Understanding Order Tracking Data and Algorithm Limitations

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Commercial Order Tracking Methods

- Time sampled FFT based
- Angle sampled FFT based
  - Computed / Resampling
- Time Variant Discrete Fourier Transform (TVDFT)
- Kalman Filter
- Vold-Kalman Filter
- Modulation / Filter based

- ALL OF THESE METHODS REQUIRE AN ACCURATE TACHOMETER SIGNAL!

General Flow of Order Tracking

- Instrument machine
  - Accelerometers, microphones, strain gages, ..etc.
  - Tachometer Signals
- Acquire Data
- Process tachometer signal
- Perform order tracking on dynamic transducers
- Plot Results

Instrument Machine

- Typical dynamic transducers are used to instrument machine keeping in mind that amplitudes will change at different RPM values
- Tachometer signal is measured
  - Optical, ICP Lasertach
  - Hall Effect Sensor, Bentley-Nevada
  - Current/Voltage Sensor, Timing Signal

TACHOMETER IS THE MOST IMPORTANT CHANNEL!!

Acquire Data

- Order tracking is performed on responses whose dominant frequencies change with machine RPM
- Must calculate the maximum frequency of interest at highest RPM

$$F_{\max} = \frac{MaximumRPM}{60} * (\text{Highest Order of Interest})$$

- Must set ADC ranges at highest amplitude response seen throughout RPM range

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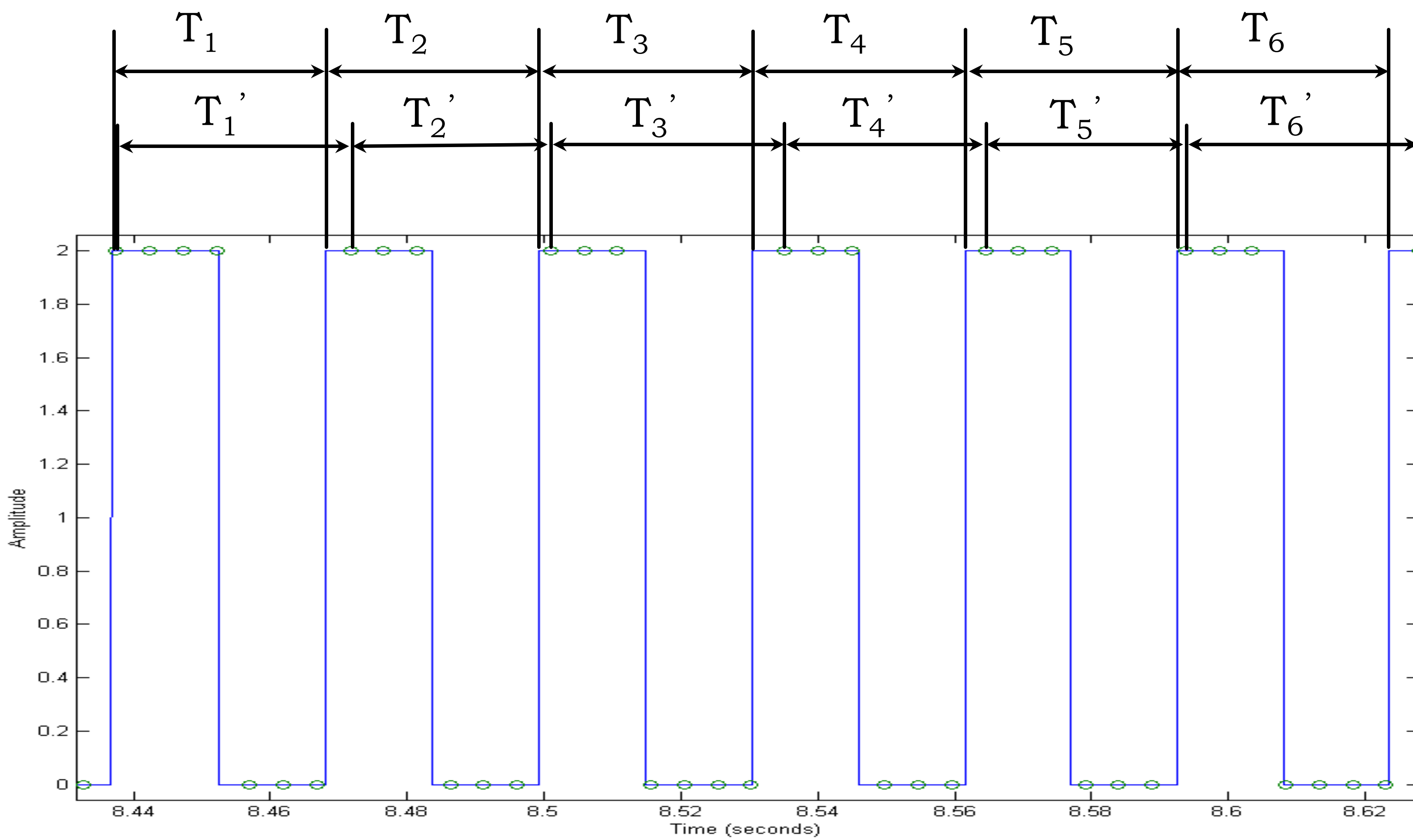
Process Tachometer Signal

- Goal is to estimate instantaneous RPM of machine
- Most tachometer signals are pulse trains which must be processed to get pulse periods and frequencies
- Many commercial order tracking packages have multiple tools for tachometer signal processing
  - Special Tachometer Inputs on DAQ systems
    - Typically sample very fast to reduce timing errors
  - Holdoff time
  - Hysteresis level
  - Upsampling/Interpolation
  - Curve/Spline Fitting

Tachometer Processing – Timing Errors



Once sampled $T_i \neq T_i'$

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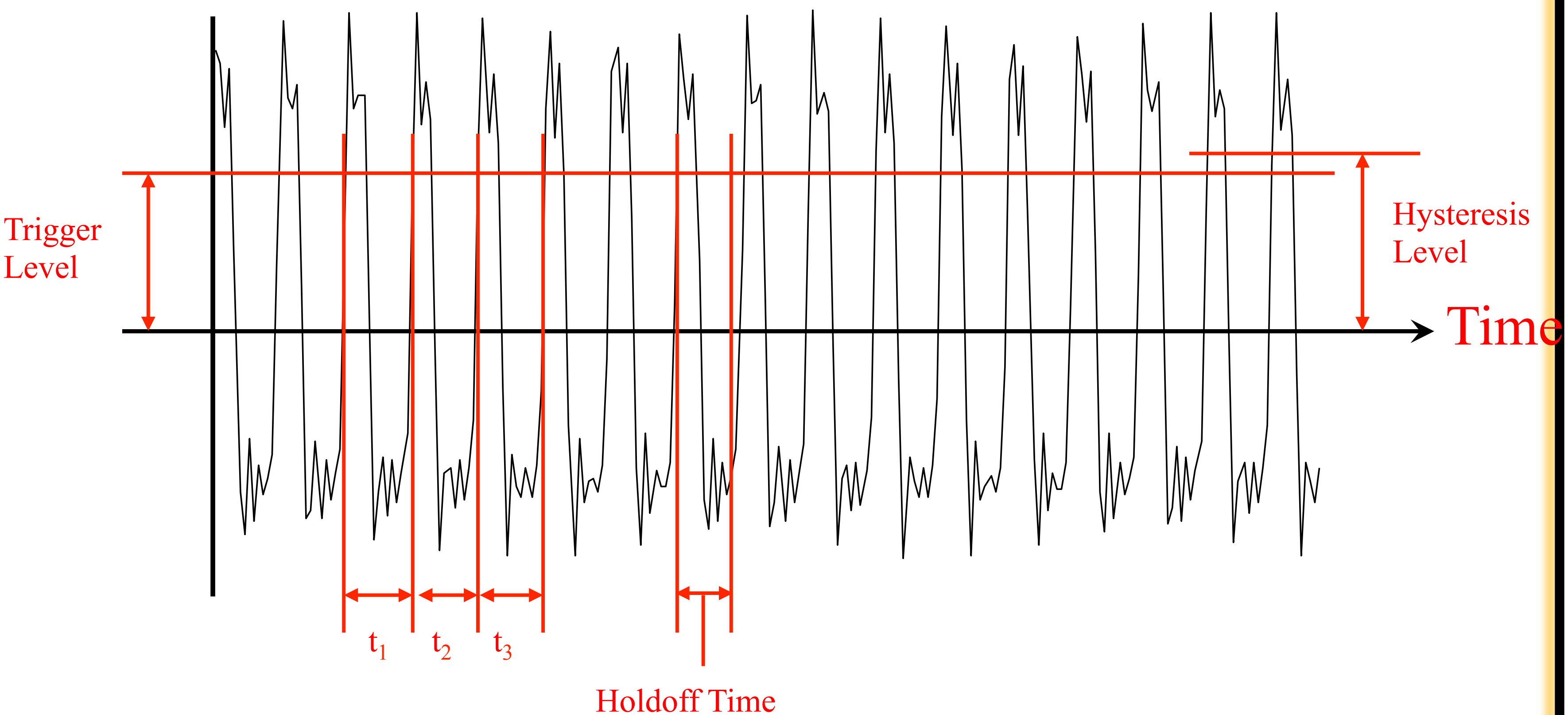
Holdoff Time

- Holdoff time is an algorithm that ignores blocks of time when looking for a trigger event
  - Ignore from last trigger event for a period of time
    - Can be difficult to use when RPM is changing rapidly
  - Ignore from last trigger event for a percentage of the last estimated period

Hysteresis Level

- Hysteresis level requires the tachometer signal to cross through some amplitude level before looking for the next trigger event.

Holdoff Time and Hysteresis Level



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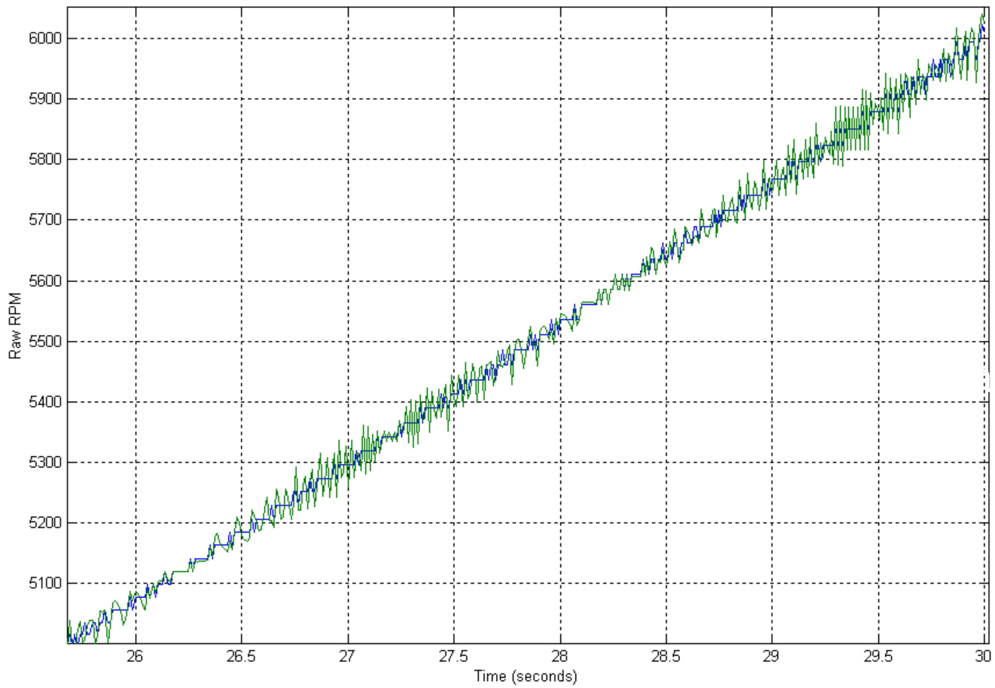
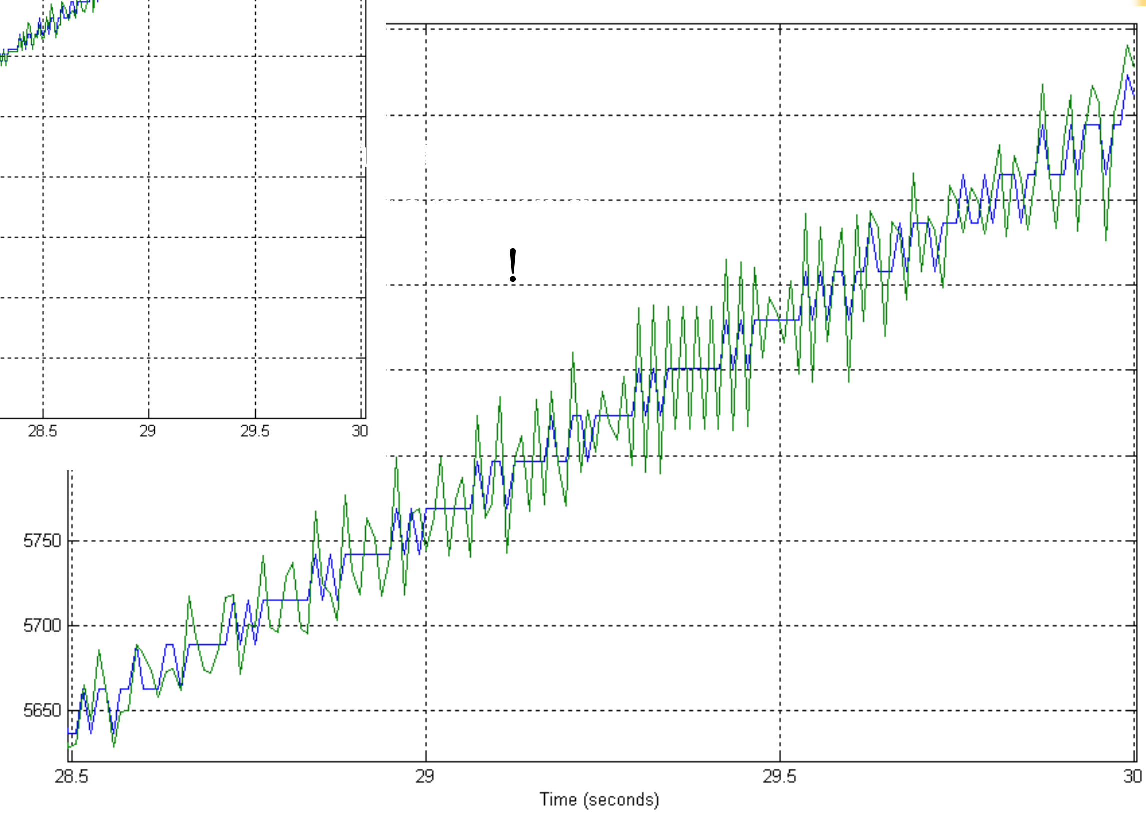
Upsampling/Interpolation

- Upsampling or interpolation are used to reduce the timing errors by first increasing the time domain sample rate of the tachometer signal before looking for trigger crossings.

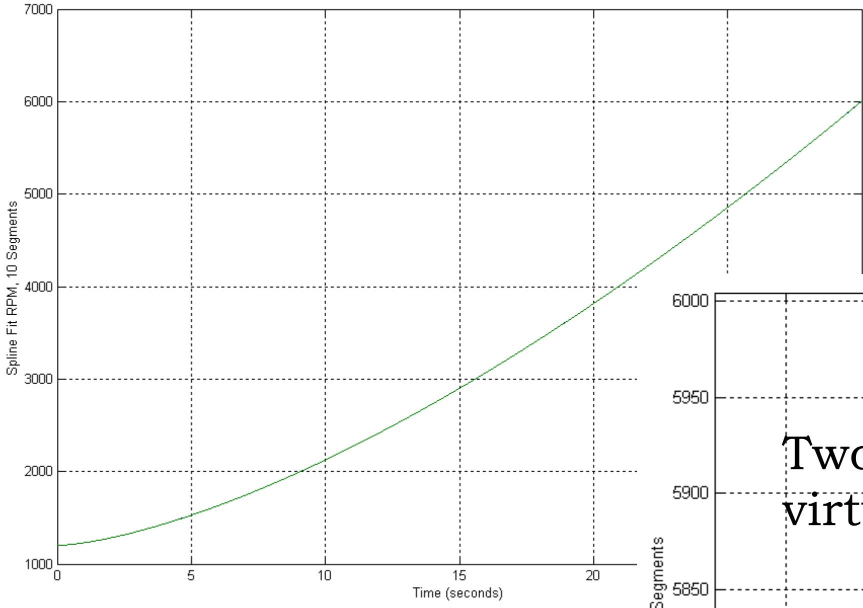
  - Upsampling or interpolation cannot restore filtered frequency content but can fill in the gaps based on frequencies in the data.

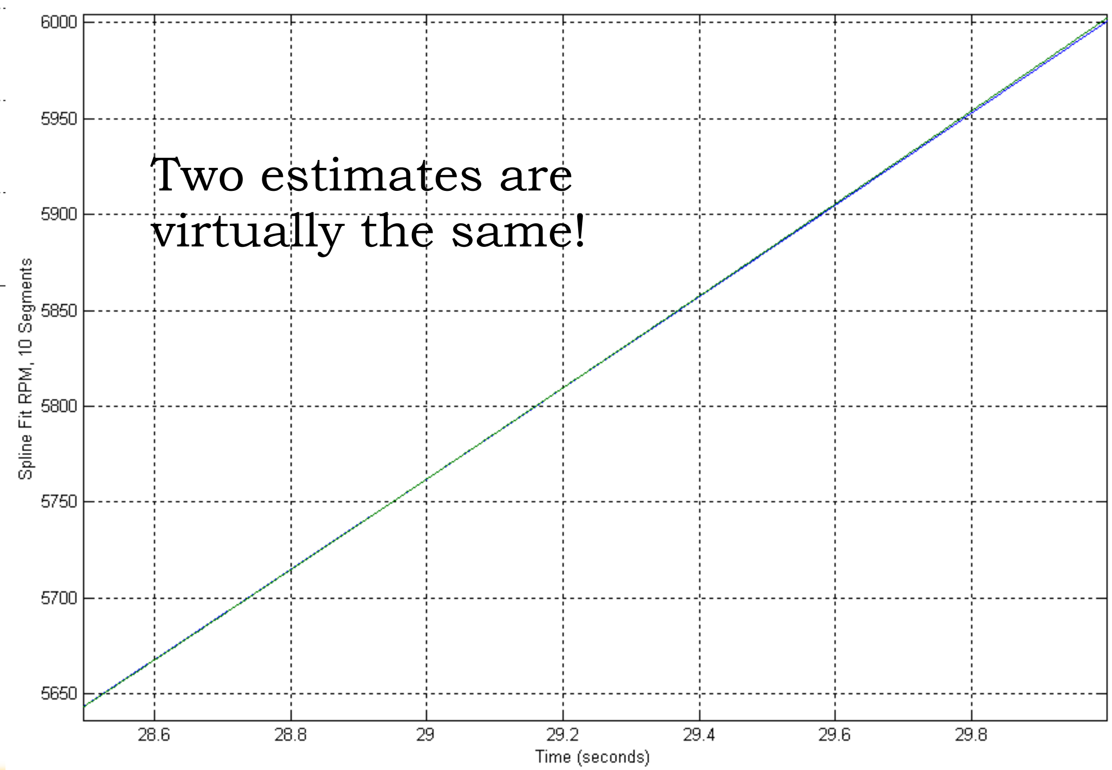
Raw and Upsampled RPM Estimates





Spline Fit RPM Estimates





Two estimates are virtually the same!

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Goal of Order Tracking

- Accurately estimate the energy associated with a rotating component on an operating machine

$$X(t) = A(k,t)\sin\left(2\pi(k/p)t + \phi_k\right)$$

- Difficulties:
  - Frequency changes as a function of time
    - We use the Tachometer Signal to solve these issues
  - Amplitude changes as a function of time

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Solving the Amplitude Variation

- Difficulty in solving the amplitude variation is that for a signal's amplitude to change it must interact with adjacent frequencies
  - How many does it interact with is the question!?
    - Faster the amplitude variation the more it needs!!
    - Sweep rate will affect this when dynamics are present
      - Higher sweep rates need more bandwidth
    - Damping in a system will influence this
      - Hence B&K optimal Vold-Kalman bandwidth determination

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Types of Order Tracking

- Time based sampling FFT analysis
- Time based sampling – Angle based resampling
  - Computed Order Tracking
  - Resampling Based Order Tracking
- Time based sampling – Modulation processing
  - Time Varying Discrete Fourier Transform (TVDFT)
  - Kalman/Vold-Kalman Order Tracking
  - Adaptive FIR/IIR Filtering

Time based sampling FFT analysis

- What is done to account for frequency change?
  - Determine frequency of order from tachometer signal.
  - Extract frequency bins which correspond to frequency of order.
    - Integrate over multiple spectral lines to account for frequency variation over transform time, T.
      - Use constant frequency, order, or percentage bandwidths.
      - Apply energy correction for window!
  - These strategies work well for slow sweep rates!
    - Fast sweep rates require more sophisticated methods!

Time Based FFT Sampling Relationships

- FFT based order tracking is the simplest order tracking method.
  - Based on standard FFT sampling laws.

$$\Delta f = \frac{1}{T} = \frac{1}{N * \Delta t}$$

$$T = N * \Delta t$$

$$F_{nyquist} = F_{\max} = \frac{F_{sample}}{2}$$

$$F_{sample} = \frac{1}{\Delta t}$$

$$a_n = \frac{1}{N}\sum_{n=1}^{N} x(n\Delta t)\cos(2\pi f_n n\Delta t)$$

$$b_n = \frac{1}{N}\sum_{n=1}^{N} x(n\Delta t)\sin(2\pi f_n n\Delta t)$$

  - Note: Sampling relationships are based on time and frequency!

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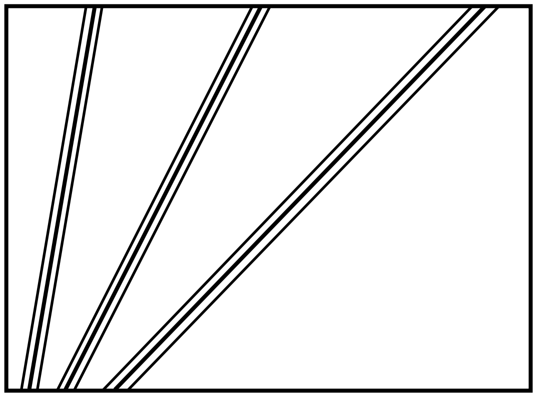
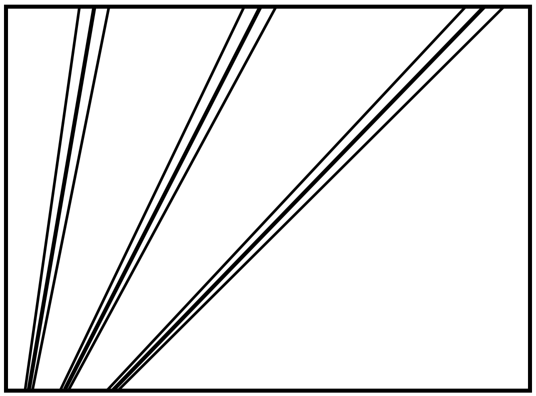
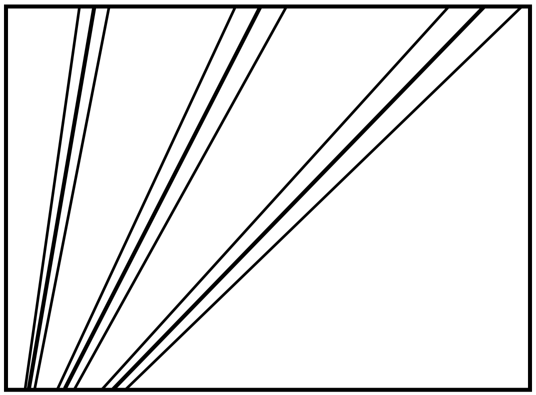
FFT Bandwidths



Constant Frequency Bandwidth
- Bandwidth is independent of order/frequency.



Constant Order Bandwidth
- Bandwidth is dependent on frequency of 1st order.



Constant Percentage Bandwidth
- Bandwidth is dependent on frequency.

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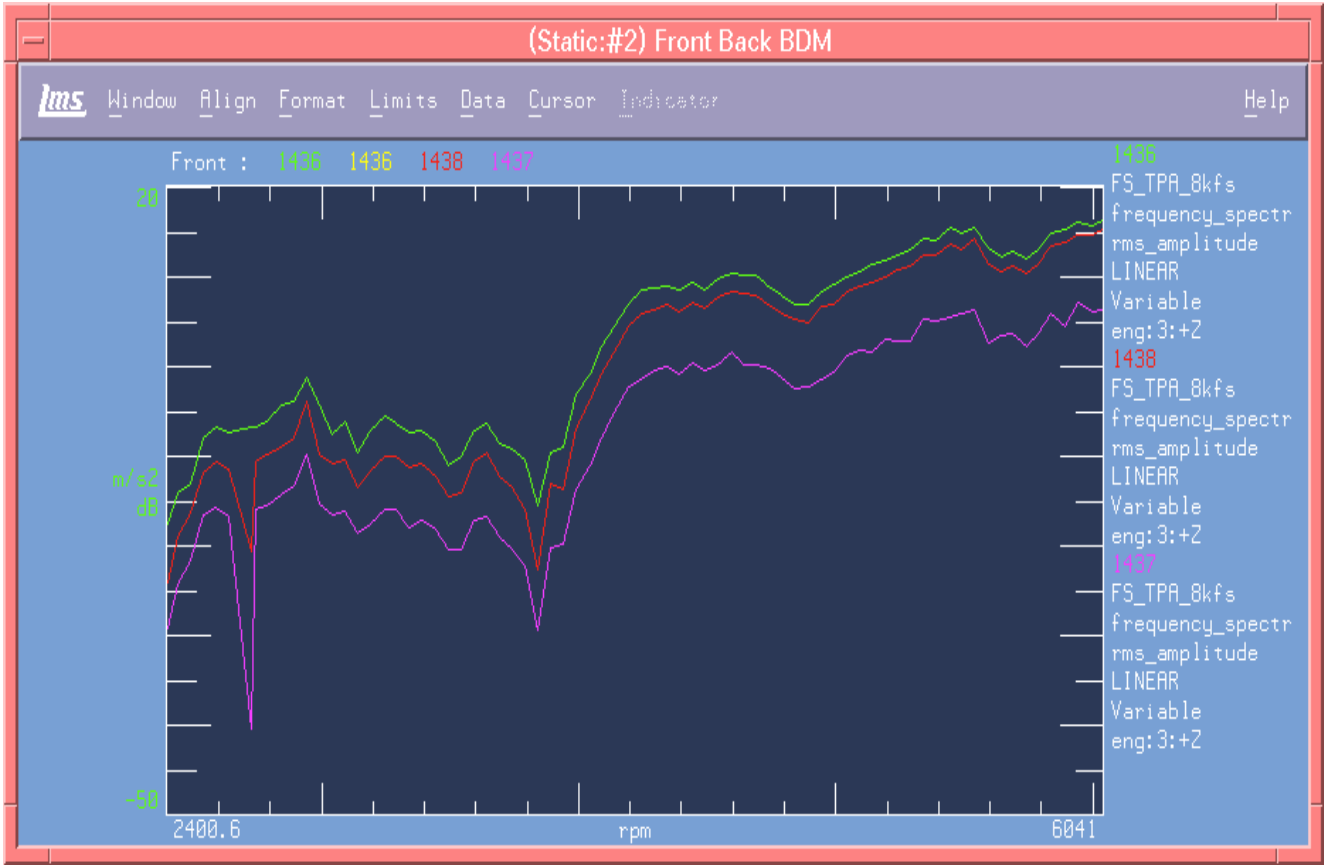
Same Order, Different Bandwidths



- Same order extracted using different bandwidth methods!

FFT Order Tracking Summary

- Kernel based on time/frequency.
  - Leakage is a problem.
    - Use windows to minimize.
  - Time varying frequency is a problem.
    - Integrate over multiple spectral lines.
  - Time varying amplitude is a problem.
    - Amplitude is average over transform time.
  - Varying number of orders present in data depending on rpm.
    - Sample rate not dependent on rpm.
  - Poor order resolution at low rpm values.
    - Same Δf regardless of rpm.

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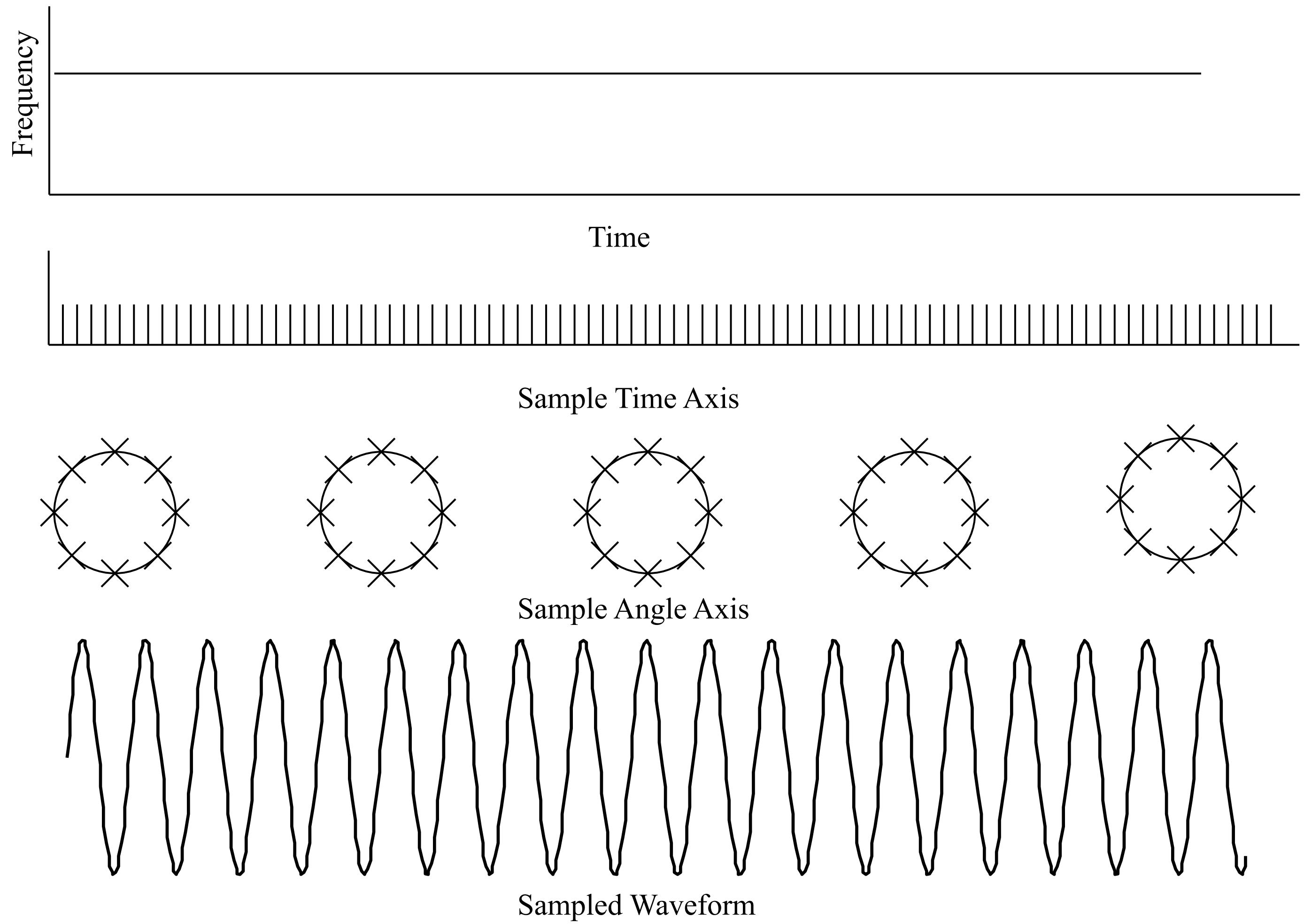
Why Resample to Angle Domain?

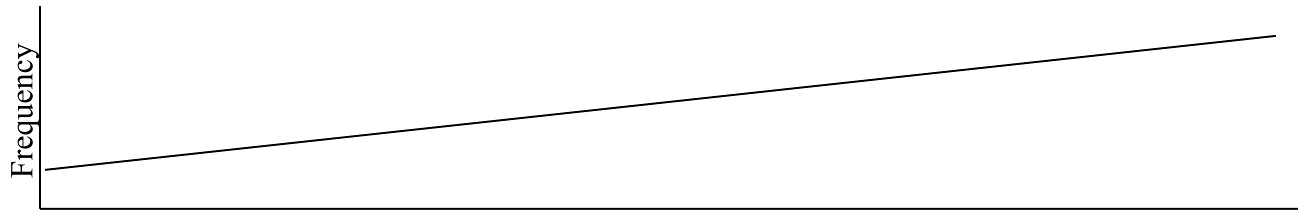
- Resampling time data to angle data straightens out orders.
  - Orders now fall on one spectral line regardless of rpm.
  - Provides leakage free estimates of orders.
- Number of orders present in resampled data is independent of RPM.
- Order resolution is independent of RPM.
  - Good order resolution at low speeds.

- All standard DSP techniques for constant frequency analysis in the time domain can be performed on orders in the angle domain!
  - ie. FFT, Digital Filtering, Synchronous Averaging, …etc.

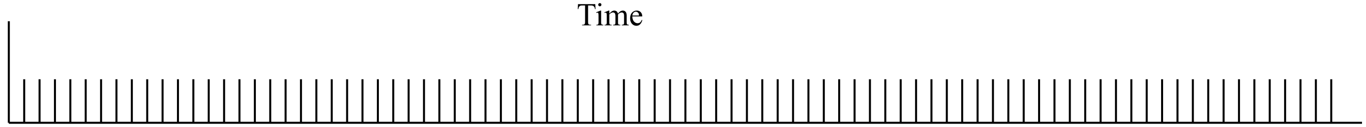
Constant Frequency, Constant Δt



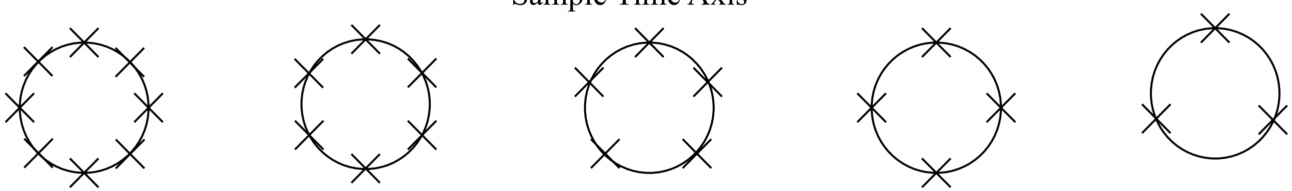
Variable Frequency, Constant Δt



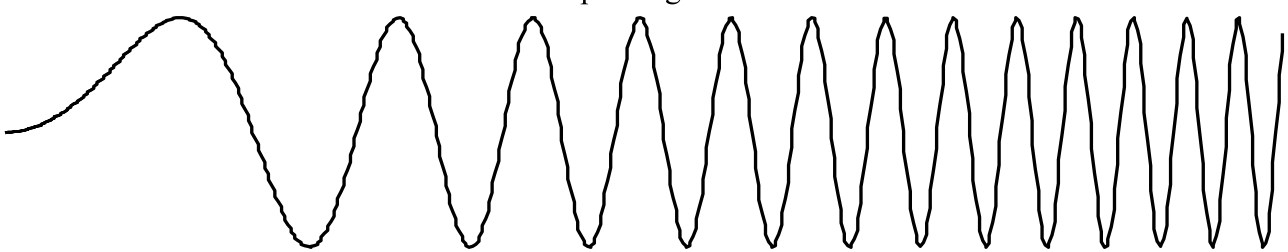
Time



Sample Time Axis



Sample Angle Axis



Sampled Waveform

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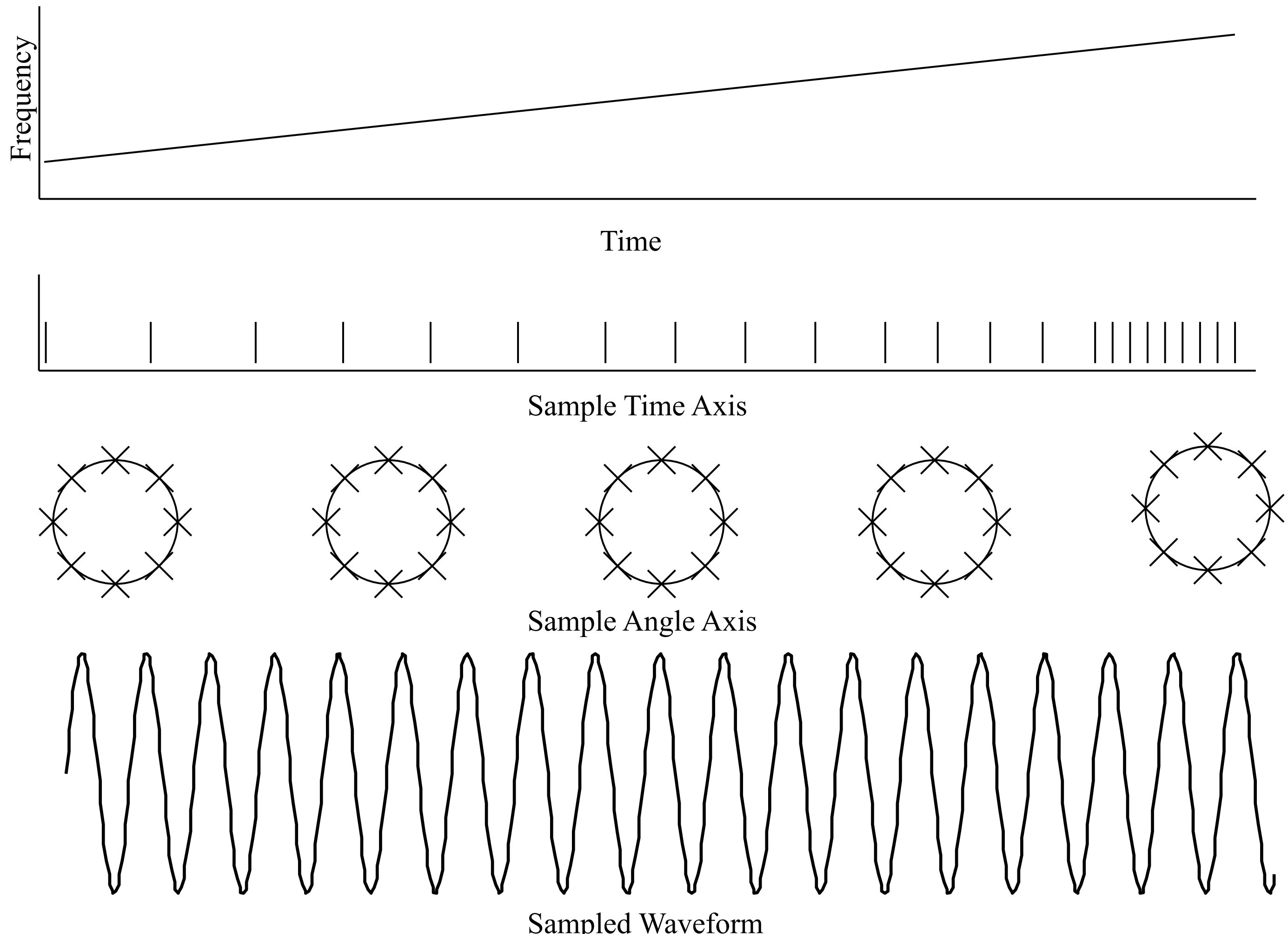
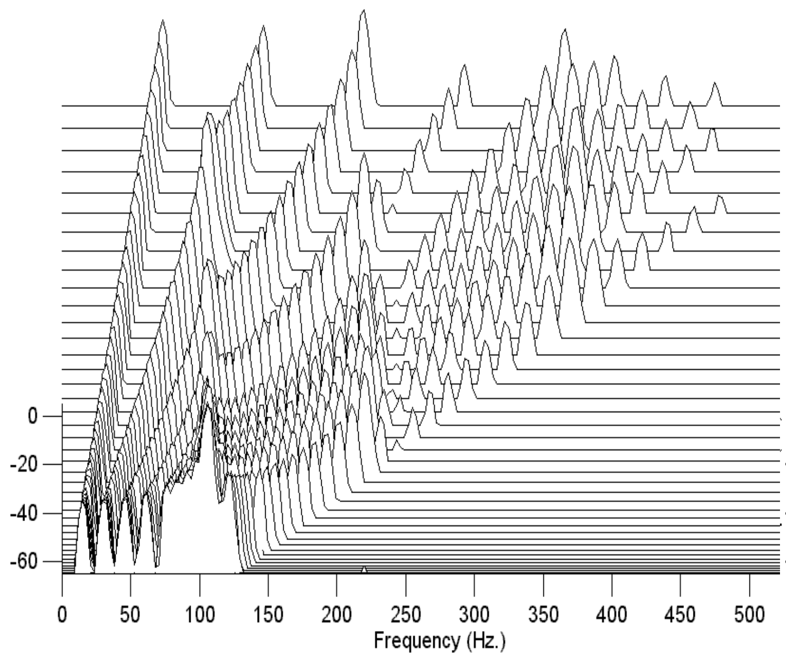
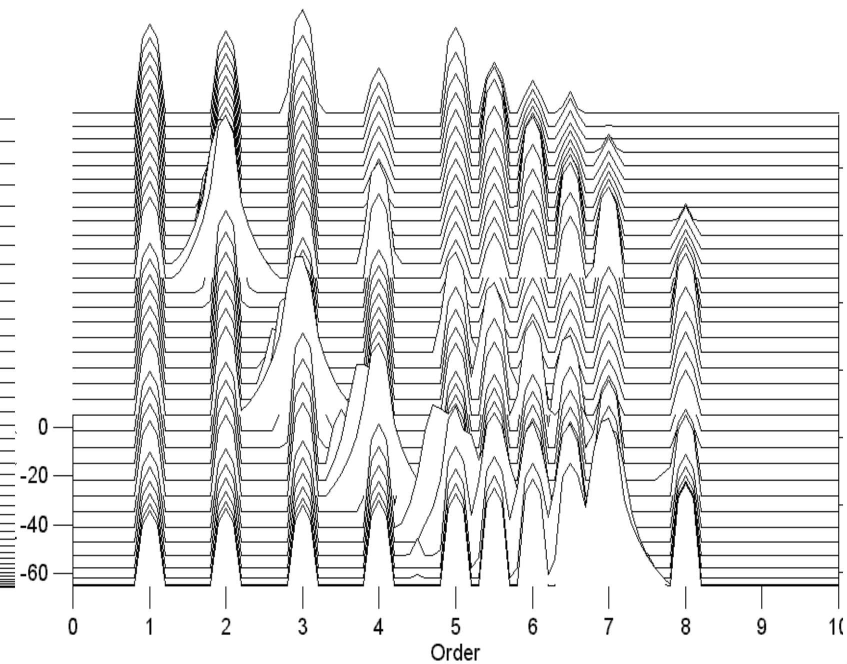
Variable Frequency, Constant Δθ



Angle Domain Sampling Results

- Let's see what happens in the order domain!
  - Orders which changed frequency now appear as constant frequency!





Here is How its Done!

Tachometer data → Obtain time instants of equal angular intervals

Constant Δt data → Adaptively digital anti-alias filter

Sample rate must be >2*max_order of interest! → Adaptively resample time to angle domain

Perform angle domain FFT

Angle Domain FFT?

- Now we have resampled angle domain data… what do we do with it?
  - Reformulate FFT sampling relationships.

$$\Delta o = \frac{1}{R} = \frac{1}{N * \Delta\theta}$$

$$R = N * \Delta\theta$$

$$O_{nyquist} = O_{\max} = \frac{O_{sample}}{2}$$

$$O_{sample} = \frac{1}{\Delta\theta}$$

$$a_m = \frac{1}{N}\sum_{n=1}^{N} x(n\Delta\theta)\cos(2\pi o_m n\Delta\theta)$$

$$b_m = \frac{1}{N}\sum_{n=1}^{N} x(n\Delta\theta)\sin(2\pi o_m n\Delta\theta)$$

  - Note: No time or frequency in these equations!
- Note: These kernels operate on orders and produce constant order bandwidth results.
  - Orders which fall on spectral lines are leakage free!!

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Modulation Based Processing - Solving the Frequency Variation

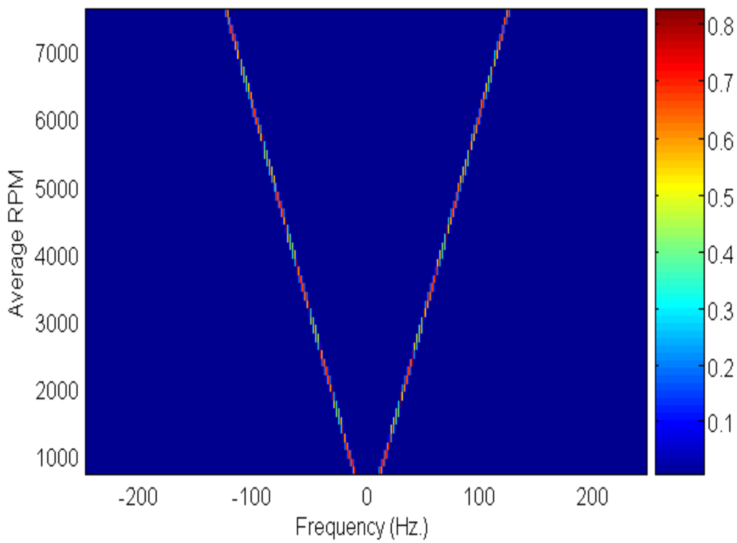
- All methods except the time based FFT method use the same kernel to solve this problem
  - Must have accurate tachometer signal to drive the process

$$x_{DC}(n\Delta t) = x(n\Delta t).*\exp\left(-2\pi i\int_0^{n\Delta t}\left(o_m \Delta t\, {}^{rpm}\!/_{60}\right)dt\right)$$

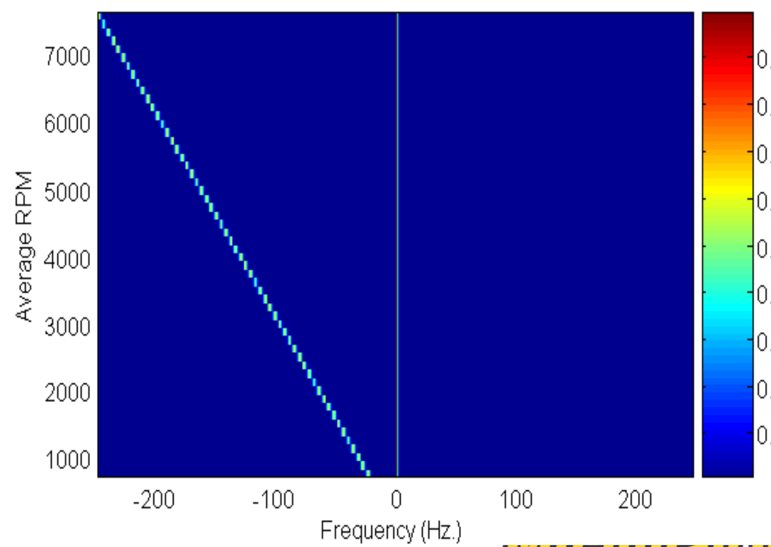
  - Used by: TVDFT, Vold-Kalman, Modulation based filtering, resampling or computed order tracking
- Time based FFT method attempts to brute force frequency variation by summing over multiple spectral lines

Frequency Variation – How does kernel work?

- Original order on left, modulated on right
- Frequency variation is removed!



- Resampling Based (Computed) order tracking methods do this through the resampling process!



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Amplitude computations?

- The modulation based methods use different formulations to estimate the amplitudes of the orders
  - All compute an average amplitude!
  - All require the necessary bandwidth to achieve an appropriate amplitude estimate

Equations

- Resampling Based (Computed) order tracking

$$c_m = \frac{1}{N}\sum_{n=1}^{N} x(n\Delta\theta).*\exp(-2\pi i o_m n\Delta\theta)$$

- Time Variant Discrete Fourier Transform (TVDFT)

$$c_m = \frac{1}{N}\sum_{n=1}^{N} x(n\Delta t).*\exp\left(-2\pi i\int_0^{n\Delta t}\left(o_m \Delta t\, {}^{rpm}\!/_{60}\right)dt\right)$$

- Modulation based filtering technique

$$c_m = \left[x(n\Delta t).*\exp\left(-2\pi i\int_0^{n\Delta t}\left(o_m \Delta t\, {}^{rpm}\!/_{60}\right)dt\right)\right]\otimes LowPassFilter$$

- Vold-Kalman Filter
  - Least squares estimate based on surrounding points as well – no clear equation to show

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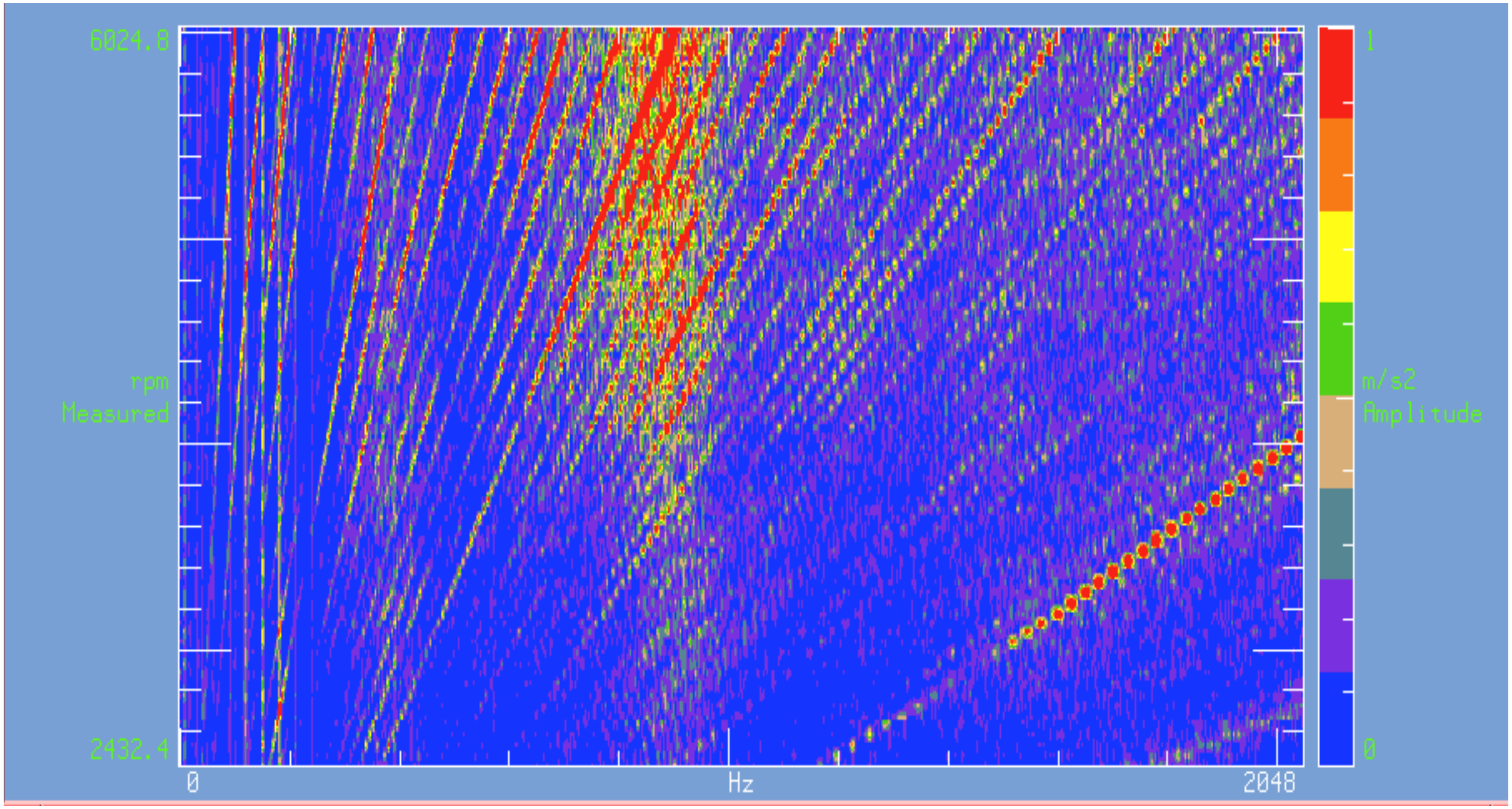
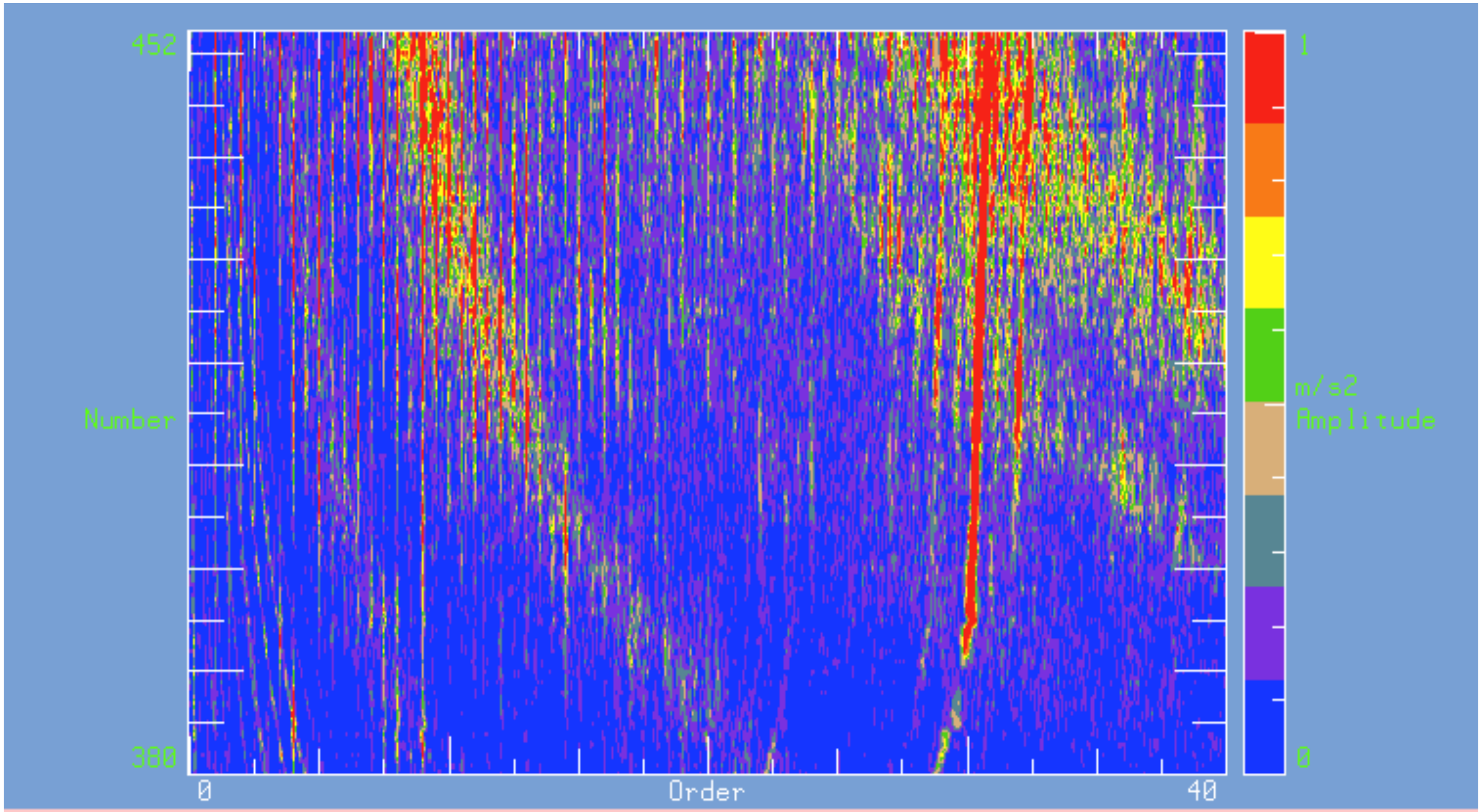
FFT Colormap, X-Axis = Frequency



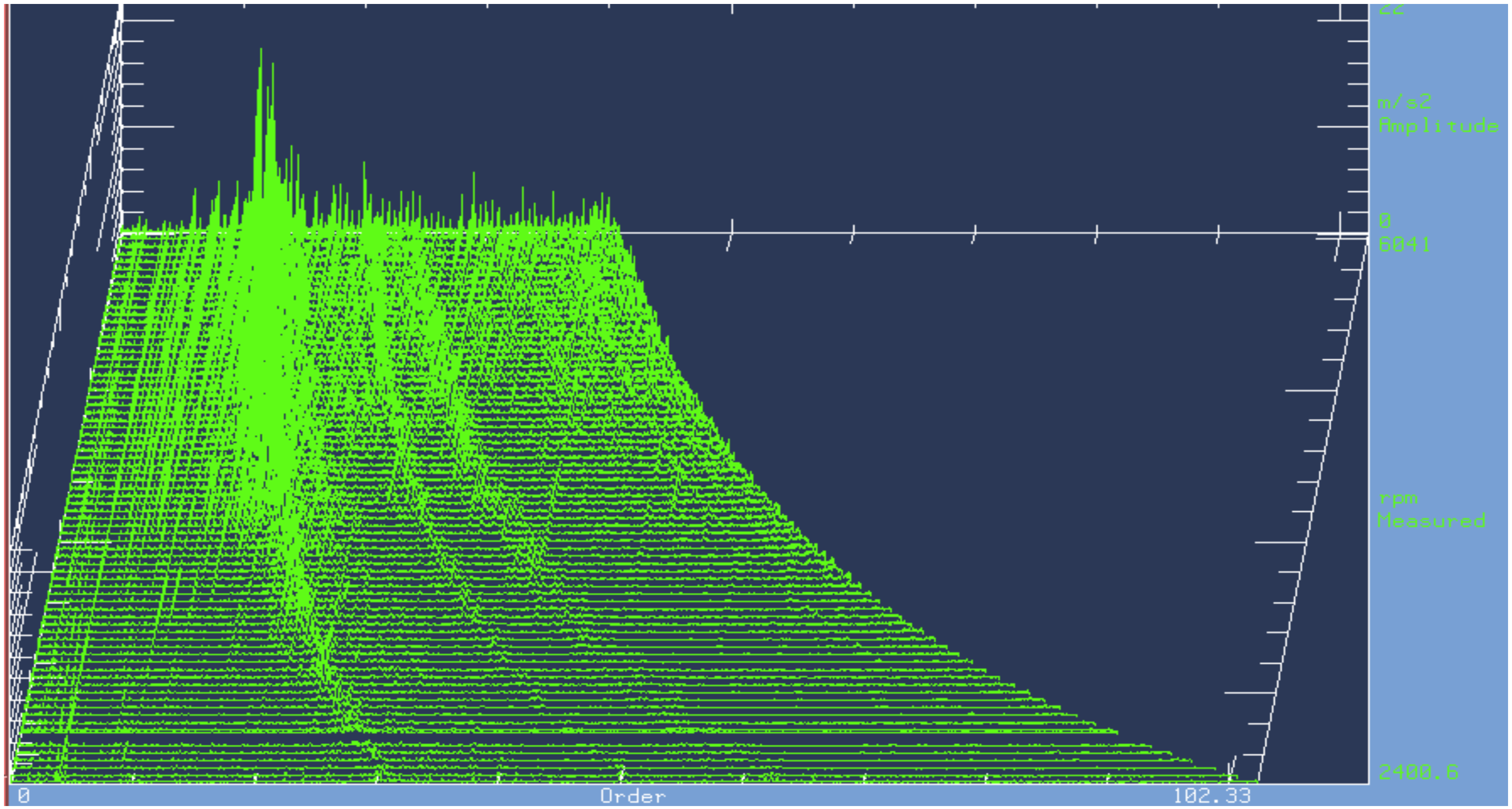
- *Constant Frequency - Vertical Line.*

FFT Colormap, X-Axis = Order



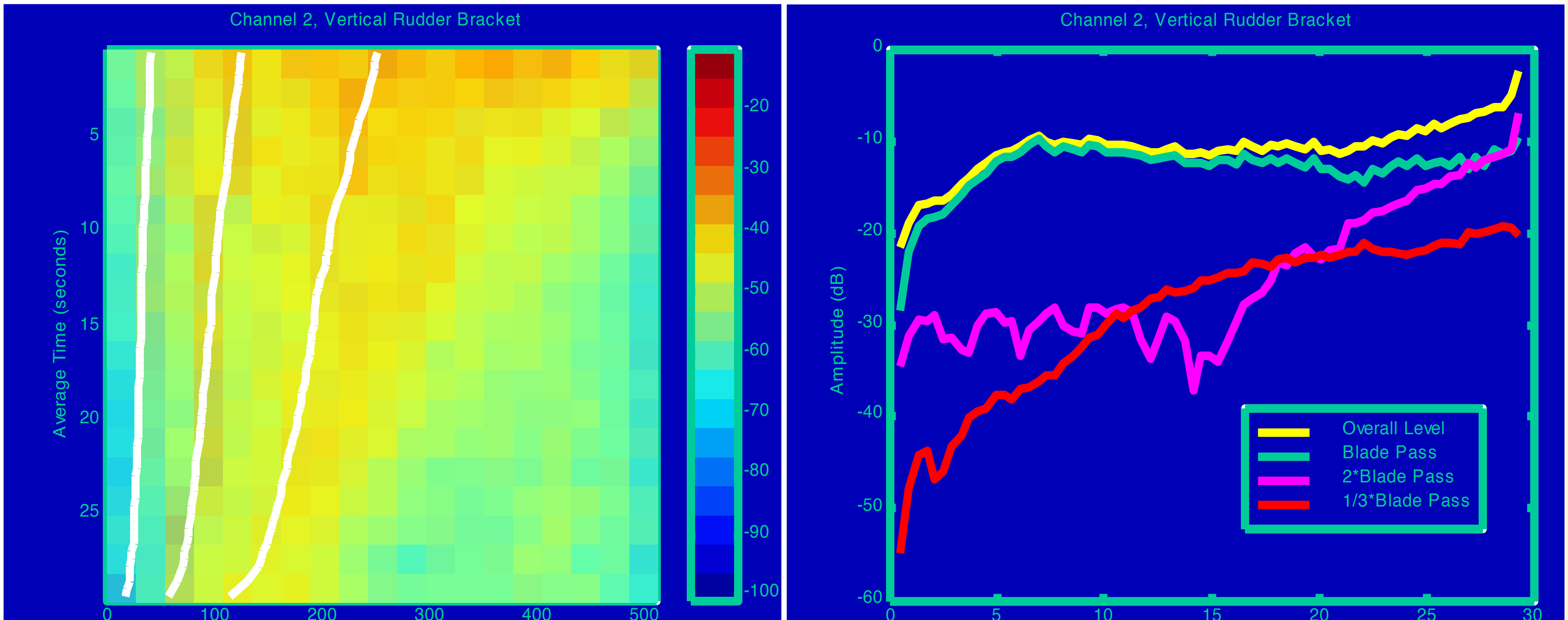
➢ *Constant Order - Vertical Line.*

FFT Waterfall, X-Axis = Order



- *Note: Number of orders changes with RPM!*

Real Data from a Boat



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Order Cuts

Understanding Order Tracking Behaviors

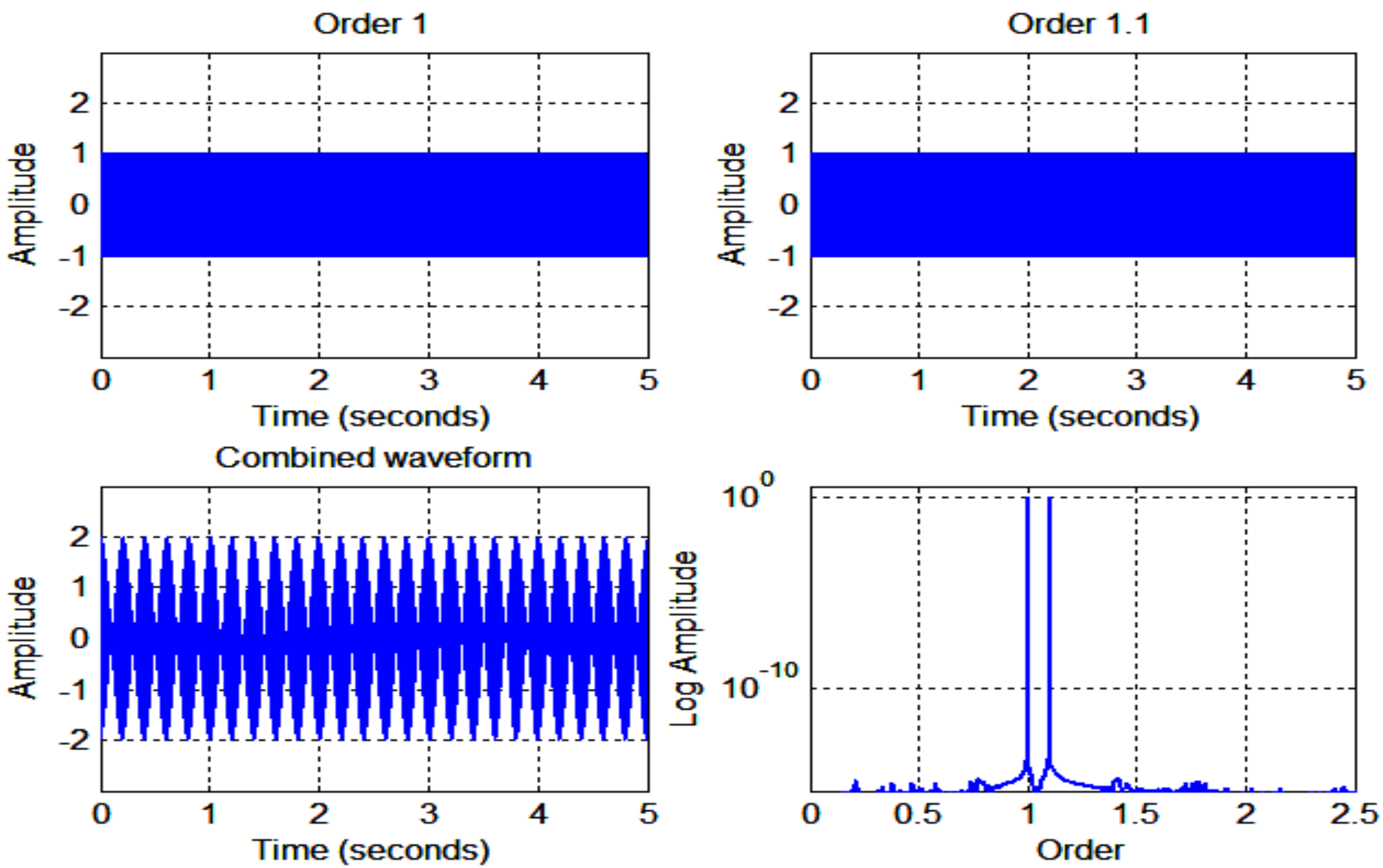
- Need to understand effect of amplitude variation
- Need to understand effect of sweep rate
- Need to understand impact of low vs. high structural damping on results
- What impacts being able to separate orders from one another?

Amplitude Variation - Analytical

- Develop analytical model with 2 orders present
- Frequency does not change as function of time
- Simulate different amplitude profiles as a function of time
  - No change in amplitude
  - Amplitude profile generated by Gaussian distribution weighting factor
    - Allows different profiles to be simulated easily
  - Study closeness of orders and varying amplitudes of orders relative to one another

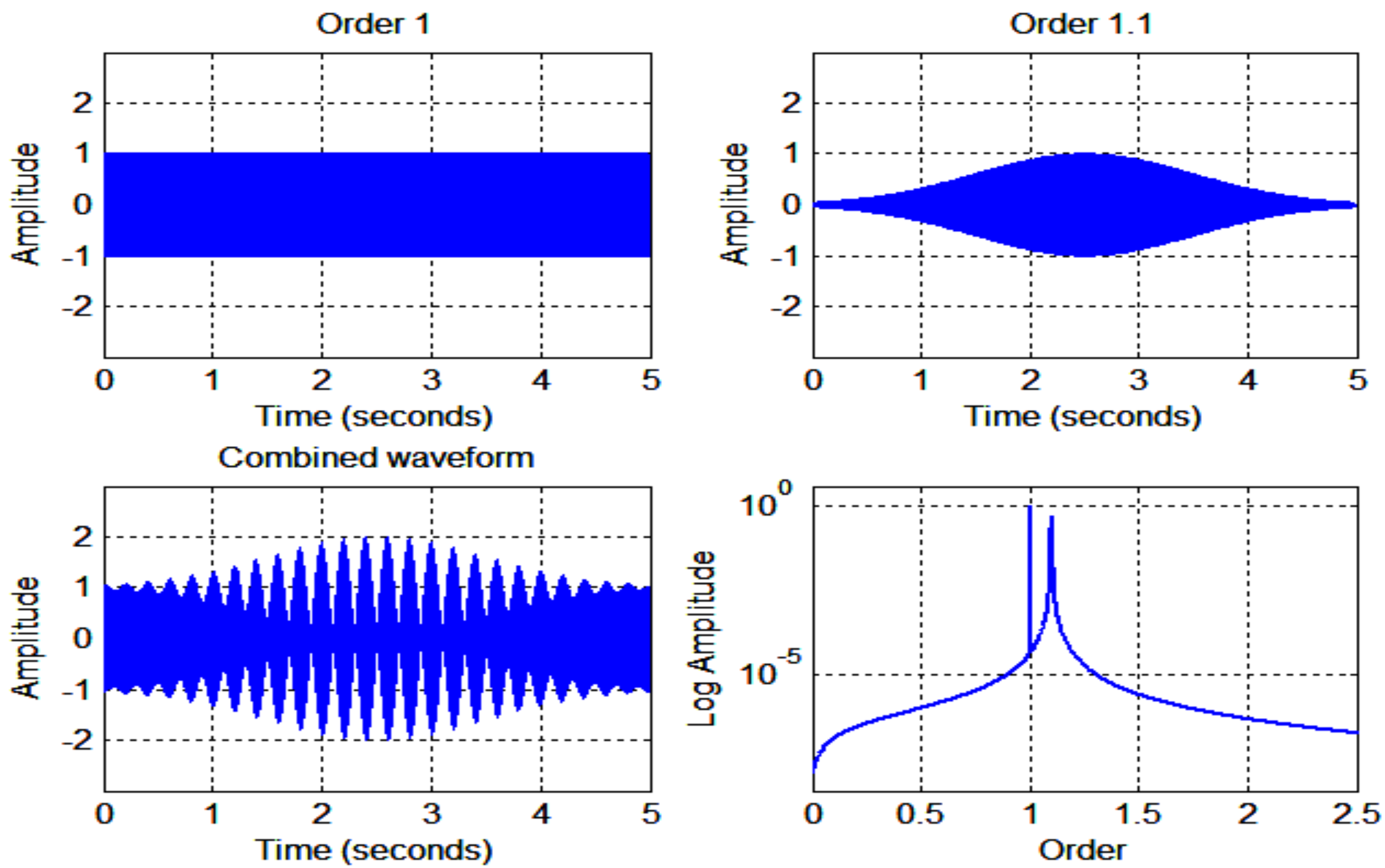
Amplitude Variation - None

- Easy to separate energy associated with each order



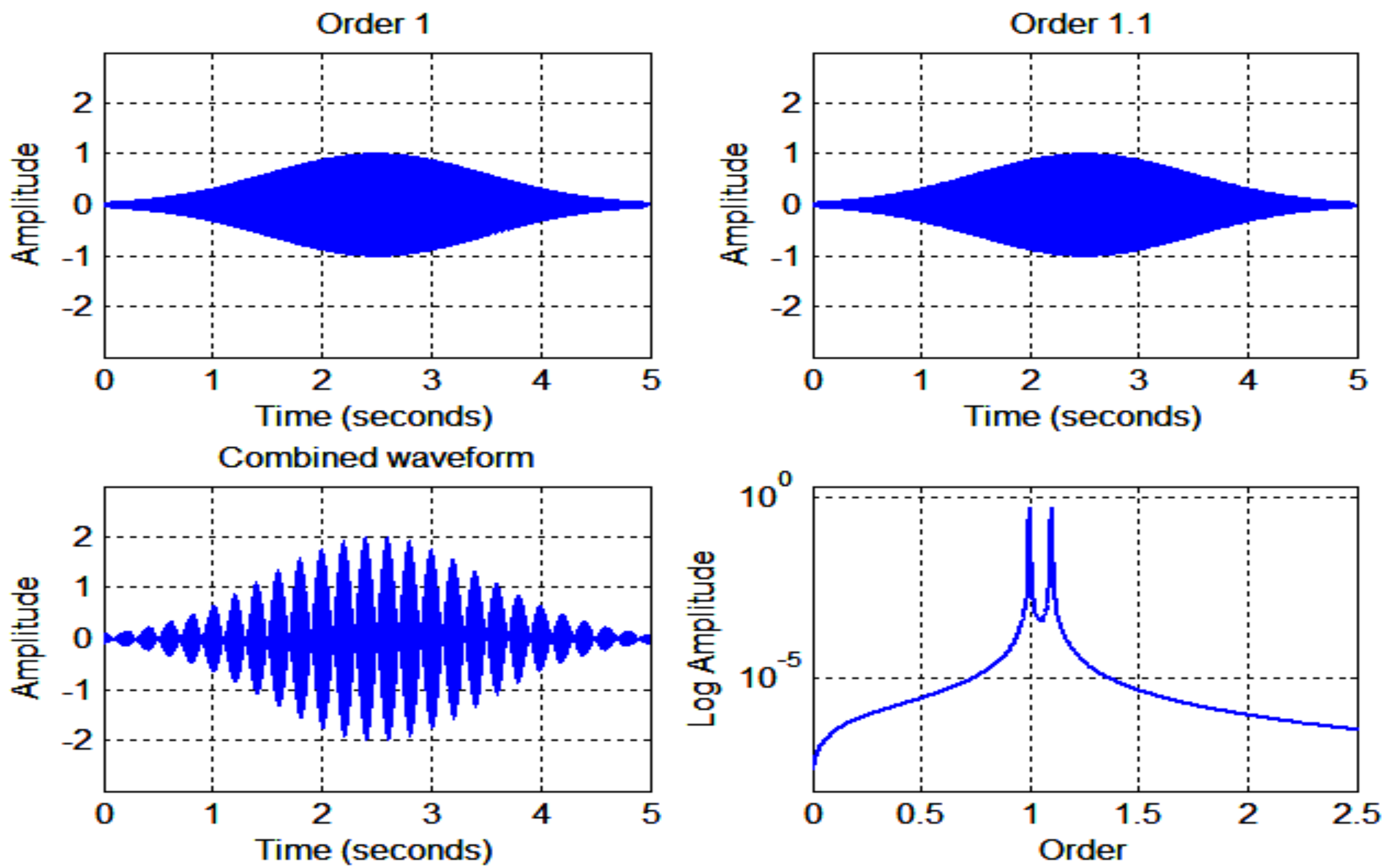
Amplitude Variation – Order 1.1 only

- Energy is “leaking” from order 1.1 to order 1



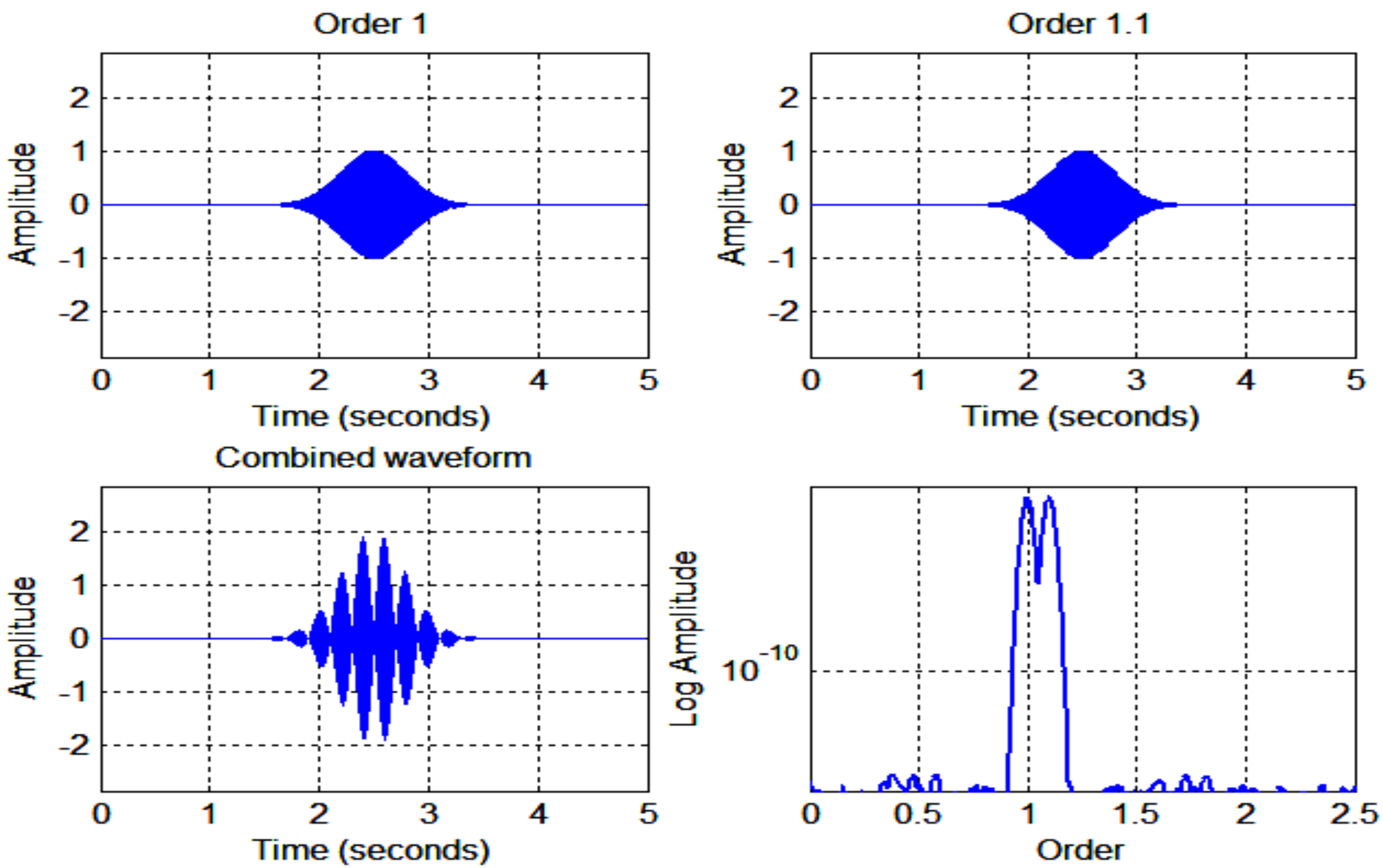
Amplitude Variation – Both orders

➢Energy is “leaking” from both orders



Amplitude Variation – Both orders

- More rapid amplitude change – more “leaking”

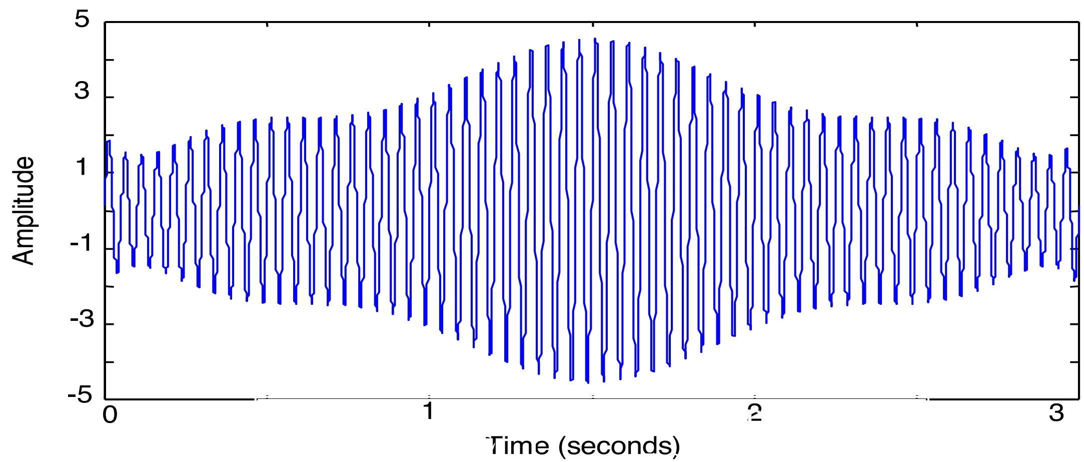


Effects of Amplitude Variation

- Amplitude variation led to energy “leaking” from the orders to surrounding order bins
- Reduction in the peak amplitude at the 1.0 and 1.1 order bins when amplitude variation present
- Difficult to separate the orders and understand what energy is associated with each order
  - More difficult when amplitude change happens faster

Average Based Order Tracking Errors

- Errors exist because an order is allowed to change amplitude as a function of time!
  - All Fourier transform type of algorithms have this limitation!



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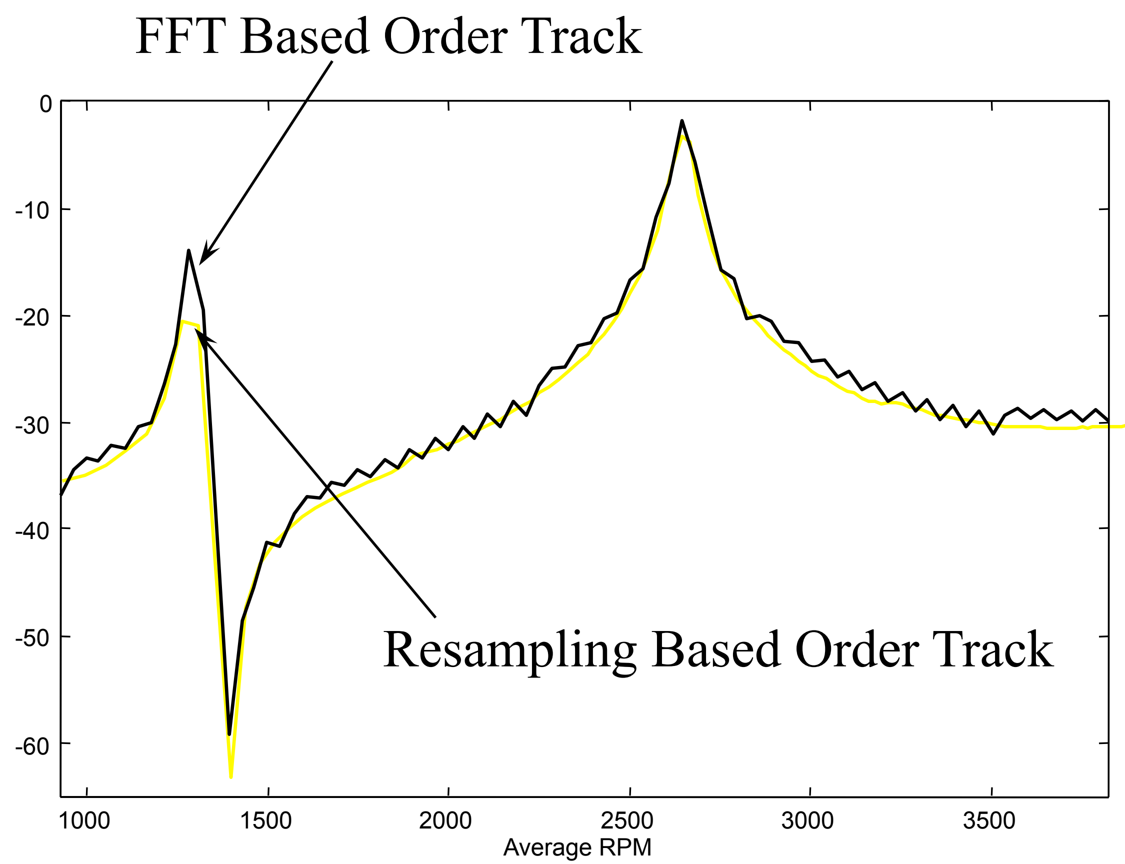
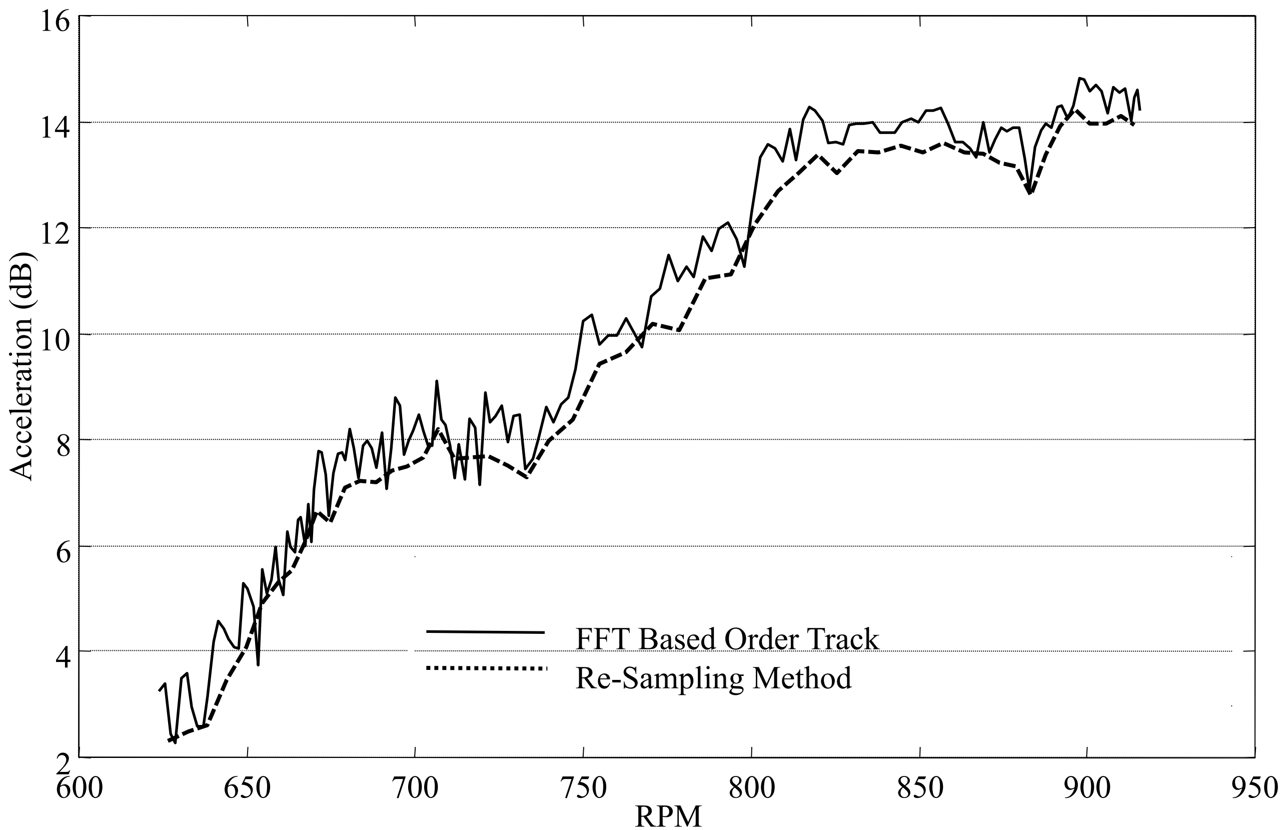
Order Track Results.

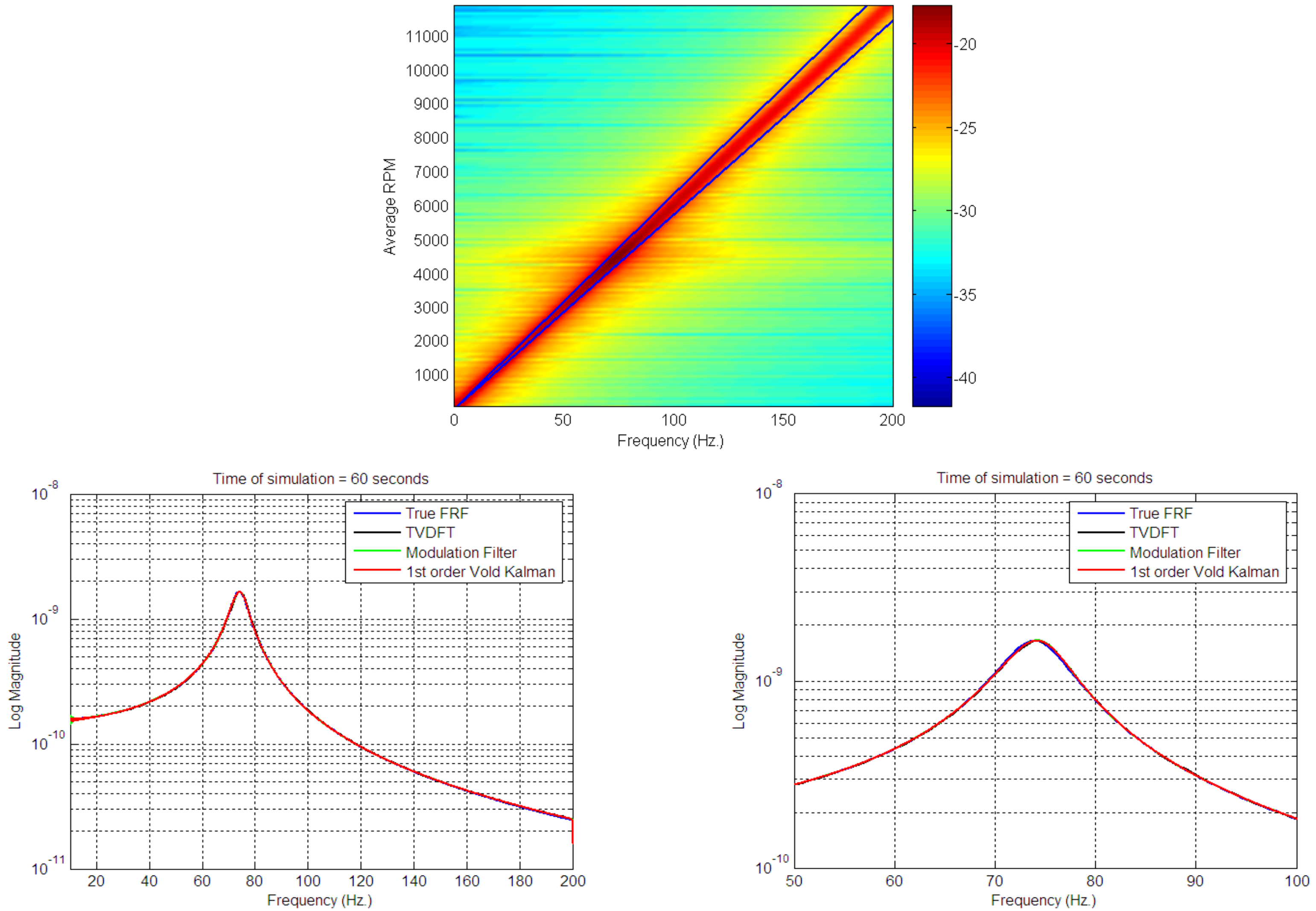


Note: Amplitude differences due to different integration lengths.

Order Track Results.



Analytical Study – Fn=74 Hz, ξ=.046, 60 seconds



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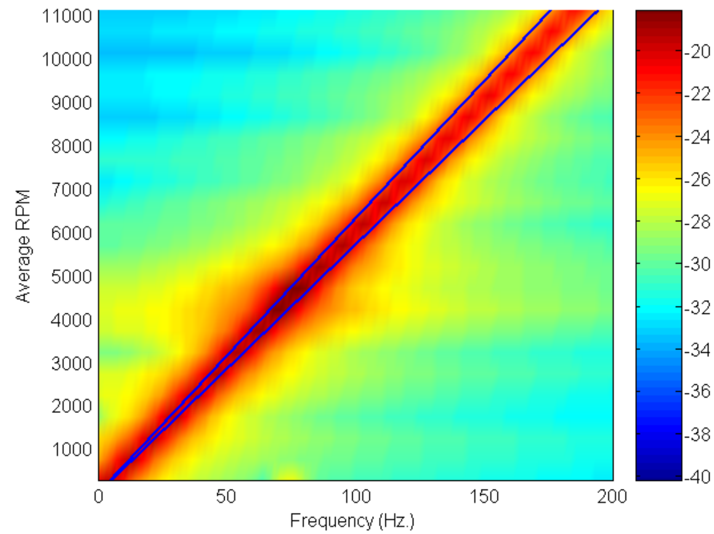
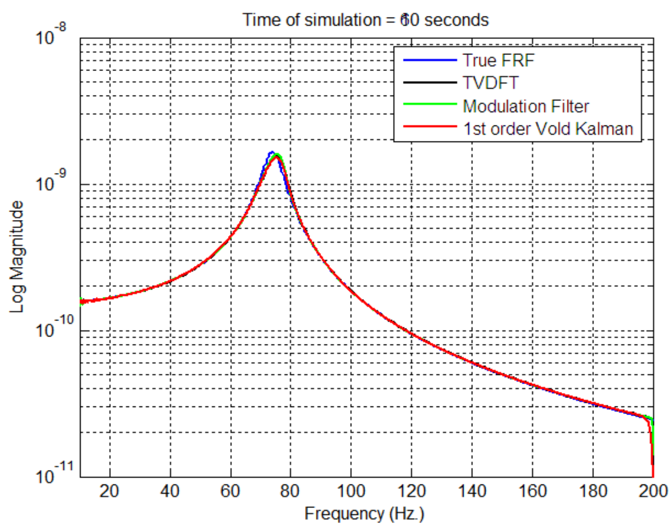
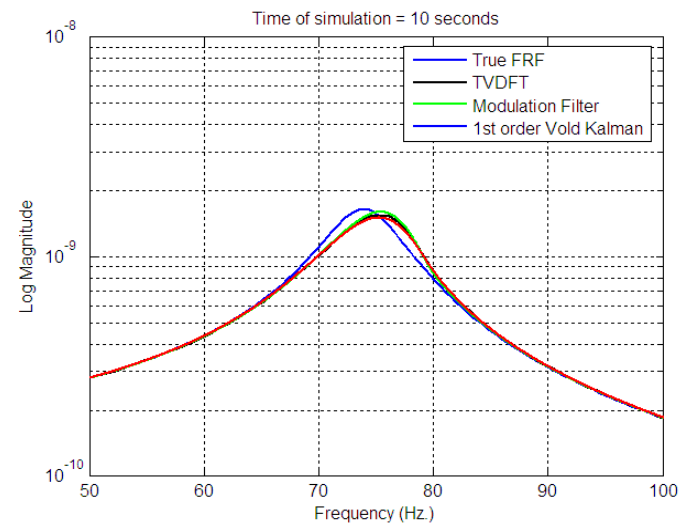
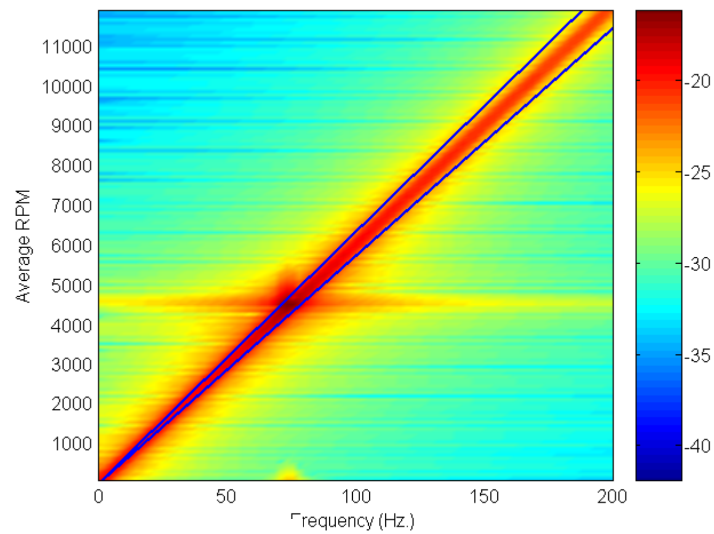
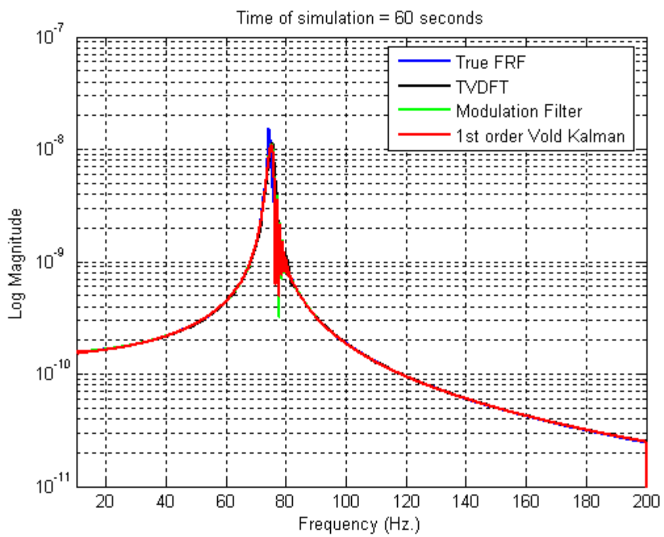


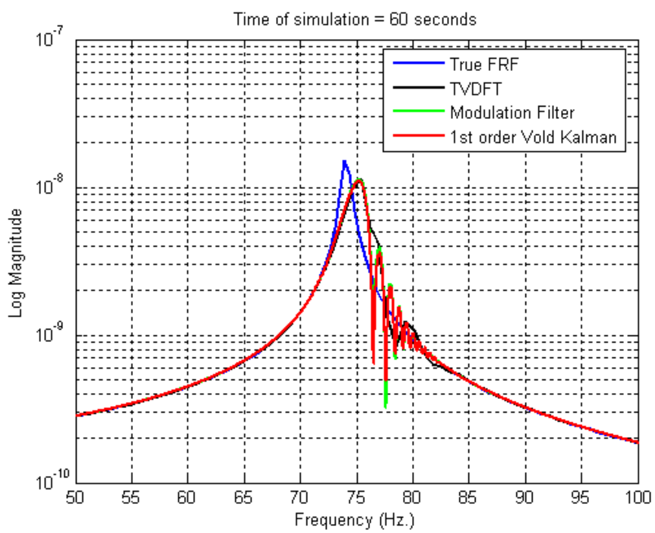




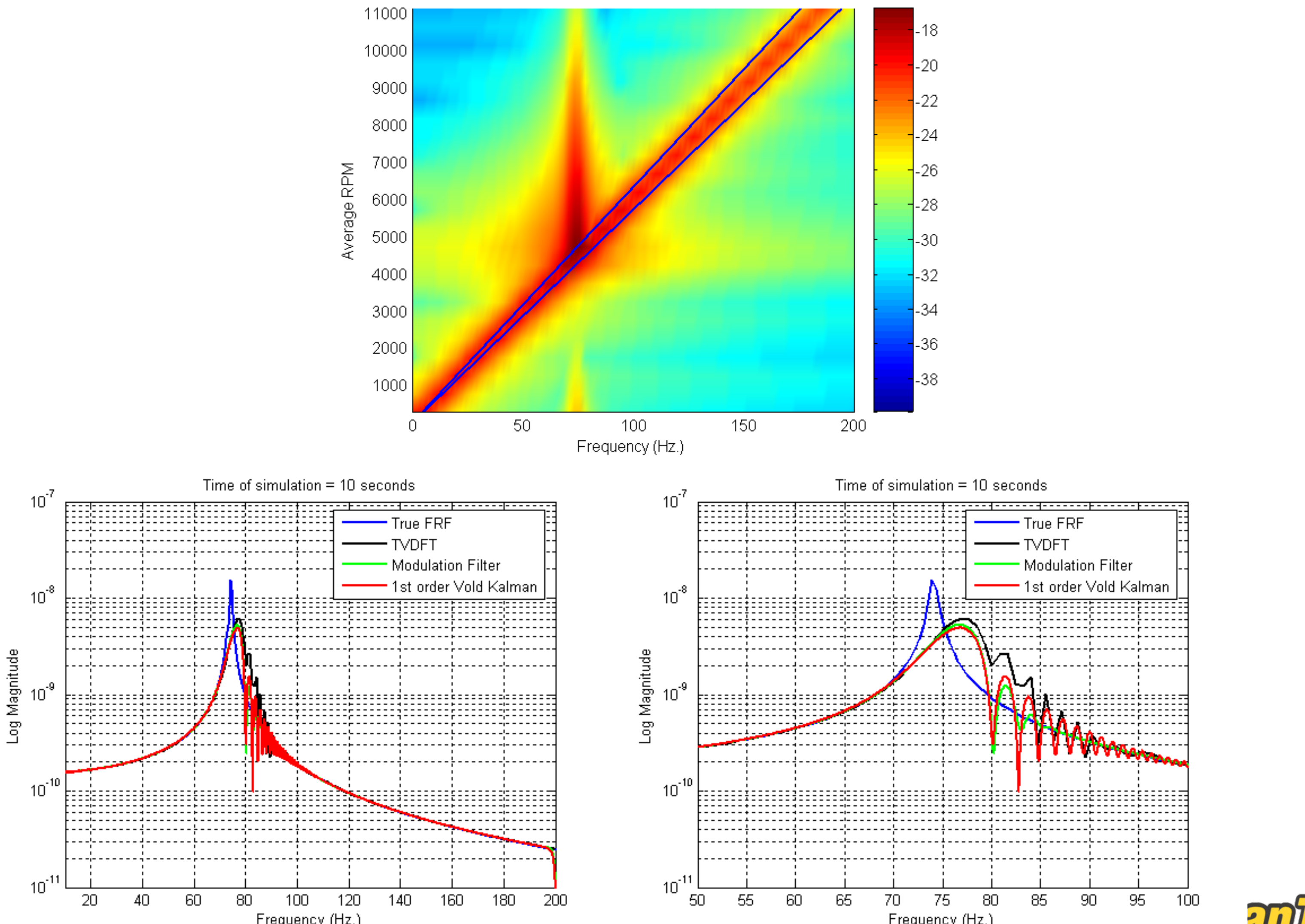
Analytical Study – Fn=74 Hz, ζ=.0046, 60 seconds



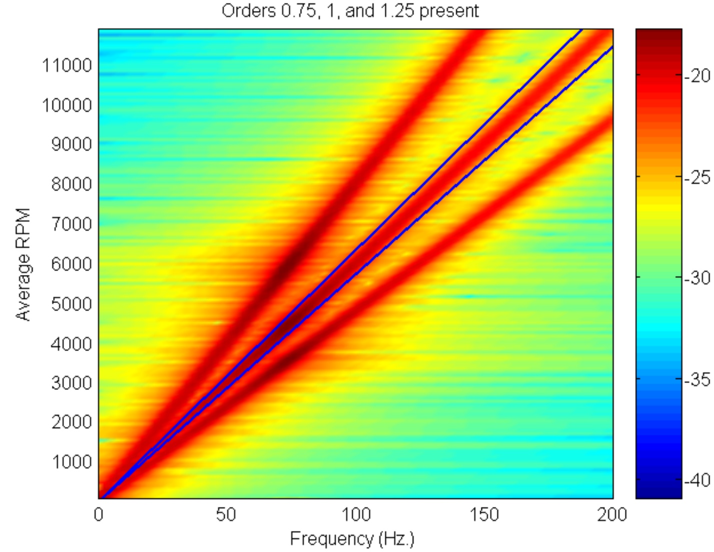


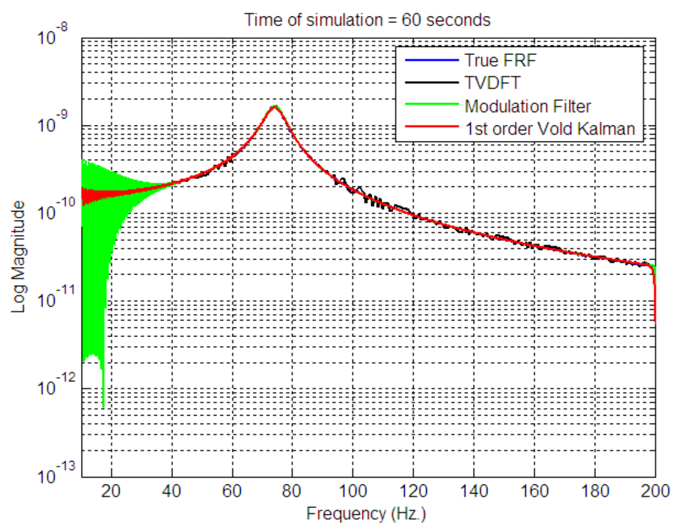


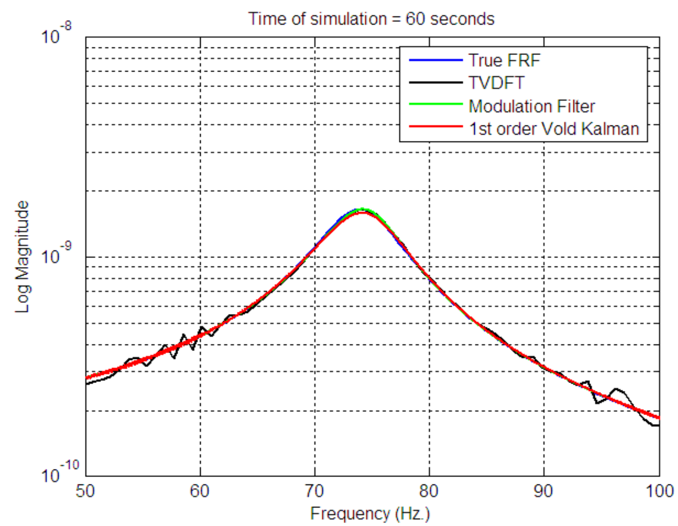
Analytical Study – Fn=74 Hz, ξ=.0046, 10 seconds



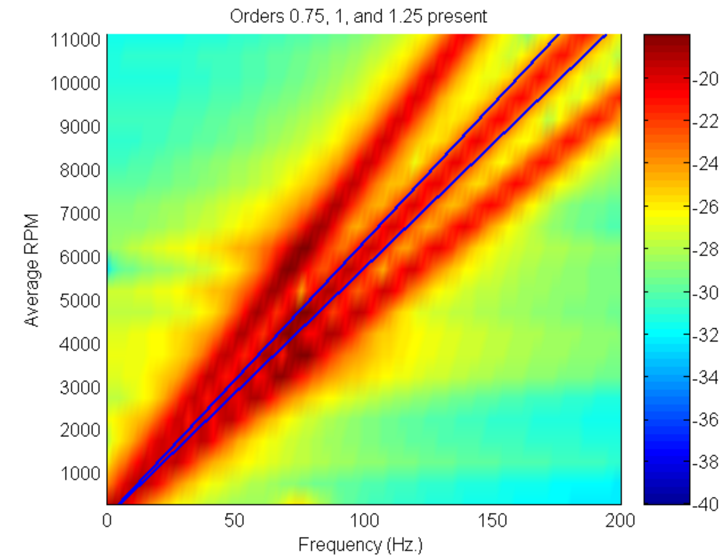
Analytical Study – Fn=74 Hz, ξ=.046, 60 seconds

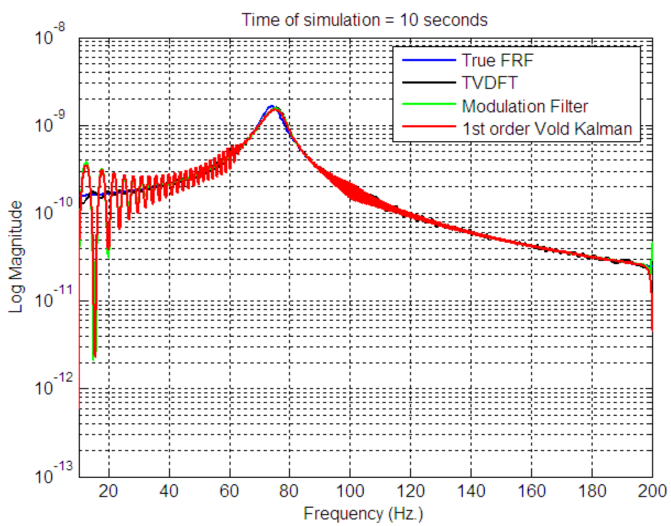


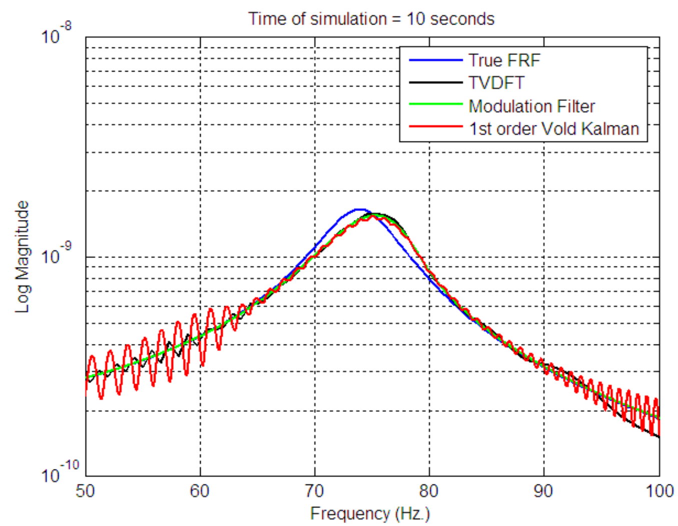




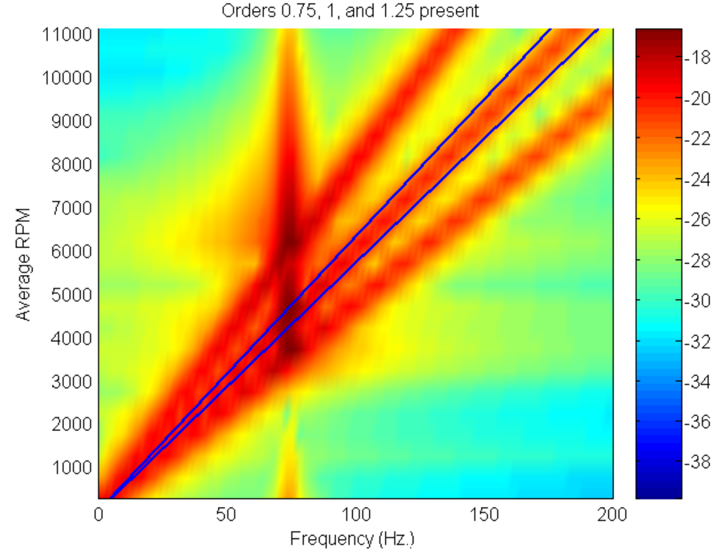
Analytical Study – Fn=74 Hz, ζ=.046, 10 seconds

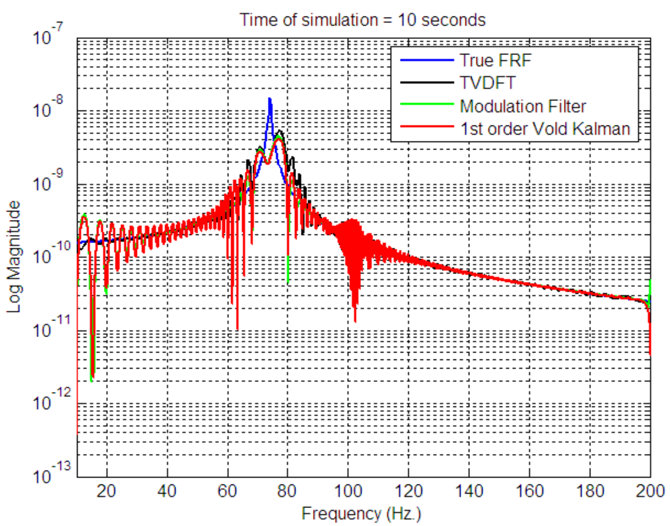


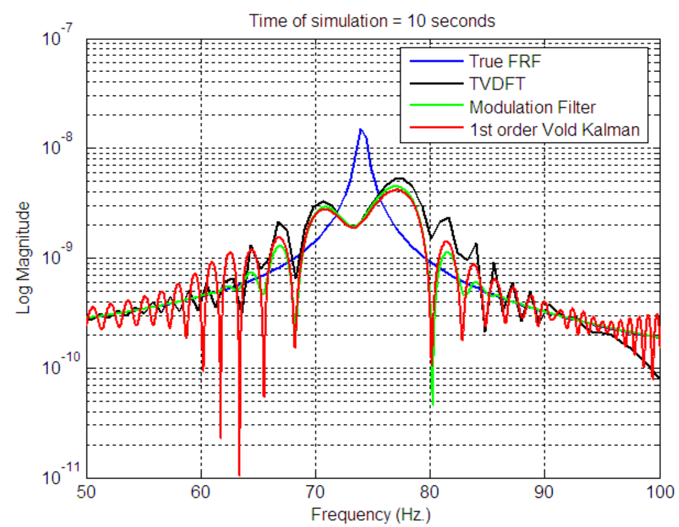




Analytical Study – Fn=74 Hz, ξ=.0046, 10 seconds







Conclusions

- Frequency variation of data is compensated for the same way in all order tracking methods except the basic FFT
- Amplitude variation is always an average amplitude over the "integration" time
- Amplitude variation requires multiple frequencies to interact
- Limitations on order tracking performance are based on rate of change of amplitude of order not strictly "slew rate"!
- Similar performance is observed from algorithms in most cases

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