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Task Title: Applications of Computational Reliability Analysis to Airframe and Engine Needs

Investigation Team: J. Gray, J. Xu, F. Inanc, T. Jensen, industrial partners at Boeing-Seattle, Boeing-Long Beach, Honeywell, and Pratt & Whitney as well as at several airlines.

Students: Y. T. Loo, Y. Chen, and W. Yan

Program initiation date: Program initiated as IA003, June 1, 1998 with scheduled ending date of March 31, 2002.

Objective:

- To apply the simulation code, XRSIM, to industrially related problems.
- To extend the models as necessary to support the analysis of real problems.
- To develop a PC version of the code for transfer to commercial use.
- To integrate theoretical and experimental results developed as part of the grain diffraction effects task as available.

Approach:

Over the last few years, XRSIM has been used for a number of industrial problems with many useful requirements being defined to be addressed as part of this program. First, a PC version will be developed to provide for wider application; second, tools to develop simple part geometries for use in XRSIM will be supplied; third, a library of CAD shapes and a means to manipulate the sizes and assembly of these shapes will be completed; and, fourth, a simple means to calibrate the x-ray tubes and films used in XRSIM will be supplied. Specific applications will also be addressed with the industrial partners. This include the extension of XRSIM to include grain diffraction effects common in nickel super alloy investment castings; the evaluation of detectability limits of ceramic inclusions in titanium turbine blades; the use of XRSIM to evaluate the detectability of water in honeycomb; the evaluation of weld repairs; the development of crack detectability standards and limits; and the use of XRSIM in training. As part of this effort, we will continue to work with a number of industrial contacts including Douglas, Boeing, Pratt, United Airlines, American, and GE in transferring XRSIM to industrial use.

Progress (March 2002):

Over the last six months the work has focused on extending the capabilities of XRSIM. These extensions are mainly motivated from interaction with Boeing, Rolls Royce, Pratt & Whitney, and Howmet. A contract was also established with Rolls Royce to extend the capabilities of XRSIM in a complimentary way to the FAA funded program and discussions are underway for cost share funding from Pratt & Whitney. Recent improvements included detector characterization using the absorbed dose method. We have added a new detector type, namely an amorphous silicon array detector. Since lead screens are often used in radiography, the film response to lead screens was characterized and added to the detector model.

XRSIM now includes the new film response as measured for AGFA D2, D4, D5, and D7 films with and without lead screens. The validation results from the XRSIM predictions for the film response with and without lead screens is accurate to ~10% of the absolute density. We also examined the efficiency of the isotope source model for XRSIM. This model resulted is some long execution times, times that are no longer necessary. Code to improve the computational efficiency of the isotope source model was added and lead to improvements of a factor of 67.

We continued to test the lead screen model by examining the contribution of the intensification by the two screens. Surprisingly the back screen contributes a greater scattering amount than the front screen. This is due to the fact that forward direction scattering (-/+30 degrees) for photon scattering is much more likely than backscatter. This can be seen from the Klein-Nishina formula. If the photon is scattered in the forward direction the electron is more likely to be scattered in the back direction. Since electrons are responsible for the intensification effect and since the forward scattering of the photon is the more likely event, the back screen contributes more electrons to the film than the front screen. This result was confirmed with experimental observation. Measurements for the dose versus detector response for the Varian amorphous silicon array detector were made. This involved the measurements of the spectrum incident on the array. An absorbed dose for the detector is calculated for the incident spectra. This is necessary since the incident x-ray spectrum from the tube is made up of a range of energies at varying intensities. Each energy in the spectrum is absorbed in varying amounts. In order to determine the quantum efficiency of the detector, the material and any material between the sample and the active element of the detector must be known. This information allows the absorbed dose to be computed. The result is a universal response curve that is independent of the amount of filtration occurring either due to filters or variable part thickness.

We have added an image manipulation window to XRSIM as requested by several users. This feature allows images to be viewed and manipulated that are stored on the hard drive. Several common formats can be read, although care needs to be taken regarding the bit depth of an 8-bit jpeg image versus a floating point XRSIM image. At present floating point images consisting of the density, as well as standard bmp, jpg, pgm, 16-bit tif and several proprietary CCD camera formats can be read and files can be written out in these formats.

Due to the large number of recent additions to XRSIM, including lead screens effects, a digital detector, refined build-up factor scattering model, new CAD models for complex flaw shapes, new image formats and several speed optimizations, a set of validation measurements are underway on the base model. This includes the measurement of the scattering effects and a comparison to the two scattering models presently used.

The scattering model used in XRSIM is a buildup factor. Measurements of the scattering in steel and aluminum were preformed to evaluate this scattering model. The measurements were taken with the sample close to the film. This measurement includes both the scatter flux from the part and the transmitted beam. The film is moved from the part to a distance of 18”. The scattered flux from the part radially diverges to about 1% of the value next to the part. The result is a measure of the scattered flux. The build up factor works very nicely for these materials accounting for the 5% difference observed in earlier experiments.

At present the blurring from various sources of unsharpness are modeled by convolving a blurring kernel with the image generated by XRSIM. The size and shape of the kernel control the amount of unsharpness. In this model the blurring is measured from the edge spread function, a measurement done by digitizing a piece of film containing an edge. We used a lead strip to provide a high contrast edge. The resulting image is differentiated to produce the point spread function used in the blurring kernel.

We have also started preparation of the final report for this task. A completion date for the first draft is the end of May.

Plans (April 1, 2002 – October 31, 2002):

Complete final report for this task.

Milestones:

Original Date	*Revised Date*	*Milestone*	*Status*
6/1/98		*Start date*	
		Phase I	
Quarter 1		Integrate isotope beam model into XRSIM. Begin development for XRSIM generator calibration standard.	Completed
Quarter 2		Complete CAD library of simple CAD parts. Begin modeling of anisotropic effects, grain scattering.	Completed
Quarter 3		Add CAD cracks to flaw library.	Completed
Quarter 4		Complete PC Windows graphical interface for XRSIM.	Completed
		Phase II	
Quarter 5		Begin simple CAD model builder. Begin beta testing of PC XRSIM.	Extended to quarter 7 Completed 12/99
Quarter 6		Add inclusions to CAD flaw library.	Completed
Quarter 7		Complete XRSIM generator calibration standard.	Completed
Quarter 8		OPEN GL visualization interface for the PC XRSIM. Complete grain diffraction model for XRSIM.	Open GL interface complete, grain diffraction moved to 9
Quarter 9		Complete flaw library for XRSIM. Begin beta testing for OPEN GL version of XRSIM.	Completed
Quarter 11		Complete under cut model for XRSIM.	Completed
Quarter 12		Complete CAD model builder.	Completed

Deliverables:

Original Date	*Revised Date*	*Deliverable*	*Status*
		Phase I:	
		Interim and final executable versions of XRSIM installed at the W.J. Hughes Technical Center and at AANC	
		Interim report on capability and features of XRSIM.	Completed, XRSIM manual.
		Phase II:	
		A report on the establishment of protocols for application XRSIM. .	
		A final report on the capabilities and features of XRSIM.	

Major Accomplishments and Significant Interactions:

Date	*Description*
9/98	Non-disclosure agreement signed with Boeing for release of CAD models
12/98	Development of a new film model which includes most industrial film types and manufacturers.
3/99	Boeing CAD models for 757 electrical access door successfully imported.
9/99	Scattering model development began. Transport equation approach found a factor of 40 faster than Monte Carlo.
12/99	Beta version of PC XRSIM released to Rolls Royce, Allison, Howmet, Boeing, Pratt, AlliedSignal, and Boeing, Long Beach.
6/00	Scattering code running simple geometries. Completed Rolls Royce specified additions to XRSIM (separate contract).
12/00	Unsharpness models complete. Geometric, undercut, and film unsharpness modeled as a blurring convolution with specified kernel.
3/01	Flexible crack flaw model added to flaw library.
6/01	Lead screens response characterization complete.
9/01	Scattering code running of 64 node linux cluster.
12/01	Amorphous silicon array detector added to XRSIM.
3/02	Validation studies complete, 5-10% difference observed in XRSIM vs. experiment.

Publications and Presentations:

B. Crouse, J. Gray, B. Larson, 'Technology Transfer Using XRSIM as a Training Tool', Review of Progress in Quantitative NDE, vol.17,p 2085, eds. D. Thompson and D. Chimenti, Plenum Press, 1998.

G. Tillack, V. Artemiev, J. Gray, The Effects of Scattered Radiation in X-ray Techniques-Experimental and Theoretical Considerations, Review of Progress in Quantitative NDE, vol18A, p631, eds. D. Thompson and D. Chimenti, Plenum Press, 1999.

J. Gray, G. Tillack, X-ray Imaging Methods over the Last 25 Years: New Advances and Capabilities', vol. 20A, p16, Eds. D. Thompson and D. Chimenti, American Institute of Physics, 2000.

S. Wendt, J. Gray and S. Beckman, Energy Dispersive Measurements of Anisotropic Diffraction Mottling Effects, vol. 20a, p514, Eds. D. Thompson and D. Chimenti, American Institute of Physics, 2000.

T. Jensen and J. Gray, Evaluation of Large Area Amorphous Silicon Array X-ray imager, vol. 20b, p 1860, Eds. D. Thompson and D. Chimenti, American Institute of Physics, 2000.

J. Gray, Recent Developments of an X-ray Simulation Tool, Modeling of Casting, Welding and Advanced Solidification Processes IX, Des P. Sahm, P. Hansen and J. Conley, Shanker, 2000.

Task Title: Understanding of Anisotropic Effects on Inspectability of Aerospace Materials: Radiographic Inspection of Complex Geometries

Investigation Team: J. Gray, T. Jensen, Iowa State University; Steve LaRiviere, Boeing-Seattle; and Kevin Smith, Jeff Umbach, Pratt & Whitney; with participation also expected from Howmet and United Airlines in the implementation of final techniques.

Students: S. Beckman

Program initiation date: Program initiated as IA004 June 1, 1998 with scheduled ending date of March 31, 2002.

Objective:

- To improve the fundamental understanding of anisotropic material properties on radiographic inspection capabilities, utilizing titanium, nickel, and other alloys as available.
- To incorporate the anisotropic scattering phenomena into the appropriate models.
- To utilize the results to improve the ability to sense and characterize casting defects in large-grained nickel alloys by improved radiographic techniques in conjunction with image processing and classification.
- To implement the results of this effort into the inspection of static parts in cooperation with Pratt & Whitney, AlliedSignal and United Airlines, including improvements to radiographic inspection techniques by minimizing the effects of diffraction mottling on images.

Approach:

Grain diffraction effects cause considerable difficulty in the evaluation of radiographic images both at production and inservice inspection of cast components such as static parts, blades, and structural airframe components. Welds exist in most static components, either as repairs or in attachments of flanges, bosses, and other geometric features. Anisotropy effects cause concern for both ultrasonic and radiographic inspection. The effect of diffraction for large grain conditions will be developed as a function of grain orientation, shapes, and sizes on the radiographic film response. Radiographic inspections of cast components and welds sometimes show effects due to the diffraction of the x-ray beam by large crystals in the sample which appear as dark spots or lines on the film. Sometimes referred to as ghost cracking, the effects can mimic porosity defects or cracks in the sample. A perfectly good part may be rejected because of difficulty in distinguishing between a diffraction signal and a true defect. Alternatively, a defect may be accepted. This problem occurs both in production inspection of cast components as well as inspection of inservice weld repairs. Improved methods of performing radiographic inspections to minimize these diffraction effects would be beneficial for both safety and cost reasons for the aviation industry. Samples of nickel and titanium will be collected that represent the range of anisotropic conditions found in normal casting processes through cooperation with the industrial partners. Materials characterization approaches based on energy sensitive radiography measurements previously developed at ISU will be used to determine the optimal filter materials for radiographic inspection of nickel and titanium. Filters will be fabricated for validation at industrial radiography facilities at the OEM (P&W), their supplier (Howmet), and the airlines (United). Similar effects exist in airframe cast components. ISU will work with Boeing to further define applications of interest and implement tools as appropriate.

Progress (March 2002):

Anisotropic Material Characterization

In the past six months two areas had noteworthy progress, namely, characterization of the high energy contribution to the mottling and the development of a model to account for the quantity of mottling and streaking observed in the radiographs.

The experimental work was focused towards further examining the contribution of the high-energy spectrum to grain diffraction. An experimental setup to look at some of the predicted elements of the diffraction model was set up, figure 1. We are using an aluminum single crystal to evaluate the model. We evaluated the experimental effects of the high-energy portion of the beam from a 250kVp tube by using a very thick filter (8mm) of copper. As the part increases in thickness, the material filters larger amounts of the energies below 120 keV. This helps in reducing the magnitude of the mottling effects, figure 2.

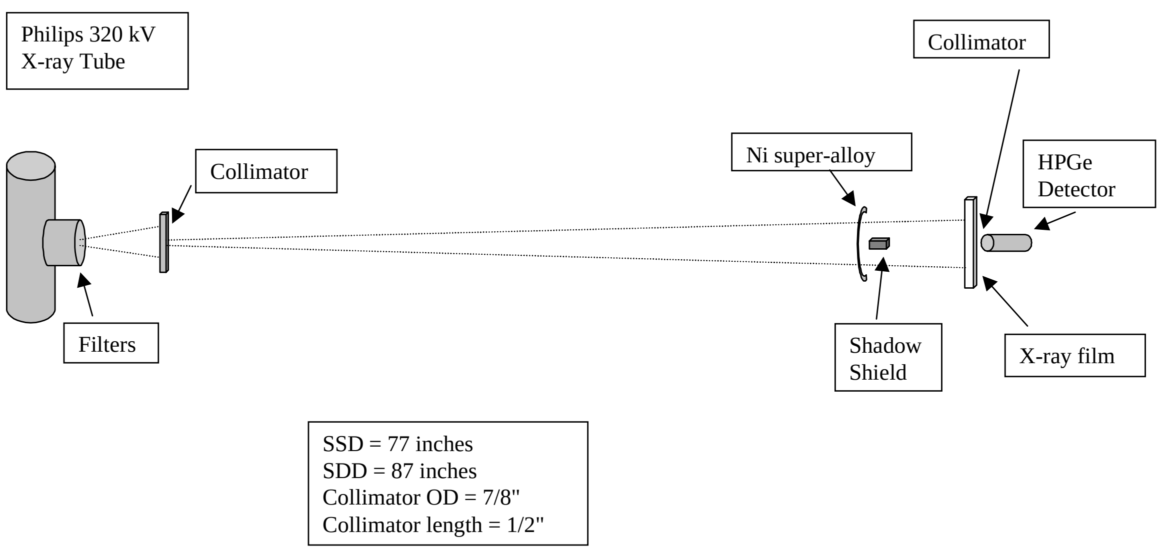


Figure 1 Experimental setup for high energy effects on mottling.

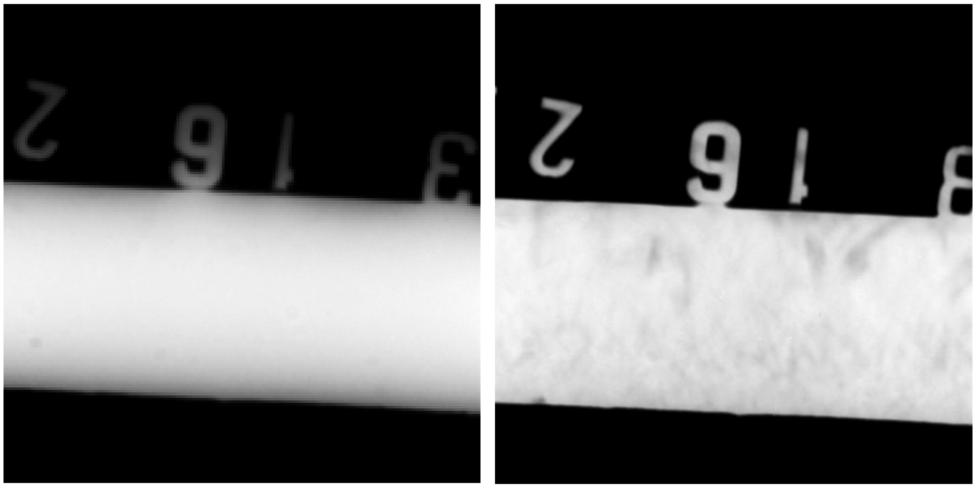


Figure 2 At high energy (200kvP) reduced mottling radiograph is shown on the left. The image on the right is for a low energy, 85 kvP. There is a reduction in the contrast sensitivity observed for the high energy image.

We began evaluating a new approach suggested by the recent data of applying an auto correlation between two images taken with different energies. The diffraction pattern from the two images will be different while the result from porosity will be the same. The auto correlation between these two images should reveal the occurrence of pores. The software was developed to run an auto correlation routine between the two images. The results were modestly successful. This is due to relatively small changes in the diffraction patterns at the energies selected. We are continuing to look at several filters and the effect of orientation of the sample. Past results have shown that 5-10 degrees change in the orientation can significantly change the pattern. This application of orientation while tedious with film is very easy to do with real time detectors and will be the focus of future efforts.

In the parallel modeling effort we have added several new features. One of the issues in comparing two mottled radiographs taken with different orientations is the intensity of the diffraction spot. This intensity effect can have an influence on the observed level of correlation. We examined the magnitude of the diffraction spot by looking at the intensity of the peaks as a function of crystal size. A set of aluminum samples were used with crystal sizes ranging from 5 mm down to typical micron grain sizes. The result was as expected, a general decrease in the diffraction spot intensity as the grain size decreased. The grains in the nickel superalloy vary over a range of sizes from a few millimeters down to a few 10's of microns. Given that the thickness of the diffuser casing can be as small as 7 mm, we have a situation where the grains can be almost as large as the thickness of the part. This means that the diffraction spots act in a manner like surface roughness. This is important for the modeling of the effect on the radiograph of the grain diffraction.

In the model development we added the energy effects of the diffraction. This is necessary to account for the spread observed in the diffraction peaks from a single crystal orientation. The different energies of the white spectrum diffract at different angles as shown by the Bragg diffraction condition: const=E$\sin\theta$. The Bragg condition implies a single spot, contrary to the observations. The proposed solution was that the white spectrum from the tube generated a range of diffraction angles as a function of the incident energy. We have now modeled this contribution and observe a smear in the single energy diffraction spot. Images from the modeled white energy spectrum generating diffraction effects show that the streaking can be accounted for by the energy distribution in the incident beam. Preparation of the results in the XRSIM modeling final report began.

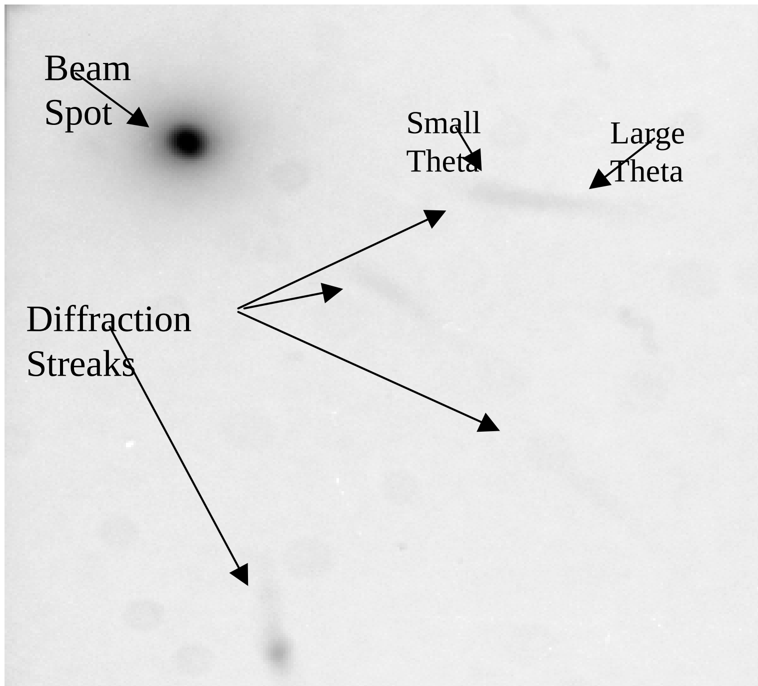


Figure 3 The main beam from the tube is tightly collimated illuminating a few grains. The diffraction from those grains is seen to be a streak on the radiograph.

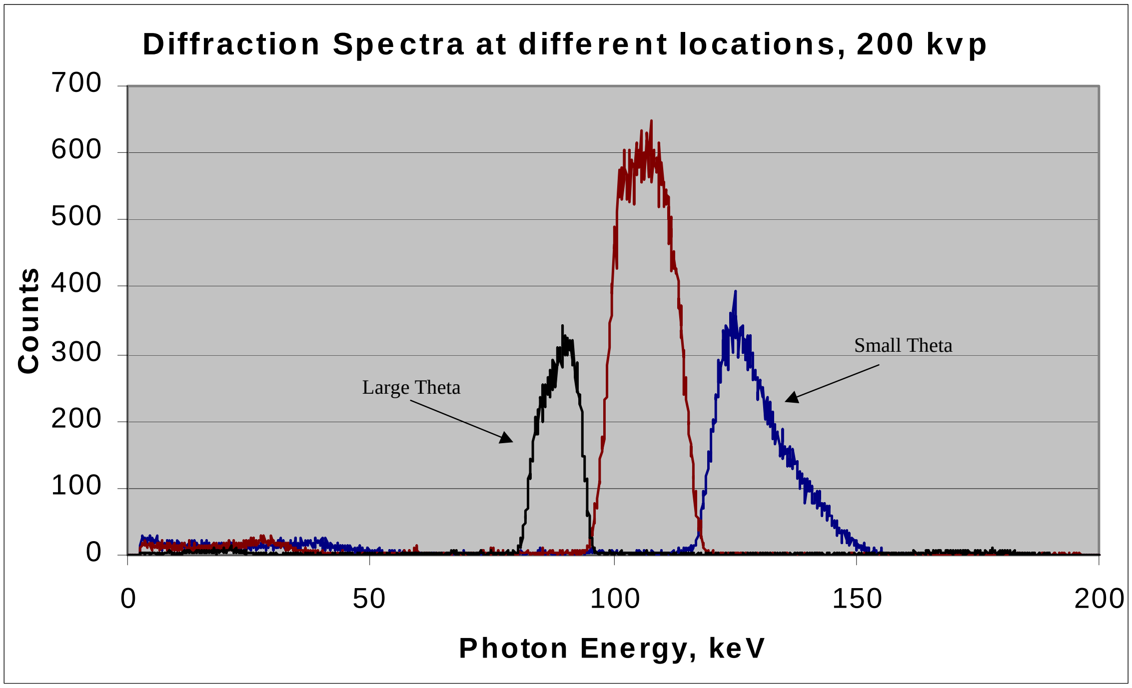


Figure 4 Energy dispersive measurements taken from one of the streaks in figure 4. The location along the streak was changed for each of the three spectra. The wide range of energy is due to the incident white spectra from the tube.

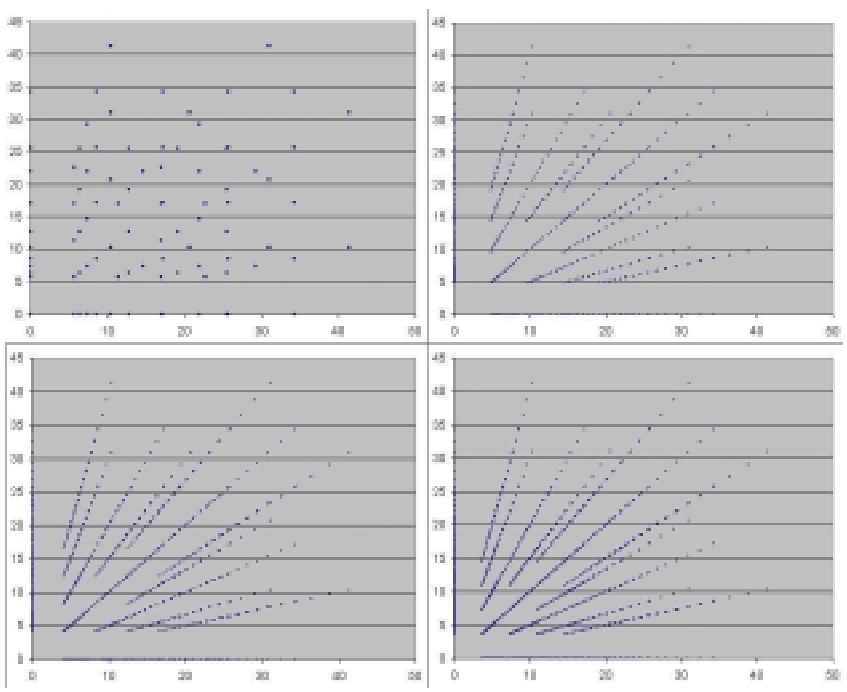


Figure 5 Results from diffraction from a single crystal in a particular direction as a function of energy.

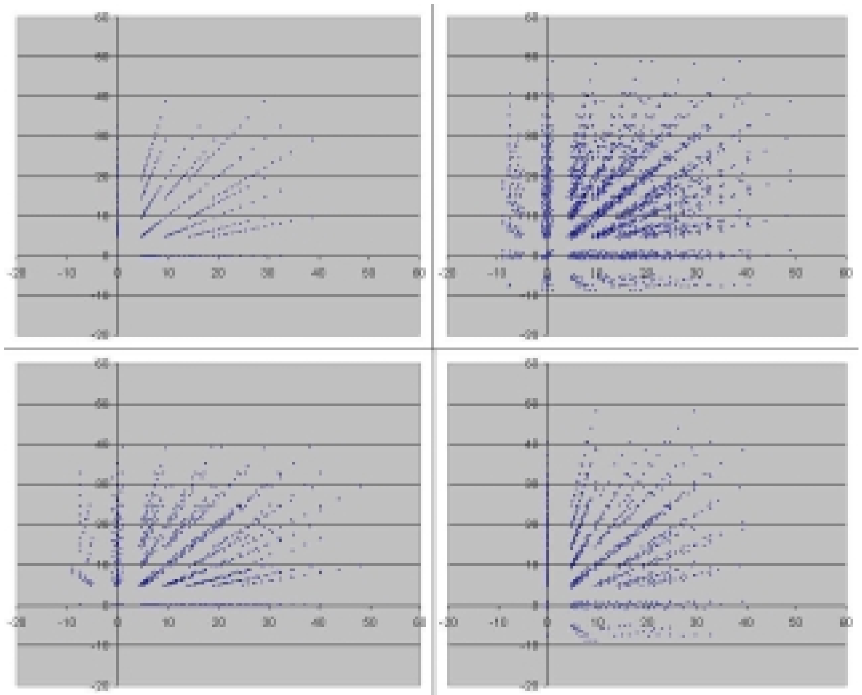


Figure 6 Results from diffraction from a single crystal as a function of energy and with different crystal orientations. The radial smearing is observed experimentally.

Plans (April 1, 2002 – October 31, 2002):

Prepare final report.

Milestones:

Original Date	*Revised Date*	*Milestone*	*Status*
6/1/98		Start date	
		A. Microstructural effects on inspectability.	
		Phase I	
Quarter 1		Develop experimental plan with industry partners including validation and implementation.	Completed
Quarter 3		Develop sample set, including weld repair samples.	Completed
		Phase II	
Quarter 6		Characterize samples using radiography.	Completed
Quarter 8		Develop grain orientation images and correlate to other measurements.	Completed
Quarter 10		Demonstrate enhanced x-ray technique. Initiate transition to OEMs.	Completed
Quarter 12		Transition betasite test to supplier facility.	Completed
Quarter 15		Final report.	In progress
		B. Radiographic modeling improvements.	
		Phase I	

Original Date	*Revised Date*	*Milestone*	*Status*
Quarter 1		Begin development of porosity flaw model in XRSIM.	Completed
Quarter 3		Begin development of grain diffraction modeling.	Started
		Phase II	
Quarter 5		Complete integration of porosity model into XRSIM.	Completed
Quarter 8		Incorporate scattering and diffraction effects into XRSIM. Initiate validation efforts.	Begun
Quarter 12		Complete model validation with industrial partners.	
Quarter 15		Complete final report.	

Deliverables:

Original Date	*Revised Date*	*Deliverable*	*Status*
		Phase I:	
		Interim report on experimental and model development including validation plan.	Completed
		Phase II:	
		Final report on the capabilities and features of the effort including industrial applications	

Major Accomplishments and Significant Interactions:

Date	*Description*
1/01	Model for diffraction from a single crystal developed on PC platform.
6/01	Hybrid filter demonstrated to remove most of the mottling effects.
8/01	Presentation of results at Review of QNDE meeting.
9/01	Multiple grains added to model.
12/01	High energy effects on diffraction evaluated, no significant
3/02	Grain size effects on mottling magnitude modeled.

Publications and Presentations:

S. Wendt, J. Gray, and S. Beckman, Energy Dispersive Measurements of Anisotropic Diffraction Motteling Effects, vol 20A, p. 514, eds. D. Thompson and D. Chimenti, American Institute of Physics, 2000.

T. Jensen and J. Gray, Evaluation of Large Area Amorphous Silicon Array X-ray imager, vol 20B, p 1860, eds. D. Thompson and D. Chimenti, American Institute of Physics, 2000.

Task Title: Optimized Ultrasonic Techniques for Detection and Sizing of Defects in Multilayered Structures

Investigation Team: I. N. Komsky and J. D. Achenbach

Students: None

Program initiation date: Program initiated as IA005 June 1, 1998 with scheduled ending date of June 30, 2002.

Objective:

- To support the application and transfer of dual probe ultrasonic techniques in the detection, characterization, and sizing of defects in multilayered aircraft structures.

Approach:

Detection and characterization of defects in the second or third layers of multiple-layered aircraft structures has proven to be a major problem in nondestructive inspection of aging aircraft. Generally, such structures consist of aluminum-alloy structural components with a sealant in the interfaces and joined by rivets or bolts. The second or third layer defects may be regions of corroded material, stress corrosion cracking, or fatigue cracks emanating from fastener holes. Ultrasonic techniques have proven to be effective in those cases where sealant is present between the layers. The ultrasonic technique generally uses a combination of pitch-catch and pulse-echo configurations with wedge-mounted transducers which produce inclined angle beams of vertically polarized transverse waves. A time-of-flight diffraction technique and satellite echoes can also be used for specific applications. A careful selection of the most effective type of ultrasonic waves and transducer provides optimal detection and imaging of defects in the second or third layer.

In the work that has been carried out thus far, optimization of transducer configurations, data selection, and interpretation for different layer thickness and other geometrical variations have been achieved by research personnel in a time-consuming ad-hoc manner by trial and error. However, in practice the equipment has to be operated by trained inspectors who must be provided with operational protocols, which systematize the applications of the technique. The following work is therefore proposed for a systematic procedure:

1. Develop a procedure to determine optimal measurement model based on the spatial orientation and sizes of structural elements (fastener holes) and defects (cracks).

2. Develop a procedure to determine optimal transducer configuration based on simple modeling, supported and verified by experimental results.

3. Define specifications for optimal data selection for maximum information contents of images.

4. Produce an appropriate decision-making algorithm for defect characterization using measured data when imaging is undesirable or not necessary.

Progress (March 2002):

New crack sizing techniques have been demonstrated to Northwest Airlines NDE staff. Application of the technique to the second layer inspection of the DC-10 #2 engine pylon has been discussed.

The section of the DC-10 horizontal stabilizer was acquired from Northwest Airlines. The ultrasonic technique for crack sizing and the scanning procedure was tested on the aircraft part with actual cracks. Multiple sets of data have been acquired using new scanning systems to image actual fatigue cracks in the stabilizer.

New specimens have been received from Cessna to continue work on the inspection techniques for the Citation 7 lower wing spar. Dual-transducer scanning technique demonstrated sufficient sensitivity during tests on the Cessna spar specimen. All artificial cracks in the third layer of the multi-layered airplane structure have been successfully detected through two sealant interfaces. Multiple echo-dynamic curves have been acquired for the crack characterization. It was demonstrated that the combination of pulse-echo and through-transmission modes could increase substantially signal-to-noise ratio (20-30 dB depending on crack depth) and would also improve accuracy and reliability of crack sizing.

Plans (April 1, 2002 – October 31, 2002):

Inspection procedures will be developed for DC-10 horizontal stabilizer and Citation 7 lower wing structure. Applications of dual-probe crack sizing technique will be demonstrated to NWA and Cessna inspection teams. The technique and procedures will be validated on in-service airplanes. Report on optimized techniques for crack characterization and inspection procedures for industrial applications will be completed.

Milestones:

Original Date	*Revised Date*	*Milestone*	*Status*
6/1/98		*Start date*	
		Phase I	
Quarter 1		Consult with Boeing on specific configurations to be considered. Formulate spec for optimal detection and data selection for max information content of images.	Completed
Quarter 2		Specify with Boeing, suitable test specimens for simulated cracked or corroded structure.	Completed
Quarter 3		Develop procedure for selection of measurement model.	Completed
Quarter 4		Initiate test of measurement models by field experiments.	Completed
		Phase II	
Quarter 5		In coordination with Boeing evaluate options for “plug-in” hardware modules.	Completed
Quarter 6		Develop and fabricate a prototype system.	Completed
Quarter 7		Complete decision-making algorithm for defect characterization.	Completed
Quarter 8		Implement an operational protocol to optimize transducer configuration and a data-selection algorithm for imaging applications.	Completed
Quarter 9		Implement defect characterization algorithm for non-imaging applications.	Completed
Quarter 10		Validate techniques on in-service aircraft structures.	Validation tests are being scheduled
Quarter 11		Receive industry response and revise the procedure and protocol if necessary.	Imaging and characterization procedures have been demonstrated to QMI and American GFM Corporation.
Quarter 12		Complete technology transfer.	Ongoing

Deliverables:

Original Date	*Revised Date*	*Deliverable*	*Status*
		Phase I:	
		Report on specifications for optimal inspection system configuration.	Ongoing
		Software which allows the inspection engineer to specify optimal inspection parameters for a dual probe ultrasonic inspection system.	
		Phase II:	
		Report on procedures for optimal acquisition, analysis, and display of dual probe inspection data including industrial applications of the technology.	Ongoing
		Data acquisition, analysis and display software for a commercially available ultrasonic inspection system.	

Major Accomplishments and Significant Interactions:

Date	*Description*
April 1998	Feasibility of the ultrasonic inspection of a T-chord in the Boeing 777 multilayered wing structure has been demonstrated to Boeing NDE personnel.
September, 1998	Calibration specimens manufactured by Boeing have been used for the sealant assessment in the Boeing 777 multilayered wing structure.
November, 1998	Calibration specimens manufactured by Boeing have been used to develop ultrasonic technique for crack detection in the Boeing 777 multilayered wing structure.
March, 1999	Experimental fixtures were designed and manufactured to provide access for ultrasonic transducers to the wing locations under doublers.
April 1999	New transducer coupling system is being developed. The coupling system is designed to provide a method of assuring constant acoustical coupling during a contact ultrasonic test.
November, 1999	Design and manufacturing of the novel interchangeable transducer holder for ultrasonic scanning of areas with limited access using angle-beam contact transducers was completed. The holder was tested on the representative specimens and cutouts from the Boeing 777.
March, 2000	Manufacturing of the prototype miniature flexible scanner for ultrasonic inspection of aircraft structures with curved and spliced surfaces was completed. Ultrasonic images of the Cessna specimens along with the portable units for data acquisition were demonstrated to Jay Amos of Cessna during his visit to Northwestern University.
July-December, 2000	New inspection procedure for crack characterization in the multi-layered aircraft structure has been tested on the Cessna 650fwd-2 specimens. The results have been sent to Cessna and discussed with Cessna NDE Staff.
January-March, 2001	Two inspection procedures have been developed for KC-10 applications and tested on the representative specimens. The results have been sent to Boeing. Imaging and characterization techniques have been demonstrated to QMI and American GFM Corporation.
April-September, 2001	New crack sizing ultrasonic technique for crack sizing using portable ultrasonic flaw detectors has been developed.
October 2001-March 2002	New crack sizing technique has been demonstrated to Northwest Airlines NDE staff. The technique and the scanning procedure were successfully tested on the DC-10 and Citation 7 structures that were acquired from NWA and Cessna.

Publications and Presentations:

"Optimization Of A Scanning Procedure For Ultrasonic Characterization Of Radial Fatigue Cracks", Annual Review of Progress in QNDE, Snowbird, Utah, July 20-24, 1998.

"Ultrasonic Maging Of Fatigue Cracks Around Fasteners In Multilayered Airplane Structures", Proceedings of the 1998 Advances in Aviation Safety Conference & Exhibition, SAE, 1998.

"Ultrasonic Imaging Of Cracks In Aging Aircraft Structures", Paper Summaries of the 1998 ASNT Conference, ASNT, 1998.

"Ultrasonic Imaging Of Fatigue Cracks In Multilayered Airplane Structures With Limited Access", in NDE of Aging Aircraft, Airports, and Aerospace Hardware, Proceedings of SPIE, 1998.

“Ultrasonic Characterization Of Radial Fatigue Cracks In Aging Airplane Structures”, in NDE of Aging Aircraft, Airports, and Aerospace Hardware, Proceedings of SPIE, 1999.

“Application Of Ultrasonic Line Scanning To Sizing Of Fatigue Cracks In Airplane Structures”, Proceeding of The Second Joint NASA/FAA/DoD Conference on Aging Aircraft, NASA, 1999**.**

“Quantitative Characterization Of Cracks Using Ultrasonic Imaging”, Presented at QNDE 2000, published in Review of Progress in QNDE, Volume 20.

“Modular Imaging Systems For Ultrasonic Evaluation Of Aircraft Structures”, Proceedings of the International Symposium on Nondestructive Testing Contribution to Infrastructure Safety Systems in the 21st Century, Torres, Brazil, 1999.

“Modular Systems For Ultrasonic Imaging In Manufacturing”, Proceeding of National Manufacturing Week Conference 2000, NAM/ASME, 2000.

“Quantitative Characterization of Flaws Using Modular Inspection Systems”, Presented at ATA NDT Conference 2000.

“Accuracy Of Fatigue Crack Characterization Using Ultrasonic Scanning”, presented at QNDE 2001.

“Ultrasonic Techniques For Sealant Evaluation In Airframe Components”, presented at QNDE 2001.

“Portable Ultrasonic Systems For Quantitative Characterization Of Fatigue Cracks In Aging Aircraft”**,** Proceeding of The Fourth Joint NASA/FAA/DoD Conference on Aging Aircraft, NASA, 2001

“Multi-Element Adjustable Transducer Arrays For Ultrasonic Scanning Of Aging Aircraft”, in Proceedings of SPIE, 2002.

Task Title: Technical Support and Coordination of Inspection Activities

Investigation Team: L. Brasche, Iowa State University

Students: None

Program initiation date: Program initiated as IA006 June 1, 1998 with scheduled ending date of April 30, 2002. No cost extension request to be processed.

Objective:

- To work with industrial leaders in the areas that impact life management including inspection, materials design and processing, and lifing/risk analysis to understand the areas where airworthiness assurance research is needed.
- To utilize input from these disciplines to define a research program that is responsive to the safety requirements of the FAA and the economic considerations of the industry.
- To work with academic partners of AACE to match their capabilities with the research needs defined by the industry and the FAA.
- To coordinate the inspection related programs with other activities in propulsion, advanced materials, and structural integrity to ensure full leverage of the results.
- To support the transition of technology from FAA R&D programs through coordination with industry, FAA personnel, and AANC.

Approach:

NDE techniques are critical to the production and inservice operation of aviation components, both aircraft and propulsion. NDE is applicable to process sensing as well as detection of damage or defects. Understanding the role of NDE in the overall life management of aviation components and systems is essential to the definition, development, and implementation of a successful R&D program. FAA CASR program management has established a strong network with government, industry, and academic participants in inspection related activities as evidenced by the strong industrial support of the proposed program. The CASR program manager will continue to work with FAA-TC inspection staff to develop and implement reliable and cost-effective inspection tools for application by the aviation industry.

Progress (March 2002):

The CASR programs were reviewed by the TCRG in early November 2001. Presentations that focused on the products and benefits of each of the tasks were provided, organized around the various inspection technologies. The current program includes tasks in ultrasonics, eddy current and magneto optic imaging, radiography, fluorescent penetrant inspection, magnetic particle inspection, and therma-sonics. A presentation was also provided at the Center of Excellence annual symposium in Cincinnati as requested by Xiaogong Lee, the FAA AACE program manager.

A monthly summary of highlights of the CASR program was initiated in November 2001. The two to three page document provides recent highlights of the work and is distributed to FAA and industry representatives. We've had very positive response to the newsletters to date.

During the months of November and December, Brasche worked with Don Hagemair to prepare a chapter in the upcoming Radiography Handbook to be published by ASNT. The chapter entitled, "Aerospace Applications of Radiography", will be published later this year.

A new poster which reflects the current focus of the CASR program has been developed and will be distributed to FAA, AANC and industry partners.

Updates to the CASR website continue.

Plans (April 1, 2002 – October 31, 2002):

Preparation for and participation in the ATA NDT Forum. This includes a special FPI workshop which is being prepared in cooperation with Al Broz.

Participation in the FAA/NASA/DOD Aging Aircraft Conference.

Major Accomplishments and Significant Interactions:

Establish monthly newsletter for distribution to industry, FAA and other government representatives.

Publications and Presentations:

Date	*Description*
2002	CASR Overview at the ASNT Spring Conference
2001	CASR Contributions to Safety, COE Annual Symposium
2001	FAA Funded FPI Research Accomplishments and Plans at the ANST Spring Conference
2000	Accomplishments of the AACE First Three Years at the AACE Annual Symposium
1999	CASR Contributions to Safety at the AACE Annual Meeting
1998	FPI: Research Needs for the Aerospace Industry at the ASNT Fall Conference
1998	Overview of CASR at the AACE Annual Meeting
1998	Partnerships: Keys to Technology Transfer at the ATA NDT Forum

Task Title: A Modular Imaging System for Ultrasonic Inspection of Multilayered Airplane Structures for Cracks and Corrosion

Investigation Team: I. M. Komsky and J. D. Achenbach, Northwestern University

Students: None

Program initiation date: Program initiated as IA007, June 23, 1998 with scheduled ending date of June 30, 2002.

Objective:

- To develop a modular inspection system for use in a variety of ultrasonic testing procedures.

Approach:

The system will integrate commercially available and newly developed scanning modules with commercially available data acquisition modules and/or conventional portable ultrasonic flaw detectors. The data will be acquired and transferred for imaging, using software modules optimized for the specific configuration of an airplane structure, the type of flaw, and the type of ultrasonic equipment available at the operator's site. The system will be utilized to detect, characterize, and image fatigue cracks and corrosion in second and third layers of multilayered airplane structures, from outside surfaces without disassembly. For corrosion inspection a complete map of material loss and/or residual thicknesses of the internal layers will be provided. For crack inspection an image of the crack will be displayed with complete information on crack size, location, orientation, and shape. The inspection system will be deployed on surfaces with limited and/or obstructed access, such as surfaces with protruding fasteners, channels, doublers, angles, etc.

Progress (March 2002):

A conformable scanning system was demonstrated to Northwest Airlines NDE staff at NWA Maintenance Facility in Minneapolis, MN. Several potential applications of the conformable scanner were discussed.

The application on the DC-10 horizontal stabilizer has been singled out for immediate feasibility study. The cut-off from the DC-10 stabilizer with cracks in-between fastener holes was acquired from NWA. The scanning head for the contact ¼" ultrasonic transducer was developed and integrated with the scanner. The scanner was tested on the DC-10 specimen to acquire crack images for direct quantitative crack measurements using portable ultrasonic flaw detectors.

Several dry coupling transducer modules with adjustable incident angles have been designed and manufactured. The modules were tested on the Cessna specimens with artificial flaws. All flaws in the second and third layers have been successfully detected. Comparison of dry coupling transducers with conventional contact transducers demonstrated only 4-6 Db difference in the sensitivity.

A belt-shaped dry coupling substrate with spliced driving edges was developed for the rotational transducer module and tested on the calibration specimens for DC-10 horizontal stabilizer and Cessna wing structure.

Plans (April 1, 2002 – September 31, 2002):

Field tests and demonstration projects of the portable modular systems at NWA and Cessna will be continued. The modules along with the inspection procedures will be validated on in-service airplanes. Procedures and documentation for ultrasonic inspections will be completed. Final report on the development and transfer of the modular ultrasonic systems will be completed.

Milestones:

Original Date	*Revised Date*	*Milestone*	*Status*
6/1/98		*Start date.*	
		Phase I	
Quarter 1		Begin analysis and classification of ultrasonic equipment deployed by operators. Begin developing of a matrix for the equipment classification.	On schedule
Quarter 2		Begin developing group of inspection techniques to fit specific types of UT equipment.	On schedule
Quarter 3		Complete classification of equipment. Begin development of scanning modules.	On schedule
Quarter 4		Begin developing data transfer protocol for different types of ultrasonic equipment.	On schedule
		Phase II	
Quarter 5		Complete development of inspection techniques.	On schedule
Quarter 6		Complete development of scanning modules. Begin manufacture of prototype modules. Begin development of software package for imaging different defect groups.	On schedule
Quarter 7		Complete development of data transfer protocol.	On schedule
Quarter 8		Complete manufacturing of prototype modules. Begin integration of modules with ultrasonic equipment. Begin planning validation studies with AANC.	Completed
Quarter 9		Complete development of software package. Complete integration of prototype modules. Begin lab tests on calibration specimens/aircraft parts.	Completed
Quarter 10		Complete lab tests of modular systems. Begin field demonstration and validation of inspection systems. Start planning and coordination of demonstration projects with aircraft manufactures, airlines, and manufacturers of ultrasonic equipment.	Demonstration projects are being scheduled
Quarter 11		Complete field demo and validation at AANC. Begin tech demonstration projects.	Portable modules have been demonstrated to QMI and GFM staff. Test results have been sent to AANC, Boeing, and Cessna.
Quarter 12		Complete technology demonstration projects at participating OEMs and airlines. Complete procedures and documentation for ultrasonic inspections.	Ongoing

Deliverables:

Original Date	*Revised Date*	*Deliverable*	*Status*
		Phase I:	
		Interim report on Modular UT system. .	Ongoing
		Phase II:	
		A final report on the development and transfer of the Modular UT system.	Ongoing

Major Accomplishments and Significant Interactions:

Date	*Description*
June 1998	The inspection system based on the portable ultrasonic flaw detector has been tested on a DC-10 airplane at NWA, Minneapolis, MN.
July 1998	Based on the field test results and recommendations of Boeing engineers, the work has begun on the modified version of the scanning inspection system.
December 1998	The modified version of the rotational scanning inspection system has been integrated with the portable ultrasonic flaw detector EPOCH III.
March 1999	Work has begun to modify a scanning module. New design of a coupling module will make it possible to inspect all fasteners (1 through 12) in a DC-10 spar-cap/strap connection regardless of their proximity to sides of the channel. The modified unit can also be deployed to inspect structural elements with various spatial orientations.
April 1999	Work has started to develop novel dual support system for wide area inspections. The system will be used with the rotational scanner to inspect fasteners on the aircraft structures with various spatial orientations.
November 1999 – December 1999	The wide area ultrasonic inspection system (positioning and coupling modules, vacuum control module, and rotational ultrasonic scanner) was integrated with a portable ultrasonic flaw detector and tested on the DC-10 representative specimens and the Boeing 777 wing structure.
February, 2000 – March, 2000	The multi-directional positioning and coupling units for the ultrasonic inspection system with wide area support modules were successfully tested on aircraft parts. Several sensors and data acquisition units from KB and Foerster have been brought to the CQEFP to start working on the integration of the modules.
July-December, 2000	Work has been completed to develop miniature control module for integration with Krautkramer-Branson DMS2. The module was integrated with DMS2 and tested on Boeing, Fairchild, and Cessna wing structures. The scanning and control modules for Panametrics and Krautkramer-Branson portable ultrasonic units were demonstrated at the meeting with Northwest Airlines NDE Staff in Minneapolis, MN in August, 2000. The modules have also been demonstrated to Panametrics and KB engineers.
January-March, 2001	Development of the conformable scanning system was completed. The scanner was tested on the aircraft parts, the results have been sent to AANC, Boeing, and Cessna. The portable scanning modules have been demonstrated to QMI and GFM staff.
April-September, 2001	A conformable scanning system for application on the aircraft structures with curved surfaces was tested on the wing structures of the SA 227 aircraft during field tests at the Berry Aviation, San Marcos, TX, Perimeter Aviation, Winnipeg, MB, and Superior Aviation, Iron Mountain, MI. The scanning system was also successfully demonstrated at the Metro Operators Conference 2001 in Las Vegas.
October, 2001-March, 2002	A conformable scanning system was demonstrated to Northwest Airlines NDE staff at NWA Maintenance Facility in Minneapolis, MN. The scanner was tested on the cut-off from the DC-10 horizontal stabilizer. Several dry coupling transducer modules with adjustable incident angles have been designed, manufactured, and tested on the calibration specimens for DC-10 horizontal stabilizer and Cessna wing structure.

Publications and Presentations:

“Ultrasonic Imaging Of Fatigue Cracks Around Fasteners In Multilayered Airplane Structures”, Proceedings of the 1998 Advances in Aviation Safety Conference & Exhibition, SAE, 1998.

”Ultrasonic Imaging Of Cracks In Aging Aircraft Structures”, Paper Summaries of the 1998 ASNT Conference, ASNT, 1998.

“Miniature Scanners For Ultrasonic Imaging Of Fatigue Cracks In Airplane Structures”, Paper Summaries of the 1999 ASNT Conference, ASNT, 1999.

“Portable Scanning And Positioning Modules For Integration Of NDE Sensors**”,** Presented at QNDE 2000, published in Review of Progress in QNDE, Volume 20.

“Modular Imaging Systems For Ultrasonic Evaluation Of Aircraft Structures”, Proceedings of the International Symposium on Nondestructive Testing Contribution to Infrastructure Safety Systems in the 21st Century, Torres, Brazil, 1999.

“Modular Systems For Ultrasonic Imaging In Manufacturing”, Proceeding of National Manufacturing Week Conference 2000, NAM/ASME, 2000.

“Modular Imaging Systems For Ultrasonic Evaluation Of Aircraft Structures”, NDT.NET, March 2000.

“Characterization Of Fatigue Cracks In Multi-Layer Aircraft Structures Using Portable Ultrasonic Modules”, Presented at ASIP 2000, published in Proceeding of ASIP 2000.

“Accuracy Of Fatigue Crack Characterization Using Ultrasonic Scanning”, presented at QNDE 2001.

“Application Of Portable Modules For Fatigue Crack Characterization” in Advanced Nondestructive Evaluation for Structural and Biological Health Monitoring, Proceedings of SPIE, Vol. 4335, 2001.

“Portable Ultrasonic Systems For Quantitative Characterization Of Fatigue Cracks In Aging Aircraft”**,** Proceeding of The Fourth Joint NASA/FAA/DoD Conference on Aging Aircraft, NASA, 2001**.**

“Multi-Element Adjustable Transducer Arrays For Ultrasonic Scanning Of Aging Aircraft”, in Proceedings of SPIE, 2002.

Task Title: Contact Transducer Optimization for Engine and Airframe Inspection

Investigation Team: T. Gray, Iowa State University; K. Smith, J. Umbach; Pratt & Whitney; J. Kollgaard, S. LaRiviere, Boeing.

Students: None

Program initiation date: Program initiated as IA014 June 23, 1998 with scheduled ending date of June 30, 2002. No cost extension request to be processed.

Objective:

- To provide a tool for the development, evaluation, or optimization of contact UT inspection of critical aviation components such that in-service inspections can be implemented in a rapid fashion when durability issues arise.
- To develop a UT contact transducer models for flaw and noise predictions for use in probe design and technique development/evaluation, including tolerance variation assessment.
- To work with the industry partners to validate the model results and develop software tools that are useable in typical engineering environments.

Approach:

Contact UT inspection sees widespread use in both engine and airframe applications. Determination of the adequacy of a contact inspection protocol typically involves consideration of component geometry, surface roughness, and material effects. Inspection optimization tools that allow consideration of probe design, technique evaluation, and tolerance variation are needed. Such tools need to address such factors as wedge coupling, beam shape, multiple sound paths, multiple UT modes, and multiple flaw types/orientations. At all steps of the model development, close coupling with industrial partners will be maintained through transfer of software and test components; through beta testing and validation experiments performed by the industrial participants; and by solicitation of industrial input to define material characteristics, component geometries, common inspection procedures and protocols.

The first phase will develop models for contact probes and wedges assuming a non-uniform couplant layer. A key element of this first phase will be the specification of probe/wedge characterization procedures. Consideration will be given to contact pressure, characterization of contact probes, delay line/wedge optimization, various wave modes (longitudinal, shear, surface) multimode generation, and acoustic properties of couplant. The second phase will extend the models to nonsymmetric inspection conditions. The third and final phase will extend the models to account for rough entry and reflection surfaces. In addition, extensions of the models for inhomogeneous and anisotropic material behaviors will be incorporated, pending related results from ETC activities. Extensions to allow other than bulk wave modes (surface waves, e.g.) will also be made.

Progress (March 2002):

The main facet of the progress in the preceding period was the solution of a compilation problem which derived from an undocumented error in the C++ compiler used for software development. After resolution of this issue, the first complete compile of the contact UT software package was successful. Features included in the compile included full graphical user interface, 3D display of a component and transducer, import of component geometry from a CAD file (IGES format), parametric description of simple geometric surfaces, 3D ray tracing, multi-Gaussian model for computing 3D ultrasonic beam patterns for both longitudinal and shear wave modes, contact UT probe widgets, small flaw models, capabilities for computing and displaying beam radiation patterns and flaw sensitivity profiles, and tools for computing DAC curves and surface curvature corrections. A demo of the software was presented to Cu Nguyen during a visit to ISU in December, 2001.

Since that time, primary emphasis in software integration has been on debugging and optimization of the code. Particular problem areas seeing attention are some discrepancies in the frequency response that are observed when computing broadband waveforms, errors in the surface-breaking crack model that incorrectly predict amplitude variation as a function of angle, and a variety of GUI inconsistencies. A major optimization thrust in the 3D display area is the use of so-called bounding boxes when computing the intersections of rays with parametric surfaces. These intersections are required both for calculations and displays employed in ray-tracing and, more importantly, in providing geometric information to the analytical beam models.

As part of the validation process, work proceeded on aspects of contact probe characterization; i.e., determination of the probe parameters needed for input to the models. These parameters include, e.g., crystal dimensions, frequency response, focal properties, etc. Due to manufacturing variability, real transducers seldom have radiation patterns that behave according to the nominal characteristics that are stamped on their case. Therefore, it is necessary to deduce the effective parameters that are consistent with measured responses. For normal incidence longitudinal wave probes, or for shear wave probes with removable angle wedges, there are characterization procedures that have been well established for immersion transducers. These approaches are typically based on analysis of waveforms acquired from ultrasonic reflections from flat surfaces or from small calibration reflectors, such as flat-bottomed holes (FBH). Similar techniques are not typically useful for contact transducers that have an integral, and possibly curved, wedge. This is mainly because the characterization procedures required for determining effective probe parameters are not the same as calibration techniques that are applied to setting up an inspection. For example, contact inspection calibration blocks typically do not contain small FBH reflectors normal to the beam propagation direction. An alternate approach would be to analyze waveforms measured from UT reflections from small slots, e.g. EDM notches, on the back surface or ID of a component. Validation of this approach requires several steps. First, use contact probes with removable wedges. With the wedge removed, these can be characterized by using the standard immersion approach. Next, effective parameters can be deduced from measurements on the EDM slots by using the probes with wedges attached. If the two methods agree, then the EDM notch approach can reasonably be applied to probes with integral wedges. We are fabricating some samples to test this approach.

Finally, two new sample applications have been initiated with one of the industrial partners (PW). The first problem is a contact UT inspection applied to cracks in a propeller shaft. The second is a contact UT inspection problem involving small pores and/or cracks in a thin fan blade. The latter problem also might require the use of pitch-catch measurements, detection of loss of backwall amplitude, and side-drilled holes as calibration reflectors. Results of model analyses of these problems will be presented next period.

Plans (April 1, 2002 – October 31, 2002):

The first plan for next period is to complete the debugging/optimization process for the initial version of the software. The package will then be demonstrated on site at the industrial partners. This will complete the Phase I milestone.

Second, we will complete the probe characterization procedure development.

Third, we will incorporate an advanced beam model, based upon a new formulation of the multi-Gaussian model, that will extend the software applicability to non-symmetry entry conditions.

Fourth, we will complete the analysis of OEM sample problems. These include contact mode inspection of a lug geometry (Boeing), of a propeller shaft (PW), and a fan blade (PW).

Fifth, we will prepare documentation for the software package and distribute it to the OEMs.

Finally, we will prepare the final report for the project.

To complete these activities, we will request a no-cost extension to the original contract.

Milestones:

Original Date	*Revised Date*	*Milestone*	*Status*
6/23/98		*Start Date*	
		Phase I	

Original Date	*Revised Date*	*Milestone*	*Status*
Quarter 1		Identify sequence of geometries for model development. Establish validation plan and user requirements with industry partners.	Completed
Quarter 4		First phase contact transducer model available.	In Progress: Analytical models available; GUI development nearly complete; expect delivery within the next quarter.
		Phase II	
Quarter 5		Demonstrate phase 1 models applied to inspection optimization.	In Progress: Validation testing of analytical models will begin next quarter; 1st phase GUI development is nearly complete; analytical modules are being integrated with ray-tracing and visualization code.
Quarter 10		Second phase contact transducer model completed.	Beam model for non-symmetric entry conditions is available for integration
Quarter 12		Demonstrate phase 2 models applied to inspection optimization.	In progress
Quarter 14		Third phase contact transducer model completed.	
Quarter 15		Demonstrate phase 3 models applied to inspection optimization.	
Quarter 16		Deliver contact transducer model software and report of results.	

Deliverables:

Original Date	*Revised Date*	*Deliverable*	*Status*
		Phase I:	
		Interim report on capability and features of the software including initial industry applications.	In Progress
		Phase II:	

Original Date	*Revised Date*	*Deliverable*	*Status*
		Final executable versions of the software installed at the W.J. Hughes Technical Center and at AANC including training to ensure that FAA and AANC personnel are proficient in the use of the software.	
		A final report on the capabilities and features of the software including industrial applications.	

Major Accomplishments and Significant Interactions:

Date	*Description*
11/00	Software breakthrough, viz. Display and manipulation of 3-D object and ray tracing results in Windows/PC environment.
11/15/00	Met with Boeing staff to guide software GUI development and to acquire realistic experimental validation specimens.
10/01	Successful compile of full software, including CAD, 3D display, ray tracing, UT beam and flaw modeling.
12/01	Demonstration of software to Cu Nguyen.
2/02	Two new OEM example problems initiated (propeller shaft, fan blade) with PW.

Publications and Presentations:

Mike Garton and Tim Gray, "A Software Package for Simulating Ultrasonic Inspections in 3D CAD Geometry," presented at Review of Progress in QNDE, Brunswick, Maine, July 29 – August 3, 2001.

Task Title: Scanning Pulsed Eddy Current for Aviation Applications

Investigation Team: Principal Investigators: J. R. Bowler, M. Johnson, Iowa State University; D. Moore, AANC, D. Wilson, B. Jappe, Boeing-Long Beach; S. LaRiviere, J. Thompson, Boeing - Seattle. Commercial Airlines: Morris Johnson, NWA

Students: Shaun Linsay and Fahad Azeem, Iowa State University

Program initiation date: Program initiated as IA026 September 25, 1998 with scheduled ending date of September 30, 2002.

Objective:

- To transition the pulsed eddy current (PEC) technology from the developer to the user community and to facilitate its rapid introduction and acceptance in commercial aviation.
- To develop and demonstrate new PEC-based detection and characterization methods for small fatigue cracks in multilayered aircraft structures.
- To transition the PEC methodologies for corrosion and crack detection in cooperation with the industrial partners.

Approach:

Pulsed Eddy Current (PEC) software has been developed at CASR and applied to corrosion detection, and on a more limited basis, crack detection. The PEC instrument developed for hidden corrosion detection will be adapted for the small fatigue crack detection and characterization in layered aircraft structures. This will entail second generation modifications to the electronic design of the instrument, including adding ability to control timing and amplification and incorporation of constant current drive capability. This, in turn, will permit the instrument to be adapted to readily available commercial eddy current probes such as absolute or differential probes, or even the sliding reflectance probes currently used in lap splice inspections. Probe design and optimization studies will also be undertaken for specific applications defined by the industrial partners. The existing fieldable scanner will be replaced by a commercial scanner capable of much finer resolution required for crack detection than for corrosion detection. Model based support of the hardware development task will enable quantitative crack characterization. Empirical interpolation formulas will be developed for integration into the data acquisition software for on-site crack characterization. A strong partnership has been established with Boeing Seattle and Boeing Long Beach. First generation software and hardware will be delivered to both locations for internal evaluations. Based on their feedback, a second-generation system will be developed. The second-generation system will be installed at Boeing and AANC to initiate the technology transfer process.

Progress (March 2002):

During the past 6 months, a new version of the pulsed eddy current (PEC) system has been developed in order to improve the portability of the hardware and to avoid software instabilities encountered with the PXI technology [1] on which the current system is based. The new system, PEC II, will use a notebook computer to control the pulsed eddy-current electronics. Instead of having a lunchbox computer communicate with a PXI-PEC instrument, a notebook computer will acquire data via the Universal Serial Bus (USB) and the analog-to-digital converter used to digitize the pulse data will be USB compatible. An Ethernet-based motion controller will direct the eddy current probe scanner and the PEC electronics will be controlled using a PCMCIA digital I/O card. Overall the new hardware will be much lighter and can be built for less cost.

All three of the original PEC circuit boards have been redesigned. The Hall-device input amplifier circuit board has been rebuilt and is about to be tested. The pulse-generator circuit board has been configured around a complex programmable logic device (CPLD), the code for which has already been generated and simulations run. Finally, the transconductance amplifier has been redesigned and the circuit entered into a CAD package. The new transconductance amplifier has not yet been built but this task will be completed shortly.

In addition to changes in the hardware, the software has been rewritten using an approach based on ActiveX controls. Two ActiveX controls have been developed to provide

1. Pulse-acquisition and pulse display functions.
2. Area scan display and data image manipulation functions.

The two modules are known as the A-scan and C-scan controls respectively since the data they process is analogous to ultrasonic A and C-scan data. The A-scan control has been tested with existing PEC hardware and works well as a stand-alone module. It acquires pulse signals from the A/D converter and displays them in an oscilloscope-style window. A-scan controls permit changes of the time base scale and the vertical sensitivity scale of the oscilloscope display to obtain an optimum view of a given pulse. The C-scan functions include zoom, pan and an interpolation algorithm that displays pulse signals acquired from a coarse scan grid as a smooth image. The C-scan control has been tested using synthetic data and functions correctly as an independent module. In addition, a new motion-control function suite has been developed that will provide the final PEC application with a set of high-level functions for directing the probe scanner.

A signal analysis package, written in Matlab code, has been developed and continues to grow and evolve. The package now includes point-analysis functions that parameterize the pulse response acquired at a user-defined point in the C-scan image. The pulse parameters can be used directly in calibration procedures to determine, for example, variation in plate thickness. Additional features of the signal analysis software includes linear reference subtraction routines that are suitable for removing edge effects and slowly varying trends in the data. An edge effect is a signal caused by a hidden plate edge in the metal structure. Often this effect can mask a flaw indication but by subtracting the edge signal the flaw is easier to detect. Examples of unwanted trends are those due to gradual changes in probe liftoff or signal variations arising from wedge-shaped air gaps between two layers in a specimen. These unwanted signals can also be suppressed.

While developing new software and hardware over the past six months, we have also continued to carry out measurements and refine signal- and image-processing techniques. Bonded plates supplied by Cessna were tested for variations in the bond thickness using the pulsed eddy current approach. A probe containing a coil and a Hall device for field detection was used for the measurements and was scanned over the specimens in a raster pattern. Two specimens were tested in this way. The first, referred to as the ‘typical’ sample contained unknown variations in bond thickness. The second, referred to as the ‘wedge’, had a slowly increasing bond thickness from one end of the specimen to the other. The bond thickness was measured using a thickness gauge to determine the overall specimen thickness at points on a line parallel to the longer edge of each rectangular specimen. Pulsed eddy-current scans were then carried out and the resulting image plotted, Figure 1. The bond thickness data deduced from the eddy current measurements acquired at the center of the long axis of each specimen is compared with the independent thickness measurement in Figure 2. The PEC measurements show a good correlation with the independent measurements of thickness and indicate that pulsed eddy currents may prove to be very effective for production and in-service assessment of bond thickness.

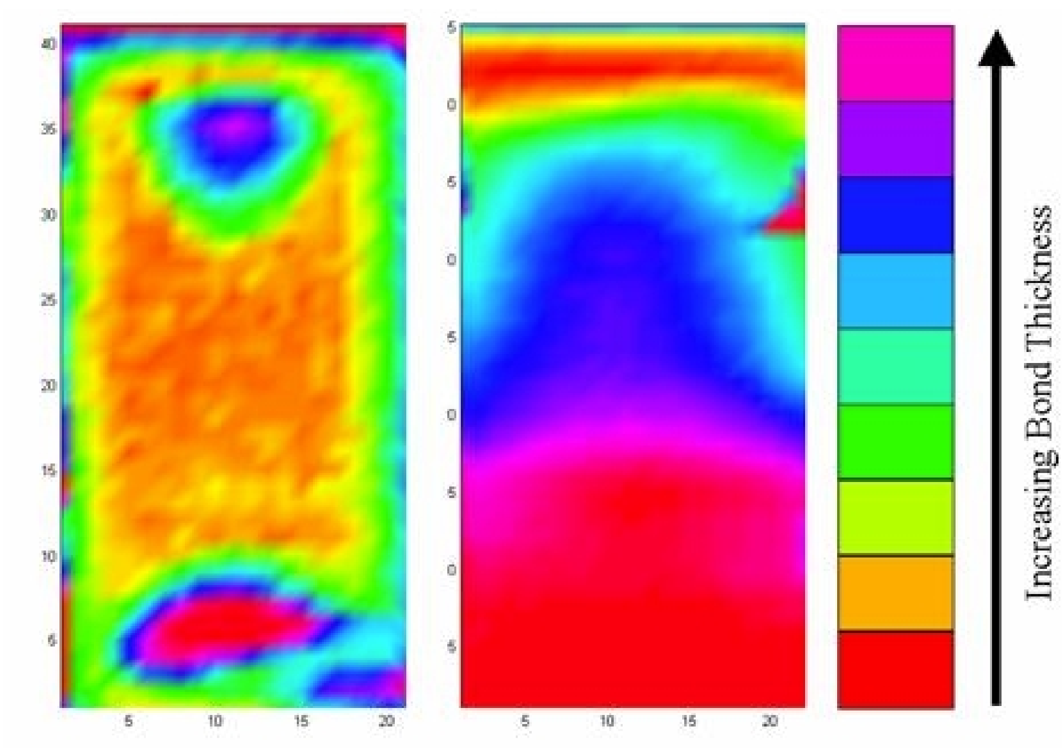


Figure 1. C-Scan images of the 'typical' (left) and 'wedge' (right) specimens from Cessna.

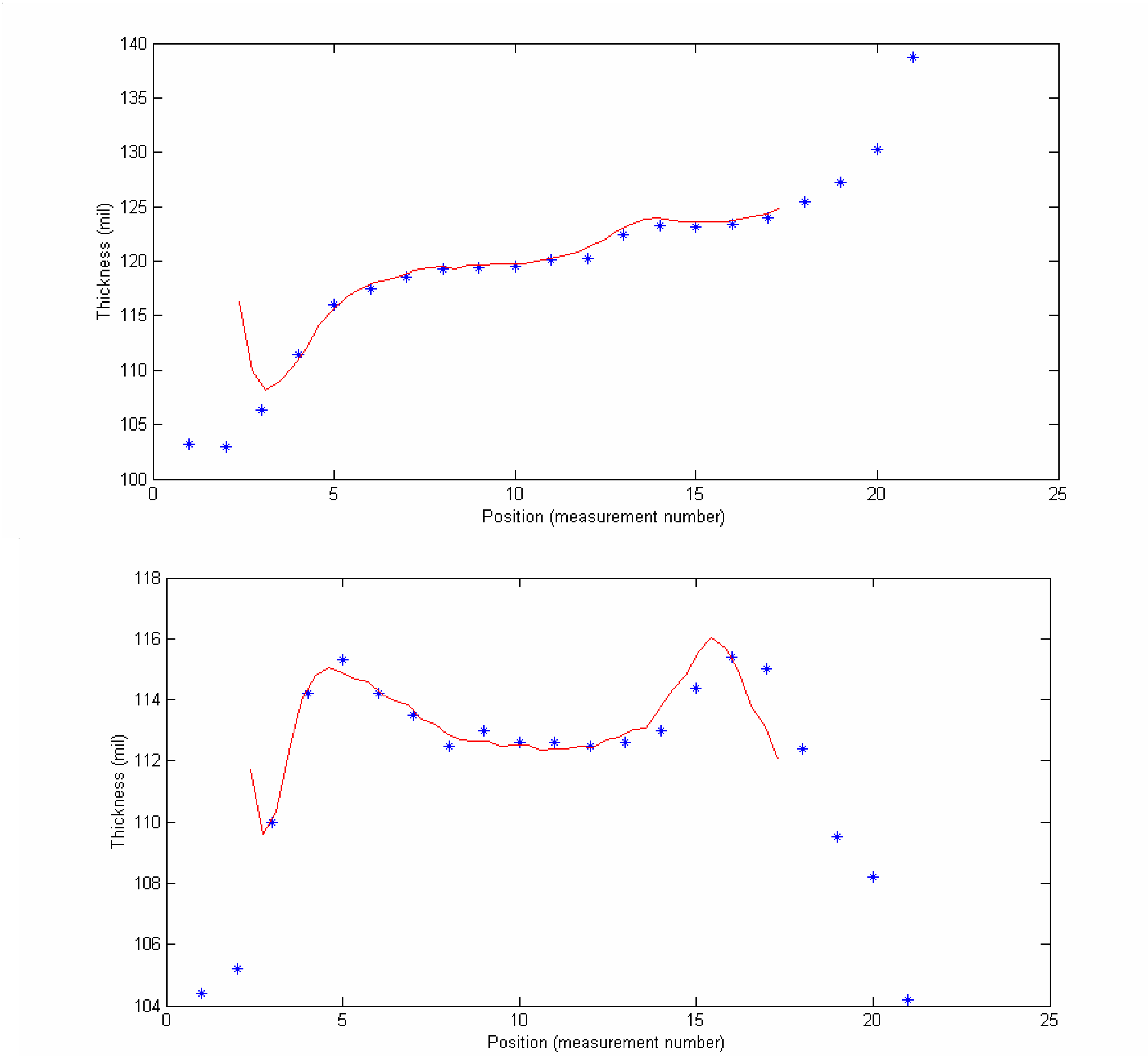


Figure 2. A comparison of independent thickness measurements (blue stars) with thickness data deduced from pulsed eddy-current measurements (red line) for the 'wedge' specimen (upper) and the 'typical' specimen (lower).

Recently we participated in a round-robin corrosion experiment organized by SAIC Ultra Image Incorporated. Specimens from SAIC were received for evaluation of PEC system performance for hidden corrosion detection. Calibration data was acquired using the 'known' specimens provided by SAIC and the results used to interpret flaw indications from the 'unknown' specimens. A C-scan image of a calibration specimen is shown in Figure 3. The specimen consists of three stacked 0.063 inch plates with six simulated corrosion regions in the bottom of the first and second layers. The eddy current data was used to produce the calibration curves shown in Figure 4. These curves are then used to estimate the material loss of flaws in specimens with unspecified flaws. It is anticipated that the results of the round-robin exercise will be available by July 2002.

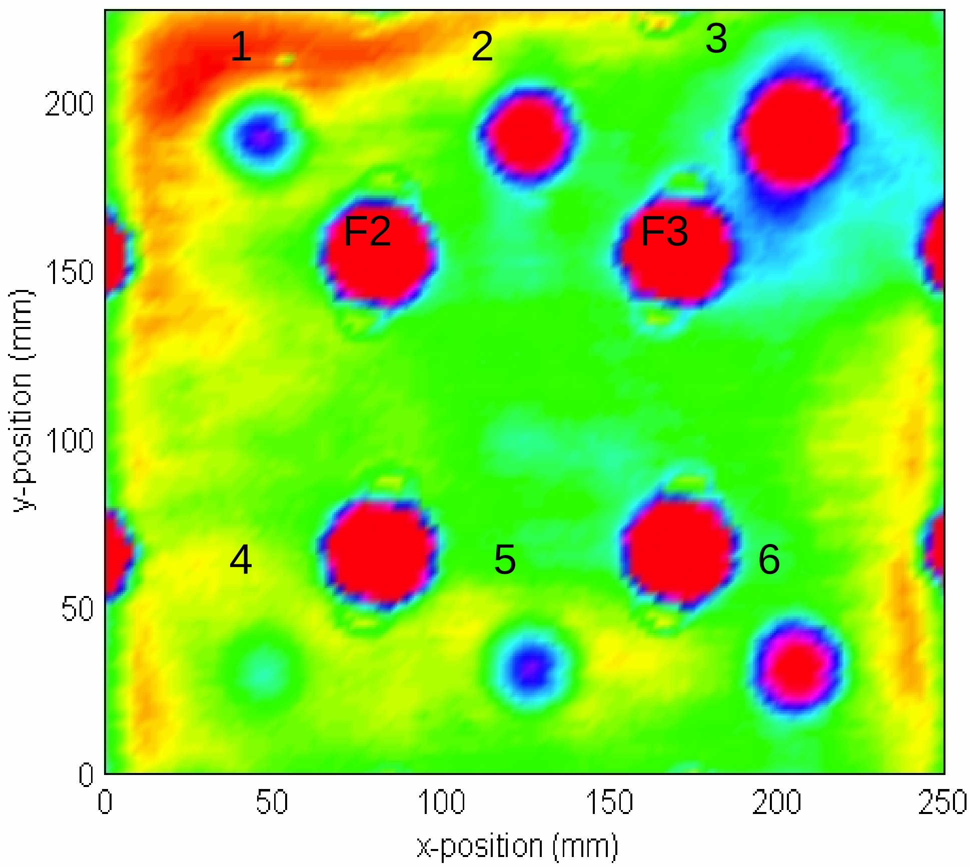


Figure 3. C-scan image generated from one of the SAIC calibration specimens.

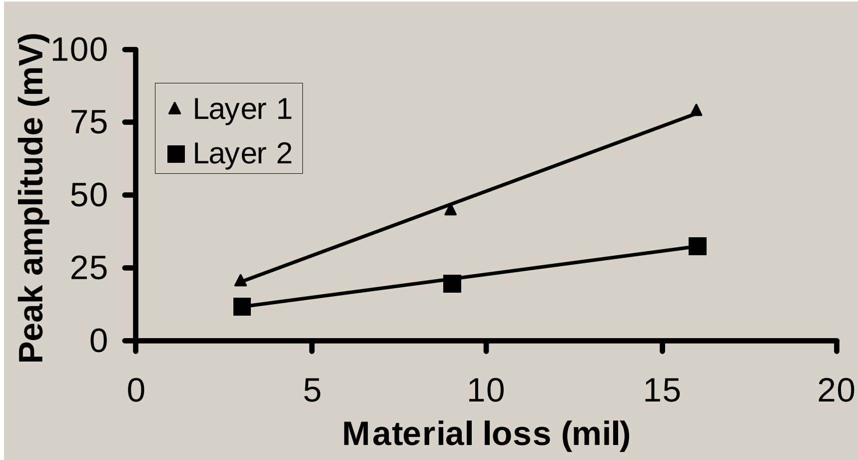


Figure 4. Calibration curves generated from the indications shown above in Figure 3.

Plans (April 1, 2002 – October 31, 2002):

Our immediate goal is to complete the hardware and software upgrade for PEC II. The future hardware tasks include completion of the pulse-generator circuit board, manufacture of the transconductance amplifier board and testing of the Hall-device amplifier board. The circuit boards will be housed in a single PEC unit enclosure and be linked to a notebook computer. Also in the PEC unit will be a commercial data-acquisition circuit for digitizing the pulse waveforms. A new PCMCIA-based digital I/O board will be used to control the PEC inspection parameters. Additional probes, aimed at a broad range of inspection problems, will be built according to the new Xactex standard. The PEC III will be housed in a foam-filled carrying case to make transportation easy, safe and convenient.

Two new software modules will be written. The first will deal with digital I/O control of the PEC hardware and communicate via PCMCIA digital I/O card. The second will provide a high-level interface to basic file I/O functions. The ActiveX controls, A-scan and C-scan, will be integrated into a single controlling application along with the new digital I/O and file I/O modules.

Extensive testing will be carried out in June and July, which will be followed by off-site visits to Boeing AANC and Cessna. The Task Schedule for the next 5 months is summarized in the table below.

Task	**Apr. May Jun. Jul. Aug. Sep.**
Software	****************
Complete individual modules	----------------
Integrate software	----------------
Hardware	*********************
Complete new boards	-------------
Test and integrate	---------------
Integrate entire system	-----------
Test	------------------
Beta-site tests	****************
Report	******

[1] http://www.pxionline.com/

Milestones:

Original Date	*Revised Date*	*Milestone*	*Status*
		Start date September 15, 1998	
		Phase I	
Quarter 1	12/31/98	Hold the first Coordination Meeting and decide on applications, electronic design I, and probe design personnel. Send A/D board specification to Boeing. Complete fabrication of two PEC boards for transfer to Boeing.	Completed. Coordination discussions were held by teleconference.
Quarter 2	3/31/99	Finish installing the current generation of PEC systems at the OEM sites. Complete software development and system integration by the OEM. Initiate extension of the CW surface-breaking crack model code to cracks under layered structures.	Beta-site was established at Boeing-Seattle.
Quarter 3	6/30/99	2nd Coordination Meeting. Initiate assessment of capabilities for cracks at Boeing-Seattle, and corrosion at Boeing-Long Beach. Initiate software upgrade. Complete crack model extension to layered structures.	A transient eddy-current crack model is now available to simulate the interaction of the electromagnetic field with cracks. The transient model will assist in studies of probe design and signal analysis. This model was substituted for CW model originally proposed because it is much better suited to the project goals. A transient field model simulates pulsed eddy-currents whereas the CW (continuous wave) model simulates traditional, time-harmonic (i.e., sinusoidal) eddy-current fields.
Quarter 4	9/30/99	Complete capability assessments of the first generation PEC system at the OEM. Hold the third Coordination Meeting to send feedback from the OEM to the developers. Initiate breadboard design and software upgrade for the second generation PEC system.	The capability assessment of the first generation PEC system is completed. The design for the second-generation pulsed eddy-current system began as scheduled.
		Phase II	
Quarter 5	12/31/99	Continue breadboard design and software upgrade for second generation PEC system. Procure commercial scanners for use by AANC and CASR.	The scanning software was upgraded successfully for the second-generation PEC system and the breadboard design phase began on schedule. A scanner has been acquired for the second generation PEC system and is currently being evaluated. AANC is responsible for providing a scanner

Milestones:

Original Date	*Revised Date*	*Milestone*	*Status*
			for PEC inspection.
Quarter 6	3/31/00	Complete breadboard design and software upgrade for the second-generation PEC system. Initiate fabrication of the second generation PEC cards based on the breadboard configuration.	The second-generation laboratory PEC system has been designed based on a MXI-3 card cage from National Instruments. Three custom circuit boards have been built, tested and assembled in the card cage. The effects of thermal are compensated for in the data acquisition software
Quarter 7	6/30/00	Complete fabrication of the second-generation PEC cards based on the breadboard configuration. Initiate installation of new systems at AANC and OEMs, including integration with commercial scanner at CASR and AANC. Complete validation of the crack model code for layered structures.	The laboratory PEC system is now operational. A performance evaluation was carried out showing that the second-generation instrument is more sensitive to subsurface corrosion, has better thermal stability and improved spatial resolution.
Quarter 8	9/30/00	Complete installation at AANC, OEMs, and CASR.	The laboratory PEC system design was reviewed and modifications made before constructing a field system for delivery to Boeing Seattle. Late modifications to the laboratory prototype meant that delivery of the field systems would be delayed.
Quarter 9	12/31/00	Complete debugging new installation at each site. Develop plan for field & betasite testing for validation.	Circuit boards were designed for the field system based on the laboratory prototype of the second generation PEC unit. Work began on constructing the unit.
Quarter 10	3/31/01	Initiate field and betasite testing. Replace detailed model for rapid PEC crack signal predictions.	A second-generation field system has been built and tested. Delivery to Boeing, Seattle will be made when funds are in place for full scale beta site testing.
Quarter 11	6/30/01	Continue field-testing and betasite testing. Incorporate empirical interpolation formulas for PEC crack signal predictions into data acquisition software.	Plans are already in place to carry out short-term (one week) field trials at Cessna in May. Negotiations are proceeding to extend this trial. If it is not possible to support a full-scale evaluation at Boeing, Seattle, short-term trials will be arranged. Crack and corrosion simulation code evaluation will be performed using specimens containing spark-eroded notches.

Milestones:

Original Date	*Revised Date*	*Milestone*	*Status*
Quarter 12	9/30/01	Complete field and betasite testing and final report.	A no-cost extension was requested for the purpose of refining the second-generation field system.
Quarter 13 (no-cost extension)	12/31/01	Formulate strategy for no-cost extension period. Begin modifications to second-generation field system.	Identified hardware and software components requiring improvement and/or miniaturization.
Quarter 14 (no-cost extension)	3/31/02	Finalize design modifications and begin integration of new components.	Completed re-design of hardware and software components. Completed construction of some of these components.

Deliverables:

Original Date	Revised Date	Deliverable	Status
		Phase I:	
	January, 1999	Deliver two 1st gen PEC boards to industry partners and tech transfer plan.	First generation system delivered to Boeing, Seattle
	September, 2000	Report summarizing assessment of 1st gen PEC	Completed
		Phase II:	
		Deliver three, 2nd gen PEC to industry and AANC and tech transfer plan	Delivery planned for the period from May, 2001.
	August, 2000	Demo of 2nd gen PEC with commercial scanner.	Completed
	August, 2002	Demo of 2nd gen PEC system following design improvements. Deliver 2nd gen PEC to industry and AANC for evaluation.	
	September, 2002	Final Report detailing technology transfer.	

Major Accomplishments and Significant Interactions:

Date	*Description*
April 23, 1998	Initial planning meeting with FAA and representatives from Boeing Seattle and Boeing Long Beach.
June 30, 1998	Demonstration of the PEC scanner at NWA-Minneapolis. Included discussion with Bill Jappe of Boeing-Long Beach about integration of PEC with the MAUS.

December 31, 1998	New generation of the PEC software completed. Two PEC boards have been fabricated. Detailed communication with the OEM partners has determined the integration strategy.
January 11-12, 1999	Visit to Boeing, Seattle. Installed the PEC card, software, and the A/D converter card.
February 15, 1999	Visit to Boeing, St. Louis. Information exchanges on ISU PEC and Boeing MAUS systems.
June, 1999	Visit to Boeing, Seattle to discuss first generation PEC performance evaluation.
August, 1999	First-generation PEC system returned from Boeing to CNDE for hardware testing. CNDE carried out the necessary checks and returned the system to Boeing for further trials.
August 15-20, 1999	Visit to AANC for field evaluation trials of the first generation PEC system.
November 10-11, 1999	Visit to Cessna for discussion on arrangements for making measurements on test specimens.
May, 2000	The laboratory prototype of the second generation PEC system is completed.
September 24-28, 2000	Meeting with partners at the ATA meeting San Francisco. Planned the next round of field trials using the second-generation system.
October 21, 2000	Completed pulsed eddy current simulation software for the analysis of flaw signals.
November 14-16, 2000	Discussion with Boeing representatives at the AACE Meeting. Arrangements were made to deliver a field version of the second-generation system to Boeing, Seattle.
August, 2001	Participation in the AANC structured corrosion experiment.
August, 2001	Visit to Cessna for an evaluation of the PEC system.
December, 2001	Applied for a no-cost extension through September 2002 in order to address some hardware-related issues with the 2nd generation field system.
April, 2002	Participated in SAIC round-robin corrosion experiment for the evaluation of different pulsed eddy current technologies.

Publications and Presentations:

"Corrosion Evaluation using a Pulsed Eddy-Current Instrument", Review of Progress in Quantitative Nondestructive Evaluation, Ames, Iowa, July 2000.

"Improved Pulsed Eddy-Current Measurements On Subsurface Defects Using Differential-Reflection And Hall-Device Probes", Electromagnetic Nondestructive Evaluation, Des Moines, Iowa, August 1999.

"Improved Pulsed Eddy-Current Measurements On Subsurface Defects Using Differential-Reflection And Hall-Device Probes", Review of Progress in Quantitative Nondestructive Evaluation, Montreal, July 1999.

Task Title: Infrared Detection of Ultrasonically Excited Cracks

Investigation Team: Bob Thomas, L.D. Favro, Xiaoyan Han – Wayne State University

Students: None

Program initiation date: June 14, 2000

Objective:

- To develop the new technology of Sonic Infrared Imaging for use in aircraft inspection.
- To explore potential applications of Sonic IR for NDI of aircraft structures.
- To design a prototype Sonic IR Inspection System that is specifically adapted for NDI of aircraft structures.
- To initiate technology transfer.

Approach:

Thermal wave imaging research has been a key element of the FAA's aviation safety program since the early 90's. Through development and technology transfer studies in cooperation with AANC, the technology was recently approved as an acceptable in-service inspection procedure by Boeing. Prior work focused primarily on the detection of disbonds and corrosion damage in metallic structures and impact damage in composites. Crack detection received little attention. Recently through communication with a scientist at the University of Stuttgart, Dr. Gerd Busse, WSU staff began studies of acoustically excited thermal wave imaging. The essence of this technique is to cause the crack to "light up", using an applied ultrasonic field. In a simple picture, one can imagine that the two sides of the crack are rubbed and banged together by the ultrasonic waves, and the crack gets hot. It is the ultrasonic field, rather than a flash lamp, that is playing the role of heat source for the IR camera. Since the unbroken skin of the plane is only minimally heated by the ultrasonic waves, the resulting images of cracks are seen as bright features against a dark background field, thus providing the potential for detecting extremely small cracks with very high sensitivity. A patent has been filed by WSU based on prior work.

While the initial results are quite promising, the underlying principles are not well understood. Understanding the physics and optimizing the technique are the focus of this project. This project began with a study of the limits of detectability of cracks in different structures. Efforts are under way to optimize the sonic transduction and methods for coupling the sound to different aircraft structures. Samples are being provided by AANC, industry, and the Air Force Materials Lab. Evaluation of signal processing methodologies for weak signals and/or small cracks is ongoing. Plans are in place to study effects of fluid or other foreign material crack infiltration on the detectability of the crack. To support the experimental work and aid in future system optimization, theoretical modeling of imaging of subsurface cracks is also planned. Results will be implemented through image acquisition and processing hardware and software including algorithms for thresholding and automation of defect recognition. As with prior efforts, close communication will be continued with AANC to facilitate the transfer of the technology.

Objective/Approach Amendments: Our objective remains the same as originally proposed in April 2000, but we have expanded our approach to include direct measurements of the vibration of samples in the vicinity of the cracks being imaged. For this purpose we have purchased (with University funds) a $77k laser vibrometer.

Progress (March 2002):

Equipment: During this period we added two major pieces of equipment, an 800w, 40kHz, Branson Ultrasonic source, and a Polytec laser vibrometer, both purchased with Wayne State funds. The purpose of these pieces of equipment is to facilitate the study of the frequency dependence of the thermosonic effect, both in terms of input frequency and in terms of the actual vibration modes that occur in parts under inspection. The vibrometer also serves another purpose, that of monitoring the sound in the sample for comparison with the apparent output of the Branson source. This latter function is necessary to determine the efficiency of the coupling between the gun and the part.

Coupling Studies: We have found that the coupling between the ultrasonic source and the sample presents a major barrier to attaining reproducible signals from cracks. Each pulse of the source produces a different acoustic waveform in the sample, so that it is difficult to compare the results of different shots. This problem appears to have two origins. One is the "intelligent" electronics in the Branson sources. Even though the source is sharply tuned, it can be forced to change its frequency by a small amount. For instance, the frequency of our nominal 20kHz systems, of which we have two, can be swept by plus or minus 500Hz. When the ultrasonic power supply is triggered to send out a pulse, it apparently sweeps the frequency through this band at a low power level in an attempt to find a "sweet spot" at which the power output is maximized. It then locks onto this frequency and cranks up the power for the actual pulse. This results in a short delay between the trigger input and the beginning of the actual output pulse. It also produces variability in the exact frequency and the pulse's waveform. This effect is accentuated by changes in the material used for coupling the sound into the sample. Because of the high power of the ultrasonic source, each shot heats and, in most cases, damages the coupling material, and these changes are sensed by the Branson electronics with a corresponding change in the exact frequency set point. As a result we are forced to use a new piece of material for each shot. This situation is different from that which occurs in ordinary ultrasonic inspection where the frequencies are orders of magnitude higher, and the power levels orders of magnitude lower. Ultrasonic inspections ordinarily use water, or in some cases special gels as coupling materials, but these are totally unsuitable for low-frequency, high-power, use. As a result, one of our major efforts during this reporting period has been focused on the evaluation of coupling materials and methods.

Our search for a suitable material has led us to some rather unlikely looking candidates. The very first set of materials was a collection of soft metals including indium, lead, and soft copper. These were rejected because they either extruded from between the transducer and the sample, and/or left a metallic residue on the sample. This was followed with cork sheet, rubberized paper (automotive gasket material), fiberglass-reinforced Teflon sheet, Nicalon (SiC) cloth, Kevlar cloth, etc., used either wet or dry. At present, the material that produces the most consistent results is leather. The combination of density, resilience, and toughness that leather possesses seems to be close to ideal. We purchased a large quantity of leather from a wholesale leather dealer when we were in Albuquerque for our annual trip to AANC, but are currently looking for a manufactured material with the same characteristics as leather, but with more consistent material properties.

Travel: We made two field trips during this period. The first was the emergency trip to Floyd Bennett Field to inspect the remains of the tail of AA-587. Bob Thomas and Skip Favro from WSU and Mike Ashbaugh from AANC used a flash system (*not* a thermosonic system) to inspect portions of the vertical stabilizer and rudder. Dave Galella assisted us in some of the inspections.

The second field trip was our regularly scheduled one to AANC in March. Three faculty members, Skip Favro, Bob Thomas, and Golam Newaz (from Mechanical Engineering at WSU), together with two students and a technician, participated in this trip. Xiaoyan Han was not able to participate because of the imminent birth of her baby (a son, born April 6). Prof. Newaz was included because he is an expert in composites, an area that Dave Swartz suggested we should investigate because of interest raised by the AA-587 incident. While at AANC we tested our thermosonic equipment for inspection of fuselage cracks in the B-737 testbed, and for detection of engineered defects in composite samples provided by Dennis Roach. The thermosonic system showed considerable promise for detection of defects in composite samples. While we do not know the exact details of the defects we detected in the composites, we understand that they included Teflon inserts, potted core, etc. We also used Mike Ashbaugh's Thermal Wave system to inspect some of the composite samples to provide a comparison between the two techniques. Several images from AANC are shown below under "Examples of Images".

Other travel consisted in part of two trips to equipment manufacturers, one to Indigo Systems, Santa Barbara, CA, in October to discuss camera design modifications, and one to Branson Ultrasonics, Danbury, CT, in January to discuss ultrasonic sources. Travel to present papers at conferences and workshops consisted of three trips. Two were in December, one to a DARPA Workshop in Washington, and one to a workshop at UDRI in Dayton. The remaining trip was to ASNT in Portland, OR in March.

One final trip, not directly related to FAA work, but of considerable interest to other government agencies, was made by Skip Favro to Fermilab in Batavia, IL, in February. This trip resulted from a novel potential application of thermosonics. An international consortium of high-energy physicists has a proposal before the NSF and DoE to build a very large solar neutrino detector, either in a salt mine in Nevada or in a gold mine in South Dakota. It turns out that they will need thermosonics to inspect the integrity of the welds in a 14 meter diameter, 20 meter long, pressure vessel. Han and Favro have been asked to participate and train the personnel who will perform the inspections if the detector is funded. This is an interesting example of applied research leading to benefits for research in fundamental physics and astrophysics.

Examples of Images

Figure 1 shows a thermosonic image taken with our large format (640x512 pixel) Indigo Phoenix camera at AANC. It shows two fasteners on the belly of the B-737 testbed, both with interesting features. The one on the left has severe skin corrosion adjacent to the fastener, while the one on the right has two cracks extending out from the fastener. The "cloudy" areas, especially near the left fastener, are indicative of corrosion on the internal surface of the skin. The internal corrosion shows only weakly in this image because it was taken soon after the initiation of the acoustic pulse, and the heat from the internal corrosion has not yet had time to propagate to the outside surface. In an image taken a longer time after the initiation of the sound pulse, these areas would be brighter.

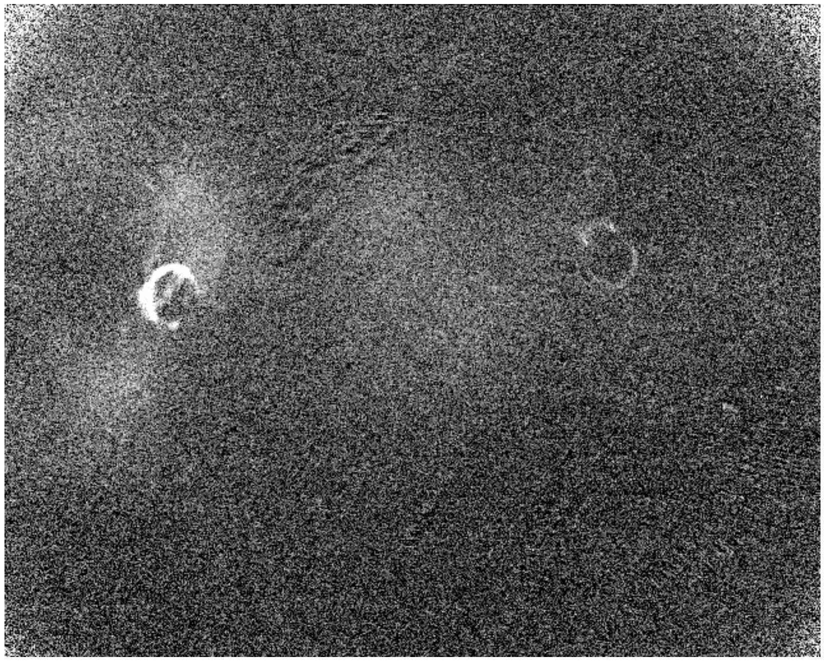


Figure 1. Two fasteners on the belly of the AANC B-737 testbed, one showing corrosion of the adjacent skin, and one showing two small cracks extending out from the fastener.

In Figure 2 we show a thermosonic image of a boron-fiber composite patch on the B-737 at AANC. The patch has numerous engineered defects. This image shows the ability of thermosonics to detect other kinds of defects beside cracks, and to detect defects in different materials.

Figure 3 shows still another example of a thermosonic image of defects in a different material. This is an image of two of the manufactured defects in a composite sample provided by Dennis Roach. This sample has a 12-ply fiberglass skin over a Nomex core. The upper defect is believed to be a "pillow" insert, while the lower is believed to be potted core. The periodic pattern seen in the image of the lower defect is an acoustic mode pattern that appears here because the fiberglass/resin composite skin, unlike aluminum aircraft skin, is acoustically lossy. The origin of the pattern in the top defect is not known, but, from its irregular appearance, we may speculate that it is the result of variations in the degree of disbonding caused by the insert.

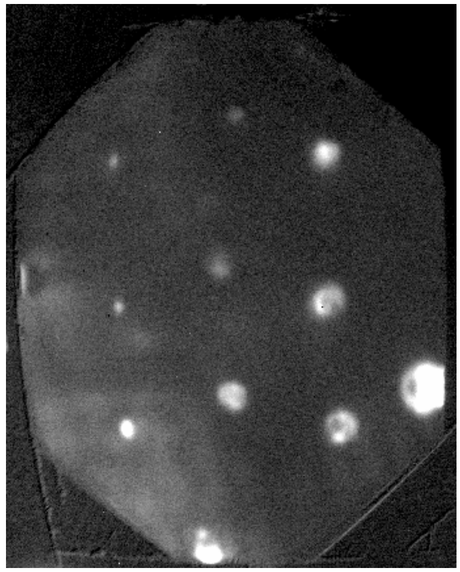


Figure 2. A thermosonic image of a boron-fiber composite patch on the skin of the B-737 testbed at AANC showing defects which were engineered into the patch.

Figure 3. A thermosonic image of a 12-ply glass-fiber skin over a Nomex core. The two simulated defects are believed to be a pillow insert (top) and a region of potted core (bottom).

Plans (April 1, 2002 – October 31, 2002):

We plan to use our new vibrometer to initiate a systematic study of the vibration of samples in the vicinity of cracks to attempt to understand the origin of the thermosonic effect. The samples will be aluminum with natural fatigue cracks with different sizes. Boundary conditions on the samples will be changed to introduce vibration to the samples using the ultrasonic gun. The focus of our measurements will be to monitor the displacement field both around the crack and in the far field from the crack to assess origin of the thermosonic excitation. This investigation will help us clarify the nature of oscillations that contribute to the thermosonic effect.

We plan to prepare samples and develop sharp natural cracks using an MTS machine in the Fatigue Laboratory of Professor Golam Newaz to produce cracks under controlled conditions so that the cracks are well characterized. Samples will be prepared with aluminum and titanium materials with a range of thicknesses to simulate plane-stress and plane-strain conditions. Since the cracks will be produced under controlled conditions, the use of standard fracture mechanics models will enable the prediction of crack parameters and interface properties to use as input to analytic and computational models, the results of which will then be compared with actual measurements on the samples.

Milestones:

Original Date 6/14/00	*Revised Date*	*Milestone*	*Status*
Quarter 1		Complete acquisition of aluminum alloy laboratory test samples.	Ongoing. We have studied a number of such specimens. Others are being designed and acquired.
Quarter 2		Complete study of transducer and acoustic coupling optimization.	Ongoing. We have studied several coupling techniques, but the study is still in its infancy.
Quarter 2		Complete study of buffer materials for coupling.	Ongoing. Several buffer materials have been found to be effective. However, optimization will be an ongoing task.
Quarter 3		Complete field trip to AANC to study laboratory AANC test samples.	Completed
Quarter 4		Complete modeling for surface breaking cracks.	Completed, but more extensive modeling is ongoing
Quarter 5		Complete modeling for subsurface vertical cracks.	Completed, but more extensive modeling is ongoing
Quarter 6		Complete the optimization of the synchronization between the ultrasonic source and the IR camera.	Completed
Quarter 6		Complete the design of suitable electronics and interfaces to achieve the synchronization.	Completed
Quarter 6		Complete field trip to AANC to field test synchronous imaging.	Completed
Quarter 7		Complete the construction of a working laboratory prototype.	Ongoing
Quarter 8		Complete study of effects of camera resolution on the detectability of cracks.	
Quarter 9		Complete design of field usable prototype.	
Quarter 10		Complete field testing of prototypes.	
Quarter 10		Complete draft of final report.	
Quarter 11		Complete draft of technology transfer plan.	

Deliverables:

Original Date	*Revised Date*	*Deliverable*	*Status*
6/13/03		Final Project Report.	On schedule.
6/13/03		Design and Specification of two Prototype Systems.	On schedule.
6/13/03		Technology Transfer Plan.	On schedule.

Major Accomplishments and Significant Interactions:

Date	*Description*
Quarter 2	Imaged a 20±2 μm long fatigue crack.
Quarter 2	Imaged cracks in a DC-10 nose wheel.
Quarter 2	Found evidence that thermosonics imaging can detect "kissing" disbonds that are missed by pulsed (flashlamp excitation) thermography (and therefore, also likely to be missed by ultrasonic inspection).
Quarter 3	Assembled a working version of a hand-held thermosonic system for on-aircraft work.
Quarter 3	Successfully obtained agreement between first modeling results and laboratory specimens.
Quarter 3	Completed a field trip to AANC and tested both the table-top and hand-held systems on targets of opportunity. Hand-held system was successfully tested on both internal framing members and fuselage skin, with cracks found in both.
Quarter 4	Conducted analytical and computational modeling of crack images. Bought a second 20kHz ultrasonic source from Branson Ultrasonics using WSU funds.
Quarter 5	Began use of the new Indigo Systems high resolution IR camera. Began work on a noise reduction algorithm for thermosonic images.
Quarter 6	Initiated laser vibrometer measurements on cracked metallic samples with a borrowed vibrometer. Ordered a vibrometer using WSU funds.
Quarter 7	Tested 40kXz system. Built a pneumatic system for holding ultrasonic gun.

Publications and Presentations:

"Sonic Infrared NDT for Crack Detection", Xiaoyan Han, Lawrence D. Favro, and Robert L. Thomas, ASNT, Portland, OR, March 19, 2002.

"Thermosonic NDE for Aircraft Structures", Xiaoyan Han, L.D Favro, and R.L. Thomas, UDRI, Dayton, OH, Dec. 3, 2001.

"Investigation of Thermosonics for Crack Detection in Turbine Engines", Xiaoyan Han, L.D Favro, and R.L. Thomas, DARPA Workshop, Arlington, VA, Dec. 12, 2001.

"Thermosonics: Detecting Cracks and Adhesion Defects Using Ultrasonic Excitation and Infrared Imaging", Xiaoyan Han, L.D. Favro, Zhong Ouyang, and R.L. Thomas, The Journal of Adhesion, 76, 151-162, (2001).

"Sonic Infrared Imaging of Fatigue Cracks," L.D. Favro, R.L.Thomas, Xiaoyan Han, Zhong Ouyang, Golam Newaz, and Dominico Gentile, The International Journal of Fatigue, 23, pp. 471-476, (2001).

“Sonic IR Imaging of Cracks and Delaminations,” ,” L.D. Favro, Xiaoyan Han, Zhong Ouyang, Gang Sun, and R.L. Thomas, Analytical Sciences, 17, 451-453 (2001).

Task Title: Aging Characterization and Lifetime Assessment of Polymeric Insulation in Aircraft Wiring

Investigation Team: L. C. Brinson, S. Carr, T. Mason, K. Shull – Northwestern University

Students: Tao Bai and Nelson Nunalee; postdoc T. Ramanathan

Program initiation date: May 23, 2000

Objective:

- To identify the critical aging mechanisms for aircraft wiring.
- To develop a reliable test method based on IS for assessing the aged state of aircraft wire.
- To develop predictive models to describe the degradation of wire insulation.

Approach:

Examination of the problem of aging of electric wire insulation is under way to determine the best methods to routinely characterize insulation integrity in existing aircraft as well as to provide insight as to how health monitoring could be installed as an integral component of new aircraft. The work consists primarily of the development of an impedance spectroscopy technique that could be used as an *in situ* test method for intact wiring. This work is being supplemented by standard characterization methods, such as Fourier transform infrared spectroscopy (FTIR), optical microscopy and scanning electron microscopy. Both naturally aged and laboratory aged wires are being evaluated. Identification of the primary aging mechanisms as well as suitable nondestructive testing techniques are under way. Results of the research effort will help define the impact of aging factors on wire insulation and provide tools to predict and detect critical degradation levels.

Objective/Approach Amendments: Objective and approach remain as originally proposed in February 2000.

Progress (March 2002):

The focus of this project has been to utilize impedance spectroscopy (IS) for the purpose of evaluating the aging characteristics of polymeric insulation in aircraft wiring. Two of the more important polymers that belong to this genre are Kapton and PVC. Therefore, our research has concentrated primarily on these two polymers and their relevant properties. The following report summarizes the general experiments and findings concerning these two polymers, along with our research plans for the coming months. Most of the focus of this report is on Kapton.

Kapton

Planar Aqueous Geometry

Great effort has been concentrated around the study of this particular geometry, in which a thin film of Kapton is placed between two chambers of aqueous solution that are in contact with two outer stainless steel electrodes. Figure 1 shows a schematic of this geometry, henceforth known as the aqueous electrode geometry (AQUEOUS ELECTRODE GEOMETRY).

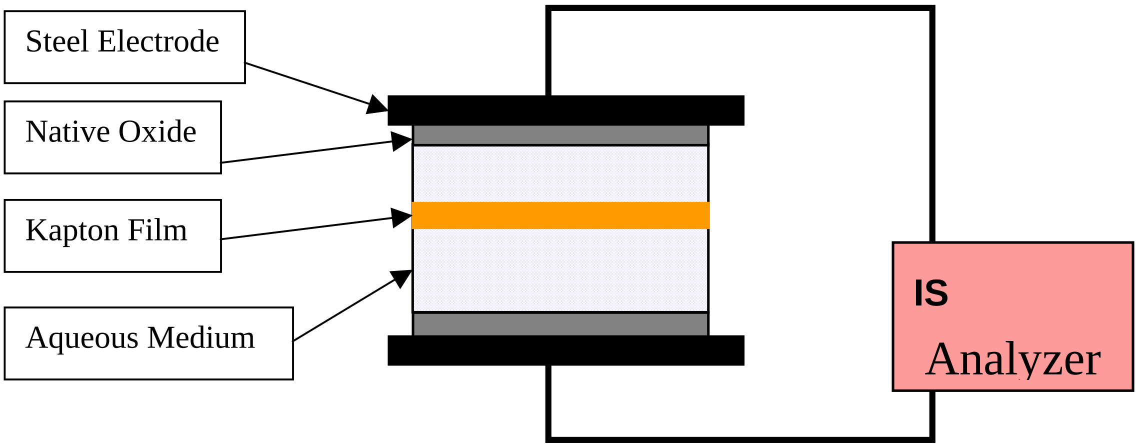


Figure 1. Illustration of the aqueous electrode geometry.

Note that the aqueous medium forms a native oxide layer on the surface of the steel electrode, a detail that will come into play in the analysis to follow. In all cases the impedance analyzer was a Solartron 1260 Frequency Response Analyzer. Most often, the new Solartron 1296 Dielectric Interface was used, providing more accurate results in the low frequency and high impedance regimes.

Impedance can be defined as the frequency-dependent current response of an alternating voltage. Therefore, impedance is the AC analog to resistance in DC. Impedance can be represented simply by a magnitude, |Z|, and a phase angle, ϕ:

$$Z(\omega) = |Z|e^{i\phi} = |Z|\cos\phi + i|Z|\sin\phi = Z' + iZ''$$

Thus, impedance is composed of real and imaginary components, which correspond to resistive and capacitive elements, respectively. The AQUEOUS ELECTRODE GEOMETRY can be modeled by assuming that the entire equivalent circuit consists of an element with a single time constant (a single resistor and capacitor in parallel). In this case, the equations relating real (Z') and imaginary (Z'') impedance to the single resistance (R_t) and capacitance (C_t) of the system simplify to:

$$Z' = \frac{R_t}{1 + \omega R_t C_t}, Z'' = \frac{-\omega R_t^2 C_t}{1 + \omega R_t C_t}$$

In reality, the system is more complicated and must be broken down into several RC components. In essence, each distinct physical contribution to the system contributes a time constant (RC) of its own to the total circuit. The art of guessing the correct circuit is known as equivalent circuit modeling, and Figure 2 shows how the AQUEOUS ELECTRODE GEOMETRY might be modeled in such a way.

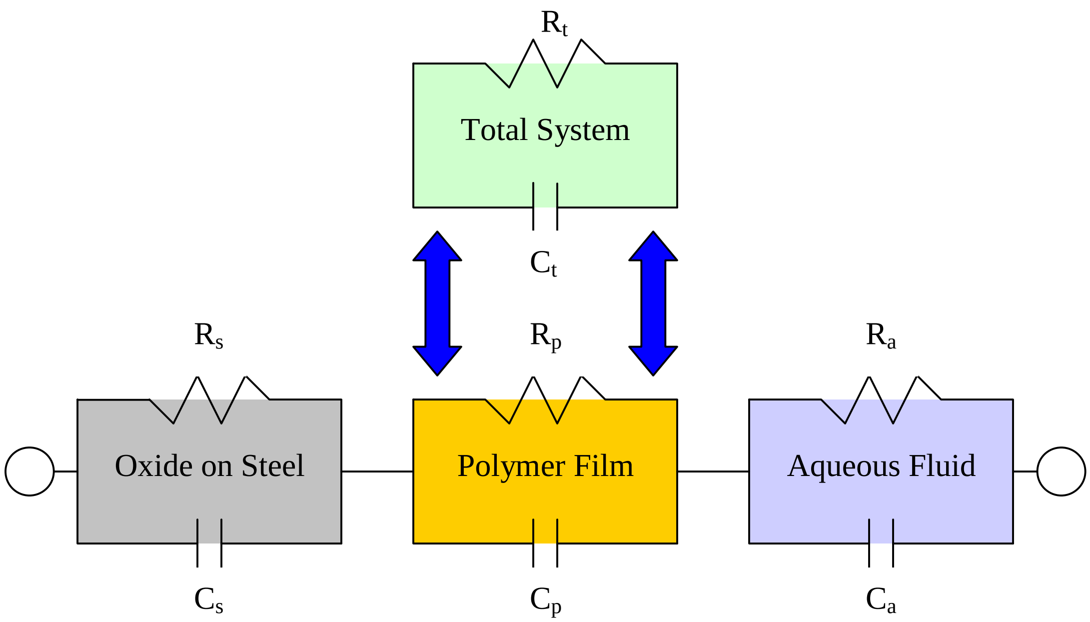


Figure 2. Equivalent Circuit Modeling of AQUEOUS ELECTRODE GEOMETRY using three RC elements in series.

The wire leads that connect the setup to the IS could also be considered a component, but in this case their contribution is negligible. Therefore, we assume it is only necessary to consider three RC elements: the oxide layer on the steel electrodes, the aqueous fluid, and the polymer itself. To determine the relative importance of the oxide and aqueous contributions, it is useful to look at a graph of Z' and Z'' vs. frequency (ω) over a large frequency range. Figure 3 shows such a plot for a 25 µm-thick Kapton film between aqueous electrodes of 2% NaCl.

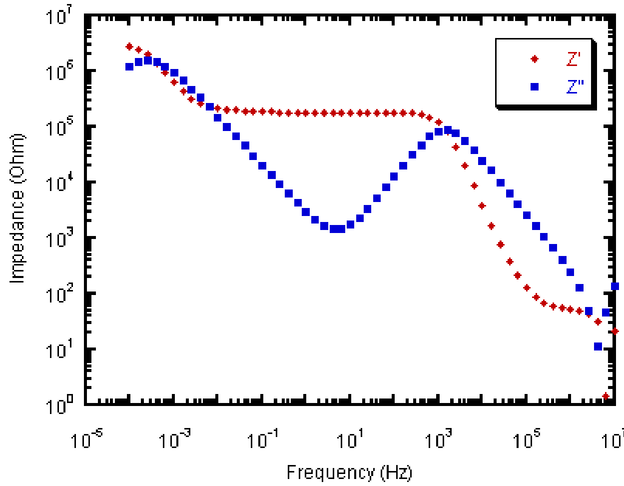


Figure 3. Real and imaginary impedance vs. frequency for a Kapton film in salt solution.

It is very interesting to note that this experiment yields useful impedance information for frequencies covering 11 orders of magnitude. The frequencies at which local maxima in Z'' occur correlate directly to the three time constants (1/RC) of the aforementioned circuit components. By assigning sensible values of R and C, we find that the peak around 10^{-4} Hz belongs to the oxide layer, the peak around 10^{3} Hz belongs to the polymer, and the high-frequency peak (~10^{7} Hz) belongs to the aqueous solution. It is fortuitous that the relaxation time for the oxide layer is at such low frequencies; this allows us to conduct our experiments at faster frequencies while systematically ignoring the oxide contribution to the system.

Impedance Modeling

Using a computer program called Equivalent Circuit, a circuit model, such as the one in Figure 2 (ignoring the oxide component), can be fit to a set of real data points to determine the values of R_p, C_p, R_a, and C_a. Figure 4 is a composite plot showing Z' and Z'' vs. ω for a Kapton film in tap water and the corresponding model fit.

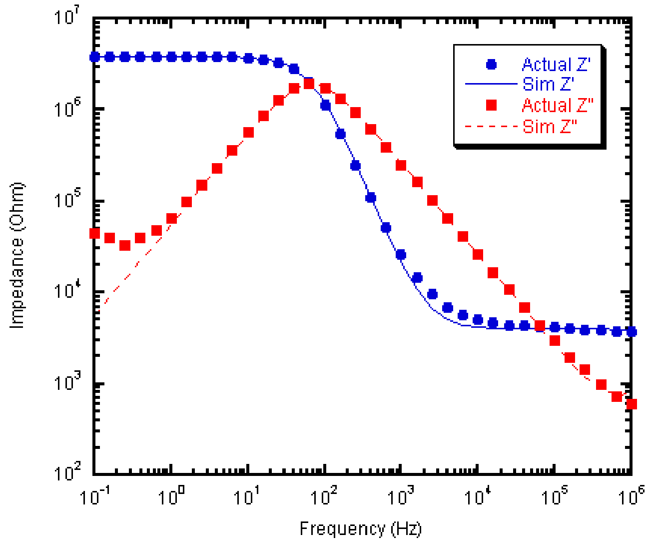


Figure 4. Fit to impedance data using Equivalent Circuit program. Here, a 25µm Kapton film lies between two tap water electrodes.

It can be seen clearly that the model fit is very good except for the imaginary impedance data below 1 Hz. This can easily be explained by the fact that the data is affected by the oxide layer component, which the model has ignored. Nonetheless, we have proven that we can accurately model the impedance behavior of polymer films in the AQUEOUS ELECTRODE GEOMETRY by assuming a circuit of two RC components in series. In the above plots, the computer-generated values for C_p and R_p are 6.14×10^{-10} F and 3.84×10^{6} Ω, respectively. Using simple physical relationships, the dielectric permittivity, ε, and resistivity, ρ, of the film can be calculated as follows:

$$\varepsilon = \frac{C_p d}{\varepsilon_0 A}, \rho = \frac{R_p A}{d},$$

where d and A are given by the geometry and ε_0 is the permittivity of free space, 8.85×10^{-12} F/m. The calculated dielectric permittivity falls nicely in line with values quoted from Du Pont, the supplier of our Kapton-H films. However, the calculated value of resistivity is much lower than the published value of 1.5×10^{15} Ω-m. Using this value, the DC resistance of the polymer film should be 7.5×10^{13} Ω, some seven orders of magnitude higher than our value found above! It bears noting that our experimental value of R_p is consistent with values of resistance found for Kapton films swollen in a 100% humidity environment (Pak, 1993). Thus, we propose that the greatly enhanced conductance in these systems occurs via the transport of ionic species in the solution-swollen media.

Swelling of Kapton

Since Kapton is known to swell by almost 4% in humid environments, it is a prime candidate for such a phenomenon. Both the tap water and salt solutions cited above are highly ionic in nature. Thus, upon swelling in the AQUEOUS ELECTRODE GEOMETRY, a relatively large amount of ionic species penetrates into the swollen polymer, which may help explain the improved conductance (lowered resistance).

Also consistent with this theory is the time evolution of impedance beginning when a dry film is first wetted and subsequently swollen to equilibrium. At first, Z'' is much higher than Z' and the phase angle ϕ is nearly -90°. This is characteristic of a perfect capacitor. This type of behavior might be expected from a dielectric layer of Kapton between two electrodes. The conductance is virtually zero, explaining why Kapton films are used as insulators in countless electrical applications. However, after a time on the order of 30 minutes to 1 hour, the impedance discontinuously changes to something similar to Figures 3 and 4. We contend that this corresponds to the penetrating aqueous solution reaching some critical degree of swelling, beyond which the IS instrumentation can decipher a significant Z' contribution (corresponding to the emergence of a resistive element). At longer times, the plateau regime of Z' gradually lessens to some equilibrium value of maximum ionic conductance. The data in Figures 3 and 4 were taken at swelling equilibrium.

Since the ultimate goal of the project is to study aging characteristics using IS, we have pursued the condition of Kapton swollen with various aqueous solutions. Kapton is clearly susceptible to changes in humidity, which greatly affect its integrity as an insulator. The swelling of Kapton in solution can be considered a form of accelerated aging. The following plot (Figure 5) shows the results obtained by swelling Kapton with four different salt solutions: 1M KCl, 2M KCl, 1M KF, and 2M KF. For simplicity, only real impedance data is shown since the low-frequency plateau value is related directly to the resistance of the film. At a glance, a trend can be seen for the four solutions: the resistance of the film decreases at higher ion concentrations and with decreasing anion size. Thus, the 1M KCl has the highest Z' and the 2M KF has the lowest. Clearly, this collection of data is incomplete, but the initial results support the idea that conductance in the films is dominated by ionic species. It stands to reason that smaller anions (Fluorine is smaller than Chlorine) and higher concentrations of them in a Kapton film will lead to a diminished ability to resist current flow.

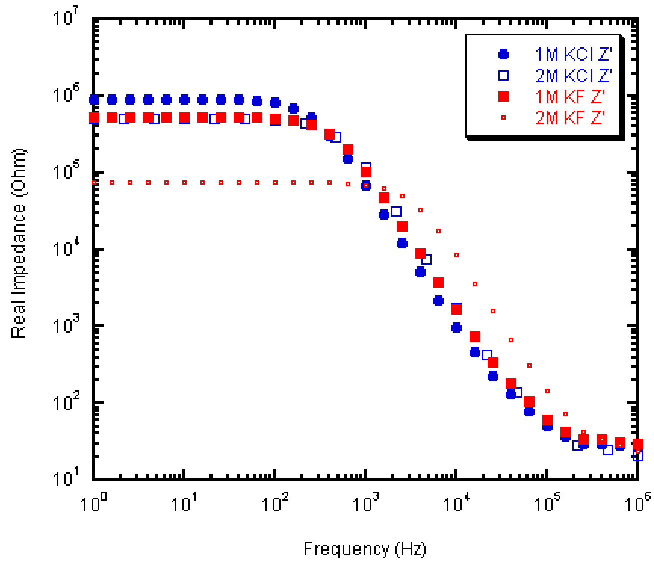


Figure 5. Comparison of the effect that various salt solutions have on the impedance behavior of Kapton upon equilibrium swelling.

Chemical Aging

As presented in previous reports, while Kapton is immune to most chemicals, it is highly susceptible to the base-catalyzed hydrolysis of its imide bonds. Figure 6 shows a schematic of the hydrolysis that Kapton-H undergoes in the presence of a concentrated, strong base such as NaOH. First, the imide bonds of Kapton are hydrolyzed, leaving an amide bond and an acid salt. It is possible that the amide bond of the polyamate salt may then further hydrolyze, thus cleaving the polymer backbone and greatly changing the properties of the system.

The aqueous electrode geometry affords the chance to simultaneously monitor several interesting impedance features if the aqueous solution is a strong base. First, the ionic swelling described up to this point should be evident over the course of the first few hours. Second, the impedance behavior of the film will most certainly change as a function of the hydrolysis process. And finally, the product of hydrolysis (the polyamate salt) is itself an ionic species that can add to the complexity of the ionic conduction.

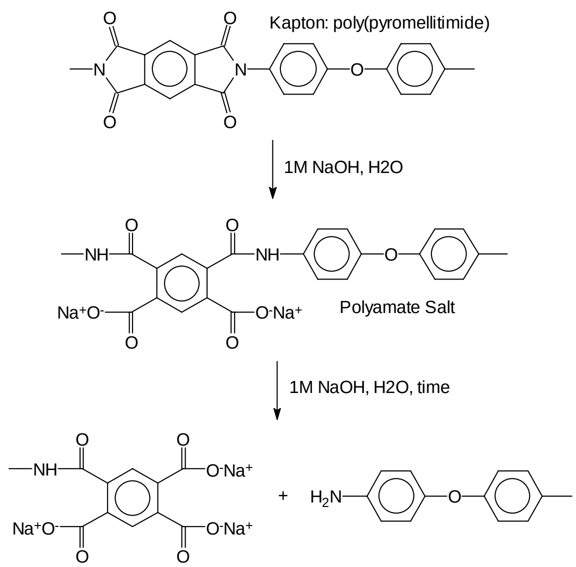


Figure 6. Schematic representation of the base-catalyzed hydrolysis of Kapton.

Figure 7 displays the results of a Kapton hydrolysis experiment using 1M KOH. Unlike the experiments cited above, this experiment begins with a vacuum-dried sample instead of one at its equilibrium-swollen state. The points represent the change in the low-frequency real impedance plateau (essentially R_p) as a function of time. At times between 1 and 5 hours, Z' seems to decrease and level off, which is to be expected based on the above arguments. The subsequent rise in impedance will be discussed later. Between 10 and 15 hours, the impedance is steady. Then, after 15 hours, there is a drastic decrease in impedance and the film eventually takes on a value of real impedance similar to that of the aqueous solution itself.

Stoffel et al. hypothesize that the process of base-catalyzed hydrolysis of a Kapton film occurs via a moving front that makes its way uniformly through the film until it reaches the other side (1996). They have followed the advancement of Potassium in films hydrolyzed by KOH using Rutherford Backscattering. In this manner, they have determined that the hydrolysis "front" moves at a rate of 0.3 μm/hr. If we apply this rate to the thickness of our films (25 μm), it follows that is should take on the order of 40 hours for the two hydrolysis fronts in the AQUEOUS ELECTRODE GEOMETRY to meet. It can be assumed that at this time, the impedance behavior would change in some discontinuous manner and would likely decrease significantly. We propose that the large drop in Z' seen in Figure 7 around 15 hours represents this sort of phenomenon. Although it may seem like the process occurs too quickly compared to Stoffel's results, the disparity is relatively small, and may be due to the existence of defects in the material.

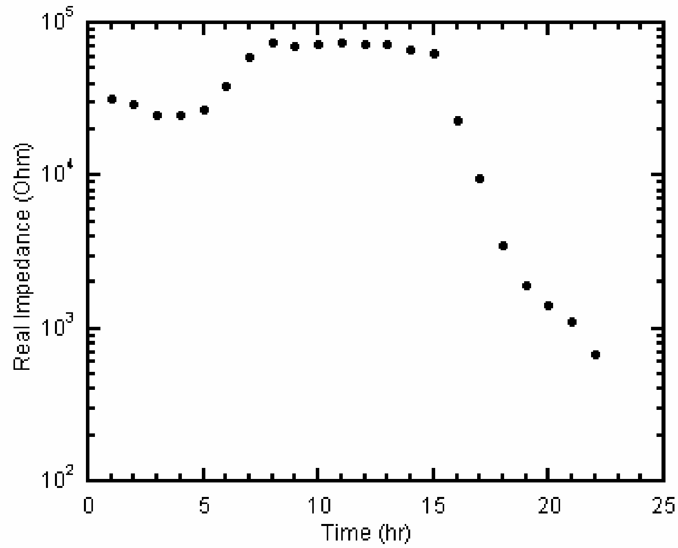


Figure 7. Time evolution of R_p for a Kapton film in the AQUEOUS ELECTRODE GEOMETRY with 1M KOH.

The increase in impedance seen in the 5-10 hour regime is not easily understood. However, one possible explanation revolves around the issue of the contribution to the impedance by the polyamate salt. Our hypothesis for ionic conduction has hinged upon the idea that our aqueous solutions introduce free ions into the swollen polymer that are able to diffuse and increase the conductance of the films. In the case of KOH, there are free K^+ and OH^- ions in solutions. However, as the polymer begins to undergo hydrolysis, a negatively charged polyamate ion is formed, which may selectively bond to Potassium cations and thus reduce the overall free ion content of the swollen polymer. In that case, impedance would indeed rise again to some other equilibrium value, which is what we see in Figure 7.

This entire section has given some examples of the work that is being done with the aqueous electrode geometry. It is clear that this geometry is very sensitive to small and large changes in the composition of thin Kapton films. The utility of the aqueous electrode geometry lies in the reduced resistance of the film through ionic solution swelling. Without this, the film simply acts as a capacitor between two electrodes. However, if swelling is allowed, then other effects such as the process of hydrolysis can be studied with relative ease.

PVC

To obtain greater control of polymer systems, PVC films were prepared in our laboratory using their precursor, which offer more control over the industrial samples. Glass transition temperatures for the homemade polymers have been measured using DSC and DMA, providing a Tg around 60°C which is ideal for facilitating accelerated aging experiments. The PVC films have been tested in the aqueous electrode geometry, a dry sample holder (a parallel brass plate fixture) and with sputter coated electrodes on the films. In the brass plate fixture, PVC film was sandwiched between the brass plate electrode and a small pressure was applied to the film. A complication of this set-up is that the actual contact area of the electrode and the film may be increasing due to the pressure effect or there may be a chance for point contacts between the electrode and sample due to the surface roughness of the PVC film. To eliminate these draw backs, we applied a layer of electrically conductive silver paste between the brass plate electrode and the sample film. Results from the three geometries have been used to help define proper equivalent circuit modeling for each system and to isolate additional impedance sources in each of the set-ups. Although the aqueous geometries provide the most consistent results to date, dry set-up alternatives are desirable for aging studies to remove influence of water on the aging results. Physical aging on the PVC films have been carried out with Impedance spectroscopy measurements using aqueous setup and brass plate fixture results indicate good ability of the spectra to reflect the aged state of the polymer film. Further, mechanical creep tests have been performed using DMA, again producing results clearly indicating the aging state of the polymer.

Single Wire Geometry

In the spirit of moving toward more realistic systems, we are also working with a new experimental setup to carry out impedance measurements on polymer-insulated wires. As shown in Figure 8, the Kapton wire is threaded through a 10 cm-long stainless steel tube and two rubber stoppers, which act as end caps for the tube. The column is filled completely with a conducting fluid such as water. The conducting wire core itself acts as one electrode and the outside of the steel tube acts as the other. A wooden frame surrounding the electrodes offers stability and isolation from other conducting media.

Early experiments with this geometry are encouraging in that the system is simple, easy to model, and offers a straightforward method of quantifying chemical and mechanical aging. Figure 9 is an example of the kind information that can be gleaned from the wire geometry; here the data are in the form of a Real Capacitance "Bode" Plot (real capacitance vs. frequency). Two sets of data are shown: one corresponding to a pristine wire sample in H_2O and the other corresponding to a wire aged in 1M KOH for 24 hours. The differences in the impedance spectra are striking and support the idea that this geometry may be quite useful in quantifying the aging of aircraft wire insulation. Note the pristine sample is in essence a pure capacitor while the aged sample has a resistive component. This is similar to the behavior of a dried Kapton film upon swelling. Therefore, it may be that if the “pristine” sample were allowed to soak for very long times, the results would look more like the aged sample. Therefore, this type of experiment warrants further investigation.

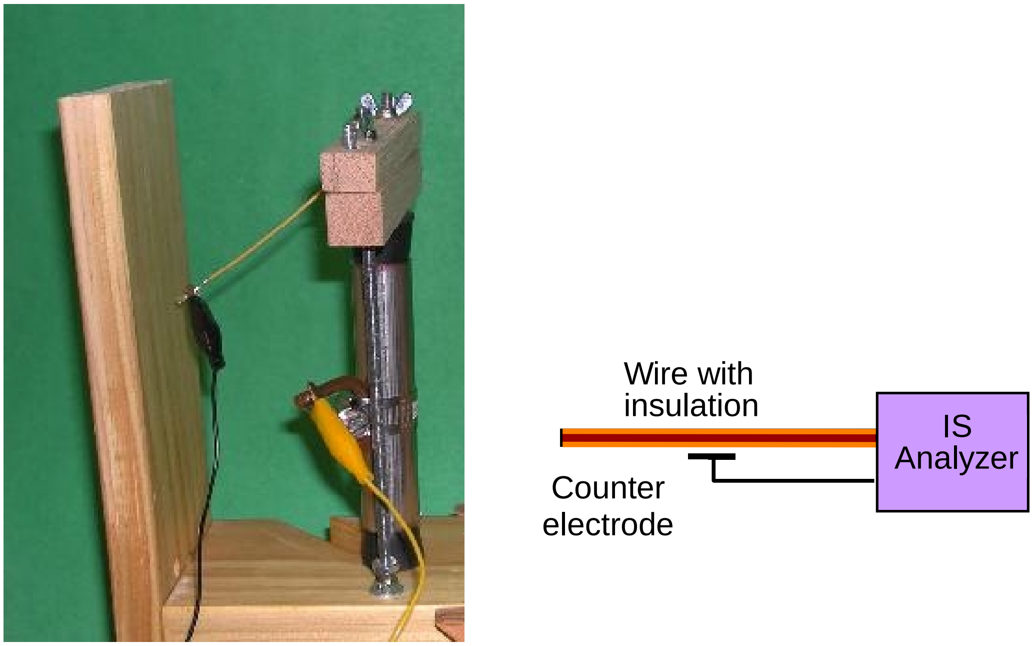


Figure 8. Digital image of a new apparatus for testing wire insulation directly. Schematic rendering is included as well.

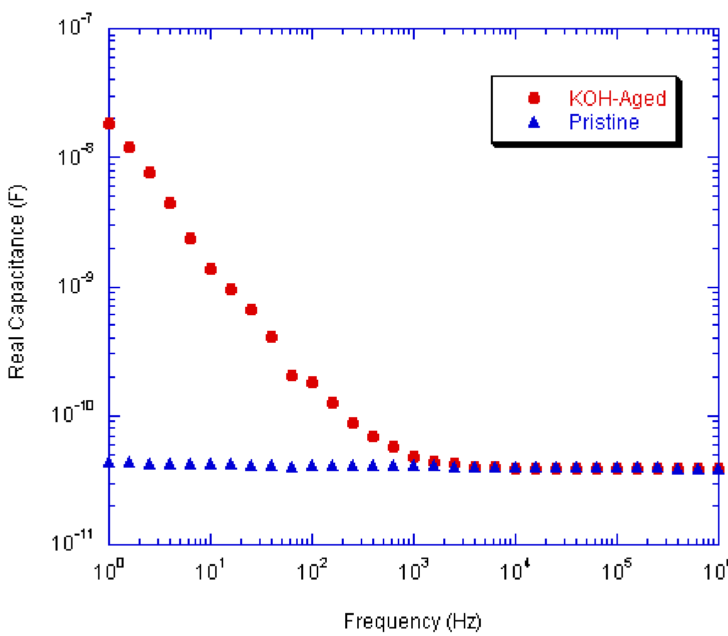


Figure 9. Comparison of real capacitance spectra for pristine and aged Kapton wires.

Plans (April 1, 2002 – October 31, 2002):

Future Work with AE and Wire Geometries

As previously noted, the swelling experiments in the aqueous electrode geometry are incomplete. To begin, a wide variety of concentrations should be used. 2M solutions of KCl and KF are close to saturated, so efforts should be made to use much less concentrated solutions. It may be interesting to extrapolate to infinite ion dilution (pure deionized water), in which case R_p should be significantly higher than in the case of saturated salt solutions. Also, to test the theory of the effect of anion size, it would be interesting to use solutions of KBr and KI in addition to KF and KCl. The goal of this particular aspect of the project is obtain a clear picture concerning the ionic transport characteristics of swollen Kapton films as a function of the ionic swelling solution. It may also be interesting to note the effect of temperature on the ionic conduction of Kapton. If the mode of conduction is through free ionic species, as suspected, then temperature should have a great effect on the impedance spectrum due to its effect on diffusion. Of course, temperature will also affect the rate and extent of swelling, not to mention the effects on relaxation behavior of the polymer chains themselves.

Another aspect of our future work is that we intend to move away from using industrial-supplied samples of Kapton films and wire. Instead, we have obtained the Kapton-precursor known as Pyralin from HD Microsystems. This precursor is essentially polyamic acid, which is similar to the polyamate salt in Figure 6 but with H^+ replacing Na^+. Pyralin is useful because it is in solution form and may be shaped in any desired fashion and then cured at appropriate temperatures to yield the polyimide that is equivalent to Kapton. Therefore, we can now make our own films and wires, thus adding another element of control to our experiments.

Films can be made by spin coating a layer of Pyralin on an appropriate substrate. The thickness of the film can be controlled easily by changing the spin rate and spin time. Higher rates and longer times result in thinner films. The substrate and film can then be baked for several hours at temperatures above 200°F to fully imidize the polymer. The ability to spin a film directly onto an electrode will simplify the aqueous electrode geometry. Figure 10 is a modification of Figure 2; the polyimide is spun and cured directly onto one of the steel electrodes.

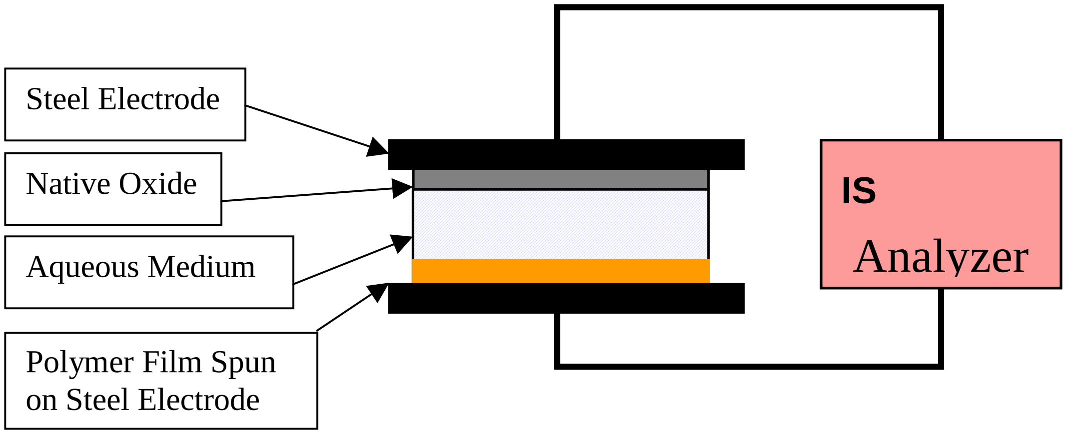


Figure 10. Revised version of the Aqueous Electrode Geometry with spun and cured film.

Since the film is rigidly bound to one electrode, any stress effects that were previously introduced by the aqueous chambers on the freestanding film will be eliminated. Also, the hydrolysis experiment will be greatly simplified as there can only be one propagating front instead of two. One drawback to this method is that film thickness will be difficult to reproduce and will thus have to be measured separately each time using some technique such as ellipsometry. Also, pinholes and other inconsistencies in the films may be difficult to eliminate.

As for the wire geometry, we seek to create our own "wire insulation" by dip coating a conducting core in Pyralin. As the name suggests, this simply involves submerging the core in Pyralin and then pulling it out at a constant rate, leaving a uniform polymer coating on the wire. As before, a curing step effects the formation of the polyimide from the polyamic acid. In this manner, we can test the properties of a polyimide wire without having to guess at the chemical makeup of our material. Again, defects that may arise in the dip coating process are a concern.

PVC Aging Studies

During this period, we will be examining the effects of moisture absorption and physical aging on PVC using both Impedance Spectroscopy and mechanical creep tests. Further investigation using a sputtered (thick coating to be made using Edwards e-beam evaporator) electrode set-up to avoid both pressure and moisture effects will be performed. Aqueous electrode and brass plate fixture may also be utilized for comparison of results. Physical aging on homemade PVC with IS measurements will be correlated with mechanical creep results in order to model the aging behavior and its impact on both mechanical and electrical properties.

Experiments with the Quartz Crystal Microbalance

Recently, efforts have been made to employ the use of the quartz crystal microbalance (QCM) as an additional means for quantifying small changes in a polymer film. The QCM consists of a thin, circular quartz crystal sandwiched between two gold electrodes. If an alternating voltage is applied to the electrodes, the quartz crystal undergoes vibrational motion and has a characteristic resonant frequency. If a polymer is attached to the surface of the crystal, the resonant frequency changes. Furthermore, if that polymer changes in mass, say from absorbing moisture, the resonance again changes. In short, the QCM can be used a very sensitive balance (as its name implies). This is useful because we now have a way to directly monitor the swelling of a polyimide film instead of doing so simply by inference. Figure 12 shows a typical QCM result for a polyimide placed in water at time = 0. In this case, Pyralin was spin coated onto a quartz crystal and subsequently cured at 200°C for five hours. Note that the resonant frequency of the crystal changes sharply at first and then quickly levels off. In the simplest case, these frequencies, f, can be related directly to the weight fraction of water in the films by the expression:

$$\phi_{w/w} = \frac{f - f_{dry}}{f - f_0},$$

where f_{dry} is the resonant frequency of crystal with the dried film attached and f_0 is the resonant frequency of the crystal by itself.

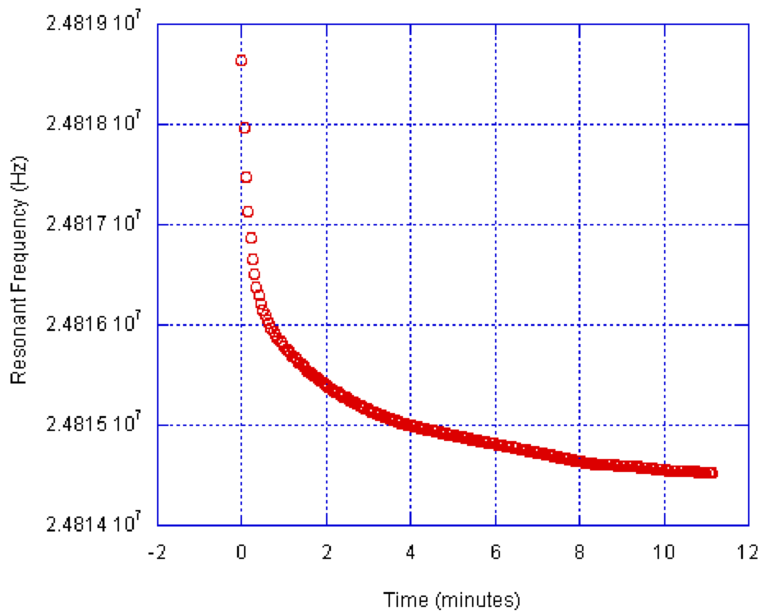


Figure 12. Resonant frequency of a quartz crystal with polyimide attached upon exposure to water.

Figure 13 shows a schematic of an experimental setup that utilizes both the QCM and the IS simultaneously to investigate the swelling behavior of a polyimide film. This method may give insight into the specific point at which the system switches from a capacitive impedance response to an RC impedance response, as discussed earlier.

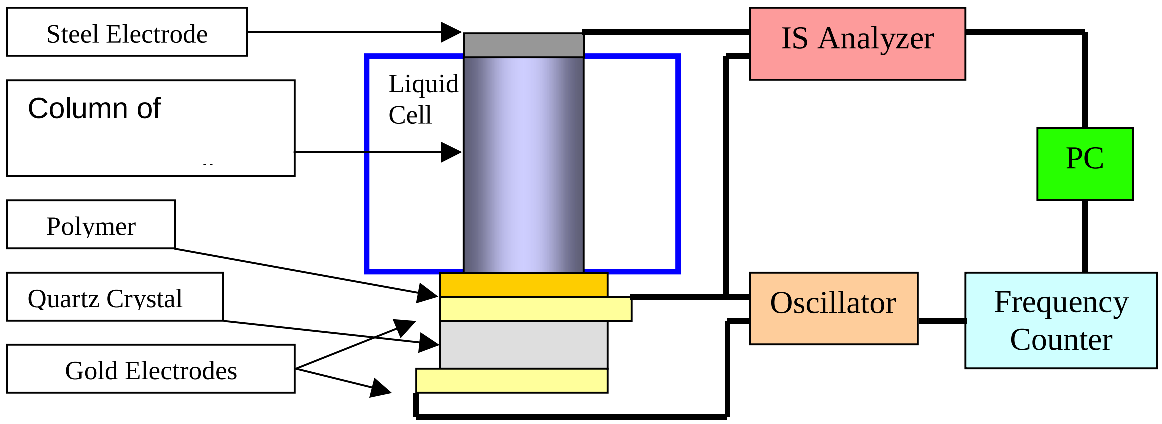


Figure 13. Possible use of QCM and IS in parallel measurements.

To conclude, the next phase of Kapton study will revolve largely around the incorporation of the quartz crystal microbalance. The use of the QCM in conjunction with IS will require some computer programming and interfacing. Also, some new test cells will have to be constructed. We feel that the use of the QCM is a worthwhile avenue to explore and is consistent with our goals of characterizing aged polymer insulation.

References:

Pak & Xu, *J. Mater. Res.* **8**, 923-926, (1993).

Stoffel et al., *Chem. Mater.* **8**, 1035-1041 (1996).

Milestones:

Quarter 1 Apr.-Jun., 2000	Preliminary experiments to demonstrate validity of impedance spectroscopy as a tool for studying aging processes in wire insulation.
Quarter 2 Jul.-Sep., 2000	Impedance experiments with aqueous and dry electrode geometries using Kapton films.
Quarter 3 Oct.-Dec., 2001	Development of equivalent circuit models for describing impedance results, including the effects of pinholes in the aqueous electrode geometry. Sensitivity of aqueous electrode geometry to a variety of mechanical defects is demonstrated.
Quarter 4 Jan.-Mar., 2001	SEM and FTIR results with aged wire. Results indicate that FTIR is not highly sensitive to aging effects. A decision is made to focus primarily on impedance spectroscopy as the major tool for studying aging. **Year 1 Report Submitted**
Quarter 5 Aug.-Oct., 2001	Low frequency results obtained with new dielectric interface. **Note: work continued between March and August – time periods correspond to project funding dates at Northwestern University.**
Quarter 6 Nov., 2001 – Jan., 2002	Development of experimental protocol for wire geometry. Physical aging experiments utilizing PVC films.
Quarter 7 Feb.-Apr., 2002	Chemical aging experiments with Kapton films, using the aqueous electrode geometry. Semiannual Report Submitted
Quarter 8 May-Jul., 2002	Reconcile aqueous and dry electrode geometries for well-characterized, solution-cast PVC films. Develop quartz crystal microbalance technique for independently measuring swelling effects of films in the aqueous electrode geometry. **Submit Year 2 Report**
Quarter 9 Aug.-Oct., 2002	Aging characterization with both mechanical loading and impedance spectra. Correlate results with indentation measurements obtained by Analog Interfaces. Work with Analog Interfaces to establish protocol for impedance analysis with mechanical contact geometry.

Quarter 10 Nov., 2002 – Jan., 2003	Continue to develop quantitative understanding of impedance results. Determine the most useful geometry for *in situ* testing and identify important system constraints.
Quarter 11 Feb. – Apr., 2003	Finalize models associated with impedance testing and mechanical testing; assimilate spectral results; develop model/tables to best describe wire state/lifetime as a function of spectral data; investigate predictive models based on aging conditions.
Quarter 12 May-Jul., 2003	Write up project results, make recommendations as to possible *in situ* testing devices **Submit Final Report.**

Deliverables:

Original Date	*Revised Date*	*Deliverable*	*Status*
Jan 2001	Feb. 28, 2001	Initial report on ability of impedance spectroscopy to reflect degraded state of aged aircraft wire, using “classic configuration”	In year 1 report.
April 2002	July 2002	Report on capability of technique for *in situ* analysis of wire pairs/bundles, effects of wire geometry, localized degradation, etc	In progress
March 2003	July 2003	Final report on all project results, with recommendations as to possible *in situ* testing devices	
March 2003	July 2003	At the end of the study, the lab equipment and methodology will be made readily available to any groups the FAA identifies as interested users. Technology transfer will be detailed in separate final report meant for potential users of the technology.	

Major Accomplishments and Significant Interactions:

Date	*Description*
Jan 2002 +	Ongoing exchange and contact with Martin W. Kendig, Rockwell Scientific. Focus on correlation between IS results and broadband impedance results.
March 2002+	Ongoing exchange and contact with Dave Puterbaugh, Analog Interfaces. Focus on mechanical degradation of PVC as measure of aging and wire insulation quality. Correlation with IS results.

Publications and Presentations:

The Boeing Company, AACE Symposium, 14 November 2000, "Impedance spectroscopy to Investigate Aircraft Wire Insulation Aging", T. Bai (presenter), L. C. Brinson, T. O. Mason, K. Shull.

K. R. Shull, L. C. Brinson, F. N. Nunalee, T. Bai, T. O. Mason, S. H. Carr, *Aging Characterization of Polymeric Insulation in Aircraft Wiring Via Impedance Spectroscopy*, Proceedings of the 5th Joint Conference on Aging Aircraft, Orlando, Florida, 10-13 September (2001).

Task Title: Modeling Optimization Tools of MOI Technology

Investigation Team: L. Udpa, Iowa State University; B. Shih, Physical Research Inc.

Students: Liang Xuan and Zhewei Zeng

Program initiation date: Program initiated as IA040 September 25, 2001 with scheduled ending date of September 25, 2002.

Objective:

- To develop a finite element code for simulating the eddy current MOI inspection geometry.
- To work with the industrial partner in the validation and application of the MOI inspection model for aviation applications.

Approach:

Magneto-optic eddy current imaging (MOI) systems have shown considerable promise in detecting corrosion and second layer cracking with the advantage being the large area coverage and easy-to-interpret images produced by the MOI systems. Most of the research efforts in this technique have been focused towards development of improved supporting hardware and electronics with limited attention given to improving the MOI film sensors. The more sensitive the sensor, the greater the probability of detection of a critical flaw. Crucial for such studies is the development of a numerical model for simulating the underlying physical process that in turn helps in making more informed design decisions. Currently, images obtained with thick single layer samples varies significantly from those obtained with thinner multilayer samples and the quantitative effect of the air gaps between layers is not well understood. The model will serve as an experimental testbed for carrying out parametric studies that are too expensive otherwise. The model will allow characterization of magnetic flux density for a given test situation under varying experimental conditions such as bias fields, frequency, excitation level, induction foil thickness, and defect parameters. The prediction of magnetic fields can be used in optimizing the imaging process. Initial work on adapting existing FE model for MOI geometry has been completed and the fields due to calibration defect computed and experimentally validated. Existing finite element code will be modified and adapted to model the MOI inspection geometry. The model will predict the normal component of the magnetic flux density, due to field/flaw interaction. Model validation will occur using a group of test cases consisting of a thin sheet with (1) hole (2) surface crack (3) hole and crack, and (4) subsurface corrosion dome. The model will be validated in collaboration with PRI (calibration samples) and AANC (additional samples). After validating the model, effort will be focused towards a systematic parametric study of the effect of test parameters such as frequency, excitation level and defect size. Experimental measurements for some of the test parameters will be done using the AANC MOI device at Sandia. The model will then be extended to multilayer geometry and field calculation for second layer cracks. Other geometries characteristic to aircraft structures, such as lap joint with subsurface corrosion and thin sheet and doubler with countersunk through-hole, will then be studied.

Progress (March 2002):

Specific examples of inspections of interest that would benefit from finite element modeling were identified by PRI, and addressed in the last six months. The presence of circumferential cracks in dimpled countersinks under rivets was found to result in anomalous MOI images when the eddy current induction was set in the linear excitation mode. The details for the countersunk rivet and crack geometry were obtained. The mesh for the geometry of circumferential cracks in countersunk rivets was generated. Conducting a study of the fields with respect to mesh parameters optimized the finite element mesh for the countersunk rivet geometry with a circumferential crack. The mesh incorporates a 0.1mm air gap between the fastener and the Aluminum layer. A circumferential crack of width 0.1mm and 22.5^{o} angular extent was introduced. The total number of nodes is 13750 and the resulting matrix size is 55000 x 2608. The incorporation of iterative matrix solution allowed the modeling of this high density mesh. The first prediction of the magnetic flux density due to the rivet geometry and crack was obtained. This result was communicated to PRI R&D Corp. for experimental validation in an interim report. The mesh for the countersunk geometry was then used to run an extensive parametric study. The effect of parameters such as, flaw size, depth, length in the circumferential direction and width, on the resulting images was studied. The results were documented in an interim report submitted to PRI R&D Corp. Similar studies were then extended to second layer cracks. An interim report documenting the results of parametric studies of cracks in the second layer were also submitted to PRI R&D Corporation.

A second effort was focused on modeling the effects on finite dimensional induction foil. Since the CUF geometry was relatively large the edge of the foil has a significant effect on the fields and resultant images. A detailed study of the effect of edges that are parallel and orthogonal to current direction was studied and the earlier work on circumferential crack in dimpled countersunk rivets was repeated with finite foil rotation in linear and rotational excitation currents. This study helped make decisions about the approximations that can be made in the model without sacrificing accuracy.

Plans (April 1, 2002 – October 31, 2002):

The next few months will be focused towards modeling the fastener-to-fastener crack geometry. POD studies by the Air Force have indicated that certain configurations of fastener-to-fastener cracks are more difficult to detect with the MOI. It would be valuable to quantify the results of such configurations in order to determine what improvements to the MOI are required to produce better results. This geometry poses a significant challenge for modeling in terms of memory and matrix dimension. Once the mesh generation for the geometry is completed, we will conduct a parametric study in terms of defect and operational parameters. The finite element simulation results can then also be used to develop a POD model for detection of fastener-to-fastener cracks. The study will be extended to cracks in the second layer. A second extension of the work will be with respect to magnetic properties of the fastener. Magnetic and non-magnetic fasteners will be investigated with regard to their effect on the POD of critical cracks of interest.

Milestones:

Original Date	*Revised Date*	*Milestone*	*Status*
6/1/98		Start Date.	
Feb 98		Generate 3-D finite element mesh for MOI corrosion geometries.	Completed
May 98		Generate magnetic flux due to subsurface corrosion and validate model.	Completed
Quarter 1		Completion of model validation for both crack and corrosion geometries.	Completed
Quarter 2		Establish model set up for crack calculations including mesh generation for multilayer geometry with rivets and cracks under rivetheads.	Completed
Quarter 3		Parametric Studies 1^{st} layer cracks - Effect of rivets (Crack parameters - depth, length, width. 2^{nd} layer cracks -Effect of rivets (thickness of 1st layer, frequency).	In process
Quarter 5	Sept. 98	Establish model setup for corrosion geometry including mesh generation for corrosion domes in multilayer geometry.	Completed
Quarter 6		Parametric Studies - 1st layer corrosion (corrosion depth, diameter, frequency, effect of 2nd layer).	Completed
Quarter 7		Repeat Parametric studies for 2nd layer corrosion domes (corrosion on top and bottom of 2nd layer).	Completed
Quarter 8		Establish model setup for CUF geometry including mesh generation for fastener to fastener cracks and cracks between fasteners.	In progress
Quarter 9		Circumferential cracks in dimpled countersinks underneath rivet heads – Parametric studies.	Completed
Quarter 10		Establish model setup for cracks along doubler edges on the backside of fuselage skin.	Not started.
Quarter 11		Investigate effect of steel fasteners. Modify the FE model to incorporate nonlinear material characteristics of steel. Generate MOI images at different levels of magnetization of steel fastener.	Not started
Quarter 12		Investigate the possibility of a nondimensional empirical laws that reflect the parametric studies.	Not started

Deliverables:

Original Date	*Revised Date*	*Deliverable*	*Status*
		Letter reports submitted to FAA and industry partner.	Ongoing
		Final report summarizing effort and industrial application.	

Major Accomplishments and Significant Interactions:

Date	*Description*
July, 1999	Presented invited paper at SPIE conference on Smart Materials, Systems and Structures.
July, 1999	Presentation in QNDE at Montreal, Canada.
August, 1999	Presentation at the ENDE conference in Des Moines.
June, 2000	Presentation in QNDE at Ames.
August, 2000	Visited by British RAF. Student (Chen Chao) graduated with M.S.
Sept. 2000	Attended ATA NDT Forum in SFO.
Nov. 2000	Presentation in TCRG meeting in Ames, presentation in 3rd AACE Annual Symposium.
July, 2000	Presentation at QNDE in Maine.
Sept. 2001	Presentation at the 5th Joint NASA/FAA/DoD Conference on Aging Aircraft, September 10-13, 2001, Hyatt-Orlando, Florida.
March 2002	Presentation at IEEE ACES conference in Monterey, California.

Publications and Presentations:

R. Albanese, G. Rubinacci, A. Tamburrino, A. Ventre, F. Villone, L. Xuan, B. Shanker, and L. Udpa, "A Comparative Study of Finite Element Models for Magneto Optic Imaging Applications", ENDE 2001, University of Cassino, Italy, June 2001.

L. Udpa, W. C. L. Shih, and G. F. Fitzpatrick, "Improved Magneto-Optic Sensors for Detection of Subsurface Cracks and Corrosion in Aging Aircraft", Aging Aircraft 2001, The 5th Joint NASA/FAA/DoD Conference on Aging Aircraft, September 10-13, 2001, Hyatt-Orlando, Florida.

L. Xuan, Z. Zeng, B. Shanker, and L. Udpa, "Development of a Meshless Finite Element Model for NDE Applications", ACES Conference, Monterey, California, March, 2002.

Title: NDI Guidance Material for FAA Aircraft Certification Engineers

Investigation Team: Lisa Brasche and David Eisenmann in response to requests from members of the Aircraft NDI Technical Community Research Group (TCRG).

Students: C. Cyrzan

Program initiation date: Awarded as IA042, September 17, 2001

Objective:

- To relate the role of NDE to the overall lifecycle of aviation components including implications for damage tolerance and safe life design strategies.
- To provide NDE resources, both written and electronic, to support the decision process for FAA certification engineers regarding the effective utilization of NDE technology.
- To determine the effectiveness of delivery of instructional content in various media including the use of written documents, CD based tools including simulations and videos.

Approach:

The Federal Aviation Administration has unique responsibilities for the certification of new designs and assurance of the safe continued operation of commercial aircraft. A work force with broad knowledge of the design, manufacture, operation and maintenance of the aircraft, propulsion systems, and auxiliary systems in required. A key technology element supporting the overall lifecycle needs of aviation is nondestructive evaluation (NDE). NDE involves the use of noninvasive sensing technologies to determine the integrity or fitness for service of an engineered system for its intended purpose. Typical technologies in use by the aviation industry include visual, penetrant, magnetic particle, eddy current, ultrasonic and radiographic inspection. FAA certification engineers are required to assess the appropriate use and frequency of inspection methods for the continued airworthiness of the commercial fleet including large transports, small transports, and rotorcraft. Guidance materials that provide background information on relevant technologies, including expected performance metrics, and relationship to life management practices is needed. The purpose of this program is to work with the FAA Chief Scientist and Technical Advisor for NDE and FAA certification engineers to define instructional needs and develop representative materials for use in engineering assessments of NDE applications. Both written (hardbound) and electronic media will be considered for delivery of the materials.

An approach similar to the prior work on CASR training materials for the ASI will be taken. The first step will be development of a NDI training design panel (TDP) comprised of CASR and FAA personnel with FAA membership to be identified by FAA. The role of the TDP will be to provide advice on the content, approach, and delivery mechanisms for the instructional materials developed in this program. The panel will define the scope and method in which the collected information is to be made available to FAA engineers. The first step will be a content outline detailing the technologies to be covered and the type of information for each technology. The techniques to be included are visual inspection, penetrant inspection, magnetic particle inspection, eddy current inspection, ultrasonic inspection, radiography inspection, and specialized/emerging technologies. The general strategy will be to relate the information to engineering decisions that are made by certification engineers. In addition to materials for specific techniques, background information on related topics such as reliability, probability of detection, life management strategies as influenced by NDE will be covered.

Upon consensus, finalized versions will be prepared for broad distribution within the FAA and to the industry in general. A workshop to distribute the information to FAA certification offices will be held at the close of the program at a location to be agreed upon with the FAA. A sufficient number of copies final product (at least 100 copies) will be generated for distribution to Directorate offices, aircraft certification offices (ACO), and relevant field offices by FAA. Additional copies will be made at the completion of the program for distribution at the annual Air Transport Association NDT Forum.

Progress (March 2002):

Funding for this task began in October 2002 and started with defining a Training Coordinator position for CASR. The position was advertised in October with approximately 15 individuals applying and five interviewed. David Eisenmann was selected to fill the position because of his unique combination of technical and education skills. Dave has a Masters degree in Education and has served as a high school physics teacher. More recently he entered the ISU Materials Science and Engineering BS program and is scheduled to receive his degree in 2002 including an NDE minor. Dave began work at CASR in December.

In January, discussions began with Rusty Jones on updates to the FAA Training Academy course materials for Aviation Safety Inspectors. CASR investigators (Brasche and Ousley) prepared materials for a one week course in 1995 and delivered it for use by FAA. The course is typically taught to over 100 people per year. On several occasions, Mr. Jones has served as the instructor for the course. In 2000, several FAA personnel including Jones and Broz, reviewed the existing course and identified several areas for improvement. Eisenmann is working with Jones to update the Chapter 2 (Certification) and Chapter 9 (Audit and Surveillance) course materials using presentation packets that Jones has successfully used for training sessions with ASIs. A meeting is planned for April to review progress to date and plan for the other technique chapters 3 – 8.

Plans (April 1, 2002 – October 31, 2002):

Meeting is planned at ISU for April to review the course material development.

Prototype delivery of chapter 2 and 9 planned to occur at the Minneapolis FAA office.

Update Chapters 2 and 9 and provide to Oklahoma City Training Academy for inclusion in course.

Initiate updates to remaining chapters for transfer to Training Academy.

Milestones:

Original Date	*Revised Date*	*Milestone*	*Status*
Quarter 1		Establish training design panel. Complete review of content outline with TDP and arrive at agreed upon outline.	
Quarter 3		Complete first module relating NDE to life management, design philosophies, and utilization of inspection by the industry. This module will include discussion of reliability, POD and other metrics used to assess performance of NDE methods. First draft of bibliography will be provided.	
Quarter 4		Complete first technology module. Confirm approach with TDP prior to development of additional modules.	
Quarter 6		Complete second technology module.	
Quarter 8		Complete third and fourth technology module.	
Quarter 10		Complete fifth and sixth technology module.	
Quarter 12		Complete workshop to distribute materials to FAA organizations. Distribute relevant materials to industry.	

Deliverables:

Original Date	*Revised Date*	*Deliverable*	*Status*
		Monthly progress reports in the AACE MIS format to be provided electronically to the FAA Technical Monitor.	
		A letter report identifying members of the steering committee.	
		A technical performance plan based on input from the steering committee on the content and format of the developed guidance materials.	
		Draft version of developed guidance material (format to be determined).	
		Workshop to disseminate final product of developed materials. At least 100 copies of the final product shall be delivered to the FAA.	
		Participation in annual review of the project with the FAA Technical Monitor and other relevant reviewers.	

Title: Enhanced Flaw Detection Using Hall Probes For Aircraft Inspection

Investigation Team: John Bowler, Marcus Johnson, Garry Tuttle, Iowa State University

Students: Haiyan Sun and Micah Decker

Program initiation date: Awarded as IA043, September 17, 2001

Objective:

- To develop a new Hall probe technology with improved detection capability and to accelerate inspections by using multi-sensor field measurements.
- To demonstrate a linear array for wide area rapid aircraft inspection.

Approach:

The key objective of this project is to develop a new probe technology with enhanced flaw detection capability. In addition, using multi-sensor field measurements will accelerate inspections. The work is motivated by a need to improve flaw detection and the need to reduce inspection time in a cost-effective way. The objectives will be accomplished through the development of novel eddy-current probes based on a new generation of high-sensitivity, semi-conductor magnetic field sensors. The sensors will be custom made at the Microelectronics Research Center (MRC) at Iowa State University (ISU) and integrated into probes designed and constructed at the Center for Nondestructive Evaluation (CNDE). The combination of thin layer techniques and novel semiconductor materials has been shown to produce devices with high carrier mobility, at least an order of magnitude greater than that for silicon. The implication of this finding is that Hall sensors can be produced with a much higher sensitivity than those generally available from component manufacturers. Material and structural studies will be carried out to find the optimum sensors. These will then be used to fabricate probes for nondestructive evaluation. The sensors will be configured in four different ways:

- Single pick-up with an excitation coil
- Linear array for rapid area inspection
- Circular planar array for the inspection of small fatigue cracks under installed fasteners
- Circular cylindrical array for the inspection of bore holes, holes with an installed bushing or fastener holes with the fastener removed

The new generation probes will be interfaced with commercially available eddy current test equipment for single or multi-frequency inspection and with the pulsed eddy current (PEC) system to maximize the information acquired during measurements. A set of new generation high-performance probes for eddy-current nondestructive evaluation will be constructed using custom-made semi-conductor sensors. Electronic hardware will be developed to interface these probes to conventional rotary probe test instruments. In addition, the PEC hardware and software will be upgraded to handle larger data throughput generated by the new multisensor probes and rapid scanning capability. Through collaboration with the Microelectronic Research Center, sensors will be obtained in their unencapsulated form. This is a major benefit since it allows us to take advantage of the small size of the sensitive region (typically 100 microns or less) to mount sensors in the small space between the induction coil and the part under test. A variety of multisensor probes will be produced for different aerospace applications with a goal to reduce inspection times and greatly increase the productivity of inspectors. Sample sets provided by industry partners and made available by AANC will be used to assess performance of the new sensors. A formal POD study is planned using existing sample sets. Comparison to conventional probe designs will also be included providing useful data to FAA certification engineers and to the OEMs about introduction of these new probes into commercial applications. A comparative study will be carried out to evaluate the performance of the new probes in terms of probability of detection, speed, and reliability.

Progress (March 2002):

Introduction

The laboratory work for this is project began in January 2002 at the Microelectronics Research Center, Iowa State University. The initial objective of the work is to fabricate Hall devices, measure their basic physical characteristics and assess the performance of these devices for magnetic field measurements in eddy current nondestructive evaluation.

The relationships between the Hall voltage and other physical parameters of a Hall sensor are summarized below together with a description of the device fabrication procedure. The measurements made on the devices are also described.

The Hall Effect

A magnetic field applied perpendicular to the current flow direction in a conductor produces force on the current perpendicular to both the magnetic field and the current direction. Consider the n-type semiconductor sample shown in Fig 1. A current *I* flows in the *x* direction and a magnetic flux density *B* is applied perpendicular to the x-y plane. An electron traveling in the x-direction experiences a Lorentz's force, which tends to deviate the electron in the y-direction. An electrical field in the y-direction is thus generated by the accumulation of charge at the boundaries AB and CD of the semiconductor, giving rise to a Hall voltage V_H between AB and CD.

The following equations described the relationship between the current *I*, the magnetic flux density *B*, the Hall voltage V_H and the dimensions of the Hall sample.

$$V_H = \frac{\mu_H V_L B w}{s} \tag{1}$$

$$V_H = \frac{IB}{qnt} \tag{2}$$

where the dimensions *w* and *s* are shown in Fig 2. In equation (1), μ_H is the Hall mobility and V_L is voltage drop over the distance *s* in the *x* direction. In equation (2), *t* is the thickness of the hall sensor, *q* is the charge on an electron and *n* is the charge carrier concentration.

Making a Mask

A mask is made to define the sensor geometry. A design layout of the mask is drawn using LED software. Both lamella-type van der Pauw samples (Fig.1) and bridge-type (Fig.2) having a different size are included in the initial designs. The design is downloaded to a tape for storage and a mask is formed using a GCA pattern generator. The mask is then put in D-5 developer for 4 minutes and finally in photographic fixer for 5 minutes.

Growing GaAs

GaAs is grown using the Molecular Beam Epitaxy (MBE) technique. A semi-insulating GaAs substrate is mounted inside a vacuum chamber and heated to 600 °C at a pressure of 10^{-10} Torr. Different source beams including gallium (Ga) and arsenic (As) are heated and introduced into the chamber. Once a gallium atom gets to the surface of the substrate, it has enough surface mobility to move around and position itself in the most energetically favorable location. An arsenic atom in contrast has low surface mobility and it will fly off the substrate unless it happens to hit a position adjacent to a gallium atom. Thus, with the MBE technique, one can grow crystal of very good quality and ensure that its carrier structure, thickness and carrier density are well controlled. The semi-insulating GaAs substrate has very high resistivity (10^7Ohm·cm), therefore it can act effectively as an insulating substrate. However the epitaxial layer is doped with the desired carrier density and hence has a higher conductivity.

Making a Van der Pauw Sensor

After a sample of GaAs has been grown, it is cut to form a 6mm × 6mm square, Fig.3. Indium foil is cut into tiny dots and pressed onto each corner of the GaAs square to make contacts. Then the sensor is sintered in a furnace at a temperature of 400 °C for 15 minutes to insure the contacts are well attached to GaAs.

Measurement Result of Van der Pauw Sensor

Two Van der Pauw sensors (VDP1 and VDP2) were made using GaAs with different properties. Their resistivity, mobility, and carrier density have been measured. The results are listed in Table 1.

Resistivity Measurements

Resistance $R_{12,34}$ is measured by passing a current through connections 1 and 2, and measuring the voltage between connections 3 and 4 (Fig. 3). $R_{14,23}$ is measured in a similar way by passing current through the connections 1 and 4, and measuring voltage between connections 2 and 3. The resistivity is determined by the following equation:

$$\rho = \frac{\pi d}{\ln 2} \cdot \frac{R_{12,34} + R_{14,23}}{2} \cdot f\left(\frac{R_{12,34}}{R_{14,23}}\right) \qquad (3)$$

where $f\left(\frac{R_{12,34}}{R_{14,23}}\right)$ is a correction factor.

Mobility Measurement

The Hall sensor is placed in a magnetic field generated by a pair of excitation coils. The magnetic flux density *B*, is controlled by changing the current through the coil. A current of 1mA is passed through connections 1 and 3 of the hall sensor and the Hall voltage V_H measured between connections 2 and 4, Fig. 3. The results are shown in Fig. 4. The gradient of the trend line in Fig.4 shows the average value of $\frac{\Delta V_H}{\Delta B}$ for each Hall sensor. Mobility is governed by the following equation:

$$\mu_H = \frac{d \cdot \Delta V_H}{\rho I \cdot \Delta B} \qquad (4)$$

where I is current through the hall transducer (1mA) and ρ is the resistivity of the material. The calculated mobilities for both sensors are listed in Table 1.

Carrier Density

The carrier density can be calculated from the mobility and resistivity using

$$n = \frac{1}{\mu_H q \rho} \qquad (5)$$

where q = 1.6×10^{-19}C is the magnitude of the charge of an electron.

Conclusions

Comparison of these two van der Pauw sensors shows that VDP1 has smaller thickness and carrier density. According to equation (2), VDP1 should give a smaller Hall voltage for the same current and magnetic field, which is consistent with experimental results. The experiment results also show that GaAs is a good material for making hall sensors.

Table 1. Measurement results for Hall sensors VDP1 and VDP2. *f* is the correction factor in equation (3).

	t (um)	$R_{12,34}$ (Ohm)	$R_{14,23}$ (Ohm)	*f*	ρ ($\times10^{-2}$ Ohm·cm)	μ_H (cm^2/V·sec)	*n* (cm^{-3})
VDP1	1.25	60	24	0.92	2.21	4301	6.61×10^{16}
VDP2	2.75	8.038	13.558	0.96	1.29	3816	1.27×10^{17}

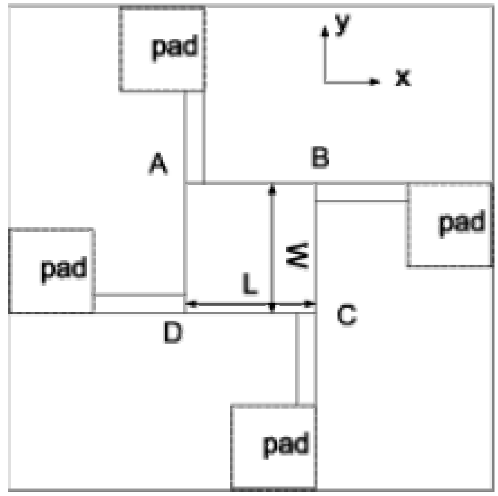


Figure 1. Mask design for a Van der Pauw sample. Note that the semiconductor occupies the region ABCD.

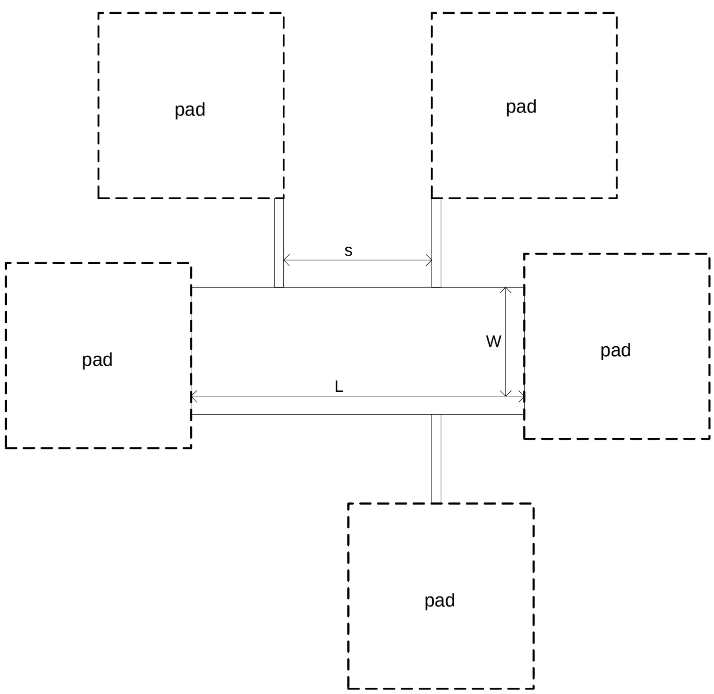


Figure 2. Mask design for a bridge-type Hall sensor.

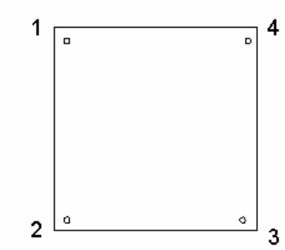


Figure 3. Van der Pauw Hall sensor made of GaAs.

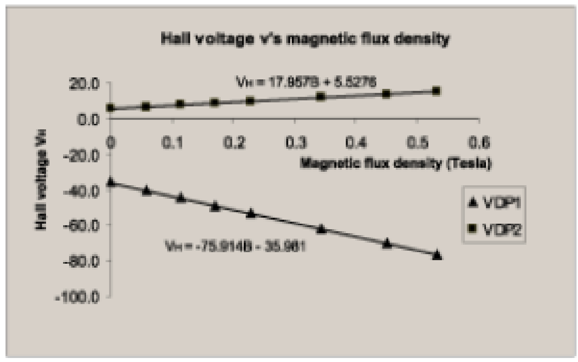


Figure 4. Relationship between Hall voltage and magnetic flux density.

Plans (April 1, 2002 – October 31, 2002):

1. The fabrication of Hall sensors will continue as will the program of testing and evaluation. This will allow us to build up experience in producing good quality sensors and explore methods of improving the performance of the devices (April-October).

2. When methods have been established for fabricating good quality sensors, these will be built into eddy current probe by CNDE for initial evaluation in an NDE application (June-October).

3. A design for an array inspection system will be produced and the first steps taken to build the array probe and its associated electronic circuits. The aim is to use the array with a commercial eddy current test instrument in its time-base mode. It is envisaged that the first prototype array probe will contain a linear array configuration (June-October).

Milestones:

Original Date	*Revised Date*	*Milestone*	*Status*
Month 10		Complete design and fabrication of initial probe prototypes based on new sensors.	
Month 10		Report on probe sensor design including test results of candidate materials and sensor structures.	
Month 12		Complete evaluation of first generation probe incorporating new sensors.	
Month 18		First fabrication of matching sensors for arrays.	
Month 21		Complete design and plans for fabrication procedure for first generation array probes. Complete design of multiplexer for interfacing with rotary probe eddy current test equipment.	
Month 24		Complete fabrication of initial set of array probes and plans for POD studies.	
Month 30		Complete POD studies. Supply partners with probes for evaluation.	
Month 36		Final Report.	

Deliverables:

Original Date	*Revised Date*	*Deliverable*	*Status*
		Monthly progress reports in the AACE MIS format to be provided electronically to the FAA Technical Monitor.	
		A letter report that assesses the feasibility of the new Hall sensing materials. The report should contain relevant test data, designs for proposed sensors, and an assessment on the ability of the contractor to manufacture the proposed sensors and arrays. (Provided within 12 months of award).	
		Final report in FAA standard technical report format (DOT Order 1700 and 1710) shall be delivered to the FAA summarizing all aspects of the project including probe design, manufacture, field testing, and performance including POD/false call assessments.	
		Participation in annual review of the project with the FAA Technical Monitor and other relevant reviewers.	

Title: NDE Technology Assessment and Infrastructure Support

Investigation Team: Brian Larson, Rick Lopez, Iowa State University

Students: None

Program initiation date: Awarded as IA044, September 17, 2001

Objective:

- To provide technical support at the request of the FAA on short term projects, sample preparation and technology base issues in cooperation with CASR and AANC staff.
- To produce an improved understanding and documentation of the science and techniques involved in inspection technologies identified with FAA and industry partners.

Approach:

This task provides technical support to the FAA-CASR, ETC and AANC programs. The participants of this project are available to work with the staff of each of these programs, the FAA, and industry in support of short-term projects and the development of test samples. Short-term projects and specimen needs are brought to the attention of the CASR staff through interactions with the FAA directorates, William J. Hughes Technical Center staff, FAA Chief Scientist and Technical Advisor for NDE, and industry contacts.

This task will also serve to produce an improved understanding and documentation of the science and techniques involved with various NDE technologies including FAA participation in the Center for NDE's Industry/University Cooperative Research Program. This program brings together over twenty industrial sponsors to collectively direct and fund basic research that has common value to the sponsors. Participation provides the FAA with the earliest possible exposure to advanced research results and interaction with NDE leaders from the aviation industry. Literature reviews and summary reports of published data will also be prepared to provide an understanding of previous research results, with focus on aviation related data. This information is very useful when trying to understand current industry practices and when developing collaborative research efforts. Having a firm understanding of the procedures and results of previous work is particularly important in collaborative efforts involving industry. Industry participants often have a different perception of the previous research results and current needs. The summary reports help to bring everyone to a common level of understanding. Prior efforts, selected from input provided by the FAA NDE-NRS, AVR personnel, and industry partners from the ATA NDT Working Group, have been well received and broadly utilized. Additional studies of this type are planned with the topics to be defined in cooperation with the TCRG and industry partners.

The Center for Aviation Systems Reliability has established a strong network with the aviation industry, particularly the OEMs and major air carriers. This includes an understanding of the regulatory process and the role of the manufacturers, operators and FAA in safe operation, maintenance, and overhaul of aircraft and propulsion systems. There are often engineering problems that require access to NDE, mechanical testing, or other special capabilities, staff and resources. The principal investigator serves as the point-of-contact to initiate projects and bring together CASR resources as necessary to answer the requests of FAA personnel.

Progress (March 2002):

AAWG Lap Splice Round-Robin Specimen

Four lap splice specimens were developed for use in evaluating the performance of various NDE techniques for detecting cracking at fastener holes. The specimens will be circulated within the aerospace industry in round-robin fashion in an effort to collect data that can be used to make a direct comparison between techniques. These specimens were based on a design produced by the Airworthiness Assurance Working Group (AAWG).   The design was slightly modified to address several issues raised by industry reviewers. Four 6” X 6” samples were fabricated using 0.063” thick 2024-T3 aluminum into a lap-splice configuration. EDM notches covering a range of sizes were implanted at two notch locations (outer layer, and inner layer) to simulate fatigue cracks. The notches were produced to have a shape similar to the thumbnail shape of a crack. Notch sizes and shapes were characterized using a dual-angle x-ray procedure. Rivets of two types: NAS1097D5-5A Anodized, and NAS1097D5-5 (current standard rivet), were installed to complete the fabrication.

The specimens will first be inspected at CASR using a scanning, pulsed-eddy current technique. Some data has been collected but the effort is currently on-hold until a new probe is delivered, which was needed to optimize the inspection. During a trip to Delta Airlines in February to perform unrelated research, the specimen set was give to Delta Airlines NDE personnel for a cursory inspection. Due to time constraints of the trip a complete evaluation was not possible. After CASR completes the pulsed eddy current inspection with the newly acquired probe, the specimens will be returned to Delta. Additionally, CASR staff continues to work to resolve industry concerns about the specimen design. Since these specimens will be used to evaluate many different NDE techniques, they need to very closely represent actual aircraft structure.

Evaluation of the Effects of Shot-Peening on an Eddy Current Signal

A project was undertaken to evaluate the effects that shot peening of titanium has on eddy current signals. This study was requested by Northwest Airlines but should produce results that are of interest to the aviation community. Three Ti-6Al-4V specimens with low-cycle, surface fatigue cracks were characterized using an automated eddy current scanner. Quantitative data was collected at three frequencies. Electron beam-based residual stress measurements were made to establish baseline values. The samples were sent to Northwest for measurements using their field equipment and then subsequently shot peened. The samples were recently returned to CASR and eddy current scans have been completed. Residual stress measurements and a comparison of the results to the baseline results will be completed in the coming months.

MPI Literature Review

Progress continues to be made in the review of the magnetic particle inspection literature. Over 200 articles have been reviewed and a draft report has been submitted for internal CASR review. Additional articles continue to be gathered to expand the breadth of the document.

American Airlines Flight 587 Crash Investigation Assistance

On November 28 and 29, 2001, David Hsu, Dan Barnard and Brian Larson traveled to Jamaica, NY to assist the NTSB in the crash investigation of American Airlines Flight 587. The Computer Aided Tap Test (CATT) instrument and close visual examination was used to nondestructively characterize the condition of the Airbus A-300-600 vertical stabilizer (tail) and rudder. The CATT system was used to map out the damage of a large section of the rudder, which was made of honeycomb sandwich structures. The images produced were similar to C-scans produced in ultrasonic scanning methods, where each point in the image corresponds to a datum taken at a particular (x,y) location in the scan region. The color of the point represents the measure impact duration (i.e., contact time) of the tap at that location.

Over the period of two days, more than 40 scans were made. Most of the scans were 6 square feet (2' x 3'). When the scan images were grouped together and overlaid on a drawing of the rudder, they provided a clear picture of the condition of the left rudder skin and right rudder skin. The tap test images revealed a number of features of possible interest to the investigators such as areas of Disbond/delamination, ply overlap and change in the number of ply, core splices, potting at edge/hinge/actuator/fasteners.

Due to time constraints, it was not possible to inspect the entire rudder surface during the November trip. However, because of the extent that the CATT system was able to document the condition of the rudder, the NTSB requested that additional work be performed. Dave Hsu and Dan Barnard spent three days in March performing additional scans at NASA Langley where the rudder had been moved. An additional 75 scans were collected during this period to complete the documentation of the outer surface and approximately 80 percent of the inner surface.

Plans (April 1, 2002 – October 31, 2002):

Continue Characterization of AAWG Lap Splice Round-Robin Specimen using pulsed-eddy current technique and send specimens to Delta for inspection. Continue to work to resolve concerns about the current design of the specimens.

Perform residual stress measurements on shot peened specimens and compare these results and eddy current inspection results to baseline values.

Continue with review of magnetic particle literature review.

Milestones:

Original Date	*Revised Date*	*Milestone*	*Status*
Ongoing		Response to FAA and CASR staff requests for quick response assistance. Typically involves 5 to 10 requests per year.	
Year 1		Completion of magnetic particle literature survey including review by FAA and industry experts. Initiate additional literature survey on topic to be determined in cooperation with the TCGR and industry partners.	
Year 2		Complete first draft of literature survey and initiate review process.	
Year 3		Complete publication of literature survey.	

Deliverables:

Original Date	*Revised Date*	*Deliverable*	*Status*
		Monthly progress reports in the AACE MIS format to be provided electronically to the FAA Technical Monitor.	
		Letter reports on the AAWG round robin activities describing all aspects of the contractor's involvement with specimen design and fabrication at the conclusion of the effort. It is expected that the AAWG round robin will be completed within 9 months of delivery order award. Further contractor support of the follow-on AAWG round robin reliability study will continue for the remainder of the 36-month delivery order.	
		A completed literature review in FAA standard technical report format (DOT Order 1700 and 1710) of magnetic particle inspection articles. The completed literature review will be delivered 2 years after award of the delivery order.	
		Participation in annual review of the project with the FAA Technical Monitor and other relevant reviewers.	

Publications and Presentations:

None to date.

Title: Data Analysis Tools for Aircraft Inspections

Investigation Team: Lalita Udpa, Michigan State University with support from NWA, Delta, Honeywell

Students: Hemabh Shekar and Nathan Markey

Program initiation date: Awarded as IA045, September 17, 2001

Objective:

- To develop and transfer a signal processing software tool box for use by the OEMs in the inspection of aviation applications.
- To extend wheel inspection software tools to low frequency EC and incorporate into betasite tests at airlines and with the commercial vendor.

Approach:

Nondestructive inspection plays a critical role in the overall safety of the aircarrier fleet with eddy current inspection being the most readily used method after visual inspection. Eddy current methods have the advantage of being sensitive to near surface cracks including multiple layers and other material property changes which affect conductivity. However, the method is also sensitive to geometrical changes in the component such as edges. The need for accurate signal interpretation which can distinguish nominal geometry or material changes from flaw signals is critical in making the right decisions during nondestructive inspection of aircraft components. The advent of PC based instrumentation for ultrasonic and eddy current inspections have made possible the availability of easy-to-use signal processing software that can help in operator analysis of the measured signals. This project is related to development of a PC-based signal processing toolbox that addresses the needs of the aviation industry.

Several applications have been identified in cooperation with the OEMs which could benefit from application of automatic data analysis (ADA) systems. Controlled data taken with wide area eddy current probes is seeing more widespread use in the industry. Wide area probe technology offers time savings as a wider area is inspected in a single pass. However, additional understanding of the sensitivity of this new technology and the implications for signal analysis is needed. One such application is the dovetail slot inspection used in some engine disks. The major issue in this inspection is proximity of defects to edge, whereby the overwhelming contribution of the edge signal distorts the flaw signal. Similar problems arise in other inspections such as eddy current rotating probe inspection of rivet holes, sliding probe inspection signals and ultrasonic data. A general-purpose signal processing toolbox that addresses the various needs of different inspection problems can be of significant value to the operator.

As with prior efforts, this task works in close cooperation with OEMs and airlines. Particular inspection challenges have been defined by the industry partners which could benefit from improved understanding of signal response. Inspection data will be provided which is representative of the signal, material and electronic noise found in the field. Signal classification methods will be tailored to account for these issues and first generation tools provided to the industry partner for betasite testing. With their feedback, improvements will be made and a final tool developed and delivered for future applications. A summary report will be provided to the FAA that details the state of existing technology and the improvements made to POD through the use of the new signal classification technology.

Progress (March 2002):

After extensive discussion with Honeywell personnel, a Graphic User Interface (GUI) has been designed for the Engine disk application. In order to provide Honeywell with a working version of the software, a MATLAB based GUI has been developed. The following functions are supported in the GUI for display of eddy current signals.

Load calibration file.

Select local origin.

Load data file.

Down/Up radio button: select the scan direction display on vertical and horizontal channel.

Cal/Data radio button: switch between the calibration and data loaded by the user.

Slider: browse through the different slot scans.

Zoom Y radio button: Allows user to scale up/down the display.

Impedance plot radio button: allows user to draw impedance plots.

a. To draw impedance plots, click the mouse button down on the Vertical channel display ONLY and drag it (with button down) along the scan. A window will appear around the mouse marking the section for which impedance plane is being plotted.

b. Display Phase, maximum and minimum voltages above the impedance plot dynamically as the plot is being drawn.

Preferences: sets analysis section, number of data points to left and right of local origin, and window length for impedance plot display.

Several functions in the above list have been completed in MATLAB and the software has been installed at Honeywell for evaluation and testing.

Plans (April 1, 2002 – October 31, 2002):

The plans for the next six months involve converting the MATLAB code to a stand-alone windows based GUI. The display functions summarized above will be incorporated in the windows code. A major effort will be involved in testing the code for failure and crash. Once the display functions have been tested, the code will be used by Honeywell to select training data from experimental signals. The training data will then be used for developing classification algorithms. The signal classification functions will then be incorporated into the windows GUI.

Milestones:

Original Date	*Revised Date*	*Milestone*	*Status*
3 months		Data collection with wide area probe of engine disk dove-tail slot.	In progress
6 months		Review of data. Develop, evaluate, and optimize analysis software.	In progress
9 months		Betasite testing of ADA software at Honeywell.	In progress
12 months		Incorporate user feedback and optimize algorithm parameters.	In progress
15 months		Data collection from low frequency eddy current probe.	
18 months		Review of data. Develop, evaluate, and optimize analysis software.	
21 months		Betasite testing of ADA software at NWA/Delta.	
24 months		Incorporate user feedback and optimize algorithm parameters.	

Deliverables:

Original Date	*Revised Date*	*Deliverable*	*Status*
		Monthly progress reports in the AACE MIS format to be provided electronically to the FAA Technical Monitor.	
		A demonstration at either the contractor's facility, an airline or OEM facility, or major conference at the discretion of the Technical Monitor to demonstrate the capabilities of the software tools described above.	
		Final report in FAA standard technical report format (DOT Order 1700 and 1710) shall be delivered to the FAA summarizing all aspects of the project including software description, development, modification, usage, testing, and validation. The final report shall quantify for each of the applications sets the improvement of performance for each.	
		Participation in annual review of the project with the FAA Technical Monitor and other relevant reviewers.	

Publications and Presentations:

L. Udpa, I. Elshafiey, and H. Shekar, "WINSAS: A New Tool for Enhancing the Performance of Eddy Current Inspection of Aging Aircraft Wheels", Aging Aircraft 2001, The 5th Joint NASA/FAA/DoD Conference on Aging Aircraft, September 10-13, 2001, Hyatt-Orlando, Florida.

Title: Detection of Disbonds and Assessment of Structural Integrity of Composite Repairs for Aircraft Components

Investigation Team: Sameer A. Hamoush, Derome Dunn, Kunigal Shivakumar, Mathew Sharpe, North Carolina A&T University

Students: Anil Bhargava

Program initiation date: Awarded as IA046, September 17, 2001

Objective:

- To develop nondestructive testing to detect disbonds in composite repairs.
- To develop analytical models to assess degradation of strength and life of repaired parts.
- To test and verify the results.

Approach:

Disbonding is a primary defect in composite repair of aircraft components. It maybe caused due to poor surface preparation, thermal mismatch, moisture and other chemical contamination, etc. These defects can occur during the repair or after prolonged exposure. In addition, aging can cause peel-out of composite layers due to asymmetric load path. Therefore, the quality assurance of repairs made on composite components and the predictability of the remaining service life of the repaired parts is essential to their continued airworthiness. Proposed is a joint effort performed by North Carolina A&T State University's Center for Composite Materials Research (CCMR) and Iowa State University's Center for Aviation Systems Reliability (CASR). This effort combines the excellence of the two centers to solve a multidisciplinary problem of composite repair. Completion of this research will yield assessment tools for detecting disbond in composite repairs and its effect on strength and life of aircraft components. The specific tasks are to:

- Identify types and procedures of composite repairs.
- Perform composite repair with and without disbonds on composite material parts. The repairs are to be performed according to aircraft manufacturers (such as Boeing) specifications, guidelines and/or standards.
- Perform nondestructive testing of the repaired parts at CASR (Iowa State University) by use of C-SCAN and Computer Aided Tap Test (CATT) systems.
- Perform destructive measurement of damage in repaired parts to map the damage size, mechanical properties, fatigue life and residual strength.
- Correlate the measured damage to the NDT measurements and assess the detectability of NDT techniques.
- Develop finite element models and perform stress analysis along with fracture mechanics analysis to assess the severity of the disbond. Correlate the severity of Project Management.

Progress (March 2002):

The work accomplished in the first 4 months (December 2001 to March 2002) appears to be within the specified tasks. The following activities have been accomplished to identify types of composite defects and to identify procedures for composite repairs:

1. On December 17, 2001, the project investigators from North Carolina A&T State University visited the repair facility of NORDAM, the nation's largest aircraft repair company, located in Tulsa, Oklahoma. The purpose of the visit was to assess the composite repair techniques adopted by the industry and approved by the FAA. Mr. Sunny Mirchandani, Senior Manager of the composite repair division, gave the tour. Mr. Mirchandani also provided a repaired part of the aircraft engine cowl, specifically performed for our program. The part has two repairs, edge repair and interior honeycomb section. This component was given to Dr. Hsu for NDE study. Mr. Mirchandani expressed interest of the NORDAM participation in our FAA-sponsored repair program. Next month, appropriate paper work will be done to make NORDAM an official partner of the program.

2. On December 18, 2001, the team visited the Center for Nondestructive Evaluation at Iowa State University to present the planned activities of NC A&T and to list to ISU's overall program, in particular, Dr. Hsu's activity. Drs. David Hsu, Bruce Thompson, Vinay Dayal, Mrs. Lisa Brasche, and the FAA technical monitor, Mr. Cu Nguyen attended the meeting. Mr. Nguyen reviewed A&T and Hsu's programs. After the review, Dr. Hsu provided the tour of their laboratories and demonstrations of the automated tap test. NC A&T prepared and delivered to Dr. Hsu a number of test samples having different types of defects, including processing, repaired, sandwiched, and fiber optics embedded for damage diagnosis.

3. NORDAM provided NC A&T with the Boeing repair manual and literature on nondestructive evaluation of composite materials adopted by Boeing.

4. Literature search is underway to identify manufacturing and service defects. This search provides more realistic data that will be used to perform simulated defects.

5. NC A&T reviewed the NDE test data of the two NORDAM repairs. The repairs were on a honeycomb section of the engine cowl. The NDE test was conducted by Dr. Hsu, Iowa State University. The results of the test reveal that NORDAM repairs are good.

6. As requested by PIs from NC A&T State University, NORDAM provided Dr. Hsu from Iowa State University with two typical bad repairs for NDE evaluation.

7. NC A&T State is working to establish a collaborative research effort with TIMCO, aircraft repair company located in Greensboro, North Carolina. The project PIs visited TIMCO's repair facilities on Thursday, March 28, 2002 and met with the composite repair facility manager. TIMCO expressed their interest in joining the research effort and to partner with NC A&T State University.

8. Destructive tests are underway for NORDAM's two good repairs that were evaluated using NDE by Iowa State University. Tests to be performed are the wedge and tensile

tests. After failure of the specimens, the bonded surface will be evaluated and analyzed to confirm the perfect bond as indicated by the NDE results.

Plans (April 1, 2002 – October 31, 2002):

Work will continue on composite repair including visits to industry partners and a team meeting scheduled for May at NCA&T.

Milestones:

Original Date	*Revised Date*	*Milestone*	*Status*
3 months		Identify types and procedures of composite repairs.	
6 to 26 months		Prepare composite repair samples for use in nondestructive and destructive evaluation studies.	
9 to 30 months		Correlate NDE and destructive data results.	
15 to 33 months		Perform finite element modeling.	
36 months		Provide final report.	

Deliverables:

Original Date	*Revised Date*	*Deliverable*	*Status*

Publications and Presentations:

None to date.

Title: Development of Nondestructive Inspection Methods for Repairs of Composite Aircraft Structures

Investigation Team: David K. Hsu (PI), Daniel J. Barnard, John J. Peters, Vinay Dayal, Iowa State University. Industrial partners will include Boeing (Jeff Kollgaard), Northwest Airlines (Jerry Doetkott), American Airlines (Jack Conrad), AANC (Dennis Roach), CACRC (Tom Dreher, et al), and British RAF (Gary Penney).

Students: Brian Danowsky and Zachary Nielsen

Program initiation date: Awarded as IA047, September 18, 2001

Objective:

- To develop nondestructive inspection and evaluation methods that can provide quantitative information and images to aid the accept/reject decision making for repaired parts. Such techniques, with an ability to map out the morphology and mechanical condition of a repair, will provide the inspector with technical records of the repaired component while it remains in-service.

Approach:

The use of composites on aircraft is steadily increasing and has begun to enter applications that include primary structure categories. The capability to repair composite components is a key technology for continued airworthiness; it follows that the integrity and quality of repairs must be assured. However, the nondestructive evaluation of repairs on composite structures is a challenging task because a repaired region is considerably more complex than the original structure. NDI techniques and instruments for composite repairs are very much lacking, especially for field repairs performed without the benefits of an autoclave.

In the field tests and beta-site tests for the Computer Aided Tap Test (CATT) system, the various airlines have consistently identified the inspection and evaluation of repairs on composite structures as a key technical issue that requires R&D support. With the increasing use of composites on control surfaces and, more recently, on primary load-bearing structures of the aircraft, the quality assurance of repairs made on such components is essential to their continued airworthiness. Unfortunately, nondestructive inspection (NDI) techniques for composite repairs are very much lacking. Field practice still relies largely on hearing-based manual tap tests. We therefore propose an R&D effort to develop NDI techniques for mapping out the morphology and mechanical condition of a repair, to establish a correlation between imaged features and the actual

internal state of the repair, and thereby help to establish the accept/reject criteria for repaired components. The main emphasis will be to adopt the Computer Aided Tap Test (CATT) system for quantitative NDE of composite repairs. A significant side benefit of developing the CATT system for inspecting composite repairs is that it would lead to a low-cost NDI scanner as a result. However, due to the complexity of a repaired zone and the variety of possible flaws it may contain, a number of methods, including resonance and mechanical impedance techniques, will be employed and compared. In addition to the conventional methods, this task will also explore and develop air-coupled ultrasound for the inspection of composites and their repairs. With air-coupled transducers, both through transmission scans and one-sided generation of Lamb waves will be applied to a variety of composite structures and repairs thereon. The team led by this PI is experienced in the inspection of repairs on both solid laminates and honeycomb sandwiches, and had collaborated with composite repair projects at Boeing and Wichita State during previous phases of FAA-funded research at CASR.

Progress (March 2002):

Formulated Project Tasks and Technical Approach for First Year

The tasks for the project are: (1) locate and accumulate references on composite repair and quality assurance, (2) solicit composite repair samples for testing, (3) imaging repairs with computer aided tap test (CATT), (4) compare CATT with other mechanical NDI methods, (5) set up air-coupled ultrasonic (ACUT) scanning capability with existing SONIX scanning system, and (6) correlate destructive sectioning results with CATT and ACUT images.

Interacted with Partners

Researchers of collaborating project at North Carolina A&T University visited CASR in December 2001 and brought a Nordam repair panel for NDE work at CASR. The panel has since been imaged with CATT and ACUT and sent to NC A&T for mechanical testing and destructive analysis. A repair panel was provided by Northwest Airlines and became the focus of intensive study for the first two quarters. The panel is scheduled for sectioning in the third quarter. Researchers of this project visited Nordam Repair Division and the composite center of American Airlines in Tulsa, OK in March 2002. In both places the CATT system was used to scan large components on the shop floor.

AA587 Airbus Rudder Investigation

Although not as a part of this project, Dave Hsu and Dan Barnard were requested by FAA to assist the NTSB investigation of the AA587 Airbus A300-600 accident in JFK, New York. CATT units were used in mapping out the damages on the rudder, first in New York and then in NASA Langley. The experience of mapping out large areas of a highly damaged composite honeycomb structure (more than 400 square foot of the inner and outer rudder surface were scanned) was very beneficial to the field application of the CATT method.

Applied CATT to Composite Repair Inspection

The CATT method and instrument, developed in the previous AACE project, has been applied to the NDI of repairs on composite components. Two issues were explored in this period: the relationship between tapper mass and probing depth, and the possible nonlinear response of a repaired region. For the former, we found that a greater tapper mass did probe deeper and yielded more detailed information in the resulting image. For the latter, we found some deviation from linearity in the impact duration squared versus tapper mass curve in some composite repairs. These two technical issues will be pursued further in the next period.

Both the NWA panel and the Nordam panel were imaged with CATT. Images of the Nordam panel were provided to NC A&T as a reference for destructive sectioning. The CATT scan images of the NWA repair panel were correlated to the air-coupled UT images. The correlation was that high stiffness regions (e.g., potted core) of the repair showed stronger sound transmission and, conversely, low stiffness regions (e.g., disbond or impact damage) showed weaker sound transmission.

Developed Air-Scan Capability

Before the start of the project, an air-coupled ultrasonic system was purchased from QMI, Inc. with cost share funds provided by ISU,. The system has since been incorporated into the existing SONIX scanning system and provided many air-coupled UT scans of composite repairs. Due to the low speed of sound in air (20 times slower than that in metals), the behavior of air-coupled ultrasound is quite different from that in water. The second quarter was devoted mainly to learn the use of air-coupled UT, in the transmission mode at 400 kHz and 120 kHz frequencies. Because of the slow velocity (and hence short wavelength) of sound in the air, the lateral spatial resolution was surprisingly good. Honeycomb cells were resolved at 400 kHz with the use of a focused receiver. However, the lower frequency of 120 kHz was found to reveal more useful features in the repair.

In addition to through transmission, we have also generated Lamb waves on composite laminates, with the two air-coupled transducers situated on the same side of the laminate and at oblique incidence. The air-coupled Lamb waves were able to image reinforcing ribs on the back of the laminate. Since the Lamb wave scan was basically done with a line source instead of a point source, the broadening of the image was direction dependent and presented opportunities for deconvolution and image processing.

Plans (April 1, 2002 – October 31, 2002):

We are scheduled to visit NC A&T and interact with TIMCO (a composite MRO company in Greensboro, NC) in May 2002. We will compare NDI results with the mechanical testing and sectioning results of NC A&T.

We plan to section the Northwest repair panel and correlate the internal conditions of the repair with the CATT and ACUT images. This comparison is expected to yield important information about what a good repair or bad repair should look like when imaged by CATT and ACUT.

We will continue to develop the air-coupled UT technique and work on ways to improve the resolution of air-coupled Lamb waves.

We plan to compare the computer aided tap test with other NDI methods, such as mechanical impedance analyzer (MIA) and other bond testers. We have made arrangement to borrow a MIA from AANC in Sandia.

We plan to visit United Airlines maintenance facility in Indianapolis to compare notes on air-coupled UT (United has bought a "Karlin Air" system) and to field test the CATT on repaired composite parts.

Milestones:

Original Date	*Revised Date*	*Milestone*	*Status*
Quarter 1		Formulating project tasks and schedule. Visiting composite repair facilities.	Underway
Quarter 2		Testing relationship between impact duration squared and local stiffness of repaired composite honeycomb sandwich. Explore and develop air-coupled ultrasound for composite repair inspection.	
Quarter 4		Correlating flaws in a composite repair as revealed by tap test imaging with actual internal condition by destructive sectioning. Field testing of repairs at airlines using CATT, MIA, and BondMaster.	
Quarter 6		Designing and fabricating (by outside vendor) test panels containing repairs and engineered flaws; acquiring NDE data on panels.	
Quarter 8		Mechanical testing of repaired panels, correlation with NDI data. Investigating issues related to repair inspection of solid laminate primary structures.	
Quarter 10		Arranging field tests for inspecting repairs in solid laminates.	
Quarter 12		Completing interpretation of test results and procedure development. Summarizing findings and results in final report.	

Deliverables:

Original Date	*Revised Date*	*Deliverable*	*Status*
		Monthly progress reports in the AACE MIS format to be provided electronically to the FAA Technical Monitor.	
		A validated inspection procedure using a low cost, simple-to-operate instrument for inspection repair on composite structures.	
		Final report in FAA standard technical report format (DOT Order 1700 and 1710) shall be delivered to the FAA summarizing all aspects of the project including probe design, manufacture, field testing, and performance including POD/false call assessments.	
		Participation in annual review of the project with the FAA Technical Monitor and other relevant reviewers.	

Publications and Presentations:

Published -- "NDE of Repairs on Aircraft Composite Structures," David K. Hsu, Daniel J. Barnard and John J. Peters, Proc. of SPIE, Vol. 4336, *Nondestructive Evaluation of Materials* *and Composites V,* edited by G. Y. Baaklini, E. S. Boltz, S. M. Shepard and P. J. Shull, 100-107, 2001.

Abstract submitted -- "Development of Nondestructive Methods for Composite Repair Inspection", David K. Hsu, D. J. Barnard, J. J. Peters and V. Dayal, Review of Progress in Quantitative NDE, Bellingham, WA, July 14-19, 2002.

Abstract submitted -- "Nondestructive inspection of composite and their repairs," D. K. Hsu, D. J. Barnard, J. J. Peters, V. Dayal and V. Kommareddy, 6th FAA/DoD/NASA Aging Aircraft Conference, San Francisco, CA, September 16-19, 2002

Abstract submitted -- "Imaging Composite Honeycomb Structures using Computer Aided Tap Test and Air Coupled Ultrasound," ASNT Fall Conf. Nov. 4-8, 2002.

Presentation -- "Nondestructive Inspection of Repairs on Composite Aircraft Structures," David K. Hsu and Daniel J. Barnard, Review of Progress in Quantitative NDE, Brunswick, ME, July 29 - August 3, 2001.

Presentation -- "NDE of Composites: Quantitative evaluation of damage," David K. Hsu, FAA/NASA Workshop on Composites, Hampton, VA, June 2001.

Title: Nondestructive Evaluation of Premium Aerospace Castings

Investigation Team: J. Gray (PI), F. Inanc, T. Jensen, J. Xu, Iowa State University with support from Boeing, Howmet, Northrop Grumman, Hitchcock

Students: J. Zhang

Program initiation date: Awarded as IA048, September 18, 2001

Objective:

- To develop optimal NDE inspections for complex aerospace castings.
- To evaluate the elements of the image formation process that can affect image quality, such as scattering and unsharpness effects.
- To develop auto-correlation image processing methods based on small translation images to enhance porosity detectability in the presence of diffraction mottling.
- To complete the integration of the diffraction modeling into XRSIM.
- To develop POD models for x-ray images and a means of determining inspection coverage for complex parts.
- To develop image processing methods for use with digital radiography detectors that improve the detectability over unprocessed images.

Approach:

The complexity of casting designs is becoming greater as casting houses develop better methods for determining the quality of a casting and therefore become more confident in their performance. The significant improvement in casting quality, especially with the tighter control in the material properties, has triggered a considerable interest in castings as a means to replace built-up structure in airframes. Boeing and Airbus are using castings for more components, in the case of Airbus; a passenger door is now being made from a monolithic casting. The inspection issues with these new components are critical as the applications for these cast parts becomes more wide spread. It necessarily also increases the FAA's attention to these new applications and their implementation in a safe manner. The complexity of an access door requires a considerable number of views (x-ray inspections) to ensure adequate coverage. This issue of coverage needs to be considered and optimized. Additional issues that impact the use of cast parts is the advent of digital imaging systems. The digital data allows the opportunity of improved detection over human only review of data. The improvements introduced by matched filters and hypothesis testing noise reduction coupled with the automation of the inspection that digital data allows represent significant improvements in the reliability of the inspection. Due to the quantitative nature of the data, effects such as scattering, undercut, and detector effects introduce distortions in the image that need to be understood for quantitative sizing to be done. The basic drive in this project is to develop the quantitative understanding of the subtler image effects, develop improved image processing tools and apply this knowledge to optimized inspection coverage of complex aerospace castings. While useful to industry in implementation of new designs, the results will also assist the FAA in certification decisions regarding new inspection methods to support these changes in design philosophy.

With the digital data available from modern x-ray systems, for example amorphous silicon detectors, a new need to understand all of the elements contributing to the makeup of the image are important. This is based on the need to determine the location, shape and size of a defect in a part. For example, scattering effects, while recognized as being present and while controlled to a degree, need to be understood quantitatively so that the information in the image can be extracted and quantified. In order to do this, the use of models based on the physics of the image formation process offer many advantages. The many industrial changes occurring both in the use of castings and x-ray inspection technology, has implications for FAA's role as the regulator. Understanding the limitations of inspection technology and assessing the role of inspection in life management decisions regarding the use and lifetime of cast components can be aided by physics-based models of the inspection processes. Tools developed and applied in this program will be available to assist the FAA in engineering decisions regarding safe implementation of cast components.

Progress (March 2002):

The CT scans on the remaining 7 tension specimens provided by Hitchcock were completed. We are beginning the work on converting the CT data structures obtained from the 3D CT scans of the defects into CAD models for use in a flaw library. This involves connecting the voxels from the CT scan into a single object, determining which of the voxels are exterior and then generating a diagonalization of the exterior surfaces for the CT object. The result will be a triangular representation of the flaw suitable to be used in XRSIM.

Most of the activity in October was devoted to preparing for the Casting Workshop held November 6th, 2001. We generated POD maps of the electrical access door and prepared the CT results for review by Hitchcock. A number of industries planned to attend the workshop, including Magma, Lockheed, Hitchcock and possible Boeing. Travel is more difficult in the present climate. Results were very well received by those able to attend.

We are also beginning to integrate the POD calculation engine into the main XRSIM program. At present this model is in a research grade state that requires considerable knowledge to use. The approach is to break the CAD solid model into small voxels at which we locate a defect of choice. The part is subdivided into as many as 1,000,000 voxel elements, a number that depends upon the complexity of the part shape. The method used to perform this decomposition is based on a trimmed octree. The program to generate this octree is a command line program, which needs to be integrated with a graphical interface. We also as beginning to develop detectability models for use in the inspection coverage and optimization activities. These detectability maps, due to the 2D nature of images, requires a more sophisticated approach than a traditional threshold /amplitude method commonly used with 1D data.

In order to compote POD maps showing inspection coverage, we needed to integrate the mesh generation program used in the POD map calculation into XRSIM. This couples the mesh generation with the 3D OpenGL visualization tools already in XRSIM. This step was completed. We have made progress on minimizing the transfer rates for the 3D CT data. The sources of the slow transfer rates turned out to include the router connection, a bounce of the data onto a campus computer before transfer to another room at CNDE and a factor of 4 slow down due to the encryption methods. We are now running at near optimum transfer speed for the line. The result is a decrease in the data transfer from 40 minutes to 5minutes.

The high-resolution CT facility upgrade is complete. The data acquisition programs including the motion control, the detector response and the CT setup are complete. Funding to support the hardware purchases was provided as part of ISU's cost share funding for the AACE programs. A calibration procedure was developed to determine the distance from the source to sample to detector. The resulting geometric magnification is automatically recorded and used in the PC version of the reconstruction. At present the data sets generated by the 3D CT scanner at high resolution are a few hundred Megabytes. This represents a significant amount of data that needs to be transferred from the data acquisition PC to the cluster for reconstruction. The time for the transfer is 30 to 40 minutes and the reconstruction time on a PC is as much as 6 hours. We plan to develop a parallel version of the CT reconstruction program for use on the Linux cluster.

The scattering modeling based on the transport equation is sufficiently mature that validation studies and a graphical interface are now beginning. We have specified a graphical interface for the scattering calculate engine and have begun model validation studies. The model validation consists of comparing experimental buildup factors, build up factors from published literature, Monte Carlo calculation using MCNP and the transport calculation of the build up factors. The experimental measurements consist of measuring the change in density from a 16" x16" plate of aluminum and steel at the center of the plate. The edge effects will be minimized. By moving the film 18" from the plate, the scattering from the plate will be significantly reduced due to radial divergence. The two densities can be converted into an absorbed dose via the film model and a build up factor computed.

Plans (April 1, 2002 – October 31, 2002):

The plans for the next period include completion of the POD coverage maps in XRSIM. The development of a CT method for obtaining the detailed flaw morphology for use in XRSIM will be completed. Finally, the first version of the full x-ray scattering model should be complete for initial evaluation.

Milestones:

Original Date	*Revised Date*	*Milestone*	*Status*
9 months		Demonstration of coverage maps, experimental validation; Image processing for matched filter begun; Amorphous silicon array detector characterization and model complete.	
12 months		Scattering models developed.	
18 months		Completion of a user-friendly detectability map program; Hypothesis test filter begun.	
24 months		Matched filter demonstrated; Scattering models validated.	
30 months		Hypothesis test filter demonstrated.	
36 months		Final report.	

Deliverables:

Original Date	*Revised Date*	*Deliverable*	*Status*
		Monthly progress reports in the AACE MIS format to be provided electronically to the FAA Technical Monitor.	
		Demonstration at either the contractor's facility, an airline or OEM facility, or major conference (at the discretion of the Technical Monitor) to demonstrate the capabilities and improved performance of the radiographic software and filters described above.	
		Final report in FAA standard technical report format (DOT Order 1700 and 1710) shall be delivered to the FAA summarizing all aspects of the project including probe design; manufacture, field testing, and performance including POD/false call assessments.	
		Participation in annual review of the project with the FAA Technical Monitor and other relevant reviewers.	

Publications and Presentations:

FAA Casting Workshop, November 6th, at Northwestern.

Title: Multi-Element Adjustable Transducer Arrays For Applications With Portable Ultrasonic Flaw Detectors

Investigation Team: Igor Komsky, Northwestern University with support from Boeing-Long Beach, Boeing-Seattle, Northwest Airlines, Cessna, AANC, Panametrics, Krautkramer-Branson, Sigma, and Technisonic.

Students: None

Program initiation date: Awarded as IA049, September 20, 2001

Objective:

- To develop a set of the multi-element adjustable ultrasonic transducer arrays for use in a variety of ultrasonic inspection procedures.
- To transfer the technology for aircraft industry use.

Approach:

A team of university and industry researchers will develop a set of multi-element adjustable ultrasonic transducer arrays for use in a variety of ultrasonic inspection procedures and transfer the technology for aircraft industry use. The arrays will be integrated with the commercially available portable ultrasonic units. The arrays will be utilized to detect and characterize fatigue cracks and corrosion as well as to monitor the sealant quality in the multi-layered airplane structures, from the airplane skin without disassembly. Consideration will be given to combination of multiple measurements into a single information set from multiple zone, multiple depth inspections of aircraft structures.

A methodology will be developed to determine an optimal number, types, and spatial orientations of transducer array elements based on the spatial orientations and sizes of aircraft structural elements and defects. Existing or modified measurement models and ray tracing software will be investigated to be applied to the array design and to development of the user-friendly tool for rapid readjustments of the arrays' elements. A procedure will be developed to select a suitable set of commercially available ultrasonic transducers for specific applications. A multi-element transducer-positioning head will be developed. The head will include multi-axial transducer holder with manual controls for rapid adjustments of the transducers' spatial orientations. An optional design of the remotely controlled holder will be also explored. A flexible coupling unit will be developed. The unit will be suitable for applications on the curved and non-uniform surfaces. The unit design will provide for a number of interchangeable coupling options including irrigated or dry-coupling flexible membranes. The transducer positioning head and the coupling unit will be integrated into the transducer module. The module design will make it possible to change a footprint of the transducer array based on the inspection requirements and configuration of the inspection area. A coupling monitoring system will be developed for an automatic monitoring of the array-to-surface acoustic interface. A methodology will be developed for a selection of the commercially available portable ultrasonic units to be integrated with the multi-element transducer arrays. If necessary, hardware interfaces will be developed to facilitate the integration of the selected portable units. Prototype transducer arrays will be integrated with the selected portable ultrasonic units for demonstration at AANC and validation on the specific application to be identified in conjunction with the FAA technical monitor. The methodology for development and applications of the transducer arrays will be transferred to industry.

Progress (March 2002):

Potential applications of the multi-element transducer arrays for corrosion and crack detection in the airplane components were reviewed. Several concepts have been explored to design transducer modules using interchangeable elements with variable incident and azimuthal angles.

Various types of flexible coupling films have been evaluated to measure attenuation of ultrasonic waves at various frequencies and incident angles as well as to examine mechanical performance of the films. It was found that the flexible coupling films did not significantly affect propagation of longitudinal ultrasonic waves (either with normal incidence of under various incident angles) with center frequencies ranging from 1 MHz to 10 MHz. However, the films provided significant damping to surface or plate waves that were generated at the same frequency range. Several flexible coupling films with different film properties, thickness and shapes were manufactured.

Plans (April 1, 2002 – October 31, 2002):

First prototype of a multi-element transducer-positioning head will be developed. Work will be continued on the selection of commercially available ultrasonic transducers for the multi-element arrays, as well as on the development of the prototype dry-coupling units using flexible polymer films.

Milestones:

Original Date	*Revised Date*	*Milestone*	*Status*
Quarter 1		Initiate development of methodology for design and applications of transducer arrays.	
Quarter 2		Initiate investigation for the measurement models and ray tracing software for development of the user-friendly tools. Initiate development of procedure for selection of commercially available ultrasonic transducers.	
Quarter 3		Complete development of methodology for design and applications of transducer arrays. Initiate development of the multi-element transducer-positioning head.	
Quarter 4		Complete development of procedure for selection of commercially available ultrasonic transducers. Initiate development of the flexible coupling units.	

Quarter 5		Complete development of the multi-element transducer-positioning head. Complete investigation of the measurement models and ray tracing software for development of the user-friendly tools. Initiate integration of the transducer positioning head and the coupling unit into the transducer module. Initiate development of a coupling monitoring system.	
Quarter 6		Complete development of the flexible coupling units. Initiate development of methodology for selection of the portable ultrasonic units and development of hardware interfaces.	
Quarter 7		Complete integration of the transducer positioning head and the coupling unit into the transducer module. Initiate lab test of the transducer module. Initiate lab tests of the transducer module. Initiate integration of the prototype transducer arrays with the selected portable ultrasonic units.	
Quarter 8		Complete development of the coupling monitoring system. Complete development of methodology for selection of the commercially available portable ultrasonic units and development of hardware interfaces. Complete lab tests of the transducer module. Complete integration of the prototype transducer arrays with the selected portable ultrasonic units. Initiate lab tests of the integrated inspection systems.	
Quarter 9		Complete lab tests of the integrated inspection systems. Initiate field demonstration at AANC and validation of the integrated systems.	
Quarter 10		Initiate planning and coordination of demonstration projects with aircraft manufacturers, airlines, and manufacturers of ultrasonic equipment. Initiate technology demonstration projects.	
Quarter 11		Complete field demonstrations and validation.	
Quarter 12		Complete technology demonstration projects. Complete documentation for technology transfer.	

Deliverables:

Original Date	*Revised Date*	*Deliverable*	*Status*
		Monthly progress reports in the AACE MIS format to be provided electronically to the FAA Technical Monitor.	
		Interim report, which identifies a specific target application.	
		Final report, which includes procedures, specifications, drawings, schematics, validation test, and test results.	

		Report of a procedure to select a suitable set of commercially available ultrasonic transducers for specific applications.	
		Demonstration of a working prototype adjustable transducer arrays that is compatible with the commercially available ultrasonic units.	
		Final report in FAA standard technical report format (DOT Order 1700 and 1710) shall be delivered to the FAA summarizing all aspects of the project including probe design, manufacture, field testing, and performance including POD/false call assessments.	
		Participation in annual review of the project with the FAA Technical Monitor and other relevant reviewers.	

Publications and Presentations:

“Multi-Element Adjustable Transducer Arrays for Ultrasonic Scanning of Aging Aircraft”, in Proceedings of SPIE, 2002.

Title: Magnetic Particle Inspection Improvements for Aerospace Applications

Investigation Team: David Jiles, Mike Garton, Rick Lopez, and Lisa Brasche, Iowa State University with support from United Airlines, Pratt & Whitney and Boeing

Students: J. Y. Lee and S. J. Lee

Program initiation date: Awarded as IA050, September 25, 2001

Objective:

- To provide fundamental support to the aviation community in the area of magnetic particle inspection including publication of the literature survey that summarizes factors affecting the inspection sensitivity.
- To develop a user friendly, PC based simulation model for magnetic particle inspection for use by the OEMs in the inspection of aviation applications.

Approach:

The magnetic particle inspection technique has been used for many years for aviation applications, but unfortunately very few aids exist that assist in proper test setup. There are many 'rule-of-thumb' equations available to calculate current settings for a given sample geometry, but very often this results in gross over-magnetization and reduced sensitivity. Further, magnetic particle test specifications prescribe current values, which are affected by the control waveforms used for regulating the current intensity. This introduces harmonics in the waveforms, which makes it difficult to establish a relationship between peak and rms values of a current waveform, which is important in the practical use of MPI. Each of the waveforms has its own characteristics and interactions between leakage fields at discontinuities and the particles can vary significantly. It is therefore possible to miss the detection of defects by choosing inappropriate current waveforms. In recent Air Transport Association NDT Forums (1999, 2000), the airlines have identified the need for additional research to support fundamental understanding of the MPI technique and the factors which affect sensitivity. Of particular concern is the direction "complete 100% magnetic particle inspection" which is common in OEM procedures. The ability to assure that a particular technique is adequate has been called into question. This program is aimed at developing an easy to use simulation program that will address the issues defined by airline and OEM users. The tool will assist by reducing test setup time, and by identifying sample regions that may have reduced magnetic flux density. This will prove quite useful to industry in assessing the effectiveness of a given technique. The simulation program will provide accurate estimations of magnetic field intensity both inside and outside of the sample, and will take power supply variability into account, which will reduce overall procedure development time and allow determination of part geometry effects. A complimentary effort is underway to generate a literature survey of the factors that affect the sensitivity of magnetic particle inspection. The survey which covers public domain data from 1970 to 1999 will be utilized to assess relevant factors for inclusion in the simulation tool.

Successful magnetic particle inspection requires that the flux density in and around the sample be within a given range. Low flux density may not lead to particle attraction, and in turn, result in indications from defects, and too high of a density will result in high background noise and reduced sensitivity. Parts with complex geometries may result in areas with little or no magnetic flux being present in extremities or recesses. Typical MPI tests are developed through the reiterative use of quantitative quality indicators affixed to critical areas, and progressively increasing current until the artificial defects are visible. Using a simulation program may effectively decrease inspection procedure development time by defining areas with reduced magnetic flux, and by providing an approximation of current setting requirements that produce the required active field strength.

A working group has been established with industry partners through discussion at the annual ATA NDT Forum. Betasite versions of the tool will be provided to OEMs and airlines for testing. The ATA meeting will be used for annual discussions with conference calls/workshops used to supplement interactions as necessary.   Industry partners will participate in the validation of the tool.

Progress (March 2002):

With the start of this project in October 2002, we began by interviewing student assistants for the program. A team that includes a student, Jun Jeul Lee and a post doc, Seong Jae Lee, is being lead by Dave Jiles, professor in the Materials Science and Engineering department, to accomplish the theoretical efforts. Mike Garton will also provide computer engineering support integrating modules from his ultrasonics work as appropriate. Rick Lopez and Lisa Brasche provide practical applications support. Over the first several months, conversations with industry partners occurred, primarily with Tom Dreher of United Airlines. Based on their input and a review of available modules from the prior work of Lalita Upda, a revised program plan was developed and is included in the milestones section below. Efforts are underway in the software development.

Plans (April 1, 2002 – October 31, 2002):

Provide overview presentation to the CNDE I/UCRC program.

Prepare prototype software for demonstration at the Fall ATA meeting.

Continue theoretical development.

Milestones:

Original Date	*Revised Date*	*Milestone*	*Status*
		Module 1 – Physics of the Inspection	
Quarter 2		Complete calculation tools for axis-symmetric non-ferromagnetic objects, linear (DC/AC) and for nonlinear ferromagnetic objects.	
Quarter 3		Initiate extensions to 2D plane-shaped ferromagnetic objects.	
Quarter 4		Initiate validation studies using solenoid-type current flow.	

Quarter 5		Complete calculation for axis-symmetric ferromagnetic objects that take into account hysteresis (DC/AC).	
Quarter 6		Initiate extensions to 3D objects including hysteresis effects for ferromagnetic materials.	
		Module 2 – Part Geometry Input	
Quarter 3		Develop simple routine to import FE meshes which will be used for testing the physics modules. Decide what types of elements to support with input from the customers. Survey FE packages in use by the customers and their mesh export utilities. Choose data translation standard. (IGES, STEP, or other)	
Quarter 7		Complete routine to import 3D meshes from various finite element packages and which supports one of the data translation standards.	
		Module 3 – Integration Package	
Quarter 3		Complete initial user assessment through conversations and meetings with the end users (OEMs, airlines, FAA)	
Quarter 4		Complete prototype GUI and interact with customers to confirm approach. Includes ability to graph output quantities.	
Quarter 6		Complete 3D graphics routines to display, rotate and translate the mesh.	
Quarter 8		Complete routines to select portions of the mesh to apply boundary conditions.	
Quarter 10		Complete routines to display the fields and/or flux density on and around the mesh as false color images.	
Quarter 11		Complete final GUI with input from customers	
Quarter 12		Complete documentation including help menus, user instructions, etc. Create tutorial using some example problems.	
		Supporting Activities	
Quarter 3		Define samples for use in simulation tool validation and begin fabrication/acquisition.	
Quarter 4		Complete first technical note on parameters of interest to industry partners.	
Quarter 6		Complete fabrication of validation samples	
Quarter 8		Complete second technical note on parameters of interest to industry partners.	

Deliverables:

Original Date	*Revised Date*	*Deliverable*	*Status*
		Monthly progress reports in the AACE MIS format to be provided electronically to the FAA Technical Monitor.	
		User-friendly P.C. based software package (5 copies), which includes manual operational instruction will be sent to FAA that can be used by inspectors to study the effects of various experimental parameters on the inspection sensitivity and thereby optimize the experimental parameters for obtaining maximum detection sensitivity to critical flaws.	
		Participation in annual review of the project with the FAA Technical Monitor and other relevant reviewers.	

Publications and Presentations:

None to date.

Title: MOI Sensor Improvements

Investigation Team: Bill Shih, Jerry Fitzpatrick, PRI; Lalita Upda, MSU. The work will be undertaken in a cooperative industry/university/government arrangement with the technical team led by PRI Research and Development Corporation (PRI)-- inventors and developers of MOI technology—with contributions by Northrop-Grumman Synoptics (Synoptics) (producer of the MO sensors), Michigan State University (ISU), and Ohio State University (OSU). MSU will perform electromagnetic (finite-element) calculations designed to guide sensor improvements, and OSU will provide expertise in the solid-state physics of garnet films.

Students: Jason Slade (MSU)

Program initiation date: Awarded as IA051, September 25, 2001

Objective:

- To significantly enhance the crack detection sensitivity of MOI-based systems through improvements to sensor design and performance leading to expanded use of MOI in the nondestructive inspection of aging aircraft systems.
- To improve the performance of MOI for subsurface crack and corrosion detection in applications of interest to FAA and the industry.

Approach:

Along with the increase in air travel throughout the world, is the growing population of aging aircraft. Accordingly, inspection requirements to ensure continued aircraft airworthiness has created a need for cost-effective NDI techniques that are accurate, reliable, and easy to use. Magneto-Optic Imaging (MOI) is such a technique, which has gained wide acceptance, including Boeing and Airbus, for detection of both surface and subsurface defects in commercial aircraft. This research program strives to improve the MOI for the detection of smaller defects such as corrosion and fatigue cracks in multi-layer aircraft structures as requirements become more stringent for the detection of such defects in the aging fleet. Specifically, the proposed improvement will be to the magneto-optic sensor used in the MOI device. In the past, feasibility was demonstrated by using practical (extrinsic) fabrication methods (e.g., cobalt button deposition) to improve the high-temperature image-forming characteristics of garnet films, which are the basis of magneto-optic sensors. This improvement has now been fully integrated into current commercial MOI products. However, there is a significant opportunity and need for practical (intrinsic) methods of increasing *sensitivity* and improving *temperature stability* of magneto-optic garnet films. Accordingly, the intrinsic properties of magneto-optic sensors (i.e., so-called "out-of-plane" magneto-optic sensors) will be improved by exploring different chemical compositions than the currently available out-of-plane sensors, and varying methods of film growth and/or annealing histories. It has also been determined that sensors of a type not previously considered for magneto-optic imaging in the MOI (i.e. so-called "in-plane" magneto-optic sensors) could lead to major advances in magneto-optic imaging technology. Accordingly, the properties of this type of sensor will be explored. Electromagnetic (finite-element) calculations, designed to guide the sensor development and improvement process, will also be carried out. A team composed of PRI Research & Development Corp (PRI), the developers and manufacturers of the MOI, ISU, OSU and Northrop-Grumman Synoptics (Synoptics) will perform the proposed two-year effort.

Progress (March 2002):

Northrop Grumman Poly-Scientific (NGP)(Mark Randles and Tom Iradi)

NGP's task is to grow magneto-optic films for use in the MOI. Specifically, NGP took a historical look at 3-inch magneto-optic sensor films provided to PRI over the last few years. Some of these films perform very well and others not so well. All films were grown from the same melt composition. Variations that may occur include post-growth annealing as well as subtle differences in the actual film growth. These differences may arise from melt depletion or changes in growth rate. Knowing that "good" films can be grown from this melt composition we decided to initiate a formal Design of Experiments (DOE) using 1-inch diameter substrates.

The two parameters chosen for study are the degree of super cooling and the rotation rate. Super cooling affects the Bismuth incorporation rate (i.e. Faraday rotation) and also the distribution coefficients of the other constituents. The rotation rate affects the growth rate and hence the distribution coefficients. The DOE matrix consists of 5 data sets: nominal, super cooling ± 25°C and rotation ± 25 RPM. Two films will be grown for each data set. To date a pair of films have been grown at the nominal plus a pair at super cooling –25°C. NGP will measure these films and core out a 3mm diameter test piece to send to Ohio State University. The balance of each film will be annealed to allow evaluation in PRI's Magneto-Optic Imager (MOI). Then another 3mm part will be cored and sent to OSU. The objective is to have 20 test parts, 10 as grown and 10 annealed.

Ohio State University (OSU)(G. Kakazei, L. Tsymbal and P. E. Wigen)

OSU's task is to analyze the films grown by NGP to provide quantitative measurements of film properties so that so-called "good" and "bad" films as evaluated by use in the MOI can be characterized relative to the intrinsic (and extrinsic) properties of the film.

The successful operation of the magneto-optic garnet films is based on the observation of the motion of magnetic domain walls. These properties are controlled by three parameters, the magnetization, M, the anisotropy energy K_U, and the magnetic coercivity, H_C. In the MOI, when microscopic imperfections (cracks or extensive corrosion) are present in some underlying structure, like a metallic sheet, the irregular flow of currents around those imperfections generate magnetic fields that penetrate the garnet film and restrict the motion of the domain walls at that location in the MO garnet film just above the imperfection. For this to occur, the magnetic properties of the magnetic film must meet some rather strict conditions. The uniaxial anisotropy energy, K_U, must be sufficient to overcome the demagnetization field, $4\pi M$, in order that the magnetization in the film is oriented normal to the film plane. The magnetization must have a value sufficient to demagnetize by breaking up into up and down domains but not so large that the domain size becomes sufficiently small that a wide motion of the domain walls, needed to enhance the contrast in the observation, is forbidden. It is estimated that the value of $4\pi M$ should be in the range of 200G.

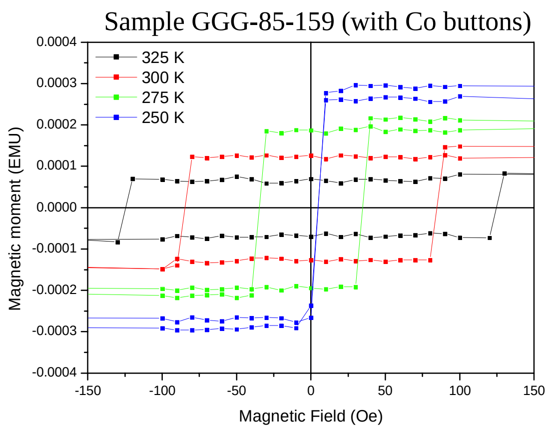
An important property of a magnetic film is the quality factor, Q, given by the ratio of the uniaxial energy to the magnetostatic energy, $Q = K_U/2\pi M^2$ or the ratio of the anisotropy field, $H_U = 2K_U/M$ to the demagnetization field given by $4\pi M$ for a thin film. Thus $H_U/4\pi M$, = Q is another expression for this important parameter. For best results this ratio should be in the range of 1.5 or 2. A third important parameter is the magnetic coercivity, H_C. As the film goes from the saturated state to the unsaturated state in the operation of these devices, the coercivity determines the applied field at which the device must be operated and that must be large enough that the variations in the switching are less than the electronic noise of the device but small enough that they can be readily obtained by the applied fields available to the device. A reasonable value of the coercivity, H_C, would be around 50 to 100 G.

Investigations

During the period January through April 2002 the magnetic properties of six garnet films were investigated to determine their magnetization and the coercivity. These parameters were measured using a Superconductive Quantum Interference Device (SQUID) [MPMS-5 by Quantum Design]. Since all the films have out-of-plane easy direction of magnetization in the temperature range above 250 K, the measurements were performed with the applied field oriented normal to the plane over the magnetic field range from -4 to +4 kGs. The field step between measurement points was 10 Gs. All of the samples were measured at 200, 250, 275, 300 and 325 K.

Of the 6 films, 3 were marked as “good” for use in the MOI (film numbers 27-159, 29-159 and 85-159) and 3 were marked as “bad” (numbers 36-159, 70-159, 83-159). In the measurements all of the films were initially covered with 40 micron square and 1000-Angstrom thick Co buttons in a hexagonal array with center-to-center spacing of 0.86 mm. The measurements were repeated with the buttons removed. This was done to study the influence of the buttons on the static magnetic properties of the films. The buttons were removed in an acid bath ($HCl+HNO_3$ bath for 10 minutes). Surface roughness of the films was also investigated both before and after the acid bath process by an Atomic Force Microscope (AFM) [Dimension 3000 by Digital Instruments]. No significant change of the surface roughness was found following this treatment.

From the experimental M(H) curves, two parameters were extracted, the saturation magnetization M_s and coercive field H_c. Typical behavior with temperature is presented in Figures 1-3 for sample 85-159 (the best of the “good” samples for sensor application). M_s decreases with temperature while H_c increases as expected. The magnetization of all of the samples had nearly the same behavior. This is not unexpected, as the films have been annealed by various processes to produce the magnetization values desired for “good” operation. The value of the coercivity was also quite uniform. While the presence of the Co buttons does not affect M_s but H_c was found to decrease by a factor of 2 to 3 when the buttons were removed. It was also found that H_c had a small dependence on the magnetic field scan range (i.e. the smaller the scan range, the smaller H_c).



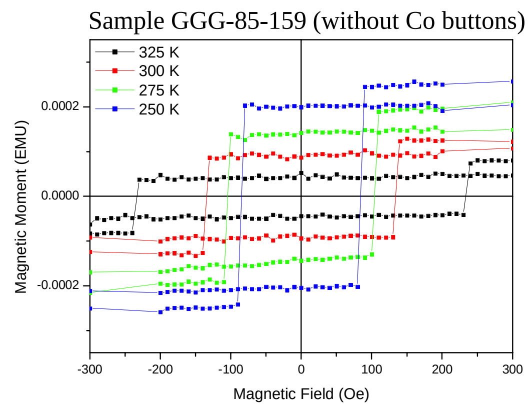


Figure 1

Figure 2

Figure 1. The hysteresis loops of sample 85-159 at temperatures of 250K, 275K, 300K and 325K with Co buttons on the sample.

Figure 2. The hysteresis loops of sample 85-159 at temperatures of 250K, 275K, 300K and 325K after the Co buttons were removed from the sample.

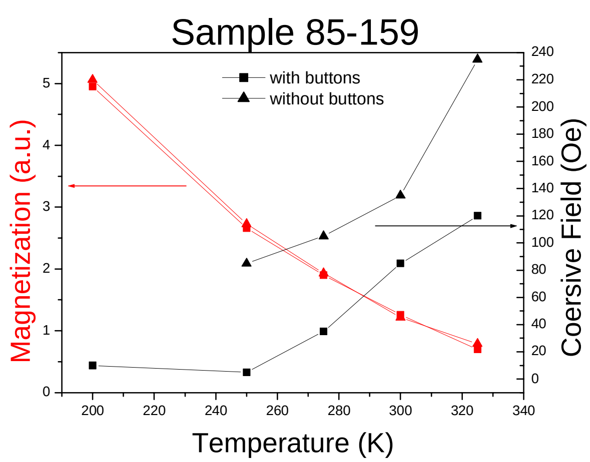


Figure 3. The temperature dependence of the magnetization and the coercivity with and without the Co buttons.

Michigan State University (Lalita Udpa, Satish Udpa)

The MSU tasks are to provide electromagnetic computations to help guide the requirements on the MO film development and to develop image processing capability to permit real time automatic defect recognition.

Computations

Modeling of subsurface radial cracks that simulate defects in multi-layer structures will be one configuration used to determine MOI detection requirements. By varying crack size and geometry magnetic field values and distributions can be calculated and compared with actual MOI results. This can be used to define the sensitivity required to detect smaller cracks than can now be detected. Thresholding of the calculated field distributions has been produced to generate expected MOI image shapes at various detection levels. The properties of these shapes are being researched to determine a reliable characteristic(s) that can be used to effect a detection.

Results continue to be obtained. Processing of the calculated data is ongoing. Calculations will continue to address current and future inspection requirements including the ability to detect subsurface corrosion and cracking in multilayer airframe structures.

Software

MOI video data was received from PRI. The data was digitized and stored in a PC compatible format. Individual frames were carefully selected from the video. These frames comprised a frame with rivets, frames with just noise and frames with noise and rivets. The image was first converted from RGB to a gray scale data. A set of simple static filtering schemes were developed and evaluated on the test image. These algorithms were chosen on the basis of their simplicity and speed of implementation. Simple band pass and median filtering schemes were evaluated. Work is currently underway to develop a wavelet based multi-scale filter as well as a dynamic processing scheme to extract motional variations in successive frames of the data.

Hardware

Work is currently underway to identify the required hardware components for real-time processing the data. The system will consist of an embedded PC board and a card to convert the processed data into NTSC format for display on the monitor. The major issue that needs to be resolved is the size of the boards, since the available space within the MOI control unit is 3”x 8”x1”, and most commercially available boards are larger than 3” wide. One of the smallest commercially available boards is manufactured by Ampro and is 3.6" x 3.8" in dimension. It contains a Pentium 266 MHz processor and 128 Mb of RAM. Other available boards are larger at 8.00" x 5.75" and contain processors at various speeds. Possible board manufactures include TMC, Formosa, Attro and Mentor. This size is still smaller than the standard motherboard size of 8.00" x 13.00". Once the size issue has been straightened out, the proper board and processor will be ordered and implemented.

PRI Research and Development Corp. (W. C. L. Shih and G. L. Fitzpatrick)

In addition to PRI's technical responsibilities in this project (see below), PRI guides, interacts with, and supports, various activities of the other participants. PRI organizes frequent phone conferences with all participants, and participates in joint report preparation.

Sensor Evaluation Support

As part of PRI Research and Development Corp's (PRI) support of the sensor development task, PRI carried out an examination of all sensor data in our possession (e.g., static optical hysteresis measurement data, and dynamic sensor evaluations while sensors were operating in an MOI). The examination by PRI of some 21 sensors in our possession identified three (exceptional) sensors that were much more sensitive to weak magnetic anomalies (under dynamical conditions) than the others. In the case of these three sensors, the domain walls seem to move or expand very easily (in response to an applied magnetic field) between the array of deposited cobalt buttons (cobalt buttons were used to stabilize magnetic domains at high temperatures, e.g., 50 Degrees C). This behavior suggests that some intrinsic physical property, such as domain wall mobility, is much higher for these three sensors than for most of the rest.

Accordingly, and because PRI possessed small samples of each of the three sensors of interest, we supplied samples –in addition to three "control" samples—to Ohio State University (OSU) for a variety of magnetic properties measurements. To date these measurements (see OSU progress report above) have not found a correlation between sensor performance and magnetic properties measurements. However, one of the most important magnetic properties is a measure of the uniaxial magnetic anisotropy, which has not yet been made by OSU. These future measurements could lead to the sought-for correlations. Any correlation between observed magnetic properties and film performance (good or bad) will provide important inputs to improving sensors.

PRI also identified a previously produced sensor that exhibits excessive "spaghetti" domain structure. Spaghetti domains are serpentine domains that tend to maintain width and increase (or decrease) length when exposed to a changing magnetic field. The most desirable sensors have serpentine domains that expand (or contract) in width while maintaining length in response to the same changing magnetic field. The desirable sensors produce excellent MOI images, whereas those exhibiting "spaghetti" domains do not. A sample of the undesirable sensor was sent to OSU to determine why "spaghetti" domains form in some sensors, but not in others. To date the answer to this question remains unknown. However, further magnetic properties measurements (e.g., uniaxial magnetic anisotropy measurements) may yet provide some insight.

In-Plane Sensors

The magneto-optic sensors we seek to improve in this project exhibit a large uniaxial magnetic anisotropy, meaning that they exhibit a "hard" axis of magnetization parallel to the sensor plane, and an "easy" axis of magnetization perpendicular to the sensor plane. However, because our main goal in this project is to significantly improve MOI imaging, we felt that we should also consider so-called "in-plane" sensors. These are sensors with a "easy" axis of magnetization in the plane of the sensor.

After considerable reflection, examination of the literature, discussions with OSU personnel, it was determined that in-plane magneto-optic sensors are inappropriate for MOI applications because of their apparent lack of relative sensitivity compared to the sensors we currently are seeking to improve. Accordingly, it was jointly decided by PRI, OSU and NG that no further work on this task will be pursued.

Modifications to the MOI

Because in-plane sensors were deemed unacceptable for MOI applications (see previous section), PRI has proceeded with other (non sensor) improvements to the MOI that will be complementary to the improvements that will result from more sensitive sensors. Accordingly, PRI has produced an MOI with foil currents at least twice as large as those in commercially available MOI systems, thereby producing fields from flaws (e.g., cracks and corrosion) that are twice as large as that produced by currently available MOI systems. As expected, these increased foil currents have created heating problems in both the foil and the power supply. However, after a series of laboratory experiments an appropriately large cooling fan was installed inside the MOI 303 style imager. This has resulted in sufficient cooling, even at the highest power levels. We have also recently installed "cutoff" circuitry that shuts down eddy-current excitation in case of a fan failure. Tests with this system in our laboratory will begin soon, after which we plan to deliver the improved system to Boeing (Seattle) for qualification tests (see Plans below). Clearly when improved sensors are available, such a system will perform even better than preliminary experiments have shown, because both the MOI and the sensors will have been improved.

Support for Anomaly Calculations and Image Enhancement

PRI is working closely with Michigan State University (see MSU Progress report above) to guide finite-element calculations and image processing hardware development. Finite element calculations are designed to quantify what is required of improved sensors (how sensitive must they be to detect the flaws of interest), and the image enhancement software and hardware is designed to improve MOI performance by synthetically improving MOI images (e.g., by removing unwanted background "noise").

Plans (April 1, 2002 – October 31, 2002):

Northrop-Grumman Poly-Scientific

Complete the Design of Experiments with growth at super cooling +25°C, and rotation ± 25RPM. Anneal all films and prepare test samples. Determine feasibility and desirability of new compositions in the melt. Participate in regular conference calls with PRI and OSU to review progress.

Ohio State University

Unfortunately measurements of the M_s and H_c values as a function of temperature (see results above) gives quite similar results for both the "good" and "bad" films and a trend between "good" films and "bad" films was not found. In the next six month period, two new measurements will be added to the investigations.

1. Uniaxial Anisotropy Energy - As indicated above, a third important parameter in the properties of domains and domain walls is the uniaxial anisotropy energy, K_U. This is a property that is related to the details of the structure of the film and is strongly influenced by the growth conditions and the effects of annealing. While our program has paid careful attention to the magnetization and modified the growth conditions and annealing processes to obtain a desired value, there has been no effort to consider the influence of the anisotropy or to measure it. It is a major missing link in the magnetic properties of our films. Ferromagnetic resonance (FMR) measurements will give information from which it will be possible to evaluate the anisotropy energy. The ratio of the anisotropy energy to the magneto static energy, $Q = K_U/2\pi M^2 = H_U/4\pi M$, is another important parameter related to the operation of these films and could be related to the qualities of "good" versus "bad" films.

2. The values of M, H_C and H_U as a function of temperature will also be measured for the new films that are being prepared by Northrop Grumman Poly-Scientific and the values again compared with the response observed by PRI for the quality of the device films.

3. It was observed in our measurements that the coercivity of the films depended on the strength of the maximum field applied during the measurements. In the real applications an external fields of no more than a few Gs. We propose to measure the coercivity over a wider range of saturation fields, especially at values near the maximum fields used in the device to determine a possible link to "good" and "bad" films over low field sweeps. In addition it has a strong contribution to the domain wall energy and therefore also influences the density of domain walls and thereby the domain structure in the materials.

Michigan State University

Our future plans are to investigate alternate dynamic processing algorithms that are based on motion detection in successive frames of MOI images to discriminate between sensor generated and sample generated features in the image. The algorithm will be evaluated exhaustively to ensure the integrity and consistency of performance on additional data.

Wavelet-based filtering algorithms will also be developed and evaluated particularly with respect to accuracy and hardware implementation.

The hardware development will start with identifying the appropriate board that satisfy space and I/O requirements of the problem. Data converters from and to NTSC format will also be included.

PRI Research and Development Corp.

Sensor Evaluation Support

PRI will examine 1.0 inch diameter sensors newly produced by NG. We will measure optical hysteresis curves at room temperature and at 50 Degrees Centigrade. We will also examine the imaging performance of these sensors in an operating MOI.

The optical hysteresis measurements provide global information on the action of the entire sensor in response to a slowly varying magnetic field. This information tells us about the sensor contrast, ability to respond to a field (sensitivity), and other useful properties that aid in guiding the film growth experiments. Measurements on new sensors, in an MOI, show how they perform in actual (dynamical) imaging applications involving high frequency (e.g., 100 kHz) magnetic fields, which is their ultimate purpose.

Modifications to the MOI

PRI will deliver a modified MOI to Boeing (Seattle) for evaluations. Prior to delivery we will also characterize the improved system in our laboratory using a variety of samples characterizing cracking and corrosion, especially subsurface cracking and corrosion.

Support for Anomaly Calculations and Image Enhancement

PRI will continue to work closely with Michigan State University (see MSU Progress report above) to guide finite-element calculations and image processing hardware development.

Overall Project Support and Guidance

PRI will continue to guide and support the various work components and interact with all participants. The latter activity will be accomplished by continuing to arrange, and participate in, frequent phone conferences, and joint report preparation.

Milestones:

Original Date	*Revised Date*	*Milestone*	*Status*
Month 1		Technical kick-off meeting with team.	
Month 2		Initiate development of new magneto-optic film compositions for improved sensor temperature stability and increased sensitivity.	
Ongoing support		Perform (electromagnetic) finite-element calculations (primarily MSU) to quantitatively determine magnetic anomalies associated with targets of interest to the aerospace industry and the FAA.	
Month 3		Measure physical properties of the films produced and provide consultation on magneto-optic film composition selection. Develop magneto-optic film patterning methods (primarily OSU).	

Month 6		Obtain and examine in-plane magneto-optic sensors as a possible alternative to the existing out-of-plane magneto-optic sensors. Modify the MOI to accommodate in-plane magneto-optic sensors if the in-plane sensors prove to be feasible.	
Month 7		First results on new 1" sensors, start modifications as necessary.	
Month 12		Results on revised 1" sensors, prepare for 3" sensors.	
Month 15		Produce and deliver 10 of these sensors on the standard 3-inch diameter GGG substrates for testing and/or cobalt button deposition (primarily Synoptics) for testing.	
Months 16-23		Laboratory tests and field tests including implementation of EBR. Determine feasibility of implementing EBR to improve the image quality of current type of sensors. If deemed feasible, a prototype version will be developed to demonstrate its performance.	
Month 24		Final report in required FAA format.	

Deliverables:

Original Date	*Revised Date*	*Deliverable*	*Status*
		Monthly progress reports in the AACE MIS format to be provided electronically to the FAA Technical Monitor.	
		Demonstration at either the contractor's facility, an airline or OEM facility, or major conference (at the discretion of the Technical Monitor) to demonstrate the capabilities and improved performance of the improved MO sensor.	
		Final report in FAA standard technical report format (DOT Order 1700 and 1710) shall be delivered to the FAA summarizing all aspects of the project including probe design, manufacture, field testing, and performance including POD/false call assessments.	
		Participation in annual review of the project with the FAA Technical Monitor and other relevant reviewers.	

Publications and Presentations:

Paper submitted to 6th Joint FAA/DoD/NASA Aging Aircraft Conference: "Improved Magneto-Optic Sensors for Detection of Subsurface Cracks and Corrosion in Aging Aircraft".

Title: Engineering Assessment of Fluorescent Penetrant Inspection

Investigation Team: Lisa Brasche, Rick Lopez, Dave Eisenmann, Brian Larson, , Bill Meeker, ISU; Clint Surber, Steve Younker, Boeing – Seattle; Dennis Smith, Dwight Wilson, Boeing – Long Beach; Lee Clements, Delta Airlines; Tom Dreher, United Airlines; Kevin Smith, John Lively, Anne D'Orvilliers, Pratt & Whitney; Bill Griffiths, Keith Griffiths, Pramod Khanderwal, Rolls Royce; Sam Robinson, Sherwin; and Ward Rummel, D&W Enterprises

Students: S. Gorman

Program initiation date: Awarded as IA052, September 28, 2001

Objective:

- To identify the most relevant factors for which existing engineering data is insufficient, assess the parameter ranges that provide acceptable performance for typical aircraft and engine components, and document the results of these studies for use in revision of industry specifications.
- To develop a self–assessment tool and protocol for use by airline and overhaul shops for performance verification compared against industry–accepted performance.
- To complete an assessment of existing process control/monitoring tools and provide needed improvements.
- To develop/validate FPI guidance materials for use by the airlines and OEMS that incorporate "lessons learned" in this program and incorporate other recently developed data and information.

Approach:

Fluorescent penetrant inspection (FPI) is a widely used inspection technique for surface crack detection in both aircraft and engine components being used for both production qualification and in-service assessment. In a recent survey, of airworthiness directives from 1995 – 1999, FPI was the third most frequent inspection called out behind visual and eddy current inspection methods. Although patented in 1941, significant changes have occurred in the chemicals/chemistry associated with the process, in many cases as a result of environmental considerations. The program will determine the most relevant factors for which existing data is insufficient, assess the parameter ranges that provide acceptable performance for typical aircraft and engine components, and document the results of these studies. Program plans and results will be coordinated with industry partners to ensure they are applicable to aerospace practices and relevant specification modifications will be supported through participation in standards committees, such as SAE Committee K. In addition to engineering studies, other needs identified through industry input will also be addressed. These include self–assessment tools that can be used by the airlines and OEMs to determine effectivity of internal processes and documentation of results which can be used by the industry in effectively instructing personnel in proper processing. Workshops will be used to keep FAA and industry partners fully informed of progress and results.

An advisory panel of technical specialists is being used to define needs, support the technical work, and review progress. The team includes Boeing (Seattle and Long Beach), Rolls Royce, Pratt & Whitney, Delta Airlines, and United Airlines in addition to other recognized sources of technical expertise which included Ward Rummel of D&W Enterprises and Sam Robinson of Sherwin. Research support will be established through subcontractor participation in support of the technical advisory panel and in other limited engineering studies. Additional expertise will be sought for the program on an as needed basis to perform specific tasks in support of the research objectives. This may include single or multiple participants from the aircraft and engine OEMs, airlines, and government agencies as the technical effort warrants and as approved by the FAA technical monitor.

Results of the studies will be documented with annual updates provided to SAE Committees K or J as appropriate, for consideration in updating specifications. In some cases, additional research studies may be performed at OEM or airline facilities as deemed appropriate by the technical team in cooperation with the FAA. This may include a formal POD study with the number and location of participants to be determined in the course of the program. Use of industry accepted POD samples to be provided by the industry partners will occur for formal POD activities. Baseline processes as described above will be used to characterize several POD sample sets for comparison to the CASR generated sample set. At the conclusion of the engineering studies program a detailed report suitable for FAA publication will be provided. A program plan will also be provided to establish of a web-site for easy public access to the data.

Industry workshops will be held at approximately annual intervals in conjunction with existing meetings to present status and continue broad industry and FAA input to program direction. Potential candidates include the ATA NDT Forum or meetings of SAE Committee K. As deemed appropriate by the FAA, FAA personnel will be invited to participate in the workshop or individual workshops will be held with FAA personnel to keep them fully informed of progress and results. Full documentation and publication of results is planned in such resources as ASNT, the Aging Aircraft Conferences, and the Review of Progress in Quantitative NDE.

Progress (March 2002):

The project began in October 2001 with much of the Fall effort concentrating on getting subcontracts in place with the industry partners. The kickoff meeting of the CASR FPI research program was held at the Pratt & Whitney facility in West Palm Beach January 18 – 19, 2002. In attendance was Boeing: Dennis Smith, Clint Surber, D&W Enterprises: Ward Rummel, Delta: Lee Clements, FAA: Al Broz, Dave Galella, Cu Nguyen, ISU: Lisa Brasche, Dave Eisenmann, Brian Larson, Rick Lopez, Rolls Royce: Bill Griffiths, Keith Griffiths, Pramod Khandelwal, Sherwin: Sam Robinson, Pratt & Whitney: Anne D'Orvilliers, John Lively, Kevin Smith, and United: Tom Dreher. Attendees focused on review of recent ETC data and problem definition as part of the planning for the new program. Preliminary results for the drying and cleaning studies of ETC were presented by Brasche, Larson, and Lopez. Included in the discussion were prior approaches to sample generation and lessons learned to be incorporated in the upcoming sample fabrication. Each organization provided a 15 minute summary of issues identified as important to be addressed by the program. Based on the issues identified by the industry partners, a matrix to use for prioritization was developed.

Robinson provided an overview of the issues surrounding fluorometry, the method used to measure fluorescent brightness of the penetrant. Rummel lead a discussion of process control issues which will be a major topic of discussion in the March conference call. The first meeting closed with a discussion of the use and design of a performance verification kit which would allow airlines and overhaul shops to perform an internal assessment of an FPI facility and/or personnel.

Monthly conference calls have been used to continue progress since the first meeting. Through the conference calls and on-going email communication, a prioritization process was used to develop the Engineering Studies Plan. A first draft of the Engineering Studies Plan (ESP) was generated based on the rankings and distributed by Brasche on March 2. The twelve topics include the following:

- ES -1 – Developer Studies
- ES – 2 – Cleaning Studies for Ti, Ni and Al
- ES – 3 – Stress Studies
- ES – 4 – Assessment tool for dryness and cleanliness
- ES – 5 – Effect of surface treatments on detectability
- ES – 6 – Light level Studies
- ES – 7 – Detectability Studies
- ES – 8 – Study of Prewash and Emulsification Parameters
- ES – 9 – Evaluation of Drying Temperatures
- ES – 10 – Part geometry effects
- ES – 11 – Penetrant Application Studies
- ES – 12 – Relationship of part thickness to drying method

In an effort to distribute the workload and expedite the planning process subteams were formed to develop the more detailed plans for each of the twelve studies with the overall team used to review/refine.

Plans (April 1, 2002 – October 31, 2002):

Drying Study (ES-9): Rolls Royce has offered use of an extensive sample set which enabled us to begin work on ES – 9 – Evaluation of Drying Temperatures. The study will take place at Delta the week of May 13 with extensive planning underway in March.

Further studies will be defined and activity initiated as samples become available.

Milestones:

Original Date	*Revised Date*	*Milestone*	*Status*
First Quarter		Establish industry advisory panel team through contracts with selected organizations. Hold first working group meeting with industry, FAA, and other government participation.	Complete
Year 1		Complete feasibility study of fluorometry development. Complete comparative study of daily performance checks.	
Years 1-2		Utilize design of experiments approach to define engineering studies. Generate necessary sample sets of selected alloys. Complete quantitative assessment of relevant parameters. Utilize industry research teams to support assessment as necessary. Determine need for POD study.	

Years 2-4		Development of training materials for FAA and industry use.	
Years 2-4		Development of performance verification kit (PVK) and protocol for its use.	
Years 4-5		Complete all documentation and final reports including plan for management of the PVK.	

Deliverables:

Original Date	*Revised Date*	*Deliverable*	*Status*
		Monthly progress reports in the AACE MIS format to be provided electronically to the FAA Technical Monitor.	
		Letter report identifying members of an Advisory Panel. (3 months after award)	
		Program plan describing efforts to be conducted regarding the Engineering Studies based on recommendations from the Advisory Panel including additional research needs regarding cleaning and drying activities. (6 months after contract award).	Complete
		Comparative study of existing measurement tools to control the FPI process. This report will identify existing shortfalls and identify possible improvements. (end of 12 months)	
		Feasibility study for improved fluorometer development. (end of 12 months)	
		Report assessing existing FPI instructional materials. (end of 16 months)	
		Program plan describing proposed guidance and instructional materials development. (end of 18 months)	
		Report describing results of Engineering Studies. (end of 36 months)	
		Validated procedure of performance verification kit (PVK) and its protocol. (end of 48 months)	
		Setup FPI instructional/guidance program on the world wide web for general public. (end of 48 months)	
		Host/conduct FPI information dissemination workshop with a formal presentation of PVK and instructional materials/lessons learned to industry and FAA. It is anticipated that 500 to 1000 copies of FPI instructional/guidance materials will be provided to the industry and FAA field offices. (end of 54 months)	

		Deliver all fabricated test panels used throughout the Engineering Studies and PVK efforts for inclusion in the Airworthiness Assurance NDI Validation Center (AANC) Sample Defect Library or to another location at the discretion of the FAA Technical Monitor.	
		Participation in annual review of the project with the FAA Technical Monitor and other relevant reviewers.	

Publications and Presentations:

None to date.