U.S. Department of Transportation
Federal Aviation Administration

FINAL PROJECT REPORT

Form Approved:
O.M.B. No. 2120-0559

PART I - PROJECT IDENTIFICATION INFORMATION

1. Institution and Address	2. FAA Program	3. FAA Award Number
Iowa State University 213 Beardshear Ames, IA 50011	Aviation and Aircraft Safety – Aging Aircraft	95-G-025
	4. Award Period 5-15-95 to 9-30-98	5. Cumulative Award Amount $2,587,470

6. Project Title
FAA Center for Aviation Systems Reliability:
Engineering Research, Development, and Application

SUMMARY OF COMPLETED PROJECT (For Public Use)

The FAA Center for Aviation Systems Reliability was established at Iowa State University in 1990 in response to the Aviation Safety Act of 1988. The objectives of the program are to develop quantitative nondestructive evaluation methods for aircraft structures and materials including prototype instrumentation, software, techniques, and procedures and to develop and maintain comprehensive education and training programs specific to the aviation industry. FAA Grant No. 95-G-025 included efforts involving engineering research, development and application of various NDE methodologies including thermal wave imaging, ultrasonics, eddy current, radiography, and optical techniques to such aging aircraft issues as corrosion, disbond detection, fatigue cracking and multilayer inspection.

The FAA Center for Aviation Systems Reliability (FAA-CASR) was established to provide support to the FAA National Aging Aircraft Program (NAARP) in nondestructive evaluation with a focus on the development of aviation specific inspection tools and training. FAA-CASR is built on a strong foundation of industrially relevant NDE research at Iowa State University's Center for Nondestructive Evaluation and includes partner universities of Northwestern University and Wayne State University. Additionally, FAA-CASR is coupled with the FAA Aging Aircraft Nondestructive Evaluation Validation Center (AANC) to further strengthen the resources available to the FAA and the industry. CASR investigators work closely with the FAA and AANC staff in addressing relevant research needs for the industry. Effort in this grant included both basic and applied research and development as necessary to determine the feasibility of a given approach and demonstrate its utility in realistic problems and aviation geometries, including eventual reduction to practice. Validation is a significant component of the technology adaptation and will range from pre-validation of first prototypes to complete validation of final prototypes. CASR staff work closely with AACE once efforts reach sufficient maturity to begin structured validation. The use of characterized samples and the neutrality that the AANC facilities offer for initial field trials is necessary as part of the development of industrially implementable solutions. From the initiation of the programs, this synergistic approach has been at the base of the NAARP.

The Technical Areas and tasks that comprise the Engineering Research, Development and Application Program are summarized here:

Adhesively Bonded and Composite Structures: Because of increased use of composites, the industry identified needs for improved methods of composite inspection and improved understanding of the bond integrity and strength of composite repair patches. Two tasks were completed:

- Thermal Wave Imaging of Adhesive Bonds and Composites - Significant progress was been made in the development of fieldable thermal wave imaging system by the WSU team. However, fundamental questions addresses in this program included development of algorithms to determine skin thickness from thermal wave images and study of the frequency domain of thermal wave imaging.
- Evaluation of Inspection Concepts for Composite Patches on Metallic Aircraft Structure - The research focused on NDE of the integrity, durability and reliability of composite repair and utilized ultrasonics, acoustic emission and acousto-ultrasonic techniques developed at Northwestern University.

Fatigue and Cracking: Crack detection continues to be a high priority area for the industry and the NAARP, particularly in multilayered structures. The occurrence of widespread fatigue damage and/or multisite damage is of increasing concern. Tasks addressed the detection of cracks in airframe structures as summarized below:

- Pulsed Eddy Current Detection and Characterization of Fatigue Cracks - This task adapted the previous CASR designed pulsed eddy current instrument for corrosion to the detection of cracks. Applications will include cracks under fasteners and multi-layered aircraft structures. Feasibility of the technique was demonstrated using EDM and actual

fatigue crack samples.

- Optical Interferometry – Investigators at NU explored the development of signal acquisition and signal interpretation approaches that can be implemented by the user community in commercial shearography systems. Results were shared with experts in the field at AANC as well as with industry.
- Laser based Ultrasonics for Aircraft Structures – This task applied laser based UT approaches developed at Northwestern University to detection and sizing of small cracks under fastener heads and in between fasteners such as occur in multi-site damage.
- Air Coupled Ultrasonics - This task had as its objective to adapt, develop and improve air-coupled ultrasonic inspection methods for in-service defect detection in manufacturing irregularities in aircraft geometries with concentration on composite materials and joints. A laboratory system was developed for feasibility studies.
- Capacitive Array Sensors for Electromagnetic NDE of Composites - This task explored applications of electromagnetic inspection methods on composite materials using capacitive sensors. Limited results were provided.
- Application of Ultrasonic Pulse Compression Technique for Aircraft Component Examination - This task quantified the improvements that are realized by use of ultrasonic pulse compression techniques in highly attenuative materials such as titanium and composite structures.
- Self Focusing Ultrasonic System for Detection of Defects - A simplified version of the time-reversal approach to ultrasonic inspection of typical engine materials was developed. Algorithms that demonstrated the approach were completed.

Reliability: The reliability of inspection procedures and inspection systems continues to be a primary focus of the NAARP. Modeling of inspection techniques and fatigue processes is a strength of the CASR program with activities summarized here:

- X-ray POD - This task applied x-ray inspection models to aging aircraft geometries in cooperation with OEMs. Results were presented to airlines, OEMs and the FAA through demonstration of software at the ATA NDT Forum.
- Analysis of Widespread Fatigue Damage and Development of Inspection Specifications - Both experimental and theoretical efforts occurred as part of this task at Northwestern University. The effort focused on providing reliability estimates of fatigue damage near rivet joints.

PART III - TECHNICAL INFORMATION (For Program Management Uses)

1 ITEM (Check appropriate blocks)	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRAM	
				Check (✔)	Approx. Date
a. Abstracts of Theses	☐	☒	☐	☐	
b. Publication Citations	☐	☒	☐	☐	
c. Data on Scientific Collaborators	☐	☒	☐	☐	
d. Information on Inventions	☐	☒	☐	☐	
e. Technical Description of Project and Results		☒	☐	☐	
f. Other (specify)		☐	☐	☐	

2. Principal Investigator / Project Director Name (typed)	4. Principal Investigator / Project Director Signature	4. Date
Lisa Brasche		9/15/00

FAA Form 9550-5 (1-93) Supersedes Previous Edition

PART III

1. Theses titles – Iowa State University
   - Vamsee Kumar Tirukkala, MS, Visualization of X-ray scattering process in XRSIM
   - Gangadhar Rao Nutakki, MS, Stereography : a low cost alternative to computerized tomography
   - Raghuram Madabushi, MS, Photo-densitometry : radiograph digitization and algorithmic enhancement of x-ray images
   - Kiran Kumar Dasoju, MS, Numerical modeling of pulsed eddy current techniques for detection of corrosion and cracks

2. Publication citations

1. “Optimization Tool for X-ray Radiography NDE”, I. Elshafiey and J.N. Gray, Center for NDE, Iowa State University, Ames, IA 50011, Review of Progress in Quantitative NDE, vol. 15, eds. D.O. Thompson and D.E. Chimenti.
2. “Flaw Detectability Modeling in X-ray NDE using an Inspection Model and Hypotheses Tests for Signal Areas”, R.M. Wallingford and J.N. Gray, Center for NDE, Iowa State University, Ames, IA 50010, Review of Progress in Quantitative NDE, vol. 15, eds. D.O. Thompson and D.E. Chimenti.
3. “Air-Couples Ultrasound and Leaky Lamb Waves in Composites”, A. Safaeinili, O.I. Lobkis and D.E. Chimenti*, Center for NDE and Dept. of Aerospace Engineering and Engineering Mechanics, Iowa State University, Ames, IA 50011, Review of Progress in Quantitative NDE, vol. 15, eds. D.O. Thompson and D.E. Chimenti.
4. “Time-Gating of Pulsed Eddy Current Signals for Depth Discrimination”, J.A. Bieber, S.K. Shaligram, J.H. Rose, and J.C. Moulder, Center for NDE, Iowa State University, Ames, IA 50010, Review of Progress in Quantitative NDE, vol. 16, eds. D.O. Thompson and D.E. Chimenti.
5. “Characterizatin of Anisotropic Materials Using Air-Couples Ultrasound”, O.I. Lobkis and D.E. Chimenti*, Center for NDE and Aerospace Engineering and Engineering Mechanics Department*, Iowa State University, Ames, IA 50011, Review of Progress in Quantitative NDE, vol. 16, eds. D.O. Thompson and D.E. Chimenti.
6. “Low Frequency, Pulsed Eddy Currents for Deep Penetration”, J.C. Moulder and W.W. Ward III, Center for NDE, Iowa State University, Ames, IA 50011, Review of Progress in Quantitative NDE, vol. 17, eds. D.O. Thompson and D.E. Chimenti.
7. “Delamination Depth Determinations in Composites Using Thermal Wave Imaging”, X. Han, L.D. Favro, T. Ahmed, X. Wang, and R.L. Thomas, Department of Physics and Institute for Manufacturing Research, Wayne State University, Detroit, MI 48202, Review of Progress in Quantitative NDE, vol. 18, eds. D.O. Thompson and D.E. Chimenti.
8. “Pulsed Eddy Current Detection and Characterization of Cracks”, J. Bieber, Center for NDE, Iowa State University, Ames, IA 50011, Review of Progress in Quantitative NDE, vol. 18, eds. D.O. Thompson and D.E. Chimenti.
9. "Self-Focusing of Rayleigh Waves and Lamb Waves with a Linear Phased Array," W. A. K. Deutsch, A. Cheng, J. Achenbach, Res Nondestr Eval, 9:81-95, 1997.
10. "Fatigue crack initiation and growth in riveted specimens: an optical and acoustic microscopic study," Z. M. Connor, W. Li, M. E. Fine, J. Achenbach, Int. J. Fatigue, 19, Supplement 1:S331-S338, 1997.
11. "Simulation of self-focusing by an array on a crack in an immersed specimen," M. Zhang, J. Achenbach, Ultrasound 37, pp. 9-18, 1999.
12. “Imaging the Early Time Behavior of Reflected Thermal-Wave Pulses”, L.D. Favro, Xiaoyan Han, P.K. Kuo and R.L. Thomas, *Thermosense XVII*, SPIE Vol.2473 pp. 162-166, edited by Sharon A. Semanovich, 1995.
13. "Pulse-Echo Thermal-Wave Imaging for Non-Destructive Evaluation", R.L. Thomas, L.D. Favro, P.K. Kuo, T.Ahmed, Xiaoyan Han, Li Wang, Xun Wang and S.M.Shephard, *Proceedings of the 15th International Congress on Acoustics*, Vol. 1 pp. 433-436, Edited by Mike Newman, 1995.
14. “Measuring Defect Depths by Thermal-Wave Imaging”, L.D. Favro, Xiaoyan Han, P.K. Kuo and R.L. Thomas, *Thermosense XVIII*, SPIE Vol. 2766 pp. 236-239, edited by Douglas D. Burleigh, Jane W.M. Spicer, 1996.
15. "Defect Depth Determination by Thermal-Wave Imaging", L.D. Favro, Xiaoyan Han, P.K. Kuo and R.L. Thomas, published in *Progress in Natural Science*, Volume 6, S139-141, 1997.
16. Thermal-Wave Imaging for Characterizating Structures in Aging Aircraft ", Xiaoyan Han, L.D. Favro, and R.L. Thomas, Volume 503, Nondestructive Characterization of Materials in Aging Systems, pp. 47-52, May, 1998, edited by Robert L. Crane, Jan D. Achenbach, Surendra P. Shah, Theodore E. Matikas, Pierre T. Khuri-Yakub, Robert S. Gilmore.
17. Fracture and Fatigue Behavior of Scrim Cloth Adhesively Bonded Joints With and Without Rivet Holes", H. Aglan, Z. Abdo and S. Shroff, J. of Adhesion Sci. and Tech., Vol. 9, No. 2 (1995) 177-197.
18. "An Innovative Approach to Fatigue Disbond Propagation in Adhesive Joints", H. Aglan and Z. Abdo, J. of Adhesion Sci. And Tech., Vol. 10, No. 3, (1996) 183-198.

19. "Effect of Surface Treatment on the Failure Behavior of Structural Adhesive Joints", Z. Abdo and H. Aglan, J. of Materials Sci. Let., 15 (1996) 469-472.
20. "Analysis of Aircraft Adhesive Joints Under Combined Thermal and Mechanical Cyclic Loadings", Z. Abdo and H. Aglan, J. Adh. Sci. and Tech., Vol. 11, No. 7. (1997) 941-956.

3. Scientific Collaborators at Iowa State University

Name	Title
Lisa Brasche	Scientist
John Moulder	Associate Scientist
Jay Bieber	Engineer
William Ward	Engineer
Kiran Kumar Dasoju	Student
Dale Chimenti	Professor
Peter Jeong	Associate Scientist
Joe Gray	Scientist
Richard Wallingford	Associate Scientist
Feizi Inanc	Visiting Scientist
Sunil Shaligram	MS
Gangadhar Nutakki	MS
Deven Hubbard	Undergraduate
Raghuram Madabushi	MS
Vamsee Tirukkala	MS
Zhuo Yang	MS
P. Rian	MS
H. Zhang	MS
O. Lobkis	MS

4. Briefly describe any inventions which resulted from the project and the status of pending patent applications, if any.

   Scanned pulsed eddy current, Patent 6,037,768 issued March, 14, 2000. The technology was licensed to Sierra Matrix between 8/15/96 - 12/8/98.

5. Provide a technical summary of the activities and results. The information supplied in proposals for further support, updated as necessary, may be used to fulfill this requirement.

Products summary provided on following pages.

6. Include any additional material, either specifically required in the award instrument (e.g. special technical reports or products such as films, books, studies) or which are considered to be useful to the Foundation.

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FAA Center for Aviation Systems Reliability – Engineering Research, Development, and Application

The mission of the Center for Aviation Systems Reliability program is to provide the FAA with cost-effective, reliable inspection tools and comprehensive training materials that meet the specific needs of the aviation industry. Engineering research, development and application efforts were performed by Iowa State University, Northwestern University, Wayne State University and Tuskegee University as part of Grant number 95-G-025. Key results for each of the tasks included the following:

Thermal Wave Imaging of Adhesive Bonds - R. L. Thomas, L. D. Favro, P. K. Kuo – Wayne State University - The objective of this task was to establish the usefulness of thermal wave imaging as a non-contacting, large area NDI technique for the evaluation of disbonds and corrosion in adhesively bonded structures. To carry out field demos of the prototype instrumentation, and to initiate Tech Transfer activity on this instrumentation under the AANC-defined validation process. Thermal wave imaging has matured from an initial CASR development task to a technology transfer initiative partnering CASR, AANC, and industry members from the OEMs and third party maintenance facilities. The WSU developed system is available commercially, is currently being used for production quality inspections by Lockheed Martin, and is under evaluation for field applications by Boeing. Efforts continued in the application of this technique under FAA grant number 95-G-032 and as part of FAA contract number DTFA03- 98-D-00008.

Optical Interferometry - Sridhar Krishnaswamy – Northwestern University – The objective of this tasks was to develop robust, noise-insensitive optical interferometric NDE systems with synchronized stressing devices for large area detection of hidden damage in aircraft structures. Significant improvements were made in noise sensitivity over traditional shearography schemes. The improved technique was patented and has been transferred to LTI for use in their commercial system.

NDE Parameters - Failure Property Relationships of Adhesive Bonds - H. Aglan – Tuskegee University – The objective of this task was to correlate cumulative induced damage detectable by NDE techniques (thermal wave and ultrasonic) with the number of aging cycles, fatigue lifetime and the strength of adhesively bonded joints. The cumulative damage was induced by a combination of laboratory cyclic aging and tension/tension fatigue. In cooperation with investigators at ISU, NU and WSU, the samples were examined. Correlations were found between destructive and nondestructive results.

Pulsed eddy current for detection of cracks – J. Moulder – Iowa State University – The objective of this task was to adapt existing PEC technology developed for corrosion detection to characterization and detection of cracks in multilayered structures. The detection of cracks requires higher resolution and greater sensitivity than the prior effort on corrosion detection. Probe optimization for crack detection capability was a focus of this effort. Electronic design and software changes were made that permit the instrument to be adapted to readily available commercial eddy current probes such as absolute or differential probes. The existing system has been field tested with good results including participation in 777 fatigue test efforts. Efforts continue in this area under FAA funding through contract number DTFA03- 98-D-00008.

Laser based Ultrasonics – J. Achenbach – Northwestern University – The objective of this task was to exploit the advantages of laser-based UT through array generation and dual point detection using noncontacting, remote placement of equipment based on fiber optics. This enables easy scanning of curved surfaces in aircraft applications. A more robust

fiberized Sagnac dual-probe interferometer was developed with a cost target of $10 - 15K, about a third of currently available interferometers. Expected application is for small crack detection such as in widespread fatigue damage and composites. The system was demonstrated at the 96 and 97 ATA NDT Forum. Efforts continue in this area under FAA funding through contract number DTFA03- 98-D-00008.

Air Coupled Ultrasonics – D. Chimenti – Iowa State University – This task explored the feasibility, applicability, development and improvement of air-coupled UT for commercial aircraft applications as applied primarily to composite materials. The investigator developed a laboratory system using traditional components and commercially available air coupled transducers with operation in through transmission mode. A correlation was established between amplitude/transducer separation and material properties.

Pulse Compression Techniques for UT – Peter Jeong – Iowa State University – This task investigated the application of ultrasonic pulsed compression techniques for aviation component examination using samples available from other FAA funded efforts such as the Engine Titanium Consortium. Pulsed compression UT involves use of a coded signal which can be generated either in software or hardware through appropriate transducer design. PC based software is used with off-the-shelf UT instrumentation to generated a “Golay” code which is then transmitted into the material. A signal processing approach correlates the output signal with the known input signal which results in an improved signal to noise ratio but at the cost of extended data processing time. The feasibility study found significant improvements for some samples but did not provide sufficient improvement for Ti and aviation composites to warrant field studies.

Self-focusing Ultrasonics – Jan Achenbach – Northwestern University – This task developed a measurement model to evaluate various system configurations and firing sequences for comparison to the time-reversal technique developed at University of Paris. The approach was extended to surface and lamb waves using contact transducers for application to cracks in thin plates. A transducer with a center element and 24 outer elements in an annular ring was fabricated. The center element of the transducer is fired first with 24 elements in outer 3 rings serving as receivers of the backscattered signals. Upon receipt of backscattered signals, relative time delay is determined and each element refired with the original signal (using the determined time-delay, the last-receiving transducer is fired first) resulting in a focused ultrasonic beam. The technique has been successfully used in detection of small cracks in thin Al plates.

Radiography Inspection Optimization using Simulation Codes – Joe Gray – Iowa State University – The approach to this task included development of simulation code that allows range of material properties, setup parameters (source, detector), and realistic flaw types for use with standard CAD files. Software that runs in a UNIX environment was developed which incorporates various physical aspects of radiography and includes a graphical user interface. Validation studies were performed with industrial partners through application of the model to real inspection problems using betasite test and problem solving at ISU. Further improvements are planned based on feedback from users. Efforts continue in this area under FAA funding through contract number DTFA03- 98-D-00008.

Analysis of Widespread Fatigue Damage and Development of Inspection Specifications - Brian Moran and Morris Fine – Northwestern University – This task was a two year effort that included bothe xperimental and theoretical efforts. It focused on understanding the crack growth mechanisms for cracks that occur around rivets. Technical reports were provided which included, “Study of Crack Growth in Multi-riveted Joint; Stress

Intensity Factors for Cracks in Riveted Specimens" and, "Application of FORM to Assessment of POD Requirements".

Capacitive Arrays – John Moulder – Iowa State University – A short feasibility study of the applicability of capacitive arrays to aviation applications was initiated. The funds were used to support student participation in the effort. The investigator for this effort passed away during the timeframe of the project.