

# Digitization of a Secondary Pump Condition-based Monitoring System



NIST Center for Neutron Research  
Reactor Operations and Engineering Group

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By:

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Undergraduate Research  
Fellowship

Grant Number: 70NANB18H070

NIST Advisors:

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Marcus Schwaderer

The NIST logo, consisting of the letters 'NIST' in a bold, black, sans-serif font.

# Background

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Abdullah Weiss

- B.S. in Mechanical Engineering at Texas A&M University-Kingsville
- Upcoming PhD in Nuclear Engineering student at Texas A&M University



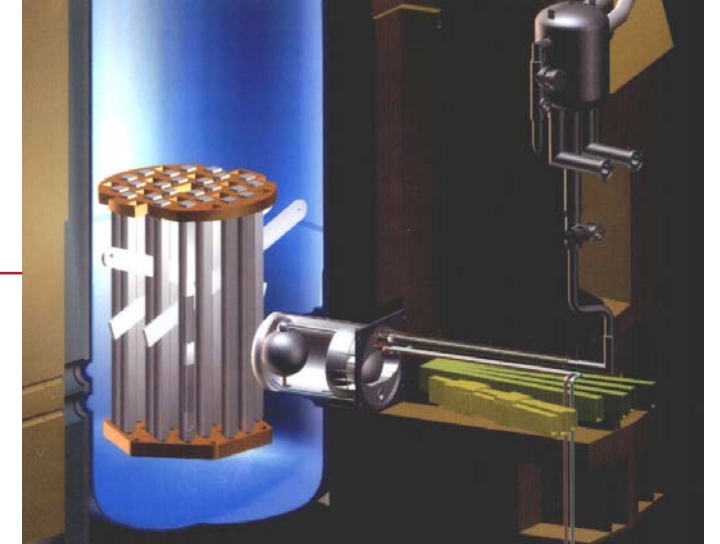
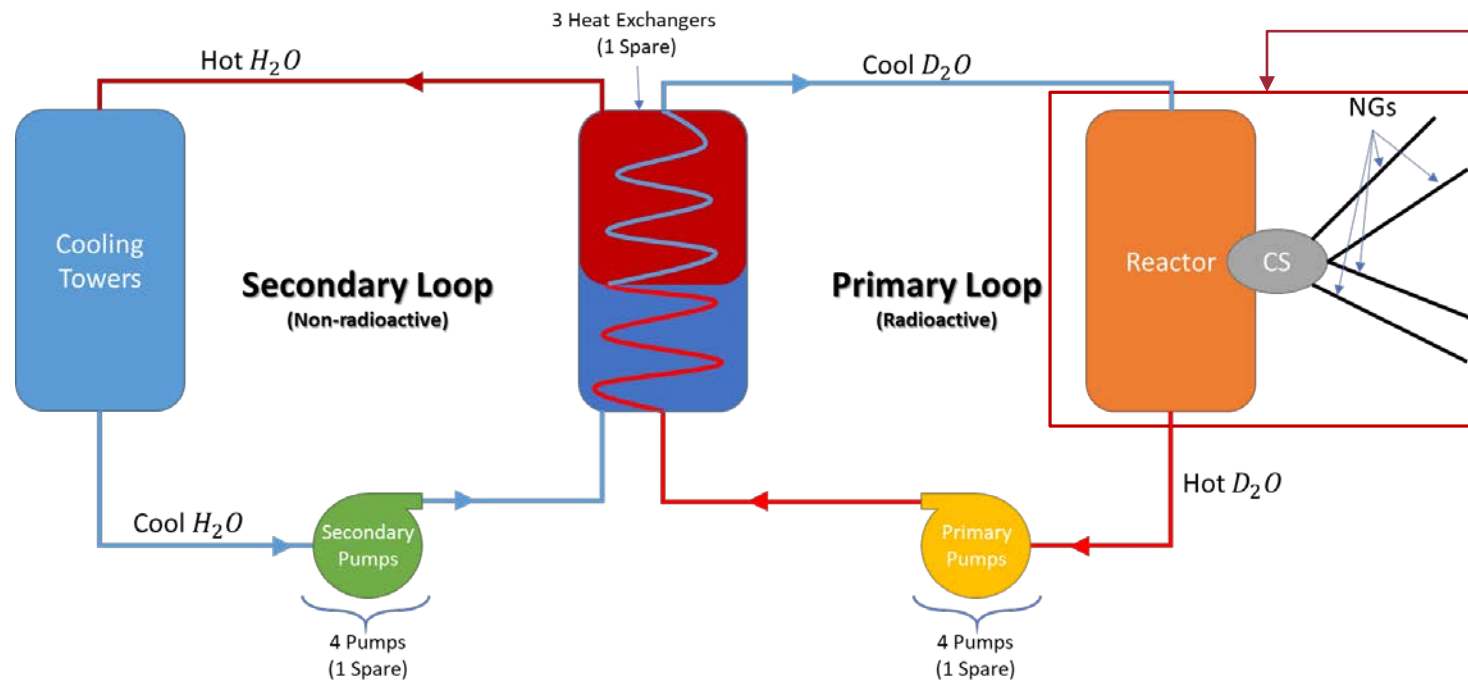
Katie Behnert

- Collaborator on the project (led the physical lump of the project)
- Upcoming Senior in Nuclear Engineering at Penn State University



# Project Background

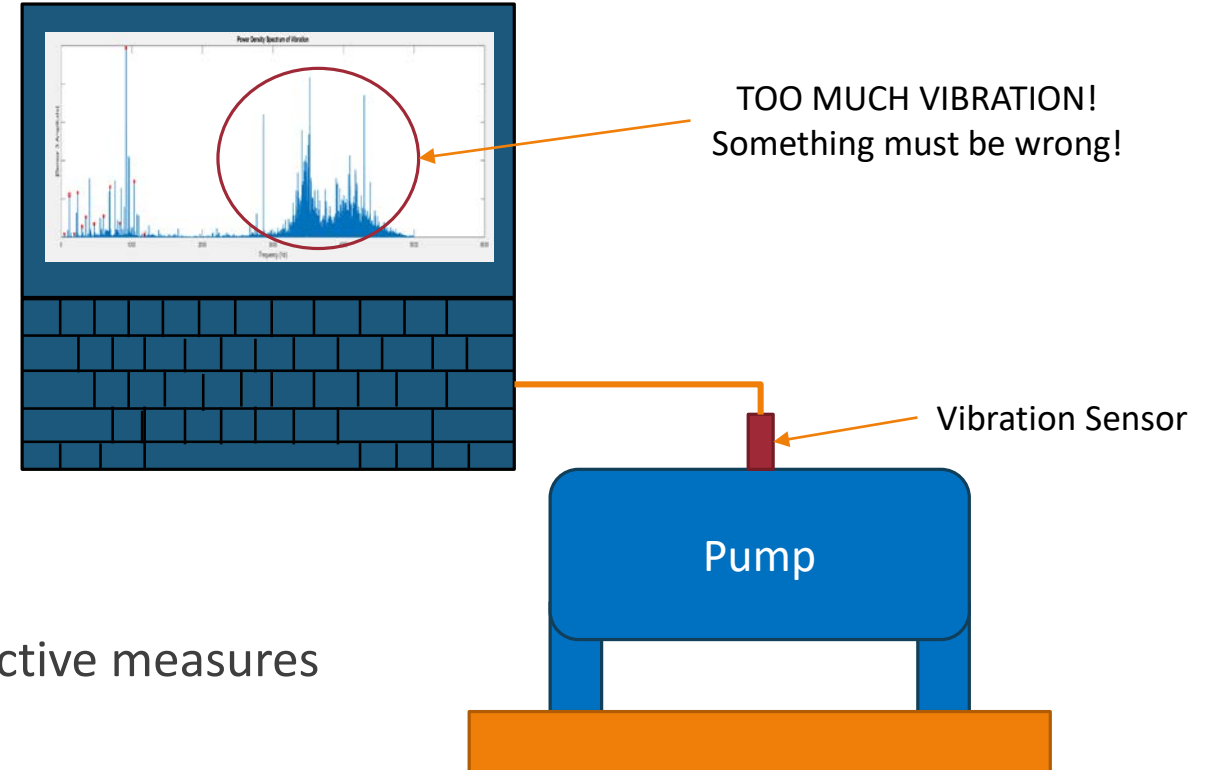
- NCNR generates neutrons via a fission nuclear reactor
  - $D_2O$  moderated and cooled
  - cooled via  $H_2O$  in a secondary loop



[https://www.ncnr.nist.gov/summerschool/ss07/bob\\_williams.pdf](https://www.ncnr.nist.gov/summerschool/ss07/bob_williams.pdf)

# Condition-based Monitoring (CBM)

- The primary form of predictive maintenance for machinery
- Monitors different conditions:
  - Vibration, Temperature, etc..
  - Via noise analysis
- Evaluates health of machinery using:
  - Time-history plots
  - Frequency spectra
- Can provide financial savings through predictive measures



# Monitored conditions in our CBM System

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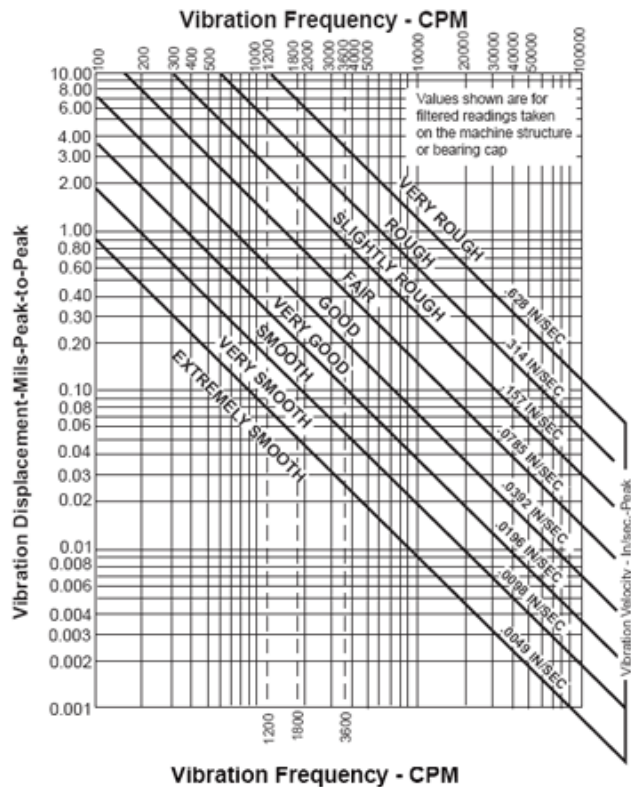
## **Temperature (simple one)**

- If the temperature of the bearing exceeds a set-limit, then you should investigate.

## **Vibrations (complex one)**

- Raw vibration history-plot reveals a severity measure of the vibrations
- FFT spectrum reveals specific faults including:
  - Cavitation
  - Mechanical Looseness
  - Misalignment
  - Turbulence
  - Oil Whirl Instability
  - Etc..

# Vibrations Analysis Literature



[https://www.engineersedge.com/vibration/vibration\\_sverity\\_chart\\_13658.htm](https://www.engineersedge.com/vibration/vibration_sverity_chart_13658.htm)

For Raw Data Assessment

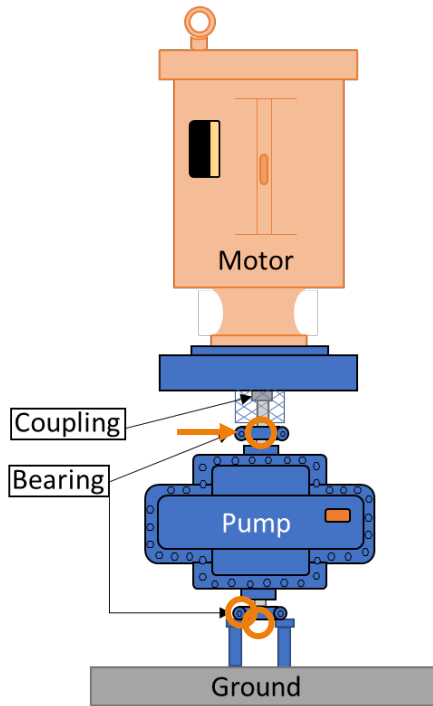
For Filtered Data Spectra Assessment

Analyze multiples of pump operating frequency

PROBLEM SOURCE	TYPICAL SPECTRUM	PHASE RELATIONSHIP	REMARKS
<b>A. FORCE UNBALANCE</b>	1X RADIAL		Force Unbalance will be in phase and steady. Amplitude starts to increase will increase by the square of speed below first rotor critical (1X speed increase = 16 higher vibration). 1X RPM always present and normally dominates spectrum. Can be corrected by placement of only one balance correction weight in one plane at Rotor center of gravity (CG). Approx. 90 degree phase difference should exist between OB & IB horizontal, as well as between OB & IB vertical. Also, approx. 180 degree phase difference between horizontal & vertical readings usually occurs on each bearing of unbalanced rotor (±30°).
<b>B. COUPLE UNBALANCE</b>	1X RADIAL		Couple Unbalance results in 180° out-of-phase motion on same shaft. 1X RPM always present and normally dominates spectrum. Amplitude varies with square of increasing speed below first rotor critical speed. May cause high axial vibration as well as radial. Correction requires placement of balance weights in at least 2 planes. Note that approx. 180° phase difference should exist between OB & IB horizontal, as well as between OB & IB vertical. Also, approx. 180° phase difference between the horizontal & vertical phase readings on each bearing usually occurs (±30°).
<b>C. DYNAMIC UNBALANCE</b>	1X RADIAL		Dynamic Unbalance is the dominant type of unbalance found and is a combination of both force and couple unbalance. 1X RPM dominates the spectrum, and truly requires 2 plane correction. Here, the radial phase difference between horizontal and vertical bearings can range anywhere from 0° to 180°. However, the horizontal phase difference should closely match the vertical phase difference, when comparing subunit and inboard bearing measurements (±30°). Secondary, if unbalance predominates, roughly a 90° phase difference usually results between the horizontal and vertical readings on each bearing (±30°).
<b>D. OVERHUNG ROTOR UNBALANCE</b>	1X AXIAL & RADIAL		Overhung Rotor Unbalance causes high 1X RPM in both Axial and Radial directions. Axial readings tend to be in phase whereas radial phase readings might be antiphase. However, the horizontal phase differences will usually match the vertical phase differences on the unbalanced rotor (±30°). Overhung rotors have both force and couple unbalance, each of which will likely require correction. Thus, correction weights will almost always have to be placed in 2 planes to counteract both force and couple unbalance.
<b>ECCENTRIC ROTOR</b>	1X RPM		Eccentricity occurs when center of rotation is offset from geometric centerline of a pulley, gear, bearing, motor, etc. Larger vibration occurs at 1X RPM of eccentric component in a direction thru centerline of the two rotors. Corrective balancing and vertical phase readings usually differ either 90° or 180° (each of which indicate opposite line motion). Attempts to balance eccentric rotors often result in reducing vibration in one radial direction, but increasing it in the other radial direction (depending on amount of eccentricity).
<b>BENT SHAFT</b>	1X AXIAL & 2X		Bent shaft problems cause high axial vibration with axial phase differences tending towards 180° on the same machine component. Dominant vibration normally occurs at 1X, 2X both near shaft center, but at 2X is found near the coupling. Be careful to account for transducer orientation for each axial measurement if you reverse probe direction. Use the indicators to confirm bent shaft.
<b>MISALIGNMENT</b>	1X AXIAL & 2X		Angular Misalignment is characterized by high axial vibration, 180° out-of-phase across the coupling. Typically will have high axial vibration with both 1X and 2X RPM. However, not unusual for either 1X, 2X or 3X to dominate. These symptoms may also indicate existing problems as well. Severe angular misalignment may excite many 1X RPM harmonics. Unlike Misaligned Coupling type, these multiple harmonics do not typically have an axial node floor on the spectra.
<b>B. PARALLEL MISALIGNMENT</b>	2X AXIAL & 3X		Other Misalignment has similar vibration symptoms to Angular, but shows high radial vibration which approaches 180° out-of-phase across the coupling. 2X often larger than 1X, but its height relative to 1X is often obscured by coupling type and construction. When severe, Parallel Misalignment becomes severe, they can generate either high amplitude peaks at much higher harmonics (3X, 4X, 5X, etc.) or even the same high frequency harmonics similar in appearance to mechanical looseness. Coupling type and material will often greatly influence the entire spectrum when misalignment is severe. Does not typically have raised noise floor.
<b>C. MISALIGNED BEARING COCKED ON SHAFT</b>	2X AXIAL & 3X		Cocked Bearing will generate considerable axial vibration. Will cause Tumbling Motion with approximately 180° phase shift top to bottom and/or side to side as measured in axial direction on some bearing types. Attempts to align coupling or balance the rotor will not alleviate problem. Bearing usually must be removed and correctly installed.
<b>RESONANCE</b>	Amplitude vs. Phase		Resonance occurs when a Rotating Frequency coincides with a System Natural Frequency, and can cause dramatic amplitude amplification, which might result in premature or even catastrophic failure. This may be a natural frequency of the rotor, but can often originate from support frame, foundation, girders or even outside belts. A factor load or wave resonance may be almost impossible to balance due to the great phase shift it experiences (90° at resonance, nearly 180° after passing through). Other major techniques do not generally change with a change in speed which helps facilitate their identification unlike one large plain bearing machine or on a rotor which has significant overhang.

H. P. Bloch and F. K. Geitner, Machinery Failure Analysis and Troubleshooting: Practical Machinery Management for Process Plants. (4th ed.)

# CBM System

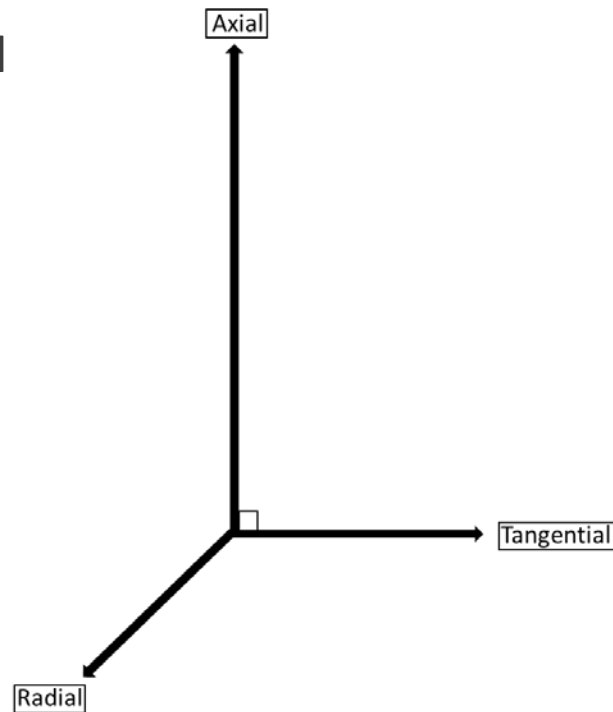


Motor & Pump Set-up

Courtesy of Katie Behnert

- Sensors installed on the following axes:

- Tangential
- Radial
- Axial



Accelerometer



Transmitter



# Sensor Locations

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Axial (Ch. 0)



Radial (Ch. 1)



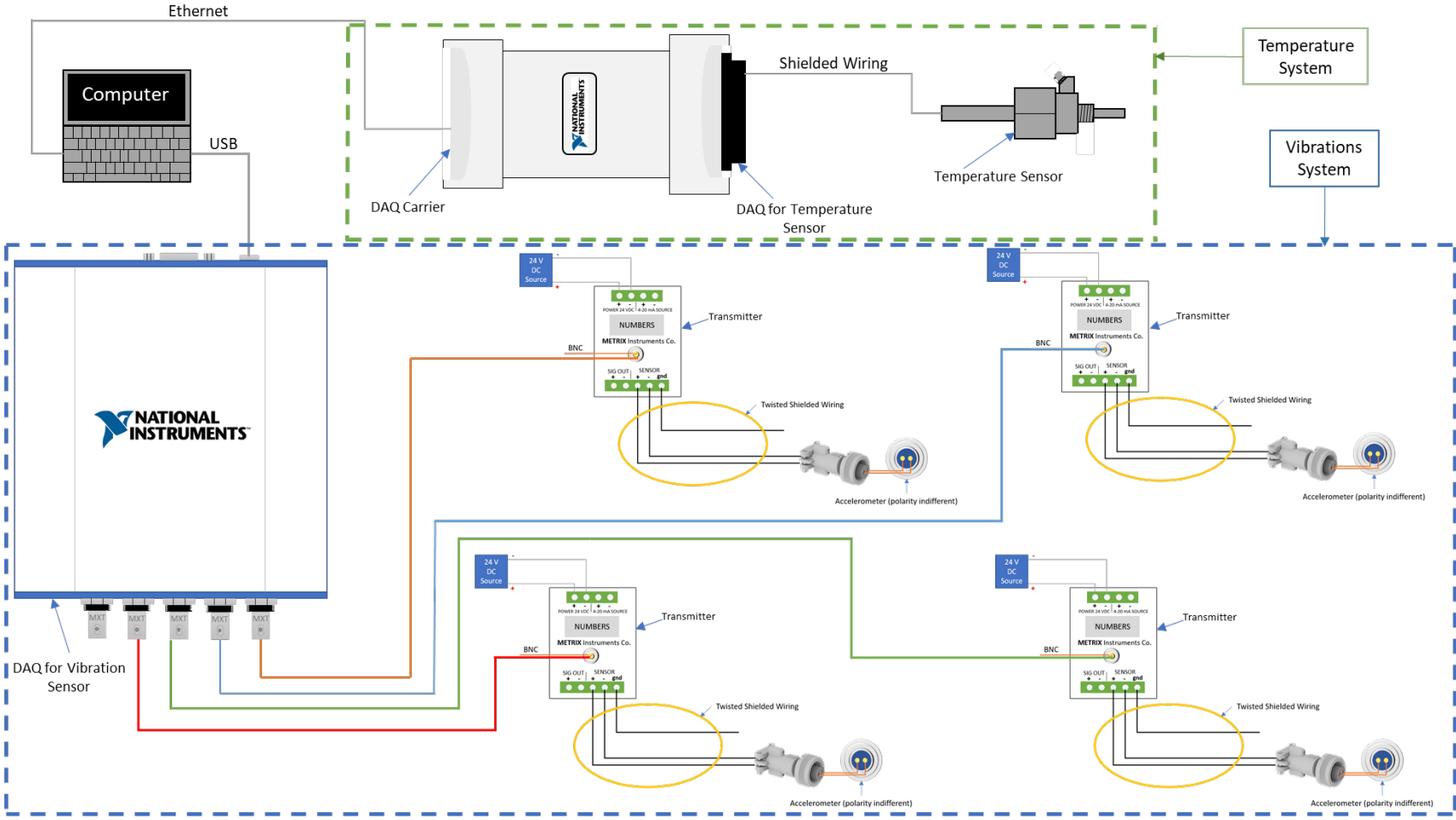
Radial (Ch. 2)



Tangential (Ch. 3)



# CBM Connections Schematic



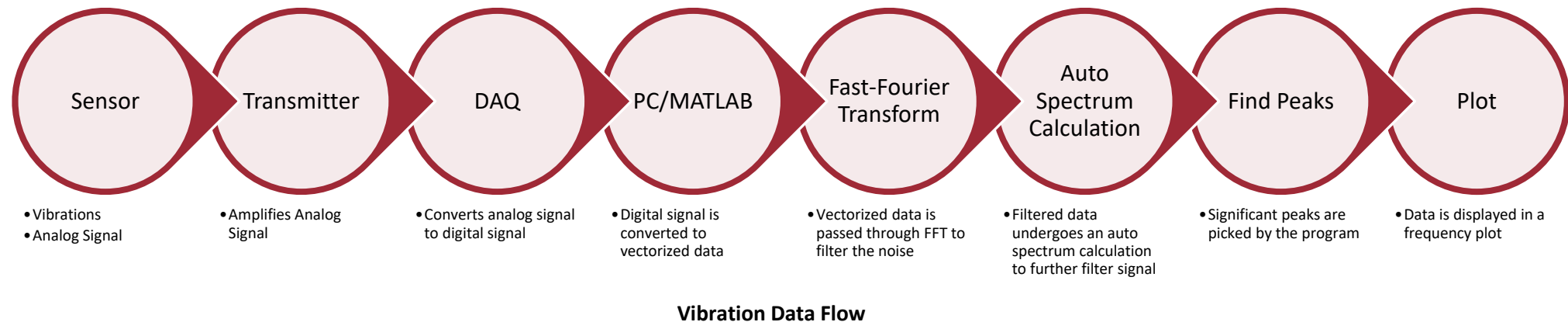
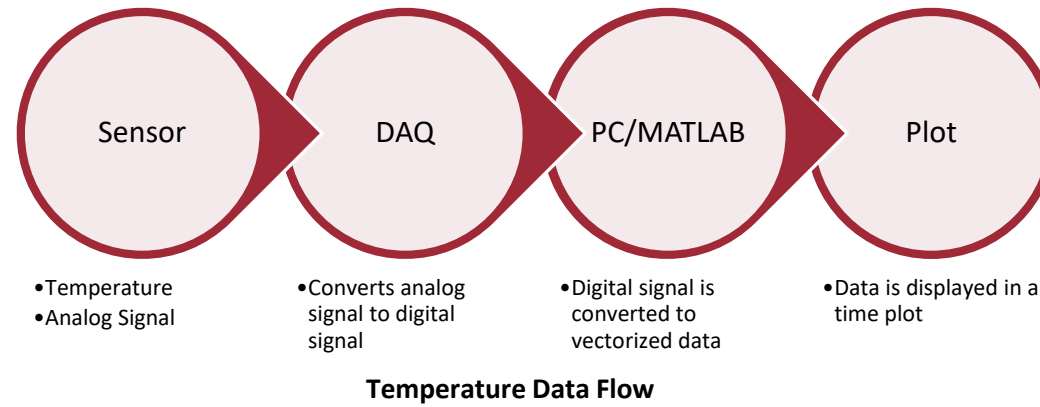
$$\sigma_{Temp} = 1.3457\%$$

$$\sigma_{Vibs} = 6.4236\%$$

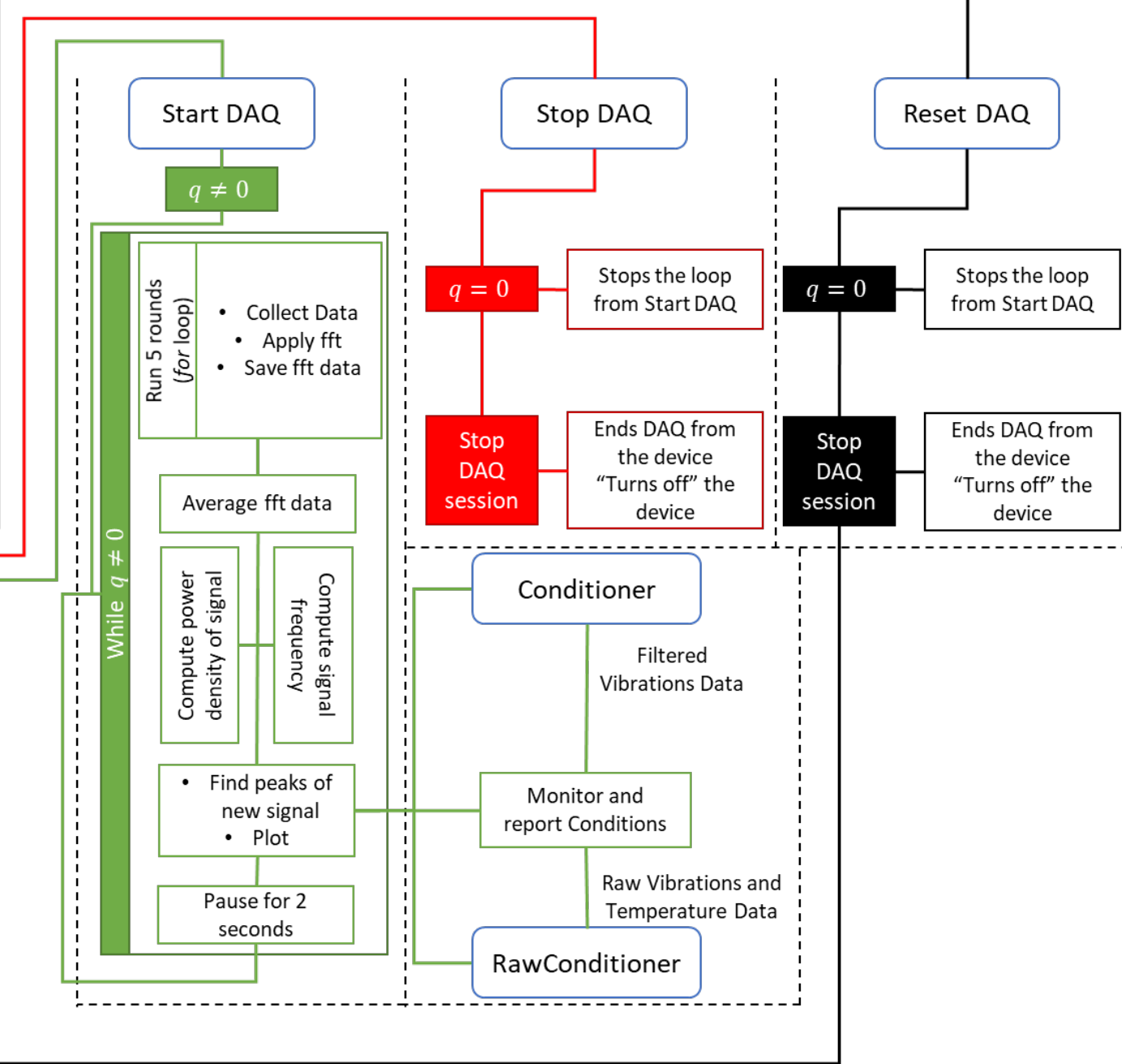
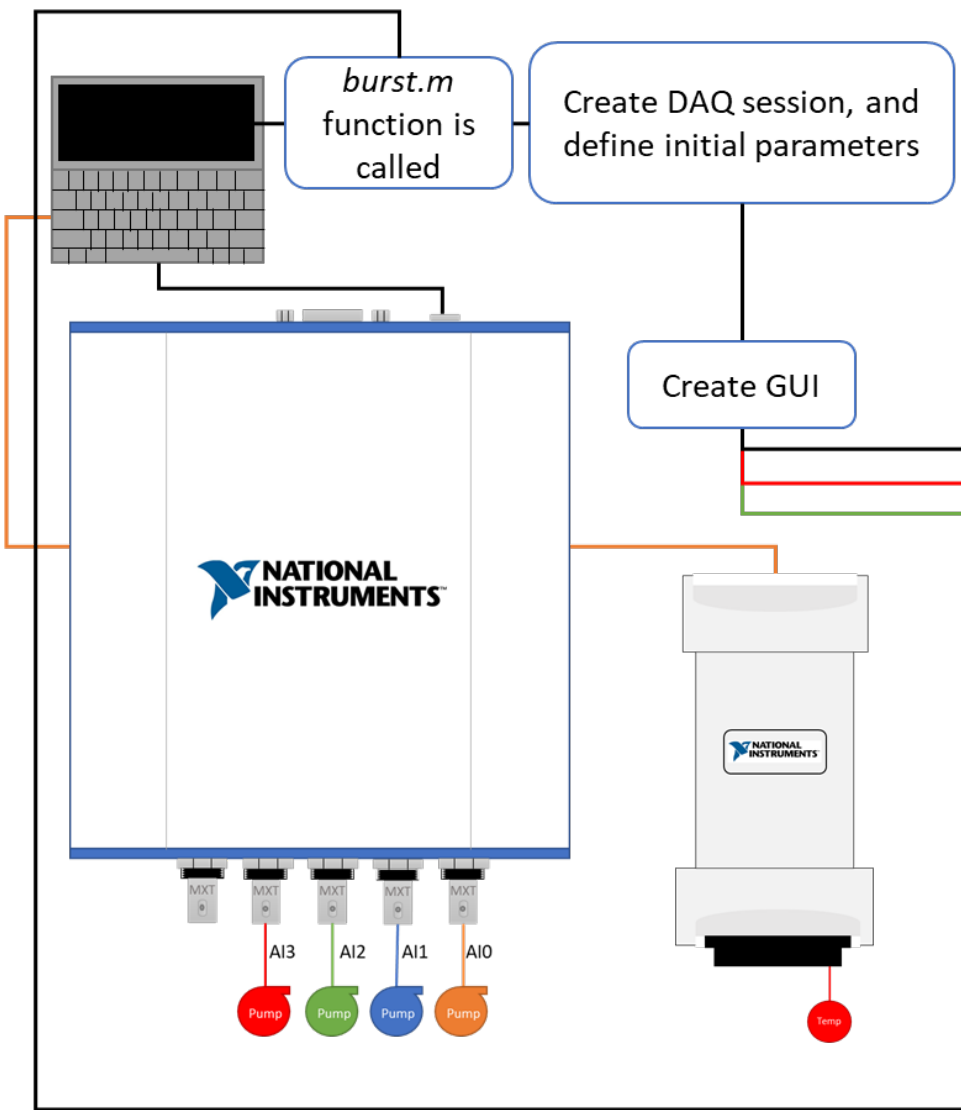


# CBM Connections Box

# High-Level Architecture of Software



# High-Level Architecture of Software



# Vibrations Data Acquisition

- Utilized a NI USB-4432 DAQ device
  - 5 BNC input channels (only 4 are used)
  - 200 kS/s (10 kS/s used)
  - Sensitivities set in MATLAB
- Performed 5 batches of DAQ (5 seconds each)
  - Average is utilized
    - Represents an average over every “30” seconds.

## ***THE ABDULLAH GUARANTEE:***

Program will always update in no more than 30 seconds



Data Acquisition Device (DAQ)



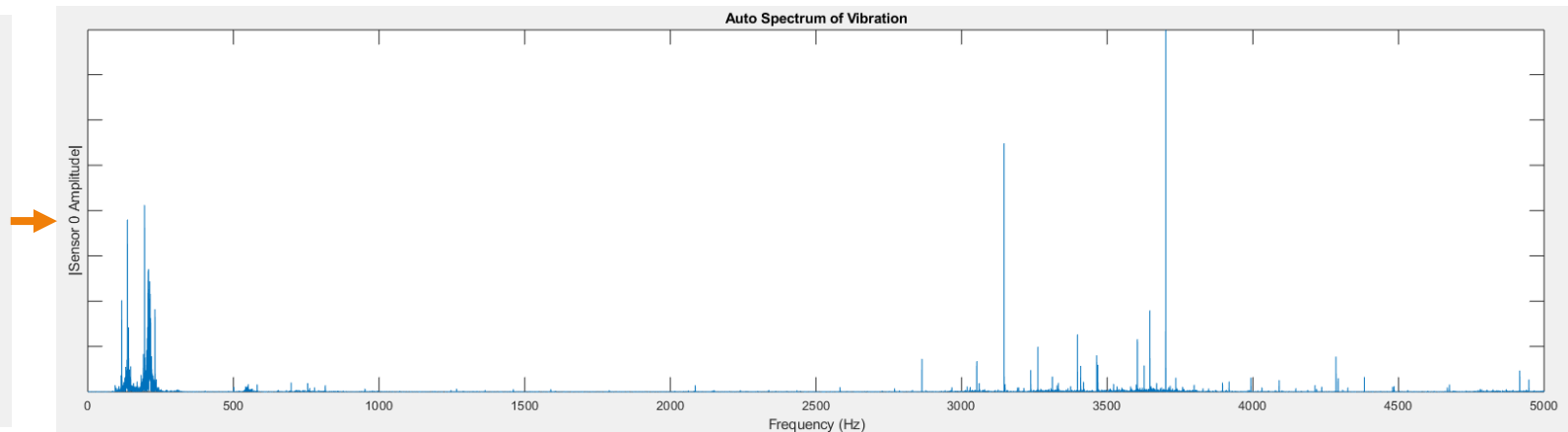
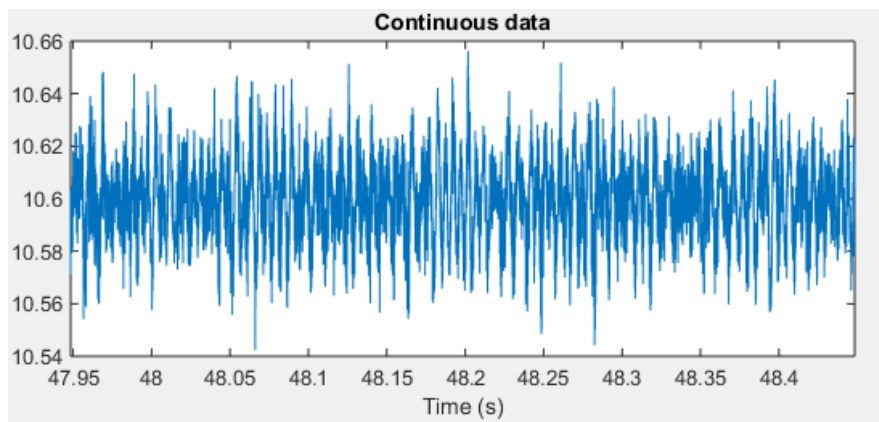
# Vibrations Data Processing

- Raw data → Fast-Fourier Transform (*fft command in MATLAB*) → Filtered data
  - Computes the Discrete-Fourier transform using a built-in MATLAB FFT algorithm:

- $Y(k) = \sum_{j=1}^n \underbrace{X(j)}_{\text{Signal}} W_n^{(j-1)(k-1)} \ni W_n = e^{\frac{-2\pi i}{n}} = \text{one of } n \text{ roots of unity}$

- Creates a complex vector of data

- $\text{AutoSpectrum} = \frac{\text{FFT}(\text{raw data}) \cdot \text{conj}(\text{FFT}(\text{raw data}))}{\text{Length of the Signal}}$



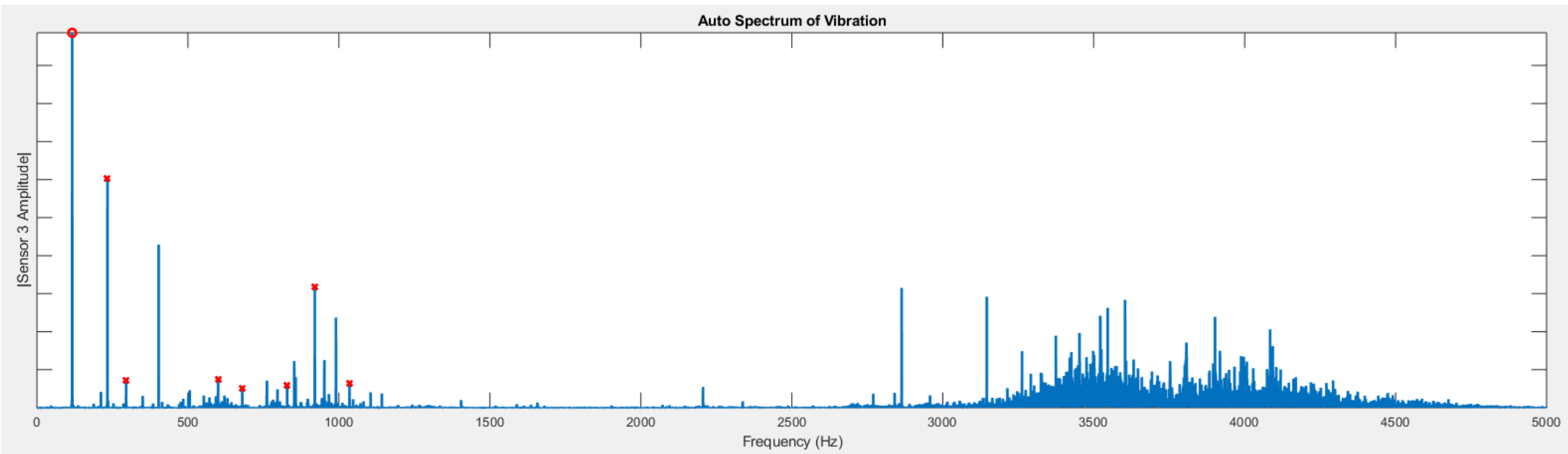
# Vibrations Data Peaks' Finder

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- Based on a user-defined RPM (for each channel), the conditioner function:
  1. looks for a frequency that matches the vane-pass frequency (VPF) within a certain accuracy
    - $$VPF = \frac{RPM}{60 \left(\frac{sec}{min}\right)} \times N_{vanes}$$
  2. finds the corresponding amplitude (principle peak)
  3. circles the point
- Based on the principle peak, the same conditioner function:
  1. finds peaks @ VPF multiples (0.5X, 1X, 1.5X, 2.5X, 3X, 4X .... 10X)
  2. leaves x at each point

# Vibrations Data Peaks' Finder

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# Vibrations Automatic Fault Detector *(Conditioner)*

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## Mechanical Looseness

- “Possible Looseness”: There are too many ‘x’ marks (> 3 ‘x’ marks).
- “Looseness detected”: There are too many ‘x’ marks, and one of them has an amplitude higher than the principle peak.

## Misalignment

- “Possible Misalignment”: The  $\approx 2X$  peak is between 50% and 150% of the principle peak’s amplitude.
- “Misalignment detected”: The  $\approx 2X$  peak is more than 150% of the principle peak’s amplitude.

# Vibrations Automatic Fault Detector *(Cont.)*

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## Oil Whirl Instability

- “Possible Oil Whirl Instability”: A peak at 0.2X to 0.8X is greater than the principle peak.

## Flow Turbulence

- “Possible Flow Turbulence”: There are several random low-frequency peaks that have an amplitude that of at least 4% of the principle peak’s amplitude.

## Cavitation

- “Possible Cavitation”: There are several random high-frequency peaks that have an amplitude of at least 8% of the principle peak’s amplitude.



Collecting Data

No Misalignment Detected

Possible Mechanical Looseness

No Oil Whirl Instability Detected

No Flow Turbulence Detected

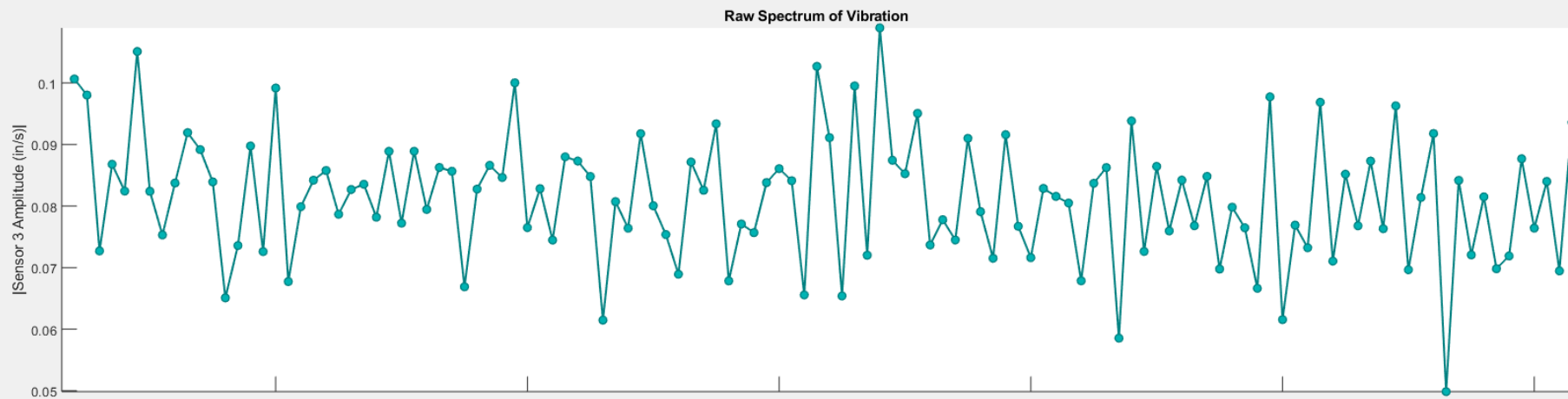
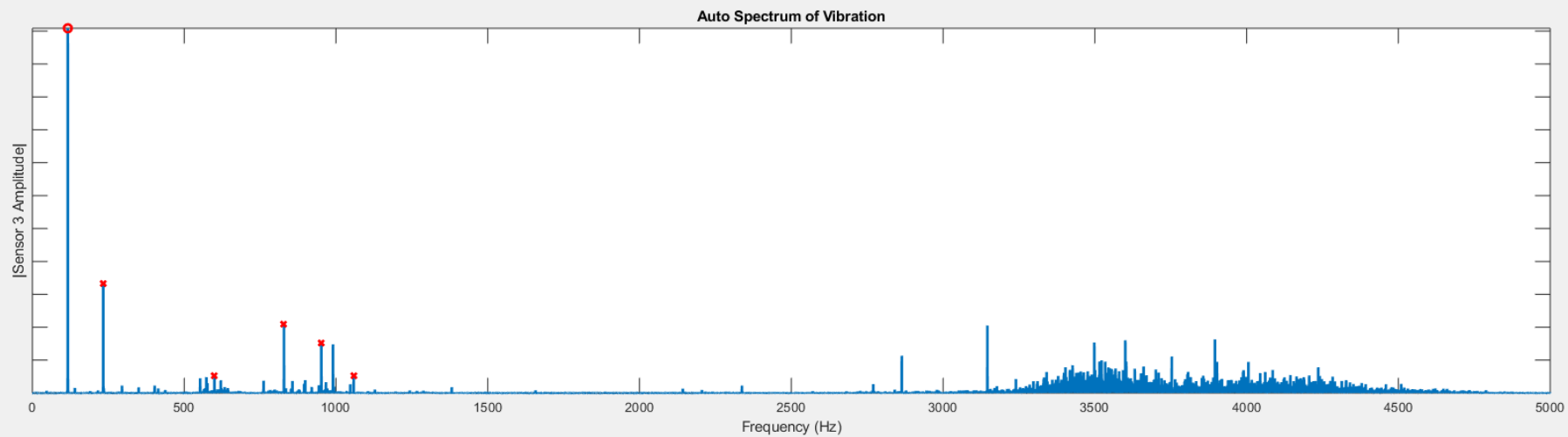
Possible Cavitation

Capture

Start DAQ

Reset DAQ

Stop DAQ



# Phase Analysis

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- Used for further verification of faults such as misalignment, soft foot, etc....
  - Utilizes phase angle difference
- Compares two channels (A & B):
  - Cross-Spectrum:
    - $XS_{AB} = FFT(A) \cdot FFT(B)$
    - Displays phase angle of  $XS_{AB}$ :
      - $\theta = \tan^{-1} \left( \frac{R}{M} \right) \ni XS_{AB} = R + i M$
      - `angle()` command in MATLAB
- Finds phase angle difference between signals from channels A and B.

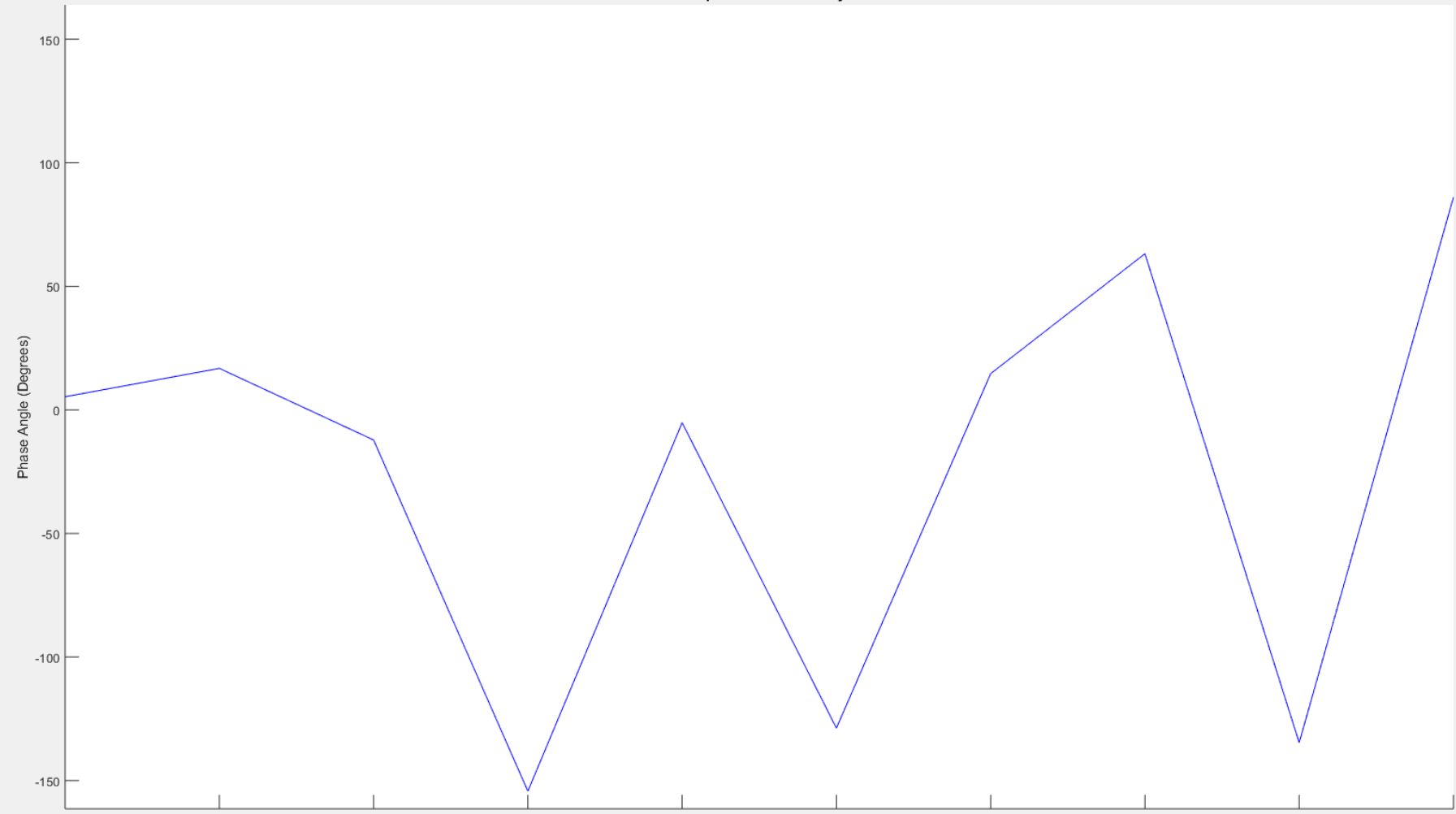
Collecting Data

Cross-Spectrum Phase Analysis

**Blue Line**  
Ch. 0

**Red Line**  
Ch. 1

**Phase Difference**  
86.0638



Capture

Start DAQ

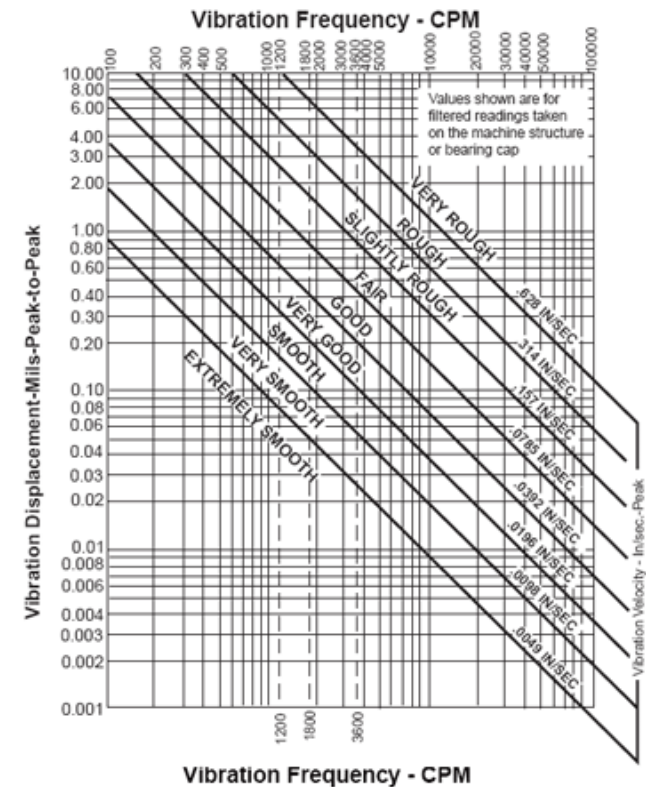
Reset DAQ

Stop DAQ

# Vibrations Severity Detector (RawConditioner)

## Average Raw Vibrations (every $\approx 30$ seconds):

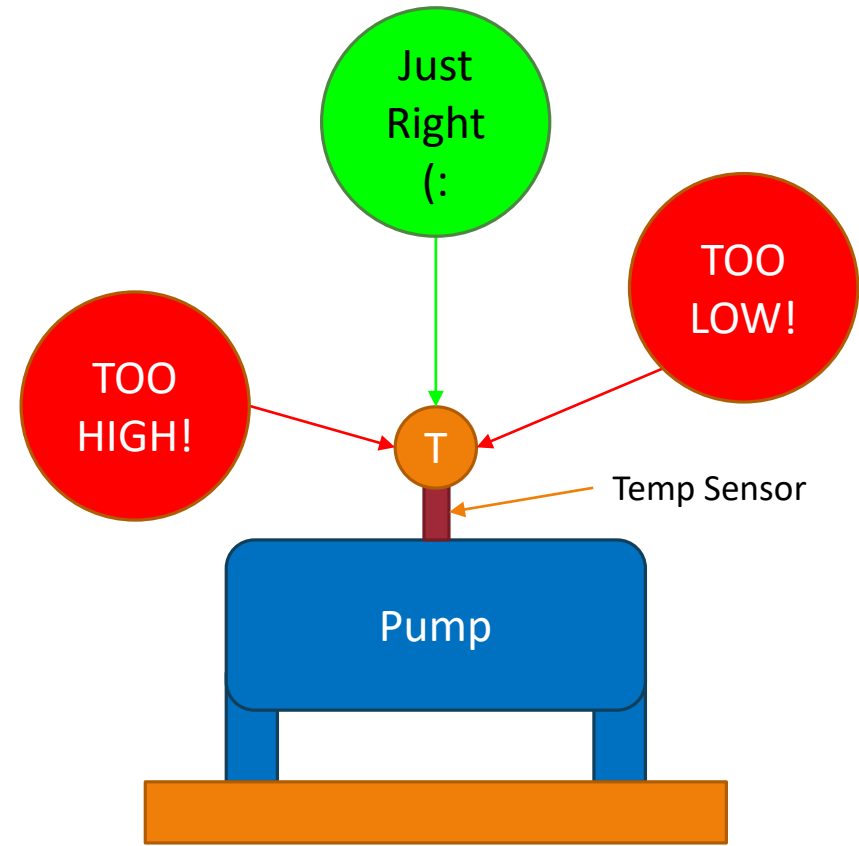
0 – 0.005 in/s	Extremely Smooth
0.005 – 0.01 in/s	Very Smooth
0.01 – 0.02 in/s	Smooth
0.02 – 0.04 in/s	Very Good
0.04 – 0.08 in/s	Good
0.08 – 0.16 in/s	Fair
0.16 – 0.32 in/s	Slightly Rough
0.32 – 0.64 in/s	Rough
> 0.64 in/s	Very Rough



[https://www.engineersedge.com/vibration/vibration\\_severity\\_chart\\_13658.htm](https://www.engineersedge.com/vibration/vibration_severity_chart_13658.htm)

# Temperature Conditioner (RawConditioner)

- Using set temperature limits ( $T_{low}$ , and  $T_{high}$ ):
  - $T_{sensor} \geq T_{high} \mid T_{sensor} \leq T_{low} \rightarrow T_{sensor}$
  - $T_{high} > T_{sensor} > T_{low} \rightarrow T_{sensor}$





Collecting Data

### Channel 0 Summary

<b>Pump Status</b> Fair	<b>Temperature</b> 92.5777 °F
<b>Ch.0 Spectra</b>	<b>Avg. Vibrations</b> 0.1106 in/s

### Channel 1 Summary

<b>Pump Status</b> Fair	<b>Temperature</b> 105.8836 °F
<b>Ch.1 Spectra</b>	<b>Avg. Vibrations</b> 0.095996 in/s

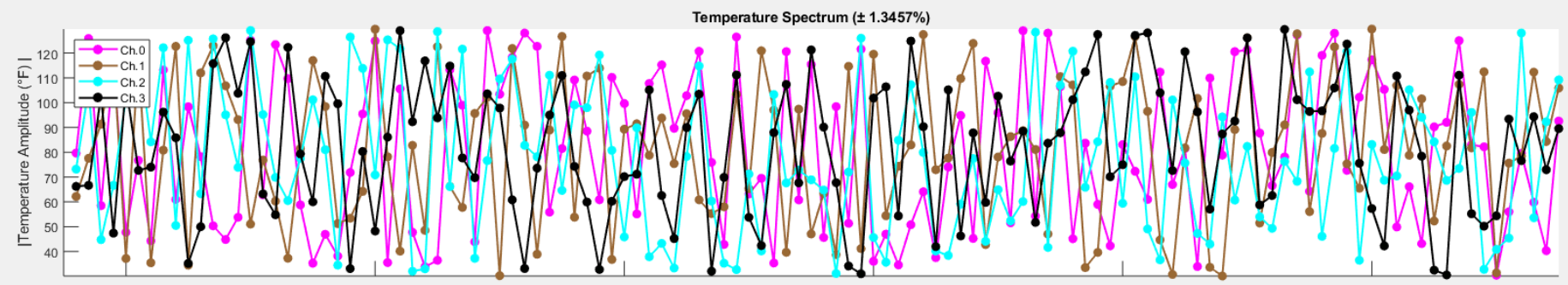
### Channel 2 Summary

<b>Pump Status</b> Fair	<b>Temperature</b> 109.1941 °F
<b>Ch.2 Spectra</b>	<b>Avg. Vibrations</b> 0.10445 in/s

### Channel 3 Summary

<b>Pump Status</b> Fair	<b>Temperature</b> 89.5497 °F
<b>Ch.3 Spectra</b>	<b>Avg. Vibrations</b> 0.091092 in/s

- Capture
- Start DAQ
- Reset DAQ
- Stop DAQ



# Human-machine Interface (Settings tab)

The screenshot displays two main sections: RPM Settings and Temperature Settings. The RPM Settings section includes an 'Update RPM' button and four channels (Ch. 0 to Ch. 3), each with a text input field containing the value '1410'. The Temperature Settings section includes an 'Update Temperature' button and two text input fields: 'Temperature Upper Limit (°F)' with the value '100' and 'Temperature Lower Limit (°F)' with the value '-50'. A yellow callout box highlights the instruction: 'The plot updates only when you click the respective update buttons'.

**RPM Settings**

Update RPM

Ch. 0 1410

Ch. 1 1410

Ch. 2 1410

Ch. 3 1410

The plot updates only when you click the respective update buttons

**Temperature Settings**

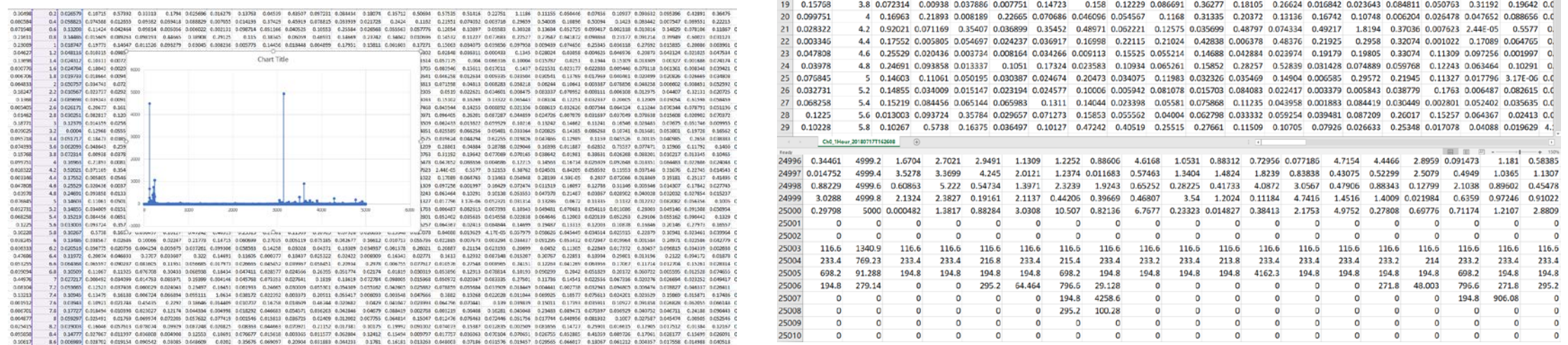
Update Temperature

Temperature Upper Limit (°F) 100

Temperature Lower Limit (°F) -50

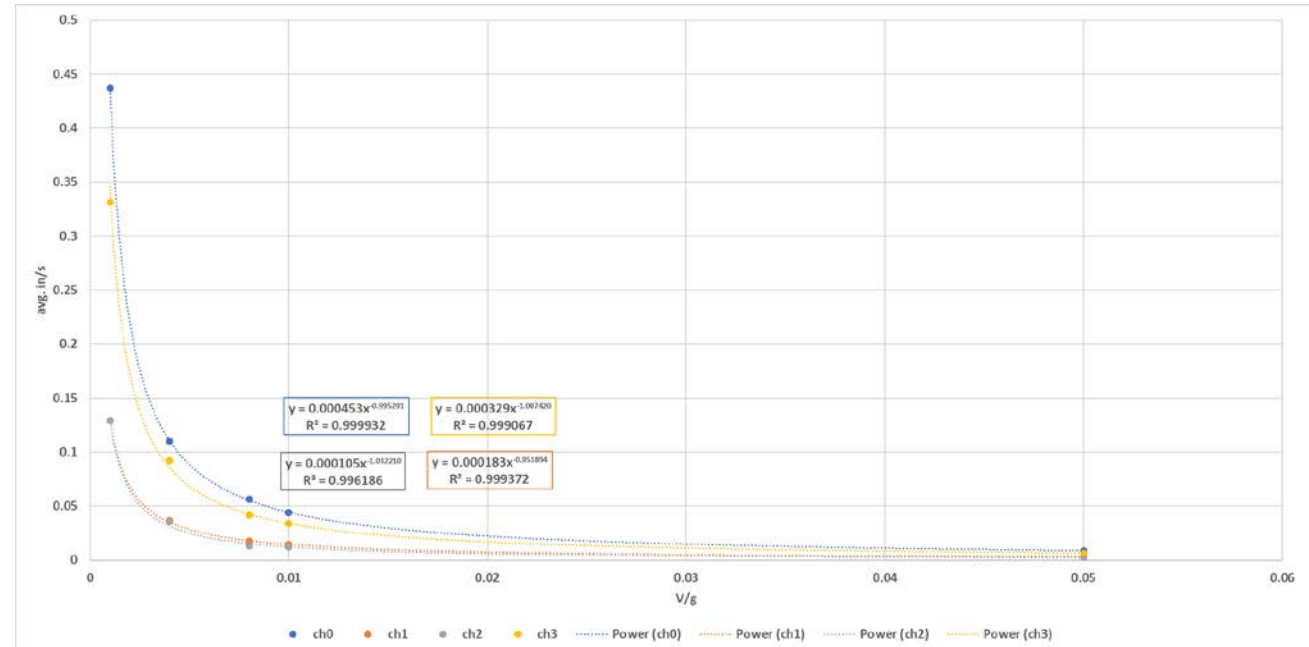
# Output File

- Generated every hour
  - .csv file
  - 20 – 25 MB
  - Each channel
  - FFT data with the peaks' frequencies
  - Enables further manual analysis



# Sensitivity Analysis & Observations

- Performed to pick reasonable sensitivities (V/g) for the channels
  - Average in/s at various sensitivities
  - Referenced to transmitters' values
  - Best-fit functions & trial-error revealed appropriate sensitivities for channels
- Different Sensitivity for each channel
  - Channels should have same sensitivity
  - Calibration needed
- $\uparrow$  Sampling rate  $\equiv$   $\downarrow$  in/s



# Conclusion

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- A working CBM system was developed and implemented successfully
- A corresponding custom software was developed and implemented successfully
- Documentation (including a manual) were put together for the software analysis

# Future Work

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- Calibrate accelerometers
- Improve GUI
- Installation of CBM system on primary pumps
- Additional Noise Analysis Applications:
  - Crack detection (for fuel channels analysis)
  - Power Noise

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NIST Research Library



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Q/A

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