RECLAMATION
Managing Water in the West

Cavitation Detection – Method Development to Detect Damaging Cavitation

Research and Development Office
Science and Technology Program
(Final Report) ST-2017-1708-01

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Mission Statements

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14. ABSTRACT *(Maximum 200 words)*
Detection of erosive cavitation damage to hydropower turbines has long been a challenge. It is very difficult to differentiate flow field cavitation from actual cavitation pitting on the turbine runner from a vibration or acoustic signal. This research used a broadband acoustic emission sensor to study the signal from these two types of cavitation in a controlled laboratory setting. Cavitation signals were analyzed in low and high frequency ranges that correspond to depth of the cavitation pit. Results showed a relationship between the acoustic signal and pitting depth in the metal which may be applied as an indicator of cavitation damage on turbine runners.

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Cavitation damage, cavitation detection, cavitation erosion, hydropower

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Cavitation Detection – Method Development to Detect Damaging Cavitation

JOSHUA MORTENSEN Digitally signed by JOSHUA MORTENSEN
Date: 2017.10.30 06:00:50 -06'00'

Prepared by: Josh Mortensen, P.E.
Hydraulic Engineer, Hydraulic Investigations and Laboratory Services Group, 86-68560

JOSEPH KUBITSCHEK Digitally signed by JOSEPH KUBITSCHEK
Date: 2017.10.27 15:03:58 -06'00'

Reviewed by: Joe Kubitschek, P.E., PhD
Hydraulic Engineer, Hydraulic Investigations and Laboratory Services Group, 86-68560

ROBERT EINHELLIG Digitally signed by ROBERT EINHELLIG
Date: 2017.10.27 16:50:08 -06'00'

Technical Approval: Bob Einhellig, P.E.
Manager, Hydraulic Investigations and Laboratory Services Group, 86-68560

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Executive Summary

The main objective of this study was to determine if the difference in damaging vs. non-damaging cavitation activity can be detected from a broadband Acoustic Emission (AE) signal. The results are intended to aid in detecting erosive cavitation on hydropower turbine runners, but can potentially be applied to other types of hydraulic equipment and structures as well.

The process of cavitation erosion begins with vapor bubble implosions on the surface of the metal and then, over time, penetrates the surface creating pitting. Eventually, the damage will penetrate the surface sufficiently for the bubble implosions to occur on the sidewalls of the pit as well as on the top surface. Acoustic theory, as well as previous studies (Dunegan, 1995), show that acoustic waves are of different frequencies depending on whether they travel on the surface (in-plane flexural waves) or through the interior (out-of-plane shear waves). The current study applied this theory by utilizing a broadband AE sensor (sensitive to both in-plane and out-of-plane waves) on metal plates exposed to cavitation at different levels of damage. While detecting erosive cavitation through field measurements at hydropower plants is the end goal, laboratory testing was conducted as an initial approach for evaluation of this methodology under tighter control over test conditions. The main conclusions and recommendations include:

- Submerged jet cavitation on an aluminum test plate indicated that there is a correlation between the signal from a broadband AE sensor and depth of cavitation erosion. The ratio of the high frequency signal to low frequency signal (counts over a threshold) increased with erosion depth, which followed the same trend as bench test results with pencil lead breaks.

- Repeatability of test results was very sensitive to the mechanical connection of the side arm component attached to the test plate on which the AE sensor was mounted. Tests where the side arm was removed and then reapplied for subsequent tests produced random results. A consistent trend with the depth of damage was found only when the mechanical connection and sensor installation remained undisturbed throughout the entire test.

- It is recommended that the broadband AE approach be repeated in the laboratory with a different cavitation source. This could be done on the venturi cavitation test rig for materials and coatings testing that was recently installed in the hydraulics lab as part of a research project for coatings. This would allow the current method to be further evaluated on different materials as well as with a different type of mechanical connection. Doing so may help further identify the robustness and/or limitations of this method.

- It is recommended that the current AE method be applied at a hydropower facility with cavitation erosion issues. J.F. Carr and Fremont Canyon hydropower plants are two candidate facilities that could be used for testing in conjunction with ongoing field research involving cavitation detection. The sensor would need to be mounted to the turbine shaft during testing and data should be analyzed in the same manner as the current study. It is preferable that the installation allow the sensor to remain in place without disruption for long periods of time to allow changes in cavitation erosion to occur. Test methods and equipment, including limitations of and potential improvements to the wireless data acquisition system, should be coordinated with TSC's Mechanical Equipment and Hydropower Research groups who are conducting other cavitation field research.

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Introduction

While cavitation monitoring on hydropower plants is not new, the boundaries of turbine unit design and operation are being pushed further than ever. The range over which modern turbine units are expected to operate has expanded due to many factors such as variable water supplies and demands to accommodate other renewable energy sources tied to the power grid. Extending the boundaries of normal operation can result in cavitation at the turbine runner, which may or may not be detrimental to the overall efficiency of the unit or cause damage to the runner.

Reclamation has monitored cavitation on hydropower turbine units and studied detection methods for many years (Germann, 2016). Findings from this effort, mostly from field testing, have shown a clear ability to detect the presence of cavitation during unit operation. Results have correlated well with designated operational limits as well as observed cavitation damage. The challenge that remains is detecting whether the cavitation is actually eroding the runner or merely present in the flow field but not causing damage. To date, various methodologies involving instrumentation, measurement location, and data processing have either failed to clearly make this distinction or have been too complex to be practical.

The main objective of this study was to determine whether the difference in damaging vs. non-damaging cavitation can be detected by conducting controlled laboratory testing using a broadband Acoustic Emission (AE) sensor. Lab tests made it easier to correlate cavitation damage with AE signal characteristics under tighter control of test conditions. The intent of this study is to apply the findings to future field testing.

Literature Review

A literature search was conducted as part of this study and relevant sources are included as Appendix A which contains a summary of their relationship to the detection of damaging vs. non-damaging cavitation. The findings considered most relevant to the current study are given below.

Acoustic Wave Theory, Measurement, and Signal Processing

As a result of Acoustic Emission research related to crack detection in bridge structures, an AE sensor was developed to detect propagation of both in-plane and out-of-plane acoustic waves (Dunegan, 1995 and 2000). In-plane waves are typically a high frequency extensional or shear wave that travels through a material and can be detected at frequencies greater than 100kHz. Out-of-plane waves generally travel across the surface of the material as flexural waves of lower frequency (below 100kHz). The AE sensor that was developed in this case has capability to detect signals as low as 20kHz which is much lower than most AE sensors used for cavitation detection, including those used in Reclamation’s field tests.

Dunegan’s testing was performed using standard pencil lead break tests on a steel plate (ASTM E 976-99) to compare the ratio of the high frequency (HF) signal to low frequency (LF) signal for increasing pencil break depth located along the edge of the test plate. The acoustic signal was processed with a highpass filter (100kHz) for high frequency waves and a bandpass filter (20-

80kHz) for low frequency waves. The results showed that the ratio increased with depth in the steel plate indicating that the change in wave type could be detected from the acoustic signal.

The same model AE sensor used in Dunegan (1995) was also used in the current study to differentiate in-plane from out-of-plane waves. Assuming the same acoustic theory tested in Dunegan (1995), cavitation implosions on the surface should produce a lower frequency signal compared to bubbles that implode deeper in the material sending a high frequency component through the test specimen. Evaluating this hypothesis for cavitation is the focus of the current study.

"On-board" Cavitation Measurements using AE and Acceleration Sensors

"On-board" cavitation measurements refer to measurements that are taken directly from either the component that experiences cavitation or one that is connected to it. For hydropower turbines this most often means the turbine shaft which has a direct mechanical connection to the turbine runner where cavitation occurs. Signals measured on the shaft represent direct transmission from the actual cavitation which is dampened or otherwise altered by passing through a fluid. Several sources reported that shaft measurements (AE and vibration) had better signal transmissibility compared to measurements taken from adjacent components such as the wicket gate stem, turbine guide bearing, or draft tube. These sources include CEATI (2009), Escaler, et al (2003), Escaler, et al (2015), and Germann (2016).

While on-board measurements may produce a better signal they are often difficult to acquire due to the rotating shaft which requires a wireless data acquisition system. These systems are typically limited by channel capacity and battery life. However, with advancing wireless technology, the capacity for on-board measurements continues to improve and has been used in much of Reclamation's recent field research (Germann, 2016). The current methodology for cavitation damage detection would require on-board broadband AE measurements during field testing.

Cavitation Erosion

Most of the literature on cavitation erosion is related to either testing material properties or correlating rates of erosion to the cavitation index of the flow or unit operation. Chahine, et al (2014) and Choi, et al (2012) discuss modifying standard test proceedures to study rates erosion and cavitation intensity for various materials. Frizell (2011) observed cavitation pitting on an aluminum sample at a cavitation index of 0.32 in a laboratory test tunnel. Wolff, et al (2005) attempted to correlate AE measurents from the draft tube with erosion rates from inspection observations in a long term study of Grand Coulee's Unit G-24. While Wolff's results did show a correlation with cavitation detection and unit operation, AE results did not correlate with erosion due to noise in the AE signal, lack of consistent unit operation, and errors in metal loss estimates.

For hydro-turbines it is difficult to correlate cavitation damage with a cavitation index because the index along surfaces of the turbine runner is not known and varies with unit operation, not to mention the logistics and uncertainty in estimating material loss due to cavitation. It is intended that this study will provide an alternative to detecting cavitation damage that does not require a correlation with known material loss or cavitation intensity.

Experimental Methods

Pencil Lead Breaks

Bench Testing

Bench testing on an aluminum plate in the dry was performed to compare sensor installation and data analysis methods with Dunegan (1995). Heat-treated annealed aluminum was chosen to be consistent with subsequent cavitation tests in the hydraulics lab. A broadband SE9125-M Acoustic Emission sensor from Score Atlanta Inc. was secured to an aluminum plate using acoustic couplant and vice grips (Figure 1). Data were collected at a sample rate of 1MHz with an Iotech Personal DAQ 3000 data acquisition system. 0.5mm mechanical pencil lead was broken near the surface and at several depths along the outside edge of the plate to produce an acoustic signal recorded by the sensor. Test plate dimensions were 6 x 18 x 1 inches.

This process was repeated on a separate plate with a machined hole to simulate a large cavitation pit (Figure 1). This plate was machined to be mounted into the test section of the high head pump facility. Pencil lead breaks were made near the top surface and at various depths within the hole to simulate the acoustic response from within the test plate similar to a cavitation pit.

Analysis

Figure 2 shows the time series of a signal from a single pencil lead break. The raw signal was divided into a high frequency (HF, greater than 100 kHz) and low frequency band (LF, 20 kHz to 80 kHz). To directly compare with results from the Dunegan study only the “trigger signal” was analyzed in the same manner by visually identifying the initial acoustic wave in the signal as shown in Figure 2 to record the maximum amplitude. Subsequent data consisted of reflections within the plate and were discarded. The ratio of the maximum amplitude of the HF and LF signals was computed and presented verses depth. Each ratio consisted of averaged data from five separate pencil breaks at each depth.

Figure 1 Aluminum plate used for bench testing of pencil lead breaks to produce acoustic waves on the surface and deeper into the material.

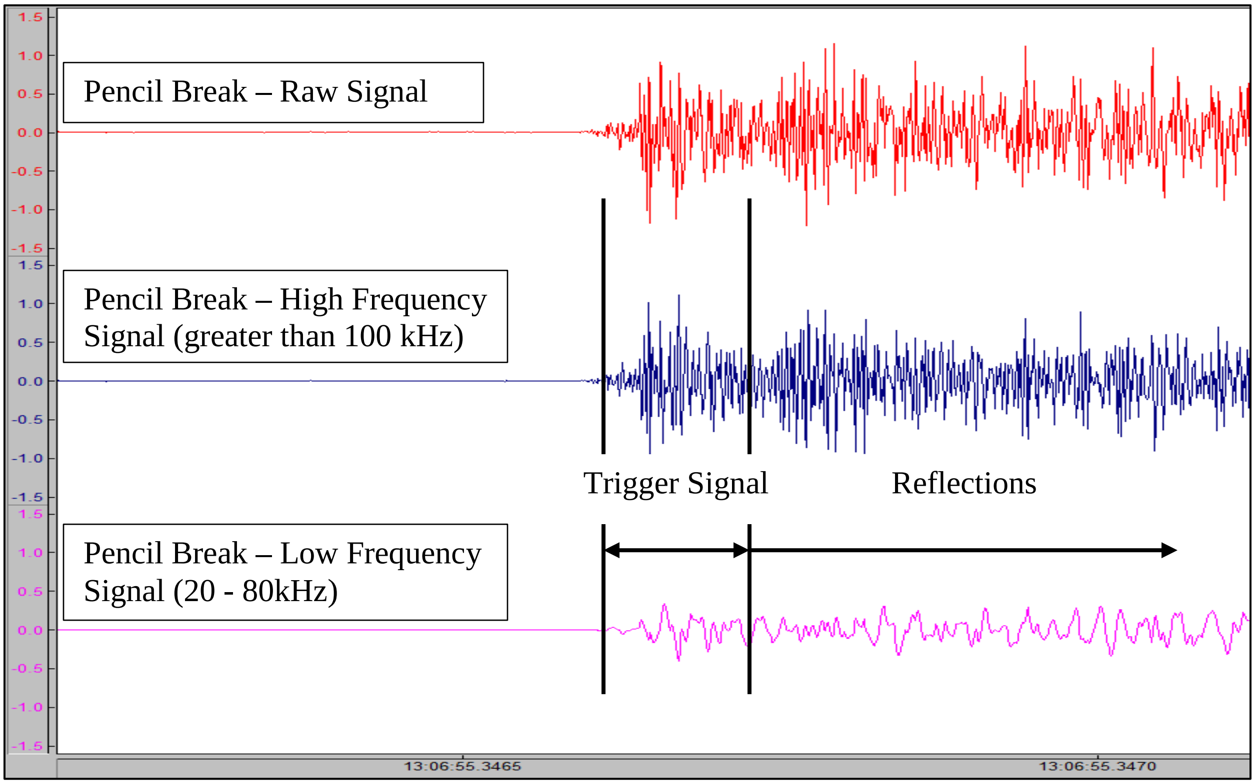


Figure 2 Time series of a pencil lead break test. The raw broadband signal is divided into the high and low frequency bands for analysis.

High-Head Pump Facility

The aluminum plates were installed in a water tunnel test section and exposed to cavitation. The water tunnel was mounted in the High-Head Pump Facility which was capable of producing test velocities greater than 75 ft/s (Figure 3). The test plates were the same geometry and dimensions as the dry bench tests and made of heat-treated annealed aluminum to reduce hardness and expedite cavitation pitting. Cavitation was induced by an offset in the test section. Multiple variations of triangular and circular arc offsets were used to induce cavitation pitting on the test plate (Figure 4). Ultimately, cavitation in the water tunnel did not produce a sufficient amount of erosion damage (Figures 5 and 6) so testing was moved to a submerged jet facility. This “failure” is an example of cavitation in the flow field, which causes noise and vibration, but does not cause erosive damage.

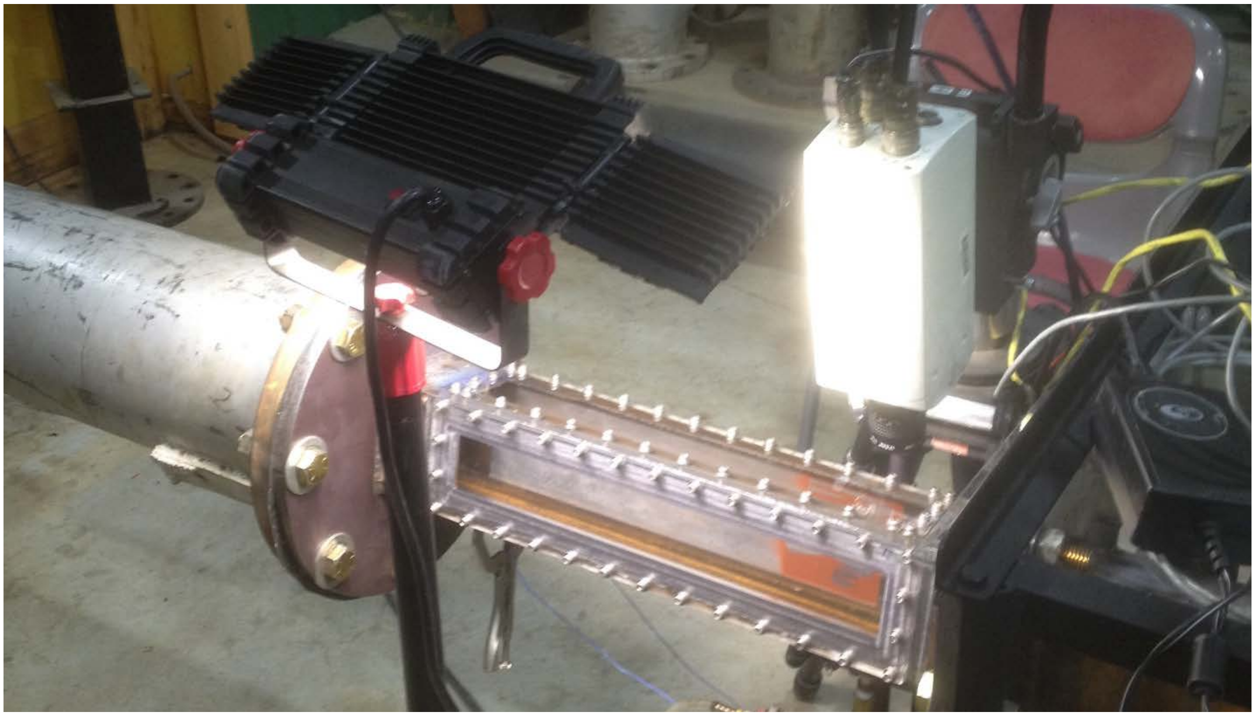


Figure 3 Test section of high head pump facility. Flow is from right to left.

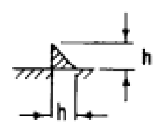
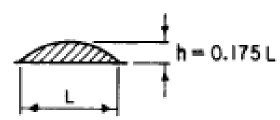
Symbol	Irregularity	Flow dimensions	Data source	a	b	C	
△	Triangles	2	Holl, 1960	0.361	0.196	0.152	
○	Circular arcs	2	Holl, 1960	0.344	0.267	0.041	

Figure 4 Dimensions and shapes of offsets tested in the high head pump test facility to induce cavitation damage on an aluminum test plate (Falvey, 1990). Both triangular and circular arcs were tested in the lab.

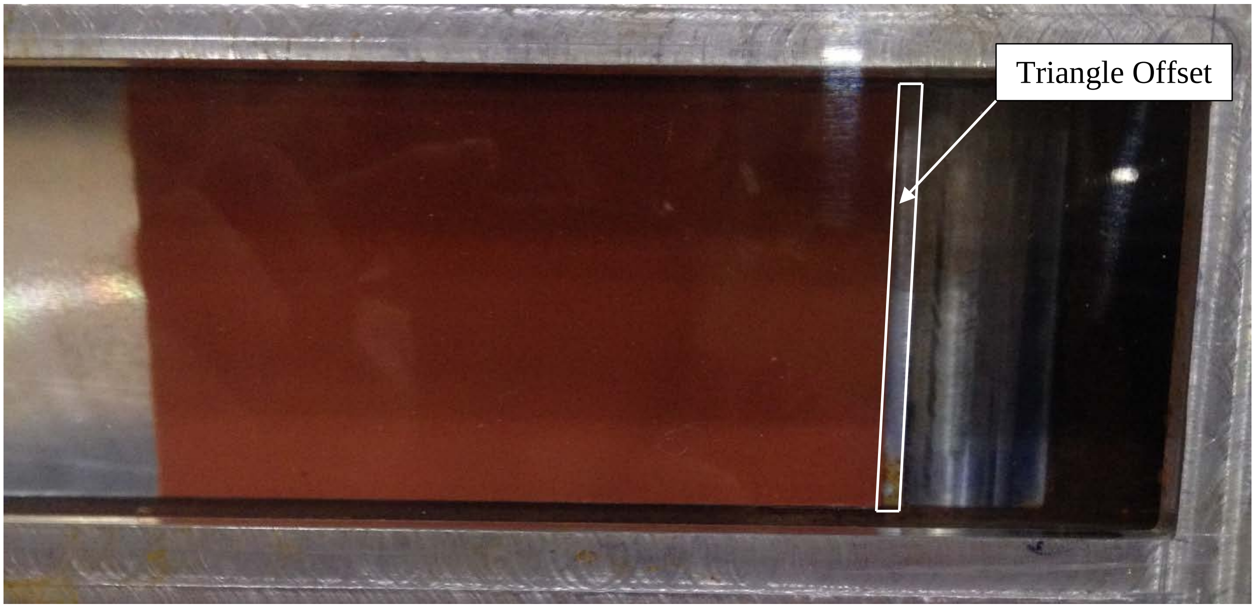


Figure 5 Top view of triangle offset and downstream test plate (painted red) at beginning of test. Flow is from right to left.

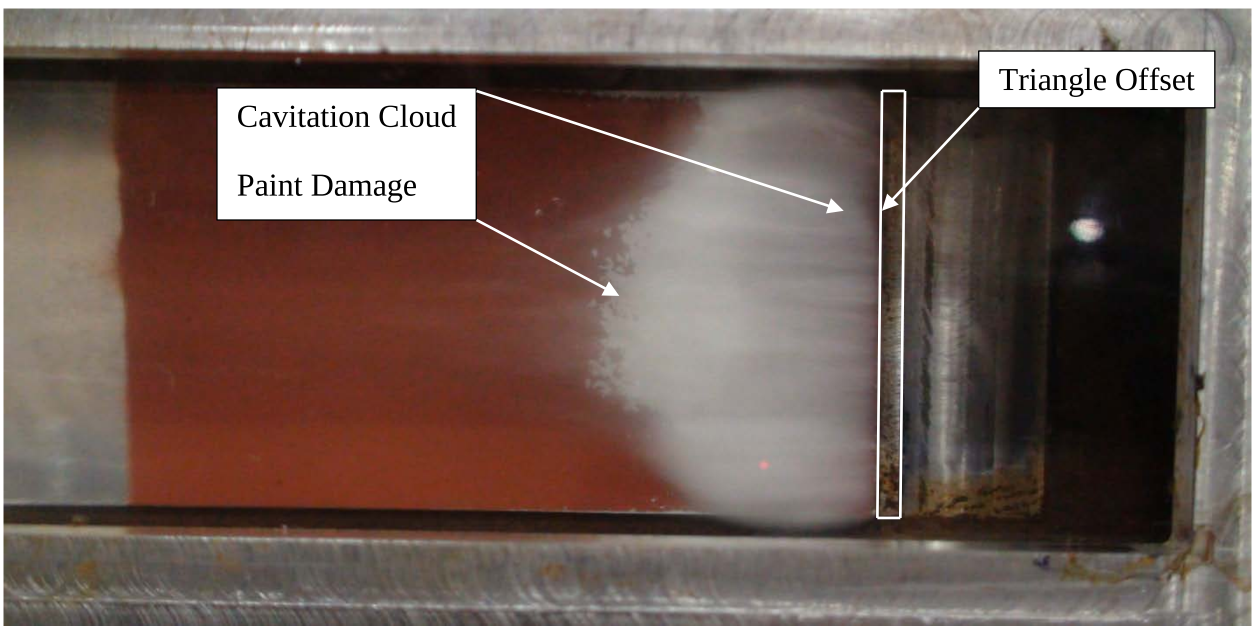


Figure 6 Top view of triangle offset and downstream test plate with visible paint removal after 30 hours of operation. However, depth of cavitation pitting was not significant. Flow is from right to left.

Submerged Jet Facility

Testing

After attempts with the high-head water tunnel were unsuccessful, tests were conducted with a high velocity submerged jet to induce cavitation pitting on the test plates. The test facility included a 120-gallon tank with a clear viewing window, a 10 HP pump with a submerged jet nozzle (0.062-inch diameter), and an aluminum test plate. Figure 7 shows the submerged jet impacting the test plate which includes an aluminum side arm attached to the plate with acoustic couplant and screws. The AE and accelerometer sensors where mounted to the arm in the dry to simulate signal detection on a component that is separate from but connected to the one exposed to cavitation (Figure 8). The test plate was slanted at both 30° and 45° away from the jet to produce impinging flows along the plate boundary in an attempt to increase damage from cavitation pitting and decrease the erosion from pure impact pressures and velocities.

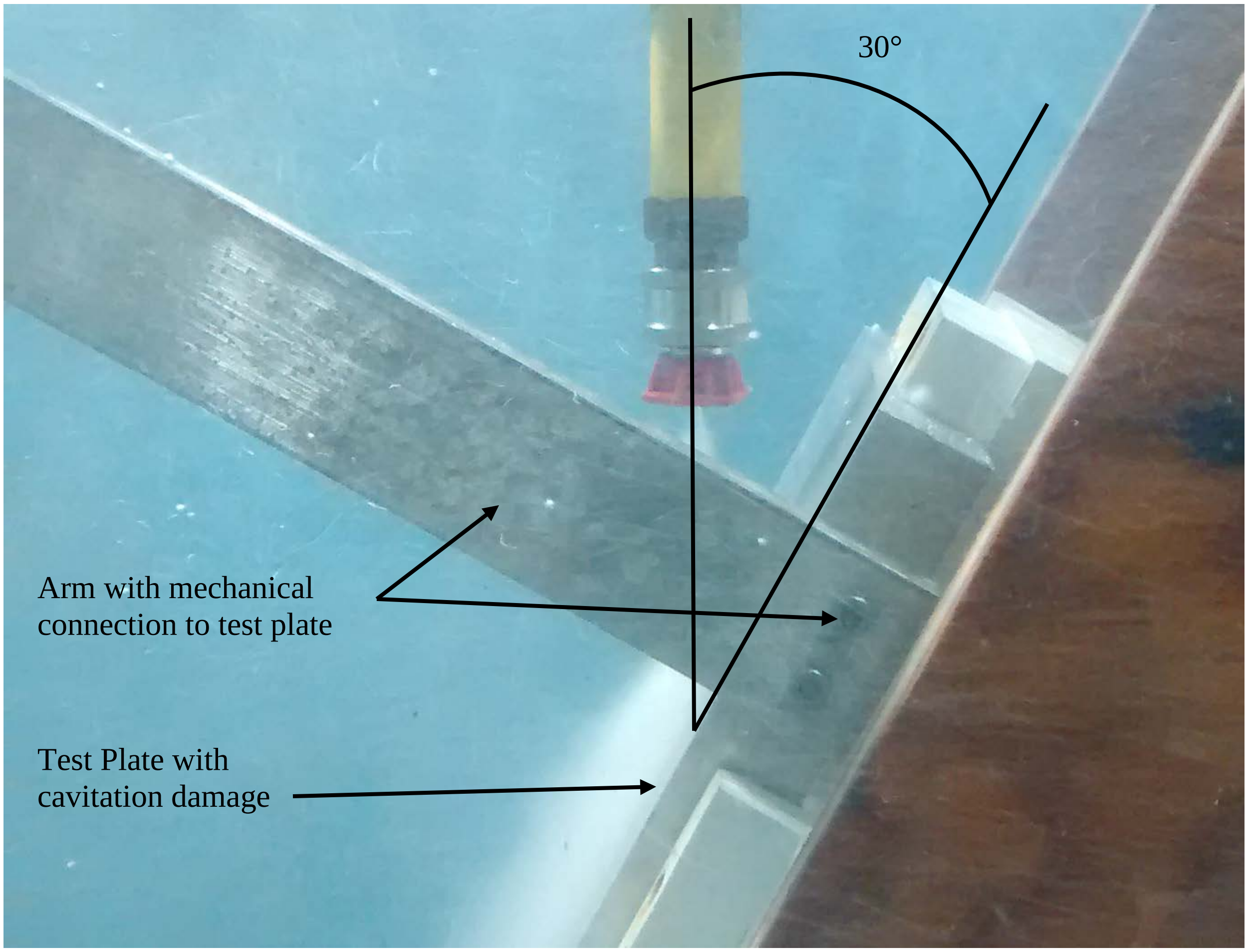


Figure 7 Test setup for inducing cavitation damage on an aluminum plate with a submerged jet.

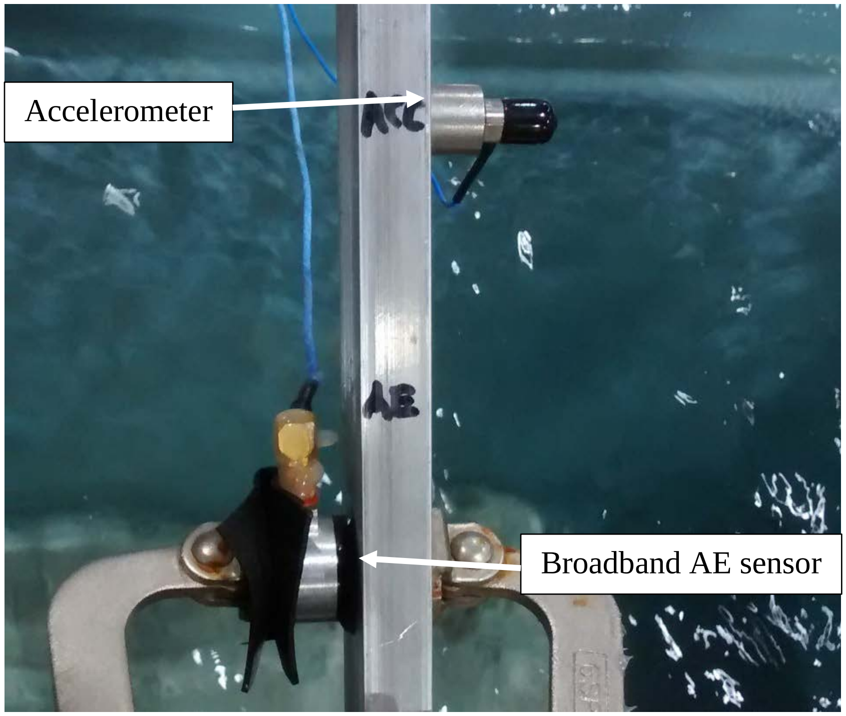


Figure 8 AE and accelerometer sensors mounted out of the water on a metal arm that is mechanically connected to the test plate.

Instrumentation included the broadband AE sensor (same used in bench testing) and a Vibrometrics Model 1000 accelerometer (3Hz – 40kHz). AE data samples were collected at 1Mhz for a duration of 0.95 seconds and accelerometer samples were collected at 80 kHz for 11.89 seconds for a total of almost 1 million samples each test run, which was the upper limit of the data acquisition system. The jet nozzle was set approximately 2-inches above the test plate and operated at a steady discharge for at least 60 minutes to allow cavitation pitting to form in the test plate. The cavitation index for the submerged jet (σ_j) was computed for each test run.

Measurements were made approximately every 10 minutes and included photographs and observation of the damage. Fifteen (15) cavitation pits were formed (Table 1). For pits 9 through 13, maximum depths were approximated using a venier scale (accurate to 0.001 ft) with a pointed needle. To accomplish this, the side arm was detached from the test plate which was then removed from the tank, measured for depth and then reinstalled. For pits 14 and 15, depths were approximated using a micrometer under water without disturbing the test plate and arm connection. Depth measurements are considered only as an indicator of the extent of damage and do not accurately represent the maximum depth due to limitations of the equipment used for such small pit sizes in the metal.

Table 1 Matrix of submerged jet test runs.

TEST MATRIX - SUBMERGED JET				
Pit #	**Test Plate Angle**	**σ_j**	**Time of Exposure**	**Depth Measurement?**
-	*degrees*	-	*minutes*	-
1	45	1.48	60	N
2	45	1.48	60	N
3	45	1.48	60	N
4	45	2.03	60	N
5	45	1.63	60	N
6	30	1.63	90	N
7	30	1.48	60	N
8	30	1.63	120	N
9	30	1.63	50	Y – test plate removal
10	30	1.63	120	Y – test plate removal
11	30	1.64	120	Y – test plate removal
12	30	1.63	120	Y – test plate removal
13	30	1.63	220	Y – test plate removal
14	30	1.63	60	Y – in place
15	30	1.63	90	Y – in place

Analysis

The raw broadband AE signal was divided into a high frequency (HF) and low frequency (LF) signal in the same manner as the dry bench testing (Figures 9 and 10). Ratios of the HF and LF maximum, root-mean-square (RMS), and counts that exceeded a determined threshold (similar to Frizell, 2009) were compared to measured depths of cavitation pitting. For the current testing every HF sample over 7mV and LF sample over 5mV were counted.

Typically, cavitation occurs at much higher frequencies than accelerometers are able to resolve. Due to the low frequency range of the accelerometer (3Hz – 40kHz) there was no value in investigating ratios of different frequency bands as was done with the AE sensor. However, RMS values were recorded to compare signal magnitude with cavitation pitting observations and depths.

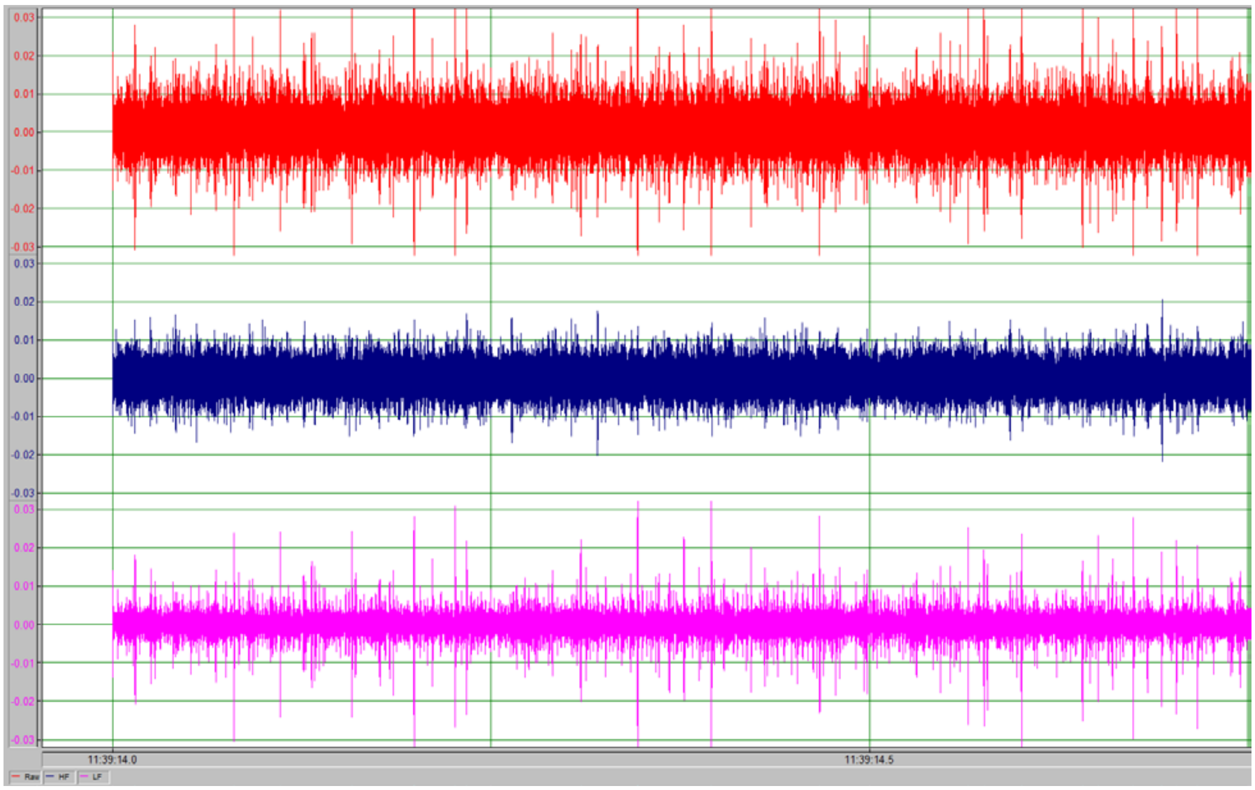


Figure 9 Example time series of the raw broadband AE signal (red), HF signal (blue), and LF signal (pink).

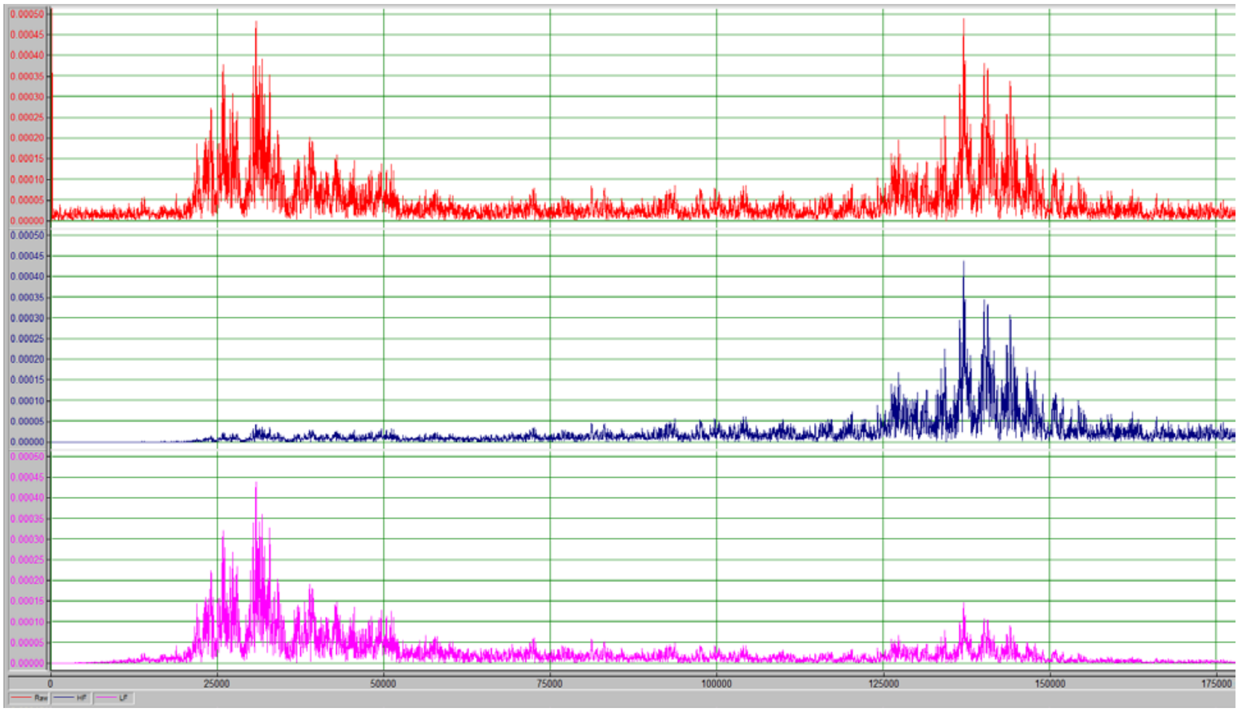


Figure 10 Example frequency spectrum of the raw broadband AE signal (red), HF signal (blue), and LF signal (pink).

Results

Bench Testing – Pencil Lead Breaks

For the standard aluminum plate, pencil lead break tests results compared very well to the original Dunegan study (Figure 11). The rising HF/LF ratio with depth indicates the increase of in-plane high frequency shear waves as the acoustic signal occurred deeper in the plate. Once past 50% depth the trend is mostly symmetrical due to the location of the pencil lead breaks occurring closer to the opposite surface. The difference in absolute values may be due to the plate material (aluminum vs. steel). Since the scope of this study was to identify relative changes with depth rather than absolute values aluminum was chosen to expedite cavitation pitting. To identify absolute values of pitting depth for turbine runners further lab testing would be required using conventional and stainless steel.

Results with the machined plate and hole showed a similar but weaker trend (Figure 12). These tests resulted in a minimum ratio value near the surface and maximum at 50% depth but variability in between. The main reason was likely acoustic reflections from the variable geometry of the machined plate and hole. Reflections were also apparent in the time series data, which revealed a skewed HF and LF trigger signal. Variability in results may have been from difficulty conducting consistent pencil lead breaks at awkward angles in the hole. Results suggest that the depth of cavitation pitting may not be detected by absolute values of the HF/LF ratio, but rather changes in the overall trend of multiple data points over time.

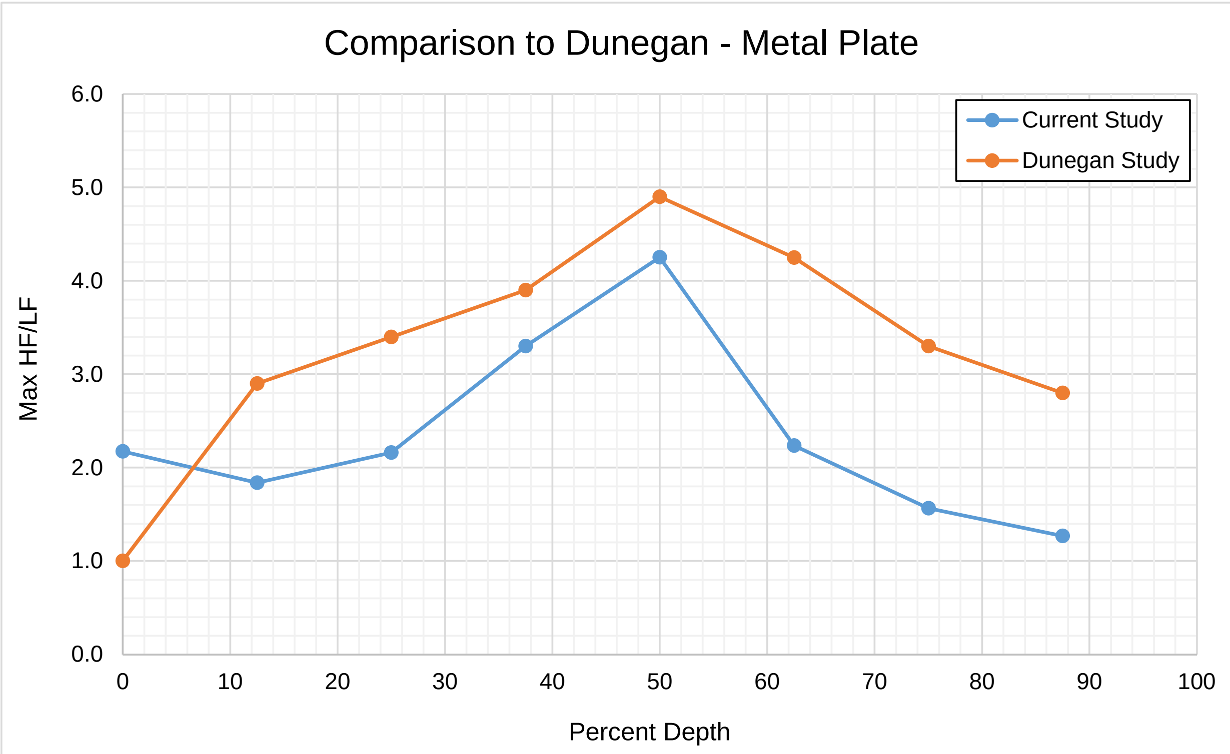


Figure 11 Comparison of pencil lead break results to the original Dunegan study (1995).

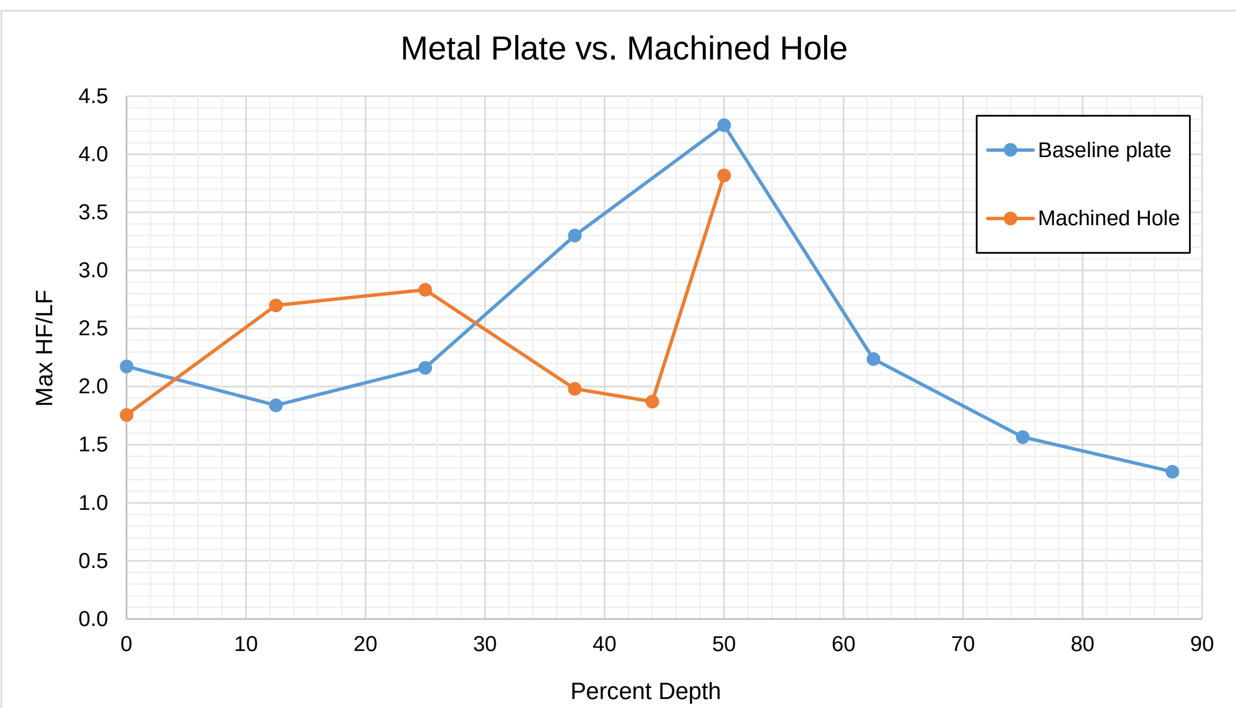


Figure 12 Comparison of pencil lead break results from the baseline plate to one with a machined hole.

Submerged Jet Testing

For the AE sensor, a correlation was found between the AE signal and size and depth of the cavitation pit. Figure 13 shows that the count ratio of the HF/LF signals increased with exposure time to the cavitating jet. Visual observations showed that both the size (length and width) and depth of the pit increased over time. The same trend is shown with estimated depth measurements for test pits 11 and 14 (Figure 14). The AE signal for test pit 15 was weak (possibly due to a disrupted mechanical connection) and produced results that did not show this trend. Results from traditional RMS values of the raw signal as well as the HF/LF ratio of maximum and RMS values did not produce a trend of any kind for #15. The photograph in Figure 15 shows the erosive damage produced during the 15 test runs.

Overall the AE test data showed that the results are very sensitive to the installation of the mechanical connection of the side arm to the test plate. For test pits #9-#13 acoustic couplant was used for the initial side arm installation in the dry but was not reapplied for each test run because it was submerged. Any disruption or modification to these connections between test runs affected the transmissivity of the AE signal and produced random results.

For the accelerometer, no trend was identified in any of the test runs. Figures 16 and 17 show the RMS values of the vibration signal with exposure time and with measured depths for the test pits that did show a correlation in the AE results.

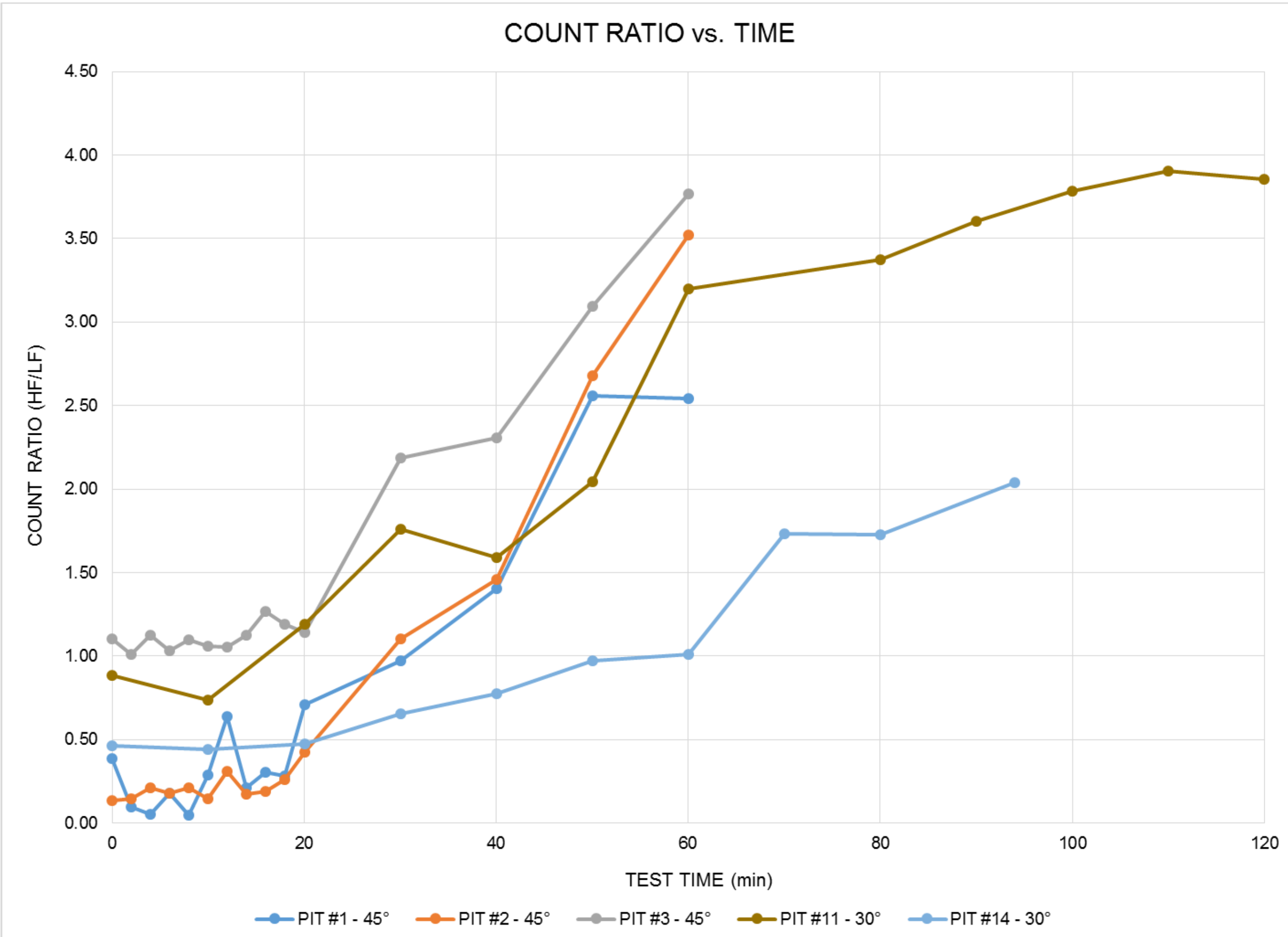


Figure 13 HF/LF ratio of counts over a determined threshold for test runs where the test setup was not disturbed between tests.

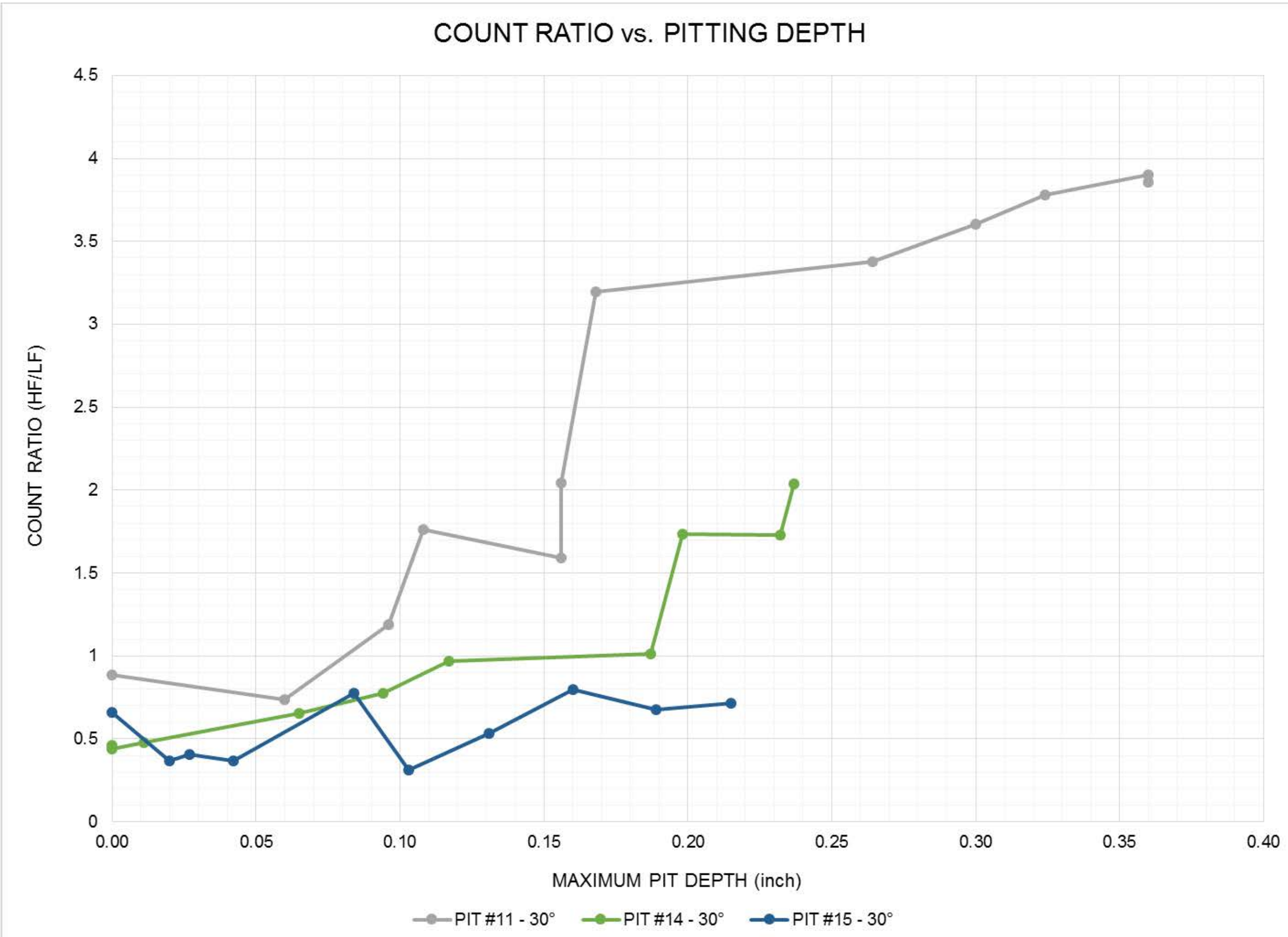


Figure 14 HF/LF ratio of counts over a determined threshold vs. max pitting depth for test runs where the test setup was not disturbed between tests.

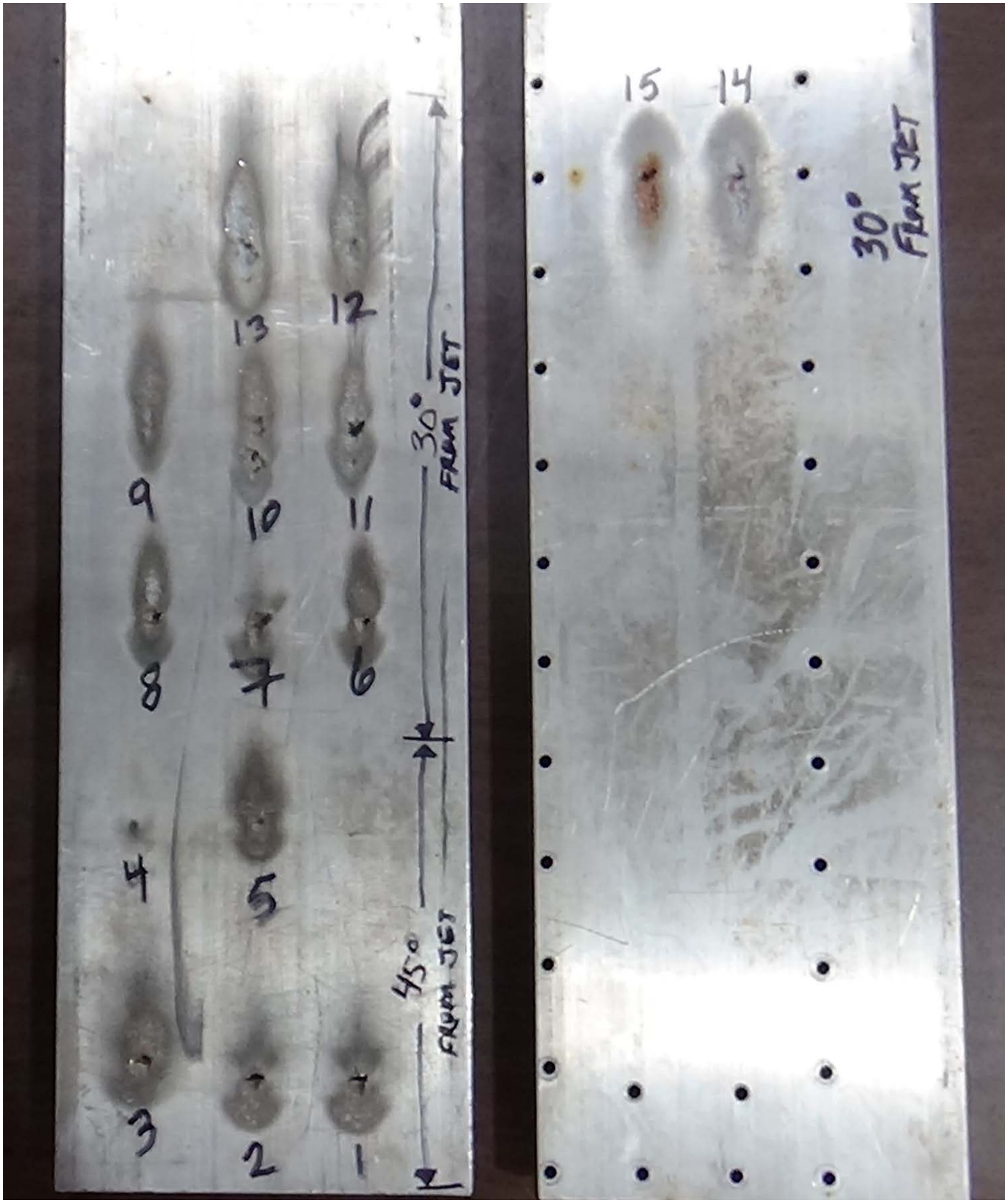


Figure 15 Photo of the 15 test pits that were caused by cavitation erosion from the submerged jet.

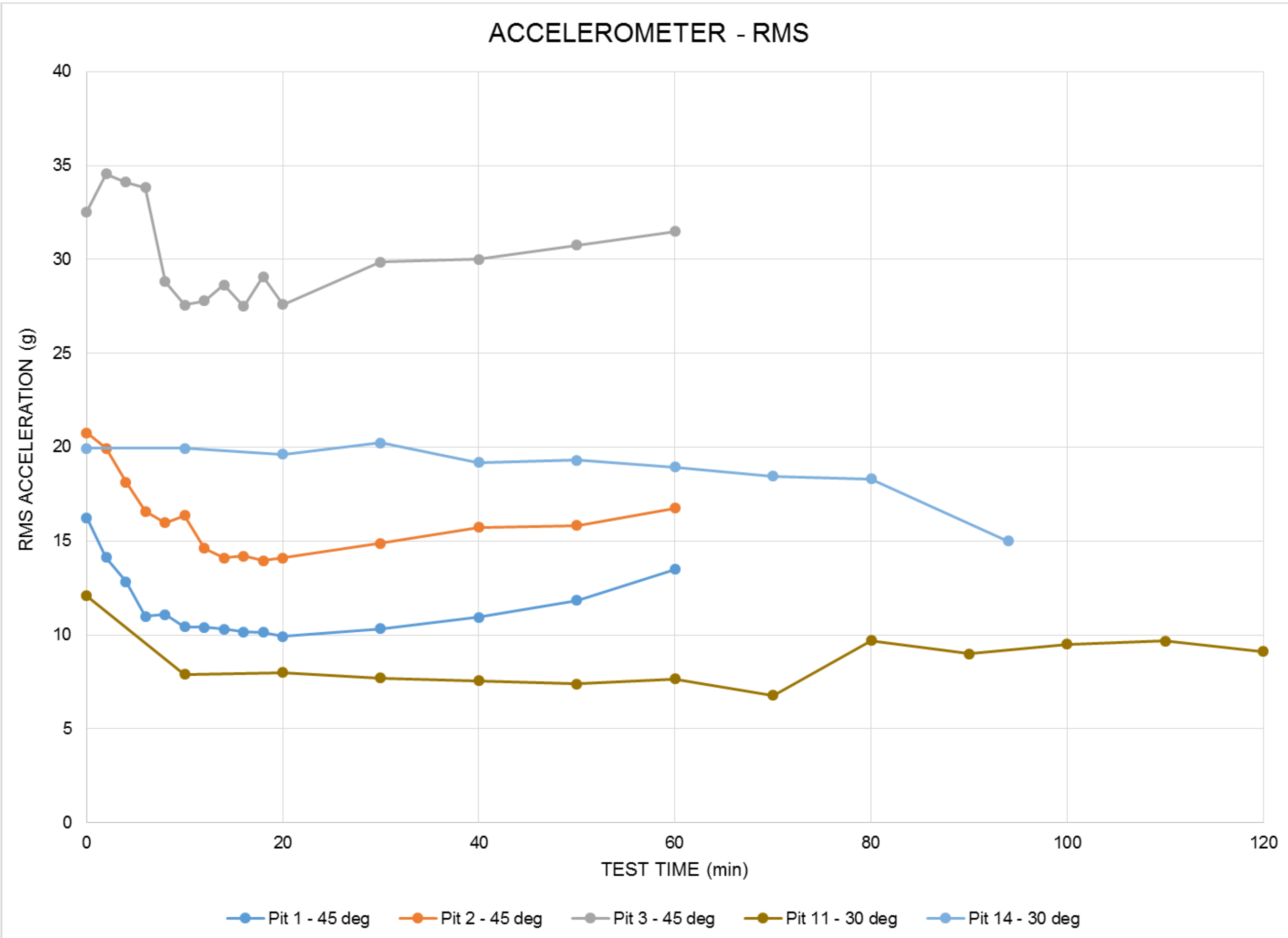


Figure 16 RMS vibration data vs. time of jet exposure for test runs where the test setup was not disturbed between tests.

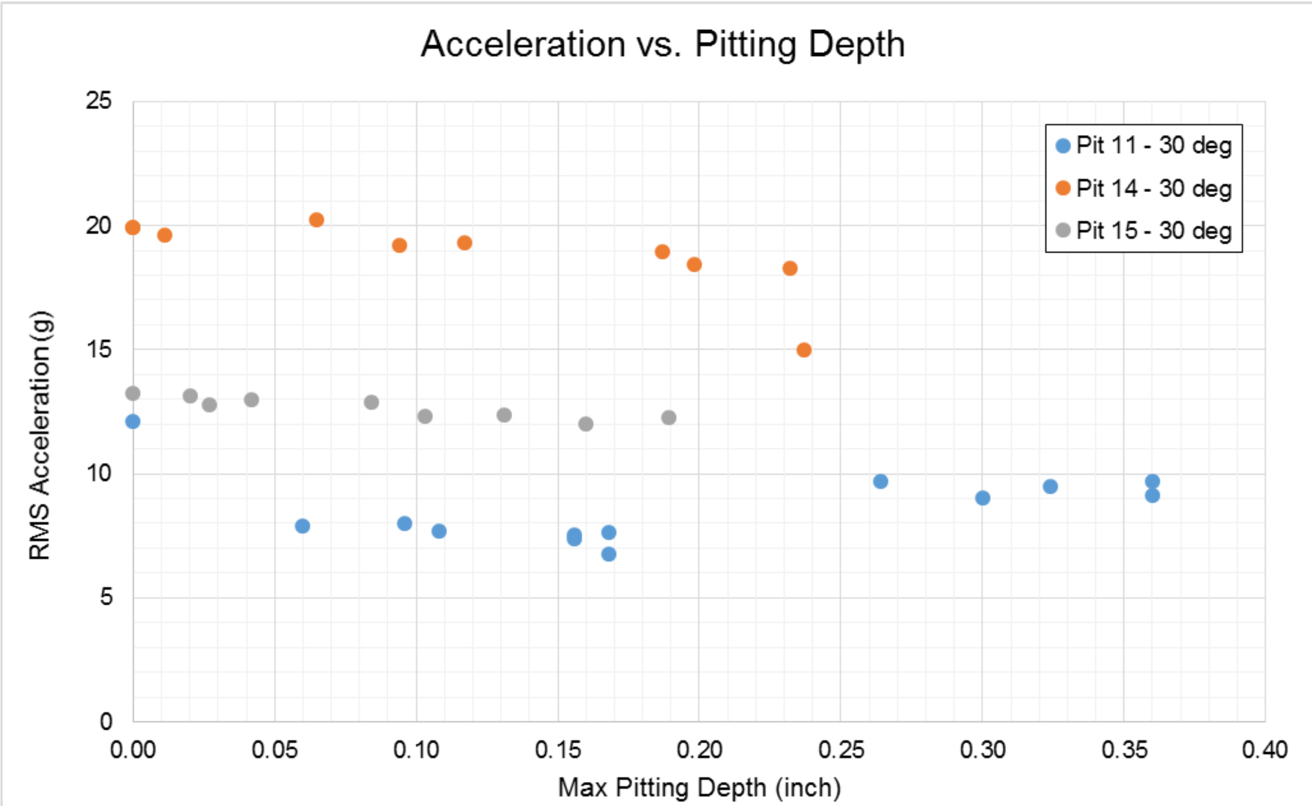


Figure 17 RMS vibration data vs. maximum pit depth for test runs where the test setup was not disturbed between tests.

Discussion

It is promising that the current method of broadband AE measurement and data analysis has shown a trend with erosive cavitation damage consistent with that demonstrated by the pencil lead tests. For the end goal of detecting erosive cavitation in the field with a monitoring system there is still much to learn about the robustness and long-term application of the current method. In this relatively simple laboratory study there were difficulties in producing repeatable results due to several factors. As is generally the case, applying a new method to the field under “real-life” conditions is even more complex. Additional lab testing and initial field testing will be necessary to determine if this method can be successfully implemented for hydro-turbine applications.

During this study, difficulties producing repeatable results were primarily due to the aforementioned disruption of the test setup for each test run. Other potential sources of uncertainty include material erosion from other processes such as jet impact pressures and velocities rather than pure cavitation pitting, short time samples due to limitations in the data acquisition system, inaccuracies in method of maximum depth measurement, and failure to record volume loss from the test plate material. Additional laboratory tests using a different source of cavitation would be helpful in determining the robustness of this approach under different conditions, with different materials (mild and stainless steel) as well as further understanding the limitations of mechanical connections. Experimentation with the rate and duration of the measurement sample should also be performed using a different data acquisition system. Additional lab testing could easily be performed using the venturi cavitation test rig for materials and coatings testing that was recently installed in the hydraulics lab as part of a research project for coatings.

While successful test runs did produce a trend where the HF/LF ratio of threshold counts increased with cavitation damage, they did not produce absolute values that were repeatable. This suggests that an application to the field would require a long-term monitoring system to capture relative changes in the signal over time as the extent of cavitation damage changes. Continuous recording of the signal is not necessary, only repeated measurement samples over time. Due to the difficulties with disruptions with mechanical connections experienced in lab testing may be necessary to develop a permanent shaft installation for field testing. For this to be possible, it is anticipated that TSC’s Mechanical Equipment and Hydropower groups are further developing their wireless onboard data acquisition system for long-term monitoring.

In the meantime, the broadband AE sensor can simply be added to the other shaft-mounted sensors used in ongoing field research. It is anticipated that further testing at J.F. Carr and Fremont Canyon hydropower plants, both of which have had known cavitation issues, will be conducted in 2018 which would provide an opportunity for initial field testing of this method.

Conclusions & Recommendations

- Submerged jet cavitation on an aluminum test plate indicated that there is a correlation between the signal from a broadband AE sensor and depth of cavitation erosion. The ratio of the high frequency signal to low frequency signal (counts over a threshold) increased with erosion depth, which followed the same trend as bench test results with pencil lead breaks.

- Repeatability of test results was very sensitive to the mechanical connection of the side arm component attached to the test plate on which the AE sensor was mounted. Tests where the side arm was removed and then reapplied for subsequent tests produced random results. A consistent trend with the depth of damage was found only when the mechanical connection and sensor installation remained undisturbed throughout the entire test.

- It is recommended that the broadband AE approach be repeated in the laboratory with a different source of cavitation. This could be done on the venturi cavitation test rig for materials and coatings testing that was recently installed in the hydraulics lab as part of a research project for coatings. This would allow the current method to be further tested with a different source of cavitation, on different materials, as well as with a different type of mechanical connection. Doing so may help further identify the robustness and limitations of this approach.

- It is recommended that the current AE approach be applied at a hydropower facility with cavitation erosion issues. J.F. Carr and Fremont Canyon hydropower plants are two potential facilities that could be tested in 2018 in conjunction with ongoing field research of cavitation detection. The sensor will need to be mounted to the turbine shaft for testing and data should be analyzed in the same manner as the current study. It is preferable that the installation allow the sensor to remain in place without disruption for long periods of time to allow changes in cavitation erosion to occur. Test methods and equipment, including limitations and improvements of the wireless data acquisition system, should be discussed and coordinated with TSC's Mechanical Equipment and Hydropower groups who are conducting cavitation field research.

References

ASTM E 976-99. (n.d.). *Standard Guide for Determining the Reproducibility of Acoustic Emission Sensor Response.* West Conshohocken, PA: ASTM.

Avellan, F. (2004). *Introduction to Cavitation in Hydraulic Machinery.* Timisoara, Romania: The 6th International Conferenceon Hydraulic machinery and Hydrodynamics.

Bajic, B. (2002). *Multidimensional Diagnostics of Turbine Cavitation.* San diego, CA: ASME.

CEATI INTERNATIONAL, Inc. (2009). *On-Line Caviation Monitoring.* Montreal, Quebec, Canada: CEATI INTERNATIONAL, Inc.

Chahine, G. L., Franc, J.-P., & Karimi, A. (2014). *Laboratory Testing Methods of Cavitation Erosion.* Dordrecht: Springer Science+Business Media.

Choi, J.-K., Jayaprakash, A., & Clahine, G. L. (March 2012). Scaling of Cavitation Erosion Progression with Cavitation Intensity and Cavitation Source. *Wear*, Vol. 278-279, pp. 53-61.

Dular, M., & Petkovsek, M. (2015). *On the Mechanism of Cavitation Erosion - Coupling High Speed Videos to Damage Patterns.* Slovenia: Laboratory for Water and Turbine Machines, Faculty of Mechanical Engineering, University of Ljubljana.

Dunegan, H. L. (1995). *The Use of Plate Wave Analysis in Acoustic Emission Testing to Detect and Measure Crack Growth in Noisy Environments.*

Dunegan, H. L. (2000). *A New Acoutic Technique for Detecting and Locating Growing Cracks in Complex Structures.*

Dyas, S. J. (2013). *Condition Health Monitoring and its Application to Cavitation Detection/Characterization within HydroPower Turbines.* Golden, CO: Colorado School of Mines, department of Mechanical Engineering.

Escaler, X., Ekanger, J. V., Francke, H. H., Kjeldsen, M., & Nielsen, T. K. (2015). *Detection of Draft Tube Surge and Erosive Blade Cavitation in a Full-Scale Francis Turbine.* San Diego, CA: ASME.

Escaler, X., Farhat, M., Egusquiza, E., & Avellan, F. (2007). *Dynamics and Intensity of Erosive Partial Cavitation.* San Diego, CA: ASME.

Escaler, X., Farhat, M., Equsquiza, E., & Avellan, F. (2003). *Vibration Cavitation Detaction Using Onboard Measurements.*

Falvey, H. T. (1990). *Cavitation in Chutes and Spillways.* Denver, CO: Department of Interior, Bureau of Reclamation.

Faria, M. T., Queiroz, F. R., Medeiros, E. B., & Martinez, C. B. (2013). *Acoustic Emission Tests in the Monitoring of Cavitation Erosion in Hydraulic Turbines.* San Diego, CA: ASME International Mechanical Engineering Congress and Exposition.

Frizell, K. W. (1995). *Cavitation Detection in Hydraulic Turbines.* Denver, CO: Bureau of Reclamation, Report No. PAP-685.

Frizell, K. W. (2009). *Cavitation Potential of the Folsom Auxiliary Spillway Stilling Basin Baffle Blocks.* Denver, CO: Bureau of Reclamation, Report No. HL-2009-06.

Frizell, K. W. (2011). *Cavitation on Stepped Spillways - Lab Studies of Damage Potential.* Denver, CO: Bureau of Reclamation, Report No. PAP-1032.

Frizell, K. W., & Renna, F. (2010). *Laboratory studies on the Cavitation Potential of Stepped Spillways.* Denver, CO: Bureau of Reclamation, Report No. PAP-1028.

Germann, J. (2016). *Cavitation Detection Technology for Optimizing Hydraulic Turbine Operation and Maintenance.* Denver, CO: Department of Interior, Bureau of Reclamation.

Gregg, S. W., Steele, J. P., & Van Bossuyt, D. L. (2017). Machine Learning for Cavitation Detection: A Step Toward Predicting Cavitation Erosion Rates on Hydroturbine Runners. *Hydro Review*, Vol. 36, Issue 3.

Korto Cavitation Services. (2008). *Grand Coulee G-20 Multidimensional Cavitation Test: Comparison of Three Cavitation Monitoring Techniques, Volumes 1 & 2.* Luxembourg: Korto Cavitation Services.

Li, S. (2000). *Cavitation of Hydraulic Machinery.* River Edge, NJ: Imperial College Press.

Rus, T., Dular, M., Sirok, B., Hocecar, M., & Kern, I. (2007). *An Investigation of the Relationship Between Acoustic Emission, Vibration, Noise, and Cavitation Structures on a Kaplan Turbine.* Journal of Fluids Engeineering.

Wolff, P. J., Jones, R., & March, P. (2005). *Evaluation of Results From Acoustic Emissions-Based Cavitation Monitor, Grand Coulee Unit G-24.*

Appendix A – Literature Review

Table A 1. Summary of literature reviewed as part of the current study.

AUTHOR	TITLE	NOTES
General Cavitation Theory and Applications to Hydropower Turbine Runners		
(Falvey, 1990)	USBR Engineering Monograph No. 42 Cavitation in Chutes & Spillways	Characterizes cavitation of irregularities in geometry and predicts location of damage. Used to develop a test design for cavitation damage testing.
(Avellan, 2004)	Introduction to Cavitation in Hydraulic Machinery	Summary of cavitation for Francis Turbine runners including location of develop and erosion, and the respective operating conditions that induce these problems.
(Li, 2000)	Cavitation of Hydraulic Machinery	Text book that covers a variety of topics in cavitation specific to turbines and pumps. Related to this study, it discusses cavitation erosion with material properties, cavitation damage in Francis turbines, and cavitation detection methods. Correlations exist between cavitation erosion rate and the resilience of the material rather than tensile strength or hardness. Detection analysis techniques include time-domain (rms, counts over a threshold, etc.) and frequency-domain (frequency shifts, demodulations, etc.).

AUTHOR	TITLE	NOTES
State of Current Practice updates		
(Germann, 2016)	Cavitation Detection Technology for Optimizing Hydraulic Turbine Operation & Maintenance	John Germann's paper presented at HydroVision 2016. Gives an overview of Reclamation's most recent cavitation detection program from a field-testing perspective.
(CEATI INTERNATIONAL, Inc., 2009)	On-Line Cavitation Monitoring (CEATI Report)	An overview of state-of-the-art cavitation monitoring systems, technologies, and methods as of January 2009. Acknowledges the challenge of differentiating between erosive and non-erosive cavitation in turbines. Supports the hypothesis that "on-board" measurements have the best signal transmissivity. Highlights the importance of further development of cavitation monitoring methods that can identify operating conditions with cavitation damage.
(Frizell K. W., 1995)	Cavitation Detection in Hydraulic Turbines	PAP-685, paper presented at Reclamation's O&M Workshop in Boulder City, NV May 1995. Overview of Reclamation's Cavitation Research Program as of 1995. Discusses use of modulation techniques to identify cavitation on rotating parts. Identifies a disconnect in the acoustic signal when the sensor is not mounted directly on the cavitating component. Mentions that noise of the unit makes it difficult to differentiate cavitation in the flow field from damaging cavitation on the surface. Suggests mounting instrumentation on the rotating equipment but at the time there was no telemetry technology capable of transmitting a high-frequency signal.

AUTHOR	TITLE	NOTES
Acoustic Emission Measurements Related to Mechanical Testing and Cavitation		
(ASTM E 976-99)	Standard Guide for Determining the Reproducibility of Acoustic Emission Sensor Response	Standard for pencil break testing used to determine reproducibility of AE sensor response. Used to develop dry test design for comparing low frequency flexural waves and high frequency shear waves at various depths in metallic material.
(Dunegan, 1995)	The Use of Plate Wave Analysis in Acoustic Emission Testing to Detect & Measure Crack Growth in Noisy Environments	Study used pencil break tests on a steel bar to compare the ratio of Shear Waves (High Frequency: greater than 100kHz) to Flexural Waves (Low Frequency: 20kHz-80kHz). Results showed that a low ratio (flexural waves) dominate near the surface and the ratio increases (shear waves) with depth in the bar. The current study tests the same theory for cavitation erosion; using the ratio of HF to LF waves to determine if cavitation pitting can be identified.
(Dunegan, 2000)	A New Acoustic Emission Technique for Detecting and Locating Growing Cracks in Complex Structures	Further explains the detection of Shear Waves (HF) and Flexural Waves (LF) and how they can be used to differentiate noise from actual crack growth. The same approach may apply to differentiate noise (impact, friction, etc.) from actual cavitation erosion. See explanation in Executive Summary and Literature Review sections.
(Faria, Queiroz, Medeiros, & Martinez, 2013)	Acoustic Emission Tests in the Monitoring of Cavitation Erosion in Hydraulic Turbines	Study using an AE sensor on a lab model Francis turbine with no damage and then repeated with a hole in one blade to simulate cavitation damage. Signals from both tests were compared using RMS. Results showed higher RMS values from the turbine with a hole indicating detecting a damaged blade is possible in a model turbine. Interesting that they didn't report any modulation techniques……

AUTHOR	TITLE	NOTES
(Wolff, Jones, & March, 2005)	Evaluation of Results from Acoustic Emissions-Based Cavitation Monitor, Grand Coulee Unit G-24	Monitored AE signals (RMS, sensor located on draft tube) of two separate time intervals which were several months each. Showed that cavitation increased at lower power outputs and efficiencies. They were not able to successfully correlate signal output to rate of metal loss as hoped due to difficulties in consistent operation, noise in AE signal, and error in metal loss estimates.
(Frizell K. W., 2009)	Cavitation Potential of the Folsom Auxiliary Spillway Stilling Basin Baffle Blocks	Describes the use of a broadband AE sensor to divide the signal into high frequency and low frequency ranges for analysis. To determine incipient and ensuing levels of cavitation, RMS and counts above a certain threshold were mainly used. No attempt was made to predict cavitation levels required for damage.
(Frizell & Renna, 2010)	Laboratory Studies on the Cavitation Potential of Stepped Spillways	Reclamation Report PAP-1028. Studied cavitation of a sectional model of stepped spillway, using the LAPC to induce cavitation. Used the AE sensor in frequency bands sensitive to both flexural and shear waves. Compared counts of AE measurements over a threshold (100mV) during a 30s period to the cavitation index (determined in post-processing of the signal). Identified critical cavitation values at changes in slope. No discussion on cavitation damage.
Cavitation Detection with Multiple Methods, Instrumentation, and Measurement Locations		
(Rus, Dular, Sirok, Hocecar, & Kern, 2007)	An Investigation of the Relationship Between Acoustic Emission, Vibration, Noise, and Cavitation Structure on a Kaplan Turbine	Study conducted on a two-blade Kaplan turbine that correlated visual images of the cavitation structure to AE and vibration measurements. While these correlations were successful and useful, they do not account for the differences in damaging and nondamaging cavitation.

AUTHOR	TITLE	NOTES
(Escaler, Ekanger, Francke, Kjeldsen, & Nielsen, 2015)	Detection of Draft Tube Surge and Erosive Blade Cavitation in a Full-Scale Francis Turbine	Pressure, vibration, and AE measurements made on a prototype Francis runner. Again, identified that a mechanical connection gives the best signal transmissibility and poor transmissibility through a fluid. Focused on the frequency band of 15-20 kHz for accelerometer measurements and 40-45 kHz for AE. No clear identification between damaging and nondamaging cavitation was found.
(Bajic, 2002)	Multidimensional Diagnostics of Turbine Cavitation	Describes a test method that utilizes AE sensor mounted on every wicket gate stem. Data from each wicket gate sensor is used to provide detailed information cavitation activity at multiple locations of the runner as it revolves.
(Escaler, Farhat, Egusquiza, & Avellan, 2007)	Dynamics and Intensity of Erosive Partial Cavitation	Laboratory study looking at sheet and cloud cavitation on a hydrofoil in a water tunnel. For this test sheet cavitation was non-damaging and cloud cavitation was damaging. Similar test plan to the current study, however they were focused only on vibration measurements and comparing modulating frequencies of the two types of cavitation. They found erosion rates of stainless steel. They compared Strouhal Numbers of results based on the maximum frequencies from the demodulation analysis.
(Dyas, 2013)	Condition Health Monitoring & It's Application to Cavitation Detection/Characterization within Hydropower Turbines	Masters Thesis which used the same High Pressure Cavitation Test Facility used in the current study. Results intended for a long term machine monitoring approach

AUTHOR	TITLE	NOTES
(Korto Cavitation Services, 2008)	Grand Coulee G-20 Multidimensional Cavitation Test, Volume 1 & 2	Documents the application of the Multidimensional method from Bajic (2002) applied to unit G-20 at Grand Coulee. Evidence of cavitation damage at higher power outputs was found. However, firm conclusions could not be made due to adverse operating conditions during testing.
(Gregg, Steele, & Van Bossuyt, 2017)	Machine Learning for Cavitation Detection: A Step Toward Predicting Cavitation Erosion Rates on Hydroturbine Runners	Master Thesis. Used new algorithms to analyze proximity probe data to identify cavitation by calibrating data based on a full ramp down of the unit. Based on this calibration ranges of operation prone to cavitation are detected. No explanation of how this will be used to predict erosion rates is given.
(Escaler, Farhat, Equsquiza, & Avellan, 2003)	Vibration Cavitation Detection using Onboard Measurements	Compared signals from an onboard accelerometer (shaft-mounted) to other accelerometers & an AE sensor mounted on the turbine guide bearing and wicket gate stem. Concluded that the onboard sensor provided the most clear & reliable data which was analogous to higher frequency data from fixed sensors.
Cavitation and Material Erosion		
(Frizell K. W., 2011)	Cavitation on Stepped Spillways – Lab Studies of Damage Potential	Report No. PAP-1032. Used the High Head pump facility to induce cavitation on a sectional model of spillway steps made of annealed aluminum. Compared the damage on the aluminum at 1 hour intervals with a reference velocity of 22 m/s ($\sigma \approx 0.32$). Pits were not very deep and appeared elongated in the flow direction. They appeared for a mild sloped step (1V:2.48H) but not at a steep slope (1V:0.4025H)
(Dular & Petkovsek, 2015)	On the Mechanism of Cavitation Erosion –	

AUTHOR	TITLE	NOTES
	Coupling high speed videos to damage patterns	
(Chahine, Franc, & Karimi, 2014)	Laboratory Testing Methods of Cavitation Erosion	Describes 3 different test methods for inducing cavitation damage on material specimens to quantify erosion rates. Two of these methods (cavitating jet and venturi cavitation tunnel) are currently being applied in Reclamations Labs for material and coatings testing. AE measurements should be taken during future testing of the venturi cavitation tunnel to determine if signal changes correlate with erosion rates.
(Choi, Jayaprakash, & Clahine, March 2012)	Scaling of Cavitation Erosion Progression with Cavitation Intensity and Cavitation Source	A study that modifies the ASTM-G32 and G134 test methods for small material samples. Correlates cavitation intensity to material loss. No AE measurements were taken.

Data Sets that Support the Final Report

If there are any data sets with your research, please note:

- U:\Active Files\Research\Active Projects\Cavitation Detection
- Josh Mortensen, jmortensen@usbr.gov, 303-445-2156:
- DasyLab Test run files, spreadsheets, word doc report
- Keywords: cavitation damage, erosion, acoustic emission, cavitation detection
- Approximate total size of all files: 1.53 GB