INL/EXT-18-45375
Revision 0

Vibro-acoustic Testing for Microstructure Characterization and Metrology

Technology Commercialization Fund—Fiscal Year 2017

James A. Smith, Anthony L. Crawford, Corrie I. Nichol, Eric D. Larsen, Larry D. Zuck

May 2018

The INL is a U.S. Department of Energy National Laboratory
operated by Battelle Energy Alliance

Idaho National Laboratory

INL/EXT-18-45375
Revision 0

Vibro-acoustic Testing for Microstructure Characterization and Metrology

James A. Smith, Anthony L. Crawford, Corrie I. Nichol, Eric Larsen, Larry D. Zuck

May 2018

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

SUMMARY

There is a need in nuclear reactors to inspect irradiated materials and structures. A portable scanning infrastructure for a material characterization technique called vibro acoustography (VA) is being developed by the Idaho National laboratory for nuclear applications to characterize fuel, cladding materials, and structures. The proposed VA technology is based on ultrasound and acoustic waves; however, it provides information beyond what is available from the traditional ultrasound techniques and can expand the knowledge on nuclear material characterization and microstructure evolution. \

VA technique has several advantages over traditional characterization techniques. VA is a non-contact submersion technique that is inherently wireless transmission and reception (from the ultrasonic transmitter to the acoustic receiver). The transmission medium can be most liquids used for reactor cooling such as water and sodium. For nuclear in-pile applications, the Ultrasonic Transducer (UT) will need to have a line of sight location that is within lower radiation flux zones. Multiple UT sources can be frequency multiplexed to allow a single hydrophone receiver to monitor several locations. The reactor structure can also be an integral part of the transmission system acting as waveguides to deliver the acoustic signal to an acoustic receiver. Because of the long wavelength of the acoustic signal, the acoustic receiver does not have to be line of sight with respect to the component under test. The focusing and generation of the acoustic beat frequency from two ultrasonic waves allows for the potential to ultrasonically image complex shapes. These features will significantly reduce experiment complexity, installation times and cost while being safe and easy to use.

CONTENTS

FIGURES

TABLES

Vibro-acoustic Testing for Microstructure Characterization and Metrology

1. INTRODUCTION

The development of new nuclear fuels and materials for next generation nuclear power plants requires a much deeper understanding of material microstructure and evolution. The fuels and materials must be able to withstand higher temperatures and stresses within the reactor. The ability to obtain greater knowledge of microstructure and thus performance requires better and *in situ* characterization techniques. This need to understand microstructure evolution in hostile environments will lead to effective in-pile and reactor pool measurements for fuels/materials characterization and process control.

Vibro-acoustography (VA) is an ultrasonic inspection approach that is being developed in the medical field to interrogate various tissues, including bone, a biomaterial that is highly attenuative to ultrasonic waves [1-6]. 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. Materials such as dispersion fuels, irradiated fuels, graphite and SiC/SiC composites, of interest for advanced nuclear reactor fuels and core components, affect interrogating ultrasonic waves in a similar manner as porous bone and are difficult to characterize using conventional ultrasonic techniques.

The VA approach can be implemented in different ways. One is to develop and use it as a laboratory NDE technique to interrogate and image materials as suggested above. Another is to implement VA as a sensor technology suitable for in-pile measurements [6]. The long term grand challenge would be developing a VA imaging system that has the capability to monitor fuel-cladding interface interactions. A leading cause of fuel failure is the deleterious interaction between the fuel and cladding.

A two element transducer is placed in the line of site of a fuel pin to be monitored. Typically at the beginning of a radiation cycle, the fuel rod diameter is less than the cladding inside diameter. Thus when the two beams from the ultrasonic transducer are 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, porosity, 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 [6].

The goal of the work discussed here is to develop a characterization system to evaluate *in situ* the ability of VA to inspect nuclear energy based fuels, materials, and components that are highly resistant to traditional ultrasonic interrogation. Development objectives are to advance VA based nondestructive evaluation technologies for nuclear energy based materials and evaluate *in situ* VA sensor technologies for reactor environments. VA is based on the low frequency mechanical response of the test sample to multiple high frequency focused acoustic waves that interrogate the sample. This will provide information regarding the structure and elastic properties at a relatively high spatial resolution with good signal to noise ratios on or within the test sample. This is not always achievable using the responses from a single high frequency ultrasonic interrogating wave.

VA is an imaging modality based on ultrasound-stimulated acoustic emission [1-5]. VA uses the force caused by the beating of two frequencies to generate an acoustic emission signal, see Figure 1. Due to absorption or reflection, the energy density in the object at an acoustic focal point changes to produce a radiation force. This force results in a localized acoustic source whose characteristics are a function 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 as shown in Figure 1. 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 or similar sensor technology. In order to form a 2D image, the whole 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 [5]. 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.

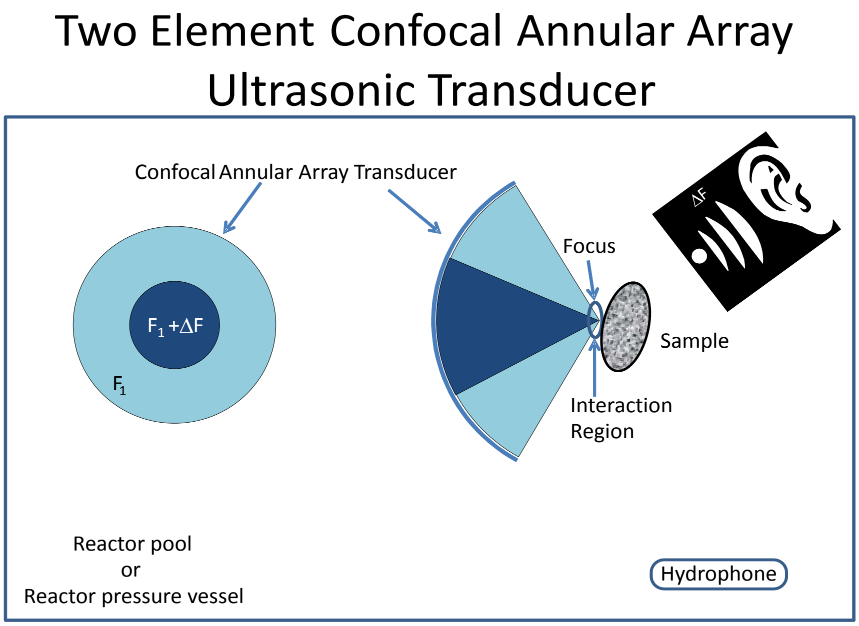


Figure 1. A low frequency acoustic signal is generated by mixing two high frequency ultrasonic signals.

VA technique has several advantages over traditional characterization techniques. VA is a non-contact submersion technique that is inherently wireless transmission and reception (from the ultrasonic transmitter to the acoustic receiver). The transmission medium can be most liquids used for reactor cooling such as water and sodium. For nuclear in-pile applications, the Ultrasonic Transducer (UT) would need to have a line of sight location that is within lower radiation flux zones. Multiple UT sources can be frequency multiplexed to allow a single hydrophone receiver to monitor several locations. The reactor structure can also be an integral part of the transmission system acting as waveguides to deliver the acoustic signal to an acoustic receiver. Because of the long wavelength of the acoustic signal, the acoustic receiver does not have to be line of sight with respect to the component under test. The focusing and generation of the acoustic beat frequency from two ultrasonic waves allows for the potential to ultrasonically image complex shapes. These features will significantly reduce experiment complexity, installation times and cost while being safe and easy to use.

2. PROOF OF CONCEPT TESTING

NOTE: *INITIAL laboratory imaging at the mayo clinic.*

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 for the INL. The Mayo Clinic was able to form an internal image showing the microstructure within nuclear grade graphite, see Figure 2. Distinct differences between various grades of graphite were noted in the images and the texture quantified by the use of an entropy classification technique [7-8]. Of particular interest is the difference between the as-received and compressed NBG-18 samples. Based on more traditional 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 [9-10], see Figure 3. 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 the development at the INL is 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.

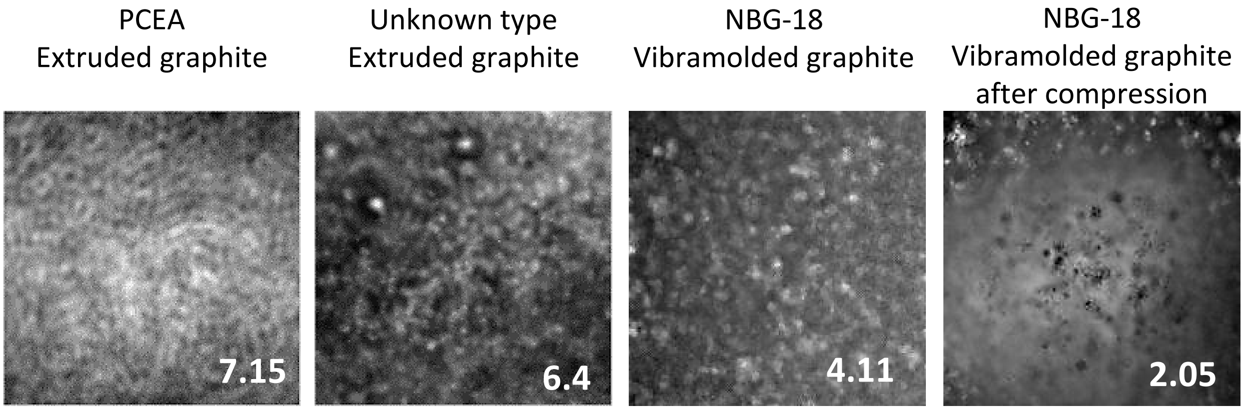


Figure 2. VA images of nuclear grade graphite obtained using a 3 MHz confocal transducer, $\Delta f = 50$ kHz, focus depth = 1 cm, 20 x 20 mm scan area. Numbers at lower right are the image entropy values showing significant texture differences.

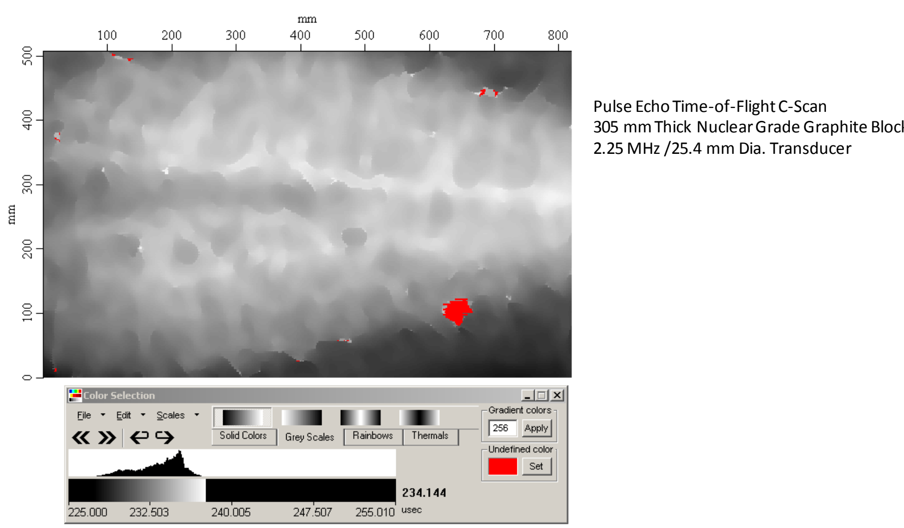
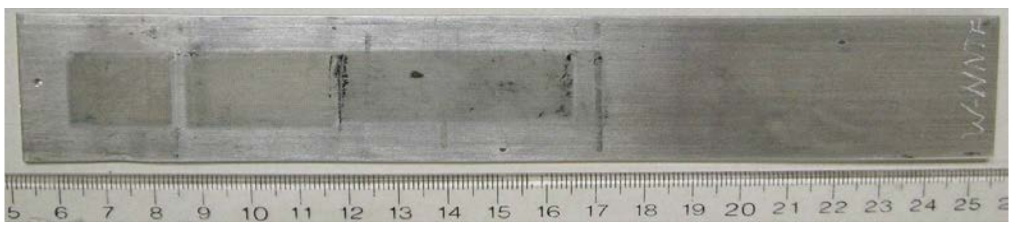


Figure 3. Ultrasonic time-of-flight measurements can be used to identify variations in mechanical properties produced by porosity or distributed damage. Knowing the path length allows an average acoustic velocity to be determined. This block demonstrates significant variations in propagation velocity but time-of-flight measurements do not provide details regarding the specific location of the anomalies along the propagation path (in this case 610 mm).

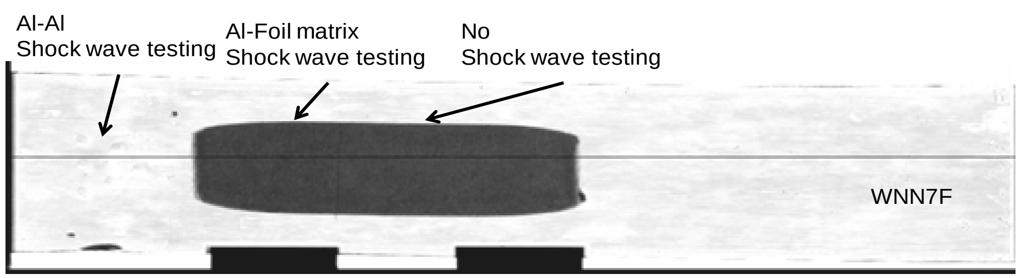
Another example of VA's potential is seen in the VA images of a surrogate dispersion fuel (tungsten particles in an Al matrix) plate. The INL has a vested interest in understanding the strength of the fuel cladding interface and the Al-Al cladding bond. The VA technique is able to image the front and 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 4 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)

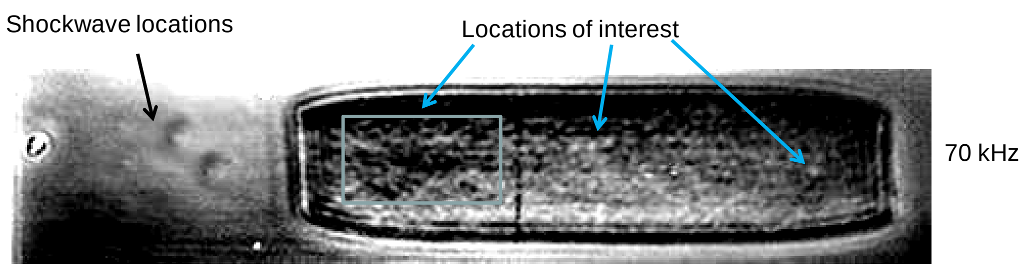


Figure 4. (a) Photograph of a surrogate tungsten fuel plate that has undergone shock wave testing. (b) INL RERTR Debond C-scan image with ultrasonic through transmission using a 15 MHz center frequency. (c) VA image of the front surface interface of the tungsten dispersion foil which shows finer details than the C-scan image.

NOTE: *IN SITU VA SYSTEM DEVELOPMENT*[JAS1][LSW2]

The work performed at the Mayo Clinic demonstrates that VA has potential to be used to image microstructure in nuclear materials. The INL is taking the next step in transforming laboratory VA technology into an *in situ* microstructure imaging system. Figure 5 shows the initial imaging prototype being developed. The system has three Cartesian scanning stages with the dual element ultrasonic source attached to the scanning stages via a rod. The ultrasonic source and the component to be scanned are immersed in a large immersion tank. Because the two interfering ultrasonic frequencies are converted to a single acoustic signal, the placement of the hydrophone within the tank is less critical and does not require line of sight with respect to the ultrasonic source and the component being imaged. This is a definite advantage over traditional ultrasound.

The beat frequency response of the system shown in Figure 5 is plotted in Figure 6. The useable range for spectrographic type measurement and analysis is shown to be approximately from 60 to 130 kHz. The strongest beat frequency for the system is shown to be 100 kHz but all of the testing in this paper has been performed at 80 kHz.

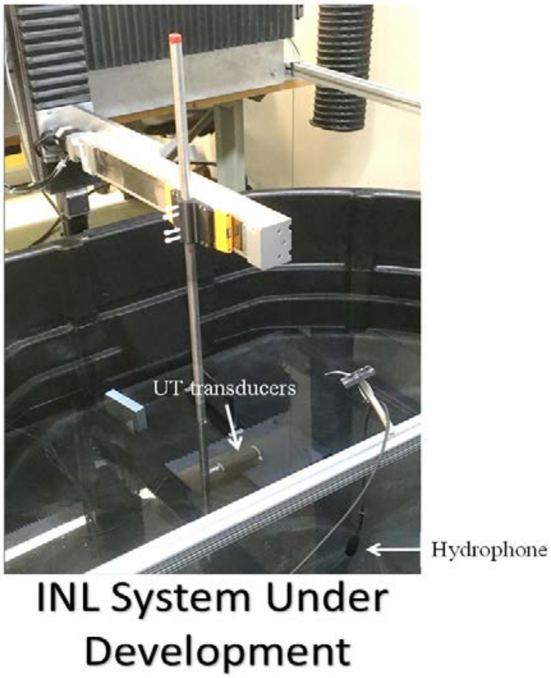


Figure 5. Figure showing the VA system that is being developed for *in situ* materials characterization.

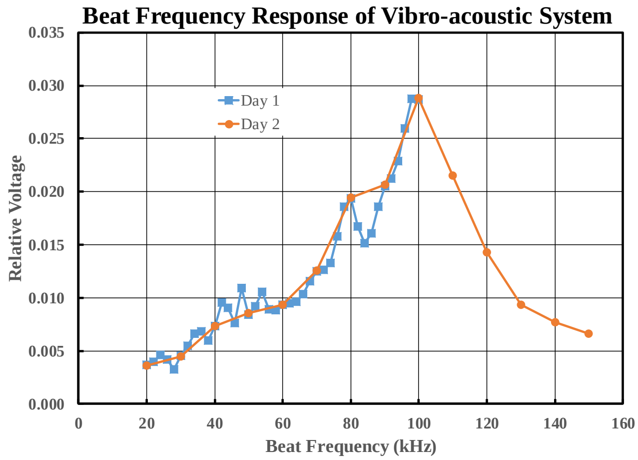


Figure 6. Frequency response of the INL VA system showing that 100 kHz beat frequency has the largest signal response and the useable frequency range for resonant acoustic spectroscopy applications is from 60 to 130 kHz.

The initial images from the *in situ* VA system are shown in Figure 7. A plastic bead was scanned as shown in the far left side of the figure. Note that essentially the entire diameter of the 2 mm diameter of the bead is imaged. Traditional ultrasound would only image the portion of the bead that is normal to the transducer. The images on the right side of Figure 7 are a series of image slices of different types of graphite blocks at differing depths into the blocks. The VA system image several planes with in the graphite over a 2x2 mm area with 0.1 mm increments with a standoff range from 35 mm to 55 mm by 5.0 mm increments.

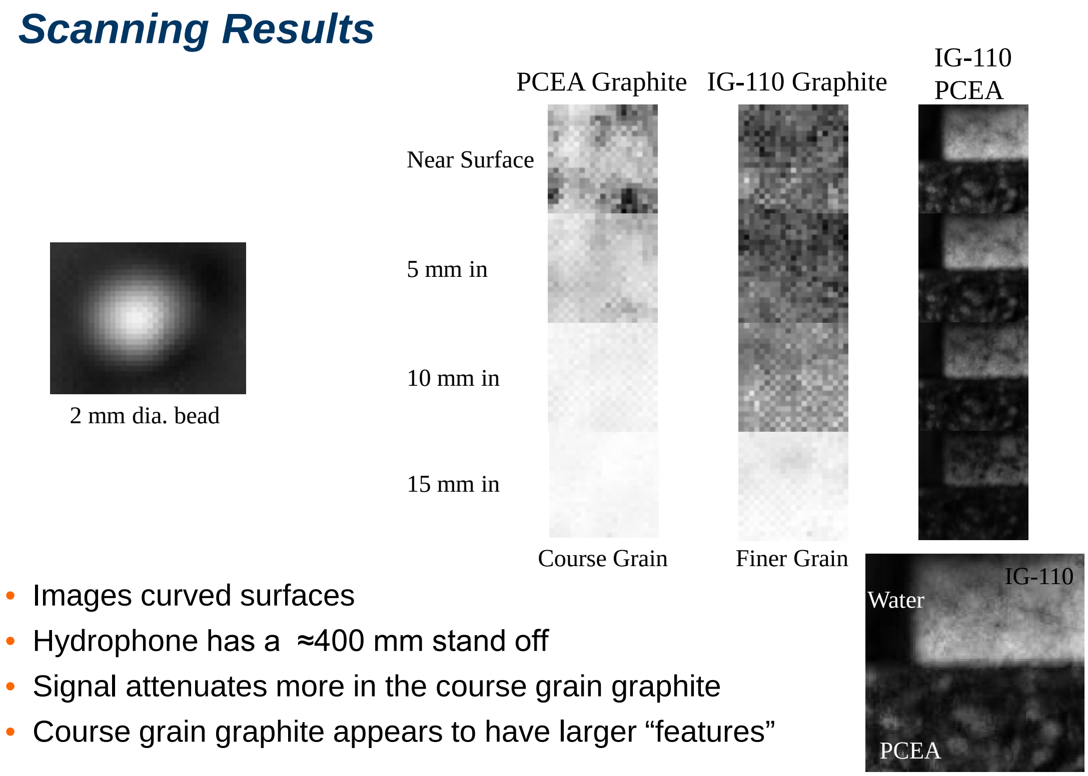


Figure 7. The results from scanning a glass sphere and nuclear grade graphite blocks are shown.

3. MOBILE SYSTEM DESIGN

3.1 Traditional Cartesian Scanning Platform

Once the VA concept was proven, the next step was to make the system portable. The first iteration was to use a traditional Cartesian scanning configuration. This configuration is shown in Figure 8. Unfortunately, the Cartesian configuration did not work. We believe that the torque produced by the scan head and the two other axes on the vertical axis was beyond the manufactures specification. The vertical axis slipped down every time we tried to image. It is unclear as to why the stepper motor encoder did not detect this slippage. We abandoned this platform without producing useful images.

Figure 8. Traditional Cartesian scanning platform is shown.

3.2 Mobile Delta Configuration

This imaging platform relies on a versatile linear delta configuration. This configuration is being rapidly adopted by the 3D rapid prototyping systems (Figure 9) and its sister rotary delta configuration is ubiquitous in pick and place systems (Figure 9). In these configurations, the end effector platform's orientation will never change despite the inputs from the three primary linear actuators to adjust position. The key design feature to ensure this desirable effect is the mechanics which allow the three linkage sets with universal or spherical joints on their ends to always remain in a parallelogram configuration. A table presenting the differences between parallel robots and conventional serial systems, such as robotic arms and gantry-systems, is presented in Table 1.

Figure 9. Linear delta robot [11] (left) and rotary delta robot [12] (right).

Table 1. Comparison between serial and parallel robots [13].

Feature	Serial Robot	Parallel Robot
Workspace	Large	Small and complex
Solving forward kinematics	Easy	Very difficult
Solving inverse kinematics	Difficult	Easy
Position error	Accumulates	Averages
Maximum force	Limited by minimum actuator	Summation of all actuators
Stiffness	Low	High
Dynamic characteristics	Poor, especially with size increase	Very high
Modeling & solving dynamics	Relatively simple	Very complex
Inertia	Large	Small
Areas of application	A great number in different areas	Currently limited
Payload/weight ratio	Low	High
Speed and acceleration	Low	High
Accuracy	Low	High
Uniformity of components	Low	High
Calibration	Relatively simple	Complicated
Workspace/robot size ratio	High	Low

As deducible from Table 1, serial robots and parallel robots have almost completely opposite characteristics. The conventional gantry-type systems, which the flat plate scanner and CGP belong, are serial systems stiffened via wide parallel rails. To summarize the table comparison, serial robots are generally intuitively simple in function but have significant inertial based shortcomings while parallel robots employ less intuitive and complex structures but have significant performance benefits. In addition to their performance benefits the associated system structure also has features which are useful for the radiological canal environment. For this application some of the desirable features are high stiffness, high accuracy, averaging position error, high dynamic characteristics, low inertia, high payload weight, speed, and component uniformity.

The general shortcomings of parallel robots per the table include algorithmic complexity and a low workspace/robot size ratio. The complexity arises in the mathematics and control which requires synchronous coordination between the multiple motors to achieve simple linear motions. Because rotary delta robots are widely utilized in many industries the complexity of their supporting control has largely been solved. Linear delta systems are only a slight variation of such systems and consequently its implementation here is relatively straightforward and thus of minimal risk. With regard to workspace, the data in Table 1 is more applicable to the traditional rotary delta platforms which have workspaces significantly more restricted than linear delta platforms and the necessary positioning and long scan movements needed by the discussed applications are very much complemented by the linear delta geometry.

The following discussion will further elaborate on the benefits generally presented above with regard to each application. For the scanning application; accuracy, averaging position error, low inertia, and speed are particularly applicable in order achieve useful scan data. Although the sensors are of low inertia the movement of the system through water will apply drag and the benefits of the high payload and high dynamic characteristics are also applicable. For the VA application the accuracy and averaging position error characteristics will help achieve the positioning needs while the stiffness and payload characteristics will help maintain the system position/orientation during transducer movement. The linear delta configuration also has an additional benefit in that the motors can functional while also being located distal to the motion platform, a characteristic highly useful for removing sensitive electronics from the hazards associated with the submerged radiological environment for example at the bottom of the ATR canal.

Table 2. System comparison.

	Current CGP	Current Flat Plate Scanner	Conceptual (combined or independent)
Footprint	~4.5’x6’	~3’x8’	<3’ diameter
# of actuators	4	2	(5 for CGP) (3 for Flat Plate Scanner)
# of submerged actuators	4	2	0
Submerged mechanical components	Constantly submerged	Constantly submerged	Most only when in use except 1 bearing and screw
Maintainability	Canal removal and decontamination	Canal removal and decontamination	Actuate platform and direct handle unsubmerged actuators
Software	Inoperable	Inoperable	Identified commercial package
Submerged Age	10 years	10 years	NA

NOTE: *IN SITU VA DELTA SYSTEM* [JAS3]*RESULTS*

The reconfiguration to Delta platform and software updates went surprisingly fast and smoothly. Which enabled the scanning performance of the delta concept to be proven at the tail end of the project for the vibro-acoustics NDE system. VA images were produced with 100 µm resolution data for the Delta configuration shown in Figures 10 and 11.

Figure 10. Mobile Delta imaging platform under development is shown.

Figure 11. Mobile Delta imaging platform is shown in use.

Comparing the Cartesian system shown in Figure 8 with the Delta configuration in Figure 11, one can immediately see the delta configuration is more compact and stable. The Delta stages are solidly affixed to the frame and the stages distribute the loads and torques between all the stages instead of summing the loads and torques as in the Cartesian platform. The scanning head platform is also far more rigid and stable than the Cartesian configuration. The potential down side to the Delta confirmation is that there are more moving structural elements and joints. The distribution of the loads and torques in the Delta configuration allowed for successful vibro-acoustic imaging as shown in Figure 12. The image is the same configuration of graphite blocks as shown in Figure 7. The IGA-110 sample is on top of the PCEA block and water only is to the right and top of the figure. In this figure the edges of the IGA-110 and PCEA blocks can be seen. The edges are obscured by “fringes” that we believe are caused by resonances at the edges. In this particular image, the interface between the two blocks cannot be seen. At this time there is no explanation why the Delta configuration produces resonances like those seen in Figure 4 and yet the stationary VA image shown in Figure 7 is free of resonances for the same graphite blocks.

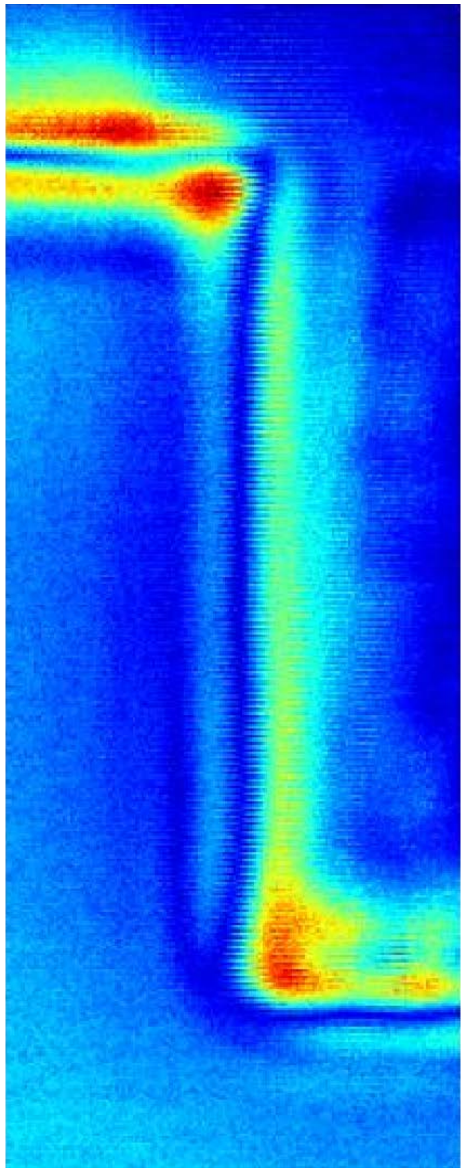


Figure 12. Sample 100 μm resolution scan using an INL developed linear delta platform is displayed.

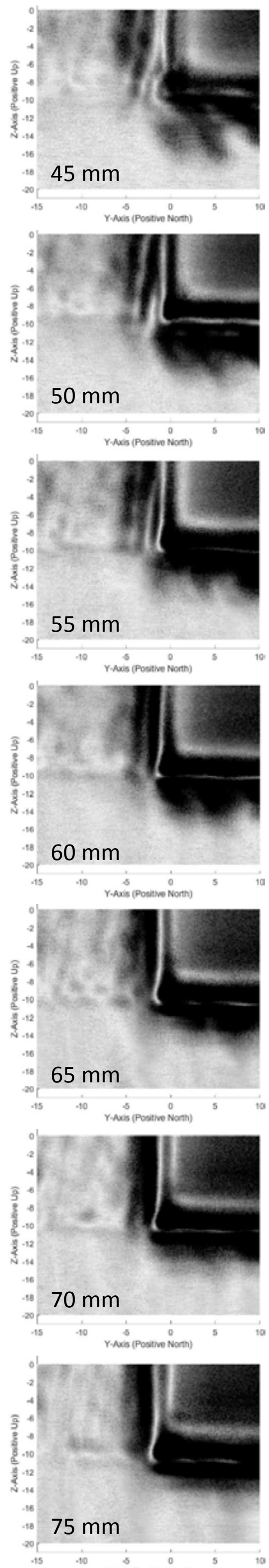


Figure 13. Series of VA images at various distances from the graphite blocks is presented.

Figure 13 shows a series of VA image slices taken at 5 mm increments from the blocks. Note that the resonances at the block edges are still visible. The VA image of the water is uniform throughout the VA slices and distinct differences can be seen between the two graphite types and the interface between the blocks can be seen. It is suspected that the VA shown in Figure 13 are more vibrational in character than microstructural as in Figure 7. Although this project was focusing on the microstructural characterization application, VA is an excellent acoustic spectroscopy technique [1, 5], as suggested by Figure 13, that can be used to characterize materials and structures.

4. CONCLUSION

Vibro-acosutic imaging has originally been developed for the medical imaging of biological tissues and highly attenuative and dispersive biological materials such as trabecular bone. Initial laboratory imaging of nuclear components such as graphite and surrogate fuel plates indicate that VA is a promising technique to monitor microstructure evolution. The design and demonstration of a portable vibro-acoustic testing system for *in situ* microstructure characterization and metrology has been discussed.

The unique characteristics caused by focusing and beating two ultrasonic waves within an object and measuring the resulting acoustic amplitude have been found to provide the following advantages in designing an *in situ* microstructure imaging system. The VA technique is a single sided measurement that works well on curved and complex surfaces and interfaces. VA is particularly good at imaging porosity, voids, and interfaces. Highly attenuative nuclear grade materials in the form of graphite blocks and surrogate fuel plates have been imaged showing the internal macrostructure of the material. The acoustic receiver has shown to have a non-line of sight capability and a stand-off distance of > 400 mm because the low frequency acoustic beat signal fills the immersion tank. The VA system has been shown to have an adjustable beat frequency form 60 kHz to 130 kHz which would enable resonant spectroscopy characterization techniques.

A mobile system was designed and built based on a Delta robot configuration. The mobile system was successfully used to image graphite blocks. The Delta platform appears to enhance the acoustic/vibrational spectroscopy capabilities of the VA technique.

It is clear that our understanding of the capabilities of the VA technique is in the initial learning stage and a significant amount of experience and development needs to be performed to effectively apply VA techniques. VA techniques have the qualities that would enable design of an effective *in situ* characterization technique. The placement of the hydrophone/microphone/accelerometer receivers are not critical since the low frequency acoustic signal fills the volume of the reactor or spent fuel pool. Many sensors can be frequency multiplexed with a single receiver. The VA System is a simplistic imaging technique that is easy to use, flexible, reconfigurable and cost effective due to the ability to use all digital data processing algorithms.

5. ACKNOWLEDGEMENTS

The work at the INL was sponsored by DOE's Office of Technology Transitions under the Technology Commercialization Fund and the INL royalty Funds. The work performed at the Mayo Clinic was sponsored by DOE office of Nuclear Energy under the Fuel Cycle R&D Program.

6. REFERENCES

1. F. Mostafa and J. F. Greenleaf, “Ultrasound-stimulated vibro-acoustic spectrography,” in Science 280(5360), pp. 82–85 (1998)
2. F. Mostafa and J. F. Greenleaf, “Vibro-acoustography: An imaging modality based on ultrasound-stimulated acoustic emission,” Proceedings of the National Academy of Sciences, 96(12), pp. 6603-6608. (1999)
3. M. W. Urban, A. Alizad, W. Aquino, J. F. Greenleaf and M. Fatemi. “A review of vibro-acoustography and its applications in medicine.” in Current medical imaging reviews 7, No. 4 (Bentham Science Publishers, Nov 2011), pp. 350-359.
4. F. G. Mitri, B. J. Davis, J. F. Greenleaf and M. Fatemi. “In vitro comparative study of vibro-acoustography versus pulse-echo ultrasound in imaging permanent prostate brachytherapy seeds,” in Ultrasonics 49, No. 1 (2009), pp. 31-38.
5. M. W. Urban, Glauber T. Silva, J. F. Greenleaf and M. Fatemi. “Multifrequency vibro-acoustography,” in IEEE transactions on medical imaging 25, No. 10 (Oct 2006), pp. 1284-1295.
6. J. A. Smith and D. C. Kunerth, “Vibro-acoustic sensors for materials characterization and related methods and systems,” U.S. Patent Application 13/226,280, (6 September 2011)
7. MATLAB and Statistics Toolbox Release 2016b, the MathWorks, Inc., Natick, Massachusetts, United States.
8. M. Fatemi and F. G. Mitri. “Method for imaging surface roughness using acoustic emissions induced by ultrasound.” U.S. Patent 8,286,467, (16 October 2012)
9. T. R. McJunkin and D.C. Kunerth, “Nondestructive Evaluation of Nuclear-Grade Graphite,” in 38th Annual Review of Progress in Quantitative NDE (QNDE 2011), University of Vermont, Burlington, VT, (17-22 July 2011)
10. T. R. McJunkin and D.C. Kunerth, “Phased Array Ultrasonics and Pulsed Eddy Current Examination for Graphite Components,” the 12th International Symposium on Nondestructive Characterization of Materials (TM) NDCM-XII, Virginia Tech, Blacksburg, VA, (19-24 June 2011)
11. “DeltaMaker 2: An Elegant 3D Printer” [Online]. Available: https://www.deltamaker.com/products/deltamaker-delta-robot-3d-printer [Accessed: 2-29-2016]
12. “ABB will Feature Robotic Picking, Packing and Palletizing Demos at Pack Expo 2016,” Robotics Industry News, November 01, 2016. Online: https://www.robotics.org/content-detail.cfm/Industrial-Robotics-News/ABB-will-Feature-Robotic-Picking-Packing-and-Palletizing-Demos-at-Pack-Expo-2016/content_id/6296 [Accessed: 2-29-2016]
13. Z. Pandilov, and V. Dukovski, 2014, “Comparison of the Characteristics between Serial and Parallel Robots”, Acta Tehnica Corviniensis- Bulletin of Engineering, Tome VII (2014), pp. 144-160