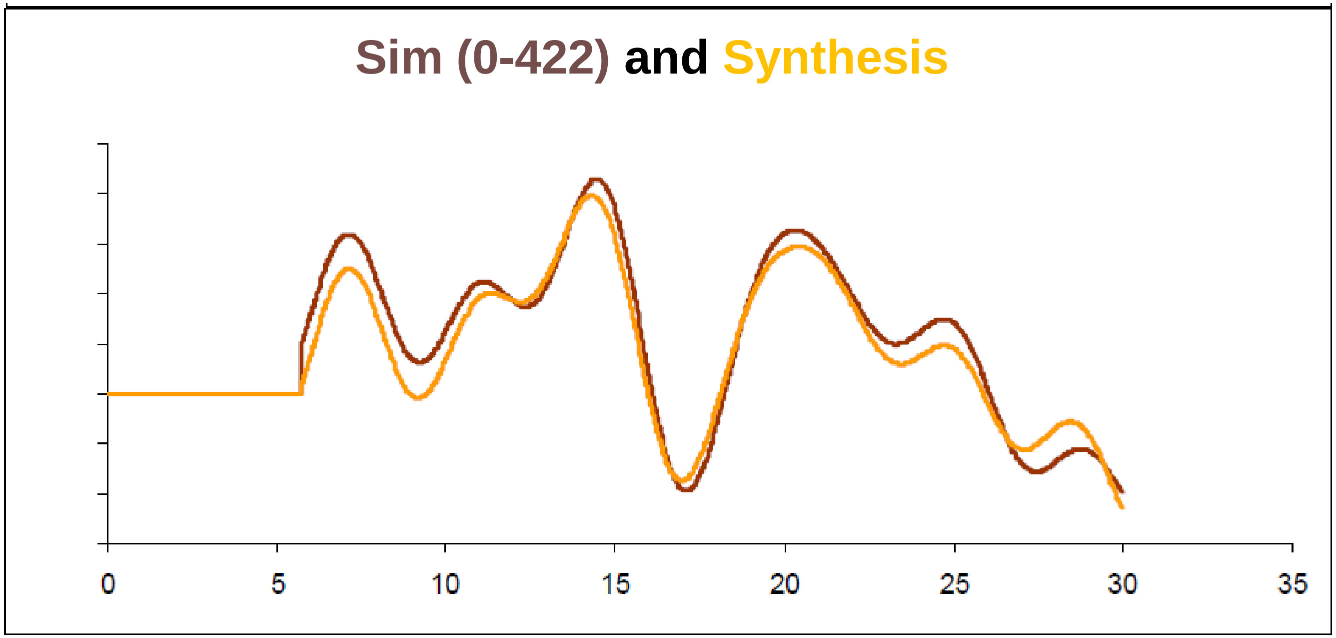

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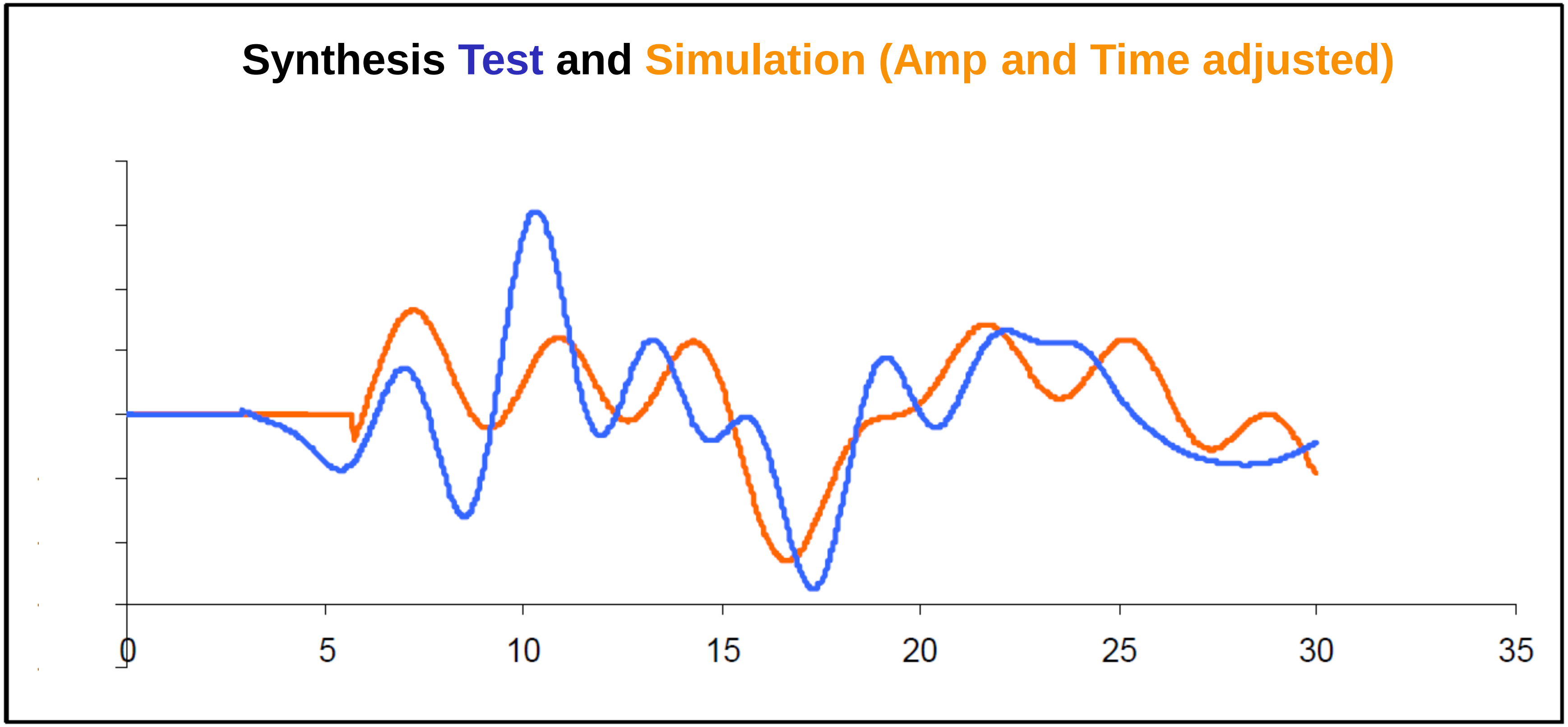


Example: Modal Analysis Validation

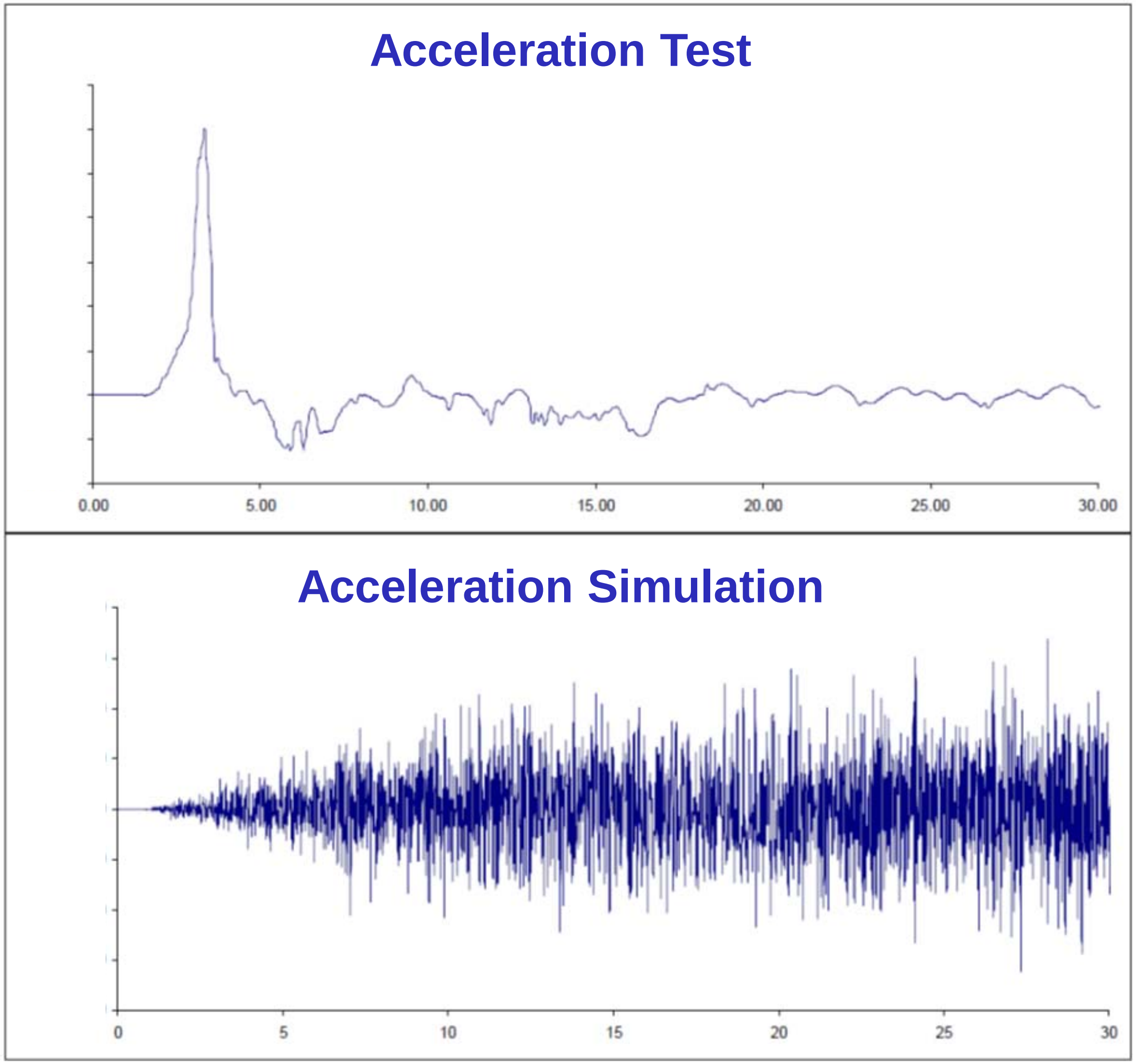
Conclusion

- Shape of simulation data curve is quite good
- Timing (phasing) and amplitude show some differences
- Actual system-level response is slower than predicted in the simulations
- System damping is not well modeled at lower frequencies

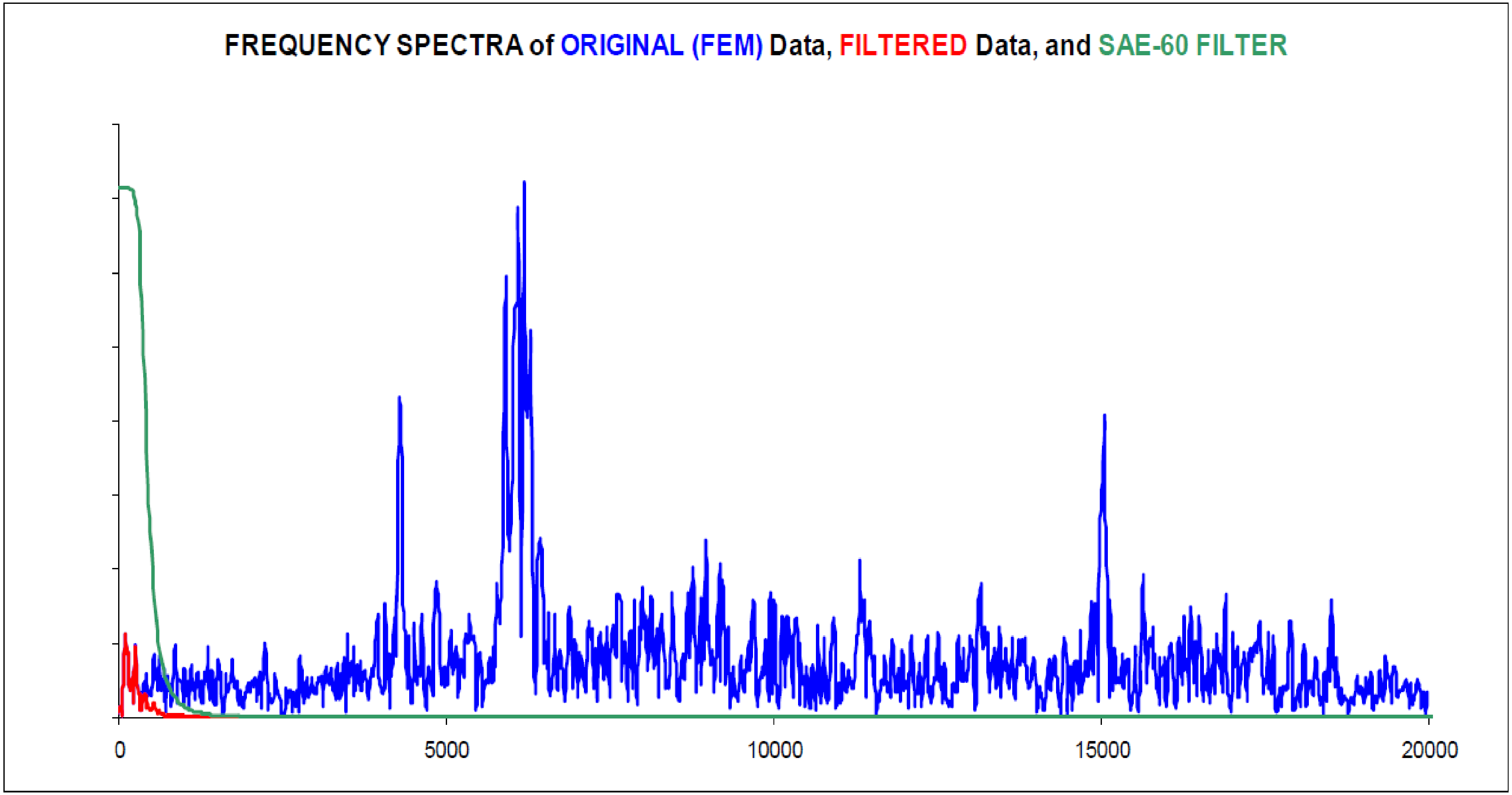
Other considerations

- Variability and uncertainty in tests
- Not the answer, but an answer
- Instrumentation: LOFFI accelerometers
- Vehicle condition/variation vehicle to vehicle

Example of Bad Simulation Output

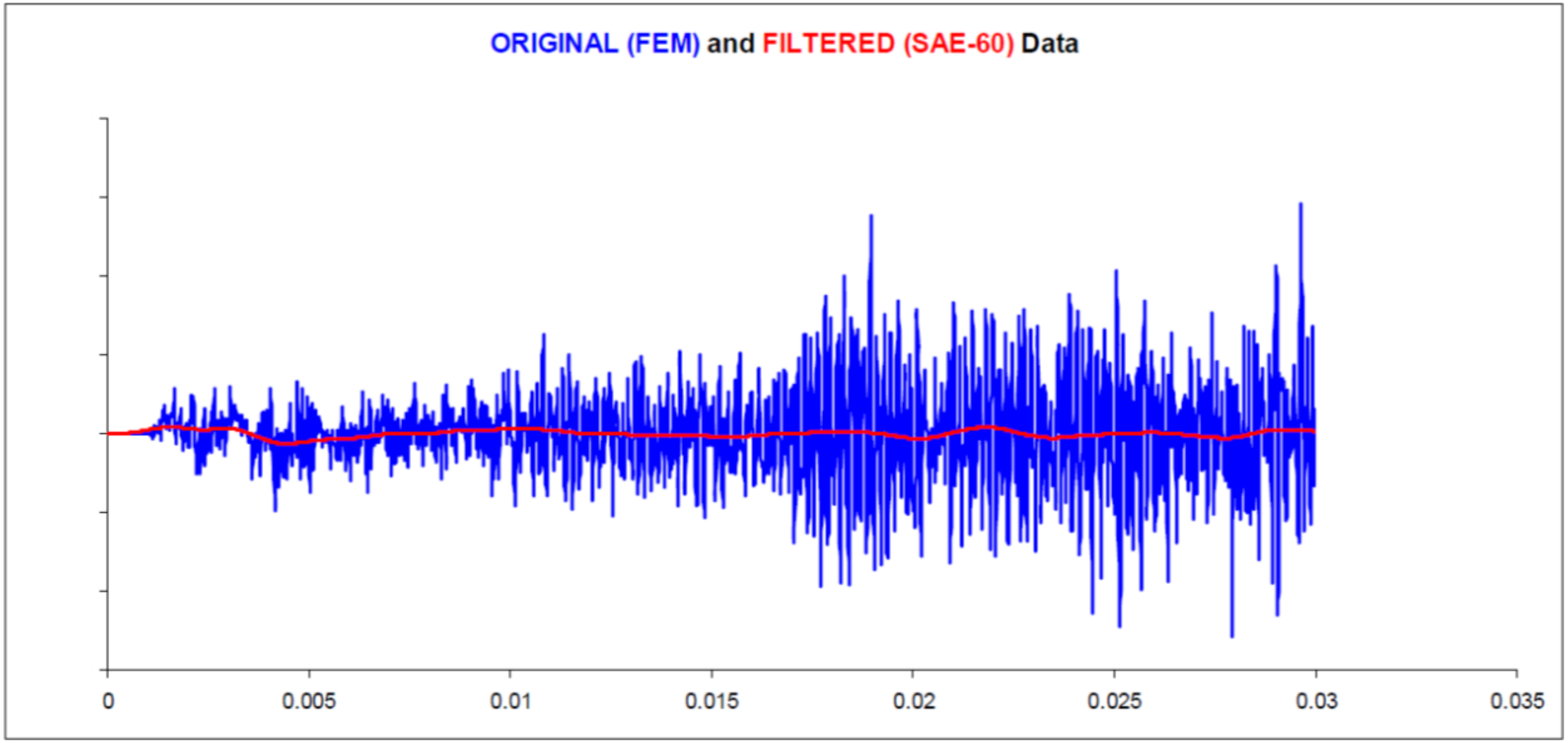


Example: Selecting an Appropriate Filter



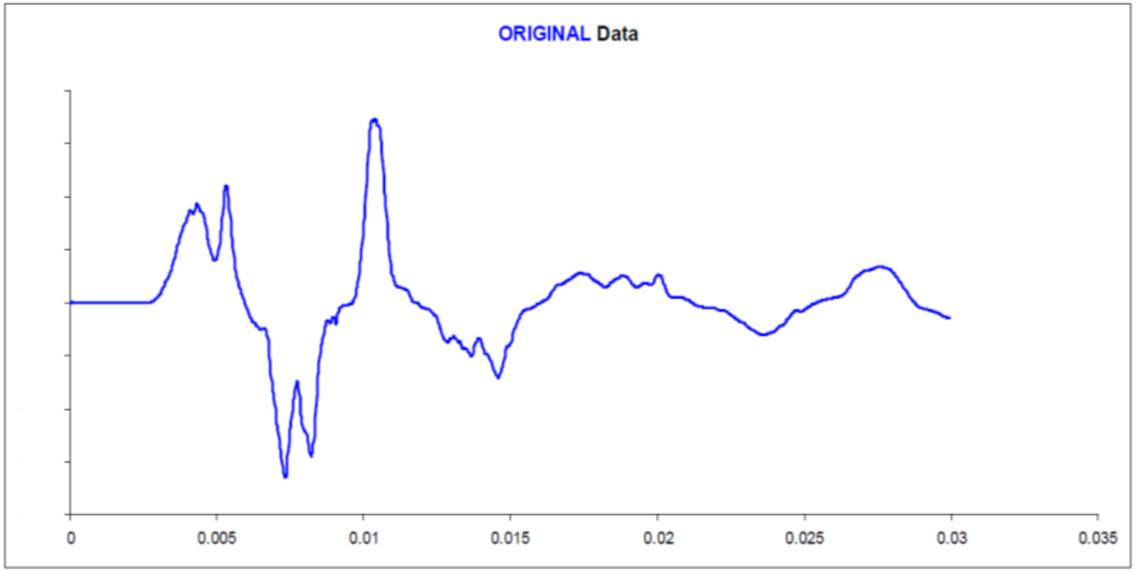
Frequency spectra of FEM output, SAE-60 filter and filtered data

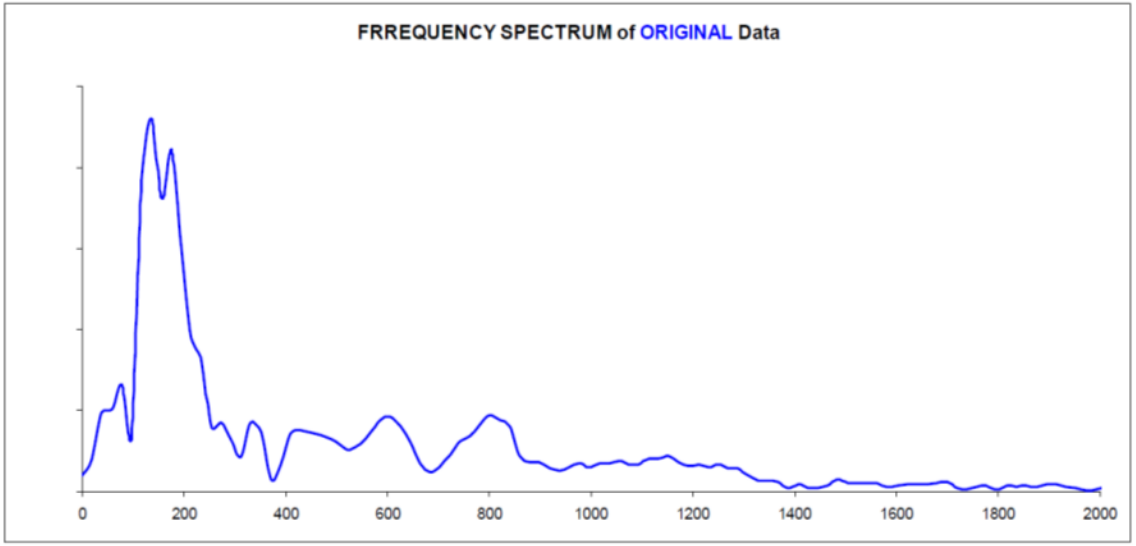
Example: Selecting an Appropriate Filter



Time history of simulation output, and SAE-60 filtered data

Example: Selecting an Appropriate Filter





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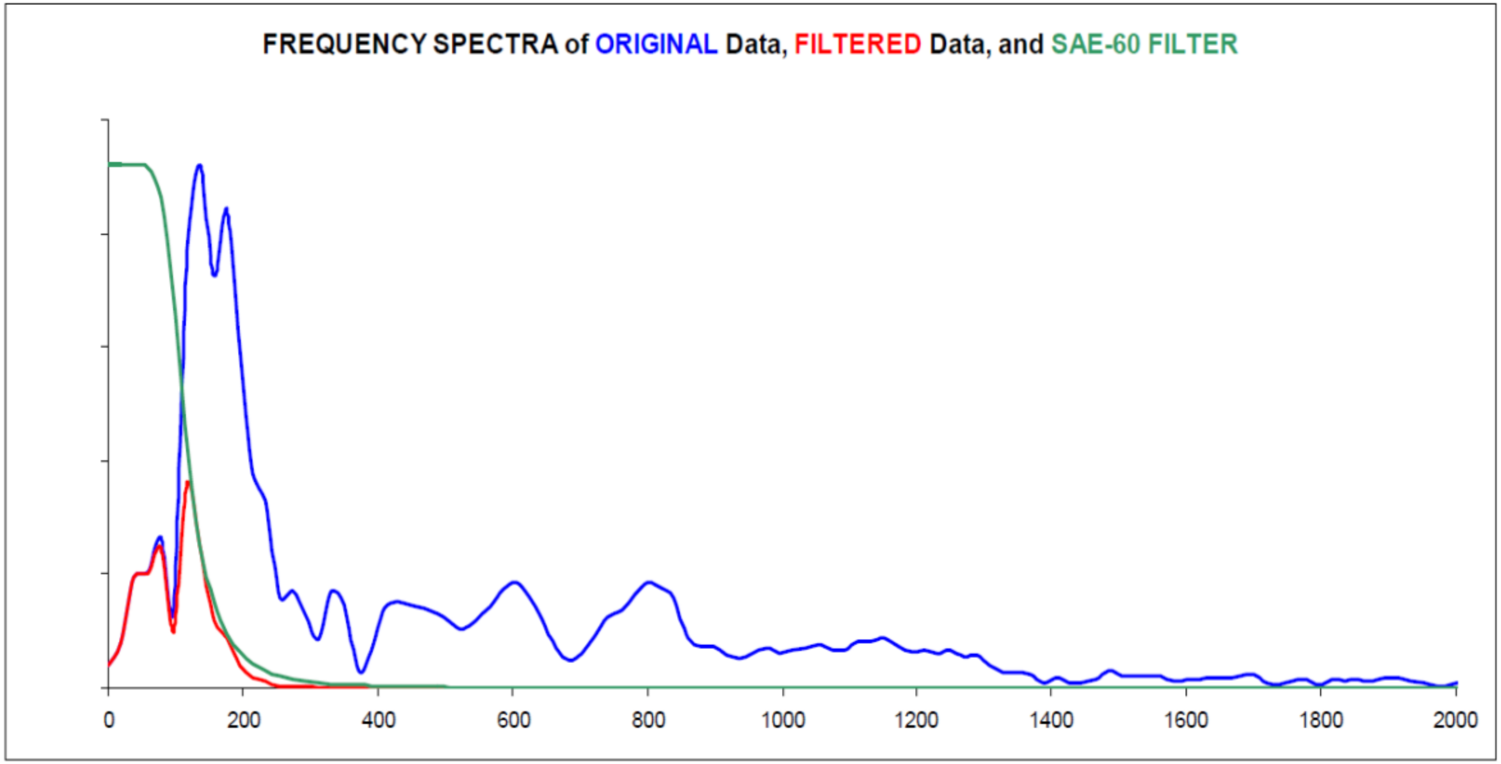
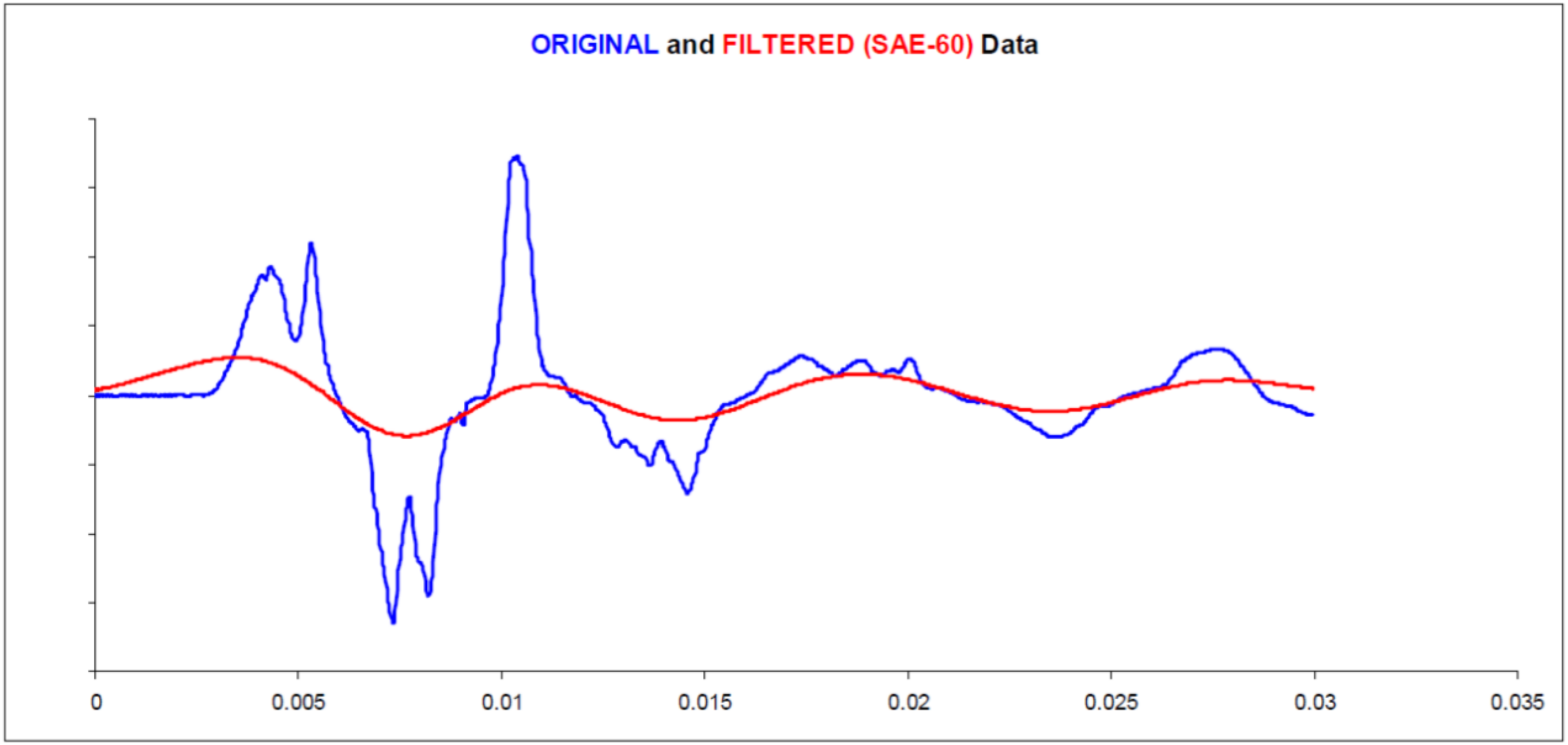


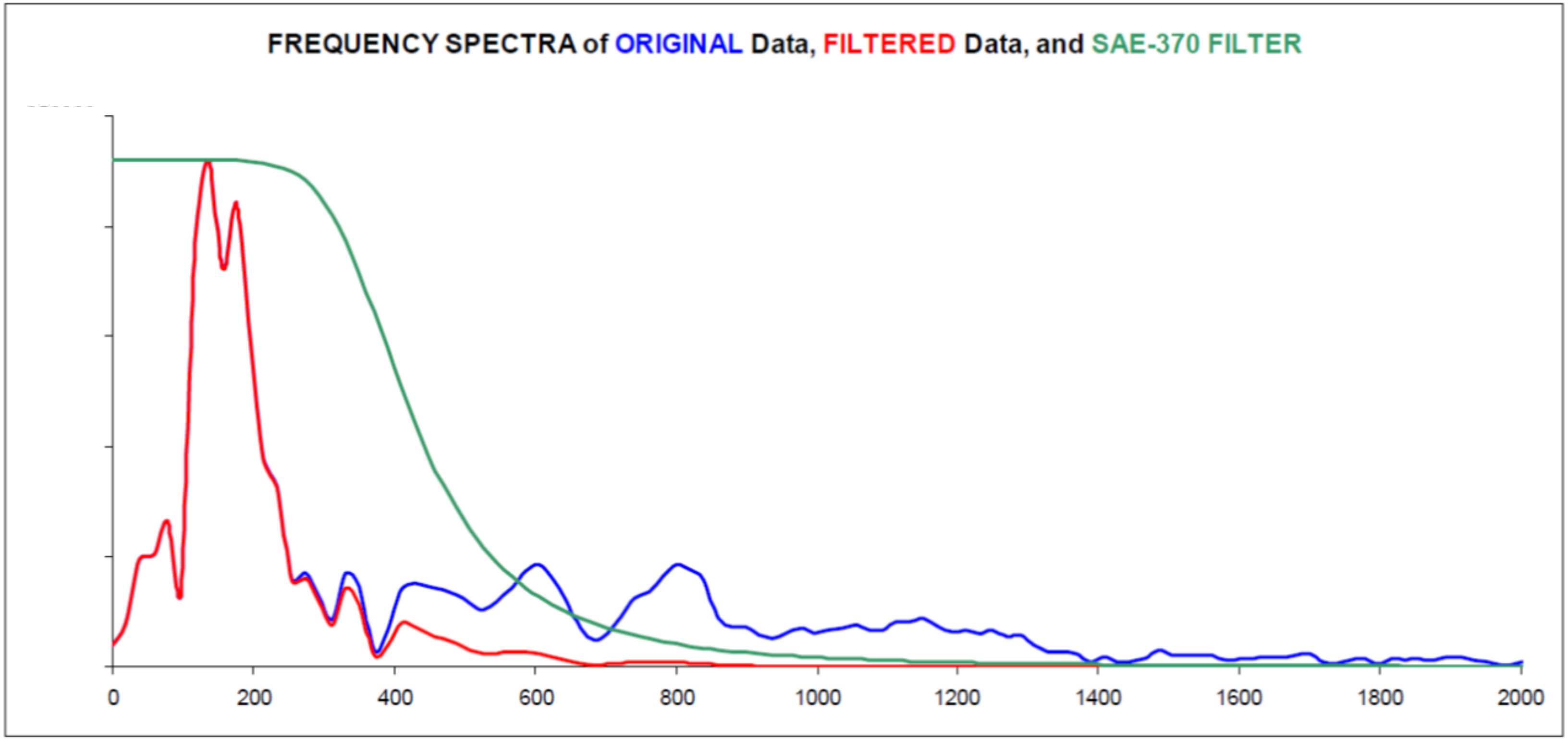
Frequency spectra of acceleration from test along with filter and filtered data spectra (SAE-60 filter)

Example: Selecting an Appropriate Filter



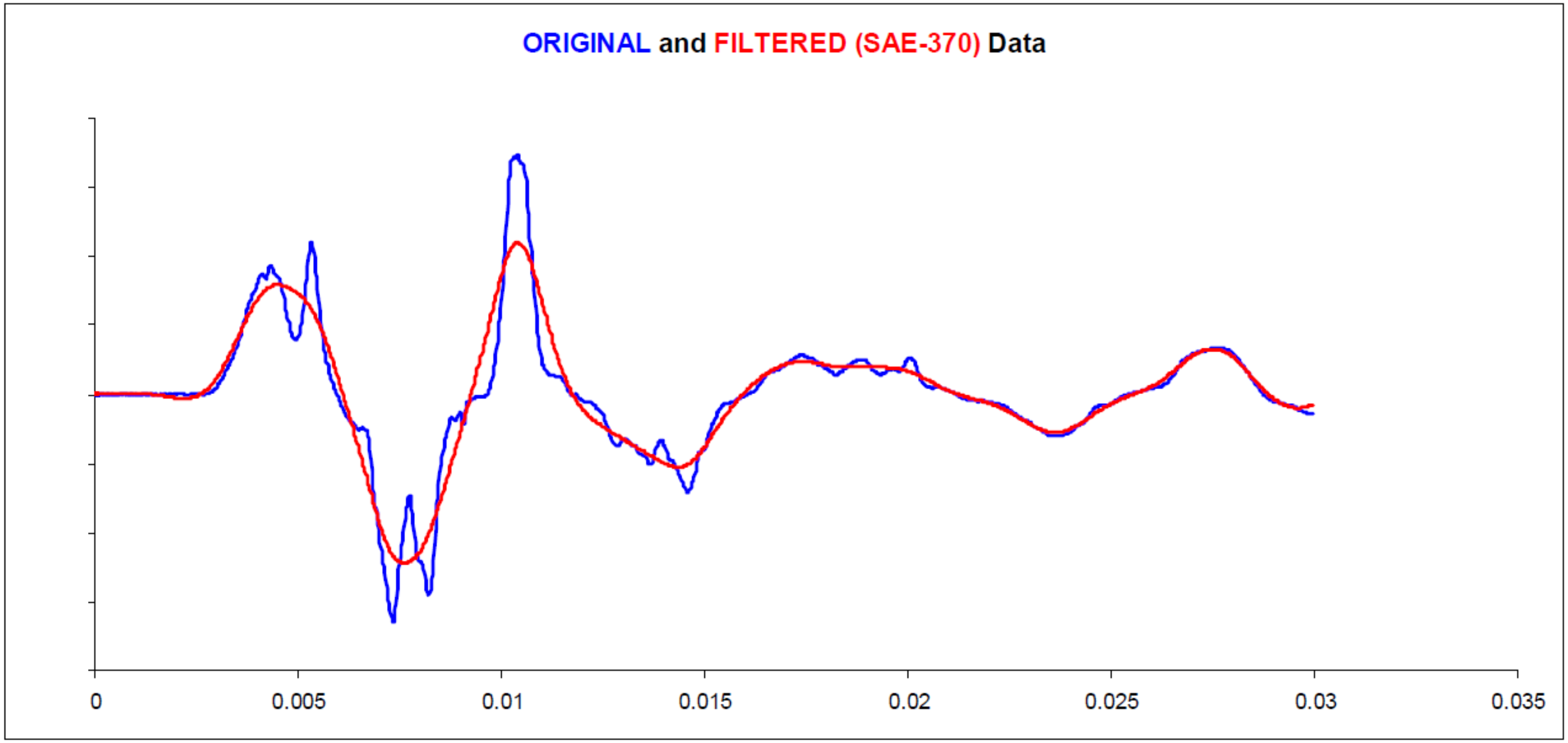
Acceleration from test and after applying an SAE-60 filter

Example: Selecting an Appropriate Filter



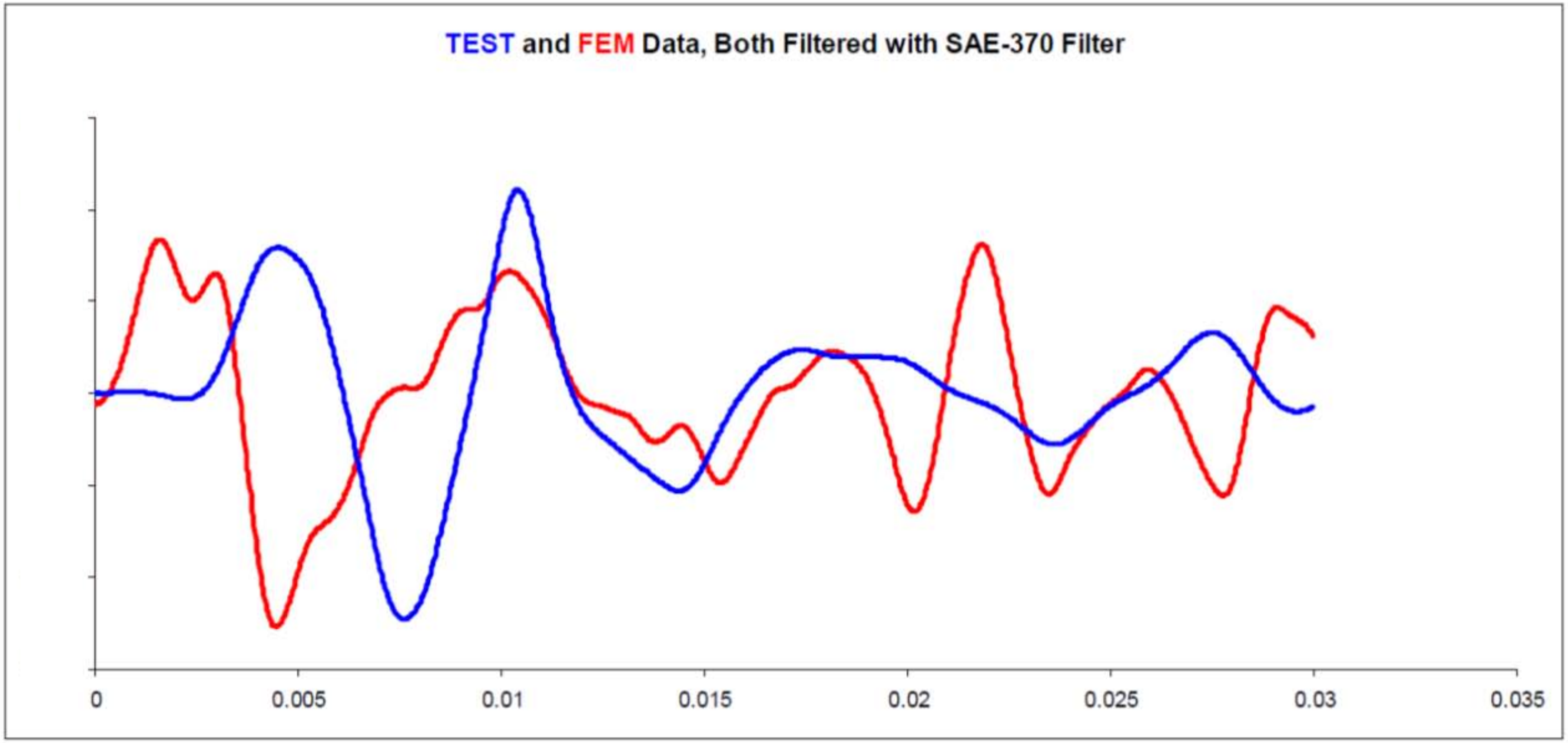
Frequency spectra of acceleration from test along with filtered data and SAE-370 filter

Example: Selecting an Appropriate Filter



Acceleration from test along with SAE-370 filter output

Example: Selecting an Appropriate Filter



Time history of FEM and test data, both SAE-370 filtered

Example: Selecting an Appropriate Filter and Applying the Validation Technique

- Up to ~9ms there is a phase problem with the simulation data
  - Shift that portion of the data roughly 3 ms to the right
  - Will line up fairly well in amplitude and frequency
- From 9 to 17 ms phase and frequency content are about right: amplitudes are close
- After 17 ms the simulation output lacks damping
  - Evidence in the frequency spectrum
  - No longer bears any resemblance to real-world acceleration

Summary

V&V process

- Defining the purpose and system of interest
- Determining intended use
- V&V Loop
  - Verify
    - Fundamental physics (model developer)
    - Vehicle model
  - Validate
    - Fundamental physics (model developer)
    - Vehicle and Occupant response
- Validation method based on modal response
  - Compare fundamental mathematical properties
  - Provides confidence and credibility in model for the intended use

Questions?

Contact

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References

- Walbert, James. *Comparing Test Data with Finite-Element Simulation Output: A Process for Verification and Validation*. SURVICE Engineering, 2012 unpublished.
- Park, Joseph and Silas, Kevin. *M&S Validation Using Live-Fire Data*. ARL Research in Ballistic Protection Technologies, Aberdeen, MD. 1-3 May 2012.
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- Wallace, D. and Fujii R. *Software Verification and Validation: An Overview*. IEEE Software 1989.
- *Systems Engineering Handbook: A Guide for System Life Cycle processes and Activities.* INCOSE-TP-2003-002-03.2.2, October 2011.
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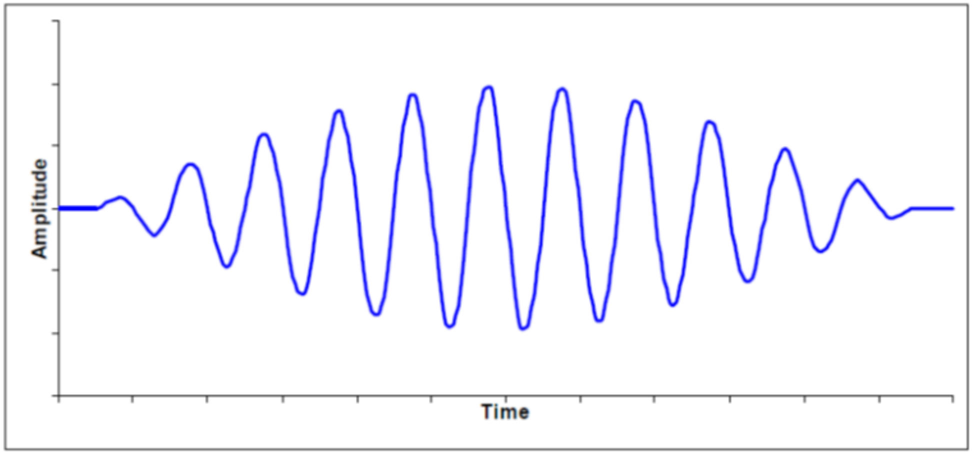
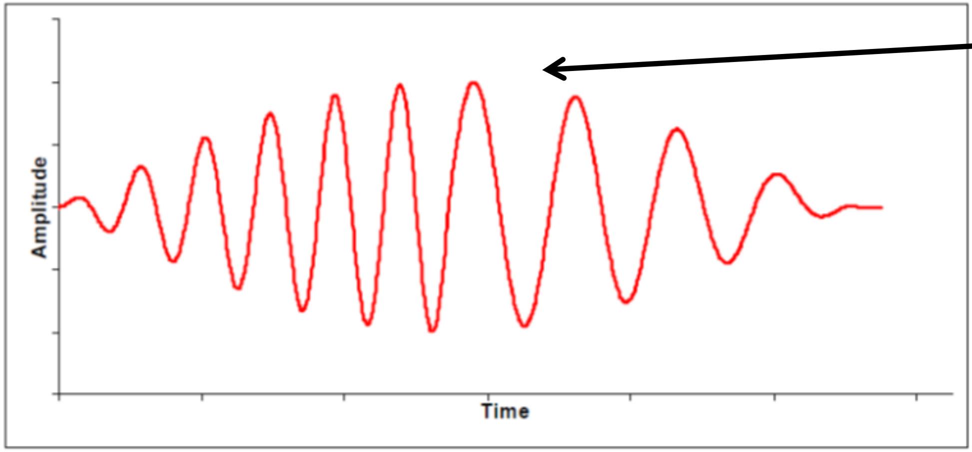
Backup Slides

- Additional information to be gained from this technique
- When things break, deform etc…

Determining when deformation occurs

- Frequency and phase are properties solely of the geometry and material make-up of the system
- Properties only change when the system becomes deformed

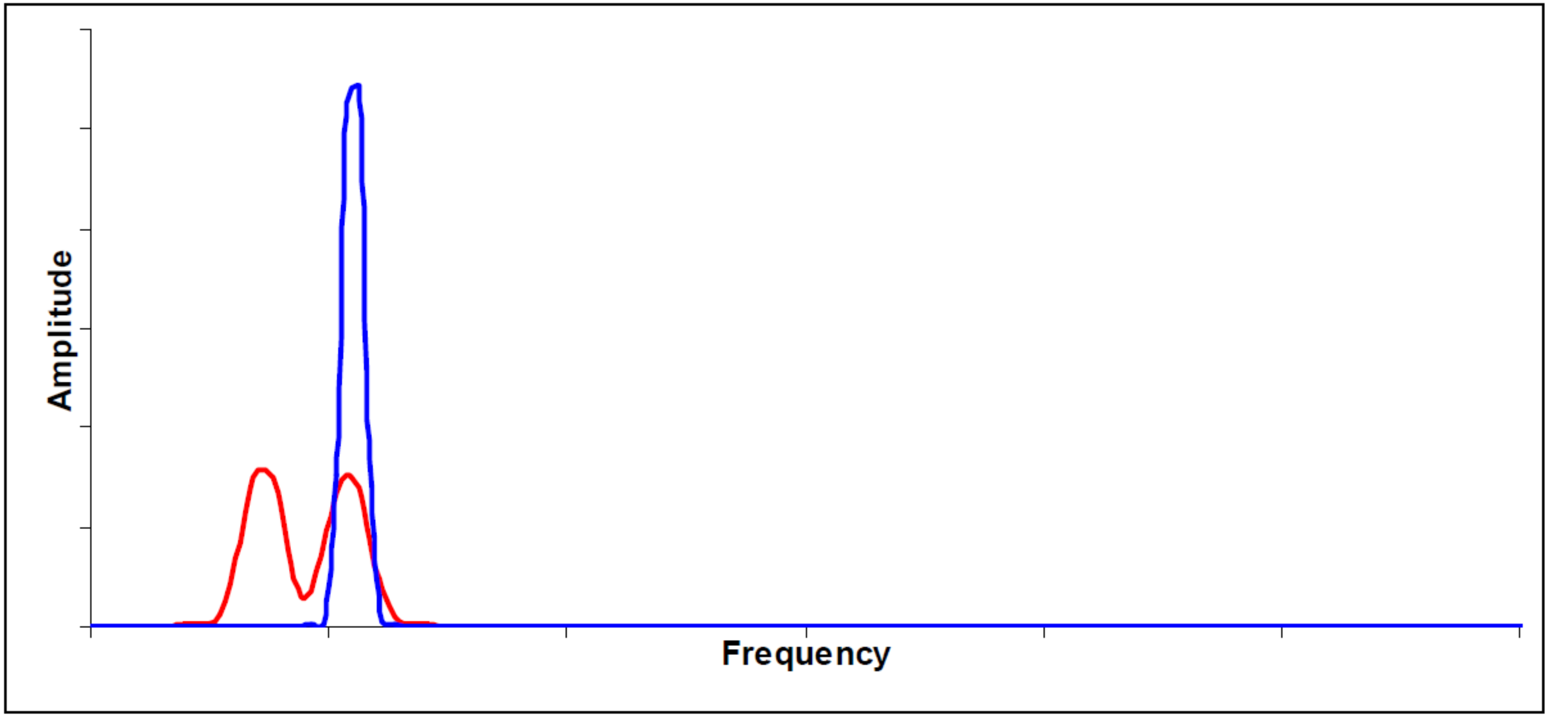




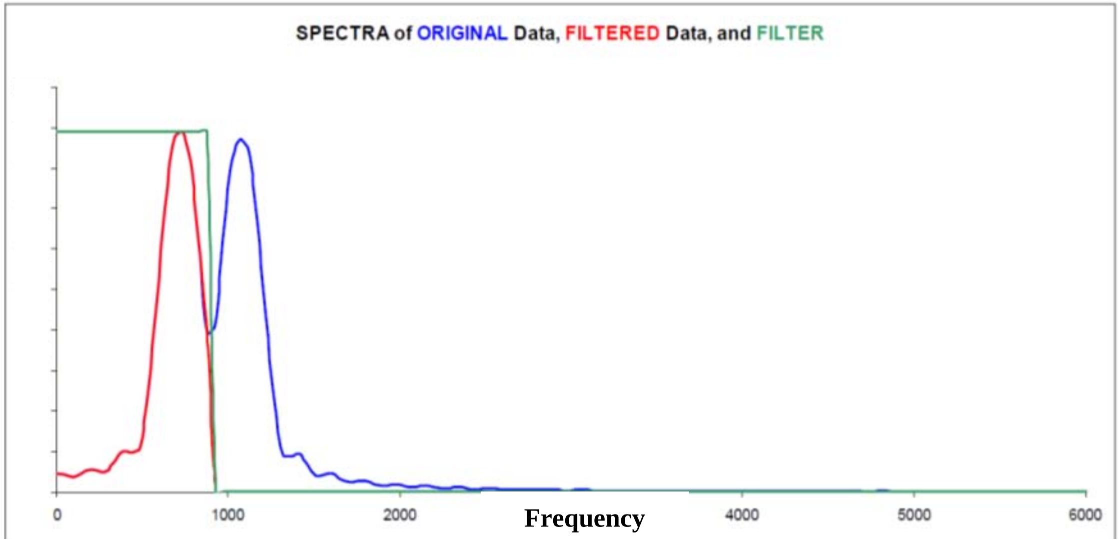
Change in Frequency

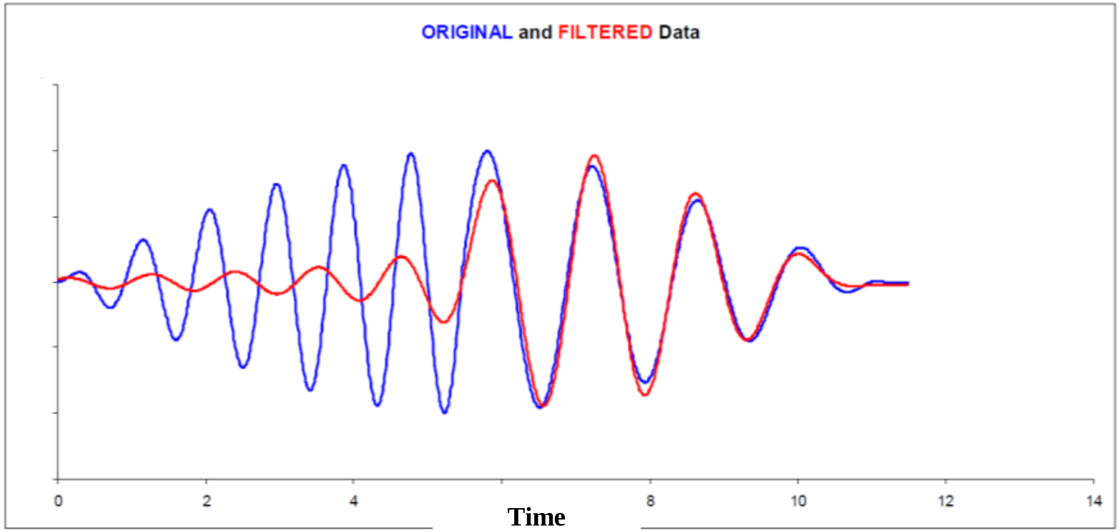
Determining when deformation occurs

- Frequency Spectra
- Presence of two distinct time series components?
- Single time series showing deformation?

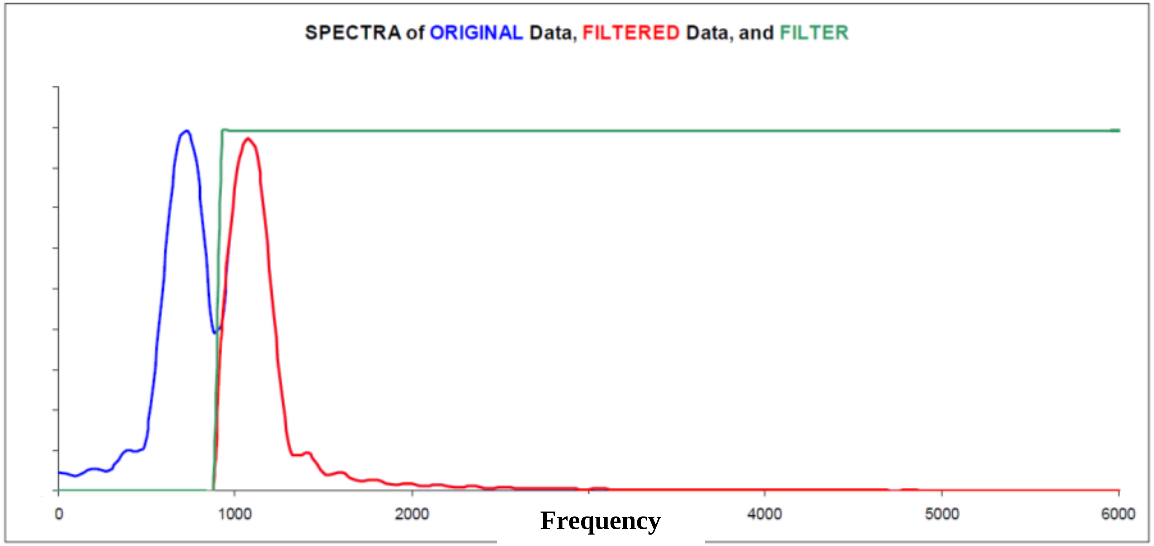


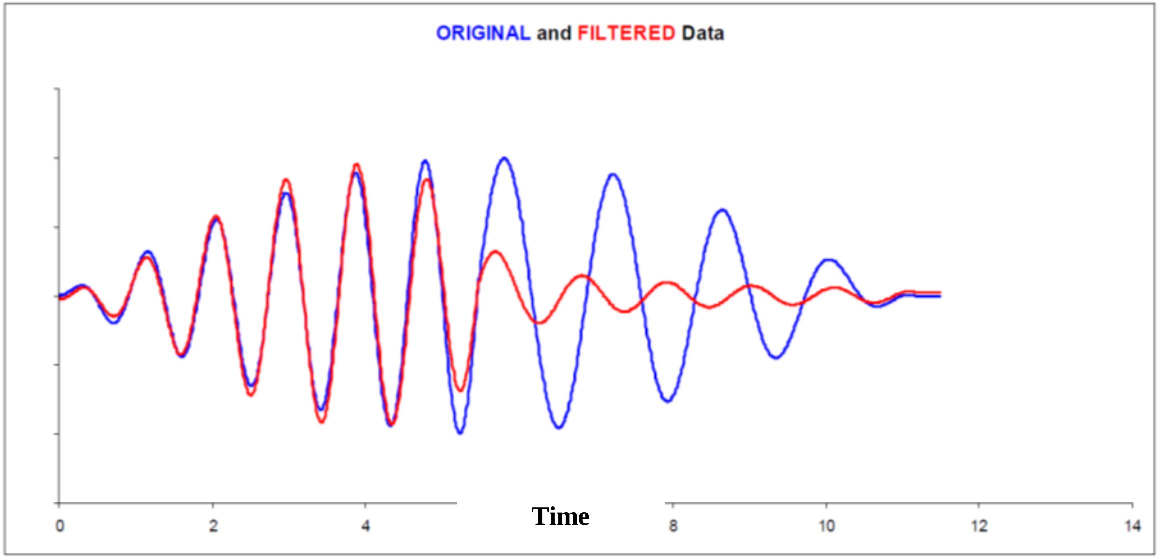
Determining when deformation occurs



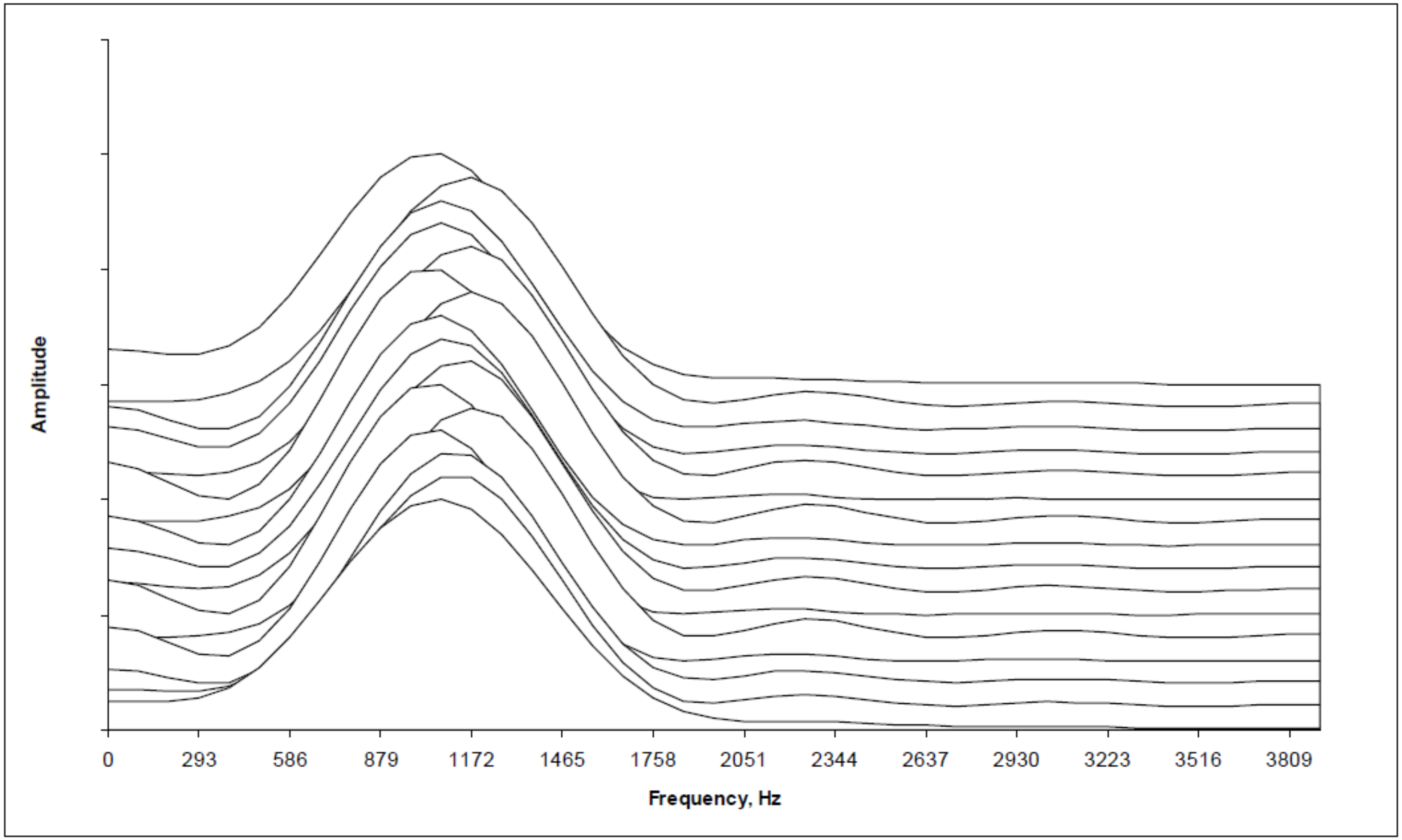


Determining when deformation occurs

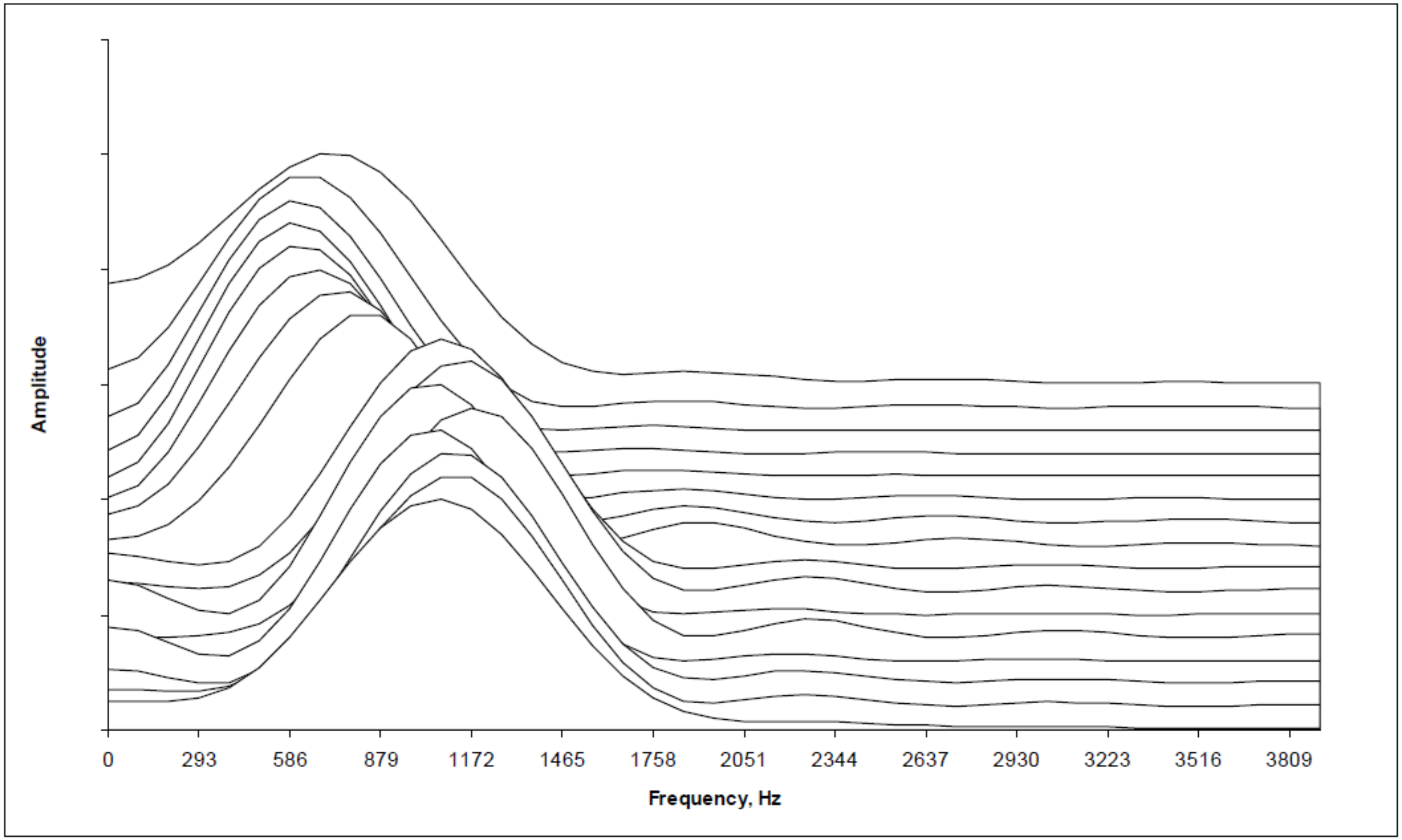




Determining when deformation occurs



Determining when deformation occurs



Determining when deformation occurs