SCIENCE OF TEST

Measurement Accuracy - Data Sampling and Filter Selection during Data Acquisition

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Outline

Background

- Data system overview
- Data quality and responsibilities
- Bad example: Impact of incorrect sampling and filtering

Data acquisition concepts

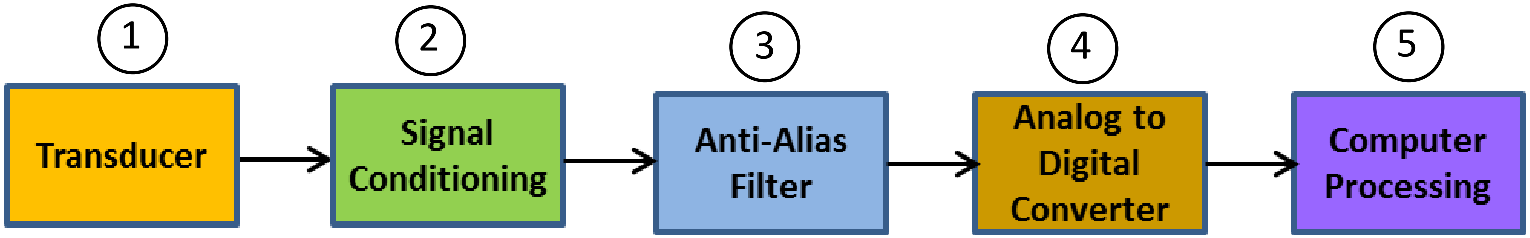
- Nyquist, data sampling, and aliasing
- Filter selection for A/D conversion

Good example: Impact of correct sampling and filtering

Background - Typical Data System

Data acquisition is the process of measuring an electrical or physical system (e,g, voltage, current, temperature, pressure, sound, or flow rate) using an analog device then converting to digital format for computer use

A data acquisition system consists of :



1. Transducer
   - AIP steady state or dynamic
   - Duct dynamic
   - Secondary flows
2. Signal Conditioning
   - DC level shift
   - Amplification or attenuation to match ADC
   - Filtering noise
3. Anti-Alias Filter
   - Low-pass filter to remove signal above one-half sampling frequency
4. Analog to Digital Converter
   - Typically SAR or ΣΔ
   - Digitizer depends on speed, lag, power, heat and cost
5. Computer Processing
   - Data for storage, visualization, or analysis

Background - Quality Data

Quality data starts with **careful setup of data acquisition system**

- Anti-alias filter selection
- Data sample rates

If acquisition setup is not understood, recorded signal can not be understood !

Background - Understanding Requirements

Discipline **<u>Engineer Responsibilities</u>**:

1) Ultimately responsible for data quality for evaluating system under test

2) **Guide instro setup** by understanding system operating characteristics, test objectives and analysis approach

-- If data is used to determine aero-mechanical impacts, analysis may emphasize accurate magnitude and frequency but less concerned with time correlation

-- If data is used for inlet distortion impact on engine stability, need accurate magnitudes and frequency but analysis emphasizes time correlation of 40 independent pressures

3) **Verify proper techniques** (data sampling and A/D filtering) were applied

Background - Sampling and Filtering (Bad Example)

Assume: Frequencies of interest up to 200Hz, A/D converter used a 6-pole Butterworth filter with low-pass cutoff at 450Hz,digitized data at 631 sps

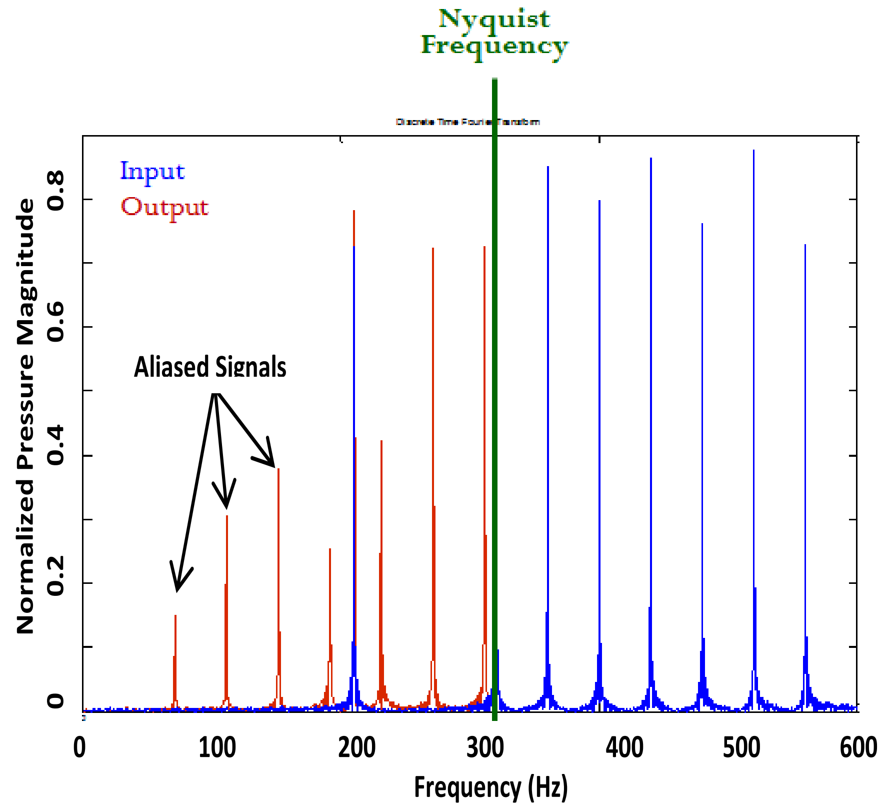
Problem: Sample rate and filter not optimal

Demonstrate: Input signal constructed of 200Hz with additional pulses every 40 Hz from 320 to 560Hz plus noise

PSD plot shows **aliasing** significantly affected output **at multiple frequencies below 200Hz**

Aliasing makes it impossible to discern actual pressure magnitude or frequency

Once filtered and digitally sampled, the **original signal cannot be reconstructed**



Input Signal: 200Hz + pulses every 40Hz (320Hz to 560Hz) + noise

Output Signal: 450Hz 6-pole low-pass Butterworth then sampled at 631sps

PSD plot showing the effect of aliasing due to incorrect sampling and filter selection

Data Sampling

Nyquist Sampling Theorem states "…at least two data points per period are required to recreate waveform"

Correct sampling (> 2x), then can recreate the original waveform, Figures 2a and 2b

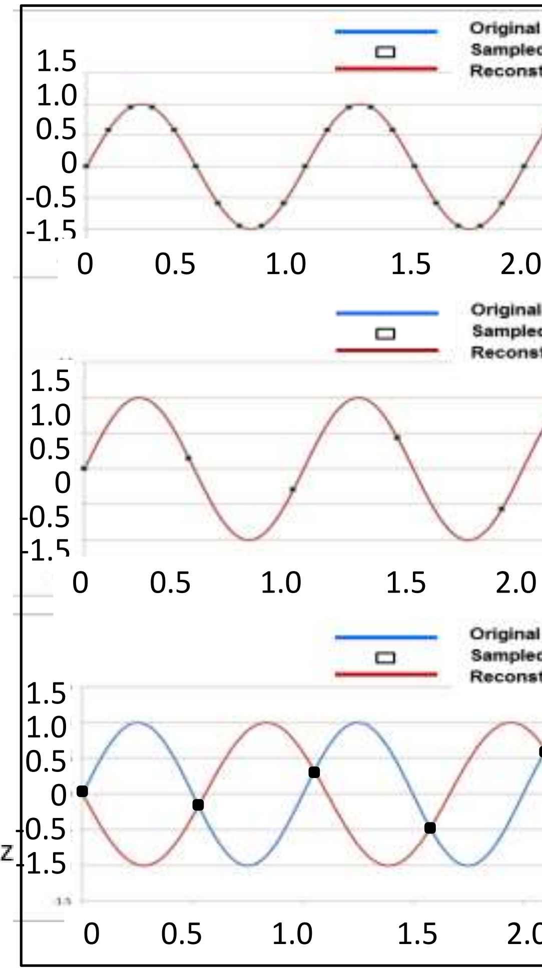
Incorrect sampling (< 2x), then aliasing results, Figure 2c shows changing the frequency and phase

Note: Two phase shifts possible: 0 deg (no phase shift) and 180 deg (inverted)

Figure a: Proper Sampling
- Frequency: 1 Hz
- Samples per cycle: 10
- Nyquist Frequency 5
- Reconstructed Frequency: 1 Hz
- Phase Distortion: 0 deg

Figure b: Proper Sampling
- Frequency: 1 Hz
- Samples per cycle: 2.1
- Nyquist Frequency 1.05
- Reconstructed Frequency: 1 Hz
- Phase Distortion: 0 deg

Figure c: Improper Sampling
- Frequency: 1 Hz
- Samples per cycle: 1.9
- Nyquist Frequency 0.95
- Reconstructed Frequency: 0.9 Hz
- Phase Distortion: -180 deg



Aliasing

If analog signal contains information above Nyquist, the digitized **signal will alias** higher frequency content into the lower frequency domain

Aliasing can be avoided by removing higher frequency content from analog signal prior to digitizing by **using a low-pass filter**

Typical anti-alias filters used during data acquisition include the **Butterworth, Chebyshev and Bessel**. Each designed to optimize a different performance characteristic (e.g. pass-band flatness, quick roll-off, or low phase distortion)

Three ways to evaluate filter performance:

- **Frequency response** looking at passband flatness and roll-off characteristic
- **Step response** looking at quickness to respond and overshoot
- **Group delay** looking at phase/time distortion

Anti-Alias Filter Selection – Frequency Response

Figure 3 shows frequency response of three low-pass filters with a 150Hz cutoff. **Note**: Cutoff frequency typically defined at 3dB (~30pct) down point

Butterworth filters (Figure 3a) have a flat passband and can be designed to have a quicker roll-off at cutoff by increasing filter order

Chebyshev filters (Figure 3b) obtains its sharp roll-off by allowing some passband ripple

Bessel filters (Figure 3c) have significantly higher attenuation across the passband and slow roll-off

Flat passband and quick roll-off are desirable for determining peak magnitude at specific frequencies for individual measurements

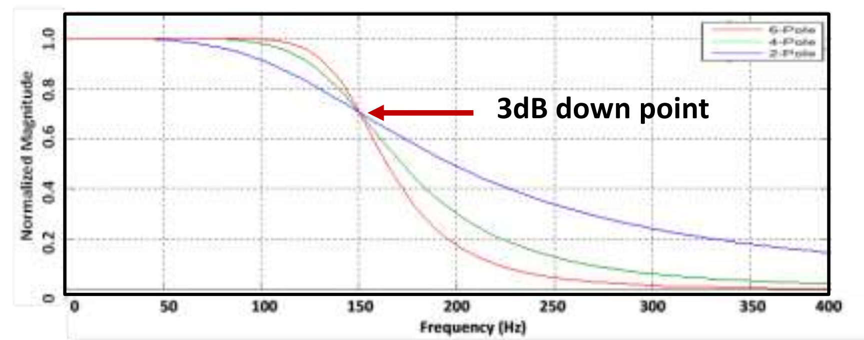


Figure 3a. Frequency response of 2-, 4-, 6-pole Butterworth filters shown with linear scales

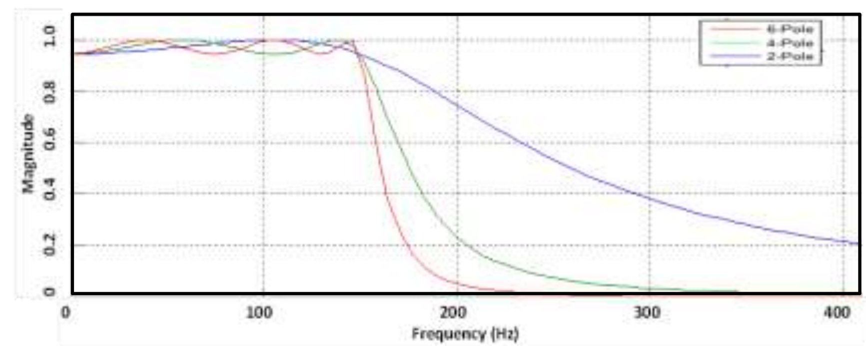


Figure 3b. Frequency response of 2-, 4-, 6-pole Chebyshev filters shown with linear scales

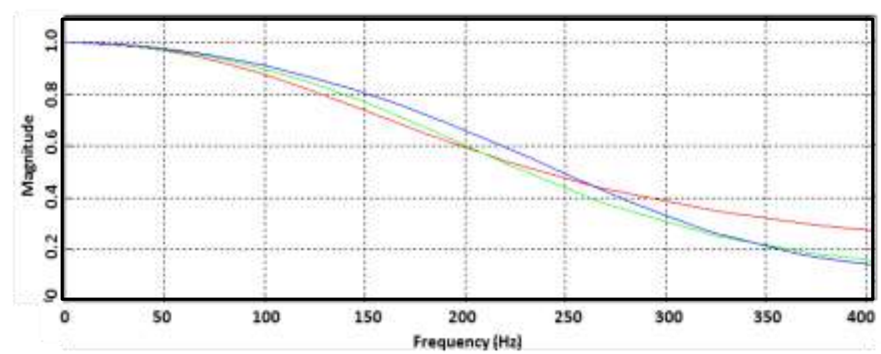


Figure 3c. Frequency response of 2-, 4-, 6-pole Bessel filters shown with linear scales

Anti-Alias Filter Selection – <u>Step Response</u>

Figure 4 shows the step response for same three filters with a 150-Hz cutoff. Fast response to step input shows how filter would respond to rapidly changing values

Butterworth (Figure 4a) and **Chebyshev** (Figure 4b) both exhibit good response characteristic but higher-order tends to overshoot, leading to over-estimate

Bessel filter (Figure 4c) is quickest to respond and doesn't overshoot, probably making it a better choice for rapidly changing magnitudes

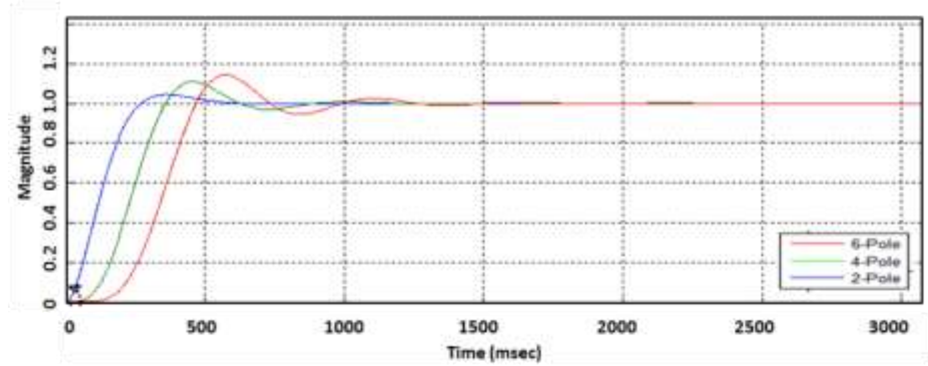


Figure 4a Step Response of 2-, 4-, and 6-Pole of Butterworth Filters

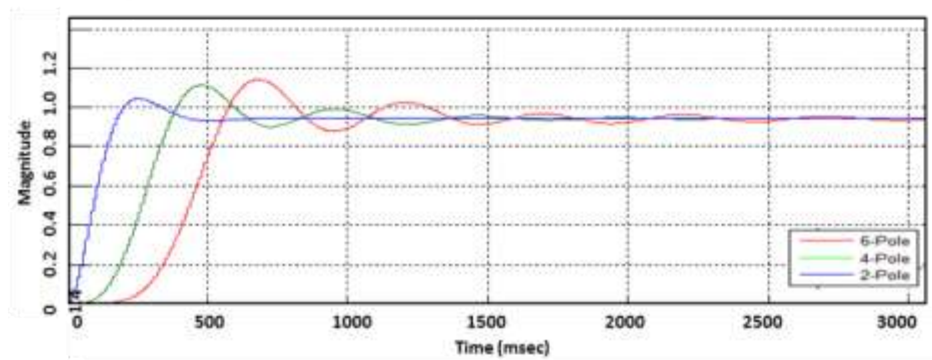


Figure 4b Step Response of 2-, 4-, and 6-Pole of Chebyshev Filters

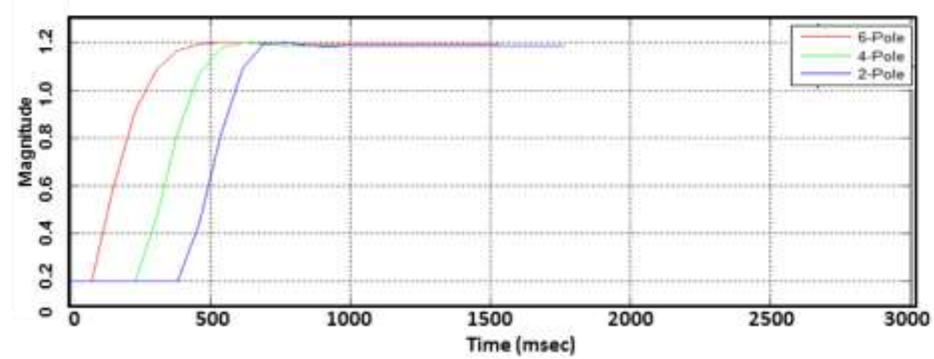


Figure 4c Step Response of 2-, 4-, and 6-Pole of Bessel Filters

Anti-Alias Filter Selection – <u>Group Delay</u>

Figure 5 shows Group delay (best indicator of signal/time distortion) for the same three filters

Higher-order **Butterworth** (Figure 5a) filters exhibit non-linear Group delay in the passband

Chebyshev (Figure 5b) exhibits significant non-linear Group delay near cutoff

Bessel (Figure 5c) exhibits constant group delay in the passband

Constant group delay in the passband is preferred for analysis requiring correlation of multiple parameters (e.g. inlet distortion)

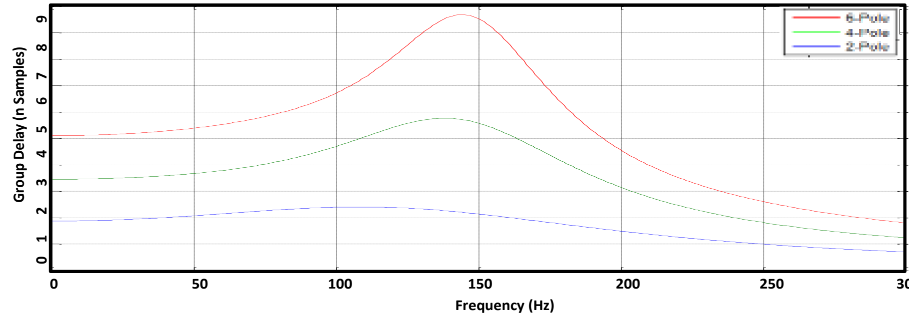


Figure 5a Group Delay of 2-, 4-, and 6-Pole of Butterworth Filters (Cutoff Freq= 150Hz)

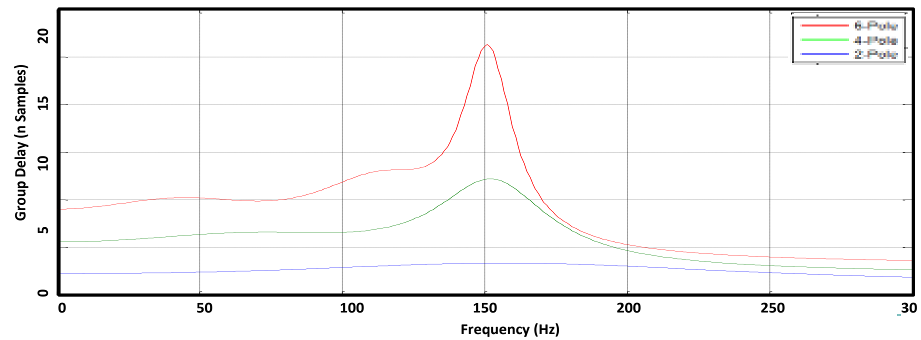


Figure 5b Group Delay of 2-, 4-, and 6-Pole of Chebyshev Filters (Cutoff Freq= 150Hz)

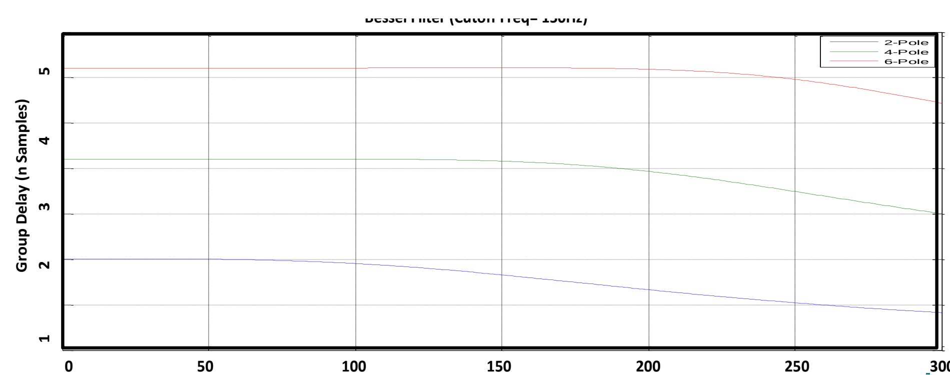


Figure 5c Group Delay of 2-, 4-, and 6-Pole of Bessel Filters (Cutoff Freq= 150Hz)

Takeaway

Most common filters used in data acquisition include the **Butterworth, Chebyshev** and **Bessel**, each having their own strengths and weaknesses

- **Butterworth** optimizes the passband flatness but has some ripple to step input and has non-linear group delay in higher order filters
- **Chebyshev** optimizes quick roll-off but is slow to respond to rapid changes, has most ripple and significant non-linear group delay
- **Bessel** optimizes quickness to respond, has no passband ripple and has constant group delay and but suffers from poor passband flatness and slow roll-off

Ultimately, selection of the anti-alias filter depends on test objectives and analysis goals

- Inlet analysis places emphasis on eliminating time distortion and ability to respond to changing conditions, making the **Bessel** the best choice
- Aeromechanical analysis using individual measurements place emphasis on flat passband and quick in roll-off, making **Butterworth** the best choice

<u>Good Example</u> – Data Sampling and Filter Selection

Assume test objective is to acquire accurate pressure magnitude from individual transducer with frequencies of interest up to 200 Hz

> <u>Note</u>: Since example is for single transducer, no attempt to control time distortion
>
> <u>Note</u>: If uncertainty in system operation, consider increasing frequency (≈ 20 percent) until better system understanding is available

<u>Good Example</u> – Data Sampling and Filter Selection

Assume: Goal is to acquire accurate pressure magnitude from individual transducer with frequencies of interest up to 200 Hz and A/D converter uses 6-pole Butterworth. Desire max attenuation of 5-percent at 200Hz

Data Sample Rate Selection: Table 1 shows ratio of flat to within 5-percent at the 95-percent attenuation frequency

$$\text{Nyquist} = Freq\ Reqd/(\frac{5pct}{95pct})$$

$$= (200\text{Hz}/0.5043) = 397\text{Hz}$$

To avoid aliasing, sample rate should be at least twice the Nyquist frequency

$$\text{Sample Rate} = (397\text{Hz} * 2) = 794\text{ sps}$$

Table 1 Ratio of flat to within 1-, 2-, 5-, and 10-percent with 95-percent attenuation at ω=1

Filter Type	Order	Flat to within			
		10%	5%	2%	1%
Butterworth	2nd	15.57	12.83	10.08	8.45
Butterworth	4th	39.46	35.82	31.75	29.06
Butterworth	6th	53.80	**50.43**	46.54	43.87
Butterworth	8th	62.82	59.85	56.35	53.91
Bessel	2nd	10.03	7.11	4.51	3.20
Bessel	4th	18.39	12.91	8.13	5.74
Bessel	6th	20.67	14.47	9.09	6.42
Bessel	8th	21.08	14.74	9.26	6.53
0.5dB Chebyshev	2nd	21.23	10.03	5.67	3.93
0.5dB Chebyshev	4th	57.67	16.07	8.81	6.06
0.5dB Chebyshev	6th	76.24	14.62	7.97	5.48
0.5dB Chebyshev	8th	85.29	12.40	6.75	4.63

<u>Good Example</u> – Data Sampling and Filter Selection

Filter Selection: Frequencies of interest up to 200Hz and 6-pole Butterworth lowpass filter selected

Recall filter characteristics usually defined based on the cutoff frequency at 3dB down point. Table 2 shows ratios of 3dB to 95-percent attenuation point

Filter 3dB cutoff frequency:

Filter freq = $Nyquist(\frac{3dB}{95pct})$

= (397Hz)(0.60709) = 240Hz

Table 2 shows ratio of 3dB to 95-percent attenuation frequencies

Filter Type	Order	Ratio 3dB to 95% attenuation point
Butterworth	2nd	0.22375
Butterworth	4th	0.47302
Butterworth	6th	0.60709
Butterworth	8th	0.68776
Bessel	2nd	0.17781
Bessel	4th	0.32317
Bessel	6th	0.36861
Bessel	8th	0.37784
0.5dB Chebyshev	2nd	0.26073
0.5dB Chebyshev	4th	0.61124
0.5dB Chebyshev	6th	0.78286
0.5dB Chebyshev	8th	0.86580

Good Example – Data Sampling and Filter Selection

Figure 7 Bode plot shows magnitude characteristics of lowpass 6-pole Butterworth filter with 240 Hz cutoff

Filter designed is flat in the passband, allows 5-percent attenuation at 200Hz and 95-percent attenuation at the Nyquist frequency of 397Hz

Filter exhibits quick roll-off characteristic

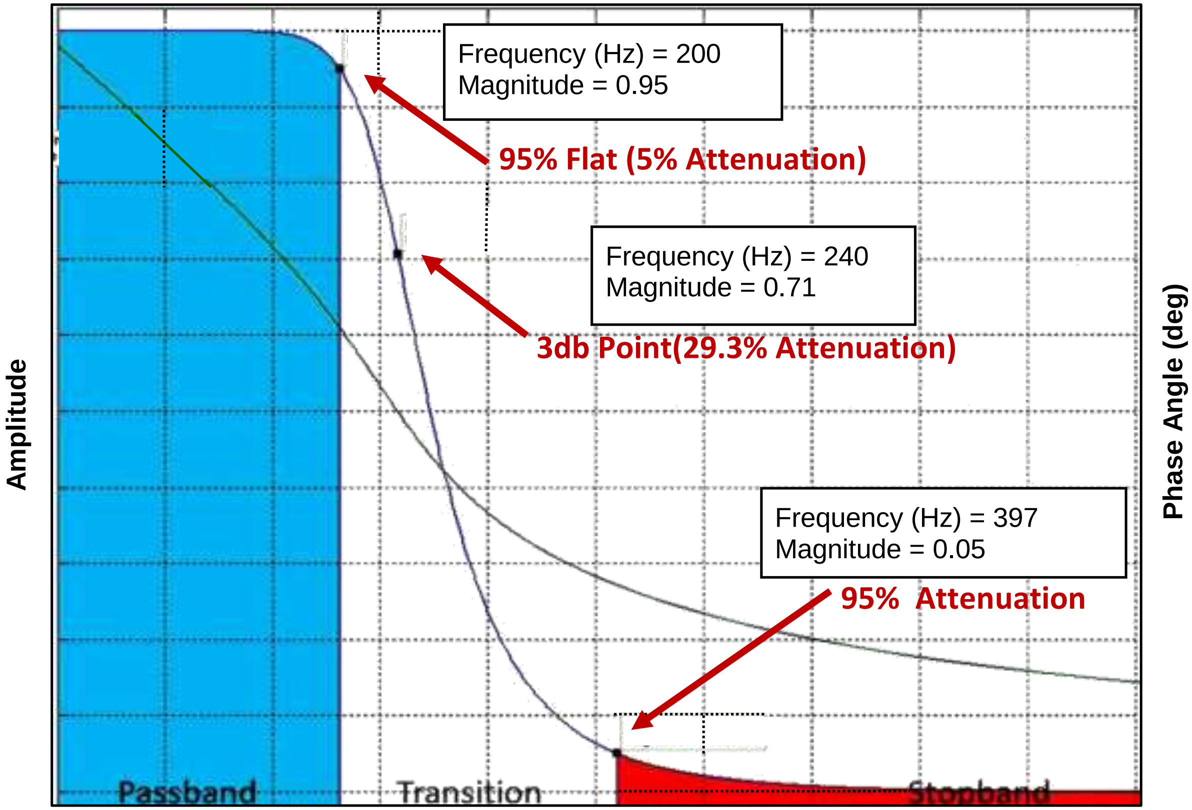
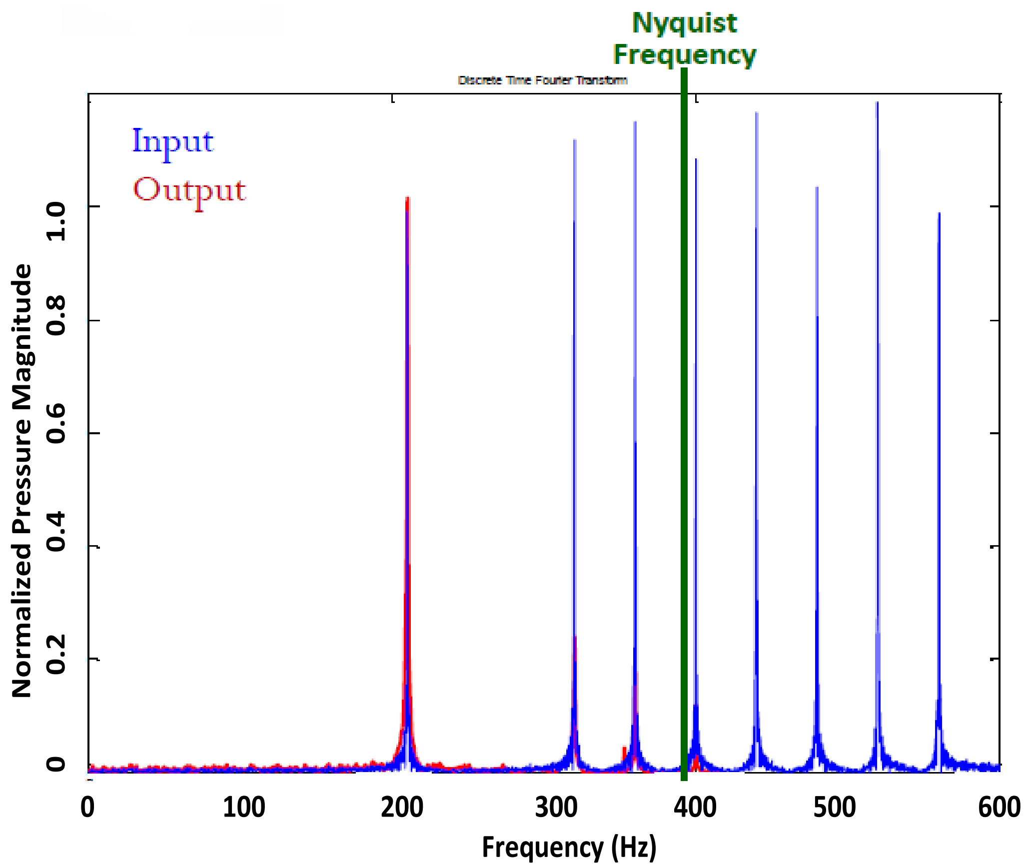


Figure 7 Bode plot showing magnitude characteristics of the 240 Hz low-pass 6-pole Butterworth filter

<u>Good Example</u> – Data Sampling and Filter Selection

Figure 8 PSD plot showing comparison of input and output signals for correct filter selection

Correct filter eliminates aliasing and magnitudes are accurate at 200Hz and below



Input Signal: 200Hz + pulses from 320Hz to 560Hz (every 40Hz) + noise.

Output Signal: 240Hz 6-pole low-pass Butterworth filter and sampled at 794 sps

Summary

Discipline Engineers:

1) **Ultimately responsible** for data quality for evaluating system under test
2) **Guide instro setup** by understanding system operating characteristics, test objectives and analysis approach
3) **Verify proper data acquisition techniques** by using both Bode and PSD plots

Reference: The Scientist and Engineer's Guide to Digital Signal Processing, by Steven W. Smith, Ph.D. **http://www.dspguide.com/pdfbook.htm**

Questions ???