U.S. Department of Transportation
Federal Aviation Administration

FINAL PROJECT REPORT

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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-032
	4. Award Period 6-27-95 to 12-31-98	5. Cumulative Award Amount $3,054,090

6. Project Title
FAA Center for Aviation Systems Reliability:
Program for Technology Deployment and Transition

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-032 included efforts involving the deployment and transistion 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 comprised the Technology Deployment and Transition Program are summarized here:

Prevalidation and Technology Support: The transition of technology from the laboratory to the field is a difficult yet admirable goal that requires the talents of various skill groups. The interpretation of the results by the end user is a critical step in the process and the various skill levels must be considered in the development and deployment of technology. Maintaining the competency and practices of the technology base is also a component of the technology transfer process to be undertaken by the CASR and AANC programs. The tasks in this technical area necessarily are in close coordination with AANC staff as described below:

- Technical Support to FPI and Short term Projects - The FAA Technical Center, Directorates and NRS for NDE utilized the NDE resources at CASR to address technology base issues such as the assessment of FPI practices. This included the participation by CASR staff in industry committees such as the SAE Committee K - NDE Specifications and ASNT Aerospace Committee. Contributions were made to various aerospace specifications including SAE 2647.
- Assessment and Image Interpretation for Ultrasonic NDI - This task developed a better understanding of the relationship between ultrasonic images and various defect types.

Adhesively Bonded and Composite Structures: This technical area received considerable attention in the initial years of CASR under prior grant funding. Many of the tools such as Thermal Wave Imaging, the Dripless bubbler, and optical interferometry were transitioned to the Technology Deployment and Transition program for reduction to practice.

- Technology Transfer of Thermal Wave Imaging System for Aircraft Maintenance - Significant progress was made in the development of fieldable thermal wave imaging system by the WSU team. A joint FAA-AF

technology development program was completed as part of this CASR Technology Deployment and Transition program. This task delivered an operational prototype to the Air Force for use in aircraft maintenance facilities.

- Incorporating the Dripless Bubbler with a Scanner for Ultrasonic C-scan Imaging of Defects in Bonded Aircraft Structures – This task developed a fully functional prototype of the Dripless bubbler for beta site testing at AANC and the airlines.
- Technology Transfer of the ASPM-SI Device - This task completed development and field testing of a ruggedized ASPM-ESPI-shearography device based on integration of CASR technology with commercially available optical testing systems from LTI.

Corrosion: The initial CASR program devoted a significant part of its efforts to development of corrosion detection techniques. Several of these are proposed here for transition to the Technology Deployment and Transition program.

- Portable Pulsed Eddy Current Scanning Instrument - This task demonstrated a ruggedized prototype pulsed eddy current instrument, capable of operation in a 2D scanning mode.
- X-ray Imaging and Material Characterization System - This task provided information supporting x-ray detection of corrosion.

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. The tasks completed in this program address the detection of cracks in airframe structures as summarized below:

- Ultrasonic Characterization of Defects in Multilayered Structures - This task continued development of multilayered inspection including several DC-9 and DC-10 examples using capabilities developed at Northwestern University.
- Signal Classification for Eddy Current Inspection - This task was performed in conjunction with Boeing to provide a signal classification tool for boltholes.
- Eddy Current Modeling for Edge Effect - This effort addressed two separate modeling requests made by industry, namely, modeling of edge effect to be used for optimized probe design as requested by Douglas, and calculation of the magnetic fields generated by magneto-optic imaging approach in cooperation with PRI.
- Technology Transfer of Ultrasonic Inspection Methods for Cracks in DC10 Spar-Cap-Strap Connection - This Phase II task completed the previously initiated technology transfer task under way with AANC on the use of self-compensating UT to detect and size cracks in the DC-10 geometry. The approach uses commercially available instrumentation and was completed in close coordination with the staff and Douglas and AANC.
- Technology Transfer of Extension Proposal for Parameter Invariant Classification System for Wheel Inspection Signals - The previously funded wheel inspection project resulted in a beta site system in operation at Northwest Airlines - Minneapolis. Operational experience indicated the need for improvements to the data acquisition system to accommodate a wider range of wheel sizes and therefore, scanning speeds. A upgraded, user-friendly PC-based software package for classification of wheel inspection signals independent of probe frequency and wheel type was developed and betasite tested at Northwest Airlines.

Reliability: The reliability of inspection procedures and inspection systems has been a primary focus of the NAARP. This technical area provided prototype systems for probe characterization to the industry for beta site.

- Technology Transfer of Eddy Current Probe Characterization Instrument - This task completed an upgraded instrument for eddy current probe characterization. It demonstrated the importance of probe parameters and performance.

The Technology Deployment and Transition program built on the research base of the CASR program and relies on the validation efforts of AANC to implement the joint results in the aviation industry. Many of the tasks involved field testing at AANC as well as establishment of beta sites at various industrial locations. The combined talents of these consortia ensure that the FAA National Aging Research Program has the resources to develop, validate and implement needed inspection technology for the aviation industry.

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) Lisa Brasche	4. Principal Investigator / Project Director Signature				4. Date 9/15/00

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

PART III

1. Theses titles – Iowa State University
    - Zhijun Cao, MS, Eddy Current Image Processing
    - Ming Yu, MS, Image Segmentation Using Genetic Algorithm and Morphological Operations
    - Shu Gao, MS, Application of Morphological Filtering to Defect in Eddy Current Wheel Inspection Signals
    - Atul Athavale, MS, Application and Imaging Techniques for Characterizing Magnetic Particle Inspection Data
    - Nawapak Eua-Anant, MS, A Novel Boundary Extraction Algorithm Based on a Vector Image Model
    - Samad Usama, MS, Texture Based Analysis of Ultrasonic Images
    - Sarit Sharma, Ph.D. Application of Finite Element Models to Eddy Current Probe Design for Aircraft Inspection
    - Madhusudhan Rao Midhe, MS, Automation of real-time X-ray scans
    - Sudha Rani Puvvad, MS, Remote control of X-ray hardware
    - Sunil Kumar Shaligram, MS, Development of a pulsed eddy current instrument for corrosion detection
    - William Westfall Ward III, MS, Development of a pulsed eddy current instrument and its application to detect deeply buried corrosion

Publication citations

1. Quantitative Measurement of Metal Loss Due to Corrosion in Aluminum Aircraft Skin, D.K. Hsu, T.C. Patton, V. Dayal, 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. Thermal Wave Imaging of Disbonding and Corrosion on Aircraft, L.D. Favro, T. Ahmed, X. Han, L. Wang, X. Wang, P.K. Kuo, 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. 15, eds. D.O. Thompson and D.E. Chimenti.

3. Recent Developments with the Dripless Bubbler ultrasonic Scanner, T.C. Patton and D.K. Hsu, FAA-Center for Aviation Systems Reliability, Iowa State University, Ames, IA 50011, Review of Progress in Quantitative NDE, vol. 15, eds. D.O. Thompson and D.E. Chimenti.

4. Wheel Inspection and Signal Analysis: A Parameter Invariant Classification System for Eddy Current Wheel Inspection, I. Elshafiey and L. Udpa, Center for NDE, Iowa State University, Ames, IA 50011, Review of Progress in Quantitative NDE, vol. 16, eds. D.O. Thompson and D.E. Chimenti.

5. Thermal Wave Imaging of Disbonding and Corrosion on Aircraft, X. Han, L.D. Favro, T. Ahmed, Z. Ouyang, L. Wang, X. Wang, F. Zhang, P.K. Kuo, 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. 16, eds. D.O. Thompson and D.E. Chimenti.

6. A Differential Magnetic Flux Density Pickup Probe, S. Sharma, L. Udpa, Y. Sun, and S. Udpa, Iowa State University, Ames, IA 50011, Review of Progress in Quantitative NDE, vol. 17, eds. D.O. Thompson and D.E. Chimenti.

7. Field and Beta-Site Testing of the Dripless Bubbler Ultrasonic Scanner, D.J. Barnard and D.K. Hsu, Center for NDE and FAA Center for Aviation Systems Reliability, Iowa State University, Ames, IA 50011, Review of Progress in Quantitative NDE, vol. 17, eds. D.O. Thompson and D.E. Chimenti.

8. An Adaptive Morphological Filter for Defect Detection in Eddy Current Wheel Inspection Signal, S. Gao and L. Udpa, 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.

9. NDE of Corrosion and Disbonding on Aircraft Using Thermal Wave Imaging, X. Han, L.D. Favro, T. Ahmed, Z. Ouyang, X. Wang, P.K. Kuo, 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. 17, eds. D.O. Thompson and D.E. Chimenti.

10. Detection of Corrosion Under Rivet Heads, M.F. Fleming[1] and D.K. Hsu[2], [1]Sierra Matrix, Inc., Fremont, CA 94538, [2]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.

11. Pulsed Eddy current Applications in Detection of Hidden Corrosion and Cracks in Aircraft Structures, 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.

12. Detection and Quantification of Intergranular Corrosion Around Wing Skin Fasteners Using the Dripless Bubbler Ultrsonic Scanner, D.J. Barnard and D.K. Hsu, 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.

13. An Ultrasonic Technique to Detect Corrosion in DC-9 Wing Box from Concept to Field Application, I. Komsky, J. Achenbach, G. Andrew, B. Grills, J. Register, G. Linkert, G.

Hueto, A. Steinberg, M. Ashbaugh, D. Moore, & H. Weber), Materials Evaluation, 52(7):848-852, 1995.

14. A Roller Device to Scan for Surface-Breaking Cracks and to Determine Crack Depth by a Self-Calibrating Ultrasonic Technique, A. Cheng, J. Achenbach, Research in Nondestructive Evaluation, 7, pp. 185-194, 1996.

15. Measuring Corrosion Thinning by Thermal-Wave Imaging, L.D. Favro, Xiaoyan Han, P.K. Kuo and R.L. Thomas, *Nondestructive Evaluation of Aging Aircraft, Airports, and Aerospace Hardware*, edited by Raymond D. Rempt, Alfred L. Broz, SPIE, Vol. 2945, pp. 374-379, 1996.

16. Thermal-Wave Imaging for Detection and Quantification of Corrosion and Disbonds in aging Aircraft , Xiaoyan Han, L.D. Favro, and R.L. Thomas, presented at *the First Joint DoD/FAA/NASA Conference on Aging Aircraft*, Ogden, Utah, USA, July 7-10, 1997, published in the proceedings, volume II, pp. 1589-1592.

17. Quantitative Detection and Characterization of Corrosion in Aircraft, Xiaoyan Han, L.D. Favro, and R.L. Thomas, *Proceedings of the Workshop on Intelligent NDE Sciences for Aging and Futuristic Aircraft*, pp. 83-91, 1998, edited by C. Ferregut, R. Osegueda, A.Nunez.

18. Quantitative Defect Depth Measurements for NDE of Composites, Xiaoyan Han, L.D. Favro, and R.L. Thomas, *Proceedings of the American Society for Composites*, pp. 1077-1081, Technomic Publishing Co. INC, 766060, Lancaster Basel, edited by Ronald F. Gibson and Golam M. Newaz, 1998

19. Thermal Wave Imaging for Corrosion Detection in Aging Aircraft Systems, L.D. Favro and R.L. Thomas, Proc. 41st Int. SAMPE Symposium and Exhibition, Anaheim, CA, March 24-28, 1996, pp. 261-264.

20. Synchronous Thermal Wave Imaging, L.D. Favro, P.K. Kuo, and R.L. Thomas, Prog. in Natural Science, Suppl. to Vol. 6, pp. S135-S138 (1996).

21. Thermal Wave Imaging for NDE of Aircraft, R.L. Thomas, P.K. Kuo, and L.D. Favro, Prog. in Natural Science, Suppl. to Vol. 6, pp. S69-S71 (1996).

3. Scientific Collaborators at Iowa State University

Name	Title
Lisa Brasche	Scientist
Joe Gray	Scientist
Richard Wallingford	Associate Scientist
Feizi Inanc	Visiting Scientist
Sunil Shaligram	MS
Sudha Rani Puvvadi	MS
Tara J.Gray	Undergraduate
Bryan Hinzie	Graduate – hourly
Joshua Neveln	Undergraduate
Michael Lundberg	Undergraduate
Dave Hsu	Scientist
Thadd Patton	Engineer
Dan Barnard	Engineer
Mathew Reed	Undergraduate
Abnesh Puthenpurackal	Graduate – hourly
Scott Brown	Undergraduate
Harprett Wasan	Graduate – hourly
John Moulder	Scientist
Jay Bieber	Engineer
William Ward	Engineer
J. Patterson	Undergraduate
L. Xu	MS
Joe Gray	Scientist
Terry Jensen	Scientist
M. Midhe	MS
L. Upda	Professor
Z. Cao	MS
C. Chao	MS
Y. Ming	MS
S. Gao	MS
A. Athavale	MS
N. Eua-Anant	MS
S. Usama	MS
S. Sharma	Ph.D
B. Larson	Engineer
Jessica Porter	Undergraduate
Tricia Devore	Undergraduate
Jamie Krull	Undergraduate

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

None.

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.

FAA Center for Aviation Systems Reliability – Technology Deployment and Transition

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. Technology Deployment and Transition efforts were performed by Iowa State University, Northwestern University, and Wayne State University as part of Grant number 95-G-032. Key results for each of the tasks included the following:

Assessment and Image Interpretation for Ultrasonic NDI – D. Hsu, T. Patton – Iowa State University – The objective of this task was to make quantitative sensitivity assessment for ultrasonic NDI of aging aircraft structures by correlation with actual flaw parameters obtained in destructive analysis. With the development of the Dripless Bubbler funded under a previous FAA grant, the quality of ultrasonic scans made on the fuselage rivals that of immersion scans in the laboratory. However, the ability to detect a known existing flaw is not synonymous with the interpretation of complex images obtained on actual complicated aircraft structures. The ability to correctly interpret images is therefore essential and was the focus of this task. The task provided a quantitative measure of the performance and sensitivity of ultrasonic NDI for aircraft structures using state-of-the-art image processing and analysis techniques for interpreting benign and defective conditions represented by features in scan images. Results were published as well as shared with the licensee of the technology.

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 extend and accelerate progress in the ongoing FAA-CASR funded development of thermal wave imaging as a nondestructive inspection technique for corrosion in DC-10-30, L-1011 and B-747-100/200 configurations for the Non Developmental Airlift Aircraft (NDAA) program requirements which were defined by the Air Force. The task carried out field demos of the prototype instrumentation at an Air Force facility. Impovements were made that incorporated a 12-bit digital electronic thermal wave imaging system and wide angle lenses for the focal plane array camera. 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 as part of FAA contract number DTFA03- 98-D-00008.

Dripless Bubbler – Dave Hsu – Iowa State University –This task resulted in technology transfer of a fully functional prototype incorporating the Dripless Bubbler technique for rapid, large area NDI of aircraft bonded structures, specifically: tear straps, lap splices, and bonded composite assemblies. The task included a survey of US airlines needs for scanner technoloogy. The need to inspect over protruding rivets led to development of captured water column which allows use of focused immersion probes for consistent coupling and high spatial resolution in multiple orientations resulting in “immersion” quality scans in a previous FAA grant. Low frequency scans were demonstrated to be more sensitive to disbonds (increased depth of penetration) and second layer corrosion. High frequency scans were more sensitive to first layer corrosion. In this task, the dripless bubbler was adapted to commercial scanners and betasite tested with Northwest Airlines and United Airlines. The dripless bubbler was also 1996 R&D100 Award winner and was featured on CNN Science Watch.

Optical Interferometry - Sridhar Krishnaswamy – Northwestern University – The objective of this one-year task was to further the technology transfer process of the newly developed additive-subtractive phase-modulated shearography and ESPI device so as to gain greater acceptability by the users. It builds on research efforts funded under FAA Grant number 95-G-025. Robust full-field optical interferometers - additive-subtractive phase-modulated shearography and ESPI - were developed at Northwestern University under previous FAA sponsored projects. These interferometers have performance characteristics superior to currently available commercial systems. The ASPM technology has been licensed to Laser Technology Inc (LTI). In phase I of the technology transfer process, LTI is currently developing a commercial product suitable for use in aircraft maintenance. Additional uses of the device as a full-field strain measurement tool, especially to characterize composite repair patches, were explored.

Pulsed eddy current for detection of corrosion – J. Moulder – Iowa State University – The objective of this task was to develop a new ruggedized and portable pulsed eddy current instrument, incorporating improvements suggested by our experience with the first laboratory prototype instrument. The system was adapted for operation in a 2D scanning mode for area scanning of corroded lap joints. Pulsed eddy current can be utilized in either a point detection or scanning mode. This effort focused on transition from a point measurement to a scanning device. The existing prototype system was field tested at AANC as well as at several airlines. Applications were reviewed with Boeing-Long Beach and Boeing-Seattle for future development. Efforts continue in this area under FAA funding through contract number DTFA03- 98-D-00008.

Portable, Low-Radiation Hazard, Real-Time X-Ray Imaging and Material Characterization System – J. Gray, T. Jensen – Iowa State University – The objective of this task was to develop an experimental method that takes advantage of the full energy spectrum in radiographic detection. This included determining optimal energy sensitive detectors for aviation specific materials characterization techniques and applying the energy sensitive measurement to industrially defined applications. Energy sensitive detectors have proven useful in various materials characterization studies for detection of damage (corrosion) and property variability that may lead to premature failure of components. ISU worked with Lockheed Martin to design an energy sensitive detector array optimized for characterization of composite components. The system is used to determine fitness for service of production components.

Eddy current modeling – L. Udpa – Iowa State University – This effort included several applications defined by the airlines and OEMs in cooperation with the FAA. Boeing-Seattle identified the need for classification tool for rotating eddy current probe signals. Software for eddy current c-scan image display and classification of rotating probe data was completed and implemented on blind samples provided by Boeing. The results were communicated to Boeing for validation. In addition, the investigator developed a finite element eddy current model for addressing aircraft inspection issues. First, existing eddy current finite element models were utilized for optimizing probe designs for the inspection of aging aircraft components. In particular, modifications to standard eddy current geometry were evaluated with respect to detection of cracks in proximity to layer edges of the aircraft crown splice. The results were provided to Boeing- Long Beach for use in future eddy current probe specification.

Wheel Inspection – L. Udpa – Iowa State University – The objective of this task was to provide a tool for improved wheel inspection for integration with existing eddy current systems. CASR developed software was installed at Northwest Airlines with minimal modification to their commercial system. C-scan capability improves accept/reject

decisions. Efforts continue in this area under FAA funding through contract number DTFA03- 98-D-00008.

Ultrasonic Inspection – J. Achenbach, I. Komsky – Northwestern University – This task completed the technology transfer of the Self-Compensating Ultrasonic Technique to detect and size cracks in a DC-10 Spar-Cap-Strap connection. This effort was compeleted in cooperation with Douglas and Northwest Arilines. The first efforts of the task concentrated on detection using currently available equipment (EPOCH II) and a small bridge to hold the transducers. The bridge was designed and fabricated using commercially available transducers. The second phase concerned crack detection and crack sizing. Specimens of the connection containing EDM notches and cracks were provided by Douglas Aircraft to finalize the transducer configurations for crack detection. The self-compensating technique was demonstrated to OEMs and airlines at ATA NDT Forum in 1998.