Digitization of a Secondary Pump Condition-based Monitoring System

NIST Center for Neutron Research

Reactor Operations and Engineering Group

By:

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Background

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

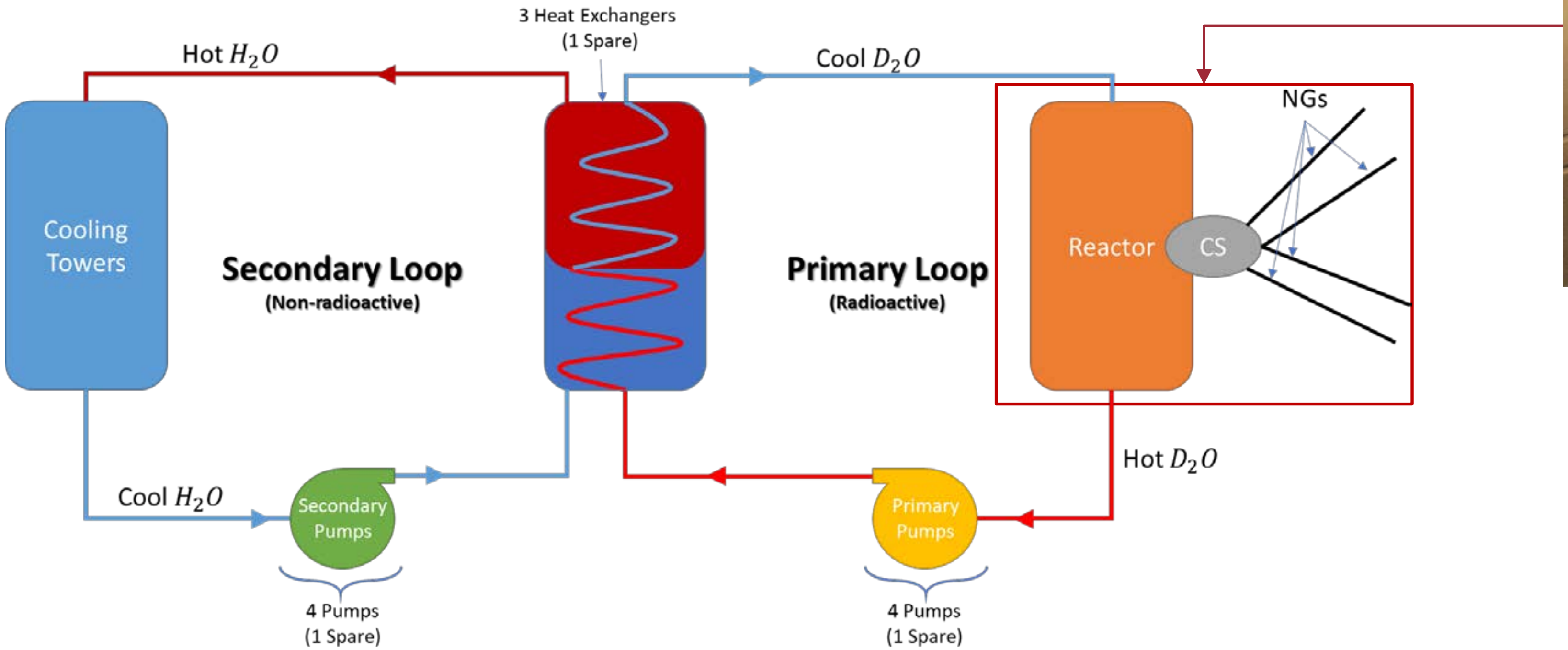
NUCLEAR ENGINEERING
TEXAS A&M UNIVERSITY

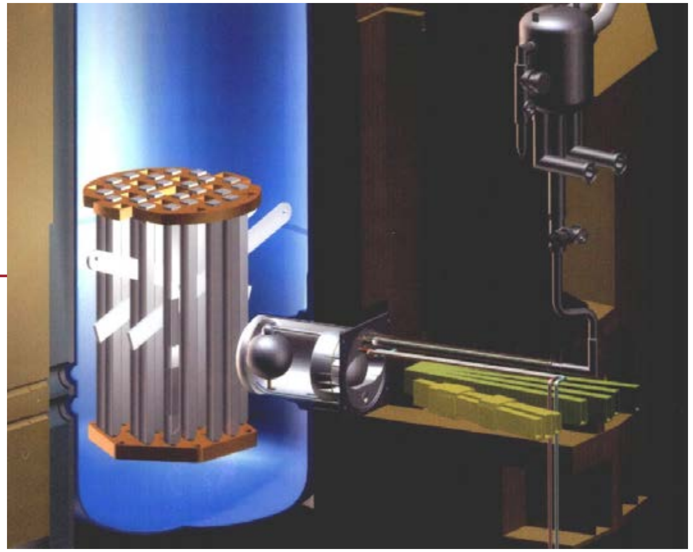
PennState
College of Engineering

MECHANICAL AND
NUCLEAR ENGINEERING

Project Background

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

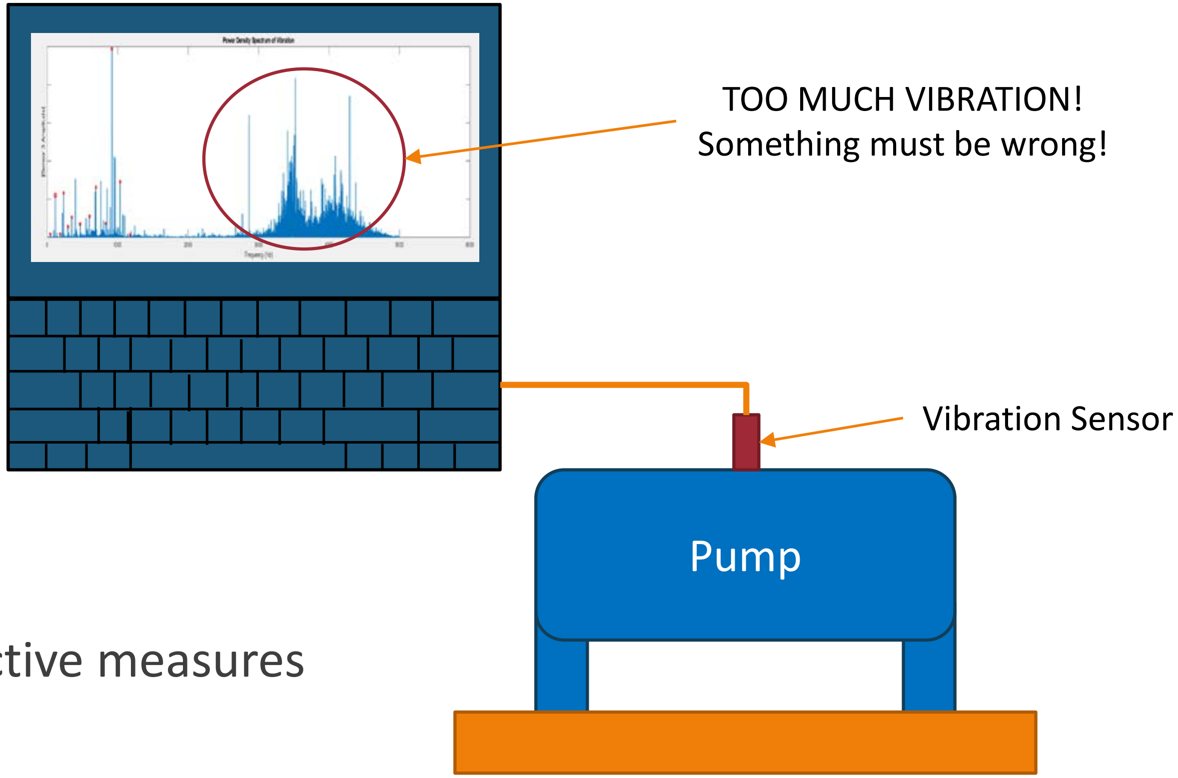




https://www.ncnr.nist.gov/summerschool/ss07/bob_williams.pdf

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

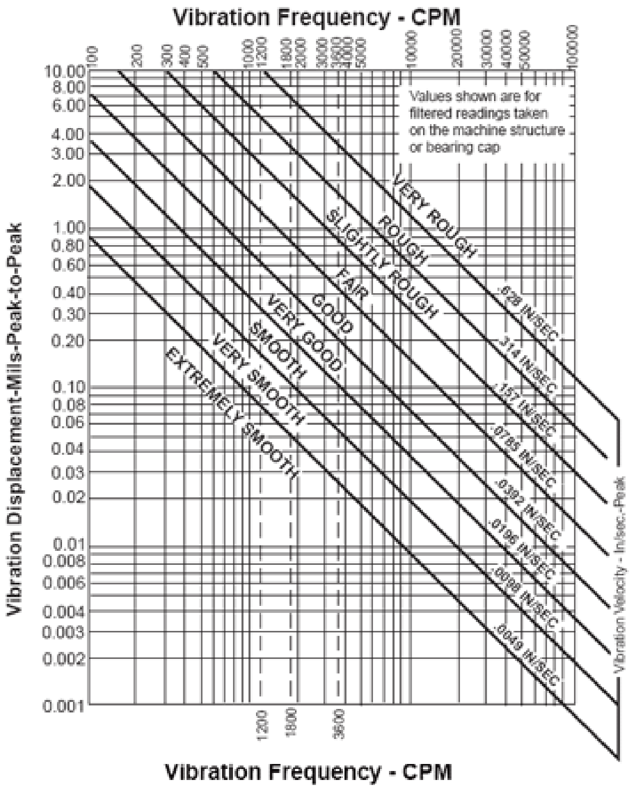
Temperature (simple one)

- 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

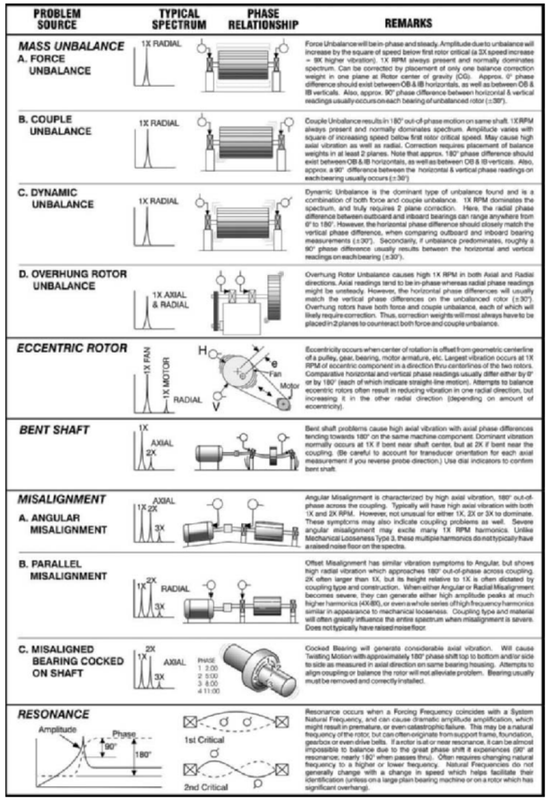


https://www.engineersedge.com/vibration/vibration_severity_chart_13658.htm

For Raw Data Assessment

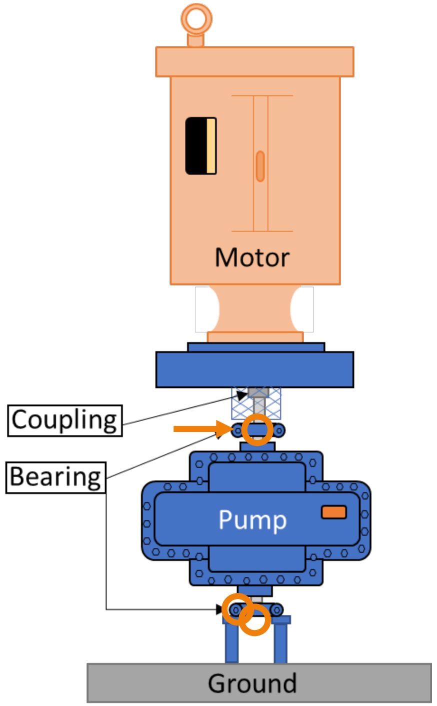
For Filtered Data Spectra Assessment

Analyze multiples of pump operating frequency



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

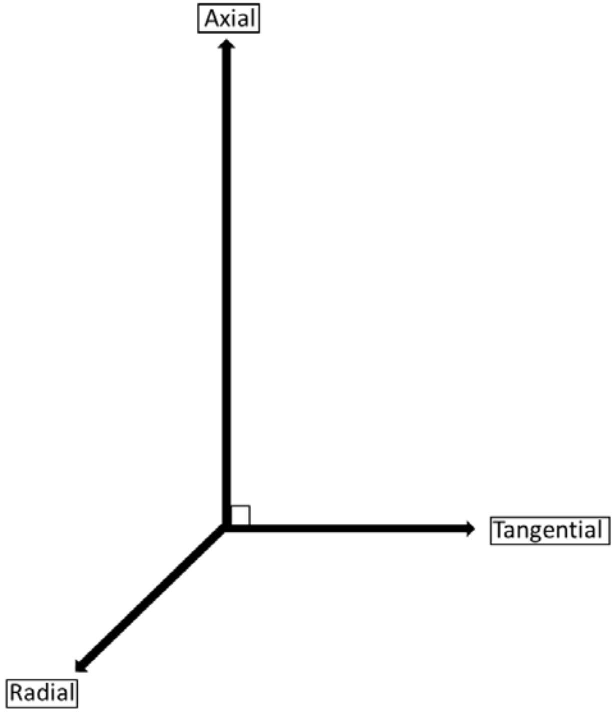
CBM System



Motor & Pump Set-up

Courtesy of Katie Behnert

- Sensors installed on the following axes:
  - Tangential
  - Radial
  - Axial



Accelerometer

Transmitter

Sensor Locations

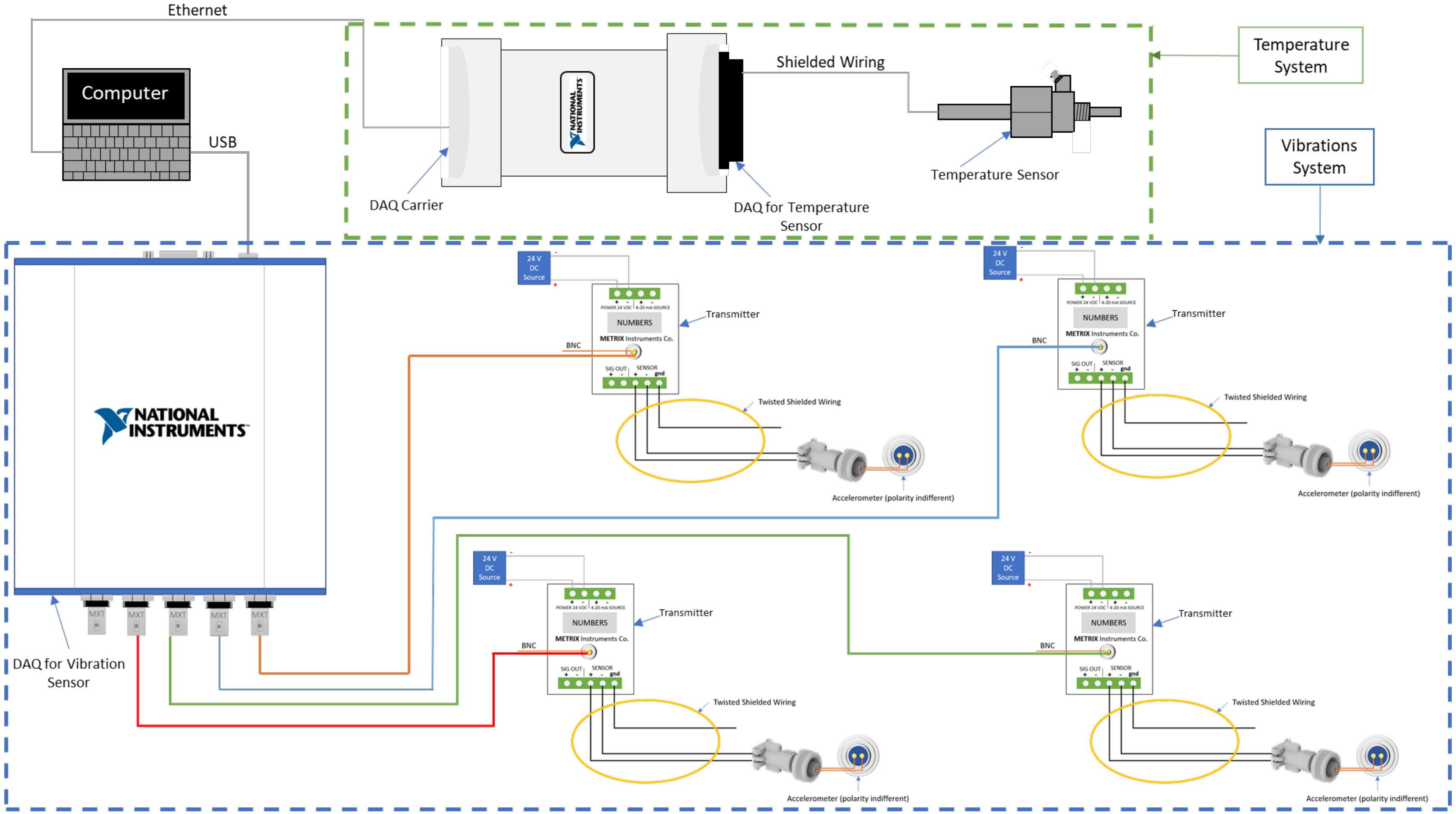
Axial (Ch. 0)

Radial (Ch. 1)

Radial (Ch. 2)

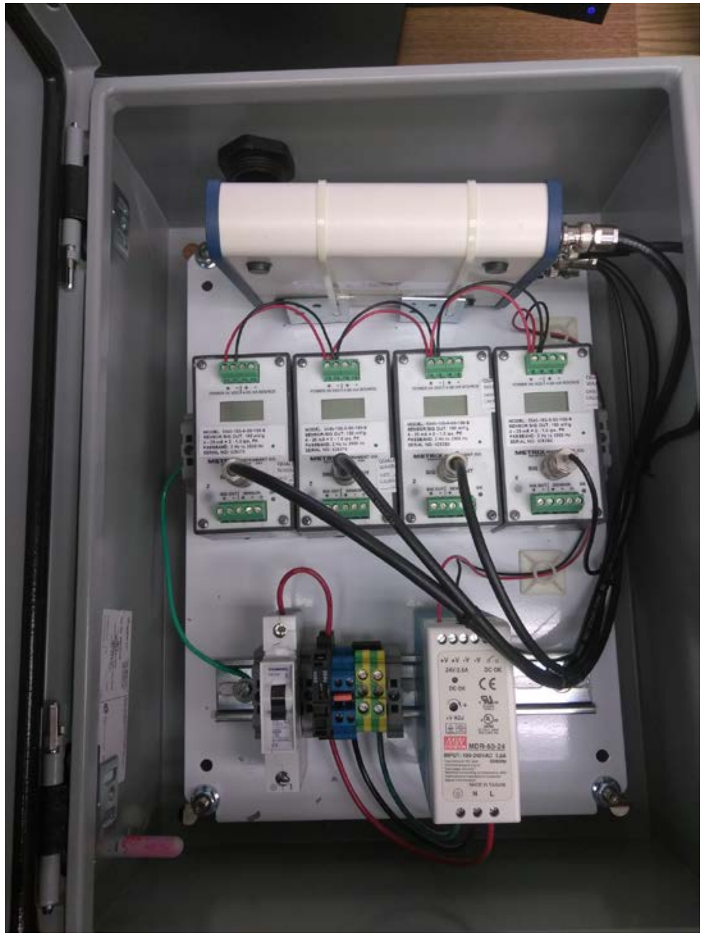
Tangential (Ch. 3)

CBM Connections Schematic



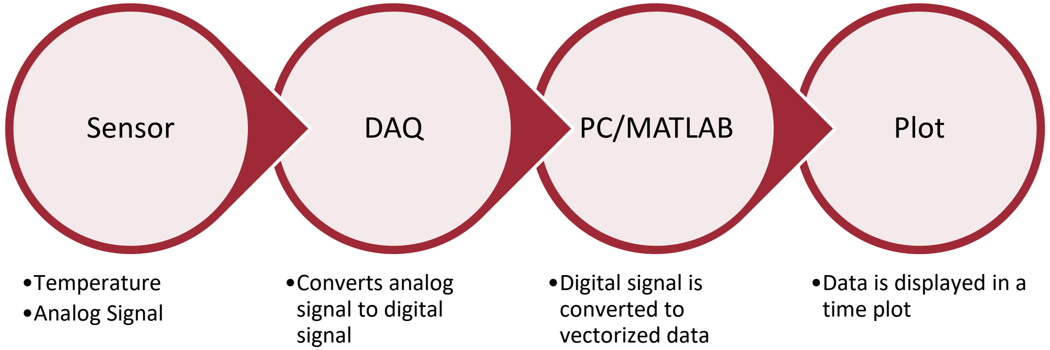
$\sigma_{Temp} = 1.3457\%$

$\sigma_{Vibs} = 6.4236\%$

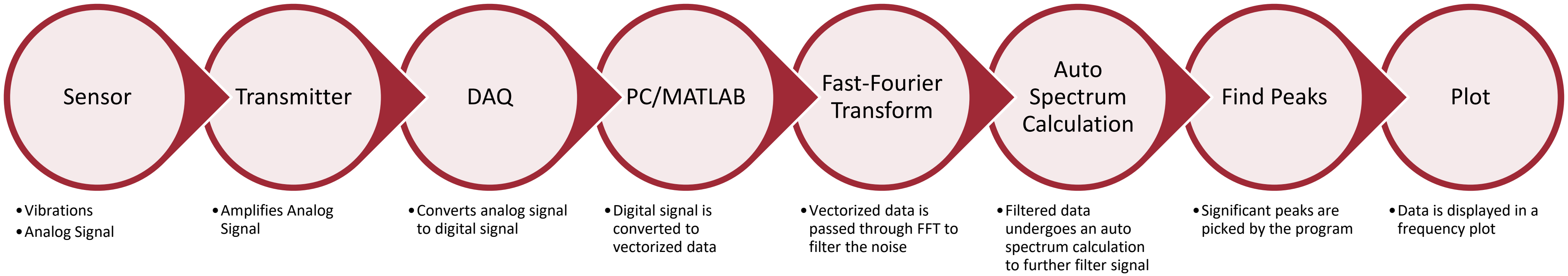


CBM Connections Box

High-Level Architecture of Software

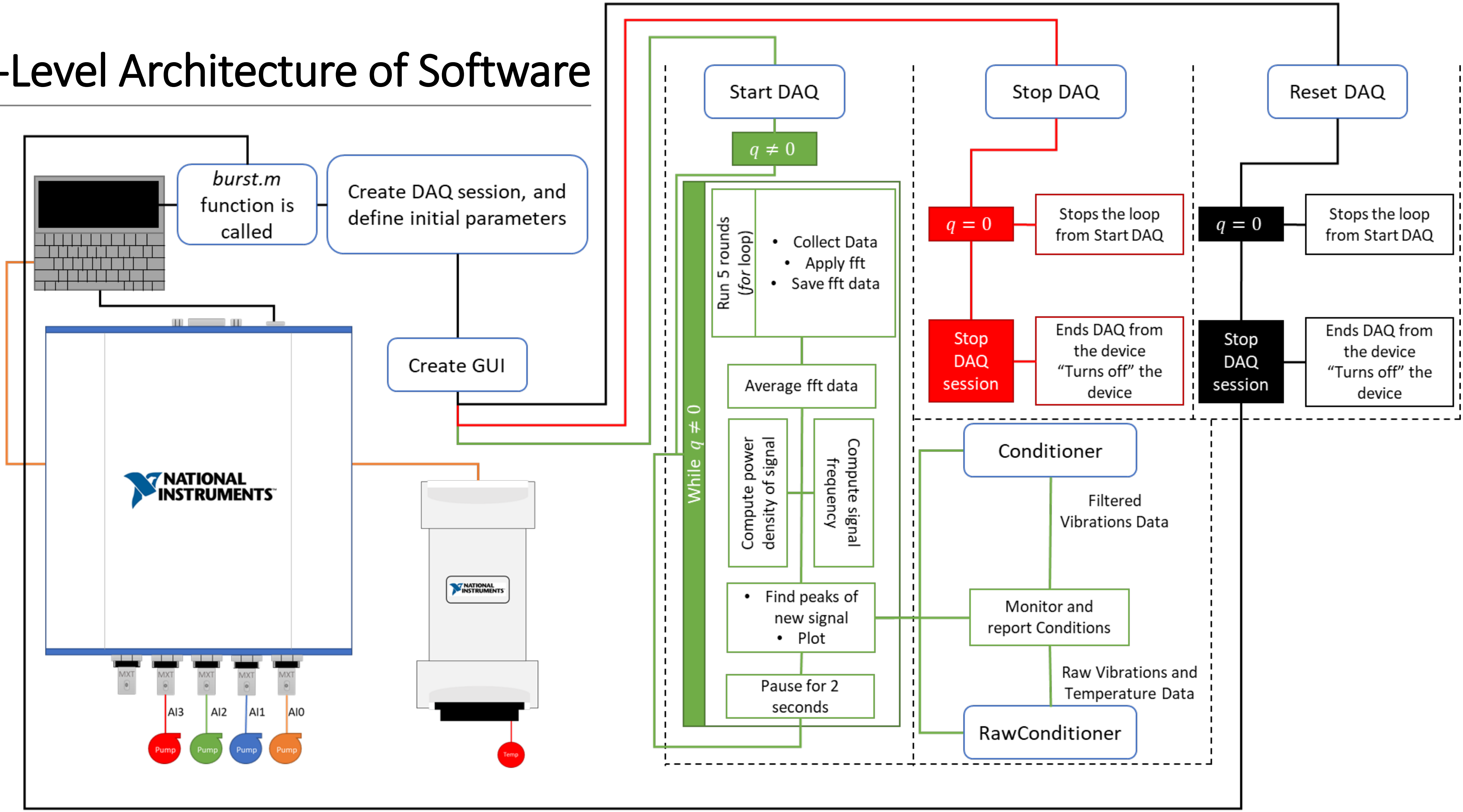


Temperature Data Flow



Vibration Data Flow

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.

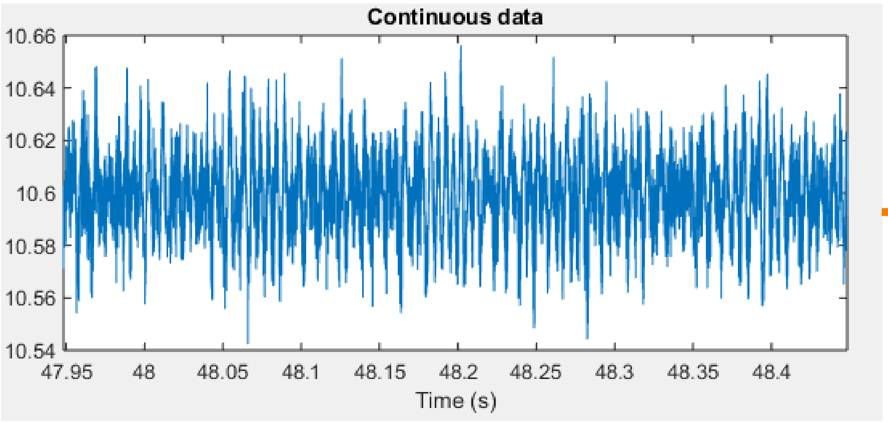
THE ABDULLAH GUARANTEE:

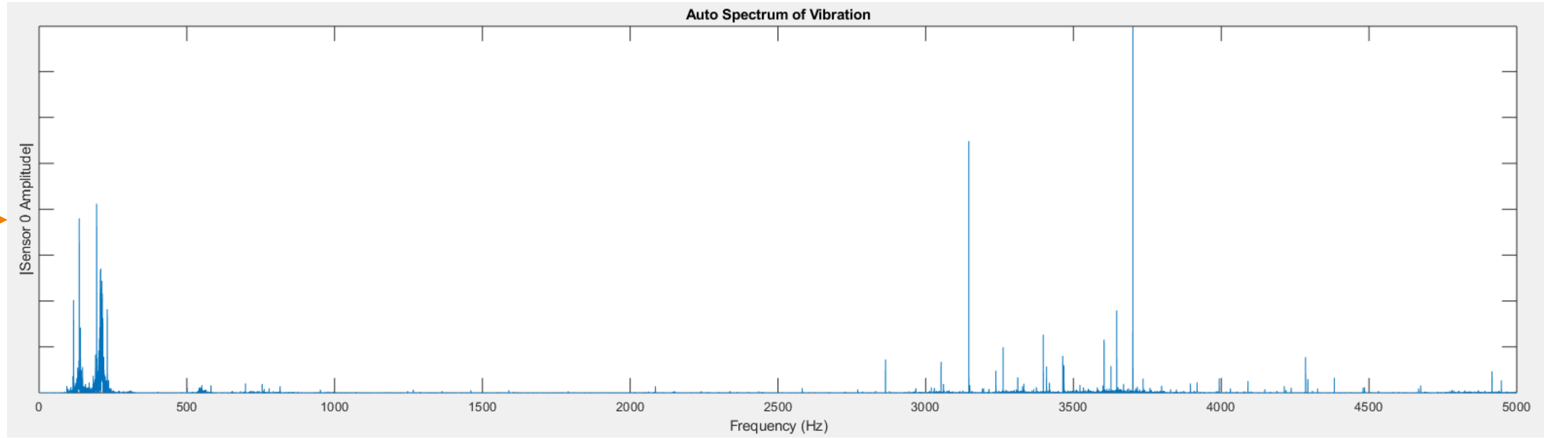
Program will always update in no more than 30 seconds

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:
    - $Y(k) = \sum_{j=1}^{n} \underbrace{X(j)}_{Signal} \; W_n^{(j-1)(k-1)} \ni W_n = e^{\frac{(-2\pi i)}{n}} = one\ of\ n\ roots\ of\ unity$
  - Creates a complex vector of data
- $AutoSpectrum = \dfrac{FFT(raw\ data) \cdot conj\big(FFT(raw\ data)\big)}{Length\ of\ the\ Signal}$

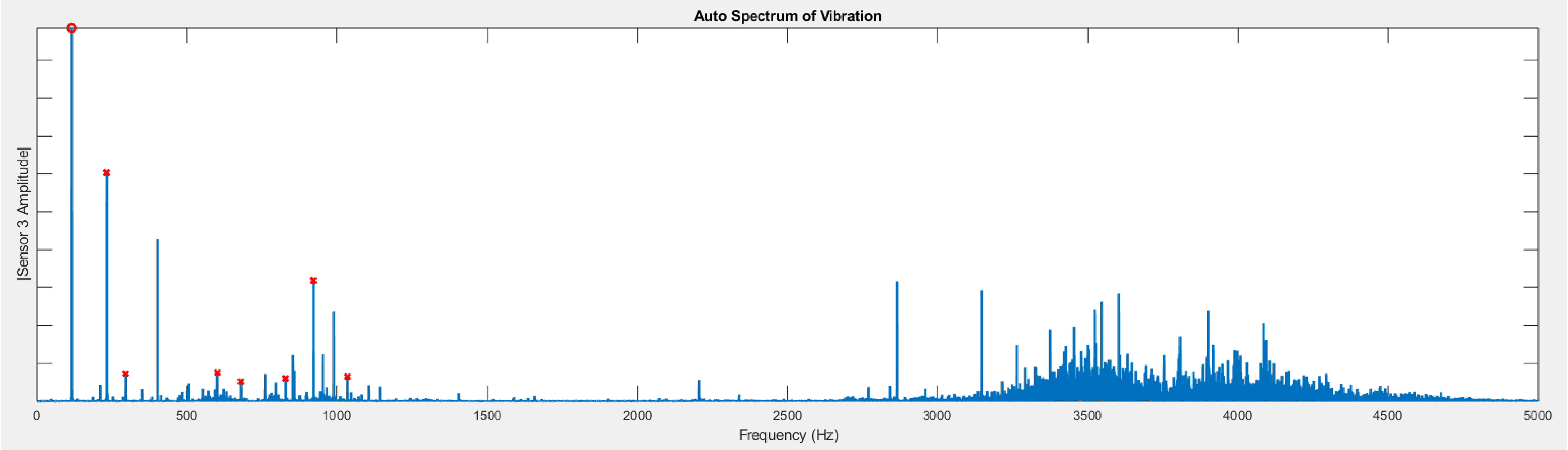




Vibrations Data Peaks' Finder

- 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



Vibrations Automatic Fault Detector *(Conditioner)*

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 ≈2X peak is between 50% and 150% of the principle peak's amplitude.
- "Misalignment detected": The ≈2X peak is more than 150% of the principle peak's amplitude.

Vibrations Automatic Fault Detector *(Cont.)*

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.

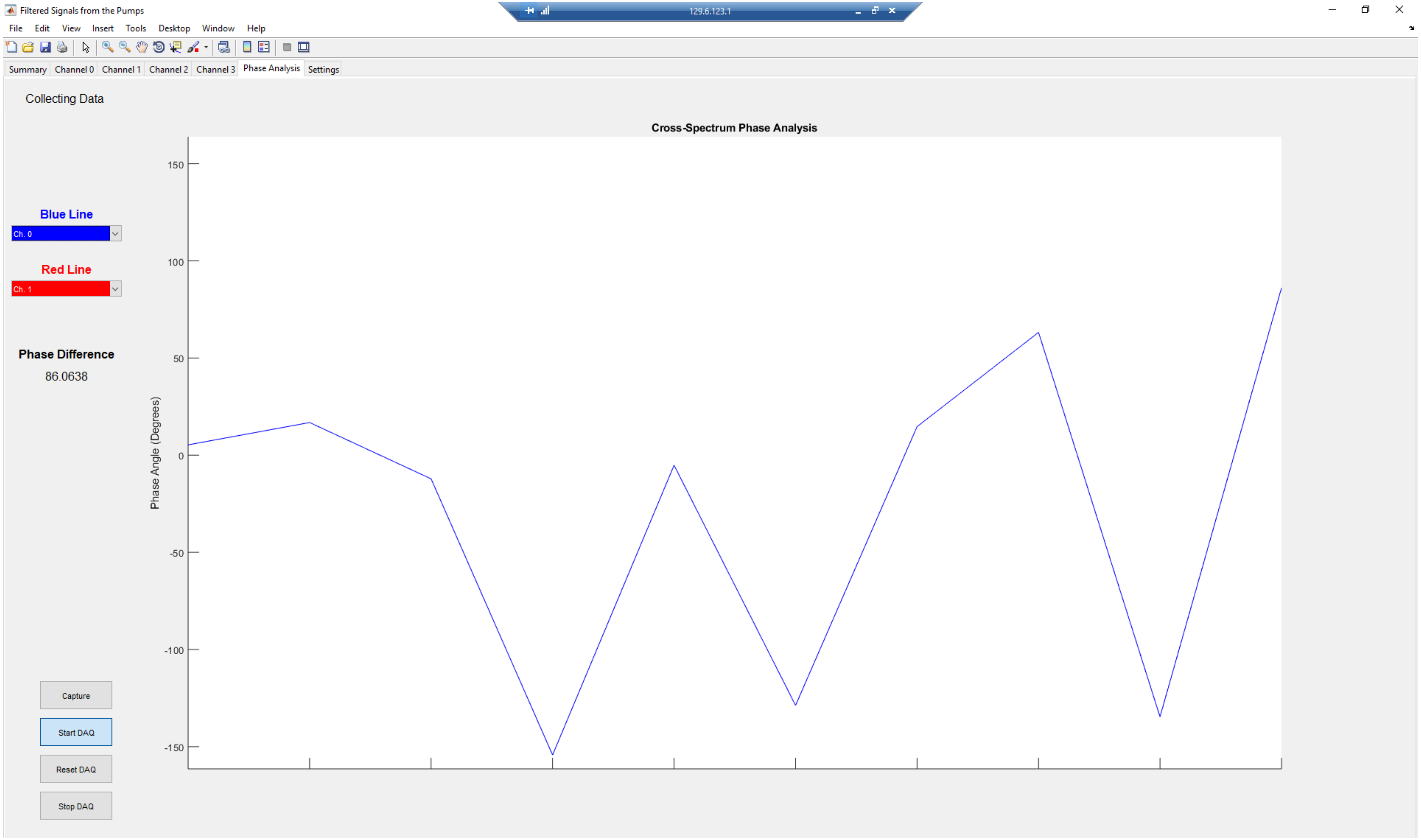
Cavitation

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

Filtered Signals from the Pumps
129.6.123.1
File
Edit
View
Insert
Tools
Desktop
Window
Help
Summary
Channel 0
Channel 1
Channel 2
Channel 3
Phase Analysis
Settings
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
Auto Spectrum of Vibration
|Sensor 3 Amplitude|
Frequency (Hz)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Raw Spectrum of Vibration
|Sensor 3 Amplitude (in/s)|
0.1
0.09
0.08
0.07
0.06
0.05

Phase Analysis

- 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.

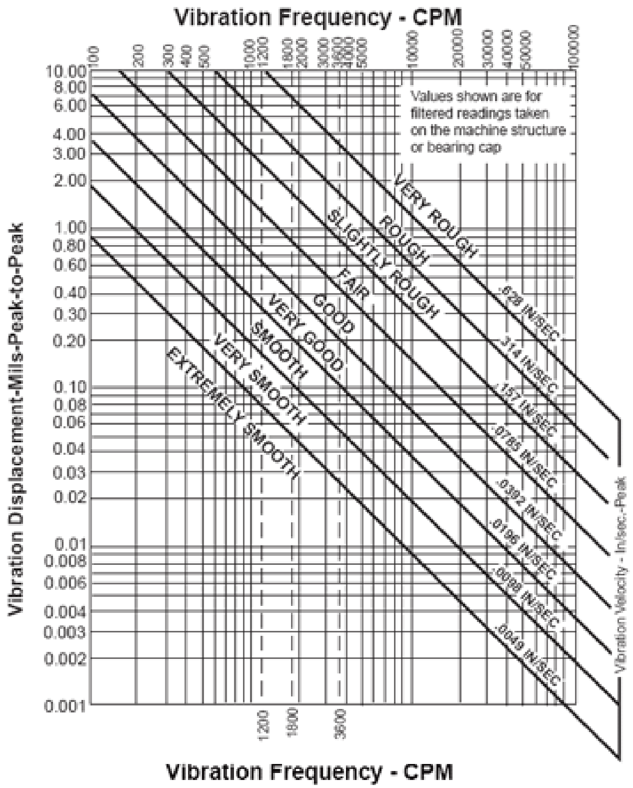


Filtered Signals from the Pumps
129.6.123.1
File Edit View Insert Tools Desktop Window Help
Summary Channel 0 Channel 1 Channel 2 Channel 3 Phase Analysis Settings
Collecting Data
Blue Line
Ch. 0
Red Line
Ch. 1
Phase Difference
86.0638
Capture
Start DAQ
Reset DAQ
Stop DAQ
Cross-Spectrum Phase Analysis
Phase Angle (Degrees)
150
100
50
0
-50
-100
-150

Vibrations Severity Detector *(RawConditioner)*

Average Raw Vibrations (every ≈30 seconds):

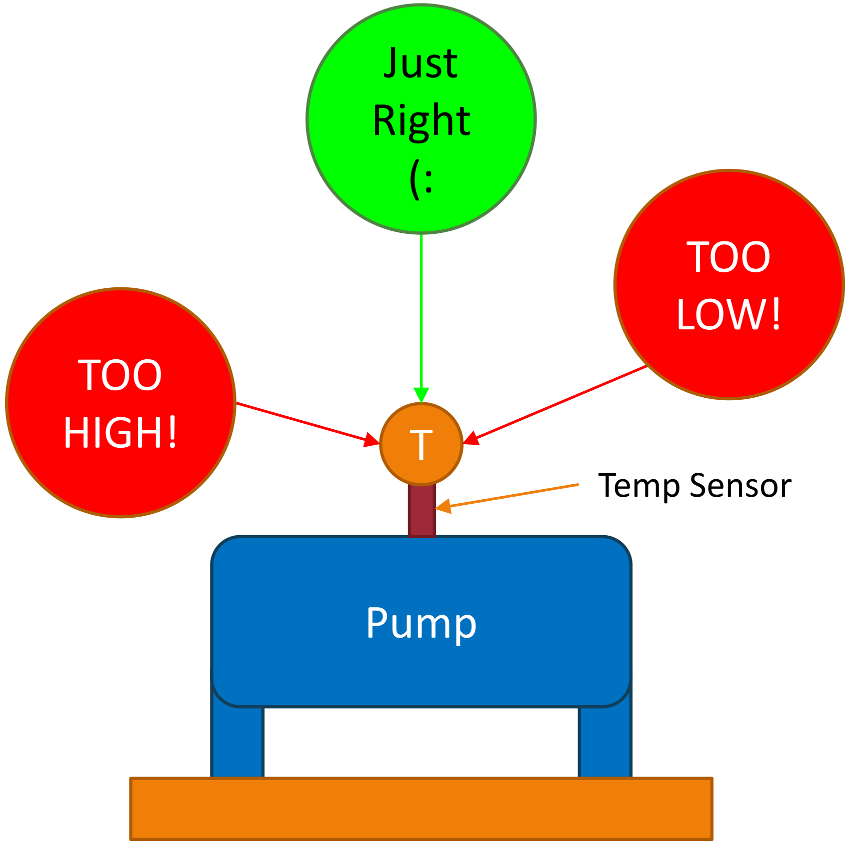
0 – 0.005 in/s	Extremely Smooth
0.005 – 0.01 in/s	Very Smooth
0.01 – 0.02 in/s	Smooth
0.02 – 0.04 in/s	Very Good
0.04 – 0.08 in/s	Good
0.08 – 0.16 in/s	Fair
0.16 – 0.32 in/s	Slightly Rough
0.32 – 0.64 in/s	Rough
> 0.64 in/s	Very Rough

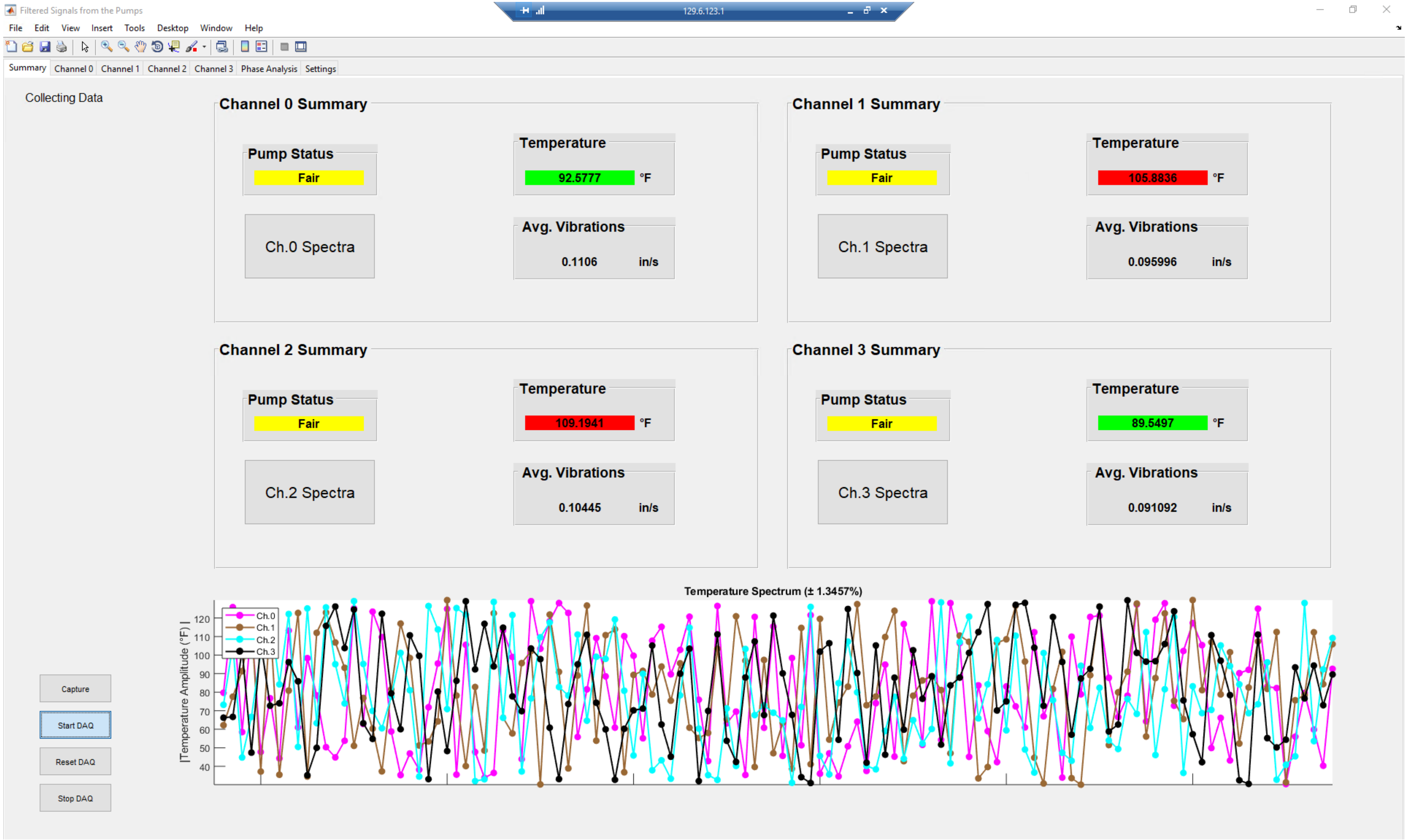


https://www.engineersedge.com/vibration/vibration_severity_chart_13658.htm

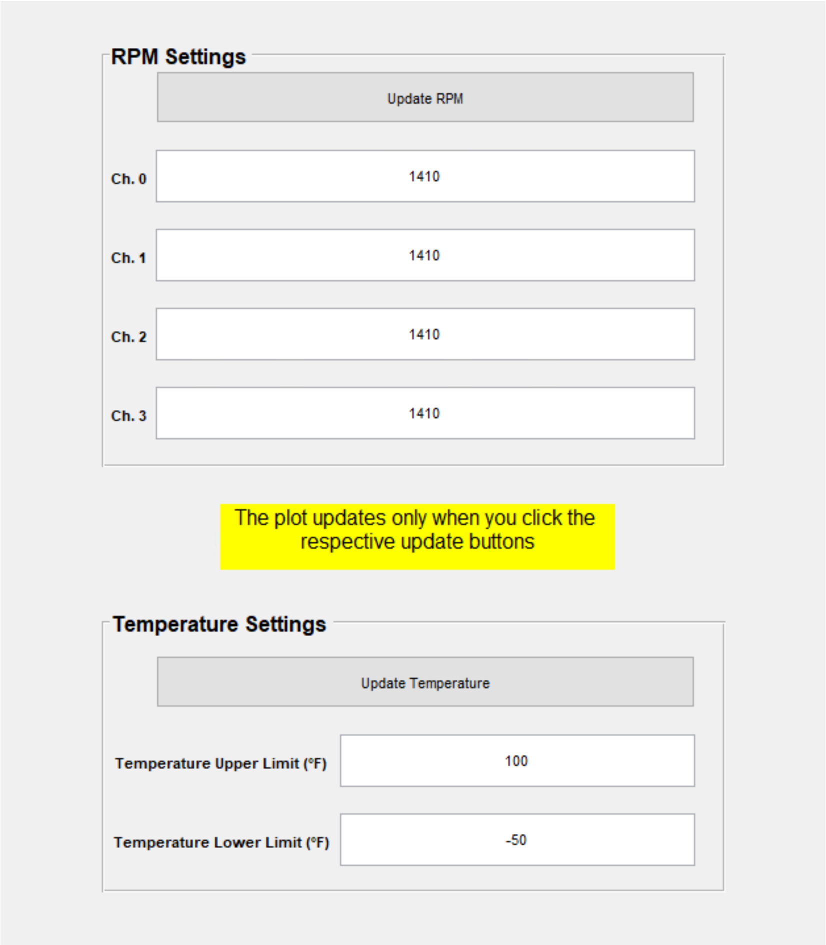
Temperature Conditioner *(RawConditioner)*

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



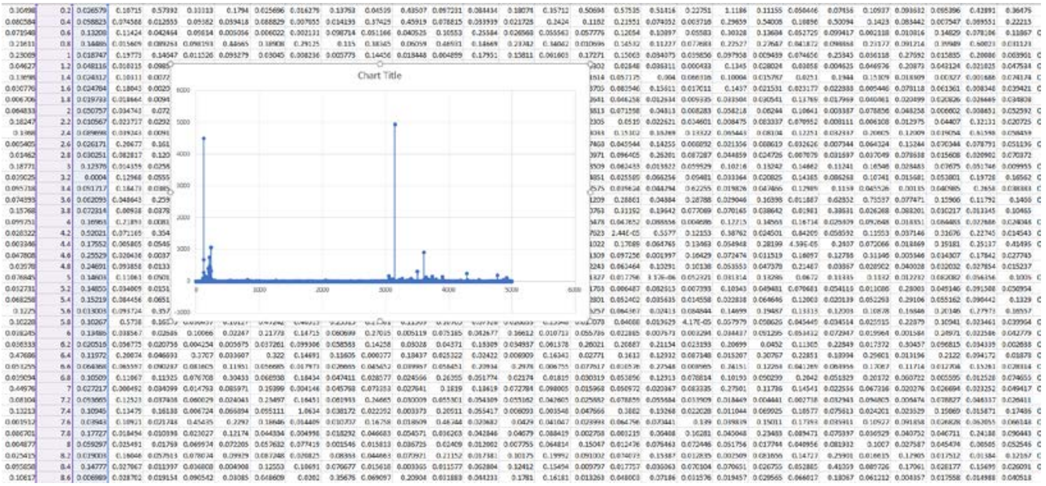

Filtered Signals from the Pumps
129.6.123.1
File Edit View Insert Tools Desktop Window Help
Summary Channel 0 Channel 1 Channel 2 Channel 3 Phase Analysis Settings
Collecting Data
Channel 0 Summary
Pump Status
Fair
Temperature
92.5777 °F
Ch.0 Spectra
Avg. Vibrations
0.1106 in/s
Channel 1 Summary
Pump Status
Fair
Temperature
105.8836 °F
Ch.1 Spectra
Avg. Vibrations
0.095996 in/s
Channel 2 Summary
Pump Status
Fair
Temperature
109.1941 °F
Ch.2 Spectra
Avg. Vibrations
0.10445 in/s
Channel 3 Summary
Pump Status
Fair
Temperature
89.5497 °F
Ch.3 Spectra
Avg. Vibrations
0.091092 in/s
Temperature Spectrum (± 1.3457%)
|Temperature Amplitude (°F) |
120
110
100
90
80
70
60
50
40
Ch.0
Ch.1
Ch.2
Ch.3
Capture
Start DAQ
Reset DAQ
Stop DAQ

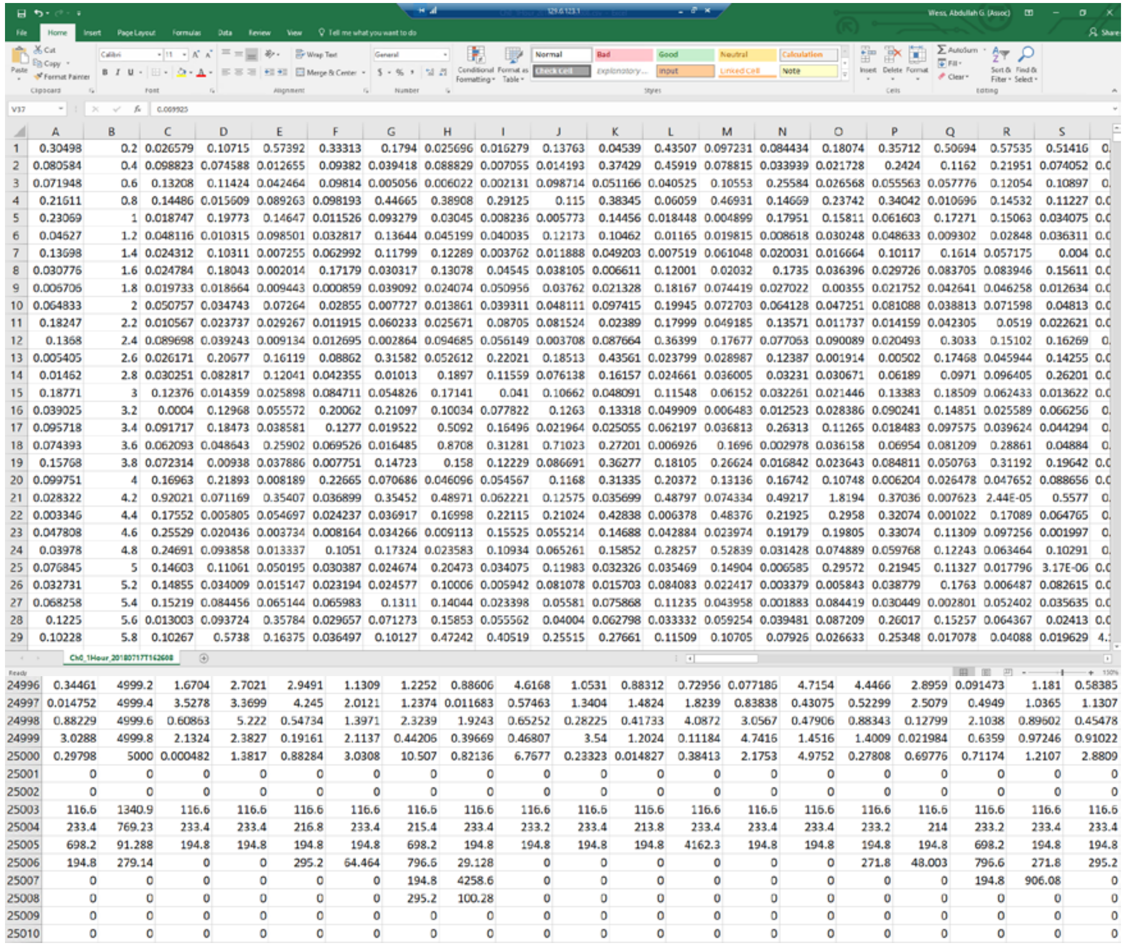
Human-machine Interface (Settings tab)



Output File

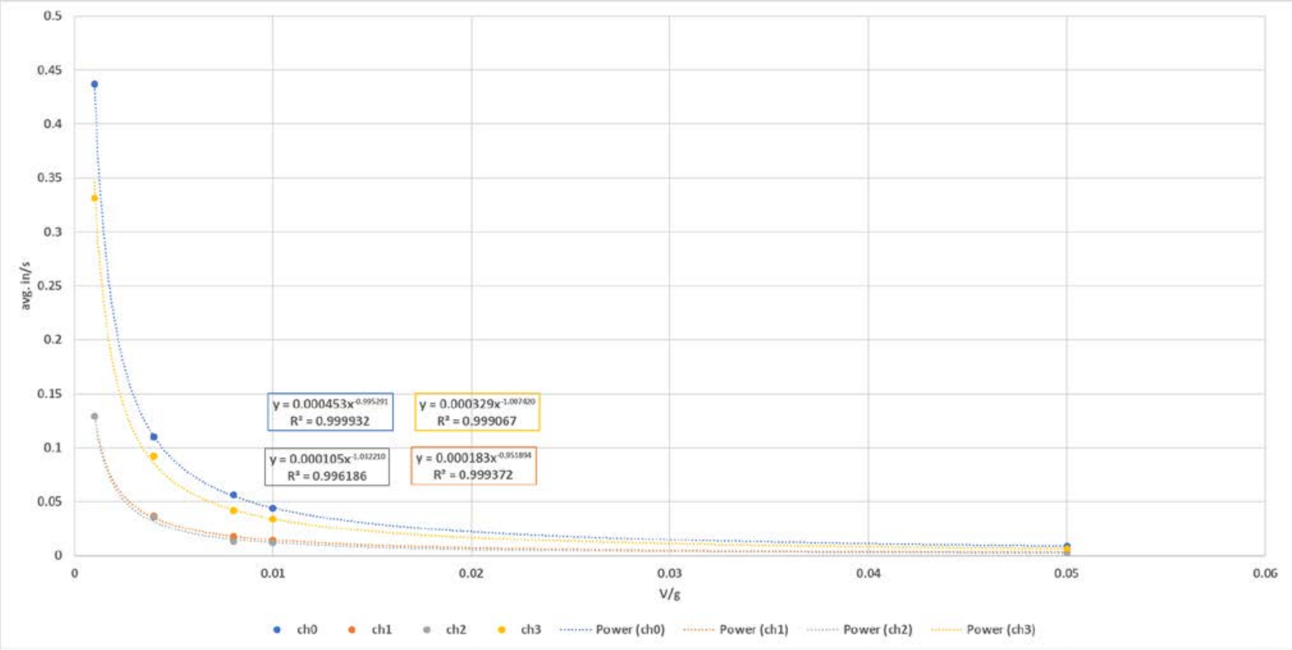
- Generated every hour
  - .csv file
  - 20 – 25 MB
  - Each channel
  - FFT data with the peaks' frequencies
  - Enables further manual analysis





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
- ↑ Sampling rate ≡ ↓ in/s



Conclusion

- 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

- 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

CHRNS

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