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Vibro-acoustic Imaging at the Breazeale Reactor

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ABSTRACT

The INL is developing Vibro-acoustic imaging technology to characterize microstructure in fuels and materials in spent fuel pools and within reactor vessels. A vibro-acoustic development laboratory has been established at the INL. The progress in developing the vibro-acoustic technology at the INL is the focus of this report.

A successful technology demonstration was performed in a working TRIGA research reactor. Vibro-acoustic imaging was performed in the reactor pool of the Breazeale reactor in late September of 2015. A confocal transducer driven at a nominal 3 MHz was used to collect the 60 kHz differential beat frequency induced in a spent TRIGA fuel rod and empty gamma tube located in the main reactor water pool. Data was collected and analyzed with the INLDAS data acquisition software using a short time Fourier transform.

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Vibro-acoustic Imaging at the Breazeale Reactor

1. INTRODUCTION

Vibro-acoustics (VA) is an ultrasonic inspection approach that is being developed in the medical field to interrogate material that is highly attenuative to ultrasonic waves. Materials such as dispersion fuels, irradiated fuels, graphite and SiC/SiC composites affect interrogating ultrasonic waves in a similar manner and are difficult to characterize using conventional ultrasonic techniques. As part of this work package, we are characterizing the ability of VA to inspect nuclear fuels, materials, and components that are highly resistant to ultrasonic interrogation. Support for this research is influenced by the demonstration of thermoacoustic (TAC) technology in Breazeale reactor in cooperation with Westinghouse. Sufficient progress was made in FY15 to include the VA technology in the Breazeale reactor demonstration in September 2015.

Work is beginning to develop VA based nondestructive evaluation technologies for nuclear materials and evaluate in-situ VA sensor technologies for reactor environments. Nuclear reactor applications are at an early stage of maturity. However, much of the same data acquisition equipment, methods, and expertise can be leveraged from investments already being made in TAC technology development. VA is based on the low frequency mechanical response of a test sample to two high frequency and focused acoustic waves that interrogate the sample. This technique provides high quality information regarding the structure and elastic properties at a high spatial resolution with good signal to noise ratios from the surface or within a test sample. INL has applied for a patent (13226280, 2011) on the VA technique for non-medical applications. This VA research should position FCR&D and INL as the leaders in this technological development with likely future funding interest from the VHTR, RERTR, and LWR extension programs, as well as interest from commercial power companies, DOD, and materials testing commercial entities.

1.1 Background

Materials such as dispersion fuels, irradiated fuels, graphite and SiC/SiC composites, of interest for advanced nuclear reactor fuels and core components, are difficult to nondestructively inspect via ultrasonics. Their microstructure scatters and attenuates propagating acoustic waves at ultrasonic test frequencies, thereby resulting in low signal to noise ratios for material anomolies or for material characterization measurements. VA is a promising alternative to standard ultrasonics for the inspection of nuclear energy based fuels, materials and components that are highly resistant to ultrasonic interrogation. Research objectives are to develop VA based nondestructive evaluation approaches for nuclear energy based materials and develop *in-situ* VA sensor technologies for reactor environments. Prototype sensors have been developed to determine capabilities and for reactor demonstrations.

As with many advances in the field of nondestructive evaluation (NDE), technologies developed in the medical field have crossed over to industry, e.g., phased array ultrasonics. In this case, INL is leading the VA effort and has the opening intellectual property rights. INL will secure the leadership role to apply VA technology to industrial materials and as a basis for a sensing technology in industrial environments. Successful completion of this research will transfer developing VA medical imaging technology to industry (nuclear, aerospace, and others) to provide new acoustic interrogation approaches to materials that are very difficult to interrogate using conventional or advanced ultrasonic inspection technologies.

1.2 Current Status

VA is an imaging method based on ultrasound-stimulated acoustic emission. VA uses the force caused by the beating of two similar frequencies to generate an acoustic emission signal. Due to absorption or reflection, the energy density in the object at an acoustic focal point changes to produce a radiation force/acoustic source characteristic of the localized material properties. High spatial resolution is achieved since the radiation force is localized to the focal point. A confocal ultrasonic transducer can be designed and built to produce two continuous beams of slightly different frequencies. These beams intersect at the focal point of the transducer on/in the object. The remote intersection and lower frequency beating of the two beams eliminates confounding between the transducer's excitation energy and the object's acoustic emission signal. The acoustic emission from the focal point is detected by hydrophone, accelerometer, or similar sensor technologies. In order to form a 2D image, the area is covered by raster scanning motion of the confocal transducer. Whereas, the stimulation frequency is generally on the order of MHz, the difference frequency (acoustic emission, Δf) is on the order of 10 to 10,000 Hz and can be swept to perform resonant ultrasound spectroscopy. However, there is no theoretical limitation on difference frequency, and it can be adjusted to suit the application. Previous studies have reported Δf from a few hundred Hertz to over 100 kHz.

An example of the VA's potential is seen in recent work at the Mayo Clinic in which proof of concept for characterizing nuclear grade graphite was demonstrated by Dr. Fatemi and his team. They were able to form an internal image showing the microstructure within nuclear grade graphite, see Figure 1. Distinct differences between various grades of graphite were noted in the images. Of particular interest is the difference between the as-received and compressed NBG-18 samples. Based on acoustic velocity measurements, the compressed sample contains damage due to the mechanical loading. Presently time-of-flight/velocity scans are used to ultrasonically characterize distributed damage or porosity distributions within graphite. The porosity or damage will scatter and attenuate the propagating wave thereby reducing the velocity. However the velocity is averaged over the propagation path and does not provide localized information. The focus of this research has been to develop VA methods, algorithms, and hardware that will efficiently image microstructure and effectively interpret the information to provide an assessment of a materials microstructure.

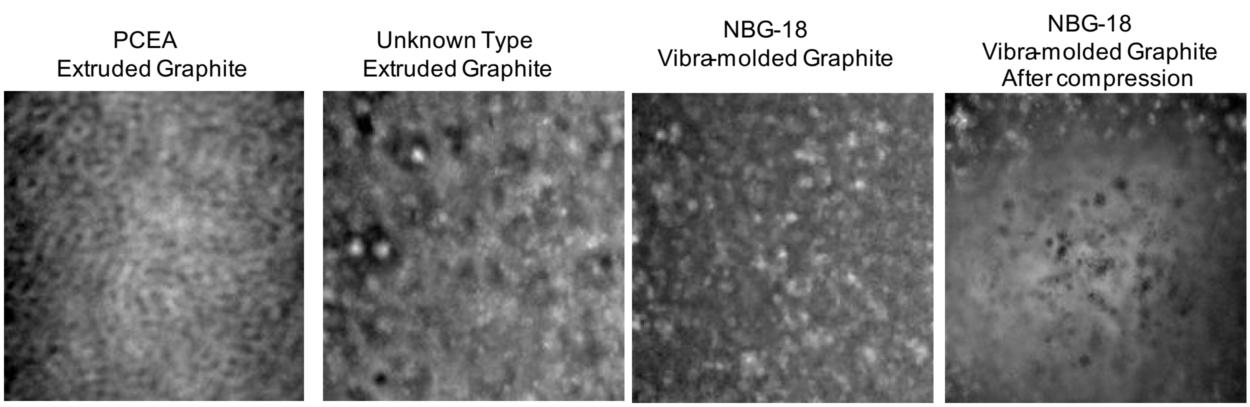
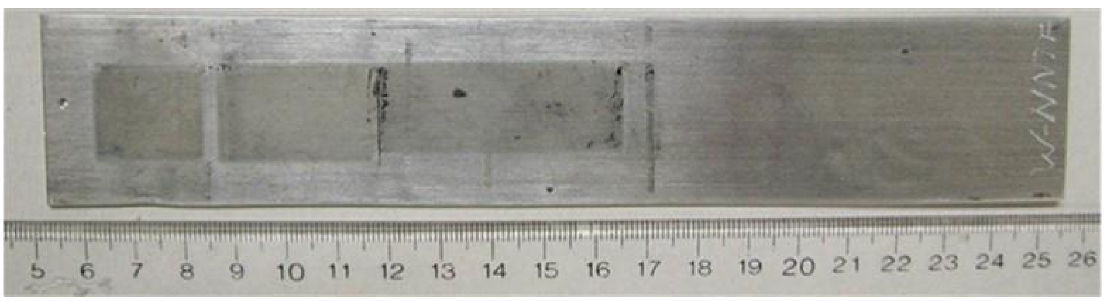


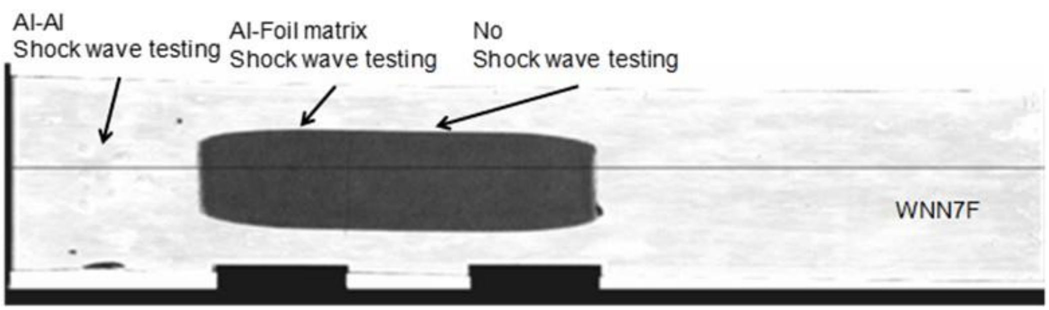
Figure 1. VA images of nuclear grade graphite obtained using a 3.0 MHz confocal transducer, delta f=50 kHz, focus depth=1 cm, 20x20 mm scan area.

Another example of VA's potential is seen in the VA images of a surrogate dispersion fuel plate. The RERTR program has a vested interest in understanding the strength of the fuel cladding interface and the Al-Al cladding bond. The VA technique is able to image the front and back interfaces of the tungsten dispersion fuel. The fuel plate was treated with shockwaves to try to break the Al-Al and Al-Tungsten foil bonds. The shockwaves are powerful enough to create significant plastic deformation in the Al. The results from the front surface interface of the Tungsten dispersion foil are shown in Figure 3 along with comparative images from conventional techniques. The VA technique definitely shows promise and highlights complimentary features as compared to ultrasonic C-scan imagining.

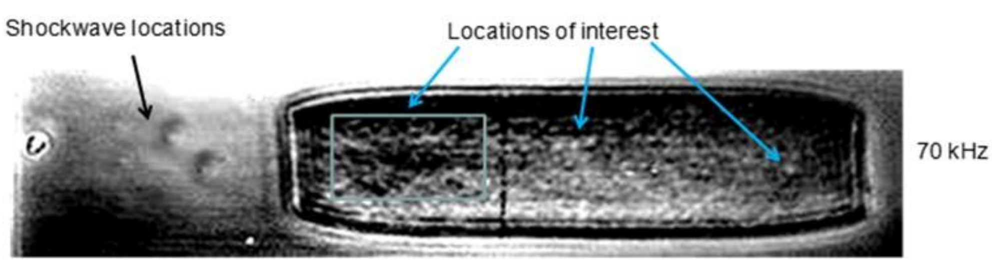
1. Large in-homogeneities within the foil can be seen
2. Front and back interfaces of the foil have been imaged
3. 3 MHz vibro-acoustic image has more detail and contrast than 15 MHz C-scan image
4. Acoustic spectroscopy imagining can be performed
5. Features are emphasized/deemphasized based on frequency.



(a)



(b)



(c)

Figure 2 (a). Photograph of a surrogate tungsten fuel plate that has undergone shock wave testing. (b) INL RERTR Debond C-scan image with ultrasonic through transmission using a 15 MHz center frequency. (c) VA image of the front surface interface of the tungsten dispersion foil which shows finer details than the C-scan image.

The initial VA development at the INL consisted of a single confocal transducer placed in a small water tank. A single hydrophone was placed off axis in the tank, and the transducer was used to image a metal washer as a test object. The experimental setup is shown in Figure 3. The confocal transducer was operated at a nominal 3 MHz, with either transducer being driven at +/- 25 kHz to create a 50 kHz beat frequency between the two transducers. This beat frequency was detected by the single hydrophone placed in the test water tank. As the test object washer was scanned by moving the transducer stage by hand in a horizontal plane across the face of the washer, the amplitude of the beat frequency was captured as a function of the scanning time by the data acquisition system. The image is shown in Figure 4, and indicates the strong peaks across the flat washer face, with the amplitude returning to background levels once the focal point is no longer on the object. From the center of the plot, the scan direction was reversed to demonstrate the reproducibility of the method. Although this initial test was simplistic and unrefined, VA techniques have been demonstrated to yield highly resolved imaging of both nuclear grade graphite and RERTR dispersion fuel plates when matched with precision scanning instruments. This simplistic proof of concept testing was sufficient to develop experience and a VA system capable of imaging in a working TRIGA reactor pool.

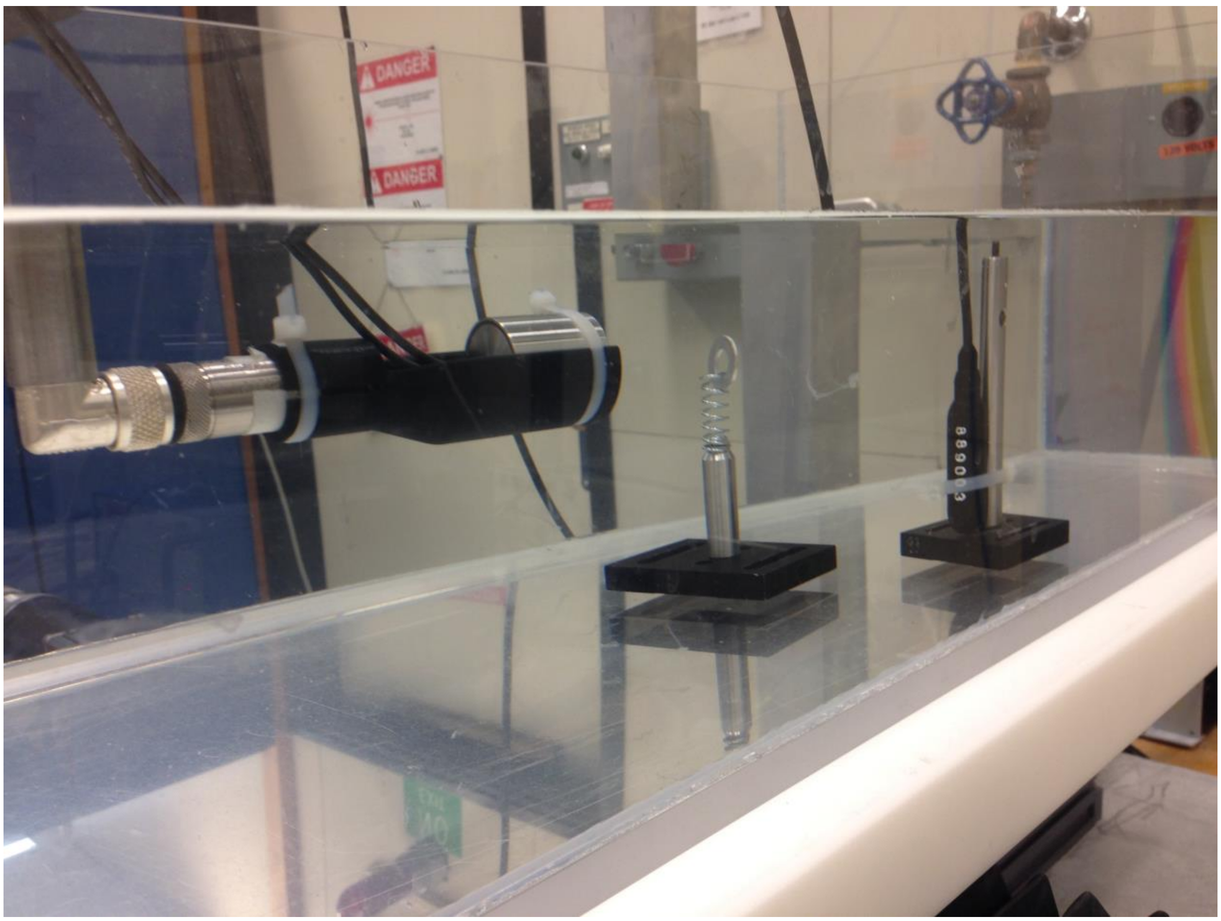


Figure 3. Laboratory experimental setup for initial vibro-acoustics testing. A small, metal washer was imaged with a single hydrophone using the beat frequency of the confocal transducer.

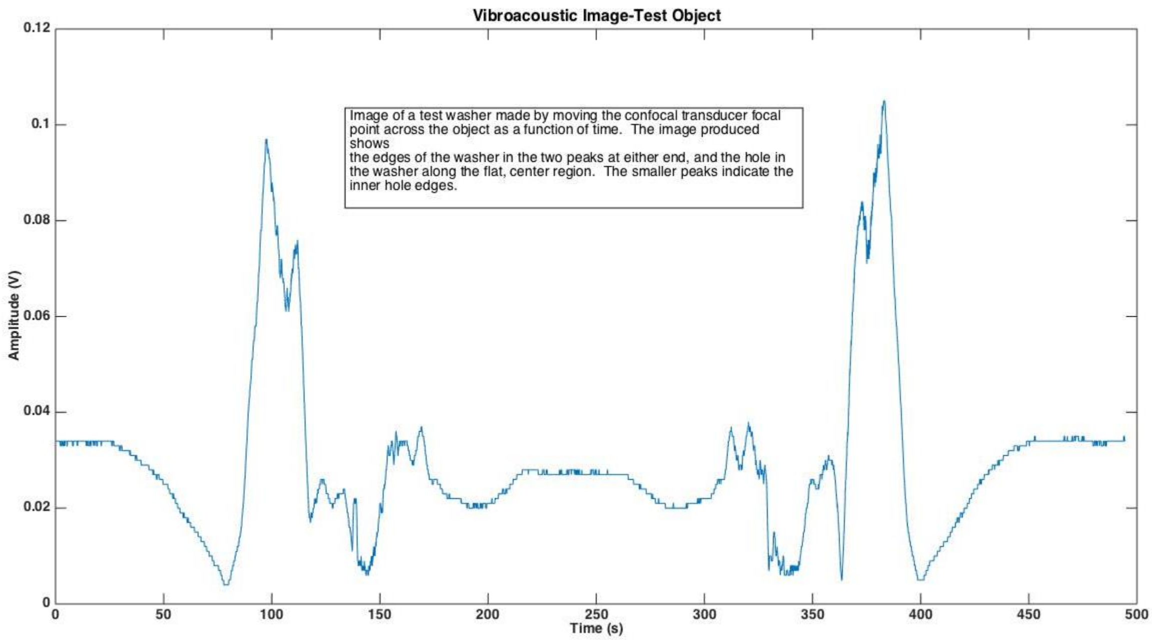


Figure 4. Image of a small washer produced by detection of the beat frequency from a confocal transducer scanned across the face of the washer, showing the major features and reproducibility. Note how the symmetry of the peaks are reversed when the washer is scanned in the opposite direction.

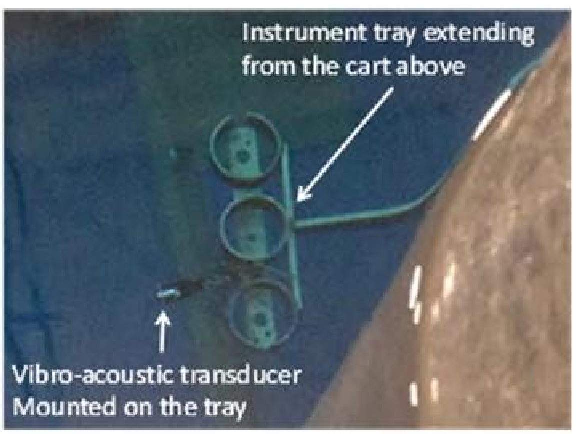
The VA approach can be implemented for a number of different monitoring applications. The most obvious application is its use as an NDE technique to interrogate materials ex-situ as illustrated above. Of primary interest to this report is its application as a sensor technology suitable for in-pool or in-pile measurements, e.g., monitoring fuel-cladding interface interactions. A two-element transducer is placed in the line of site of a fuel pin to be monitored. Typically at the beginning of an irradiation run cycle, the fuel rod diameter is less than the cladding inside diameter. Thus when the ultrasonic transducer is focused on the inner interface of the cladding, a large acoustic signal will be reflected from the gap between the cladding and the fuel. As the fuel rod begins to expand and contact the cladding, the acoustic signal will drop in amplitude as the interface reflection coefficient begins to drop. Diffusion and corrosion in the cladding will transform a sharply defined boundary into a blurred boundary. Any surface cracks or voids cause the interface reflection coefficient to increase, which in turn will generate a larger acoustic signal. In this manner, cracks, voids, corrosion, and diffusion can be detected along the fuel rod/cladding interface. In a similar manner, the VA technique can be used to characterize fuel plate interfaces for monolithic and dispersion fuels.

VA is a natural technology for wireless in-core applications, using the reactor cooling water as transmission and reception conduits. This allows the VA transducer to be at cooler temperatures and at a reduced radiation fields because the transducer can be farther from the component under test. Because the acoustic signal is in the 50 kHz range, the reactor volume is filled with sound for signal reception. The receiver can either be a hydrophone in the reactor or an accelerometer external to the pressure boundary, using the steel as a sound conductor.

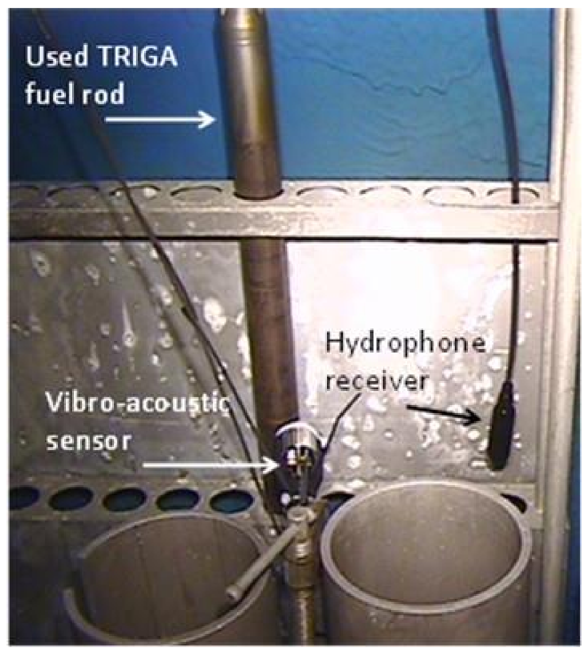
2. BREAZEALE REACTOR MEASUREMENTS

In late September of 2015, a test was performed at the Breazeale reactor at Penn State University. The purpose of the test was primarily to demonstrate an in-core, uranium fueled thermoacoustic (TAC) device that monitored temperature and neutron flux by the detection of sound waves at the reactor pool periphery. The reactor access also allowed for additional testing of the VA system.

A simple VA imaging system was set up at the Breazeale reactor and used to collect data during cooling times between the TAC run cycles. The system used a 3 MHz confocal transducer driven by an amplified and matched sinusoidal wave at 3.030 MHz and 2.970 MHz to give a 60 kHz beat frequency between the two signals. A single hydrophone was placed off-axis of the transducer and used to monitor the 60 kHz signal generated from inducing the vibrational frequency in the test object. Data was collected on the INLDAS data acquisition software through a National Instruments analog to digital converter and a laptop computer. Figure 5(a) is a top down look at the transducer placed in front of a spent TRIGA fuel rod that was available for imaging in a storage rack along the partial wall of the reactor pool. Figure 5(b) shows the vibro-acosutic instrumentation and set-up to "image" the TRIGA fuel rod. Similar position scans were made of the large diameter empty gamma tube shown in the right hand corner of Figure 5(a).



(a)



(b)

Figure 5. (a) Top down view of a VA transducer attached to an instrument tray used to image a spent TRIGA fuel rod located in a storage rack within the Breazeale reactor pool. (b) Figure showing the VA instrumentation and positioning of the VA sensor and acoustic hydrophone receiver. Note that the location of the hydrophone is not critical and is at least 0.3 m from the TRIGA fuel pin.

The transducer was mounted on an instrument tray that is attached to an x-y instrument cart for positioning items within the reactor pool, shown in Figure 6. Due to the very limited positioning resolution and significant backlash, detailed position scans of the spent fuel and gamma tube were not possible. Qualitative scans were made by slowly rolling the cart and transducer from one side of the fuel rod (and gamma tube) to the other, and the resulting data shows the location of the rod (tube). The excellent signal to noise ratio from the fast Fourier transform is revealed in Figure 7 (a) & (b). Figure 7 clearly shows the dominance of the 60 kHz beat frequency between the two transducer driving frequencies when the VA imager is operating.

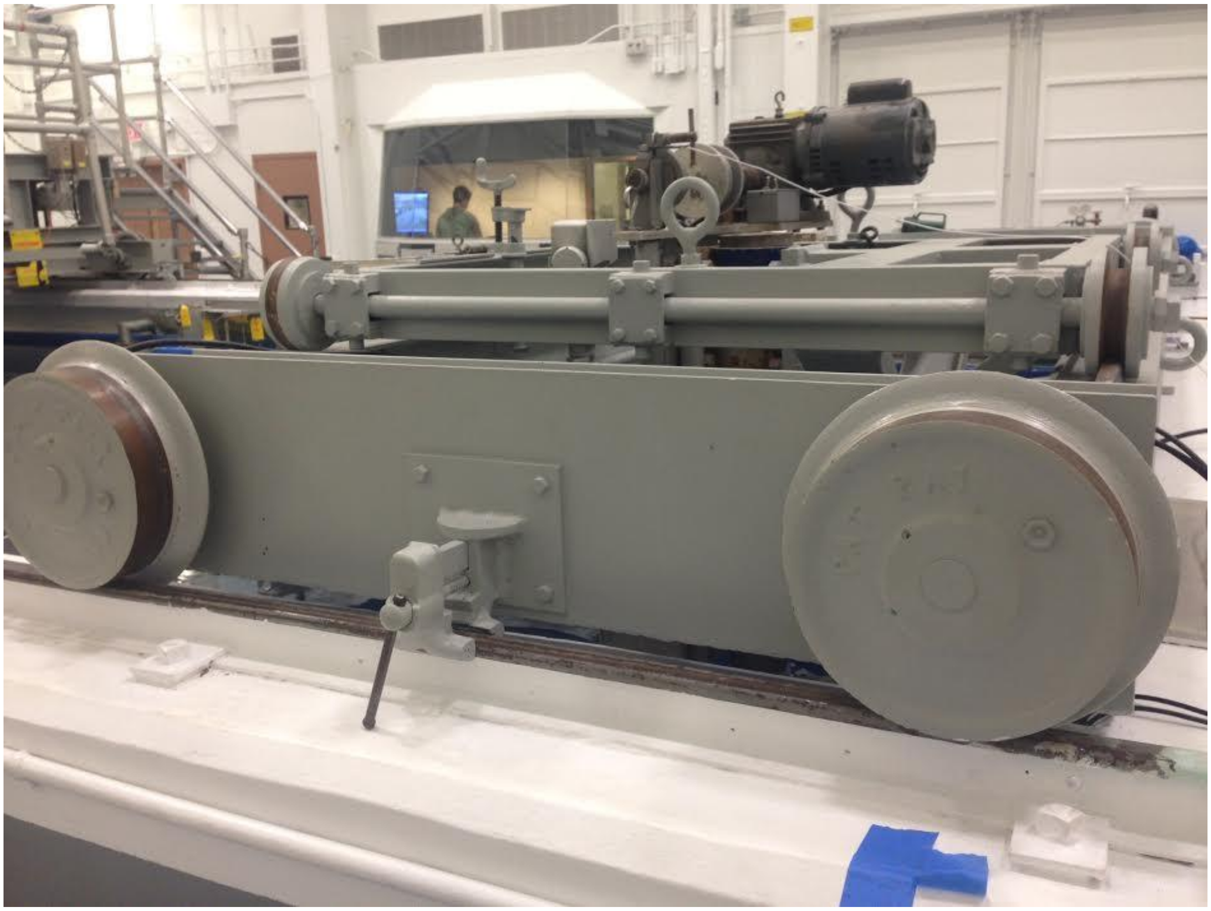
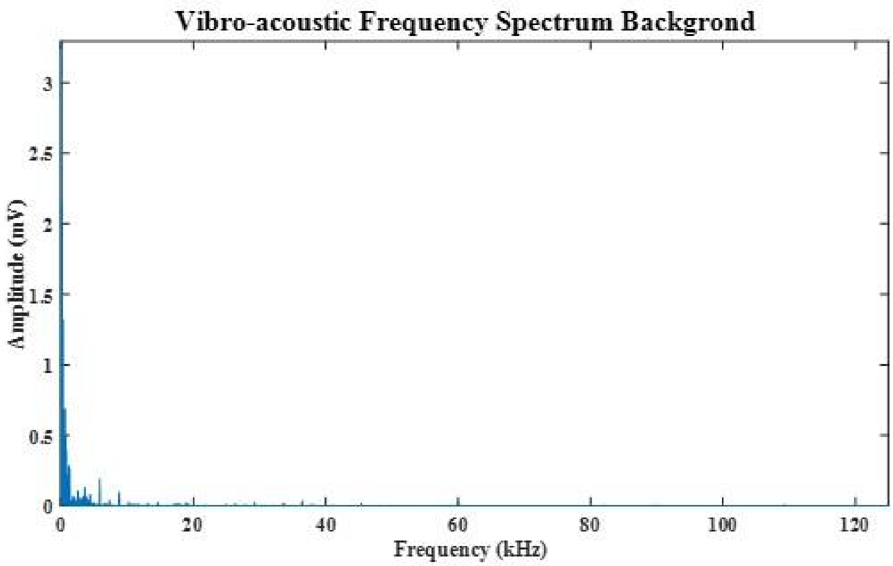
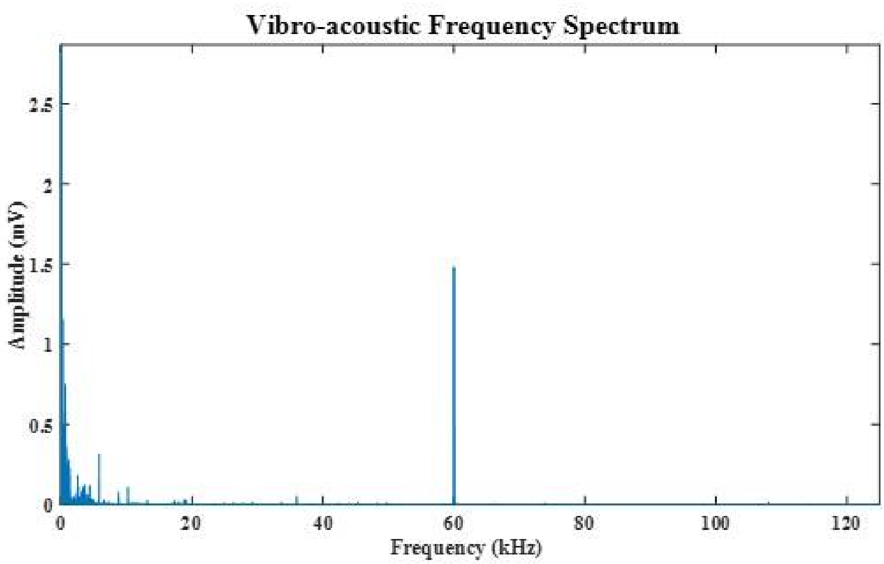


Figure 6. x-y positioning bridge used to mount the transducer. The crude positioning resolution and large back lash severely limited the VA scan detail.



(a)



(b)

Figure 7. The frequency spectrums for hydrophone data taken when all of the reactor pumps were working for background noise only and with the VA sensor operating are displayed. (a) Spectrum showing the noise floor for background noise only. (b) FFT spectrum taken from VA imaging a spent TRIGA fuel rod, showing the dominance of the 60 kHz beat frequency.

The INL DAS system allows for a data collection mode where the amplitude of the maximum frequency component is recorded over time. The instrument cart was moved across the reactor pool width to scan the across the TRIGA fuel rod. Unfortunately, a filter parameter was incorrectly set and only amplitude values at or above 1.0 mv were recorder. Thus Figure 8 shows the binary location of the fuel rod with time as the rod is scanned in one direction and then after a period of time scanned back in the opposite direction. The ability to accurately raster scan and have the full signal dynamic range would enable the VA imaging of structures and components within the reactor pool.

VA was used to measure the wall thickness of a 6.35 mm thick stainless steel dry tube with a 254 mm diameter. The VA signal was maximized at the front surface interface and the back surface interface by moving the instrument cart toward and away from the dry tube. The imaging of the front and back surfaces was performed three times and the travel distance between the two interfaces was 15.9 mm. When refraction and mode conversion to a shear wave is accounted for, see Figure 9, the actual travel distance is estimated to be 15 mm to focus the VA signal on the two surfaces. Tim McJunkin also verified this by developing a ray trace model. Given the constraints on the resolution afforded by the instrument cart, the resulting thickness measurement from focusing the VA signal on the front and back surfaces is promising.

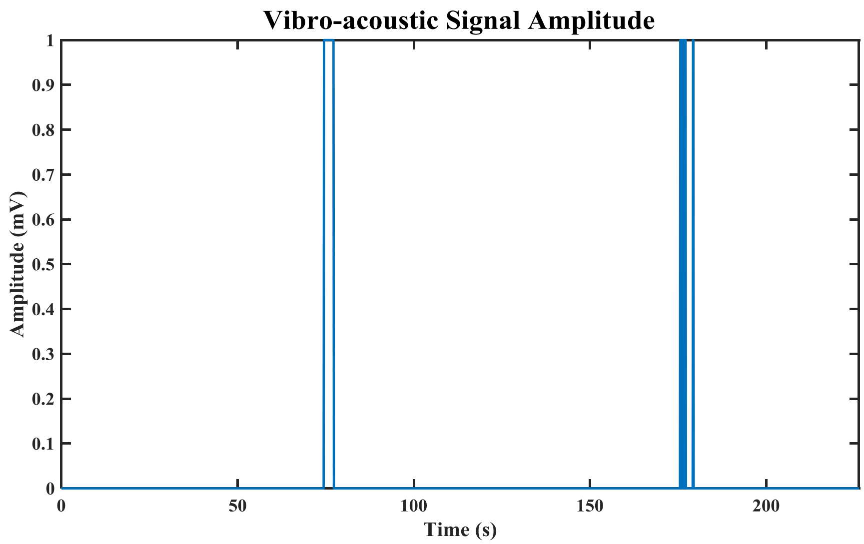


Figure 8. Binary indication in time when the VA sensor was positioned over the TRIGA fuel rod as the instrument cart scanned across the reactor pool and then back.

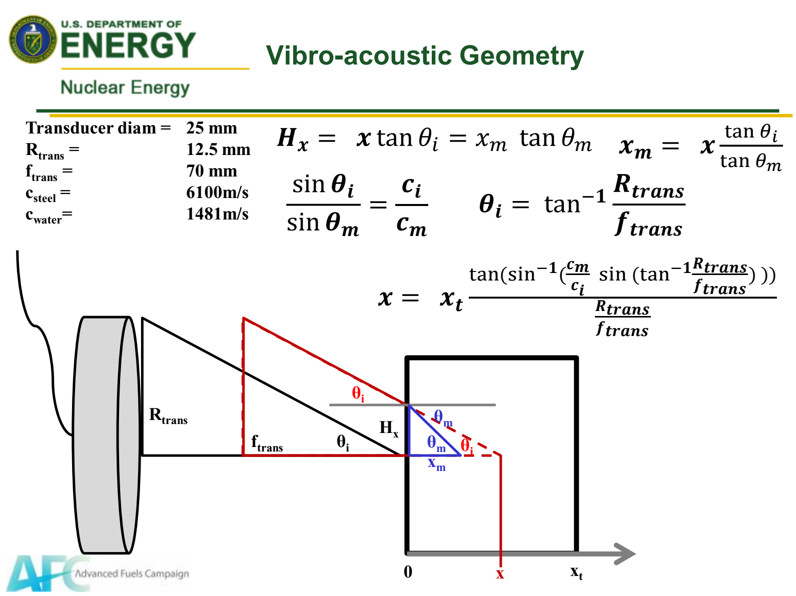


Figure 9. Analytic model used to calculate the distance required to move the VA focus from the front face to the back face of an object to measure the thickness. Note: It is actually the mode converted shear wave that is focused on the back wall.

3. CONCLUSIONS

The FCRD program and INL are working to transfer medical imaging technology to industrial applications. VA imaging technology has significant synergy between medical and industrial applications. The VA imaging technique has already been proven capable of producing high resolution imaging of nuclear fuel and reactor components, and has the potential to provide information not easily obtained with standard ultrasonic methods. The current work leveraged an existing demonstration of TAC technology for in-core monitoring. For minimal cost and effort, the VA system was deployed in the Breazeale reactor pool and used to take initial binary images of a spent TRIGA fuel rod and an empty gamma tube. The crude x-y positioning limited the resolution of scanning, but did allow the demonstration of the VA technique and a measure of the background noise in an actual working reactor environment. Development work will be needed to develop techniques to characterize microstructure, fuel-clad interfaces and other fuel/materials phenomena of interest.