Structural Integrity Associates, Inc.
1951 Pine Hall Road
Suite 100
State College, PA 16801

Phase I Final Report for DE-SC0011852: Development of a Versatile Ultrasonic Internal Pipe/Vessel Component Monitor for In-service Inspection of Nuclear Reactor Components

Principal Investigator: Clifford T. Searfass, Ph.D.

Department of Energy SBIR Program, FY 2014 Phase 1 Release 2

Topic 19: Advanced Technologies for Nuclear Energy
Subtask A: Advanced Sensors and Instrumentation

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EXECUTIVE SUMMARY

As a Phase I effort, Structural Integrity Associates, Inc. (SI) proposed the development and feasibility demonstration of a versatile ultrasonic technique for characterizing displacement, vibration, and cavitation of and in critical internal piping and vessel components, such as valve internals and jet pumps. The primary advantages of the proposed technique over existing technologies are as follows:

- Actual component displacement can be measured with very high accuracy. Displacement amplitude during vibration is a critical number for accurately determining the stress levels present within a component.
- Cavitation can be detected and characterized using an ultrasonic approach. Early detection will aid in minimizing long-term damage to components.
- The proposed approach can be used to remotely verify and monitor the position of valve internals.

The Phase I effort had the following objectives and corresponding results:

Objective 1:

Obtain information on component internal location, vibration, and cavitation formation often observed in real industry situations. Use this information to design and build experimental mockups.

Result:

Through consultation with SI's internal industry experts and with several of our nuclear clients, it was determined that a commercially viable system would have to measure displacements as small as 0.025 mm, vibration frequencies in the range of 0-300 Hz, and be able to operate continuously in environments up to 550 oF. To help determine the feasibility of achieving these results, SI built two mock-ups; one specifically for evaluating frequency and displacement sensitivity and one that was meant to simulate an actual plant component and that could also be used to test vibration and cavitation sensitivity.

Objective 2:

Develop prototype user interface in LabVIEW for monitoring and categorizing component location, vibration, and cavitation.

Result:

The prototype LabVIEW user interface for the developed monitoring system was broken down into three simple modules for system setup and data acquisition: A-Scan Monitor, *Vibration Monitor*, and *Cavitation Monitor*. The *A-Scan Monitor* module displays an A-scan ultrasonic waveform and basic ultrasonic data acquisition parameters that can be adjusted to achieve the optimal parameters for the specific monitoring setup. Once data acquisition parameters are set, the user may proceed to *Vibration Monitor* or *Cavitation Monitor*. *Vibration Monitor* displays the ultrasonic A-scan, time-domain vibration waveform, and frequency-domain vibration waveform.

Upon entering a few additional vibration-specific parameters, the user may start the acquisition, which will continuously refresh the time- and frequency-domain vibration waveforms and log/display the vibration amplitudes and frequencies to the user. *Cavitation Monitor* logs and displays a monitoring time history chart of the ultrasonic time-domain and frequency-domain signal. Using these displays, the user can easily visualize the disturbances in the time- and frequency-domain ultrasonic signals that are indicative of incipient cavitation.

Objective 3:

Complete feasibility testing to demonstrate the ability to monitor vibration, internal component location, and cavitation formation.

Result:

Using the two mock-ups developed for the Phase I effort, SI successfully detected target displacements as small as 0.020-mm and vibrations in the range of 17-Hz to 1000-Hz, far exceeding the 300-Hz goal. The limitation on the lower end of the vibration spectrum (17-Hz) was a limitation on the equipment used to vibrate the target. Furthermore, an ultrasonic processor was used to generate cavitation in the water filled mock-ups and SI successfully demonstrated the ability detect the cavitation using the same ultrasonic sensors used for measuring displacement and vibration. SI feels that these results represent a significant accomplishment and clearly demonstrate the potential of the developed ultrasonic vibration and cavitation monitoring system.

Objective 4:

Acquire and test commercially available probes, couplants, and epoxies for performance at elevated temperatures for extended periods of time.

Result:

SI acquired high-temperature radiation-resistant ultrasonic transducers from two different manufacturers, as well as two different materials for coupling the sensors to the component. The probes were shown to survive at temperatures up to 300-F for several weeks. The same manufacturers also have probes that can operate up to 550-F; however, due to the long lead times on these higher temperature probes, the project team was forced to go with the 300-F probes. Several of the high-temperature ultrasonic couplants and epoxies tested were also shown to survive well at these temperatures.

SUMMARY FOR THE DEPARTMENT OF ENERGY

The stated goal of this work was to develop a versatile system which could accurately measure vessel and valve internal vibrations and cavitation formation under in-service conditions in nuclear power plants, ultrasonically. The developed technology will benefit the nuclear power generation industry by allowing plant operators to monitor valve and vessel internals during operation. This will help reduce planned outages and plant component failures. During the course of this work, Structural Integrity Associates, Inc. gathered information from industry experts that target vibration amplitudes to be detected should be in the range of 0.001-in to 0.005-in (0.025-mm to 0.127-mm) and target vibration frequency ranges which should be detected were found to be between 0-Hz and 300-Hz. During the performed work, an ultrasonic measuring system was developed which utilized ultrasonic pulse-echo time-of-flight measurements to measure vibration frequency and amplitude. The developed system has been shown to be able to measure vibration amplitudes as low as 0.0008-in (0.020-mm) with vibration frequencies in the range of 17-Hz to 1000-Hz. Therefore, the developed system was able to meet the industry needs for vibration measurement. The developed ultrasonic system was also to be able to measure cavitation formation by monitoring the received ultrasonic time- and frequency-domain signals. This work also demonstrated the survivability of commercially available probes at temperatures up to 300-F for several weeks.

1. INTRODUCTION

Turbulent flow within fluid power systems results in several side effects that are detrimental to component lifetime. The presence of turbulent flow is known to cause unwanted component vibration, such as with jet pumps and valve internals, and is also the cause for generation of cavitation within the fluid. In the case of jet pumps, vessel internals are subject to unwanted turbulent flow-induced vibrations which cause additional wear on the components. Another source of degradation is cavitation which is the formation of vapor cavities in liquids and is the product of forces generated from turbulent flow acting upon the liquid. These cavities are formed when pressure on the liquid falls below the liquid vapor pressure. These vapor voids continue to flow with the rest of the liquid, and upon encountering higher pressure regions, the cavities collapse in upon themselves violently. The violent collapse of the cavities in turn generates high pressure shockwaves. The presence of such shockwaves is known to be able to ablate pipe/vessel internals and as such can lower component lifetime as it is major contributor to degradation mechanisms such as flow accelerated corrosion (FAC).

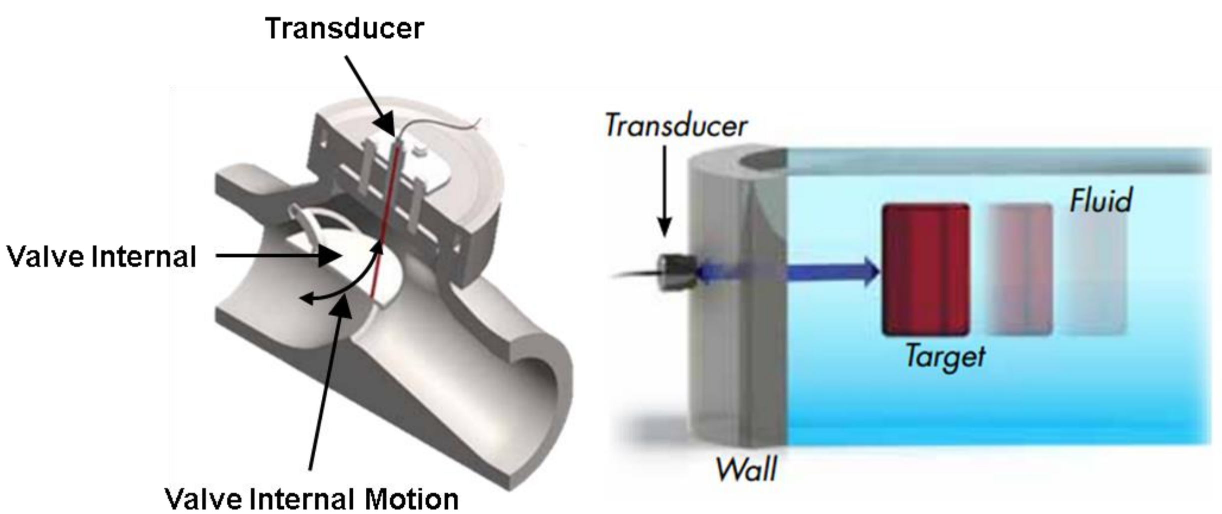

Figure 1. Envisioned concept of ultrasonic location, cavitation, and vibration monitoring system.

Phenomena like cavitation and component vibration are particularly apparent in and around valves and jet pumps. These mechanisms are particularly troublesome in nuclear plant service water systems as they may occur in areas where access is limited, such as in the containment region of a nuclear power plant. The work performed throughout the course of this Phase I was concerned with the development of an ultrasonic interrogation system which will be capable of monitoring the location and vibration of multiple plant system components, such as jet pump and valve internals, as well as detecting cavitation formation. The objective was to develop a system which will operate by launching an ultrasonic wave into the plant component, such as a reactor vessel or system piping, and the reflected ultrasonic wave will give information on target location and vibration, as well as detect any cavitation. The Phase I work involved the design and testing of the system to make it as multi-purpose as possible and test the feasibility for a signal to be able to detect internal component location, vibration, and cavitation formation within fluid power systems. Figure 1 shows an illustration of the envisioned concept of the ultrasonic location, cavitation, and vibration monitoring system. Additionally, work focused on testing probes capable of performing in-service inspection, and thus the probes were designed for high temperature radiation environments. The scope of this Phase I was only concerned with testing the probes for extended high temperature functionality.

1.1. Phase I Technical Objectives

The objective of the project was to develop a diverse system which is capable of in-service monitoring multiple phenomena associated with internal pipe and vessel components. Two of the parameters targeted to be monitored were internal component location and vibration. Measuring these parameters will find utility in applications for measuring location of valve location (height) and vibration, as well vibrations of jet pumps. The other targeted parameter for the system to simultaneously monitor was the generation of cavitation in and around these internals. The specific goals in order to achieve this can be outlined as follows:

- Evaluate commercially available high temperature and radiation resistant probes offered from companies such as Imasonic and Applus RTD.
    - Will involve quantifying probes signal strength to determine their ability to penetrate through pipe and vessel walls.
    - Establish the probes resistance to long term temperature exposure to gauge their feasibility as a solution for ultrasonic in-line inspection.
- Evaluate commercially available couplants/epoxies such as Sonotech 1100 and Duralco’s 4703.
- Establish their ability to maintain good adhesion of probe to metallic structures during constant exposure to elevated temperatures
- Establish reactivity of couplant/epoxies to sensor housing.
- Develop software in software packages such as LabVIEW, MATLAB, etc. as a prototype for in-service component monitoring.
    - Will require development of experimental mockups to simulate jet pump and valve plant components with simulated component vibration and cavitation development.
    - Simulate vibration with electrical/pneumatic actuators. Develop algorithm to track signal TOF in order to establish part vibration.
    - Cavitation can be simulated with ultrasonic cavitators. Develop algorithm to monitor signal in order to detect cavitation.

These technical objectives were broken down into five tasks.

1.2. Phase I Work Tasks

Task 1: Obtain information on component internal location, vibration, and cavitation formation often observed in real industry situations from Structural Integrity Associates’ industrial contacts. Use this information to design and build experimental mockups.

Task 2: Develop prototype user interface in LabVIEW for monitoring and categorizing component location, vibration, and cavitation.

Task 3: Initial tests of what probe frequencies and sensitivities will be necessary to monitor vibration, internal component location, and cavitation formation.

Task 4: Acquire and test commercially available probes for performance at elevated temperatures for extended periods of time. Obtain high temperature couplants/epoxies and test their ability to maintain stable contact between probe and structure, as well as test their ability to couple ultrasound into components.

Task 5: Project Management.

2. PROJECT RESULTS AND FINDINGS

Task 1: Obtain information on component internal location, vibration, and cavitation formation often observed in real industry situations from Structural Integrity Associates' industrial contacts. Use this information to design and build experimental mockups.

Information regarding pipe internal vibration frequency and amplitudes was obtained by Structural Integrity Associates industrial contacts. The information obtained revealed that target vibration amplitudes to be detected should be in the range of 0.001-in to 0.005-in (0.025-mm to 0.127-mm). Target vibration frequency ranges which should be detected were found to be a range from 0-Hz to 300-Hz.

Task 2: Develop prototype user interface in LabVIEW for monitoring and categorizing component location, vibration, and cavitation.

Task 2.1: Development of Software Interface

The first task of this work was concerned with developing a software interface for displaying measured vibrations and cavitation, which is referred to subsequently as the Ultrasonic Vibration Monitoring System (UVMS). This was carried using the LabVIEW software package. The software was interfaced with an Ultratek EUT3160M16 16-channel ultrasonic pulser-receiver. The Ultratek unit is capable of both pulse excitation and tone burst excitations.

Figure 2 shows a screen shot image of the developed interface. The screen shot shows the portion of the software where transducer excitation and reception options can be controlled. Options such as the excitation voltage, pulse width, data recording start time and length, band pass filter options, sample rate, gain, offset, choice of tone burst or pulse excitation types, and investigation type (pulse-echo or through transmission) can be controlled on this screen. In the screen shot, near the top of the image several tabs can be seen with the labels "Vibration Monitor" and "Cavitation Monitor". By selecting one of these tabs, the user can perform vibration monitoring or cavitation monitoring with the signal shown on the A-scan tab. It should be noted that the raw data of the results displayed in each tab can be exported external analysis of the data is desired.

Figure 3 shows an image of developed vibration monitoring software which is accessed by selecting the “Vibration Monitor” tab. Here, the A-scan is displayed near the top right of the screen. In order to track the vibration, the user must gate the echo corresponding the component they wish to monitor for vibration. This is performed by selecting the green and red cursors and arranging them accordingly on the time axis. The green cursor is set to amplitude to reduce noise in the measurement. Once the gates are set, the user then selects start. The software then begins to interpret the data it is receiving from reflector.

As the program runs, the location of the reflector is tracked by monitoring the arrival time of the peak amplitude of the echo being monitored. For example, see Figure 4. For the sake of demonstration, assume that wavelets shown in are the echoes of the ultrasonic signal are received from the component when at its maximum displacement location. The frequency of the vibration, *f*, is then determined by

$$f = \frac{2}{t_2 - t_1}$$

If the velocity of the fluid, *v*, in which the component is immersed is known, then the amplitude of the displacement, *u*, can be determined by

$$u = v(t_2 - t_1)$$

As the software monitors the signal, these parameters are determined and the time domain of the measured vibration amplitude is then plotted below the A-scan. To the right of the measured vibration time domain, the frequency domain of the vibration is plotted. In real world applications one should not assume that the vibration of the component has a single frequency component. Knowing the vibration modes of a real world pipe or valve internal would be valuable information. In the case of Figure 3, the software is measuring the vibration of a reflector which is from the second echo in the signal and is vibrating at 30-Hz with a peak-to-peak amplitude of roughly 4-mm. More on the systems measuring capabilities is discussed in subsequent sections.

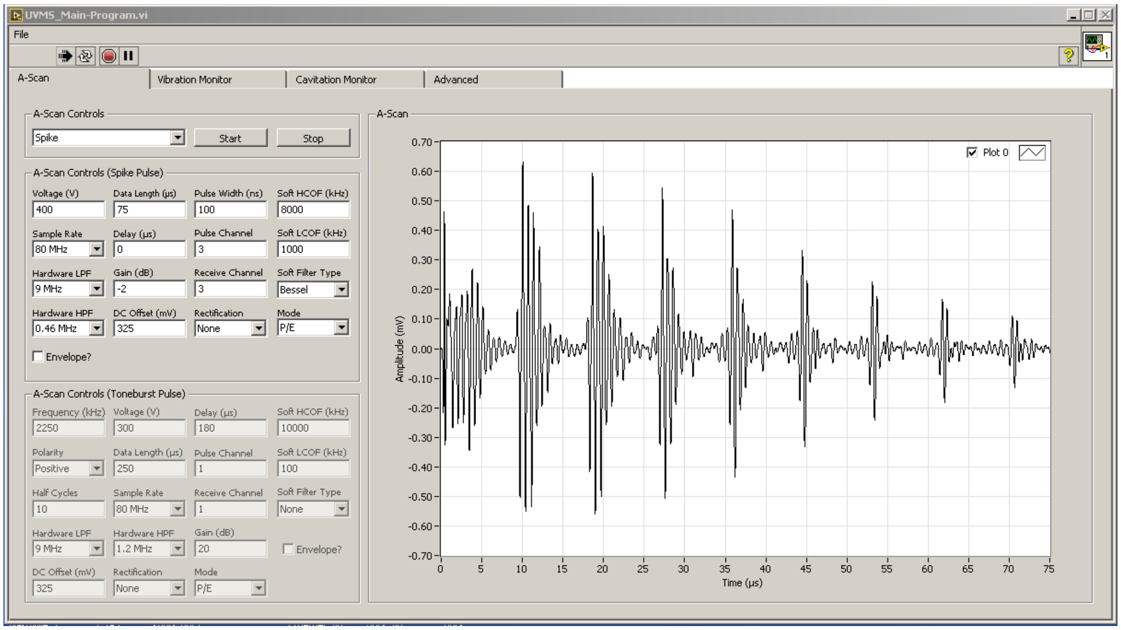

Figure 2. *A-Scan Monitor* interface in the UVMS software showing pulse-echo ultrasonic waveforms.

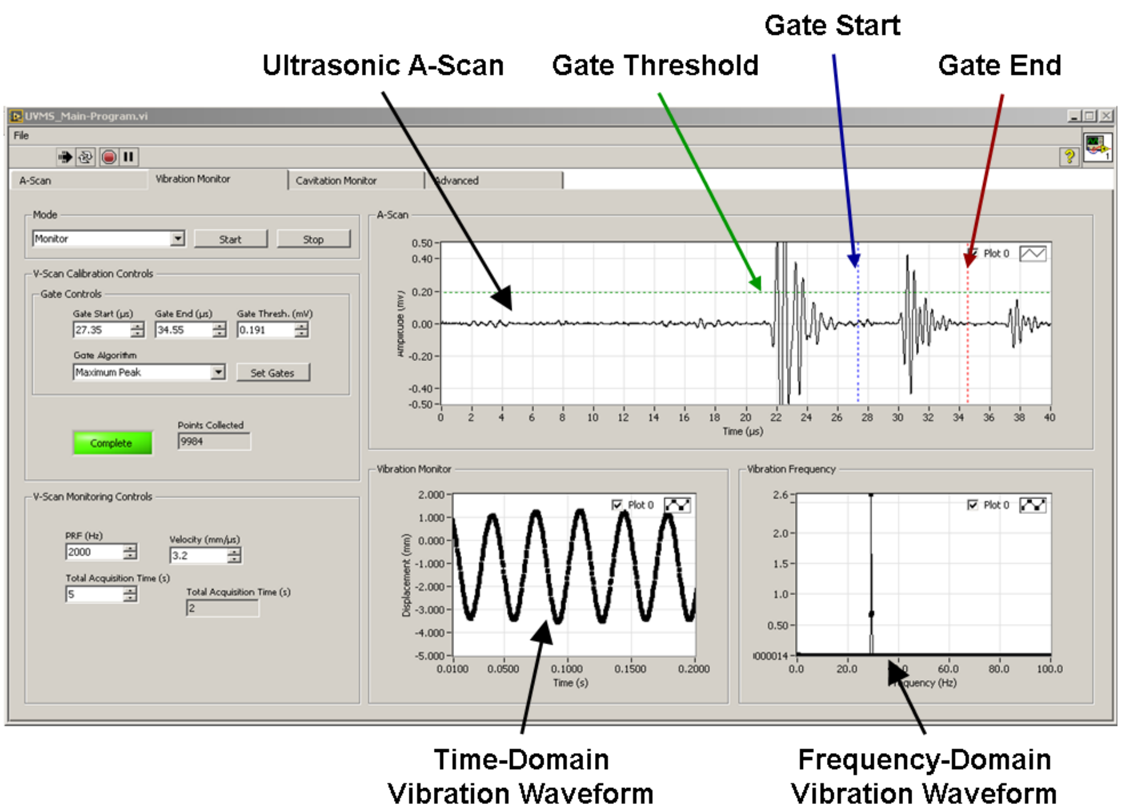

Figure 3. *Vibration Monitor* interface in the UVMS software showing (top) the ultrasonic A-scan, (bottom left) time-domain vibration waveform, and (bottom right) frequency-domain vibration waveform.

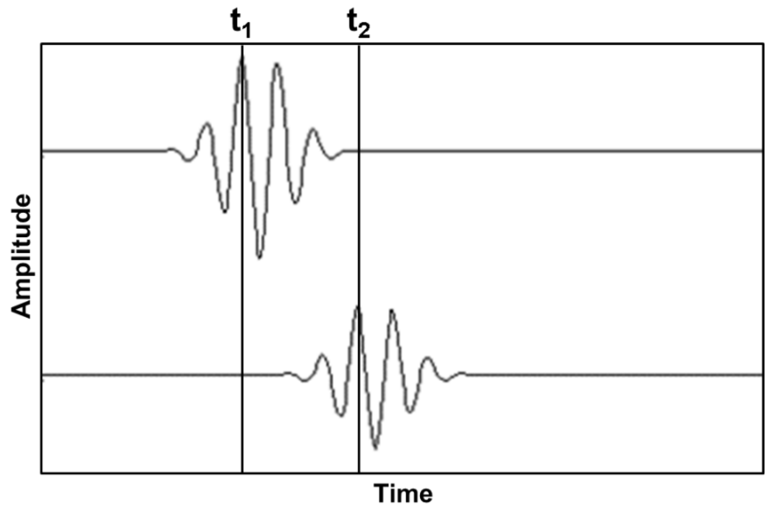

Figure 4. Conceptual illustration of the echoes received from a vibrating component. Assume that the wavelets represent echoes received from a vibrating component at its maximum and minimum vibration amplitude locations.

Figure 5 shows an image of the "Cavitation Monitor". On this screen, two displays are presented. The top display is referred to as the Recorded Signal vs. Monitoring Time display. This is an image of the time domain signals recorded as monitoring of the systems progresses. What this shows is each signal received from the probe, recorded at a time interval specified by the user. The recording interval time is limited by the pulse repetition frequency (PRF) of the hardware being used. Each recorded signal is plotted along the vertical time axis, with the color indicating the amplitude of the received signals at particular points in time of the recorded ultrasonic waveform. The x-axis corresponds to the monitoring time. In the case of Figure 5, a simple example of multiple round trip echoes of an ultrasonic wave in a 1-in thick stainless steel sample with a recording interval of 0.02-s is being shown. Each recorded signal is 60-μs in length, and is recorded every 0.02-s. To further clarify, the right of Figure 6 shows the static ultrasonic signal being recorded every 0.02-s. Arrows are drawn from each echo from received waveforms to where their corresponding positions are on the colored display.

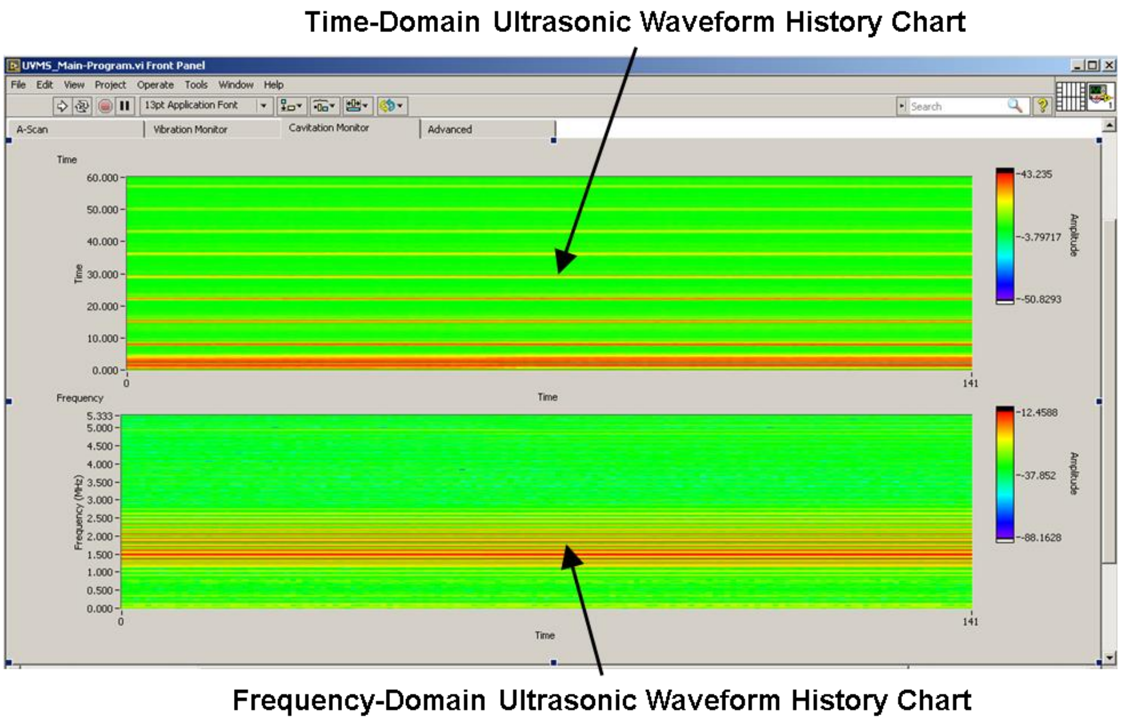

Figure 5. *Cavitation Monitor* interface in the UVMS software showing (top) time-domain ultrasonic waveform history chart and (bottom) the frequency domain ultrasonic waveform history chart.

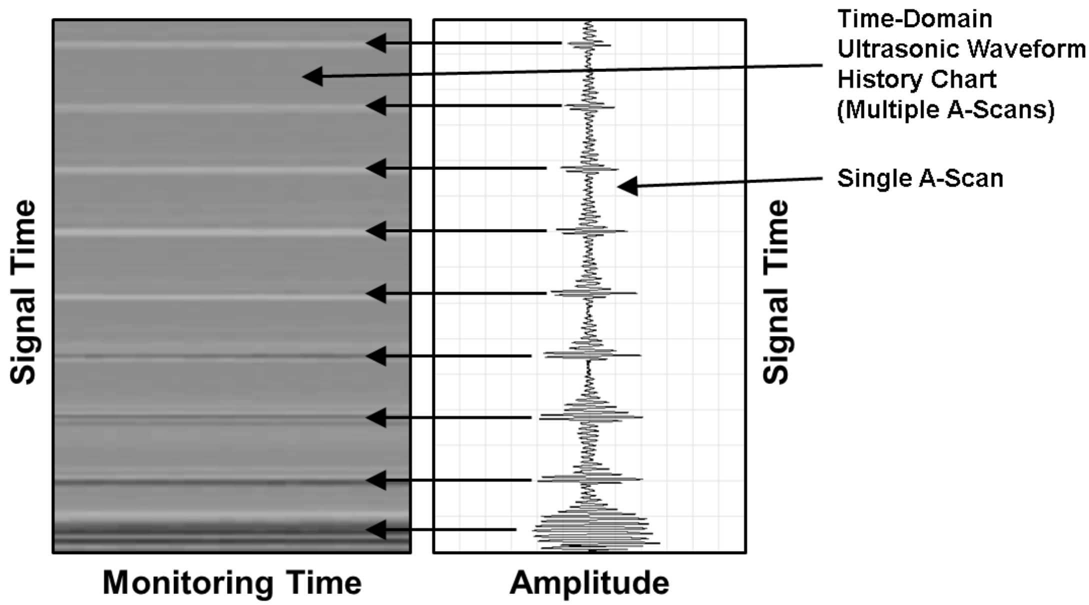

Figure 6. Zoomed in screenshot of the (left) time-domain ultrasonic waveform history chart (multiple A-scans) and (right) a single time-domain ultrasonic waveform (A-scan). This history chart update rate is adjustable, but is typically set to refresh 50 times per second.

The second display located on the bottom in the cavitation monitor tab is similar to Recorded Signal vs. Monitoring Time display. What this display shows is Fast Fourier Transform (FFT) for each recorded signal as monitoring time progress. Thus, an FFT of each waveform that is recorded is performed and is displayed in the lower image as monitoring progresses. Figure 7 shows a single FFT of the recorded signal with arrows indicating the region of where the corresponding peaks are located in the colored image. The transducer in the case of the data being displayed in Figure 3 through Figure 7 is 1.5-MHz, which is clearly demonstrated in Figure 7. It should be noted that to one experienced in evaluating the frequency domain of ultrasonic signals that the frequency spectrum shown in Figure 7 may appear to be noisy. This is simply because the FFT in this case is being taken of the entire signal (several echoes) is being performed. This has been done here purely to simplify the discussion at hand.

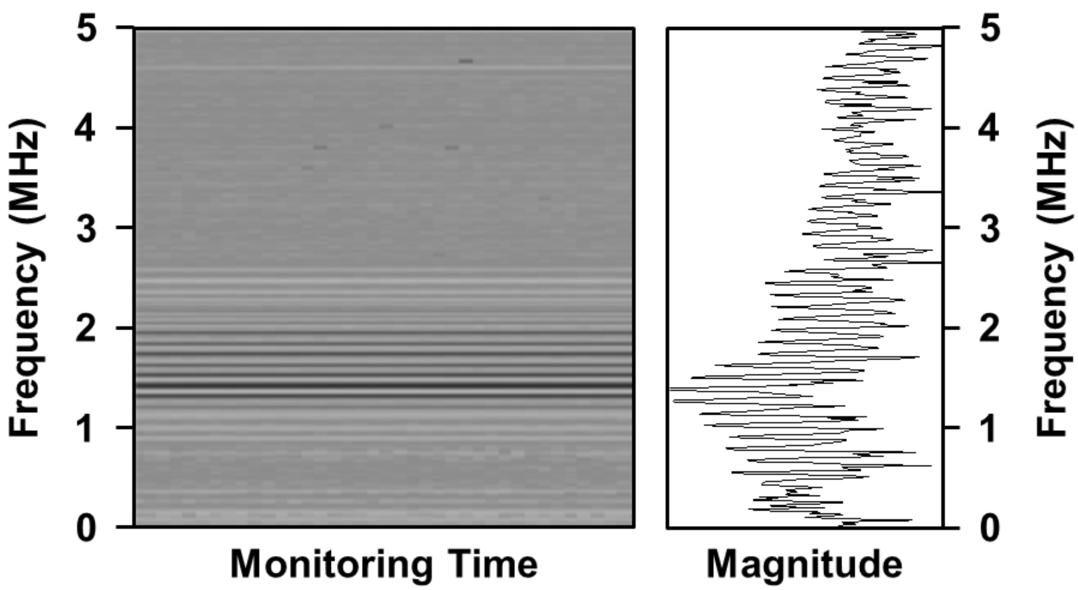

Figure 7. Zoomed in screenshot of the (left) frequency-domain ultrasonic waveform history chart and (right) a single frequency-domain ultrasonic waveform. This history chart update rate is adjustable, but is typically set to refresh 50 times per second.

Task 2.2: Test Capability of Developed System for Vibration Monitoring and Cavitation Monitoring: Initial Mockup

In order to test the developed system's capabilities of monitoring vibration, an initial mockup was constructed. An image of the constructed mockup is shown in Figure 8. The test system consists of a test chamber and an actuator control unit (ACU). The test chamber consists of a 6-in thick steel cylinder. The steel cylinder mimics a thick steel valve casing or containment vessel wall. The steel cylinder is encased in a larger Plexiglas tube which is filled with water and thus acts as a water column. This water column serves to mimic the fluid immersing a valve or pipe internal. The water column is filled to the top of the Plexiglas tube where a steel plunger is located. The steel plunger is roughly 6-in away from the steel water interface. The plunger, is connected to an actuator which is controlled by the ACU. The ACU is used to sinusoidally vibrate the steel plunger, thus simulating the vibration of a valve or pipe internal. Figure 9 shows an image of a close up the plunger vibrating at 30-Hz. Note the standing wave patterns visible on the water surface induced by the plunger vibration. The water path simulates a valve filled with water, while the actuated steel plunger is for simulating a vibrating pipe or valve internal. An ultrasonic transducer is placed at the bottom of the steel cylinder, opposite the steel-water interface. The transducer is controlled by the data acquisition laptop and is the transducer used for monitoring the vibrations of the steel plunger.

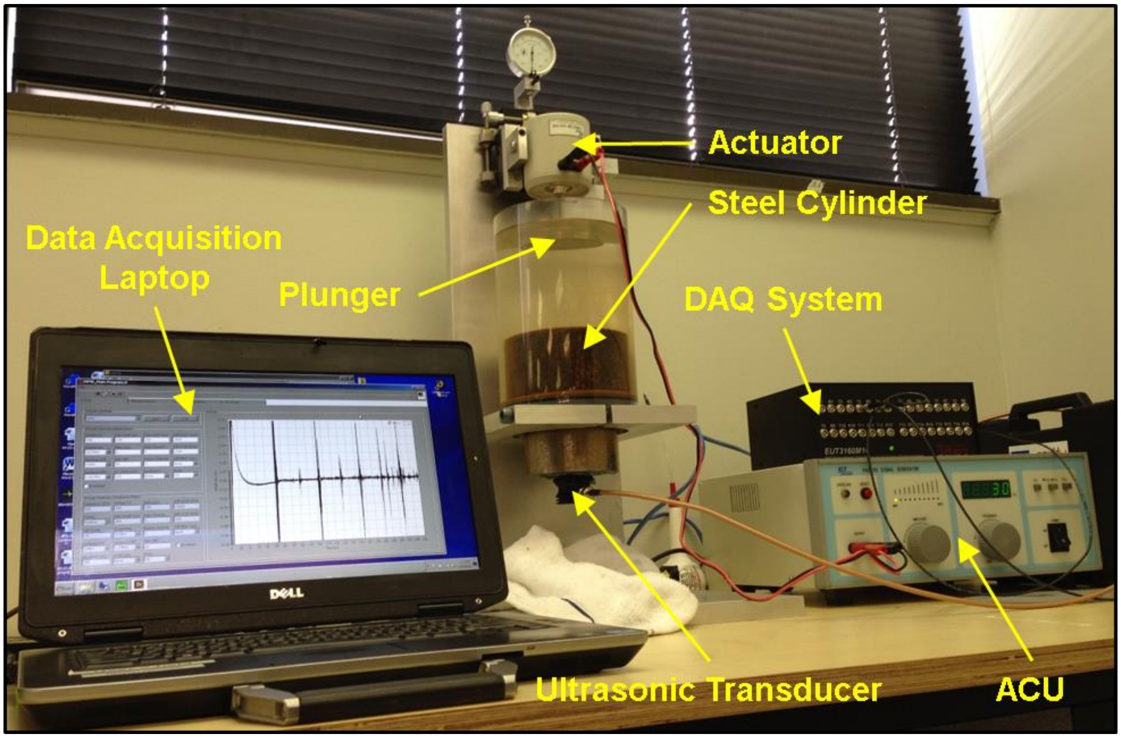

Figure 8. Photograph of the experimental setup for measuring vibrational amplitudes and frequencies. Note: ACU stands for Acquisition Control Unit.

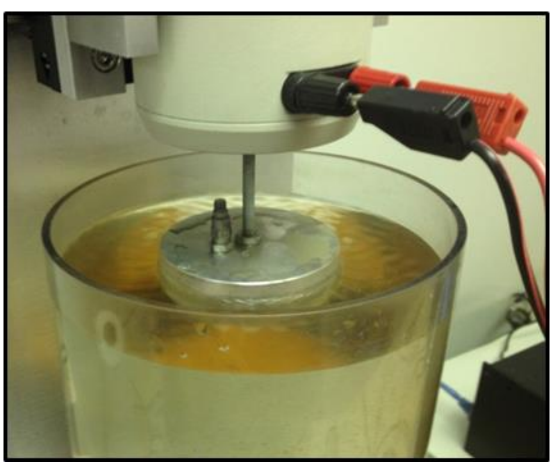

Figure 9. Zoomed in photograph of the actuator, and plunger shown in Figure 8.

The ultrasonic wave generated from the transducer traverses the steel and enters the water column. The wave travels through the water column until it encounters the steel plunger. The wave is then reflected from the plunger back towards the transducer where the signal is received. The received is then analyzed by the developed software mentioned in the previous section to track the vibration of the plunger as it is driven by the ACU. Figure 10 shows a plot of the ultrasonic signal obtained from the system with a 2.5-MHz transducer. The echo reflected off the plunger is indicated. The other echoes detected in the signal are round trip signals of the ultrasonic wave in the stainless steel cylinder.

To test the systems vibration monitoring capabilities, the plunger was sinusoidally driven at frequencies in the range of 17-Hz to 1000-Hz. The upper limit of 1000-Hz is the maximum frequency which can be measured and is limited by the maximum PRF of electronic hardware. The vibration monitor was able to successfully track the plunger vibrating at all frequencies throughout this range. Figure 11 shows data recorded of the relative plunger vibration amplitude at 20-Hz with a peak-to-peak vibration of amplitude of roughly 3-mm. Figure 12 shows the measured vibration frequencies of the plunger when the ACU was set to 17-Hz, 211-Hz, 493-Hz, 706-Hz, and 961-Hz. The smallest vibration amplitude the system was able to measure was 0.0008-in (0.02-mm), which is lowest vibration amplitude the hardware being used can be able to detect. The lower limit of the vibration amplitude which can be measured is dictated by the velocity of the fluid sample frequency of the hardware, which in this case is 160-MHz.

The vibration monitor frequency measurements were completely accurate to the control limit of the control of the ACU, which was 1-Hz. Also note how narrowband the recorded center frequencies of the measured vibrations are. These findings indicate two things. The first is that this demonstrates that the plunger is being driven very accurately with regard to frequency, almost coherently. The second is that this demonstrates that the measured frequency domains are also extremely accurate. This a critical finding as the same principles, i.e. the location of the echo peak in time, are being used to calculate both the vibration frequency and amplitude. Thus, since the measured frequencies have been proven to be extremely accurate, this confirms that any amplitude measurements made are also equally accurate, provided that the wave velocity of the fluid is known. In this case, of course, the fluid is water at ambient temperatures whose wave velocity is a well-documented 1.483-mm/µs. Recall that Task 1 revealed that the industry would desire vibration frequency measurements over the range of 0-Hz to 300-Hz and vibration amplitudes with a minimum amplitude of 0.020-mm. Thus, the system meets the minimum measurement criteria preferred by the industry.

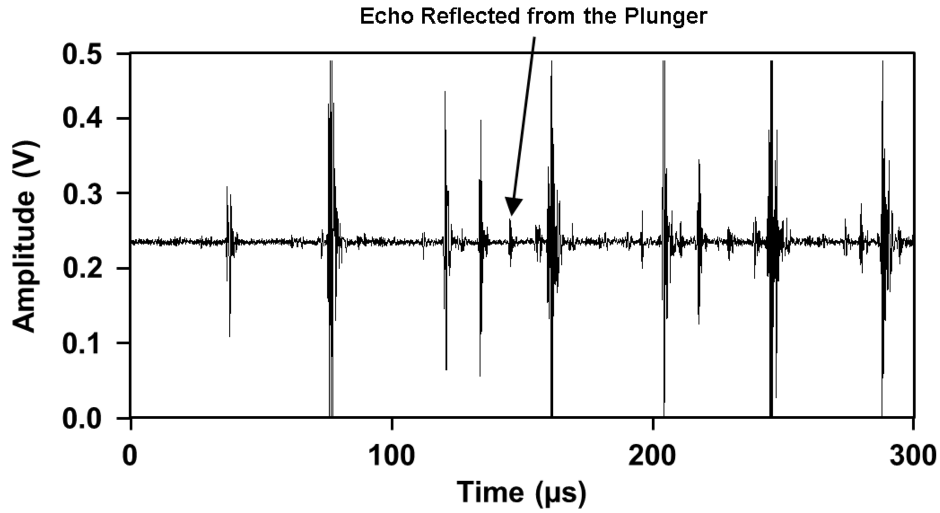

Figure 10. Signal recorded for the experimental mock-up shown in Figure 8. The echo received from the reflection of the wave off of the plunger at the top of the water column is indicated.

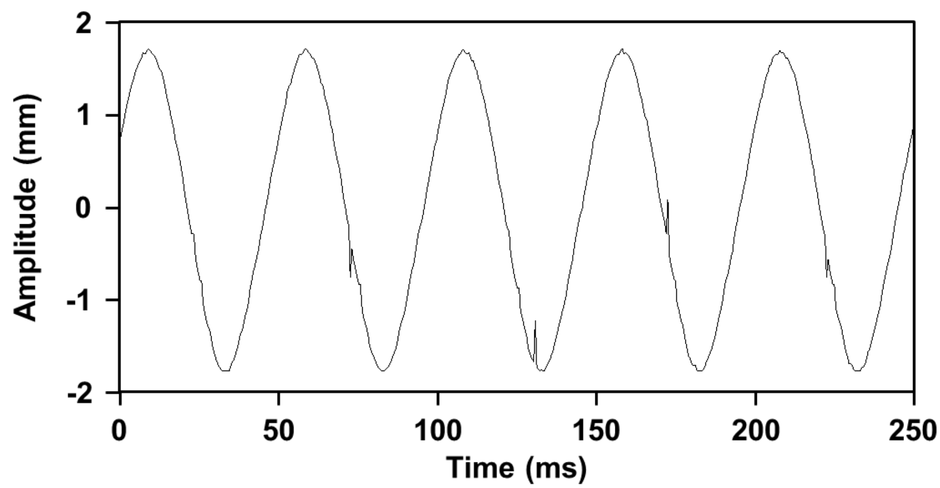

Figure 11. Measure vibration waveform while the plunger was being driven with a 30-Hz sinusoid.

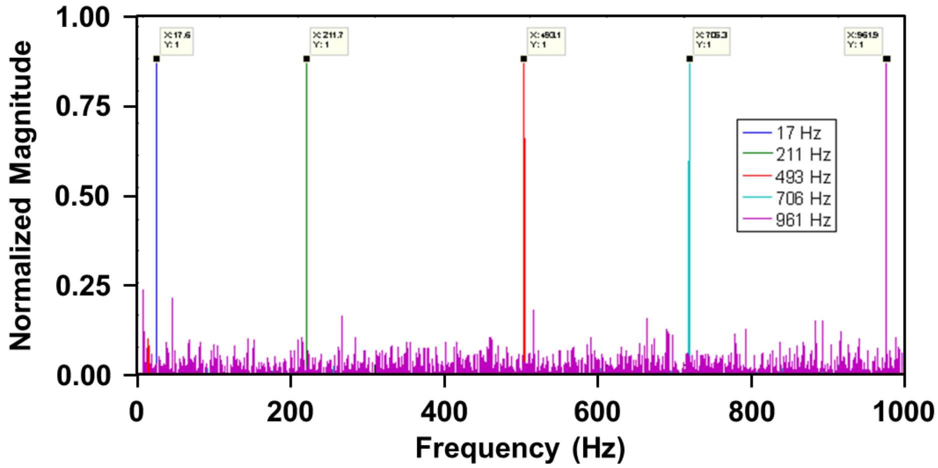

Figure 12. Center frequencies of vibration waveforms measured at several frequencies between 17-Hz and 1000-Hz.

Task 2.3: Test Capability of Developed System for Vibration Monitoring and Cavitation Monitoring: Actual Valve Mockup

The results obtained from the initial mockup were extremely successful. To further demonstrate the system, an actual valve was purchased to demonstrate the system's ability to successfully monitoring cavitation and valve internal vibration/location on a real world valve. The idea behind this was to purchase a valve, and to modify it such that vibration of the valve internal could be achieved, as well as introduce cavitation into the valve area. The valve which was purchased was an 8-in gate valve with a 1-in thick iron casing.

Figure 13 shows an image of the experimental valve setup. To induce vibration of the gate valve, a 0.25-HP, 1625-RPM motor was clamped onto the valve stem. The valve stem controls the location of the gate valve. An unbalanced mass was attached to the motor. As the motor spins the unbalanced mass, a rocking is induced which translates down the shaft of the valve stem, which in turn shakes the valve gate inside the valve chamber. Figure 14 shows an image of the unbalanced mass which induces the vibrations with its rotation. The valve area was sealed shut using Plexiglas and silicone caulking. One on side of the valve, a whole was cut into the Plexiglas and the ultrasonic cavitator was inserted into the valve chamber. Ultrasonic cavitators use high intensity ultrasonic waves which generate cavitation. In this case the ultrasonic cavitator frequency is 20-kHz. This therefore enabled being able to generate cavitation in between the valve gate and the valve wall. Figure 15 shows an image of cavitation being generated in between the valve gate and the valve wall. A hole was cut into the Plexiglas on the other side of the valve to enable filling the valve chamber with water. To measure the vibrations and cavitation, the transducer was placed at the bottom of the valve, per the image in Figure 16. Figure 17 shows a plot of the echo received from the valve gate at a position where the valve is roughly 90% open.

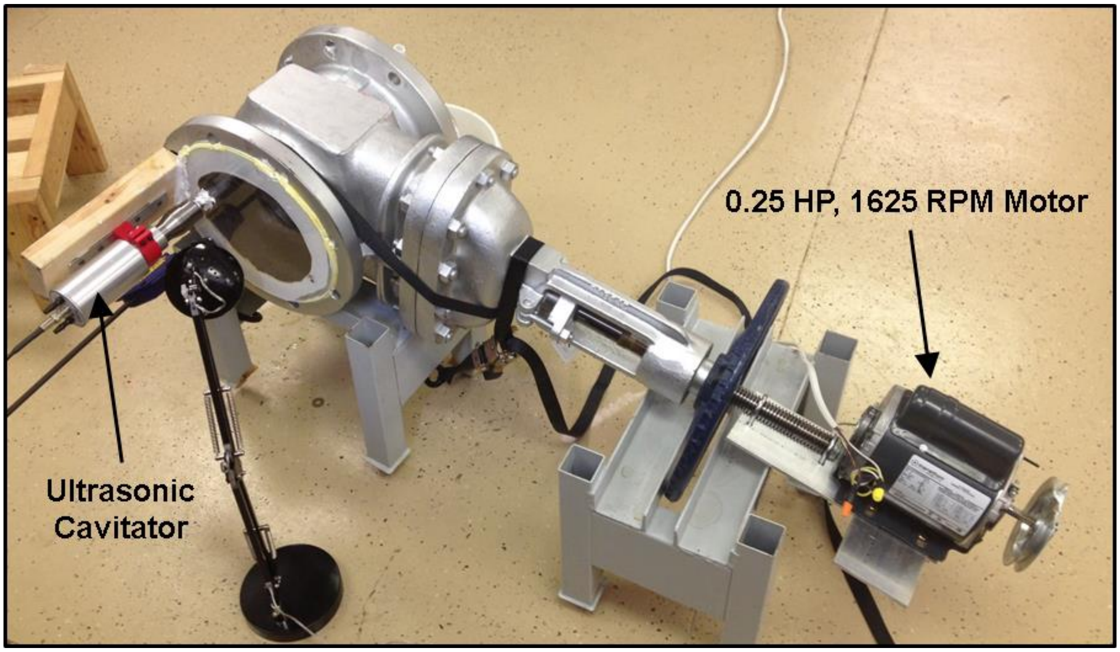

Figure 13. Photograph of the gate valve experimental setup indicating the motor with unbalanced mass for vibrating the gate and the ultrasonic cavitator for generating cavitation in the ultrasonic sound path.

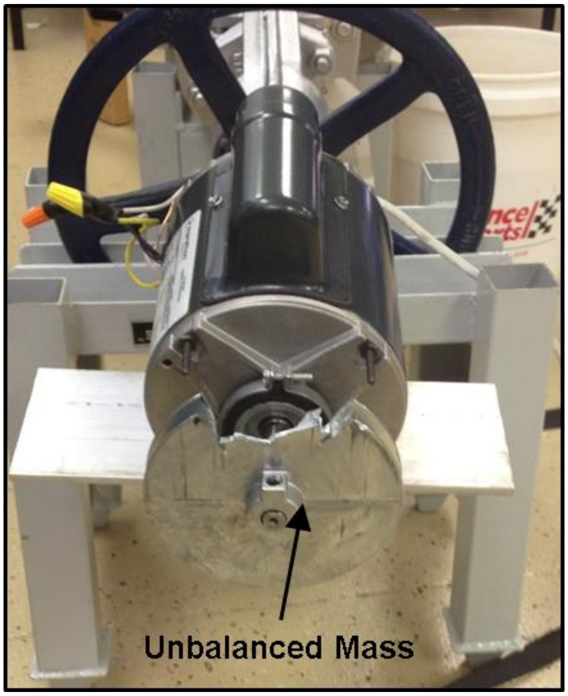

Figure 14. Photograph of the 0.25 HP, 1625 RPM motor clamped to the valve stem. The rotation of the unbalanced mass induces a vibration which is transferred to the valve gate.

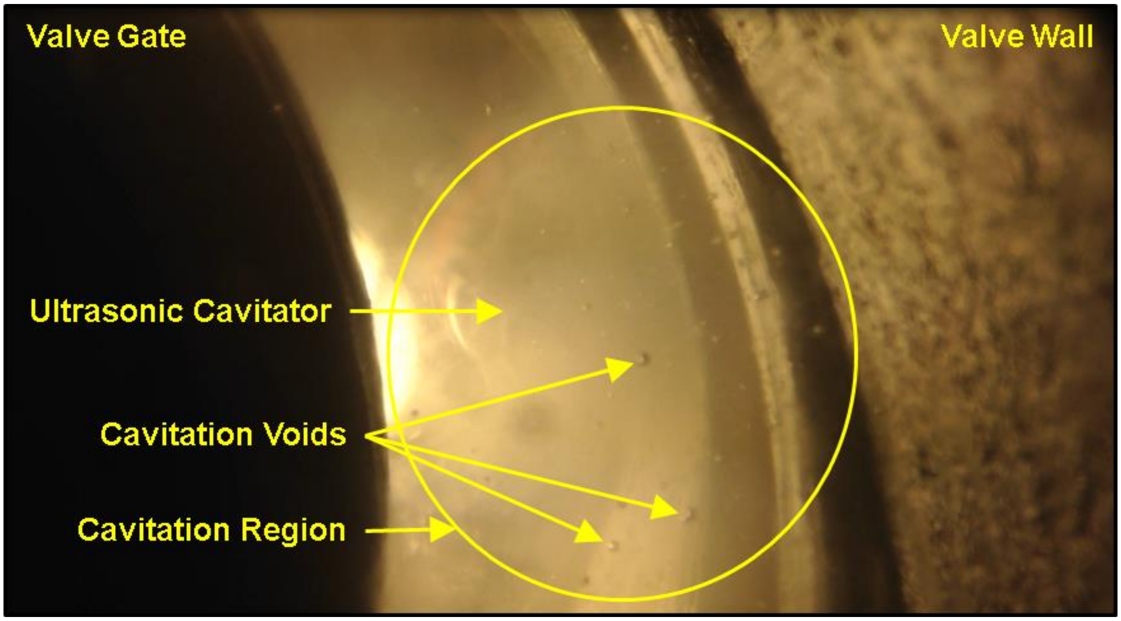

Figure 15. Photograph of cavitation voids generated by the ultrasonic cavitator. Note: For clarity, three specific voids have been identified in the photograph.

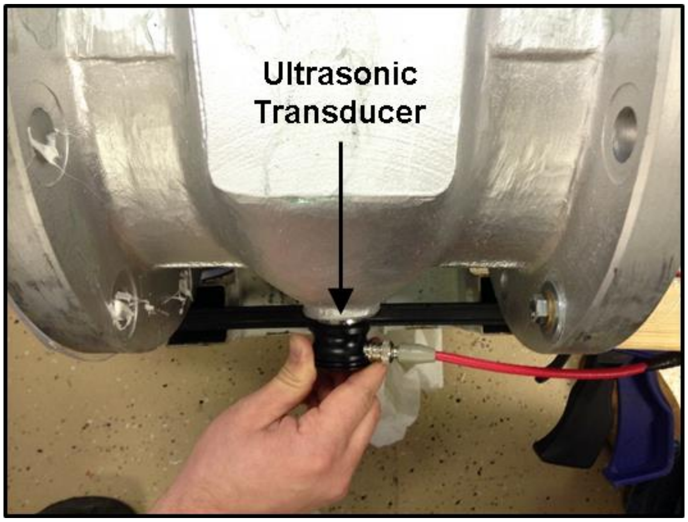

Figure 16. Photograph of the ultrasonic transducer coupled to the valve in the experimental setup for measuring vibration and cavitation.

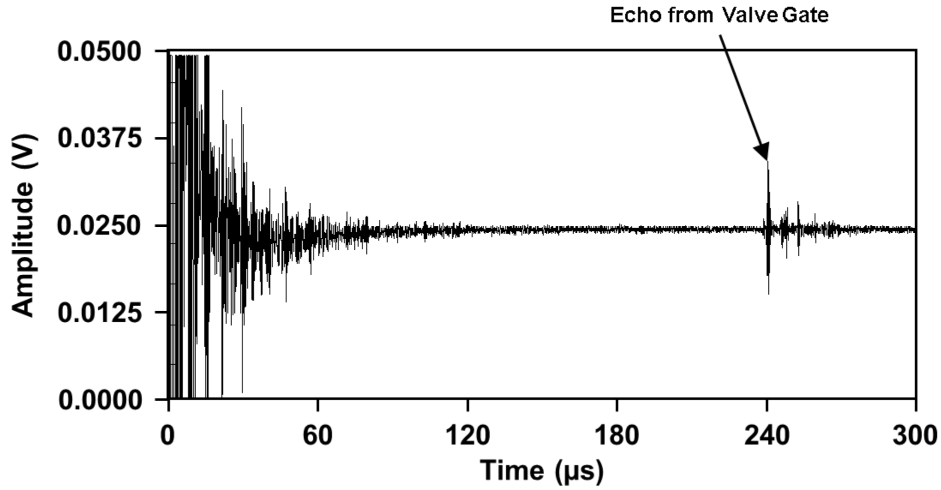

Figure 17. Ultrasonic A-scan identifying the echo from the valve gate.

To monitor the vibration of the valve gate induced by the motor, the motor was switched on and the system was left to monitor the return echo from valve gate. In Figure 18 is a plot of the data recorded for the frequency of the vibration. The data shows that a central vibration frequency of 29-Hz being measured. This result is accurate, since the motor rotates at 1625-RPM which is equivalent to 27-Hz. The data also show that harmonics of the 29-Hz vibration are being generated, indicating that the valve is vibrating nonlinearly. Figure 19 shows a plot of the measured displacement of the valve. The results show that the valve had vibrated with a maximum peak-to-peak displacement of 0.08-mm, or 0.003-in, displacement. These are excellent results. Figure 20 shows an image of what the software display looks like while recording this data.

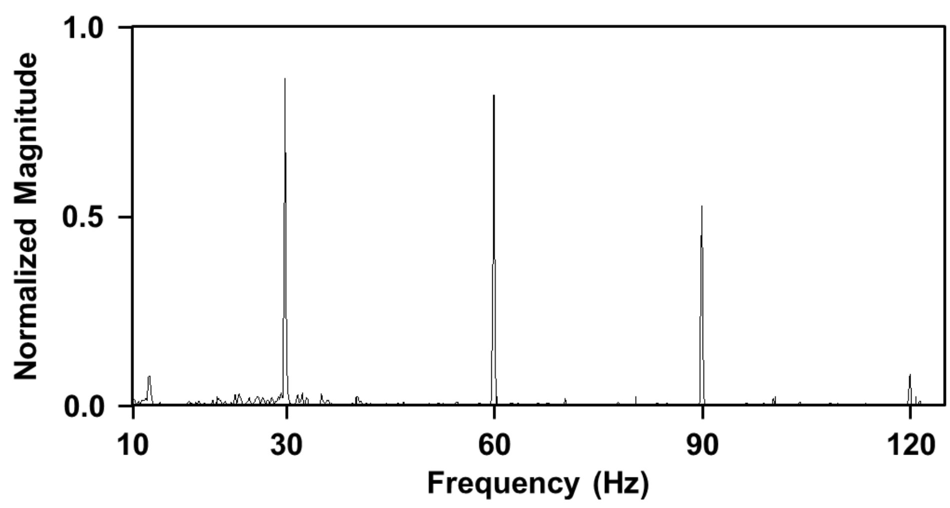

Figure 18. Measurement of the frequency of the vibrating valve gate. The presence of the higher harmonics (integer multiples of 30-Hz) indicate that nonlinear vibration is being induced.

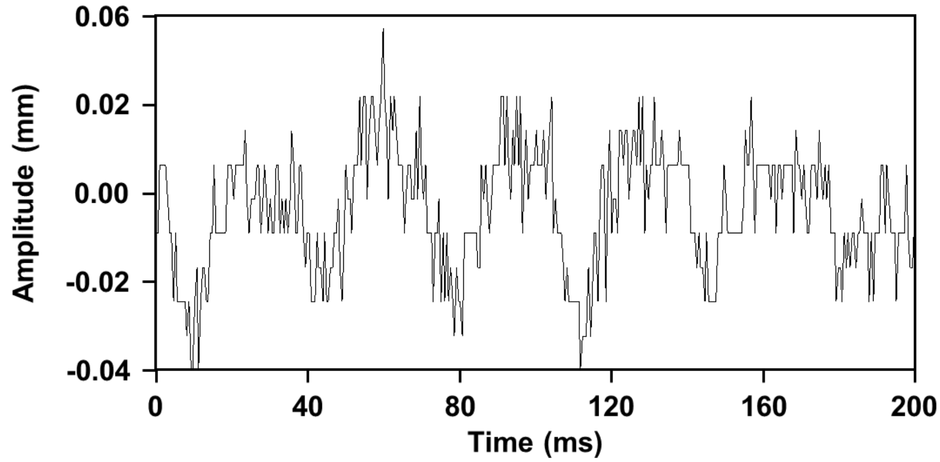

Figure 19. Measurement of the vibration amplitude of the valve gate, which was approximately 0.08-mm peak-to-peak.

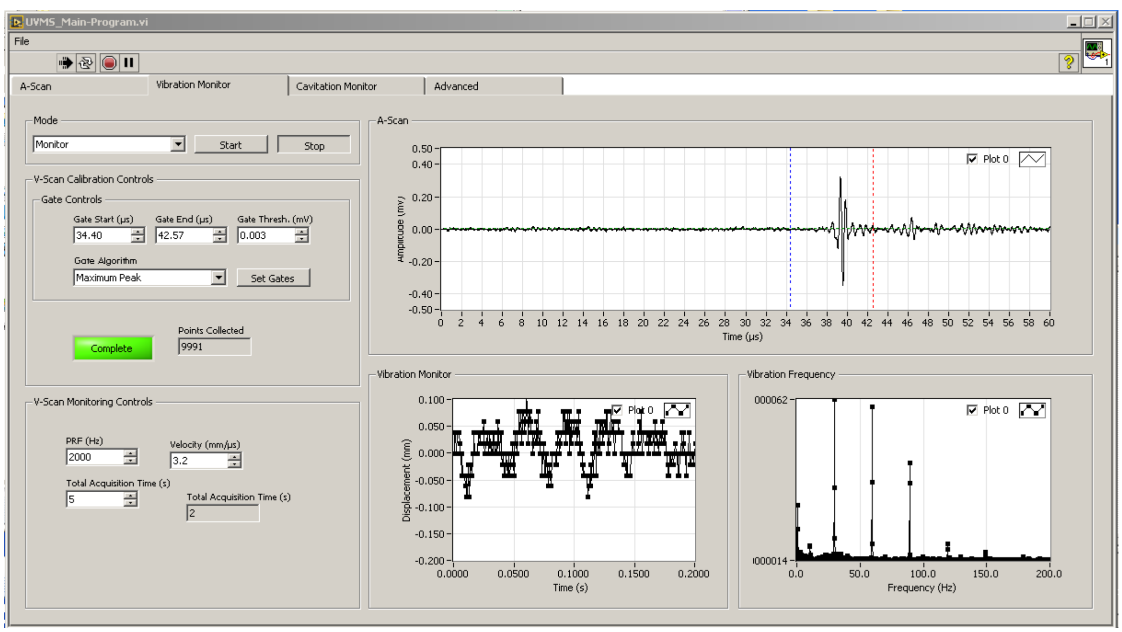

Figure 20. Screenshot of the *Vibration Monitor* interface of the UVMS software recording the vibration of the valve gate, which was vibrating with a frequency of 29-Hz and a peak-to-peak displacement of approximately 0.08-mm.

For the cavitation measurements, the ultrasonic cavitator was pulsed while the transducer monitored the echo from valve gate. The cavitator cycled on for 3-s and off for 6-s. Figure 21 shows a screen shot of what the cavitation tab displays during the cavitator duty cycle. From the time-domain display at the top of the image, it is clear that heavy cavitation significantly affects the echo received from the valve gate. This is due to attenuation of the ultrasonic wave as it encounters the cavitation. Additionally, it can be observed in these plots that the noise floor of the signal raises due to the shockwaves generated by the collapsing cavitation. This is further demonstrated in the bottom display which is display the frequency domain. What this shows is that cavitation can be monitored by monitoring the signal in both the time and frequency domains.

To get a clearer understanding of the effects of cavitation on the received signals, the recorded data was exported from the developed software and analyzed in the MATLAB software package. Figure 22 shows a three-dimensional plot of the recorded signals during the cavitator duty cycle. Figure 23 shows an image of the plot rotated such that the view is from the perspective of signal amplitude as function of the monitoring time. Figure 24 shows a three-dimensional plot of the frequency domain as a function of monitoring time. In this image the intrinsically chaotic nature of the cavitation becomes clearer by noting its effects on the frequency domain. The results presented here in Figure 21 through Figure 24 demonstrate quite clearly that monitoring of the cavitation is easily achieved with the system developed throughout the course of this work. Unfortunately, lower levels of cavitation could not be achieved because the lower limit of the ultrasonic cavitator power was too high, and thus the lowest power limit still generated high amounts of cavitation

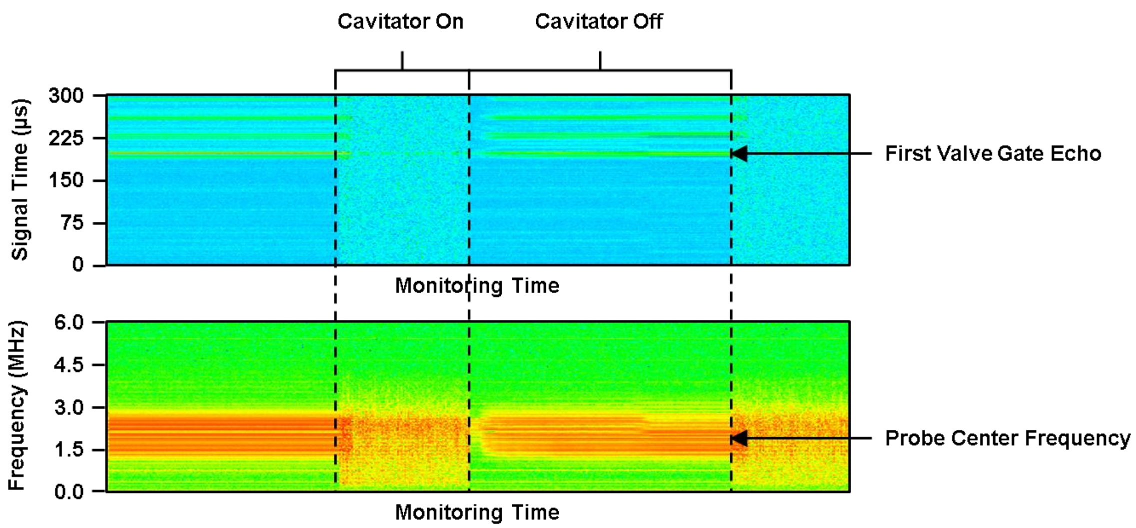

Figure 21. Experimental data from the *Cavitation Monitor* interface of the UVMS software showing two on and two off cycles of the ultrasonic cavitator.

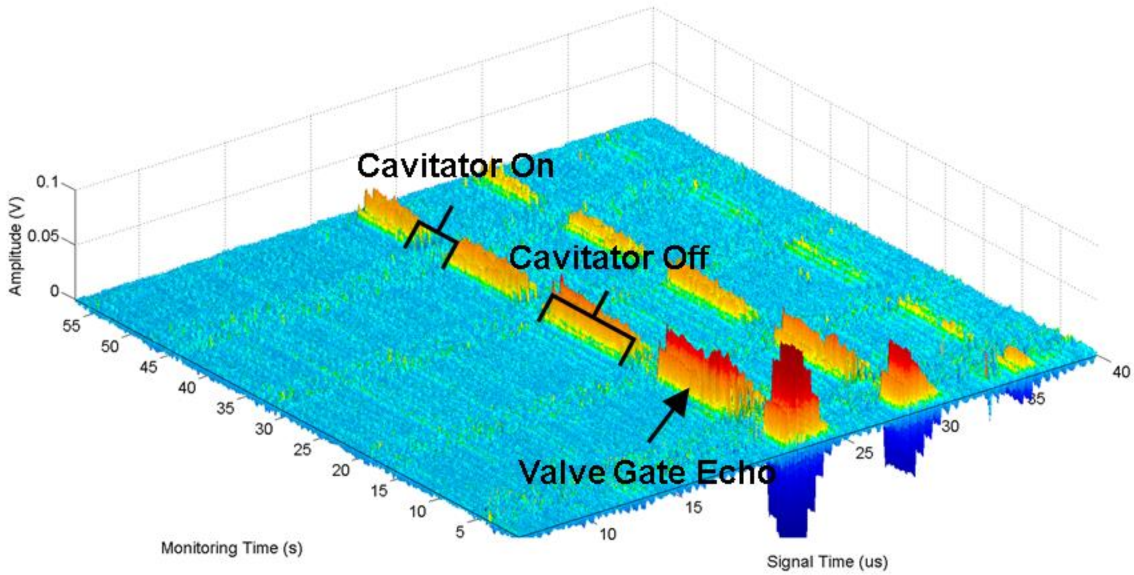

Figure 22. Three-dimensional representation of the time-domain signals from the *Cavitation Monitor* interface of the UVMS software showing four on and five off cycles of the ultrasonic cavitator.

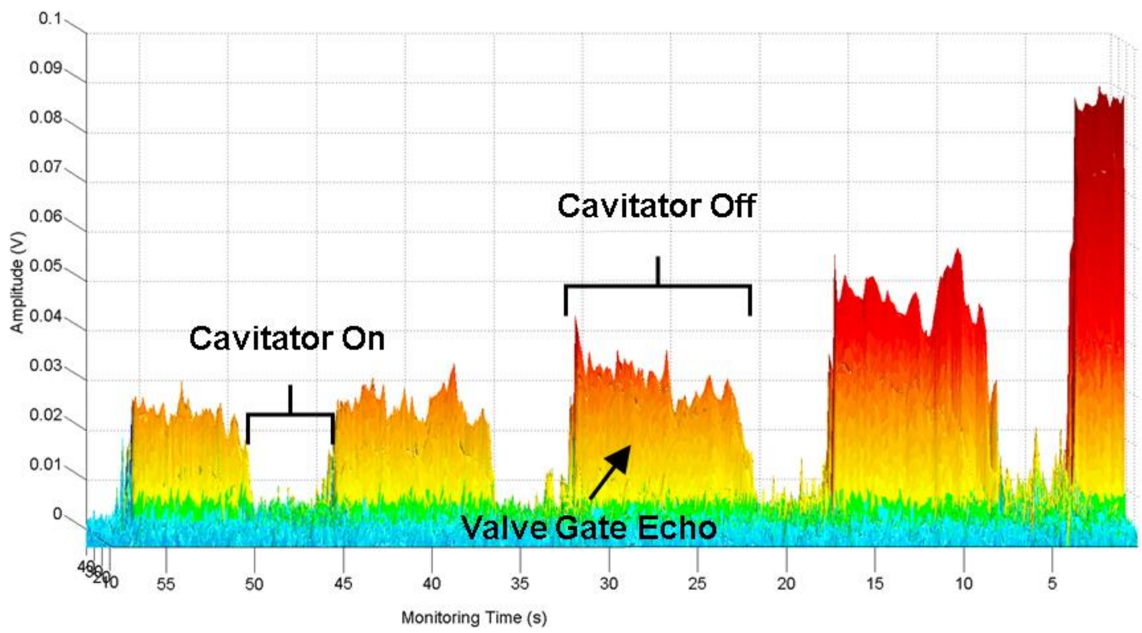

Figure 23. Three-dimensional data from Figure 22, rotated to show ultrasonic waveform amplitude as a function of monitoring time.

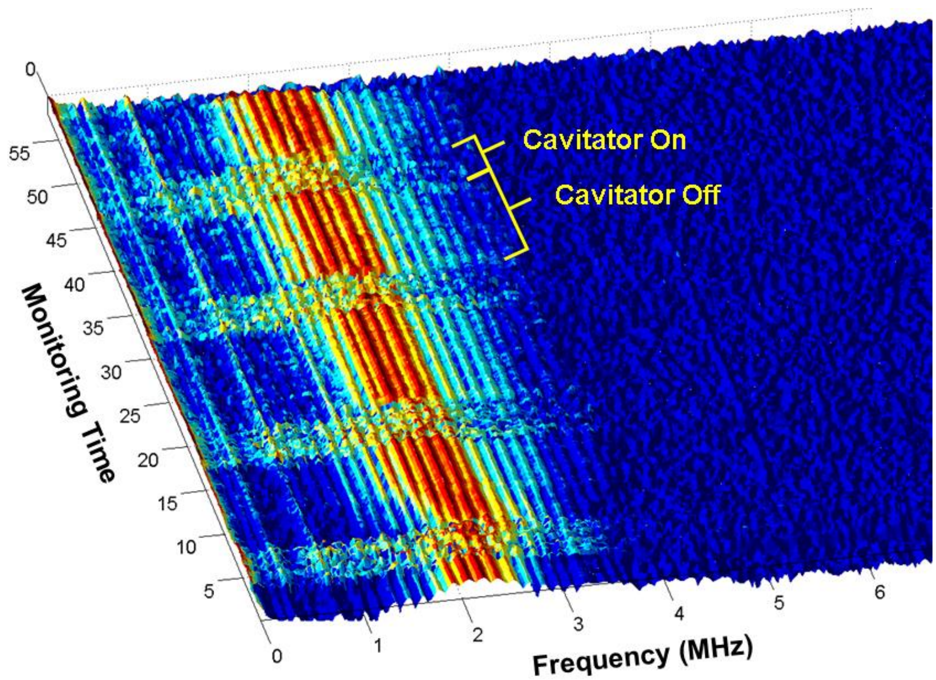

Figure 24. Three-dimensional representation of the frequency-domain signals from the *Cavitation Monitor* interface of the UVMS software showing four on and five off cycles of the ultrasonic cavitator.

Task 3: Initial tests of what probe frequencies and sensitivities will be necessary to monitor vibration, internal component location, and cavitation formation

Probes with center frequencies ranging from 1.5-MHz to 10-MHz were acquired and tested. All the probes were equally capable of measuring vibrations within the range of 17-Hz to 1000-Hz. The same can be said for their ability of measuring cavitation. However, the lower frequency probes, 1.5-MHz to 2.25-MHz are best suited for these applications due to their stronger signal strength as a result of less attenuation of the wave. This was expected as the vibration frequency and amplitude measurement accuracy are more limited by the electronic hardware than the ultrasonic transducer center frequency.

Task 4: Acquire and test commercially available high temperature probes and couplants/epoxies and assess their operation.

Task 4.1: Acquire Probes and Perform Initial Performance Assessments

High temperature, radiation resistant probes were obtain from two commercial suppliers, Applus RTD and Imasonic. As Task 2 describes, probes with lower center frequencies of 1.5-MHz were ordered due to their larger signal strengths relative to high frequency probes. The ordered probes from both suppliers were specified to have 1-in diameters. Figure 25 shows images of the probes from each supplier. The probes received from Applus RTD have a stainless steel housing, while the probes from Imasonic were custom ordered with a polyether ether ketone (PEEK) housing. PEEK was selected because of its resistance to both relatively high temperatures, as well as its resistance to radiation. Figure 26 shows a plot comparing the ultrasonic response of the

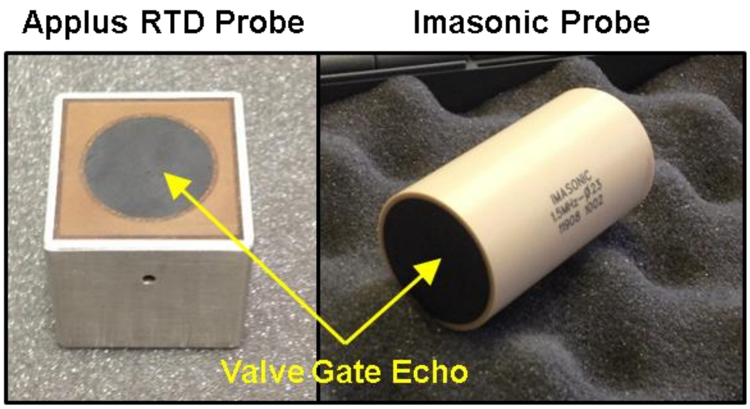

Figure 25. Photographs of the ultrasonic transducer probes from (left) Applus RTD and (right) Imasonic.

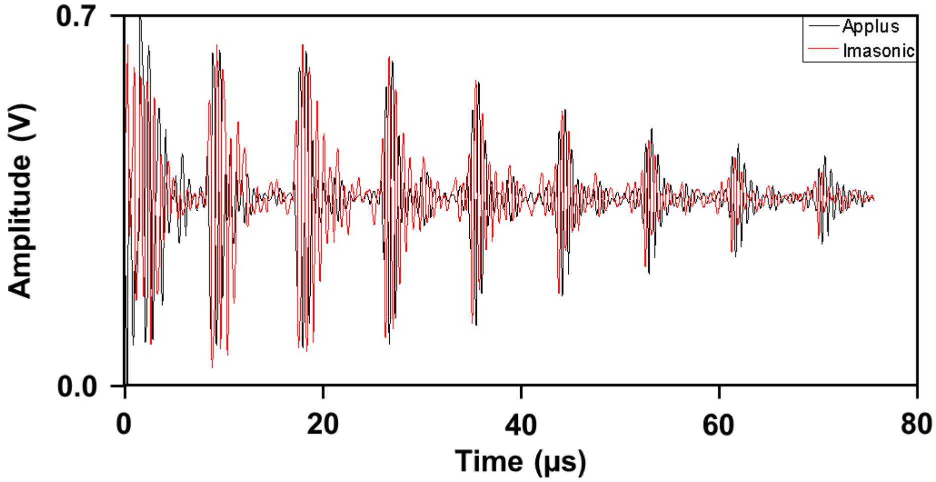

Figure 26. Comparison of the ultrasonic transducer probe amplitudes on a 1-in thick stainless steel block.

probes when tested at room temperature on a 1-in thick stainless steel sample under identical pulsing and receiving conditions. As Figure 26 demonstrates, the probes are almost equal in both pulse-width response and signal strength. It should be noted that the probes have sufficient strength and bandwidth to perform all the measurements carried out in Task 1.

Task 4.2 Acquire High Temperature Couplants and Epoxies and Assess their Capabilities

During this task, one high temperature couplant and one high temperature epoxy were obtained. The high temperature couplant which was obtained was Sonotech's 1100. According to the manufacturer, this couplant should allow for ultrasonic measurements up to 700-F. The high temperature epoxy which was obtained was Duralco 4703. According to the manufacturer the epoxy can withstand temperatures up to 600-F. The epoxy and couplant were also both selected due to their lack of toxicity and radiation resistance, which would increase their chances of being permissible in industrial applications. The Sonotech couplant had a grainy consistency. Whereas the Duralco epoxy, post cure (cure temperature of 250-F) was a more permanent, rigid bond. Figure

27 shows images of the probes coupled to a stainless steel samples with both the Duralco epoxy and the Sonotech couplant. Figure 28 shows a comparison of the

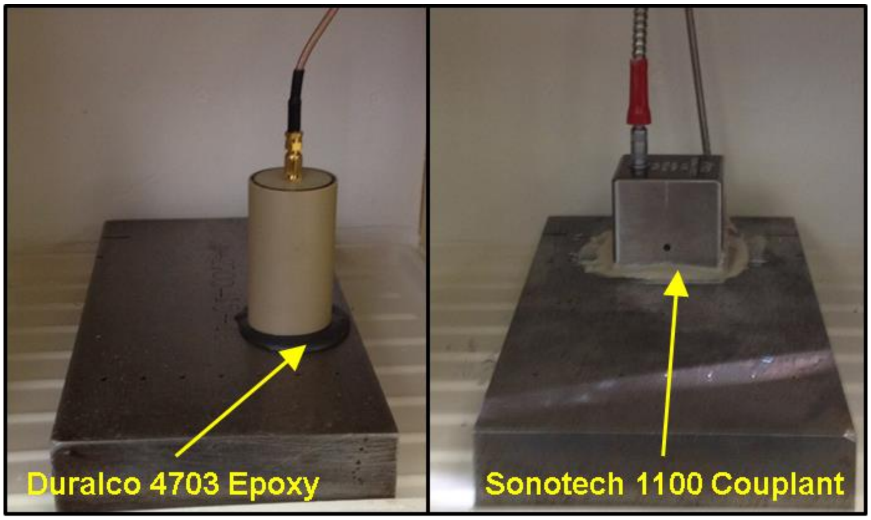

Figure 27. Photographs of (left) the Imasonic probe coupled to a stainless steel calibration block with Duralco 34703 epoxy and (right) Applus RTD probe coupled with Sonotech 1100 couplant.

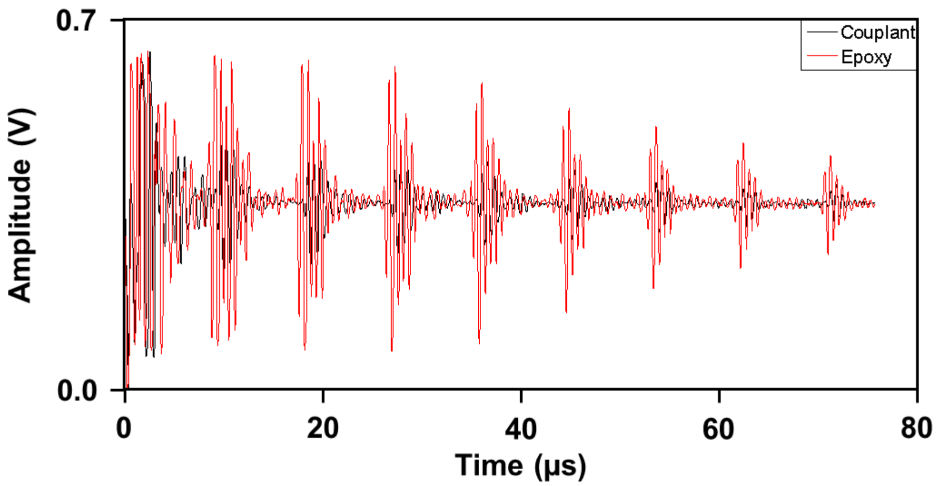

Figure 28. Comparison of the ultrasonic echoes for the high-temperature couplant and high-temperature epoxy.

couplant and the epoxy, post-cure, taken at room temperature on a 1-in thick steel block. As Figure 28 shows, the post-cure epoxy is more efficient at permitting ultrasonic energy to enter the steel block. Quantitatively, the signals coupled with the epoxy are approximately 3-dB stronger than those coupled with couplant.

Task 4.3 Assess High Temperature Capabilities of Probes, Couplant and Epoxy

Since the probes were special ordered, it took some time for their fabrication and arrival. The probes from Applus RTD were the first to arrive and were the first to be tested. These probes were also used to test both the epoxy and couplant capabilities. The probes, couplant, and epoxy were first both tested at 250-F for a 31-day period of time on 1-in thick stainless steel calibration blocks (see Figure 27 for the arrangement). In both cases, there were was little or no change in amplitude and signal for the probe-couplant/epoxy combinations. Figure 29 shows a plot of waveforms measured with the probes at room temperature, Day 1 at 250-F, and Day 31 at 250-F for the Applus RTD probes coupled to the cal block with the Duralco epoxy. Figure 30 shows a plot of signal peak amplitude of the first backwall measured several times throughout the 31 day period. As Figure 30 shows, there was no change in amplitude throughout the experiment, and close examination of Figure 29 shows no change in the signals frequency spectrum (only a change in the time of flight because of thermal expansion and change in material properties). Thus, since the signals are quite stable over this temperature range these probes are well suited for vibration and cavitation monitoring in real world situations at these temperatures. The epoxy has demonstrated to be the best candidate for coupling since it is more permanent and also helps couple more ultrasound into the structure. However, for completeness, Figure 31 shows a comparison of the signals probes coupled with both the couplant and the epoxy at Day 31 at 250 -F.

After completion of the 31-day trial of the Applus probe, the temperature was raised to assess the performance of the probe, couplants, and epoxies and 300-F. Above 250-F, the epoxy began to smoke. This implies eventually the couplant would eventually breakdown and lose the ability to couple ultrasound at these temperatures. Therefore, working with the couplant was abandoned and only the epoxy was investigated for the remainder of the work, as it displayed high stability with the temperature increase. In fact, the signal amplitude actually increased. This is likely due to epoxy curing more at the higher temperature. Figure 32 shows a plot of the Applus probe at Day 1 and Day 7. To date, the probe has only been tested for seven days, but the probe will continue to be held indefinitely.

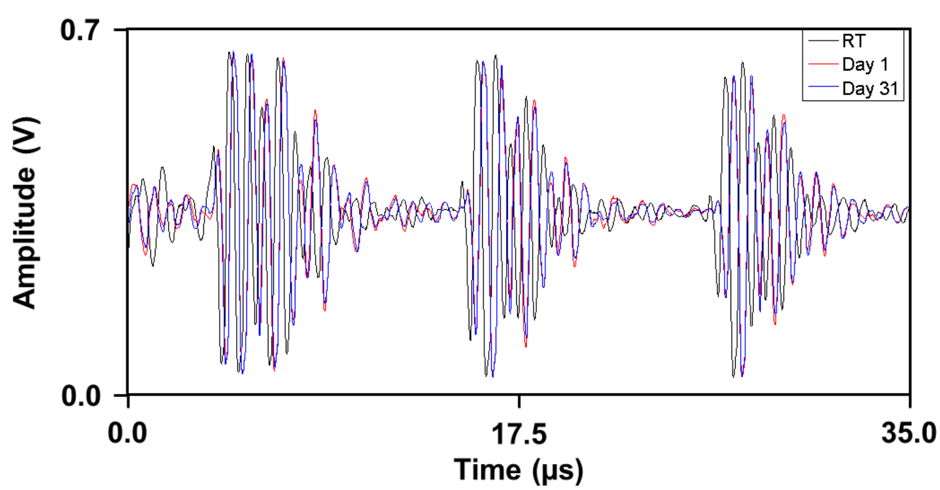

Figure 29. Applus RTD probe coupled with the Duralco 4703. The displayed measurements were made at room temperature at Day 1 and at 250-F at Day 31.

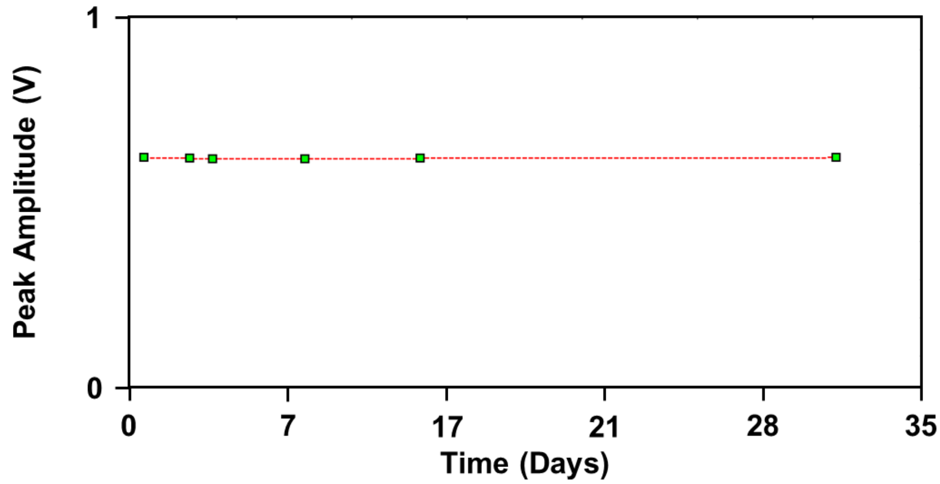

Figure 30. Plot of the measured amplitude throughout the 31-day experiment for the Applus RTD probe coupled with Duralco 4703 epoxy.

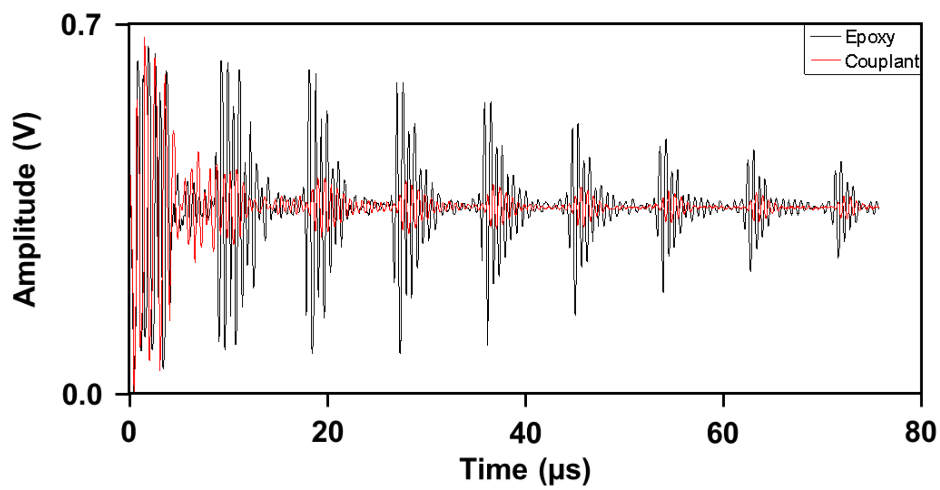

Figure 31. Comparison of the ultrasonic signals obtained at Day 31 of the 250-F exposure when the probes were coupled with Duralco 4703 expoxy and Sono 1100 couplant.

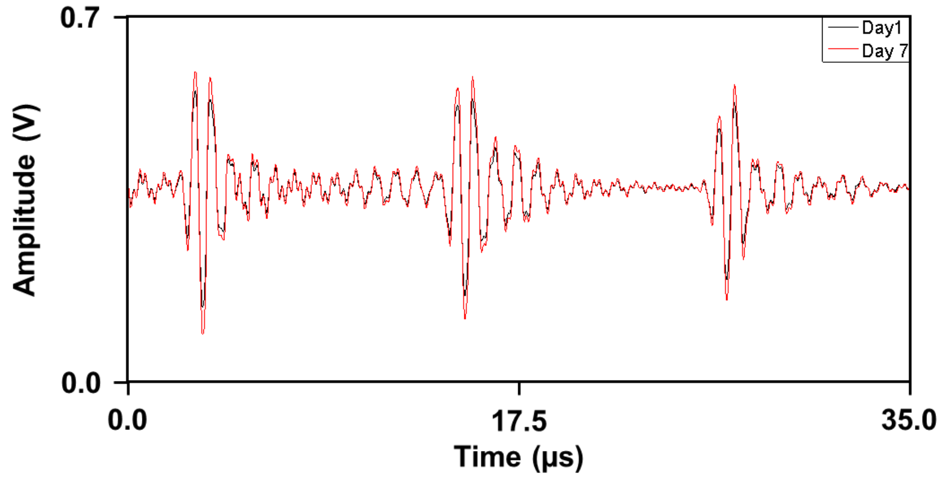

Figure 32. Signals recorded from the Applus RTD probe with the Duralco 4703 epoxy and Day 1 and Day 7 during the 300-F exposure.

Since the Imasonic probes were custom made with PEEK, its arrival came much later so high temperature on the probe have been limited. As of the current date the probes have only been tested at 250-F for 11 days. However, the results to date have shown very little change in amplitude and we expect that the probe will sustain performance with long-term exposure to high-temperature environments. Show Figure 33 shows waveforms from the Imasonic probe measured at room temperature and Day 1 and Day 11 at 250-F. Again, per Figure 33, the probes have shown no decrease in amplitude and no change in frequency content. These probes will be tested for 31 days at 250-F. After completion of this experiment the temperature will again be raised to 300-F, in the same light as to the tests which are being performed on the Applus probe.

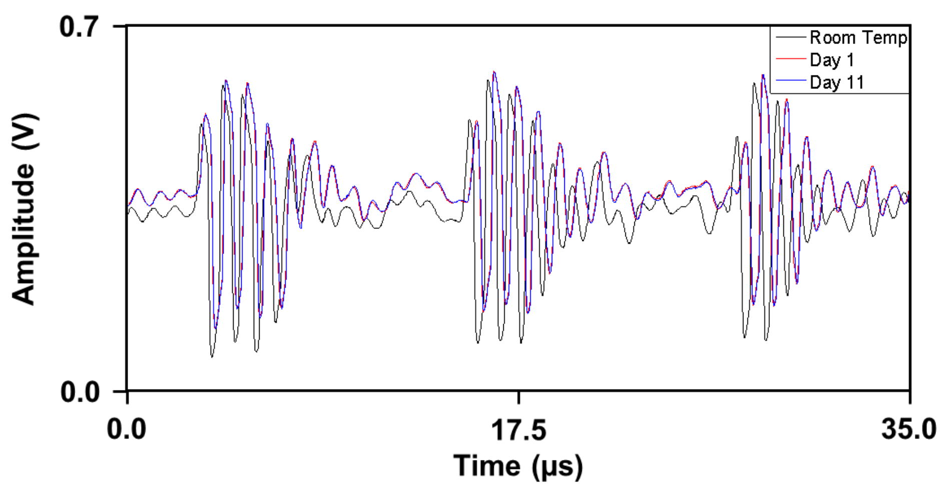

Figure 33. Comparison of the signals obtained from Imasonic probes coupled with the Duralco 4703 at room temperature and Day 1 and Day 11 of the 250-F exposure.

3. QUESTIONS ANSWERED

In the original proposal, the following questions were predicted to be answered upon completion of the project. The answers generated by what has been learn through

How well do commercially available ultrasonic probes handle extended exposure to high temperatures? Is there a need for more research to develop better, high temperature ultrasonic probes?

The purchased probes from Applus RTD and Imasonic have shown no signs of degradation at 250-F. Currently, the Applus RTD has shown no signs of degradation at 300-F.

What is the performance of high temperature couplant/epoxies when held at elevated temperatures for prolonged periods and are they a viable solution for in-service component monitoring?

The Duralco 4703 epoxy has proven to be stable at temperatures up to 300-F for extended time periods. The Sonotech 1100 couplant has been shown to only be stable up to 250-F. At 250-F, no degradation of the couplant was observed.

What is the best method to monitor internal pipe/vessel components ultrasonically?

This work has shown using basic time-of-flight measurements are capable of at least measuring peak-to-peak displacements as low as 0.020-mm over a frequency range of 17-Hz to 1000-Hz. The upper limitation of the vibration frequency range measurement is limited by the electronic hardware and not the measurement method. The same is true for the lower limit of measuring the vibration amplitude. Thus, the ultrasonic time-of-flight measurement method for measuring vibration amplitude and frequency is definitely a viable method for measuring component vibration frequency and amplitude. Recall that Task 1 revealed that the industry would desire vibration frequency measurements over the range of 0-Hz to 300-Hz and vibration amplitudes with a minimum amplitude of 0.025-mm. Thus, the system meets the minimum measurement criteria preferred by the industry.

4. PROJECT SUMMARY

The stated goal of this work was to develop a versatile system which could accurately measure pipe and valve internal vibrations and cavitation formation under in-service conditions in nuclear power plants, ultrasonically. During the course of this work, Structural Integrity gathered information from industrial that target vibration amplitudes to be detected should be in the range of 0.001-in to 0.005-in (0.025-mm to 5-mm) and target vibration frequency ranges which should be detected were found to be a range from 0-Hz to 300-Hz. During the performed work, an ultrasonic measuring system was developed which utilized ultrasonic pulse-echo time-of-flight measurements to measure vibration frequency and amplitude. The developed system has been shown to be able to measure vibration amplitudes as low as 0.025-mm with vibration frequencies in the range of 17-Hz to 1000-Hz. Therefore, the developed system was able to meet the industry needs for vibration measurement. The developed ultrasonic system was also to be able to measure cavitation formation by monitoring the received ultrasonic signals frequency and time domain signals.

5. FUTURE PHASE II WORK

The Phase II work for this project will involve a much more rigorous investigation of the developed systems capabilities such that in can be accordance with the strict codes and regulations nuclear plant operators must adhere to. The Phase II is currently being projected to be an STTR work, where Structural Integrity Associates, Inc., (SIA) will partner with researchers at the Pennsylvania State University's Applied Research Laboratory (PSU ARL). The researchers at PSU ARL have been world leading experts in the fields of turbulent flow and turbulent flow-induced cavitation since it was established in the 1940's. The facilities at PSU ARL contain several high velocity fluid flow loops, which can accurately control generation of turbulent flow-induced cavitation. SIA and PSU ARL will work collaboratively to determine to determine the following:

- Experimentally and numerically determine to what degree turbulent flow and temperature will have on ultrasonic signals in general.
- Experimentally and numerically determine to what degree turbulent flow-induced cavitation and temperature will have on ultrasonic signals, in general, and how it can be monitored. This will be used to determine what degree of cavitation will develop.
- Experimentally and numerically gain insight on how the development of turbulent flow-induced cavitation in and around valve types commonly found in nuclear power generation industry forms.

Ideally, power plant operators would prefer the measuring system to be able to survive a minimum of one operating cycle, which is typically two years. Therefore, SIA will continue to perform durability testing over the duration of the Phase II effort. This will involve continuing to test the probes obtained for functionality at high temperatures for a minimum of two years, a process which has already begun during the Phase I work. The temperature ranges of the probes will also be increased to 600-F. Additionally, validation of the probes radiation hardness must also be performed. Investigation into epoxies and couplants used will also need to be performed to prove these materials are not corrosive to plant components. In order for vibration amplitude measurements to remain accurate, the velocity of water over a range of temperatures and pressures which are commonly found nuclear power plant service water lines will also require characterization. Furthermore, the electronic hardware of the system will need to be developed in order to withstand the operating conditions found in nuclear power plant environments. Considerable effort will also be given fully characterizing the measuring systems vibration amplitude and frequency measurement limits, and will be upgraded per the needs communicated from SIA's contacts in the nuclear power generation industry.