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Pump Cavitation Data Acquisition

1. EXECUTIVE SUMMARY

The following work outlines the data acquisition and analysis process undertaken for pump cavitation detection purposes at Schneider Electric's Knightdale (US) facility. Cavitation is a known harmful state of operation for electric pumps and the value in recognizing when it occurs is established as a potential customer value proposition. This report outlines the test bench, test procedure, data processing, and data visualization as well as documents relevant aspects of the project. The result of the work is software supporting automated data acquisition, processing, and visualization. Visualization enabling various views of the data proved valuable for analysis, leading to initial results. Preliminary analysis is discussed suggesting cavitation is detectable via straightforward processing of mechanical (vibration and pressure) signals. All testing and developed software is cataloged and archived for future reference.

2. INTRODUCTION

With the intent of creating greater value for their customers, Schneider Electric is pursing research of pump cavitation. More specifically the detection of pump cavitation via electrically acquired signals. Cavitation is the vaporization of fluids within a pump at ambient temperature due to a decrease in pressure [1]. Consequently, this leads to deterioration of hydraulic performance, damage to the pump's components, generation of high vibration, and increased noise [2]. As such, it is in pump operators' best interest to minimize cavitation making automated detection an asset to such entities. Figure 1 displays typical damage to a pump's blades due to cavitation.

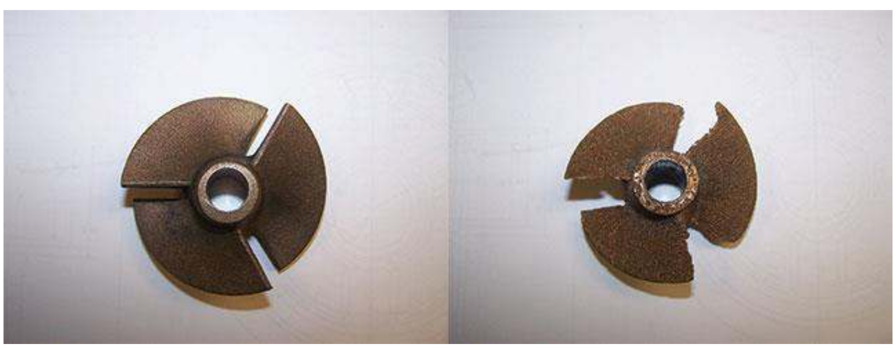

Figure 1. Bronze pump inducer before (left) and after cavitation (right) [3]

Schneider's innovation team has undertaken a laboratory test program to explore methods to detect cavitation in pumps. The work described in this report summarizes acquisition and automated analysis of data acquired on a pump for signals of interest. The acquisition, analysis, and visualization of both mechanical and electrical signals are supported. Subsequent sections outline the methodology and procedure for the acquisition, processing and analysis of data, and reviews preliminary results.

3. DATA ACQUISITION

To ensure accurate, robust data is obtained for analysis, an in-depth data acquisition process was undertaken. This process began with the technical rigging of the test bench, in this case a pump stand. The pump stand used for testing can be seen in Figure 2 and pump specifications can be observed in [4]. The stand is designed as a continuous loop, recycling water from the tank through the pumps and back into the tank via a network of pipes. Manual control valves are located at both the suction and discharge ends of the pump and are used to manually induce cavitation during testing. The stand is equipped with the necessary instrumentation to collect both mechanical and electrical signals of interest, including two pressure sensors, two accelerometers mounted on the body of the pump (Figure 3), a microphone and additional sensors to measure pump motor current and voltage for all 3 input phases. Table B1 in the appendix lists all monitored signals, sampling rates, and sensors used for data acquisition. Management of acquired waveforms is automated using the National Instrument's LABVIEW environment, using a LABVIEW program developed by the lab.

To maintain consistency in valve positioning, ad hoc measuring tools were implement shown in Figure 4. Although these measurements are informal, they create a standard way to evaluate repeatability and tracking of the valves for various pump conditions, allowing for more well defined and accurate testing.

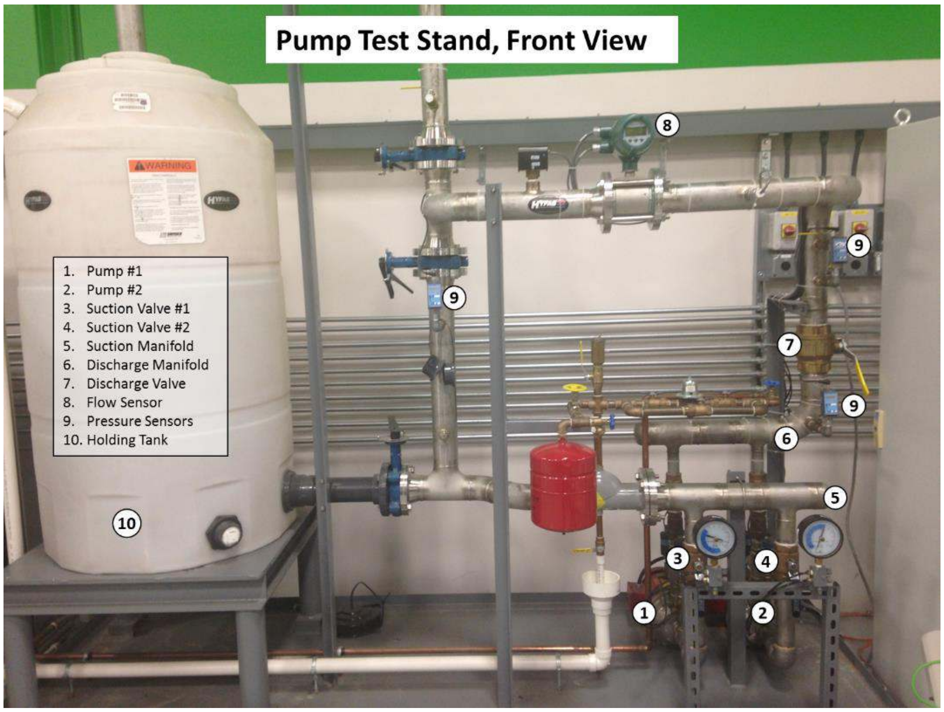

Figure 2. Pump stand test bench

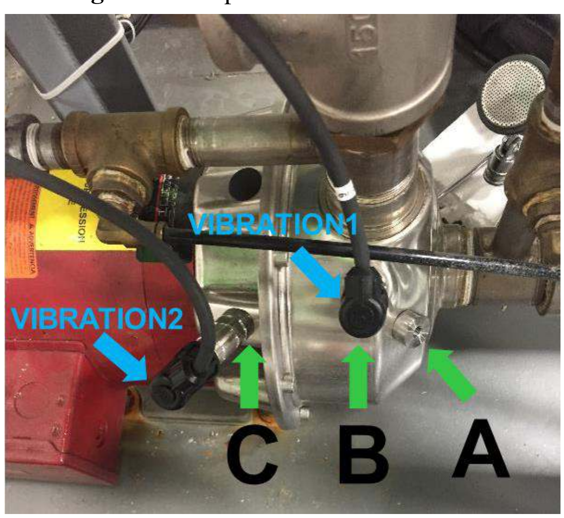

Figure 3. Accelerometer positions A,B,C & labeled vibration signals

Once the test bench was configured and confirmed operational, a test plan was developed. To develop the plan, preliminary testing was conducted on the pump exploring various cavitation conditions. The plan considered two different ways of reaching a cavitation state. The first, which will be referred to as suction valve technique in this document, involves keeping the discharge valve at a fixed position while closing off the suction valve until cavitation occurs. The second, referred to as discharge valve technique, involves putting the pump in an initial state with both valves partially closed followed by opening the discharge valve until a cavitation condition is reached. Defined tests are conducted for both cavitation methods separately as well as for both heavy and light cavitation conditions. All conducted tests are tabulated in Tables 3 & 4 of the appendix.

Figure 4. Ah hoc measuring tools for suction (left) and discharge (right) valves

4. DATA PROCESSING & ANALYSIS

After testing is conducted, the acquired raw data must be processed and visualized before it can be assessed. MATLAB is used for this process. Scripts were developed to convert from LABVIEW's .tdms file format to MATLAB's .mat format, enabling the data to be processed and graphed leveraging MATLAB's computation power. Further scripts were developed to automate the data visualization using a convenient graphical user interface. Prior to visualization, acquired data signals, listed in Table B1, are segmented and run through both time domain and frequency domain analysis.

4.1 DATA SEGMENTATION

To observe the evolution of quasi-steady state behavior, acquired data is segmented before the appropriate time and frequency domain calculations. Figure 5 displays the segmentation used in both time and frequency domain analysis. For time domain analysis, the data was split into half second segments with the zeroth segment centered at 500ms. Frequency domain analysis necessitated larger 2s segments with the first centered at the 1s mark and each consecutive segment centered 500ms from the previous segment's center. Table 2 lists the respectively time domain and frequency domain analysis conducted. Certain calculations provide no valuable information and are thus excluded from the analysis.

Table 2. Time and Frequency domain analysis conducted on waveforms

	Time Domain Analysis			**Frequency Domain Analysis**		
	Mean	RMS	Variance	Find Peaks	Energy	Noise Floor
Pressure 1	X	X	X			
Pressure 2	X	X	X			
Flow	X	X	X			
Vibe 1		X		X	X	X
Vibe 2		X		X	X	X
Mic.		X		X	X	X
Pwr	X	X	X	X	X	X
Qwr	X	X	X	X	X	X
Current Vector	X	X	X	X	X	X
Voltage Vector	X	X	X			
Power Factor	X					

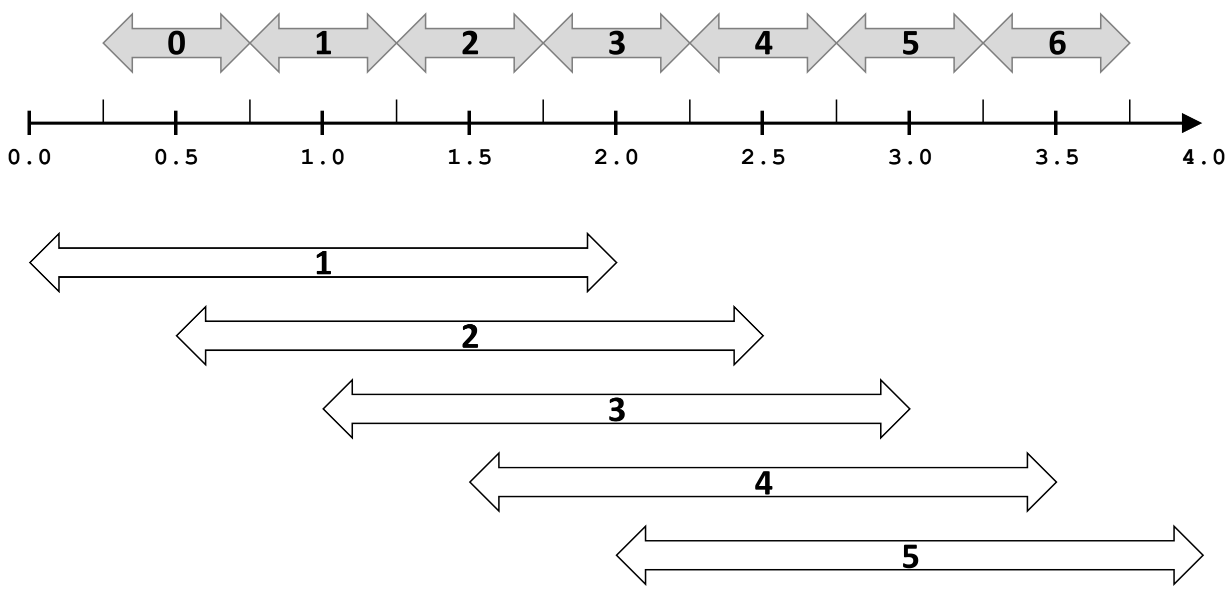

Figure 5. Definition and relationship of segmentation for waveform analysis, shown on the time axis. Half-second segments are shown in gray, and two-second segments shown in white. The two-second segments overlap by 75%. Segments are numbered to show the temporal relation between the half-second and corresponding two-second segments.

4.2 TIME DOMAIN ANALYSIS

Time domain analysis was conducted on the 500ms segments. Mechanical variables are analyzed directly as acquired. Electrical variables are preprocessed to yield power and vector magnitudes, scalar quantities that are then subjected to analysis. Voltage and current vectors, real power (Pwr), and reactive power (Qwr) are calculated from the three current and voltage phase measurements, reference Table B1 & 2 and equations (1), (2), (3), and (4) in the appendix. Mean, rms, and variance values are calculated for each segment and stored in a data structure for future use. The process yields three arrays with length equal to the number of segments, for each respective waveform.

4.3 FREQUENCY DOMAIN ANALYSIS

Frequency domain analysis involves running every 2s segment through the Fast Fourier Transform. Noise floor and signal energy are evaluated in frequency bins over the 0-2500Hz signal frequency range (half of the sampling frequency). Main spectral peaks are subsequently also calculated. Frequency domain analysis uses the same Real power (Pwr), reactive power (Qwr), Current Vector, and Voltage Vector calculations as for time domain analysis and are similarly stored in a data structure indexed by segment number.

4.4 DATA VISUALIZATION

Visualization is a key step in data analysis allowing researchers to compare various views of the data and formulate conclusions. To facilitate visualization of the acquired data, a MATLAB graphical user interface (GUI) was developed to automate the analysis process described in sections 4.1, 4.2, & 4.3 and plot various views of the processed data. The GUI is composed of a main screen, Figure 6, displaying four charts, each with a selection to change the data displayed, options to run frequency domain analysis on a specific segment or frequency range, ability to plot scatter plot two variable against each other, as well as relevant metadata of the file. The four graphs on the interface, enable engineers conducting analysis to visualize four different sets of data from the same test, allowing for straightforward side-by-side comparison of various quantities, e.g. power, pressure, vibration, ect. Two slider bars, located below the upper left chart, allow for convenient selection of a desired segment range (time range), which is displayed with vertical lines on the upper left chart. The 'Scatter' button takes the selected segment range and plots the bottom charts against each other, reference Figure 8. The 'Frequency Analyzer' button seen on the middle of the main GUI screen, take the selected segment number and displays the graphs seen in Figure 7. For reference, all MATLAB code used in this work is documented in Table 5 and file dependencies are listed in Table 6 of the appendix.

5. PRELIMINARY RESULTS

Visualization of the acquired signals provided valuable insight into possible metrics to detect cavitation. Various views of the data reveal several areas of potential regarding cheap and reliable detection methods. Perhaps the most obvious, the microphone signal, exhibits a clear and consistent indication of change upon the onset of cavitation for all tests. However, the microphone signal is not practical for many industrial applications in which the background noise will overpower the microphone's ability to detect acoustic changes caused by cavitation. The accelerometer signals appeared noisy and inconsistent at first glance, but additional observation of the waveform in different frequency bins reveals that the desired energy of the signal appears in lower frequencies. As such the incorporation of a low-pass filter on the vibration waveform results in far less noisy and more distinguishable waveform. This is demonstrated in the bottom two charts in figure 6, in which the left chart displays the RMS accelerometer1 signal and the right chart displaying the same signal after a 400Hz low pass filter was applied. This is advantageous as it is fairly simple and computationally cheap calculation. However, multiple rounds of testing indicated that the accelerometer signals are susceptible to ambient vibrations which are unrelated to cavitation, such as turbulence in pump piping. Similar results were observed with the pressure signals in which it was found that visualization of the signal under the frequency range of the once-per-revolution frequency displayed a relatively clean and distinguishable signal.

The observation of the different views of the data also suggests that correlation of pressure and power may be a good indicator of cavitation. Figure 8 demonstrates this phenomenon. It can be seen that there are two clusters of points corresponding to the normal operation and cavitation states as well as a line of points connecting the two corresponding to the transition between the states. This method was observed to function well for the suction valve cavitation technique but inconsistent for the discharge valve method, raising concerns for its viability.

More detailed analysis is still required to confirm or deny the feasibility and practicality of the discussed methods. Future work is also recommended on a variety of pump installations to learn how broadly applicable and robust the techniques explored in this report will be.

6. CONCLUSION

In conclusion, the data acquisition, processing, and visualization work described in this document supports high level engineers conducting pump cavitation analysis in adding potential value to Schneider's customer propositions. Data acquisition was automated using the LABVIEW environment and a test bench developed by lab technicians. Data processing, visualization, and analysis was facilitated using MATLAB scripts and GUI. The visualization capabilities of the developed GUI proved to be a valuable tool for data analysis and is recommended to be used to support future proposed cavitation work. Such capabilities may also be applicable for other work dealing with multiple process variables, e.g. power & another signal. Preliminary analysis of data suggests cavitation detection is possible and several potential methods were discussed. Further work and testing is recommended to develop and review the practicality and applicability of the detection methods discussed in this report.

7. ACKNOWLEDGEMENTS

The author would like to extend gratitude to Steve Colby for his expert guidance throughout this work as well as Joshua Adams and Duncan Whinna for their assistance with the lab hardware and software.

8. REFFERENCES

[1]. S. A. Al-Hashmi, "Statistical analysis of vibration signals for cavitation detection ISIEA 2009", *2009 IEEE Symposium on Industrial Electronics & Applications*, 2009.

[2]. B. Schiavello and F. Visser, "Pump cavitation—various NPSHr criteria, NPSHa margins, and impeller life expectancy.", Proceedings of the 25th International Pump Users Symposium, 2009.

[3]. Ceco Environmental, http://www.pumpsandsystems.com/pumps/november-2014-avoid-system-damage-when-pumping-hot-water. [Accessed: 21- Jul- 2017].

[4]. Bell & Gossett, 1998. [Online]. Available: http://documentlibrary.xylemappliedwater.com/wp-content/blogs.dir/22/files/2012/07/B-311A-Series-3530-Quantek-Pumps.pdf. [Accessed: 21- Jul- 2017].

9. APPENDIX

A. Figures

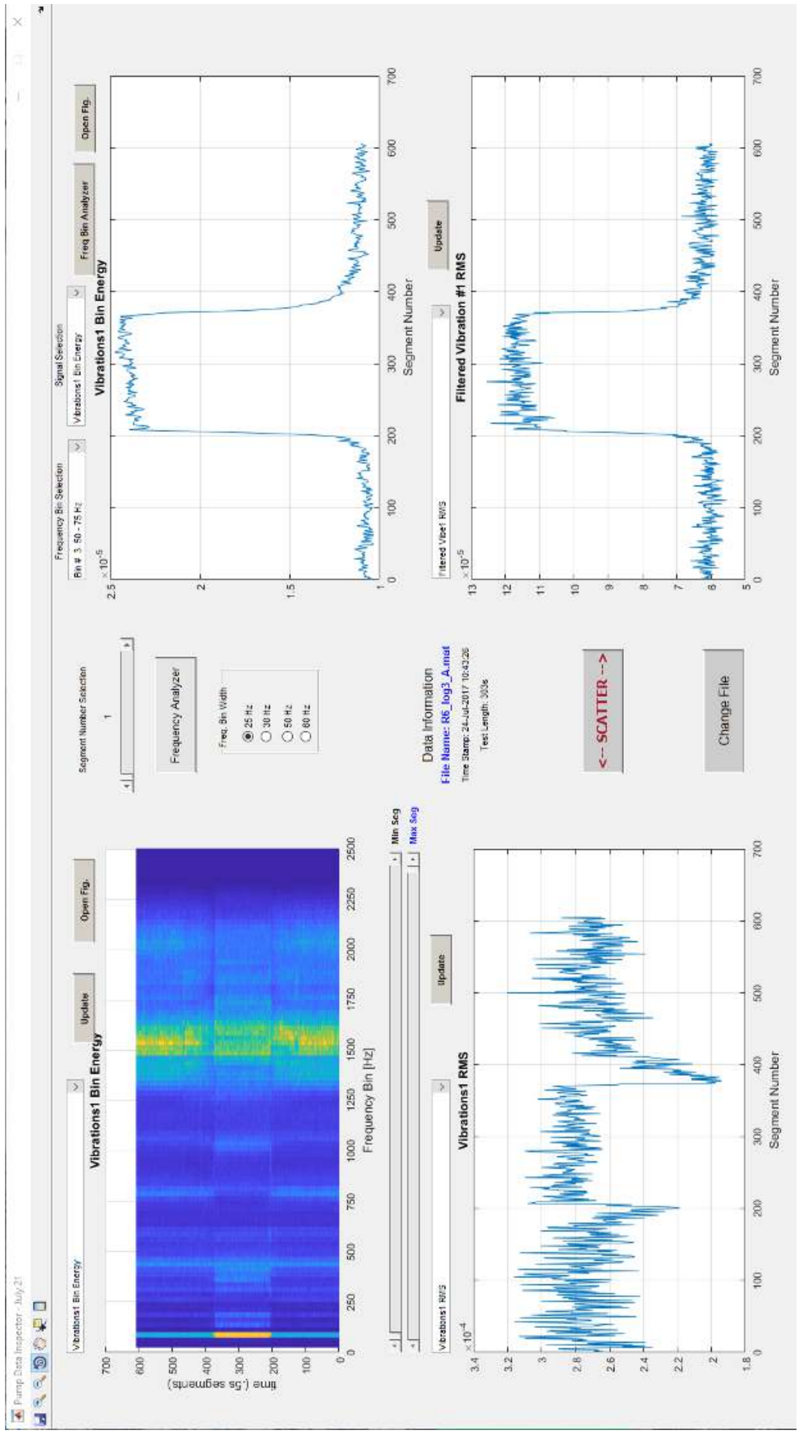

Figure 6. Main GUI screen, displaying results of Round6 log2_A test (see table 4)

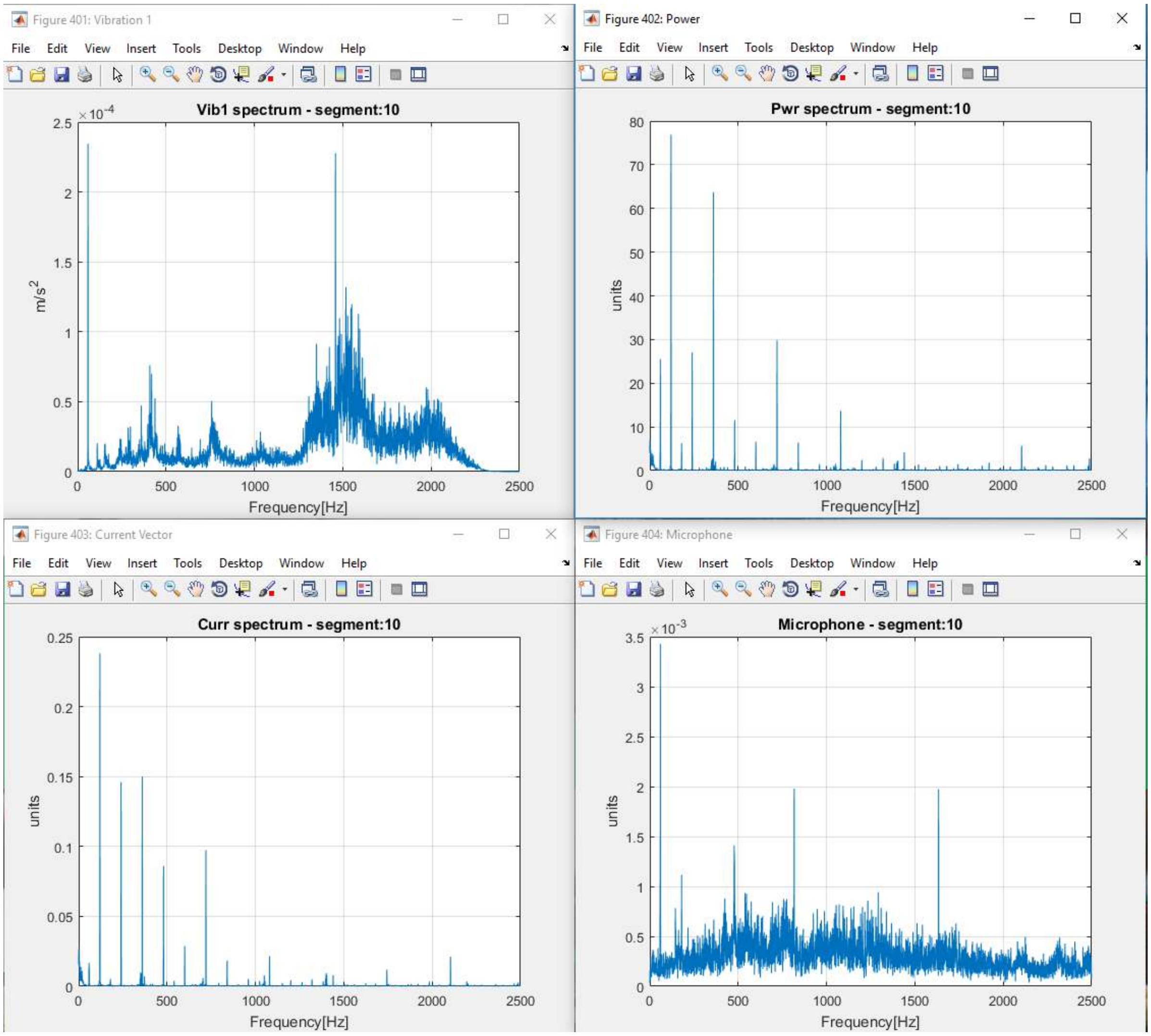

Figure 7. 'Frequency Analyzer' button output

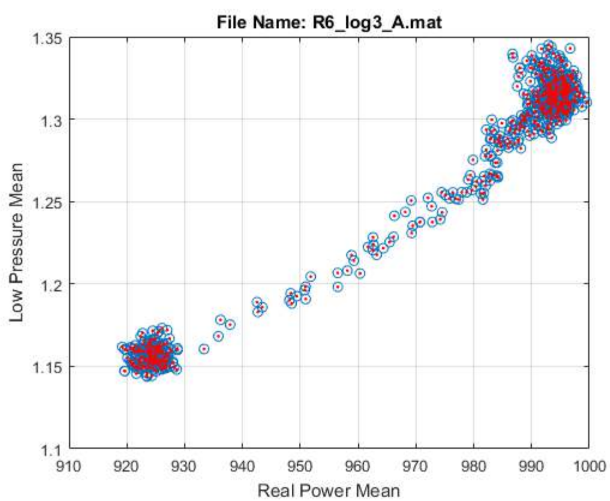

Figure 8. 'Scatter' button output

B. Acquired signals and instrumentation

Table B1. Available signals for data acquisition

Signal	Unit	Sample Rate	Sensor	Physical
Current A	Amperes	5000 S/s	Pearson CT	± 10 Volts
Current B	Amperes	5000 S/s	Pearson CT	± 10 Volts
Current C	Amperes	5000 S/s	Pearson CT	± 10 Volts
Voltage A-B	Volts	5000 S/s	0-10 Volts	± 10 Volts
Voltage B-C	Volts	5000 S/s	Tektronix P5200	± 10 Volts
Voltage C-A	Volts	5000 S/s	Tektronix P5200	± 10 Volts
Suction Pressure	Bar	5000 S/s	Tele. #XXXXXXX	4-20 mA
Discharge Pressure	Bar	5000 S/s	Tele. #XXXXXXX	4-20 mA
Flow Rate	g/min	5000 S/s	ADMAG Flowmeter	4-20 mA
Vibration #1	m/s	5000 S/s	PCB #603C01	± 10 Volts (IEPE)
Vibration #2	m/s	5000 S/s	PCB #603C01	± 10 Volts (IEPE)
Microphone	volts	5000 S/s		± 10 Volts

C. Equations for preprocessing of waveforms

$$v_x = \frac{2}{3}\left(v_{as} - \frac{1}{2}v_{bs} - \frac{1}{2}v_{cs}\right) = (2v_{as} - v_{bs} - v_{cs})/3 \quad (1)$$

$$v_y = \frac{2}{3}\left(\frac{\sqrt{3}}{2}v_{bs} - \frac{\sqrt{3}}{2}v_{cs}\right) = (v_{bs} - v_{cs})/\sqrt{3} \quad (2)$$

Equations 1 and 2 display the Clark mathematical conversion from a three-variable system to an equivalent two variable system used in power calculations.

$$Pwr = \frac{3}{2}\left(v_x i_x + v_y i_y\right) = \frac{3}{2}\left(v_q i_q + v_d i_d\right) \quad (3)$$

$$Qwr = \frac{3}{2}\left(v_y i_x - v_x i_y\right) = \frac{3}{2}\left(v_q i_d - v_d i_q\right) \quad (4)$$

Equations 3 and 4 display the real and reactive power calculations used in preprocessing of waveforms. The voltage and current variables are derived from equations (1) and (2).

D. Testing and test definitions

Table 3. Standard test definitions

Name	Definition	Length (minutes)
A	Begin at steady-state(@init cond.) -> induce cavitation -> turn pump OFF	2
B	Begin with pump OFF -> turn on to a cavitation state -> adjust valve to reach steady-state(@initial conditions defined in A)	2
C	Begin at steady-state(@init cond.) -> induce cavitation(@~1min)	2
D	Begin at steady state -> induce cavitation -> adjust valve to reach steady-state	5

Table 4. Tabulation of completed tests

Testing Round	**Description**	**Data Log**	**Test Definition*** (reference acc position & standards)
1 (Accelerometer position & repeatability)	Run standard test C on pump, changing accelerometer position each time	1	C: Vibrations1@B Vibrations2@A
		2	C: Vibrations1@B Vibrations2@C
		3	C: Vibrations1@B Vibrations2@A
		4	C: Vibrations1@C Vibrations2@A
		5	C: Vibrations1@B Vibrations2@A
2 (suction valve technique)	Run standard tests A & B for both light and heavy cavitation conditions	1	A: (light cavitation)
		2	B: (light cavitation)
		3	A: (heavy cavitation)
		4	B: (heavy cavitation)
3 (suction valve technique)	Run standard tests A & B for both light and heavy cavitation conditions	1	A: (light cavitation)
		2	B: (light cavitation)
		3	A: (heavy cavitation)
		4	B: (heavy cavitation)
4 (discharge valve technique)	Run standard tests A & B for both light and heavy cavitation conditions	1	A: (light cavitation)
		2	B: (light cavitation)
		3	A: (heavy cavitation)
		4	B: (heavy cavitation)
5 (suction valve technique)	Run standard test D with slow valve transition between states. Each log begins at new initial condition	1 (A&B)	D
		2 (A&B)	D
		3 (A&B)	D
		4 (A&B)	D
6 (Suction valve technique)	Repeated tests conducted in round 5 with addition of Flow Meter as a signal	1 (A&B)	D
		2 (A&B)	D
		3 (A&B)	D
		4 (A&B)	D
7 (Discharge valve technique)	Repeated tests conducted in round 6 with discharge valve technique	1 (A&B)	D
		2 (A&B)	D
		3 (A&B)	D
		4 (A&B)	D

*Note more detailed test information available in attached files

E. Software catalog and dependencies

Table 5. Matlab code catalog for data processing and analysis

File Name	Description	Author(s)
PumpDataInspectorJuly21.m	GUI - prompts user to choose .mat file which it then processes and opens Graph_Prompt.m for visualization	M. Sonnenberg R.S. Colby
Graph_Prompt.m	GUI - for second window which displays 4 customizable charts and relevant file info	M. Sonnenberg
AnalyzeData.m	Script - Allows for manual processing of data if GUI unwanted	R.S. Colby M. Sonnenberg
Run_tdms_Conversion_Script.m	Script - Converts from .tdms file format to .mat format, stores data in a struct compatible with PumpDataInspector & AnalyzeData scripts	M. Sonnenberg
TDMS_dataToGroupChanStruct_v5.m	Function – Ensures Run_tdms_Conversion_Script.m output struct is organized correctly	M. Sonnenberg
TDMS_getStruct.m	Function – Supports Run_tdms_Conversion_Script.m	N/A
TDMS_readChannelOfGroup.m	Function – Supports Run_tdms_Conversion_Script.m	N/A
TDMS_readTDMSFile.m	Function – Supports Run_tdms_Conversion_Script.m	N/A
abc2dq.m	Function – Transformation from (a, b, c) to stationary (d, q) reference frame	R.S. Colby
abc2xy.m	Function - Clarke Transformation from (a, b, c) to stationary (x, y) frame	R.S. Colby
pwrFromDQ.m	Function - Compute real and reactive power from (d, q) frame V & I	R.S. Colby
pwrFromXY.m	Function - Compute real and reactive power from (x, y) frame V & I	R.S. Colby
vectorRMS.m	Function - Compute RMS value of data vector	R.S. Colby
vll2dq.m	Function - Transform line-line voltages from (a, b, c) frame to (d, q) frame	R.S. Colby

vll2xy.m	Function - Clarke Transform line-line voltages from (a, b, c) to (x, y) frame	R.S. Colby
xy2abc.m	Function - Inverse Clarke Transformation from stationary (x, y) to (a, b, c) frame	R.S. Colby
FreqDomainAnalyzer.m	Class - Computes frequency-domain statistics on a 1-D waveform	R.S. Colby
TimeDomainAnalyzer.m	Class - Computes time-domain statistics on a 1-D waveform	R.S. Colby
SlidingWindow.m	Class - Manage indices for sliding window into a vector	R.S. Colby
inspectSegData.m	Function – take a segment number & raw data structure and runs frequency domain analysis for that segment	R.S. Colby
processDDStructure.m	Function – crunches raw data from pumpstand for inspectSegData.m analysis	R.S. Colby
filterWaveformData.m	Function - Applies lowpass filter to waveforms in pumpstand data	R.S. Colby
crunchPumpStandData.m	Function – runs data through time and frequency domain analysis, then stores results in a single data structure	R.S. Colby M. Sonnenberg
segmentFreqAnalysis.m	Function – computes frequency analysis on specified segment	R.S. Colby

Table 6. Matlab code dependencies

File Dependencies*	
File Name	**Dependencies**
PumpDataInspectorJuly21.m	• PumpDataInspectorJuly21.fig • filterWaveformData.m • crunchPumpStandData.m • segmentFreqAnalysis.m
Graph_Prompt.m	• Graph_Prompt.fig • SlidingWindow.m • FreqDomainAnalyzer.m • TimeDomainAnalyzer.m • abc2xy.m • analyzedatafunction.m • inspectSegData.m • processDDStructure.m • pwrFromXY.m • vectorRMS.m

	• vll2xy.m
AnalyzeData.m	• SlidingWindow.m • FreqDomainAnalyzer.m • TimeDomainAnalyzer.m • abc2xy.m • pwrFromXY.m • vectorRMS.m • vll2xy.m
crunchPumpStandData.m	• SlidingWindow.m • FreqDomainAnalyzer.m • TimeDomainAnalyzer.m • abc2xy.m • pwrFromXY.m • vectorRMS.m • vll2xy.m
Run_tdms_Conversion_Script.m	• TDMS_dataToGroupStruct_v5.m • TDMS_getStruct.m • TDMS_readTDMSFile.m • **all files in tdmsSubfunctions folder
FreqDomainAnalyzer.m	• SlidingWindow.m • vecotrRMS.m
TimeDomainAnalyzer.m	• vectorRMS.m
inspectSegData.m	• SlidingWindow.m • FreqDomainAnalyzer.m • TimeDomainAnalyzer.m • abc2xy.m • processDDStrucutre.m • pwrFromXY.m • vectorRMS.m • vll2xy.m
processDDStructure.m	• SlidingWindow.m • FreqDomainAnalyzer.m • TimeDomainAnalyzer.m • abc2xy.m • pwrFromXY.m • vectorRMS.m • vll2xy.m
segmentFreqAnalysis.m	• SlidingWindow.m • vll2xy.m • abc2xy.m • pwrFromXY.m

*A file will not be listed if it does not contain any dependencies. Note: File & System dependencies may be found using the MATLAB commands: [fList,pList] = matlab.codetools.requiredFilesAndProducts('FileName'); fList