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Development of Sonic Infrared (SIR) Inspection Technology for Nondestructive Evaluation of Critical Aircraft Engine Rotating Components – Phase 2

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16\. Abstract
As a possible alternative to fluorescent penetrant inspection (FPI) of critical rotating engine components, the Federal Aviation Administration funded the development of a nondestructive testing (NDT) method known as acoustic thermography (AT) or sonic infrared (SIR) imaging. The objective of this program was to address key technical challenges associated with the planned use of SIR in the overhaul environment and to design a viable prototype system suitable for disk inspections. Technical challenges addressed during this phase included: (1) assessing whether existing surface residual stress from normal finishing processes, such as peening, have a detrimental effect on SIR test results; (2) determining optimal fixturing and test parameters for SIR disk inspection; (3) improving a previously developed defect recognition algorithm (DRA) and investigating other automated concepts; and (4) developing a conceptual prototype design and an implementation plan. To achieve these objectives, the researchers formed a team led by Florida Turbine Technologies (FTT), an engine OEM, a commercial airline, and Sandia National Laboratories. This program built upon a previous FAA-funded phase and benefited from a related program sponsored by the US Air Force (USAF), which resulted in the development of an SIR production system for the automated inspection of engine airfoil blades. Results from this phase indicate that SIR's ability to detect cracks was not negated by the presence of a localized residual stress field from shot peening. This was demonstrated using both cracked low-cycle fatigue (LCF) test coupons and a retired USAF engine rotor, which contained actual service-induced cracks and evidence of prior shot peening. An experimental effort was conducted to assess SIR testing variables that had not been previously investigated. This task focused on the variables inherent in the testing setup, such as excitation location and orientation of the sonic exciter. The DRA software developed cooperatively with the USAF was improved by this program with sophisticated signal processing and a display that aids inspector decision making. A conceptual design for a prototype disk inspection system was produced. The design includes a graphic representation of the prototype system, robotic manipulators, and fixturing concepts suitable for a variety of disks found in the production environment. Along with the conceptual design, a field implementation plan was also developed.

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LIST OF ABBREVIATIONS AND ACRONYMS

3D	Three-dimensional
AFB	Air Force Base
CIS	Cold Image Subtraction
DOE	Design of Experiment
DRA	Defect Recognition Algorithm
ECI	Eddy Current Inspection
EDM	Electro Discharge Machined
EDRA	Enhanced Defect Recognition Algorithm
FAA	Federal Aviation Administration
FPI	Fluorescent Penetrant Inspection
FTT	Florida Turbine Technologies
HPT	High Pressure Turbine
IR	Infrared
LCF	Low Cycle Fatigue
LWIR	Long Wave Infrared
MRO	Maintenance, Repair and Overhaul
MSR	Monthly Status Report
MWIR	Mid-wave Infrared
NDE	Nondestructive Evaluation
NDT	Nondestructive Testing
OD	Outside Diameter
OEM	Original Equipment Manufacturer
PCA	Principal Component Analysis
PCRT	Process Compensated Resonance Tomography
ROI	Region of Interest
SIR	Sonic Infrared
SVD	Singular Value Decomposition
SWIR	Short Wave Infrared
TRL	Technology Readiness Level
USAF	United States Air Force

EXECUTIVE SUMMARY

This program addressed key technical challenges associated with the use of the sonic infrared (SIR) nondestructive evaluation (NDE) method on turbine engine disks as a potential alternative to fluorescent penetrant inspection (FPI). The program began with the reconfiguration of the Phase I SIR breadboard system to allow evaluations of improved part fixturing and sonic excitation setups. Fixture configurations ranged from rigid clamping, to simply supported, to fully suspending the part, with each in several orientations. Excitation arrangements varied in location, direction, and coupling between the part and the ultrasonic driver. These setup studies included several disk sizes and geometries. This included two PW2037 high pressure turbine (HPT) disks retired on cyclic life, a JT8D HPT disk with blade attachment cracks and modified in the previous phase to include artificial defects, and an F101 compressor 1-2 fan rotor having field cracks in the blade attachments.

Several improvements to the Defect Recognition Algorithm (DRA) signal analysis methods were developed and demonstrated. Building upon earlier developments, these alternate post-processing methods were coded and tested using inspection results from several of the subject disks.

The impact of residual compressive stress on the effectiveness of SIR inspection had been a key concern. In this program, an experimental effort was conducted to investigate this concern using two approaches. For one, specimen tests were conducted to compare crack signals in fatigue specimens prepared both with and without shot peening. The other made use of a rejected engine rotor having field-generated (service induced) fatigue cracks in the shot peened blade attachment slots. Both efforts provided meaningful results; the shot-peened specimen tests showed no significant IR signal degradation relative to the baseline specimen with a crack of similar length, and the SIR inspection of the rejected rotor showed detectability of cracks in zones that had been processed with high-intensity shot peening.

Supporting this program was Delta Air Lines Technical Operations (Delta TechOps), which provided (1) the retired PW2037 HPT disks used during this program for SIR testing studies, and (2) insight of how a large engine overhaul facility might qualify and implement future SIR technology. Researchers from Sandia National Laboratories and Roll Royce also provided test parts and valuable insight throughout this project.

The completion of this program has successfully advanced the Technology Readiness Level (TRL) of the SIR method for engine disks from TRL 3 (Initial Feasibility) to TRL 4 (Integrated Components Tested in Laboratory Environment). Although significant development efforts still need to be conducted, results from this program indicate that no major technical hurdles remain which would prohibit the future use of SIR on engine disks.

1. INTRODUCTION.

1.1. PURPOSE.

Sonic Infrared (SIR) imaging is a relatively new nondestructive testing (NDT) method that has been advanced by academic institutions, industry, and government agencies over the past several decades. Laboratory tests have shown it to be a viable alternative to florescent penetrant inspection (FPI) to detect certain types of surface-breaking flaws in engine blades, vanes, and air seals. Recent programs have further demonstrated reliable crack inspection in blades -- both with and without surface coatings. The previous phase of this Federal Aviation Administration (FAA) program demonstrated the potential to use SIR testing on engine disks (Development of Sonic Infrared Inspection Technology for Nondestructive Evaluation of Critical Aircraft Engine Rotating Components, 2017). This phase of the program advanced the previous investigations to: 1) identify potential reliability issues; 2) optimize the test setup, 3) improve defect detection capabilities and 4) identify and work towards maintenance, repair, and overhaul (MRO) shop implementation.

1.2. BACKGROUND.

SIR testing has emerged from being a laboratory curiosity to a practical NDT methodology for various turbine engine overhaul applications. This evolution is due to efforts within the research community, the FAA, the USAF, and the aircraft-engine and the industrial-gas-turbine OEMs and their suppliers. While the first basic programs investigating SIR inspection capabilities were being administered by the FAA and USAF, Siemens Energy was developing and implementing several variants of SIR testing (also referred to as Acoustic Thermography or AT) for use in their power-generation turbine-overhaul facilities.

Under contract with the Air Force Research Laboratories (AFRL) in 2012, Siemens and Florida Turbine Technologies (FTT) collaborated to develop a prototype SIR inspection system for aircraft engine blades (Sonic IR NDE Validation for Engine Blades, 2012). This semi-automatic system was completed in 2015 and successfully demonstrated at the USAF engine depot at Tinker AFB. Focused on both achieving better inspection reliability and reducing cost, the USAF engine depot at Tinker AFB commissioned the development of an automated SIR system for production inspection of engine blades in 2014. The first system was delivered in late 2017 and is currently supporting a trial lot study and training of inspection personnel (Automated, Integrated Inspection System, 2014) (Automated, Integrated Inspection Station (AIIS), 2017).

In parallel with the Air Force program, in 2013 the FAA Hughes Technical Center launched a phase 1 program to investigate the use of SIR for inspection of critical rotating parts, such as disks and rotors. That program successfully demonstrated the basic capability of SIR to inspect engine disks, pioneered methods of inserting artificial defects which mimic the response of cracks during SIR testing, and developed the first of a series of defect-recognition algorithms (DRAs) able to provide signal disposition automatically and improve reliability (Development of Sonic Infrared Inspection Technology for Nondestructive Evaluation of Critical Aircraft Engine Rotating Components, 2017).

Based on encouraging results from the preceding SIR disk inspection studies, in 2016 the FAA funded this phase of the program, to expand upon the earlier technical efforts as well as to further collaborate with industry and government, to implement a highly capable and reliable inspection method for critical rotating components (Sonic Infrared Inspection of Critical Rotating Engine Components, 2016).

1.3. OBJECTIVE.

The overall goal of this program is to develop an SIR inspection method for engine disks to replace FPI with a more reliable, environmentally friendly, faster, and cheaper crack-inspection method that can also compliment eddy-current inspection (ECI), by detecting surface-breaking low-cycle fatigue (LCF) cracks in instances where part geometry would prohibit ECI.

In order to advance the SIR technology toward this goal, the following objectives were identified:

- Determine whether a residual compressive-stress field might reduce or negate the vibratory SIR response of a crack and its accompanying IR signal that is used to detect the flaw.
- Investigate various SIR setup options and parameters including part fixtures, excitation orientation, coupling, and excitation energy to determine optimal conditions for each.
- Refine the Defect Recognition Algorithm (DRA) software developed in the preceding program to more reliably detect and notify the inspector of crack-like defects for further disposition.
- Incorporate the optimal setup parameters into an SIR conceptual design that would be able to accommodate a variety of engine disk sizes and configurations.
- Develop an SIR implementation plan in consultation with a jet-engine MRO facility.

1.4. APPROACH.

During this two-year phase, a team consisting of Delta TechOps, Rolls Royce, and Sandia National Laboratories was used to review various aspects of the project. In addition to retired test parts, Delta TechOps and Rolls Royce provided valuable industry insights and perspectives from a potential airline user and an engine OEM, respectively, while Sandia National Labs aided with additional test parts and independent SIR testing.

To accomplish the stated objectives, a series of five technical tasks were established. These tasks, numbered 2-6, were in addition to routine program management and reporting which were numbered as tasks 1 and 7, respectively.

Task 2 focused on formulating the requirements for an engine-disk SIR inspection system that would later be used as the framework for the system conceptual design. Candidate engine disks which served as relevant test articles during later investigations were also identified and obtained during this task.

In Task 3, the breadboard SIR testing system that was constructed during the previous phase was reassembled and tested to show that crack-detection sensitivity had not changed. Results during this task were used as a performance baseline upon which subsequent SIR setup parameters and system modifications would later be assessed.

The effects of residual surface-compressive stresses on SIR testing were investigated in Task 4 to determine whether the effect could preclude the use of SIR testing in certain scenarios. An experimental approach was taken that included the use of specimens and a cracked disk to evaluate the impact of shot peening on crack detection.

Task 5 focused on exploring variables in the execution of SIR inspection. This included a subtask to make setup changes to the breadboard inspection system in order to assess the effects of part fixturing, excitation location and orientation, and excitation intensity parameters and coupling. A second subtask experimentally evaluated likely automation subsystems such as rotary tables to manipulate parts, and robotic arms to position the IR camera. Another investigated numerical methods to improve the defect-recognition algorithms (DRA). A final subtask task was to prepare a conceptual design of a prototype disk inspection system based upon the results of the other subtasks.

Task 6 was to develop an implementation plan by collaborating with Delta TechOps in order to gain insight into the operational requirements for the introduction of new inspection methods, such as SIR, into an MRO jet-engine facility.

2. DISCUSSION.

2.1. TASK 1: PROJECT PLAN AND MEETINGS

2.1.1. Kickoff Meeting and Periodic Program Review Meetings

Throughout the program, annual on-site review meetings were held at the FTT facility in Jupiter, Florida. A kickoff meeting was held on 19 January 2016 in which the agenda included a detailed discussion about the statement of work, a review of the detailed project plan, plans for MRO involvement, and a facility tour which included a demonstration of various SIR inspection systems. The meeting was attended by representatives from FTT and the FAA Hughes Technical Center.

A first-year review meeting was held on 24 January 2017, which included a progress-report presentation as well as a demonstration of the USAF automated blade-inspection module, which was undergoing NDT reliability demonstrations in preparation for delivery to Tinker AFB. In attendance were representatives from FTT, the FAA Hughes Technical Center, Sandia National Labs, Delta TechOps, and Rolls-Royce Corp.

A final program review was held on 23 January 2018. In addition to a technical review of the past year’s activity, SIR demonstrations and inspection trials were conducted on the prototype setup-modified breadboard system. In attendance were representatives from FTT, the FAA Hughes Technical Center, and Sandia National Labs.

2.1.2. Detailed Project Schedule.

A detailed project plan and schedule were prepared and reviewed during the program kickoff meeting. Figure 1 shows the as-executed project schedule and includes a task, described in Section 2.4.3, which was added during year two to evaluate the effects of variables on SIR testing.

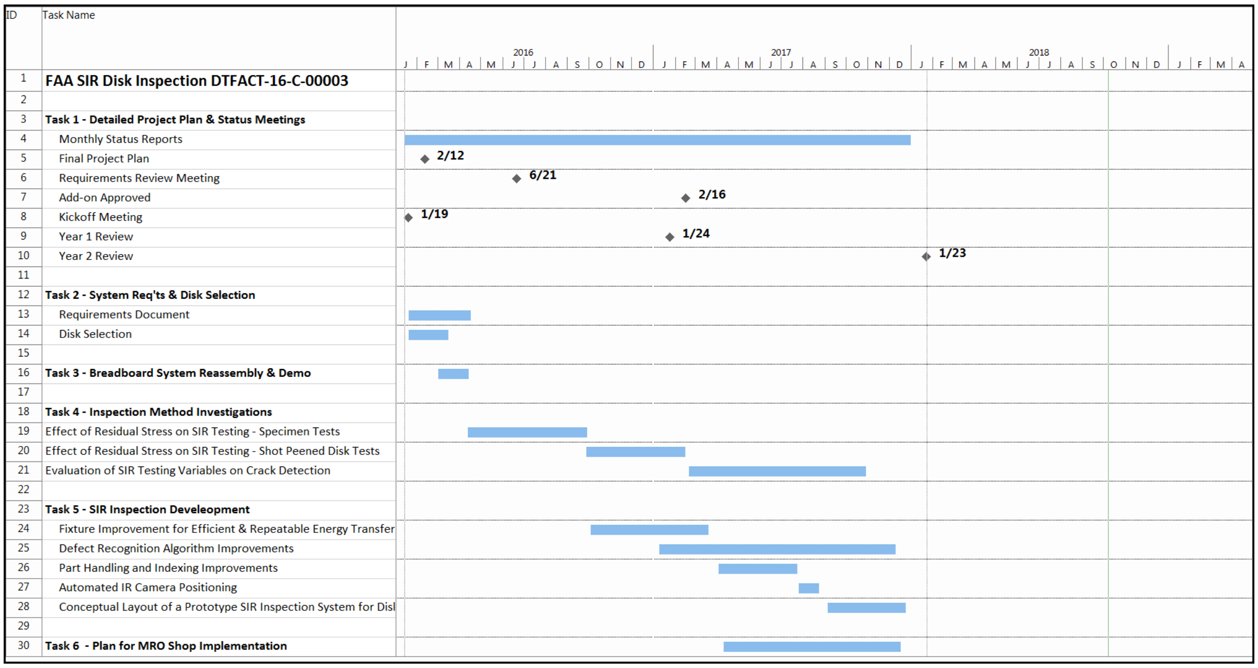

FIGURE 1. AS-EXECUTED PROGRAM PLAN

2.2. TASK 2: SYSTEM REQUIREMENTS AND SELECT ENGINE DISK OF INTEREST

2.2.1. System Requirements Document.

A draft version of the "System Requirements" document for the SIR prototype disk-inspection system was prepared and distributed for initial comments early in the program. It was intended to be a "living" document that was to be updated throughout the program. The document was modeled after the system-requirements document that FTT developed for the USAF blade-inspection system. This document specified required functionality and major components in the production-inspection system, as well as compliance to the guidelines set forth in the ASTM Standard E3045-16, "Standard Practices for Crack Detection Using Vibrothermography" (Standard Practice for Crack Detection Using Vibrothermography). For the FAA program, the requirements document became the basis for the prototype system conceptual design prepared in Task 5. The requirements document was periodically updated and distributed for review to the technical experts within FTT, the FAA, USAF, and airline MRO (Delta TechOps) engineers.

2.2.2. Focus Disk Selection.

Two "timed out" PW2037 turbine disks were provided by Delta TechOps to serve as the "focus" disk for this program. One of these disks is shown in Figure 2. This turbine disk is fabricated from a Pratt & Whitney proprietary powder metallurgy super-alloy, MERL 76, and weighs approximately fifty pounds. This disk design is typical of other commercial turbine disks, being approximately twenty-two inches in diameter by six inches thick, with a multitude of blade slots and other complex features. For these reasons, they were considered good choices by the research team as focus disks, with the exception that neither disk had been inspected at retirement, and subsequent SIR inspections found no service-induced field cracks. FPI inspection was planned to verify this finding but was not done due to the availability of an F101 1-2 spool with field-induced cracks in the lugs.

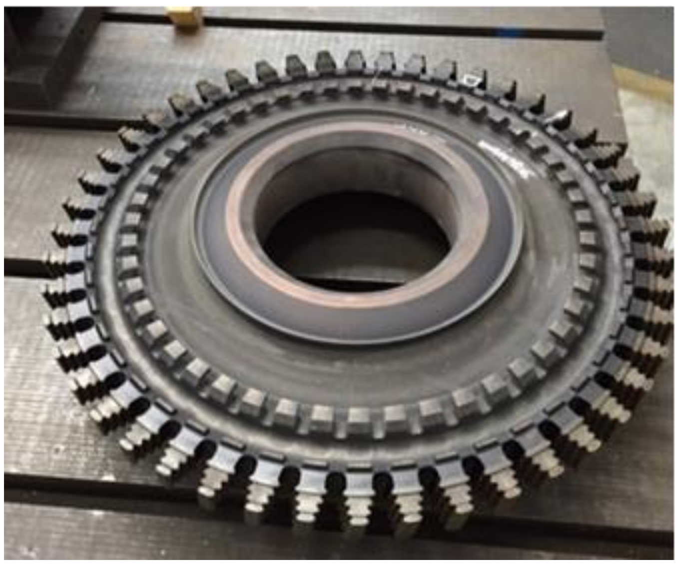

FIGURE 2. ONE OF TWO PW2037 HPT DISKS PROVIDED FOR SIR INSPECTION

2.3. TASK 3: RE-ASSEMBLE BREADBOARD SIR DISK INSPECTION SYSTEM

The breadboard system components from the previous FAA-funded phase were reassembled and tested. Figure 3 shows the breadboard system set up for inspection of the focus disk. The system consists of a bedplate, Branson exciter, FLIR 6700 series mid-wave IR camera, and multipurpose fixture tooling. The purpose of Task 3 was to repeat SIR tests using the same JT8D turbine disk from the prior program, which contained service-induced cracks and a variety of manufactured artificial defects. The test objective was to verify that the SIR sensitivity to detect these defects had not changed, so that the results could be used as a baseline for comparison to the alterations planned for Task 4.

FIGURE 3. SIR BREADBOARD SYSTEM SETUP

Figure 4 shows a comparison of IR signals obtained from a test during the phase 1 program and signals obtained from a test with the reassembled system. Tests were run with the same excitation conditions of duration, power, and pressure. IR signal strength from both natural and artificial defects was found to display similar heating and cooling characteristics as in past tests. Peak signal strengths, however, were generally higher, but for the most part considered within the range of typical test variability, due to slight variations of fixturing, viewing angle, and coupling with the ultrasonic exciter. The higher signal strength from the set-screw artificial defects also may be partly due to some loosening or wear in the thread interface, resulting in more motion and frictional heating.

The reassembled breadboard system was used as a basis for the verification of concepts and redesigns for more sophisticated prototype subsystems. It was also used to test specimens and the shot-peened disk in studies on the effect of residual stress. The breadboard system was later used to compare different excitation conditions and orientations in Task 4, and different fixturing variations explored in Task 5.

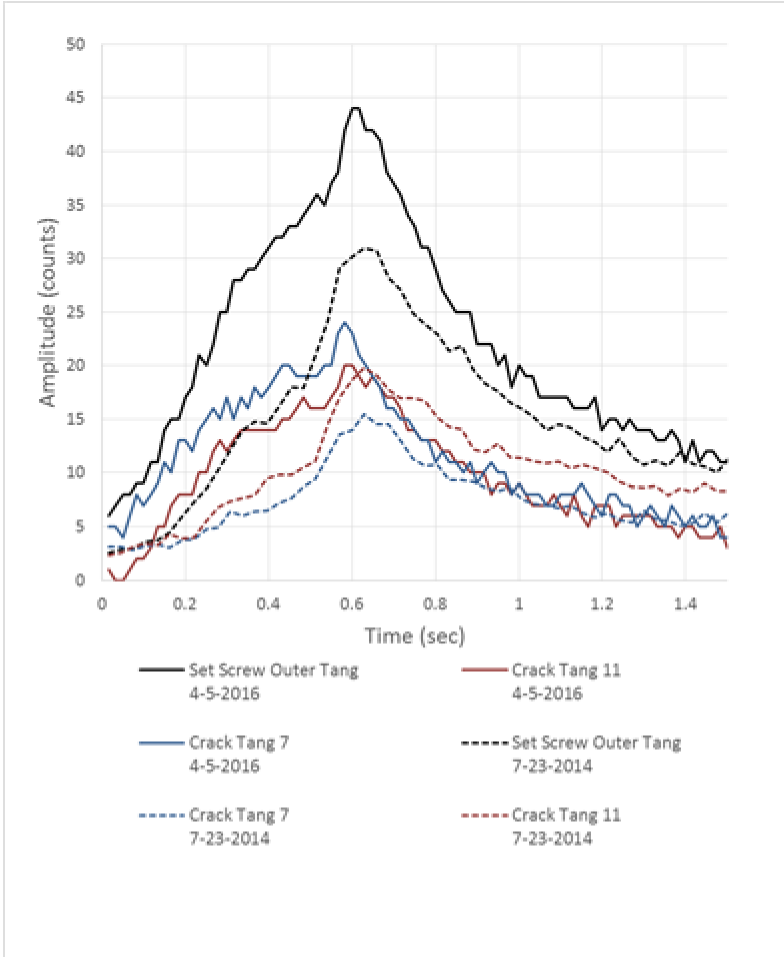

FIGURE 4. COMPARISON OF SIR RESULTS FROM JT8D DISK WITH CRACKS AND ARTIFICIAL DEFECTS

2.4. TASK 4: INSPECTION METHOD INVESTIGATIONS.

This task investigated one of the potential technical issues with using SIR for the inspection of engine disks. There has long been concern that residual compressive stress from mass media finish or similar processing could be high enough that ultrasonic excitation used during SIR might not displace crack surfaces enough to allow frictional heating. Possibly mitigating this concern, however, is some evidence that surface residual stress due to media finish can be significantly reduced from long-term service, before the component reaches the depot.

2.4.1. <u>Residual Stress Specimen Testing</u>

The initial plan to evaluate the effect of media surface finish on SIR results was to inspect INCO 718 specimens having the geometry illustrated in Figure 5 and cracked via 3-point bending as described by AMS 5663. Basic dimensions were three inches wide by six inches long by 0.25 inches thick. The specimens contained a gentle-radius, transverse notch that was intended to guide the initiation of cracks without the need for a pre-flaw. This approach was preferred since it most closely replicates the sequence leading to an in-service crack and would eliminate the need to machine away the pre-flaw, which would also remove the peened surface and the compressive stresses trying to close the crack. This approach was first tested on baseline specimens with no media finish and then executed successfully on specimens peened to a 4A intensity condition. The color contours in Figure 5 show how displacement and stress vary as the specimen is loaded in three-point bending. The goal was to produce specimens with a crack length of approximately 0.06 inch.

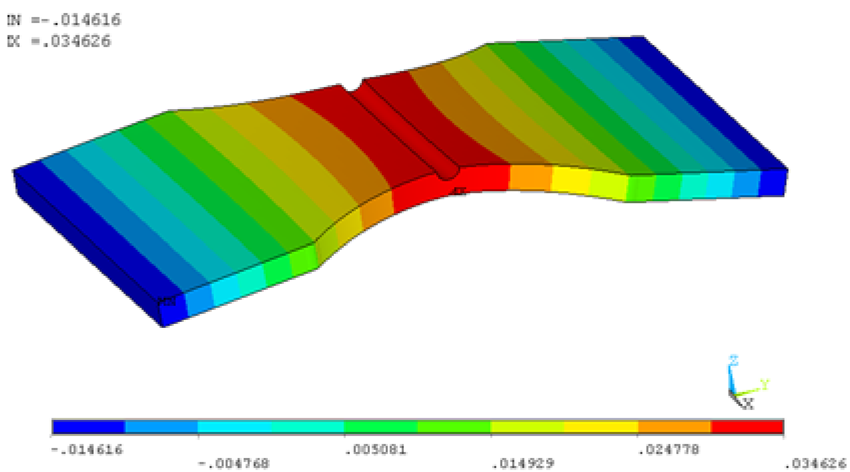

FIGURE 5. NOVEL FATIGUE SPECIMEN USED TO ASSESS EFFECT OF MEDIA FINISH

In addition to assessing the effect of localized residual stress due to peening, it was also the original intention of the research team to investigate what effect bulk residual stresses (due for example, from forging) had on SIR testing. For this purpose, a separate, unique test specimen was designed consisting of a small disk having a fatigue crack that was then press-fit into a larger flat rectangular test specimen. The small disk was cut from an unpeened coupon that was first subjected to three-point bending to produce a crack size of interest. The interference fit between the small disk and the rectangular specimen was to be sized to introduce radial compressive stresses onto the crack sample. Efforts to produce this type of coupon, however, were later discontinued due to several concerns, one being the ability to tailor the compressive fit reliably and to know whether the resulting stress field actually represented a bulk residual compressive stress field. For this reason, and because the research team was primarily interested in how surface residual stress from peening affected surface breaking fatigue cracks, the study concerning bulk residual stresses was abandoned.

Fifteen specimen pre-forms were fabricated, and five specimens were final machined to the configuration shown in Figure 5. Fatigue cracking of two unpeened baseline specimens began shortly thereafter at Martin MetLabs in Stuart, Florida. Figure 6 shows the fatigue machine used to conduct three-point bending. Although this lab has cracked approximately 1,000 NDT demonstration specimens, this design had never been tested.

It took significantly longer than usual to initiate a crack in the first specimen, serial number 1B, and it was 0.09 inches long before the test was stopped. With the process better defined, the next specimen, serial number 2B, was produced quickly to the goal crack length of 0.06 inch. The crack in each specimen appeared typical of a tight LCF crack in a nickel engine disk. Figure 7 shows a section of the crack in specimen 2B.

FIGURE 6. LCF TEST MACHINE USED FOR 3-POINT BEND CRACKING

The two baseline specimens were then evaluated using SIR testing to confirm that the cracks were detectable. After some initial fixture setup and parameter optimization, SIR was able to detect these cracks consistently. The SIR inspection equipment used to test the specimens is shown in Figure 8.

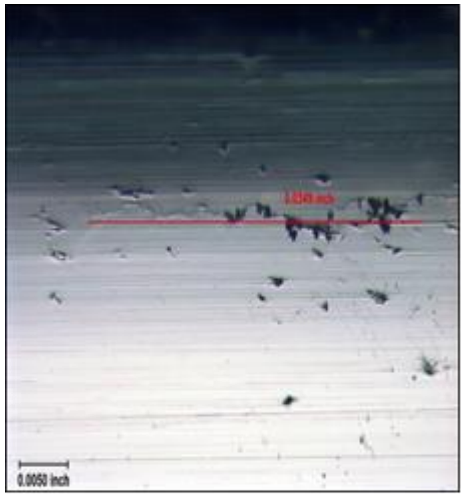

FIGURE 7. SECTION OF TIGHT LCF CRACK IN SPECIMEN 2B

It is important to note that the SIR setup and testing of a specimen such as the design shown in Figure 5 can be more difficult than testing actual engine hardware. Actual compressor blades and all engine disks tested to date have been relatively easy to excite using a Branson 20kHz ultrasonic welder; however, due to geometry and fixturing methods, flat-plate specimens, such as these residual stress specimens, are often more difficult to excite ultrasonically. From this observation, two points can be made: (1) it is first necessary to conduct an initial inspection feasibility study of any not previously tested with SIR; and (2) results and trends from geometrically simple specimen testing may not easily translate to actual complex parts. The NDT community is used to working with subcomponent specimens that typically provide similar responses to those of actual parts, but this is likely not the best practice when evaluating the reliability of SIR testing.

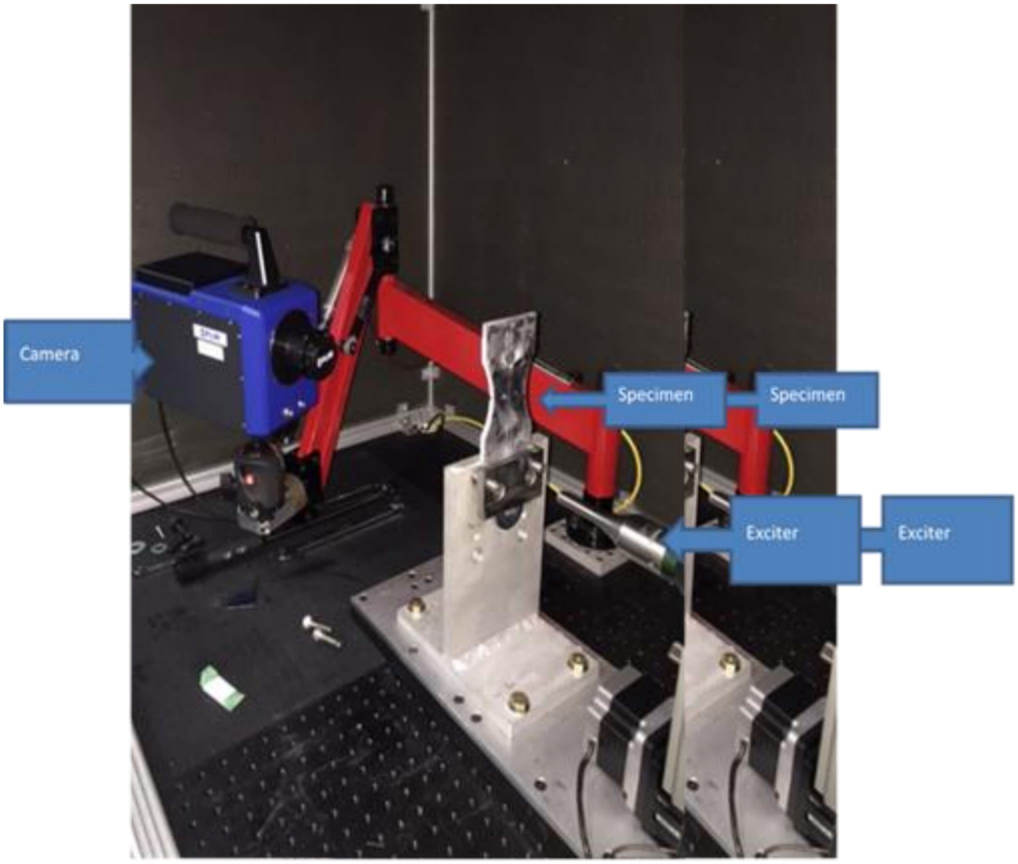

FIGURE 8. SIR TEST SET-UP FOR SPECIMENS

After the optimization of the SIR testing parameters, images of the baseline cracks were recorded for later comparison with images from cracks in peened specimens 4P and 5P. Figure 9 shows the SIR image of the crack in specimen 2B with the IR background subtracted, while Figure 10 shows the same crack using SIR and the DRA software developed during the phase 1 program. In addition to the crack image, IR reflections can be seen from the shiny surfaces adjacent to the crack.

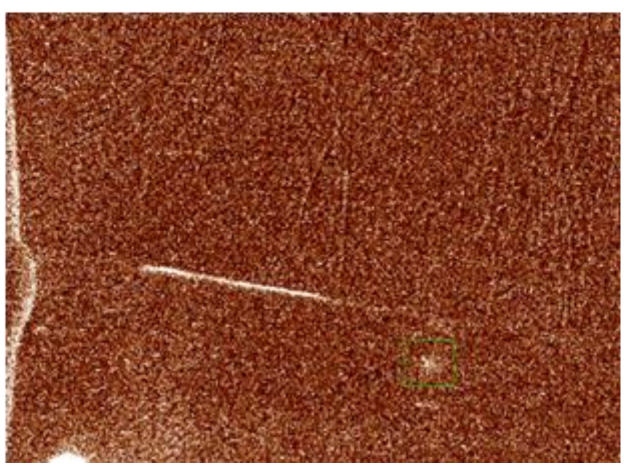

FIGURE 9. SIR INDICATION FROM 0.060 IN. CRACK IN BASELINE SPECIMEN 2B

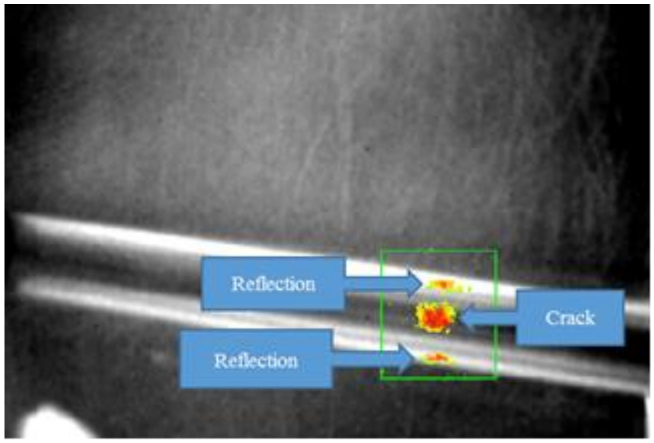

FIGURE 10. SIR INDICATION FROM 0.060 IN CRACK IN SPECIMEN 2B USING DRA

Peened and cracked specimens were characterized visually and with FPI. Figure 11 shows one of the FPI indications confirming the presence of a fatigue crack in the shot peened surfaces.

Specimen 5P cracked in two places along the notch. SIR indications of these fatigue cracks in the shot peened surface are shown in Figure 12.

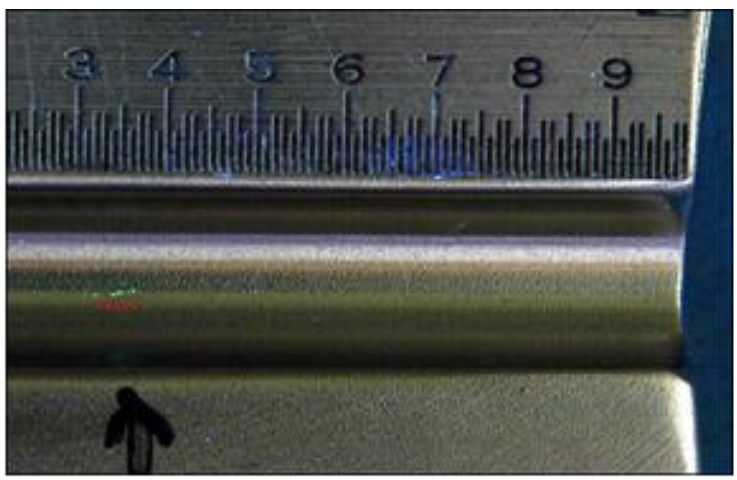

FIGURE 11. FPI INDICATION FROM 0.055 IN. LONG CRACK IN PEENED SPECIMEN NO. 40

A comparison of SIR signals from specimens tested with identical setup parameters is summarized in Figure 13. No significant difference was noted between the peened and the baseline cracks. For example, signal history for the cracks in specimens 1B and 2 were ultimately toward the upper and lower end of the amplitude spread, respectively. These specimens made up the baseline tests and were not peened. Signals from the cracked and peened specimens, 4, 5A, and 5B, were mixed with the baseline test signals, as one would assume if the peen made no difference. Although this finding is based on a very small sample size, the results indicate that shot peening does not necessarily impair crack detection by SIR.

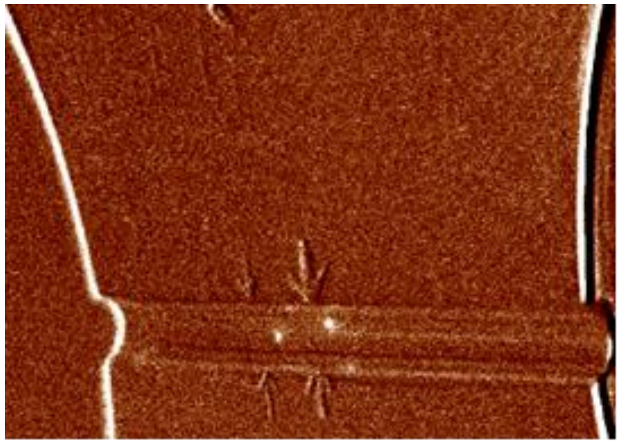

FIGURE 12. CRACKS IN PEENED SPECIMEN NO. 5P; 0.031 IN. (LEFT) AND 0.055 IN. (RIGHT)

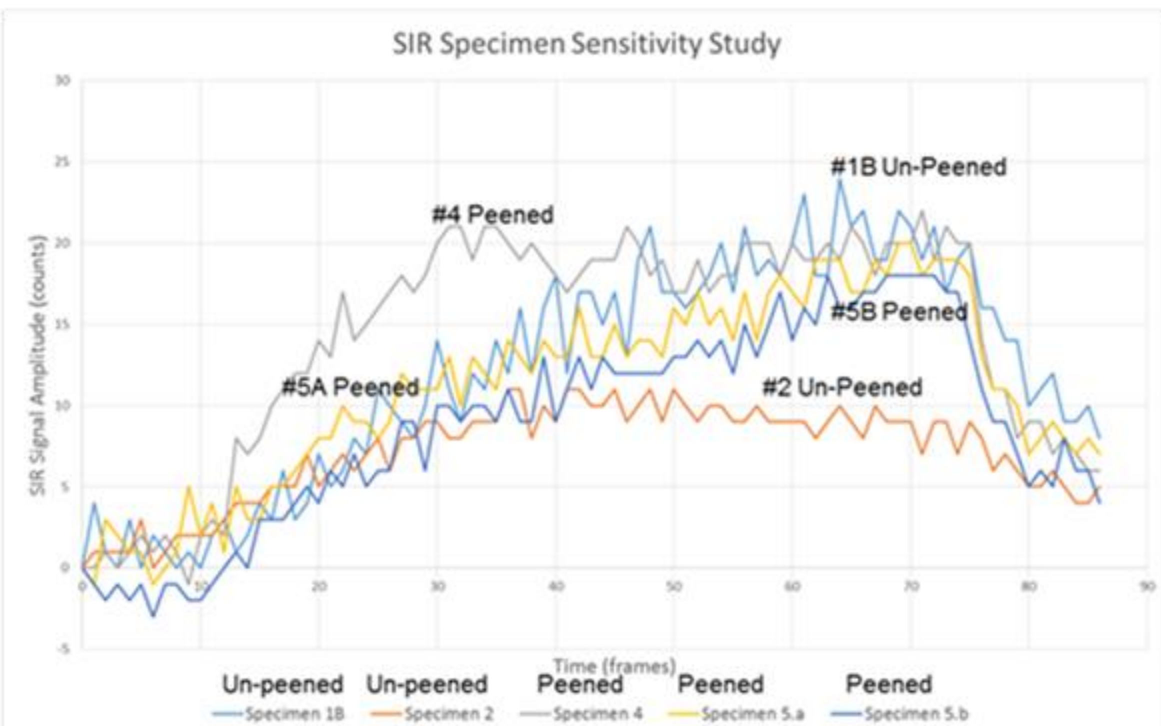

FIGURE 13. COMPARISON OF IR SIGNALS IN BASELINE AND SHOT PEENED CRACK SPECIMENS

2.4.2. Impact of Shot Peen on Disk Testing

In collaboration with the USAF jet-engine depot at Tinker Air Force Base, a field-cracked disk from an F101 engine was made available to this program. This 1-2 compressor spool has blade-attachment slots that were shot peened during manufacture, as indicated in the drawing note shown in Figure 14. The photo shown in Figure 15 indicates that this was, in fact, shot peened, as demonstrated by the wrinkled surface appearance typical of shot peening. Experimental measurement of remaining residual stress by x-ray diffraction or other nondestructive methods was not conducted.

AFTER DEBURRING AND FLUOR PENETRANT INSP. SHOT PEEN PER P11TF8 CL-B (METALLIC SHOT·PEENING FOR CRITICAL APPLICATIONS) AS FOLLOWS:

A) ENTIRE PART INCLUDING HOLES EXCEPT AREAS W (C17) USING S-110 CAST STEEL SHOT WITH A DIRECT IMPINGEMENT ANGLE OF 35° MINIMUM. EXCEPT AREAS SEE VIEW DU (H12) WHERE RICOCHET PEENING IS ALLOWED.

B) 100 PERCENT MINIMUM COVERAGE REQUIRED ON ALL SURFACES TO BE PEENED. OVERSPRAY IS ALLOWED EXCEPT IN AREA W (C17). VERIFY COVERAGE PER P3TF23 CL-A

C) THE SYMBOL "-----" INDICATES AREAS WHERE VERIFICATION OF .004A-.010A INTENSITY IS REQUIRED USING SCRAP PART FIXTURE. SEE VIEW CS (A19)

D) IN AREA TO BE PEENED, BREAK EDGES .005-.015

E) SURFACE FINISH APPLIES BEFORE SHOT PEENING

F) CURE THE COATED PART AT 400° F ± 25° F IN A PREHEATED OVEN; MINIMUM CURE TIME FOR ANY AREA SHALL BE 60 MINUTES, MAXIMUM ACCUMULATED CURE TIME FOR ANY AREA SHALL BE 150 MINUTES

FIGURE 14. DRAWING NOTE C INDICATES PEEN INTENSITY RANGE

This compressor spool represents the best-possible test scenario to assess the impact of media finish on SIR capability; that is, an actual engine part with significantly peened features and field-generated cracks in those features. The spool is shown in Figure 16 as it is being readied for testing on the breadboard system. The spool was fixtured using three nylon support pads and constrained by three nylon-capped tooling clamps. Initial testing showed significant SIR indications from cracks in the peened zones of the disk, and Figure 17 shows two cracks detected in adjacent slots during the same inspection.

FIGURE 15. PHOTO OF BLADE SLOT REVEALS SIGNIFICANT DISTURBED METAL

Test results from both the coupon specimens, and the retired USAF disk, clearly showed that in these cases, shot peening of the surfaces did not impact the crack-detection capability of SIR testing.

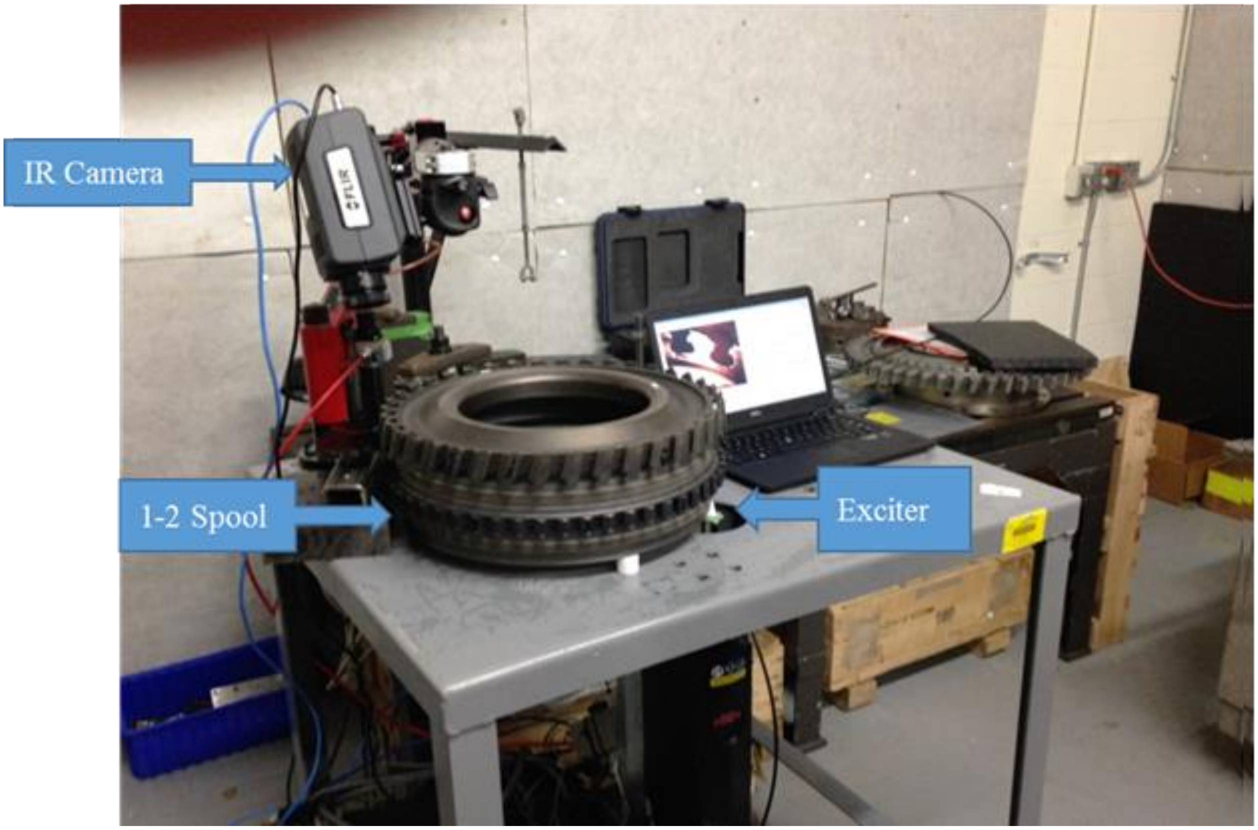

FIGURE 16. COMPRESSOR SPOOL ON MODIFIED BREADBOARD SYSTEM

Based on this demonstrated ability to detect cracks in the shot peened 1-2 compressor spool, the specimen-testing approach to answer this question was considered less relevant due to the uncertain applicability to actual parts. Further investigation of the spool continued throughout the program, and particularly during the Task 2.5 studies.

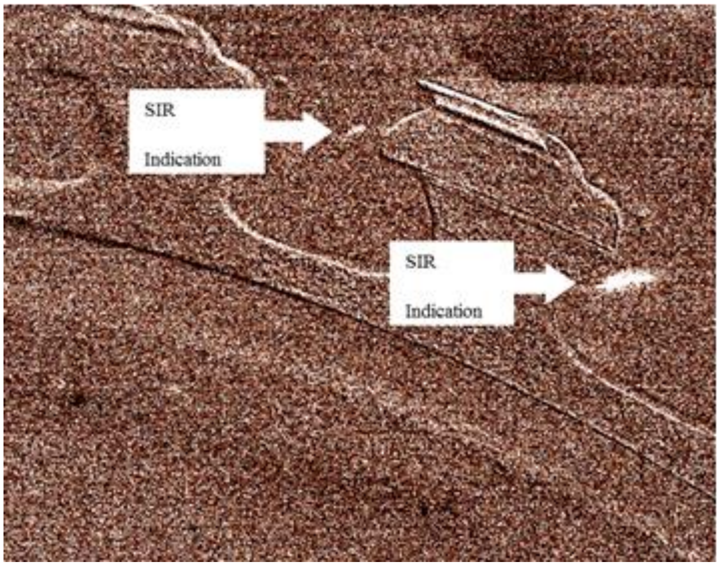

FIGURE 17. SIR INDICATIONS ON TWO ADJACENT BLADE SLOTS

2.4.3. Evaluation of SIR Testing Variables on Crack Detection in Disks

The intent of this task was to assess the robustness of the SIR inspection processes with respect to several variables that might have a significant influence on crack detection. Down-selection of variables resulted in fifteen experimental variants.

The task was originally planned to be conducted using specimens, but after obtaining the F101 engine spool, it was decided to use this field-cracked part instead. The variables investigated included coupling between the Branson ultrasonic welder and the part, the location of the excitation, and the orientation of the ultrasonic excitation.

A test plan was formulated that stipulated the number of repetitions for each test and the data to be recorded. A detailed protocol was established and closely followed during testing to assure valid comparisons of the stated testing variables. The experimental setup on the breadboard system is shown in Figure 18. Due to the part geometry, however, radial excitation was possible only from the dead-rim (top of attachment lug) and the live-rim (bottom of blade slot) locations. As testing progressed, there were other instances where the protocol had to be violated in order to accomplish the full test program. Those instances were noted but results from those tests did not change any conclusions.

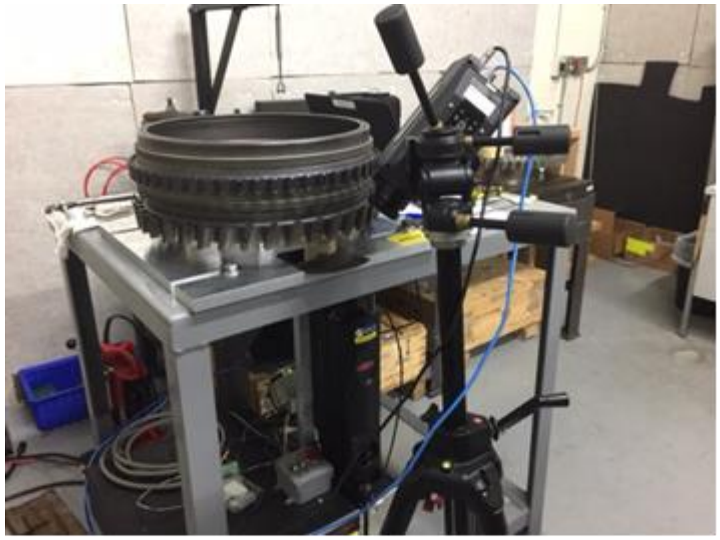

FIGURE 18. F101 1-2 COMPRESSOR SPOOL DURING SIR VARIABLES TESTING

A summary of the various test conditions that were evaluated in accordance with the design of experiments (DOE) plan are shown in Table 1. The various “Deg.” listings indicate the circumferential position around the disk rim from the attachment-slot crack of interest (“Slot 7”), where the ultrasonic welder contacted the disk. Ten repetitions of nominally identical tests were run for each condition.

TABLE 1. TEST PLAN FOLLOWING DOE FORMAT

Radial Excitation 180 Deg. @ Attachment Post
1. Direct to Disk (10 repeats)
2. Card Stock Interface (10 repeats)
3. Nickel Plate Interface (10 repeats)
Axial Excitation 180 Deg. @ Disk Rim
4. Direct to disk (10 repeats)
5. Card Stock Interface (10 repeats)
6. No Test
Axial Excitation 180 Deg. @ Disk Bore
7. Direct to disk (10 repeats)
8. Card Stock Interface (10 repeats)
9. No Test
Axial Excitation 90 Deg. @ Disk Bore 10. Direct to Disk (10 repeats)
11. Card Stock Interface (10 repeats)
Axial Excitation 90 Deg. @ Disk Rim
12. Direct to disk (10 repeats)
13. Card Stock Interface (10 repeats)
Radial Excitation 90 Deg. @ Attachment Post
14. Direct to disk (10 repeats)
15. Card Stock Interface (10 repeats)

Under the first set of conditions, a small nickel-plate interface was used for coupling between the Branson horn and the disk. Shown in Figure 19, it consisted of a flat plate in contact with the dead rim surface of a disk post, held in place by bolts threaded into two modified blade roots, which were installed in the adjacent slots. Results from this fixture were disappointing, however, as too much excitation energy was apparently dissipated by friction within the fixture and surfaces in contact with the disk. For this reason, the use of the nickel-plate coupling interface was dropped from further matrix testing.

From prior SIR research, card-stock coupling has been found to be a simple and effective method of avoiding direct contact between the Branson horn and disk, with minimal dissipation of excitation energy. In these tests, the card stock was held in place with tape, but card-stock caps fit over the horn tip were also considered. The experience with card stock has been that it takes one or two excitation cycles to “break in” and become compressed. Once broken in, the card stock usually lasts another 10 to 15 cycles before becoming charred, brittle, and no longer useable.

FIGURE 19. NICKEL PLATE COUPLING FIXTURE ON F101 1-2 SPOOL

In SIR testing, direct coupling between the horn and a part was usually avoided out of concern for damaging a part, but with disks, contact at the disk post dead rim is considered acceptable, since there is no operating stress in that location.

An automated process for system setup and data acquisition was used for the experiments, with relevant testing parameters shown in Table 2. Where applicable, parameters were held constant across the different test conditions.

TABLE 2. F101 1-2 SPOOL SIR DOE TEST PARAMETERS

Test Procedures & Parameter Variables:
- Number of tests – 10 to 12 sequentially
- Wait Time – 30 sec between tests
- Branson Amplitude – 80%
- Branson Excitation time – 1.25 sec
- Branson Pressure – 8, 10.5, 11 & 11.5 psi for Radial Input and Axial Inputs
- Branson Hold Time – 1.5 sec
- Branson Trigger – 4.5 sec
- Branson Speed – 50%

Test result are given in Figure 20 with the average IR signal from 10 repetitions plotted for each of the 15 experimental conditions. For the F101 1-2 compressor spool, radial excitation 180 degrees away from the crack produced the strongest signal. This result was unexpected, as most disk inspections to date have been with axial excitation, with horn contact closest to the region of interest. Not surprising was that direct contact between horn and part produced the highest IR signal, with card stock showing to be slightly less effective, but better than the nickel plate fixture. An overall conclusion to be made from these tests is that the best setup may not be intuitive, and that a parameter-optimization study should be conducted for each specific part number.

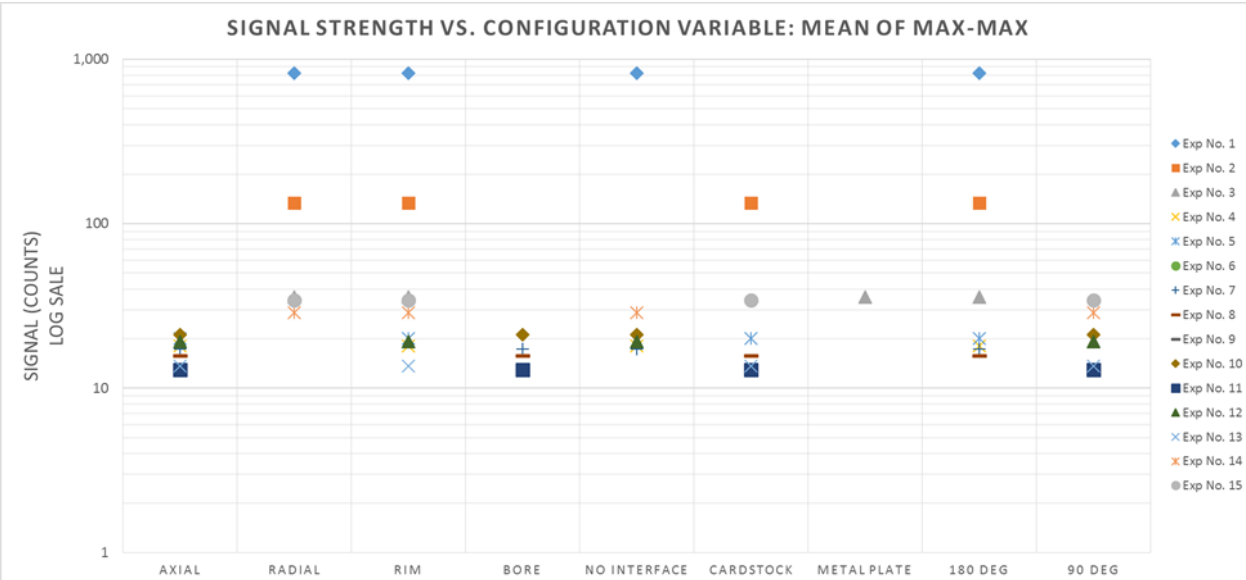

FIGURE 20. SIR VARIABLES TEST RESULTS

The images in Figure 21 provide a visual comparison of the relative strengths of the signals when interface materials are varied. While the metal plate was determined to be an impractical approach, the results did indicate that hard coupling will work, but further development of such devices is needed to reduce unwanted energy dissipation.

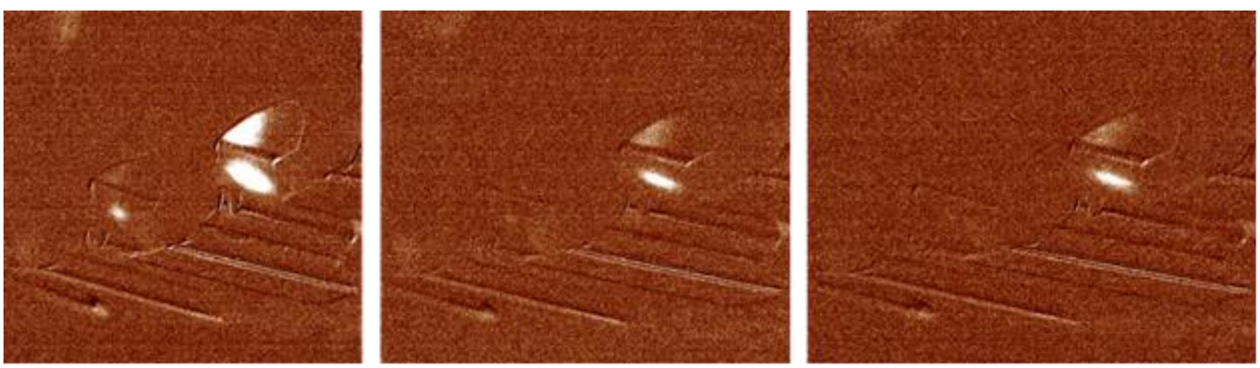

FIGURE 21. SAME CRACK WITH (L TO R): DIRECT, CARD-STOCK AND NI-PLATE CONTACT

2.5. TASK 5: SIR INSPECTION-SYSTEM DEVELOPMENT

The purpose of this task was to assemble a reasonably diverse set of test components and fixture variations, and then conduct experiments to guide the general configuration of a prototype SIR system for disk inspection.

2.5.1. Artificial Defects in Focus Disks

The two timed-out PW2037 1st stage HPT disks provided by Delta TechOps were to be used to test feasibility and versatility of various system configurations. Neither of these retired disks was found to have any field cracks, so artificial defects were needed. Due to the anticipated difficulties of drilling and tapping set-screw-type defects (such as those used during phase I) into the difficult-to-machine MERL 76 material disk, an alternate method using press fit pins as artificial defects was attempted. One of the disks was modified with a group of pins, 0.078 inches in diameter, and pressed into EDM drilled holes with a 0.001 tight interference fit. After installation, any remaining pin material was ground off, to be nearly flush with the disk surface. Shown in Figure 22, these defects were placed at seven different locations: the bore ID, the bore axial face, the bolt flange, the integral arm ID, the outer web surface, the bottom of the fir tree slot, and in the axial face of the fir tree.

FIGURE 22. PW2037 DISK PRESS FIT PIN LOCATIONS

During SIR testing, however, none of the press-fit pins showed any significant heating due the ultrasonic excitation. This is shown in Figure 23 and is contrasted by the pieces of polymer tape, which did heat up. Although press-fit pins had been used successfully in blades and has demonstrated long-term stability for use as setup standards, it seems likely in this case that the interference fit was too tight or there was too much surface contact to permit any significant slippage and heat generation during ultrasonic excitation. Programmatic constraints prevented an iteration or further efforts to develop this type of artificial defect for installation in the PW2037 disks, so subsequent tasks were revised to make use of disks that already had field cracks or effective artificial defects.

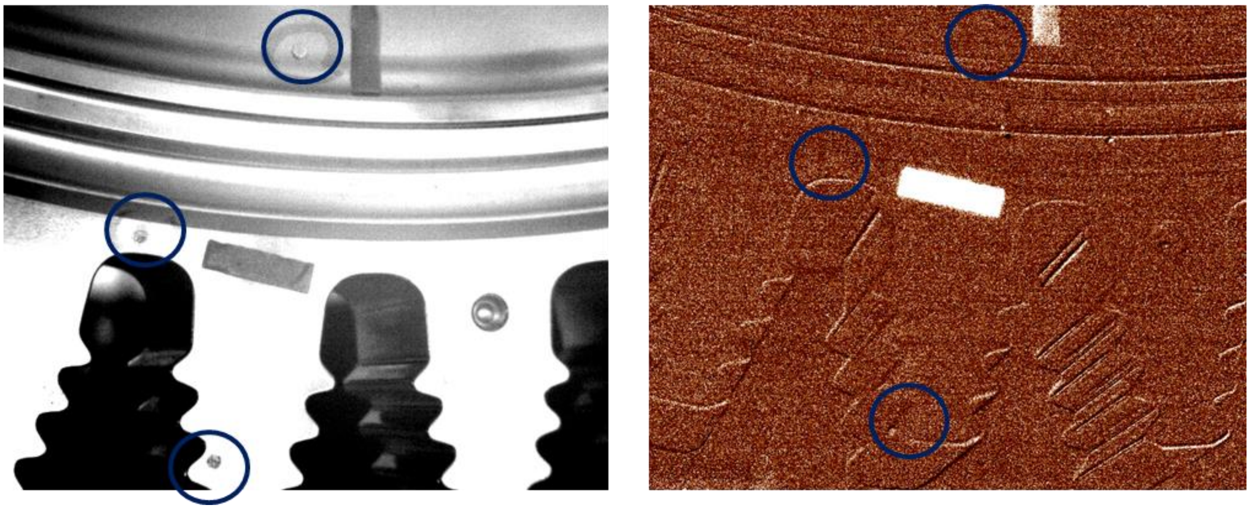

FIGURE 23. PHOTO AND SIR IMAGES OF PW2037 HPT DISK SHOWING PRESS-FIT PIN ARTIFICIAL DEFECTS AND POLYMER TAPE

2.5.2. <u>Disk-Inspection Fixture-Improvement Studies</u>

A series of experiments was conducted to evaluate various fixture and excitation concepts. In some cases, testing of the PW2037 turbine disk was replaced with either the JT8D turbine disk or the F101 1-2 compressor spool, since they had either real cracks or artificial defects. Modifications were again made to the breadboard system for seven different setups:

1. Setup 1 was performed with the system in its basic configuration from the previous program. The disk was mounted in a chuck with the axis of rotation vertical and the Branson excitation radial. Both PW2037 disks were inspected with this setup.
2. Setup 2 used a "hanging-disk" approach in which the PW2037 disk was suspended by rope, with the axis of rotation horizontal and with axial excitation. A support frame was required to react against the Branson pressure in order to keep the disk relatively stationary.
3. Setup 3 was the same as Setup 2, except that it was built on a different bedplate that was more adaptable to numerous disk scenarios.
4. Setup 4 used the hanging-disk approach, with the axis of rotation horizontal, but with improved lateral restraint. Excitation was in the axial direction.
5. Setup 5 used a table with the Branson welder mounted vertically underneath, and the JT8D disk set on and clamped to three nylon posts, in order to provide axial excitation.
6. Setup 6 was another hanging concept, but with the JT8D disk axis of rotation vertical and the excitation axial.

7. Setup 7 was similar to Setup 5, with the test article changed from the JT8D disk to the F101 1-2 spool.

2.5.2.1. Disk SIR System Setup 1

Setup 1consisted of one of the PW2037 disks mounted in the breadboard SIR system with a center-chuck (3 posts with plastic inserts in contact with the disk bore) securing the disk bore to the table, as seen in Figure 24. The Branson exciter horn was set up to dynamically impact in the radial direction on the top of a blade-attachment post using a card-stock interface. The IR camera was positioned to capture IR signals from angular sectors of the disk. To inspect the next sector, the center chuck was loosened, and the disk manually rotated to the next segment.

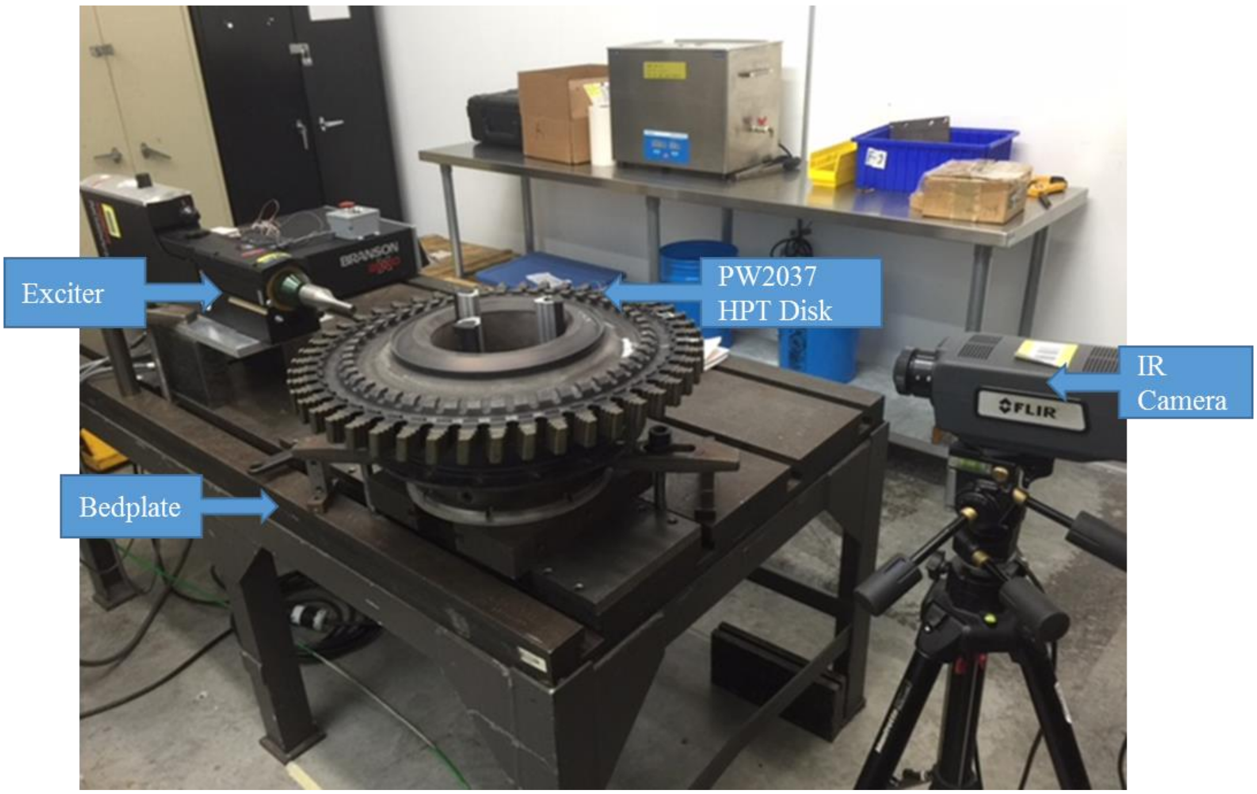

FIGURE 24. SIR BREADBOARD SETUP 1 WITH PW2037 HPT DISK 1

The Branson excitation parameters were initially set to levels used in the phase 1 program on the assumption that the PW2037 disks would be like those used on the JT8D disk. Test parameters were: power - 80%; energization time - 1.0 second; and Branson pressure - 12 psi. Adhesive-backed polymer tape, used to verify vibration from the ultrasonic welder, was applied at various locations on the disk. Shown in Figure 25, SIR inspection showed strong IR signals from the polymer tape which indicated sufficient ultrasonic excitation. Also observed, however, were IR signals from an unknown residue on the surface of this retired ("dirty") disk. The residue was removed, and the part inspected again, this time showing no indications. The occurrence demonstrates that unlike penetrant inspection, SIR testing can usually be conducted without first having to clean the part, but in this case the scale was somewhat loose and could have resulted in false calls.

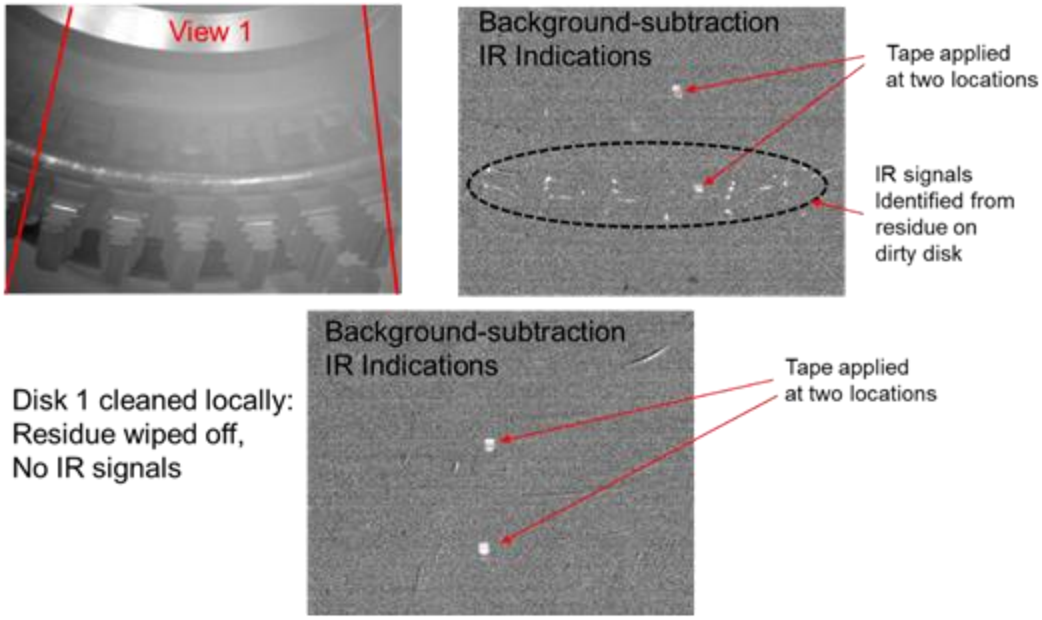

FIGURE 25. SETUP 1 SIR INSPECTION RESULTS FOR PW2037 HPT DISK 1

Figure 26 shows a comparison of surface conditions of the two PW2037 disks. The “dirty” disk shows relatively dark patches of carbonaceous deposits from fuel residue, etc., while the “clean” disk surface is shiny and reflective by comparison.

FIGURE 26. COMPARISON OF UNCLEANED DISK (DISK 1) COMPARED TO CLEAN DISK (DISK 2)

Next, the second part (the “clean” disk), was mounted in Setup 1 for inspection of both the forward and aft sides. Six views were needed to image the aft side, and ten views for the forward side. The IR camera was suitably positioned to image one of the angular sectors during an excitation cycle. The center-chuck was then loosened, and the disk rotated to inspect the next segment. On the aft side, polymer tape was placed at three locations (flange, web, and attachment post) for each inspected segment, as shown using arrows in Figure 27. Adequate excitation was indicated by the tape; however, no crack-like features were found.

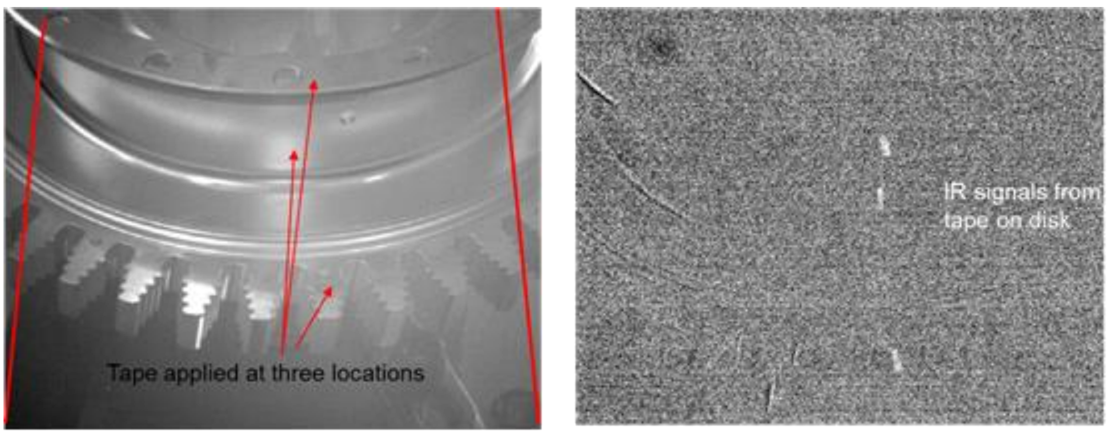

FIGURE 27. SIR INSPECTION OF THE AFT SIDE OF DISK 2

The clean disk also featured a torch-burned attachment lug, which was purposely defaced upon part retirement. Inboard of this lug, there was metal spatter well-adhered to the disk surface. SIR testing of this sector revealed strong IR signals from the spatter, as shown in Figure 28. This observation reinforced the conclusion that enough ultrasonic excitation was being applied during the inspection. It also suggested that a temporary surface coating that similarly responds to ultrasonic excitation, might be useful to quickly determine whether adequate ultrasonic energy is distributed throughout a part. As a result, the FAA tasked Sandia National Labs to conduct initial investigations to develop such a coating. Although the initial results of this investigation were promising, the results are beyond the scope of this report and are not reported here.

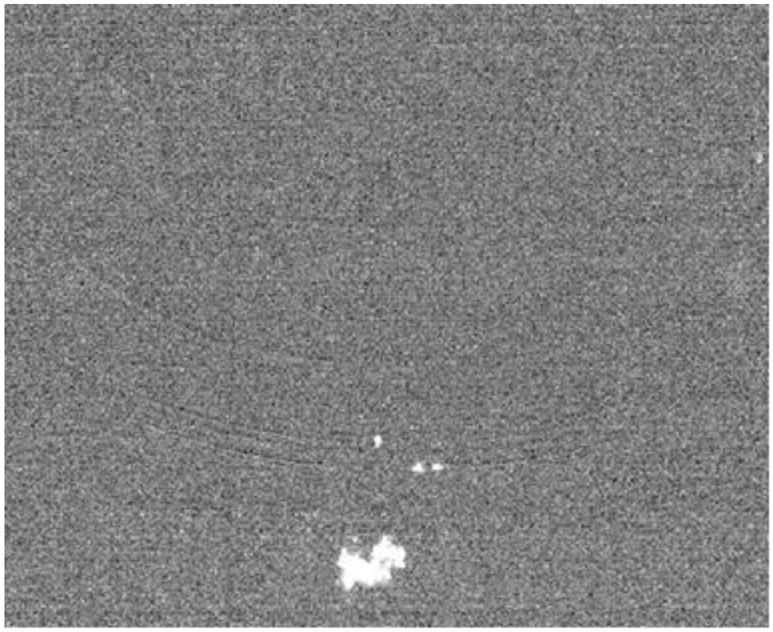

FIGURE 28. SETUP 1 SIR RESULTS OF PW2037 1ST STAGE HPT SHOWING SPATTER

2.5.2.2. Disk SIR System Setup 2

A fixture design having the least constraint on a disk was theorized to provide optimal excitation energy throughout the disk. As a simple test, one of the PW2037 disks was installed in the breadboard SIR system by suspending it with a nylon rope looped through blade attachment slots as shown in Figure 29. The Branson exciter horn was set-up to impact dynamically the disk in the axial direction, on the forward face of an attachment post, using a card-stock interface. The IR camera was positioned high, to image large sectors of the disk. A bolt protruding from a stiff metal structure was placed in contact with the disk post on the opposite side of the Branson horn, to restrict displacement of the disk from the steady force applied during excitation. The intent was both to keep the part in focus, and to avoid false temperature-change indications from occurring due to background-subtraction image post processing.

In the suspended configuration, SIR inspections adequately energized the tape locations, but IR images were still out of focus, despite attempts to hold the disk steady. As a result, Branson horn engagement parameters were reduced by 25%, to minimize disk displacement while keeping energization at sufficient levels to excite the tape. Figure 30 shows a typical tape signal from a blade-attachment slot during this setup. Setup 2 was successful in demonstrating that a disk can be suspended with no special fixture and excited at low energy levels.

FIGURE 29. SIR INSPECTION OF AFT SIDE OF DISK 2

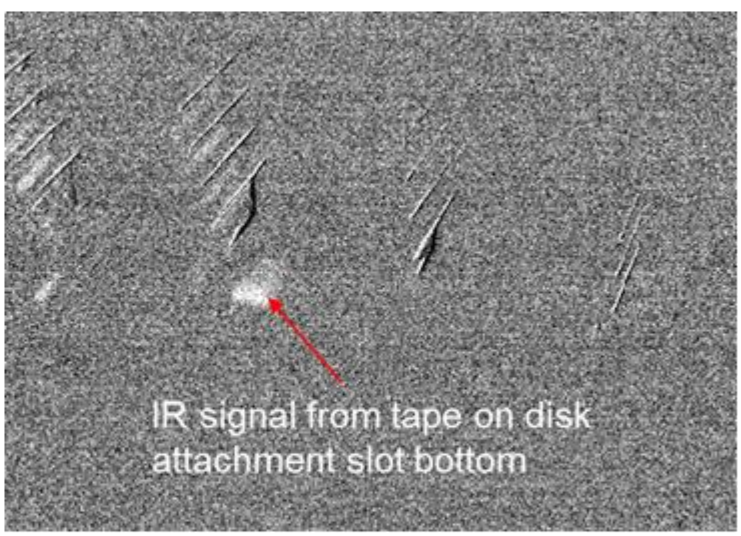

FIGURE 30. SIR SIGNAL FROM BLADE ATTACHMENT SLOT BOTTOM IN SETUP 2

2.5.2.3. Disk SIR System Setup 3

Setup 3 is nominally the same as Setup 2, but with a different bedplate having more useable mounting locations for hardware attachments. The fixture was modified to add a metal bumper to reduce disk motion and image blurring. A nylon interface was later added to eliminate metal-to-metal contact and to reduce excitation-energy loss with a low-friction material. Experimentation included variations of the Branson horn engagement parameters: 80% power, 0.5 sec duration, and pressure reduced from 12 psi to 4 psi. This configuration produced SIR images with acceptable quality as shown in Figure 31.

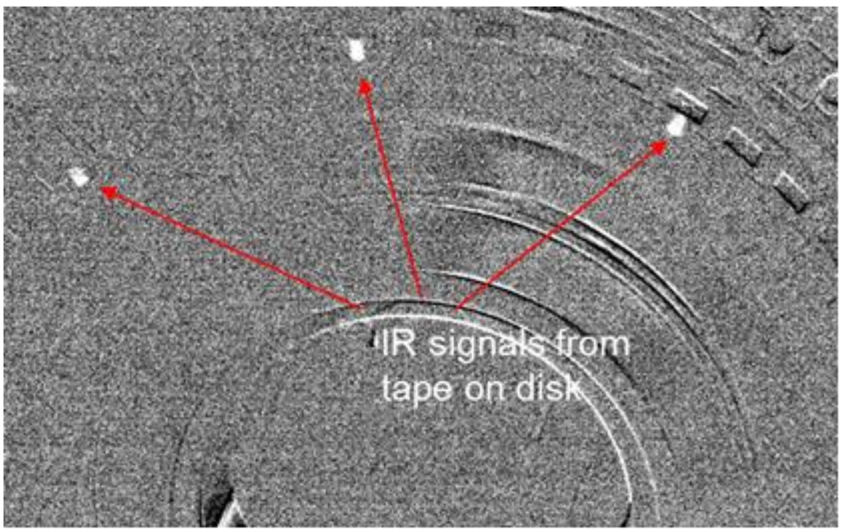

FIGURE 31. SIR INSPECTION RESULTS OF DISK 2 IN SETUP 3

2.5.2.4. Disk SIR System Setup 4

Due to the absence of either cracks or functional artificial defects in the PW2037 disks, the cracked JT8D 1st disk from the phase 1 program was tested in this setup. Seen in Figure 32, this setup also used the hanging fixture approach of Setup 3. The Branson exciter horn was now set-up to dynamically impact axially, on the forward face of the disk bore, using a card-stock interface. The IR camera was positioned to image large sectors of the disk. Two forward-side, heavy steel bumpers, clamped to the bedplate with plastic strip interfaces, were positioned to restrict the displacement of the disk from the hammering force of the Branson horn during excitation. Reducing the Branson horn engagement parameters from 12 psi to 4 psi also lessened the disk displacement during the SIR inspection.

In this configuration, very strong IR signals resulted from the natural cracks and from several of the artificial defects during SIR testing. Figure 33 shows indications from both types of defects with reasonable focus. The set-screw artificial defects varied in brightness, depending on location in the disk relative to the rope suspension and the Branson horn position.

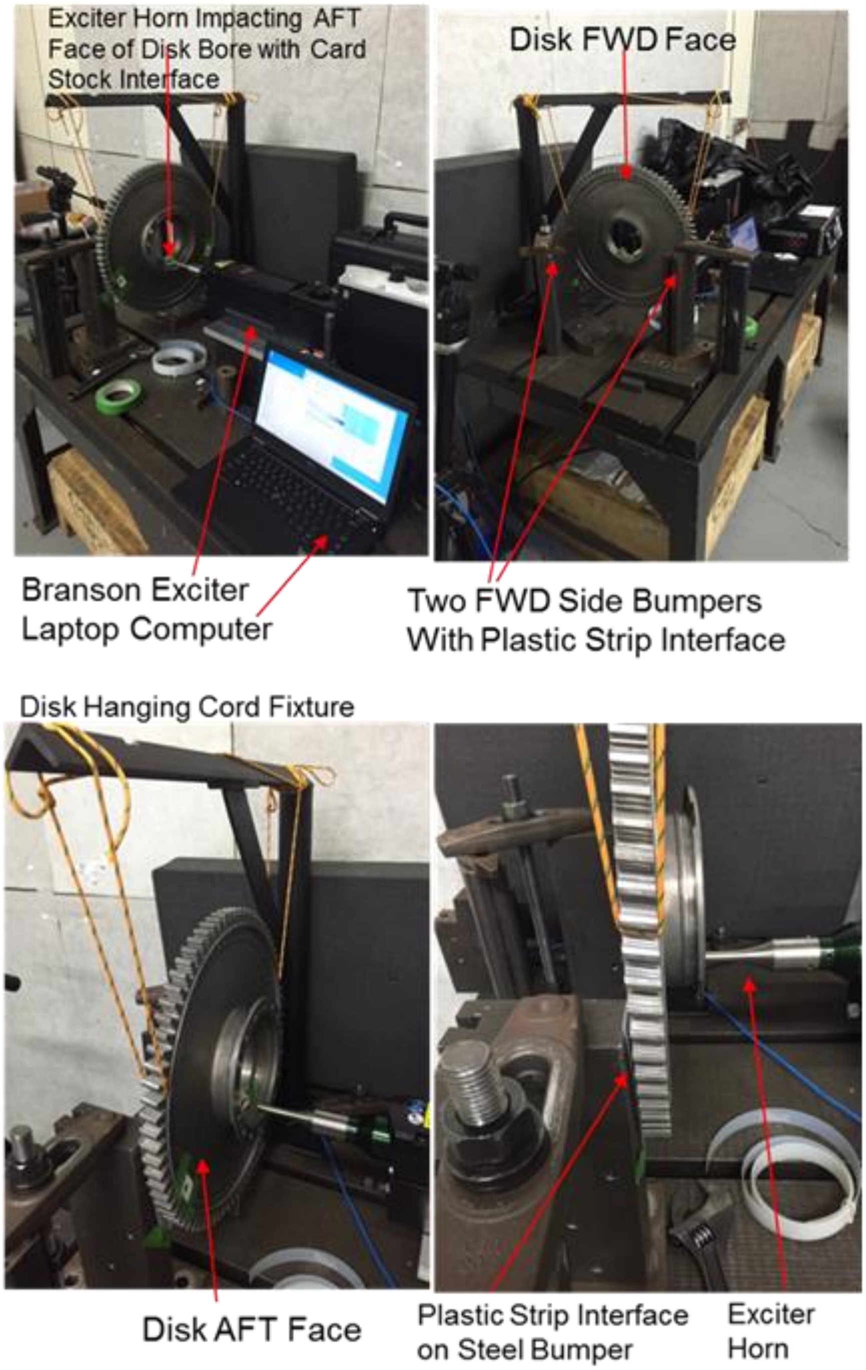

FIGURE 32. SYSTEM SETUP 4 WITH SUSPENDED JT8D DISK

Upon completion of the first four breadboard experiments, two observations were made. First, a disk-holding fixture with the least constraint promotes better excitation, and thus, the potential for increased sensitivity with SIR inspection. The suspended fixture made SIR excitation more effective with fewer features to dissipate the energy. Second, it was found that motion instability caused by a suspended fixture could be overcome without seriously damping the excitation.

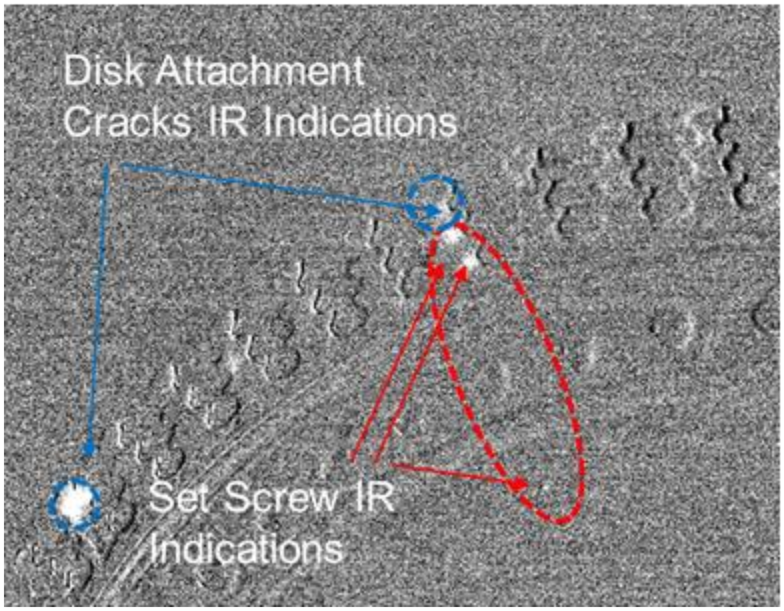

FIGURE 33. SETUP 4 SHOWING SIR INDICATIONS FROM CRACKS AND ARTIFICIAL DEFECTS IN THE JT8D DISK

2.5.2.5. Disk SIR System Setup 5

The first four setups demonstrated that acceptable sensitivity and image quality could be obtained for a variety of fixture configurations. As the setup designs were changed, a better understanding developed of the requirements for a versatile prototype disk-inspection system. It would need to accommodate many disk styles and sizes, and this requirement could necessitate shifting equipment positions from part to part. Although the hanging configuration setups showed good excitation with a minimal part constraint, there were concerns with its practicality as a future production system. For this reason, the remaining setup studies focused on the more conventional approach of supporting the disk on a horizontal inspection table.

For Setup 5, components of the breadboard system were reconfigured onto a 3-foot by 3-foot steel table. The Branson ultrasonic welder was installed vertically beneath the table, with the actuated horn passing through a hole in the table surface. The new Branson position cleared the area above the tabletop for manipulation of the camera and disk-fixture hardware.

The cracked JT8D 1st stage HPT disk was installed on the Setup 5 breadboard SIR system. The disk was positioned in the horizontal plane, supported by three, equally spaced nylon-tipped studs, as shown in Figure 34. Rubber-tipped tool clamps locked the disk down onto each of the studs, preventing both vertical lifting and horizontal translation during excitation. The support studs and clamps were arranged such that with a part in position, the Branson horn made contact at the disk rim in an axial (vertical) orientation with a card-stock interface. The IR camera was positioned above the table to image a large sector of the disk.

As shown in Figure 35, the Setup 5 experiment shows the set-screw artificial defects are sufficiently energized. A comparison of this inspection image to those made with the original breadboard system setup showed no loss in defect detectability.

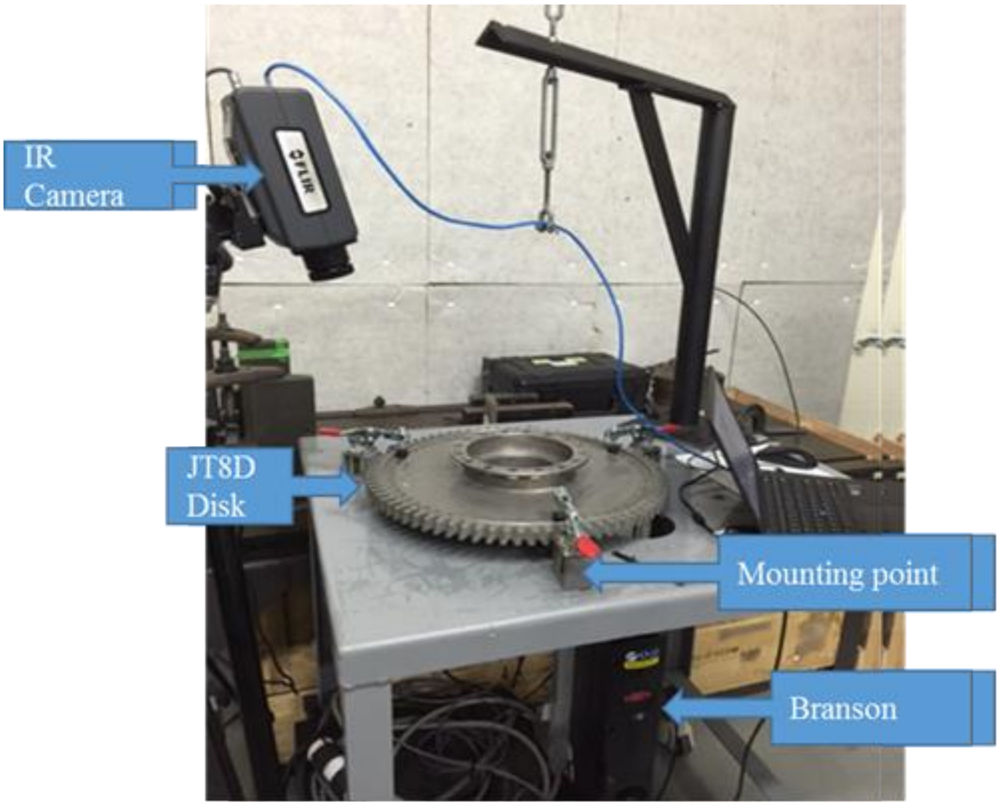

FIGURE 34. FOR SETUP 5, THE DISK LAYS FLAT ON THREE POINTS AND EXCITATION IS AXIAL

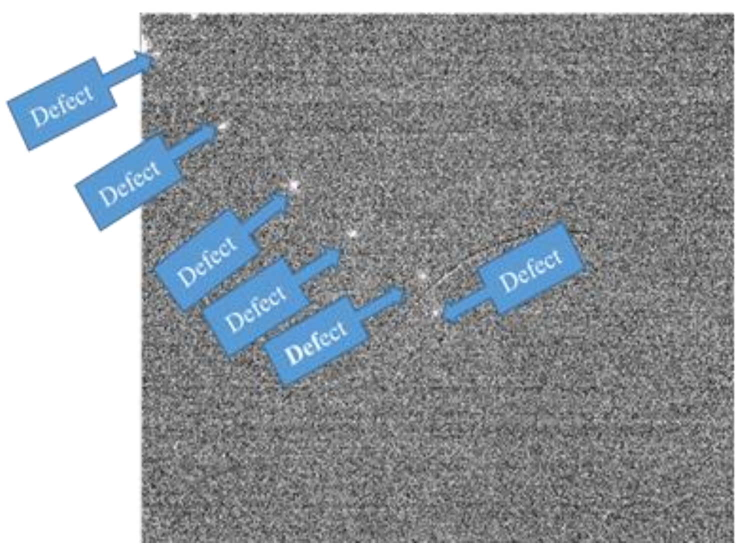

FIGURE 35. SIR RESULTS FROM SETUP 5 SHOWING ARTIFICIAL DEFECTS IN JT8D DISK

2.5.2.6. Disk SIR System Setup 6

In this study, a hybrid arrangement was tried with the JT8D disk suspended over the table by nylon cord and tooling clamps to keep it from lifting and translating as shown in Figure 36. The Branson exciter horn was again set up to impact axially at the rim with a card-stock interface. The IR camera was positioned to image a large sector of the disk.

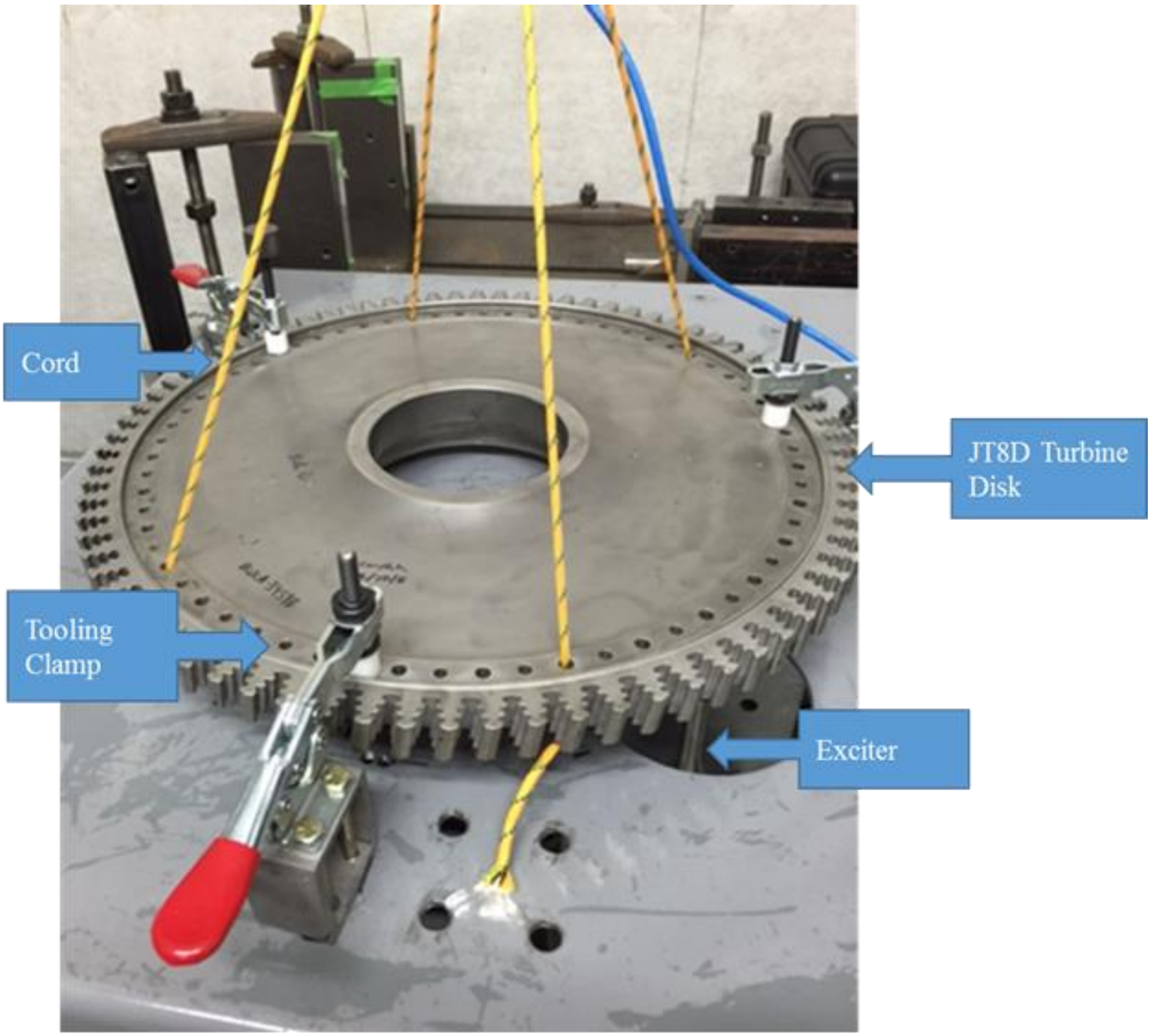

FIGURE 36. IN SETUP 6, THE DISK IS FLAT, HANGING FROM CORD AND EXCITATION IS AXIAL

Setup 6 provided a good signal-to-noise ratio when performing SIR testing. The support arrangement is relatively simple and should accommodate multiple disk configurations. The area around the OD of the disk is uncluttered for IR camera positioning, although the cords above the disk will restrict some viewing positions.

2.5.2.7. Disk SIR System Setup 7

This setup switched back to the F101 compressor 1-2 spool as shown in Figure 37. In this arrangement, similar to Setup 5, the spool was oriented with the part axis vertical and Branson excitation axial. The spool was attached to the surface of the table by three, equally spaced nylon-tipped bolts fastened to the forward-flange bolt holes. Through a hole in the table, the Branson horn contacted the underside of the spool, using card stock at the rim flange between holes. Excitation parameters were: 80% power, 1.0 sec duration, and 12 psi pressure.

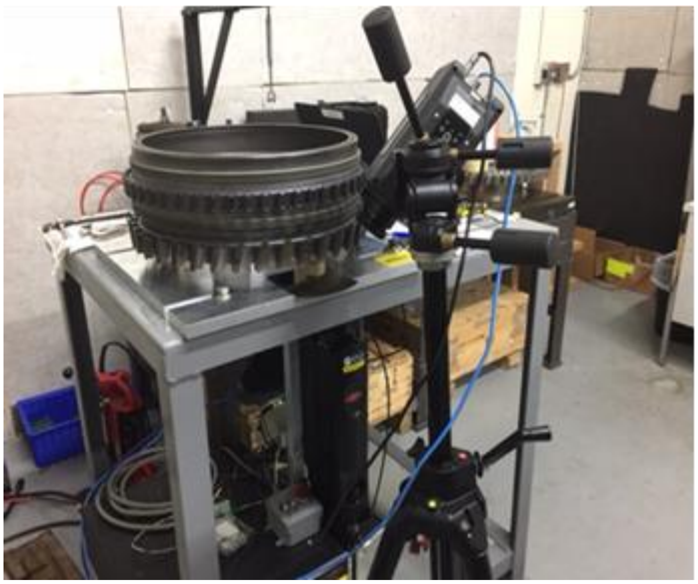

FIGURE 37. SETUP 7 WITH F101 1-2 SPOOL

This arrangement (disk horizontal, supported on nylon posts) worked well, leading to it being the preferred setup for the Task 4 activity for several reasons:

- Cracks were successfully found at three lug locations: 7, 8, and 13.
- A wide, clear area above and around the OD of the disk is available for IR camera positioning, for multiple SIR inspections.
- Support and fixture requirements are relatively simple and could accommodate multiple disk configurations.

2.5.2.8. Selection of Setup for Year-Two Task 4 Activities.

All seven fixture/disk scenarios showed feasibility, but some produced better sensitivity, and some were more practical than others. The approach used in Setup 5 and Setup 7, with the disk supported horizontally on nylon posts, was selected as the basis for the prototype subsystem development efforts. This approach was also found most adaptable to different rotor styles – from single stage rotors with short integral arm flanges to a two-stage-spool drum rotor. Defect detection sensitivity was good for this setup, and the concept is compatible with typical depot overhead-crane systems. It features a three-point mounting system of posts and clamps that restrain the part sufficiently, to avoid issues with camera focus and image post-processing, but which did not interfere significantly with the excitation signal.

2.5.3. Defect-Recognition Algorithm Improvements

This task focused on expanding upon the IR image-data post-processing, commonly referred to as the defect-recognition algorithm (DRA). First developed during the phase 1 program, the DRA is intended to assist in the interpretation of infrared-video data that is collected during an SIR inspection. Displayed visually, the post-processing enhances the contrast in the playback display to highlight suspect locations that could be reject-sized surface or near-surface defects. As currently implemented in the breadboard prototype, and in the USAF blade-production SIR systems developed by FTT, the DRA is used simply to highlight suspect indications, leaving the pass/fail disposition to the system operator. The goal of this task was to develop an "Enhanced DRA" (EDRA), incorporating additional or alternative post-processing code that could ultimately lead to autonomous pass/fail dispositions with high reliability and with an acceptable false-call rate.

Development was over a three-month period, which produced a useable and well performing tool for assisting inspectors in analyzing SIR inspection data. The evolution of the algorithm began with a survey of industry and academia for signal-processing and analysis. From the survey results, selected methods were programmed in LabVIEW.

The EDRA process is summarized in Figure 38 and described in more detail in Appendix A. In the first step, each frame of the IR camera video is run through the original DRA, a thermal correlation matching algorithm. This serves as a filtering step to identify regions of interest (ROIs) in which individual pixels in the camera image exhibit crack-like heating and cooling behavior.

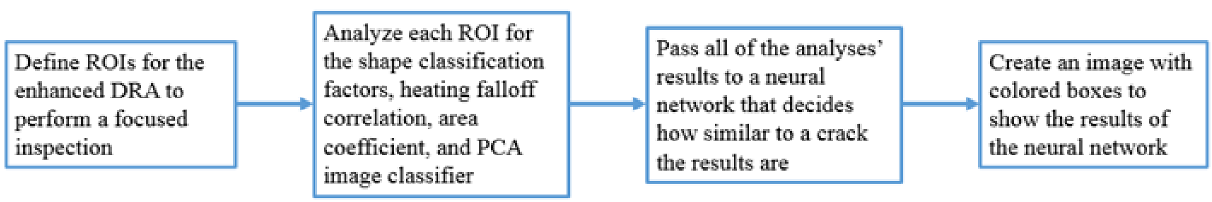

FIGURE 38. ENHANCED DEFECT RECOGNITION ALGORITHM PROCESS

In the next set of steps, the time-history of clusters of pixels within ROIs are analyzed for shape characteristics using elongation, compactness, type, and Heywood circularity factors. They are then assessed against a heating falloff correlation, a particle-area correlation, and a principal-component analysis to identify regions that exhibit an expected heating and cooling behavior. The ROI clusters are then processed through a nearest-neighbor particle-classification program that had been trained with many samples, both cracked and non-cracked.

In the last post-processing step, all the analysis results are input into a neural network, initially trained with a large number of samples. Output values are then overlaid onto a still IR image using colored DRA boxes. Shown in Figure 39, low-probability ROIs are displayed in green, somewhat probable in yellow, and very likely defects in red. These results are encouraging, with all known defects properly flagged in this example. Further development is needed, however, to declutter the display of low probability boxes and to reduce false calls due to signal noise.

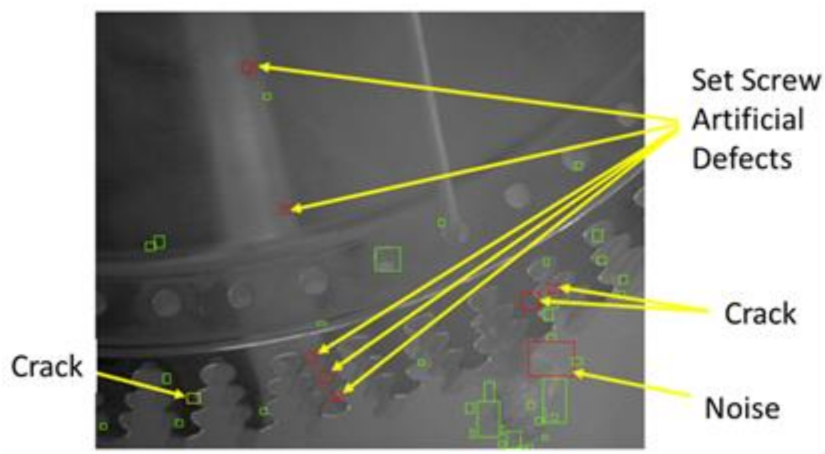

FIGURE 39. ENHANCED DRA IMAGE OF JT8D DISK HAVING CRACKS AND ARTIFICIAL DEFECTS

2.5.4. Part-Handling and Indexing Improvements

Due to the size and weight of commercial engine disks, mechanical lifting assistance is required for many parts. Early in the program, a part-handling concept-development effort was scheduled. The solution was envisioned to be a portable lifting device like a small engine crane, to pick the disk up from a pallet bin at floor level, roll to the inspection area, and then raise and position the disk onto the inspection fixture. Subsequent discussions with MRO shop personnel, however, led to the understanding that overhead bridge or beam trolley cranes equipment is available throughout these facilities for part handling. For this reason, and because the disks being used in this program are manageable with a two-person lift, procurement and prototype testing of a disk-lift system was not pursued. The prototype concept design prepared later in Task 5 assumed part handling would be accomplished by existing facility cranes.

Understanding that multiple SIR excitation cycles and multiple camera views are required to inspect an engine disk fully, a means of angular indexing, without having to constantly re-fixture the part, is needed. The approach selected is to use a commercially available, motorized-indexing rotary table such as those commonly used with numerically controlled machines. Figure 40 shows an example of a large-bore, vertical rotary table, but these are also available as horizontal tables or as 2-axis-capable tables. Although the testing from Task 4 showed that for the F101 1-2 spool radial excitation performed better, it is expected that there will be circumstances where an axial excitation is preferred. Specification and procurement of a rotary-table system to support subsystem prototype tests had been in the original program, but was dropped in favor of conducting a more complete conceptual design of the prototype disk-inspection system. This change was considered low risk due to the wide range of commercially available rotary tables.

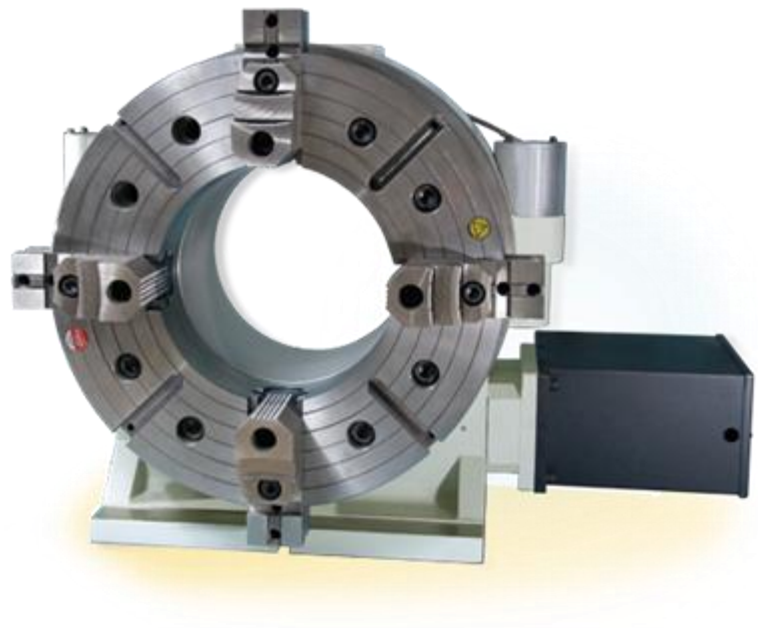

FIGURE 40. ROTARY TABLE CONSIDERED FOR PROTOTYPE DISK SIR INSPECTION SYSTEM

2.5.5. Automated IR-Camera Positioning

Because multiple excitation and imaging setups are necessary, a means for fast and repeatable IR-camera positioning is needed for a production disk-inspection system. The intent of this task was to specify, procure, and test a commercially available robotic arm to evaluate its initial capabilities and to trial it in a prototype-inspection system.

Specification of this subsystem was also delayed until the prototype-system concept design had been evaluated and down-selected among the options for imaging an entire disk. From the tests conducted, it was determined that a combination of a turntable to index the rotor, and a robot arm to position the camera within a given sector, was preferable over a stationary disk serviced by a very long robotic arm. As this conclusion was reached late in the program, the procurement and subsystem prototype testing were dropped from the program. This subsystem was considered low risk due to the earlier application by FTT of a Universal Robotics UR-5 model in the USAF production blade SIR inspection system, shown in Figure 41 during the prototype evaluation phase.

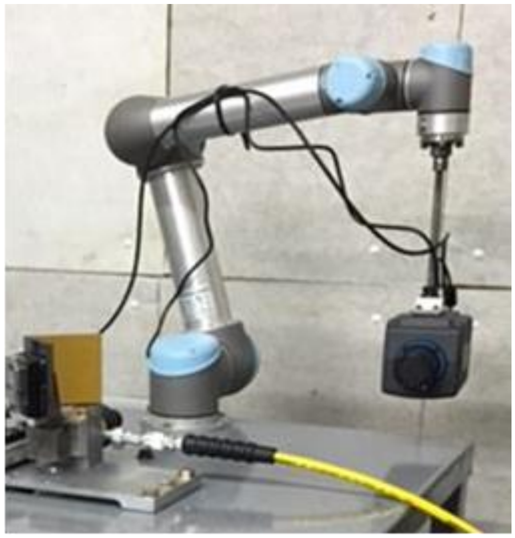

FIGURE 41. ROBOTIC ARM IR CAMERA POSITIONING PROTOTYPE TRIALS

2.5.6. Prototype-System Design Concept

The last update of the system Requirements Document, and the successful results of the numerous inspection-setup configurations explored throughout this program for reliable and efficient SIR inspection of engine disks, were assimilated into a conceptual design for a prototype system. Shown in Figure 42 and Figure 43, and described in more detail in Appendix B, the system is composed of five modular subassemblies:

1) the inspection table, which supports and positions the disk during inspection;
2) the excitation stand, which supports the ultrasonic welder;
3) the robot stand, which supports the robotic arm and IR camera;
4) the computer rack, which packages the exciter power supply and operating system computers (see Appendix B); and
5) the enclosure, which surrounds the three subassemblies shown, shields the disk from external heat sources, and provides sound suppression (see Appendix B)

In this system, the disk to be inspected is placed on a universal disk-fixturing system, integrated into a motorized rotary on the inspection table. Each leg of the trilobate-shaped fixture plate is fitted with a set of nylon-tipped support posts and clamps, which can be positioned anywhere along a radial track to accommodate disks of different sizes. If required, specialized kits of posts and clamps would be interchangeable, for mounting disks of different sizes and styles.

The trilobate configuration allows line-of-sight viewing of all three sectors on the lower side of the disk, by indexing the rotary table 120 degrees. A manual 60-degree rotation is required to image the regions beneath clamps, or in the shadow of the fixture plate. Numerous variations in excitation position are possible through indexing the rotary table and translating the excitation stand. For some disk styles, it may be possible to inspect upper and lower surfaces completely without having to flip the disk over.

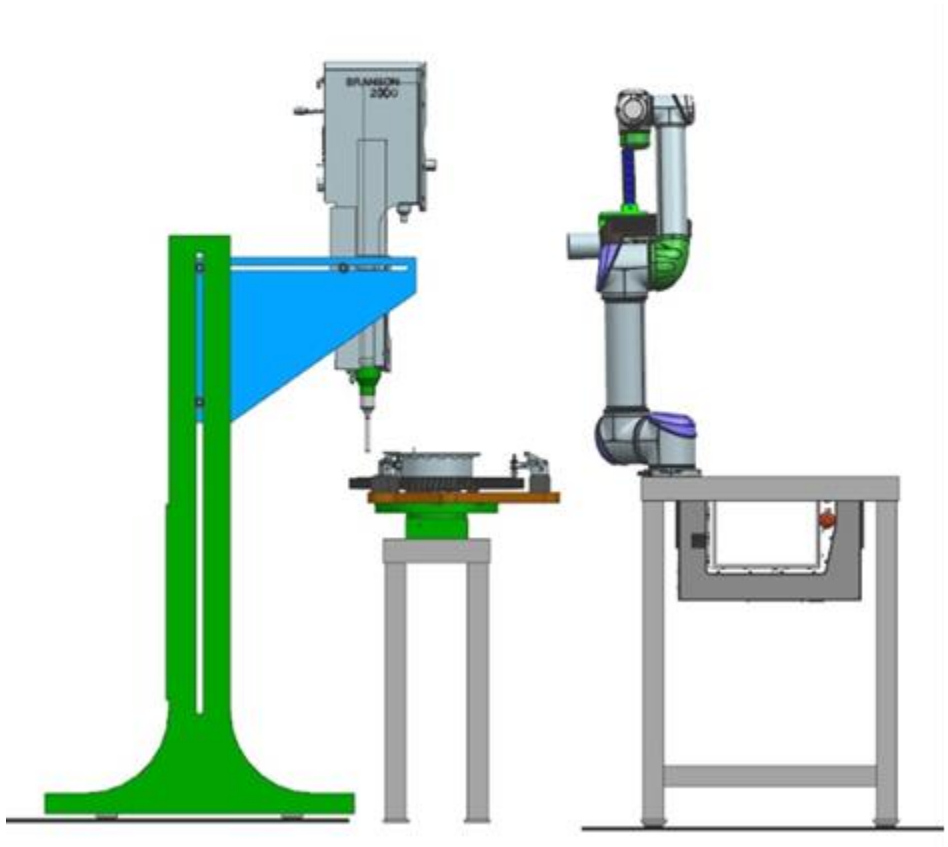

FIGURE 42. PROTOTYPE DISK SIR INSPECTION-SYSTEM CONCEPTUAL DESIGN

The excitation stand supports a 20 kHz Branson ultrasonic welder in a pivoting bracket to allow excitation orientations of either axial or radial with respect to the disk. The stand allows adjustment of both vertical and horizontal position, accommodating a wide variety of disk sizes and styles, and enabling variation in excitation position and orientation.

The robot stand supports the UR5 robot arm and controller hardware. It is mounted on floor rails to accommodate disks of varying size and style. As previously mentioned, because of the rotary indexing capability of the inspection table, the robot only needs to reach one sector of the disk. The table heights are set to allow the robot arm and camera into all necessary positions, both above and below the disk. Experience with the breadboard system indicates that two or more views may be required to image a single blade attachment slot fully, while larger sectors of the rim and web can be captured in a single view. Many variations in scan plan are possible with this arrangement; from indexing the rotary table for every attachment, to programming the robot to acquire all needed views on smaller parts without any table rotation.

The system concept works with either a FLIR mid-wave IR camera, such as an A6700 series, or a wide-format A8300 series camera.

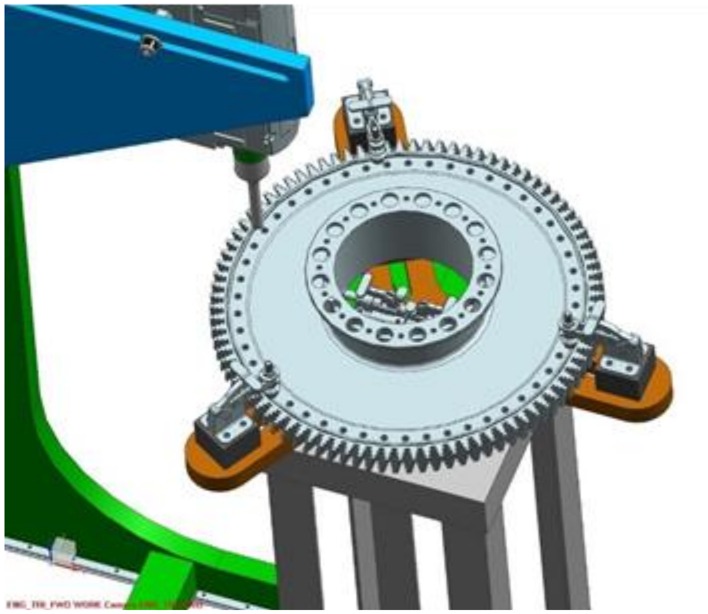

FIGURE 43. DISK SIR INSPECTION TABLE CONCEPT

A system enclosure is needed to protect shop personnel from the robot arm and to protect the test article from possible reflections of external heat sources. Because part handling is expected to be by an overhead crane, an opening is needed above the inspection table. This opening can be left uncovered if the facility has high ceilings.

2.6. TASK 6: PATH TO MRO SHOP IMPLEMENTATION

FTT collaborated with Delta TechOps to prepare an SIR inspection implementation plan, to serve as a guide for the possible transition of a prototype system from the FTT laboratory to an MRO jet-engine facility. The plan is based on one prepared by others for the introduction of Process Compensated Resonance Testing (PCRT) at Delta TechOps. The SIR implementation plan covers a broad range of topics including the following:

- Suitability and durability of inspected components
- Statistically based Verification for NDT Method Substitution
- Influence upon On-wing Monitoring Programs and Inspection Intervals
- One-to-one Correlation of SIR Testing with FPI
- Vibration Characteristics of Components Tested by SIR
- Influence on Surge and Stall Characteristics
- Safety Analysis
- Major Alterations, Major Repairs, and Preventative Maintenance

- Packing, Shipping, and System Location at Customer Facility
- Customer-required Contract Data Requirements
- NDT Reliability Demonstration on Fully Implemented System
- Customer Meetings and On-Site Support
- Fixtures and Setup Standard Kits
- Health and Safety Considerations

Appendix C contains the SIR Implementation Plan.

3. CONCLUSIONS AND RECOMMENDATIONS

This program furthered the development of Sonic Infrared Inspection (SIR) for engine disks through the investigation and development in five technical tasks.

A Requirements Document was prepared in Task 2 and then periodically updated throughout the program as progress was made in the other tasks. This task also identified the PW2037 HPT disk as the “focus” part, and two retired (timed-out) parts were donated to the program.

Task 3 rebuilt the breadboard SIR testing system developed in the lead-in program and repeated some earlier tests. This showed that sensitivity had not changed, and the results could serve as a baseline for the inspection setup studies that followed.

The possibility that residual surface stress might interfere with SIR inspection was experimentally investigated in Task 4. Results showed that shot peening does not impede crack detection with SIR testing, in either coupons or in a shot-peened disk having fatigue cracks.

Task 5 included several subtasks that supported the concept development for a prototype system. First, several variants of possible breadboard system setups were constructed and successfully tested to demonstrate the capability of detecting defects in different styles of disks. Next, a controlled experiment was conducted to determine the sensitivity of crack detection on specific parameters related to part fixturing and excitation. Another series of subtasks considered aspects of SIR inspection such as part handling and loading equipment, the inclusion of a rotary table with the disk fixture, and the use of a robotic arm to position the IR camera repeatedly. It also included a subtask that successfully improved upon the earlier defect recognition algorithm, and then demonstrated its use to more reliably identify and display regions of interest for operator disposition. Finally, in Task 5, building upon the results of earlier efforts in this program, a conceptual design of a prototype disk inspection system was prepared for possible development in a future program.

This program concluded with the development of an Implementation Plan in Task 6. Prepared through a collaboration with Delta TechOps, the plan now serves as a guide for the possible adoption of SIR inspection for engine disks at an airline MRO jet engine facility.

The successful completion of this program advanced the Technology Readiness Level (TRL) for the Sonic Infrared Inspection of engine disks from TRL 3 (Initial Feasibility) to TRL 4 (Integrated Components Tested in Laboratory Environment). It is recommended that the goal of the next program be to further the technology to TRL 7 through the design and development of a prototype system, and then demonstrate it in an MRO jet engine shop.

4. BIBLIOGRAPHY

(2016, January 12). *Sonic Infrared Inspection of Critical Rotating Engine Components*. Contract DTFACT-16-C-00003, FAA W.J. Hughes Technical Center to Florida Turbine Technologies.

Automated, Integrated Inspection Station (AIIS). (2017, November 30). Final Report, Contract FA8100-14-C-0006.

Automated, Integrated Inspection System. (2014, September 18). Contract FA8100-14-C-0006, Dept. of Defense to Florida Turbine Technologies.

(2017). *Development of Sonic Infrared Inspection Technology for Nondestructive Evaluation of Critical Aircraft Engine Rotating Components.* FAA Report (DOT/FAA/CT-17/31).

Sonic IR NDE Validation for Engine Blades. (2012). Contract FA8650-10-D-5210, Dept. of Defense to Universal Technologies.

Standard Practice for Crack Detection Using Vibrothermography. (n.d.). ASTM Standard E3045-16.

APPENDICES

The following appendices are attached:

- Appendix A – Enhanced Defect Recognition Algorithm for Sonic Infrared Inspection

- Appendix B – Conceptual Design of an Engine Disk Sonic Infrared Inspection System

- Appendix C – Implementation Plan for a Prototype Sonic Infrared Disk Inspection System

Enhanced Defect Recognition Algorithm for Sonic Infrared Inspection

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1 Introduction

The intent of this report is to identify algorithms that (1) can improve characterization of SIR signals, (2) enhance display of DRA interpretations, and (3) identify signals that are problematic to current methods. EDRA development was performed under Task 5.2 of the contract.

The goal of the EDRA is to assist operators analyzing SIR inspection data in determining if an indication on a component is crack like. The EDRA also aims to make the inspection analysis more reliable since human interpretation and human error are factors that affect reliability. The EDRA is intended to make the decision process easier and clearer for the operator.

The current DRA assesses signal correlations by comparing the IR data of each pixel to an expected crack profile. The DRA results will sometimes give false calls, and will also sometimes miss crack indications. The goal of this task is to find methods of characterizing these regions of interest (ROI) that will assist the original DRA in its final answer of whether a crack is detected or not.

2 Survey of Signals and Methods of Processing

Signal types that cause issues with the current DRA were first reviewed, followed by research into processing methods that could be useful in helping with the issues.

2.1 Problematic IR Signals

FTT has encountered several different signal types recorded during SIR inspection. Reflections can often cause the current DRA to give false indications. An example of a reflection can be seen in figure 1 which is the cold image subtraction (CIS) playback of full excitation. The heat source beneath it (which is a crack) is reflected onto the surface above it. These reflections undergo heat-up and cool-down exactly like a crack will. Sometimes because of the angle that heat is reflected, the center of heat is not in the center of the ROI indicated by the DRA. This characteristic is helpful in determining if an ROI is a reflection of a heat source and was the driving factor for the heating falloff correlation discussed in Section 3.3. The shapes of reflections also sometimes differ from cracks. In figure 1, the reflection appears to be more triangular than the original crack heat source. This characteristic can be determined using shape identification, which is described in Section 3.2, and an image classifier which is described in Section 3.6.

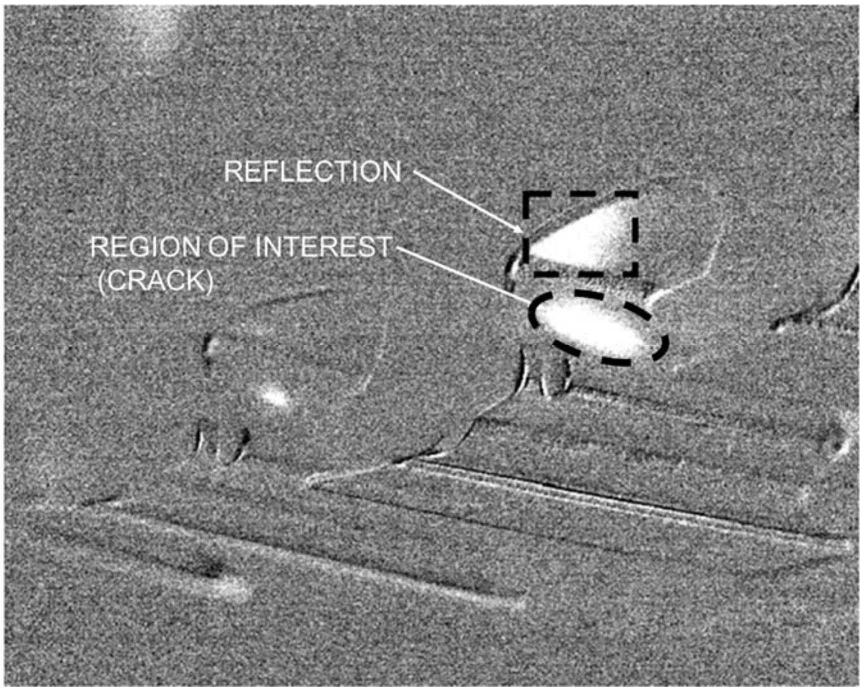

Figure 1. Example of Reflection on CIS Disk

Another common source of error is fixture heat-up. Areas of interface between the part of interest and the fixture that holds the part will heat-up and cool-down similarly to cracks. This is evident in the JT8D disk at the locations shown in figure 2. The shape of the heat source can sometimes be used to determine whether these ROIs are a crack.

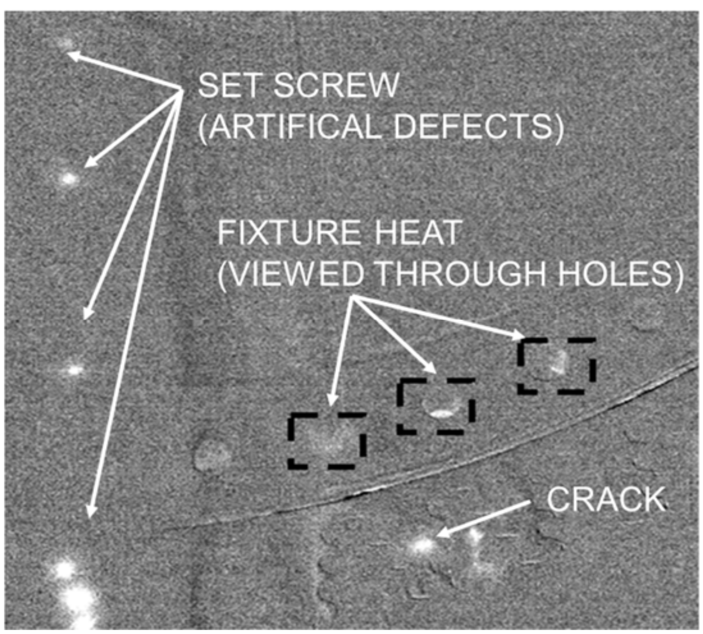

Figure 2. Example of Fixture Heating on CIS JT8D Disk

Weak IR signals, or ones with a low delta in heat counts can also be difficult for the current DRA to detect. There is a balance that must be maintained with the current DRA to be able to detect weak IR cracks, but also not gather a lot of false calls on reflections and fixture heating. One of the goals in enhancing the current DRA would be to allow for detection of weaker IR cracks, while also not gathering the false calls that the current DRA does.

2.2 Commonly Used Algorithms for Image and Video Processing

Commonly used algorithms for image processing include classification of shapes, thresholding by intensities, and nearest neighbor classification training. LabVIEW has implemented methods to define shape through elongation factor, compactness factor, Heywood circularity, and type factor. It also has an interface through which to train a particle classifier based on the nearest neighbor algorithm.

Optical flow is another processing algorithm for video and can show trends in movement from one frame to another. Although the algorithm was interesting, it did not prove to be useful enough in detecting cracks.

A watershed transform was set up to separate close ROIs if there was a need based on signal peak locations. The caveat to using the watershed transform all the time, was that more false calls were generated since it created more ROIs overall.

2.3 Investigation of Methods Used in Academia

The principal component analysis (PCA) is commonly used to analyze data that has trends or correlations in the data. It has been used to analyze flash thermography data, but can also be applied to vibrothermographic data.

2.4 Conclusions of the Survey

At the conclusion of the survey each method was implemented to understand their effectiveness. The results of these implementations can be seen below.

3 Enhanced Defect Recognition Algorithm

The Enhanced Defect Recognition Algorithm (EDRA) was developed over the course of approximately 2.5 months during the contract effort. This section provides details and a full breakdown of the algorithm. Below is the flowchart of the algorithm. Each process in the flowchart is detailed in the following sub-sections (3.1 through 3.8).

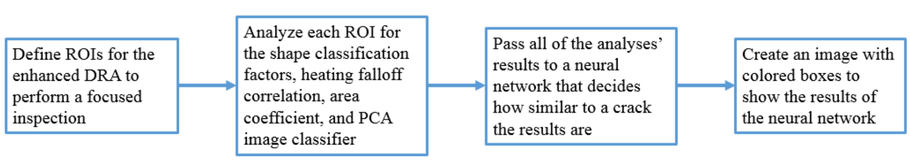

Figure 3. Enhanced Defect Recognition Algorithm Flowchart

3.1 Defining Regions of Interest

To start, the EDRA uses the original DRA's correlation matching analysis to find ROIs. The original DRA inputs are set very loose (low curve fit correlation coefficient) since the EDRA will then perform a detailed inspection of each ROI. For an example showing the loose DRA's results, see figure 4 below.

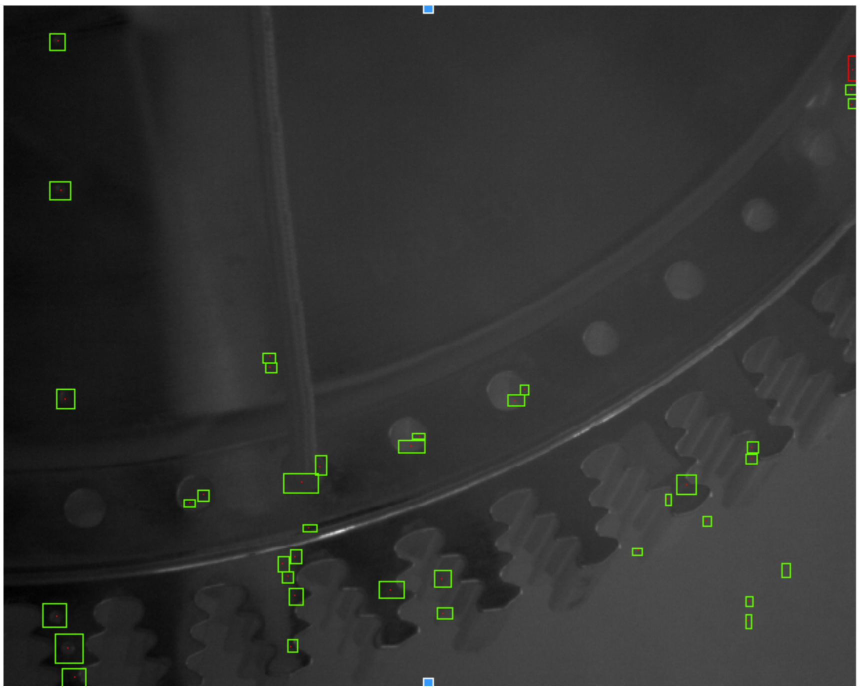

Figure 4. Example of Loose DRA Results – Defining ROIs

3.2 Shape Classification of ROIs

The next step in the algorithm is to start analyzing the average shape of each ROI through time. In order to analyze the shape, a binary threshold is set to 25% of the max signal for each frame and then averaged through the entire playback. For each frame the area, elongation factor, compactness factor, Heywood circularity, and type factor are acquired. Information on what each of these mean can be found in the LabVIEW documentation. It is also shown in figure 5 for convenience. Figure 6 shows the signal values found for crack and non-crack signals. These shaping factors can significantly help in determining whether a ROI is a crack or not.

Factors

The following table lists the NI Vision particle factor measurements.

Measurement	Definition	Equation
Elongation Factor	Max Feret Diameter divided by Equivalent Rect Short Side (Feret). The more elongated the shape of a particle, the higher its elongation factor.	$\frac{F}{RF_b}$
Compactness Factor	Area divided by the product of Bounding Rect Width and Bounding Rect Height. The compactness factor belongs to the interval [0, 1].	$\frac{A}{W \cdot H}$
Heywood Circularity Factor	Perimeter divided by the circumference of a circle with the same area. The closer the shape of a particle is to a disk, the closer the Heywood circularity factor is to 1.	$\frac{P}{2\sqrt{\pi A}}$
Type Factor	Factor relating area to moment of inertia.	$\frac{A^2}{4\pi\sqrt{I_{xx} \cdot I_{yy}}}$

Figure 5. LabVIEW Shaping Factors Described

Elongation Factor	Compactness Factor	Heywood Circularity	Type Factor
2.78	0.6	1.45	0.92
2.34	0.51	1.61	0.78
3.92	0.55	1.61	0.82
2.16	0.49	1.68	0.75
3.54	0.42	1.84	0.58

Crack Signals

Elongation Factor	Compactness Factor	Heywood Circularity	Type Factor
16.68	0.23	3.11	0.31
17.95	0.11	3	0.14
16.08	0.22	2.88	0.27
7.18	0.16	2.7	0.19
22.15	0.16	3.6	0.18

Non Crack Signals

Figure 6. Crack ROI Shape Factors (left), Non-Crack ROI Shape Factors (right)

3.3 Heating Falloff Correlation

At the transition between excitation and cool-down, cracks typically show their greatest intensity of heat. The heat is concentrated at their centers and falls off in a Gaussian form. Shown in figure 7, when plotting the distance from the crack center vs delta in heat intensity the result can be correlated to a logarithmic function.

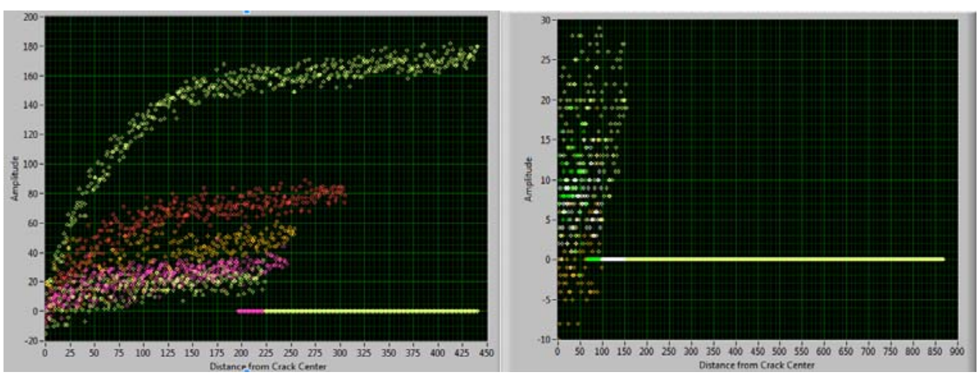

Figure 7. Crack ROI Heating Falloff Correlation (left), Non-Crack ROI Heating Falloff Correlation (right)

3.4 Particle Area Correlation

As the EDRA obtains shape information about the ROI for the full playback data, it also retains area measurements. The area of the crack signal should increase throughout excitation and then decrease throughout cool-down. The resulting plots from crack and non-crack ROIs can be seen in figure 8 below. For the purpose of this study, the correlation was compared against a delayed linear increase and decrease signal with peak at the transition between excitation and cool-down.

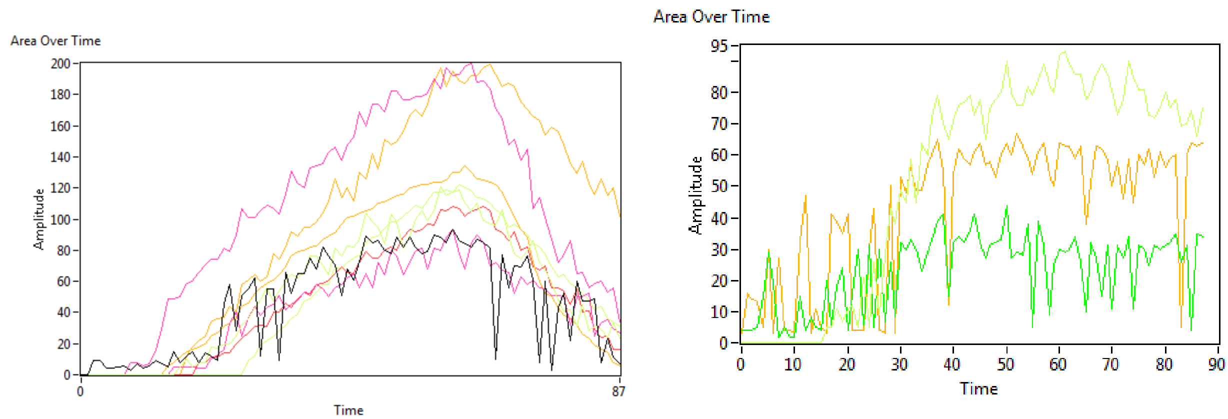

Figure 8. Comparison of Particle Area Correlation for Several ROIs on JT8D Disk – Cracks (left), and Non-Cracks (right)

3.5 Principal Component Analysis

In order to use the PCA with thermographic data, the data must first be arranged into a 2D format (pixel number / time). Then, each pixel of data is normalized using the mean and standard deviation. The data is separated into 2 series, excitation and cool-down. An efficiently designed PCA calculating only the first mode is run for each of these series and then the difference is taken. The subtraction is similar to cold image subtraction, except it also further enhances the contrast of cracks. The result of PCA on the JT8D disk can be seen in figure 9 below.

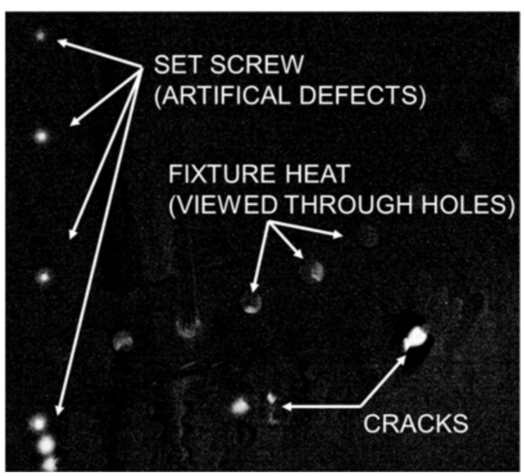

Figure 9. Principal Component Analysis of JT8D Disk Enhances Contrast at ROIs (compare with background image subtraction images in figure 2)

3.6 Nearest Neighbor Crack Likeness

A binary particle classifier was trained using the LabVIEW Vision Particle Classification Training program. The classifier uses the nearest neighbor algorithm based on 88 crack ROI samples and 225 non-crack ROI samples to classify ROIs. The number that is output from the classifier is the distance to the nearest sampled crack signal. These distances are shown in figure 10 below. Images sent to the classifier are re-sampled to a 32 X 32 format to be less dependent on crack size and shape.

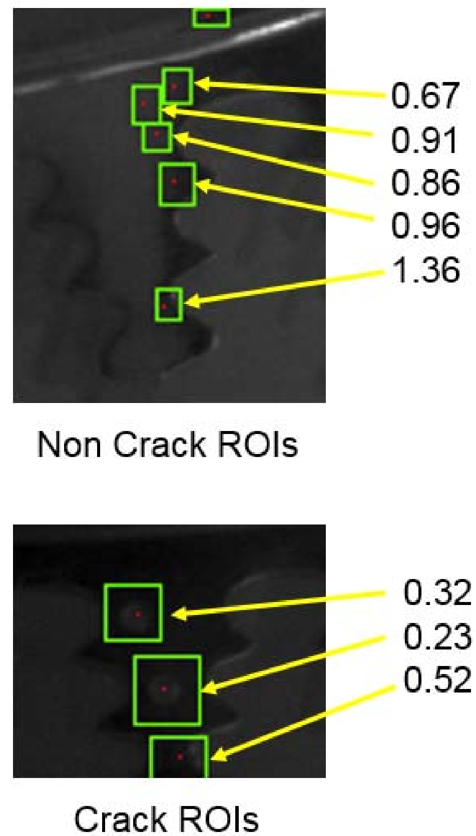

Figure 10. Example of Principal Component Analysis

3.7 Input Data to Trained Neural Network

All the factors described above in sections 3.2 through 3.6 were input into a neural network for training. The neural network was initially trained with over 300 samples which were divided into a training set (90% of the data) and validation set (10% of the data). The error trend of the training after sufficient epochs settled at 10. Listing the inputs determined by the neural network to be most important: Compactness factor (33%), area coefficient (15%), particle frame persistence (14%), crack likeness (13%), heating falloff correlation (12%), original DRA mean value (4%), original DRA max value (2%), elongation factor (2%), Heywood circularity (2%), type factor (2%), linear signal mean (2%), and linear signal max (0%).

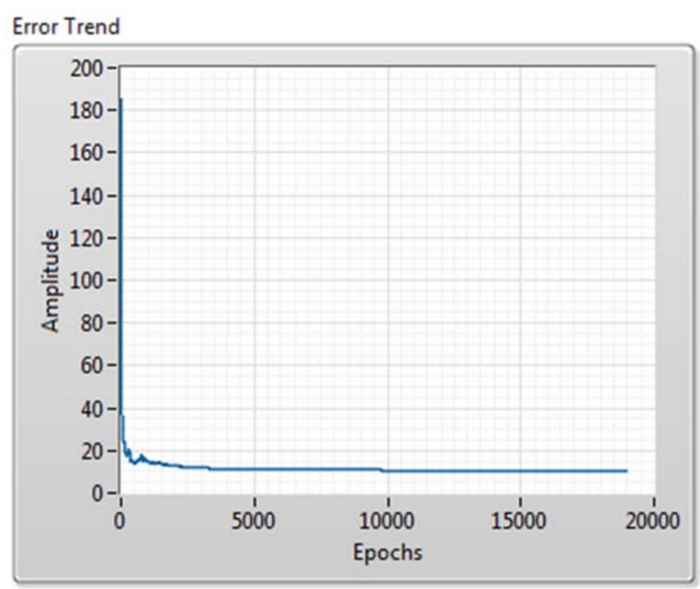

Figure 11. Error Trend over Training Epochs

3.8 Neural Network Output

To make viewing the results of the EDRA easier to understand, ROIs whose output values from the neural network of 0.0 – 0.4 were colored green, indicating very low probability of a crack, 0.4 – 0.5 were colored yellow, indicating a crack was somewhat probable, and 0.5 – 1 was colored red, to indicate the ROI is very likely crack. Further development of this algorithm would probably not show as many green boxes as the examples below have. They are shown in the examples simply to demonstrate the effectiveness of the algorithm.

3.9 Example Results of EDRA on SIR Inspections of Disks

The following images are the EDRA results produced from various SIR inspections of various disk geometries.

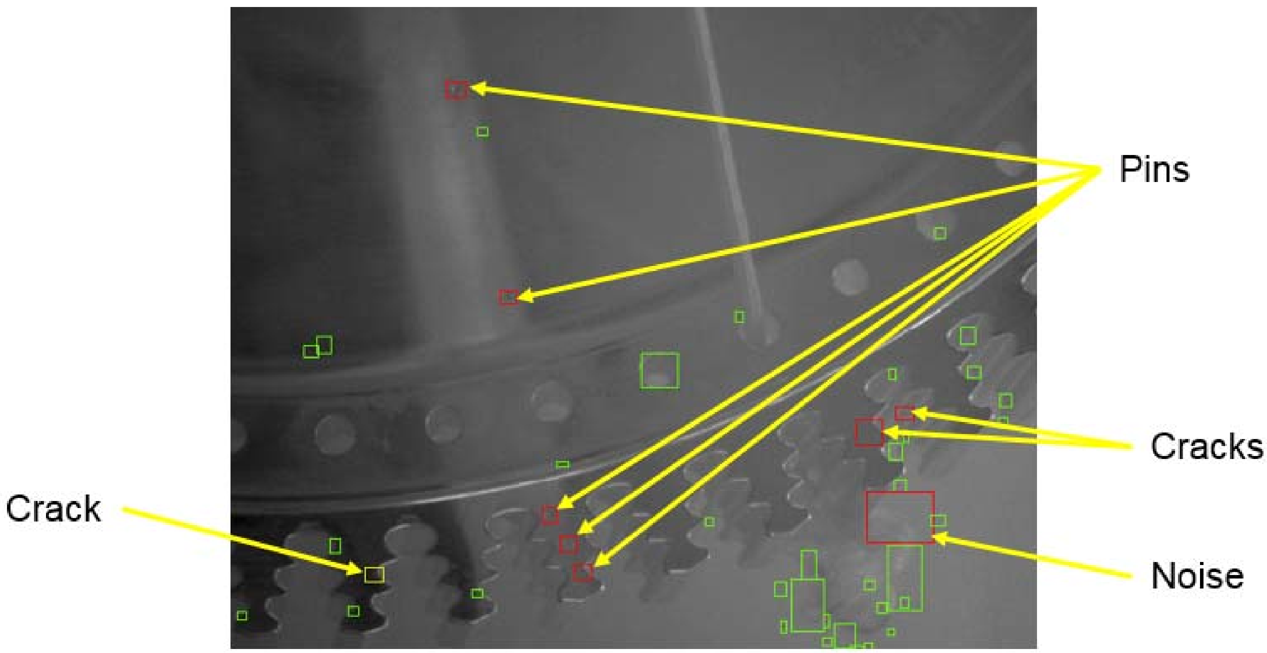

Figure 12. JT8D Disk with Various Pins and Cracks

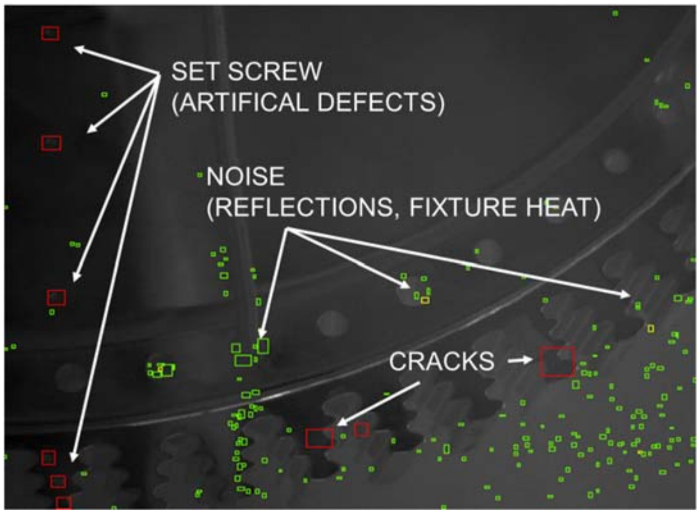

Figure 13. JT8D Disk with Artificial Defects and Cracks

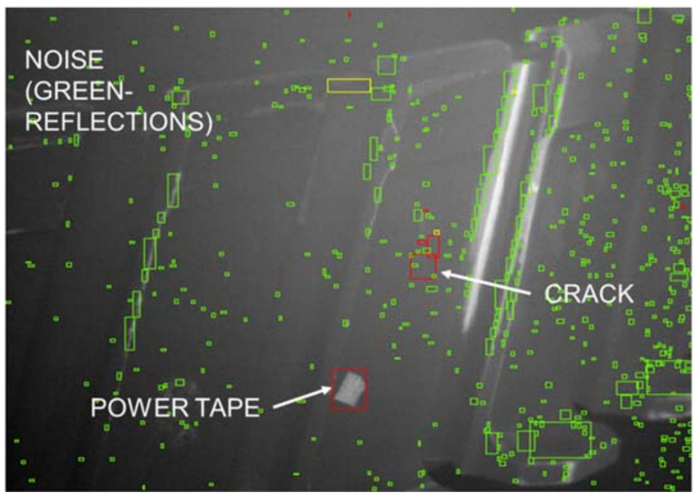

Figure 14. F110 Fan Disk with Power Tape and Various Defects

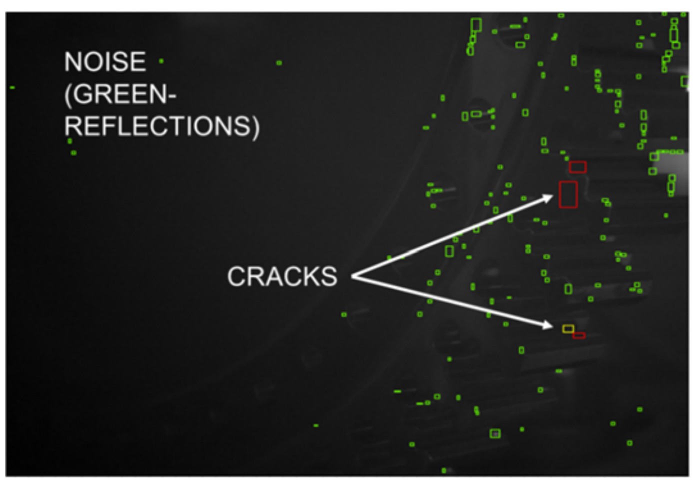

Figure 15. JT8D Disk with Various Cracks

4 Final Statements and Future Development

The Enhanced Defect Recognition Algorithm development was a three-month effort that produced a useable and well-performing tool for assisting inspectors in analyzing SIR inspection data. The evolution of the algorithm began with a survey of industry and academia for signal processing and analysis methods that are in existence. From the survey results, selected methods were used as the foundation for the algorithm. The algorithm then matured to incorporate some custom designed methods specifically used in SIR. In the end, the full algorithm can produce color mapped ROIs that depict where the algorithm results indicate relevant indications. This visualization makes is easy for an inspector to understand where the indications are located and a relative confidence level on whether the indication is relevant. Overall, the EDRA is at a point where it can be used to reduce the human variability of making a decision while inspecting engine components for surface cracks.

There are some natural next steps. The following is a list of ideas for future development and testing of the EDRA:

- Create alternative methods for displaying the EDRA ROI results
- Test, tune and adapt (as necessary) the EDRA on other components
  - Ex: blades, vanes, and other disk geometries
- Geometry identification
  - Algorithm automatically identifies the component within the field-of-view, and only analyze the pixels that makeup that component
- Develop a neural network that analyzes ROIs based on a 10 X 10 X 10 (length X width X time) resampled structure that takes in the raw, cold-image-subtracted heat values and then outputs an answer based on a deep convolutional neural network
  - Google TensorFlow provides an API for Python. This environment would work well for developing the neural network.

Conceptual Design

of an Engine Disk Sonic Infrared Inspection System

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1 Introduction

2 Purpose of the System

Reducing sustainment costs while extracting the maximum worthwhile life from turbine engine components is a need recognized by the Federal Aviation Administration and the U. S. Air Force. Florida Turbine Technologies, Inc. (FTT) was tasked to use the technical advancements from a recently completed program (DTFACT-13-C-00017) to move forward with important features of a prototype sonic infrared (SIR) disk inspection system. It is anticipated that a practical SIR inspection system for disks will lower inspection costs while improving inspection reliability.

Detection of surface-breaking defects in critical engine components using fluorescent penetrant inspection (FPI) has been a well-established technique in the Aerospace Industry for many years; however, production FPI processes have shortcomings that still remain, despite many years of use and process improvements. One of the most critical shortcomings is the high variability in inspection capability due to human factors. It is also well recognized that surface preparation and surface opening of crack-like defects strongly influence performance. Although still a relatively new method, SIR inspection technology has shown the potential to be a replacement for FPI, with less time consumed by inspection, thorough documentation of each inspection, higher inspection reliability, less surface preparation, and no environmental concerns. This is the basic purpose for the envisioned SIR disk inspection system. Based on previous FAA funded research and complimentary research funded by the USAF, SIR demonstrations in a production environment have now shown statistical evidence of the ability to detect cracks reliably in turbine engine compressor blades. Furthermore, an automated production blade inspection system has been produced for USAF depot inspections; however, for more massive components such as engine disks, critical fundamental and practical implementation questions still need to be addressed before SIR can be commercially viable.

2.1 Scope of the system

The basic capability of the SIR disk inspection system will be to perform rapid, accurate crack inspections for a variety of disks in an engine overhaul shop. The scope of the initial system design will cover most of the possible commercial engine disk designs, but boundaries must be established, leaving off some larger and more exotic engine components and assemblies. Once a prototype system has been thoroughly proven, it may be possible to develop several versions of the inspection system to accommodate radically different disk designs and envelopes. This isn't a unique idea. Automated eddy-current inspection systems have been produced for various special applications. As with eddy-current inspection, SIR testing is not expected to be a panacea or a superior inspection tool for every part design. Baseline studies should be performed for each significantly different implementation before spending much time and money.

There were five main technical tasks defined in the lead-in program in order to achieve the primary objectives. (1) Task 1 involved generating a working document that eventually evolved into this conceptual design, as well as selecting a specific disk of interest. Delta Tech Ops provided two disks of their choice, the PW2037 high-pressure turbine disk. (2) Task 2 included re-assembly of the breadboard disk SIR inspection system and experimental verification that the system produces identical results to the initial assembly. It was tested using a disk containing artificial defects from the previous program, to verify that inspection sensitivity for those defects had not changed. (3) Task 3 included assessment of the impact of residual compressive stress on the sensitivity of disk SIR testing. This phenomenon can be divided into two categories. The first is residual compressive stress caused by media finish, localized to a few mils beneath the surface of the part. The second is compressive bulk stress caused by manufacturing or operational stresses. This would be much harder to define and test than media finish effects, because any special constraining fixture to simulate bulk stress will reduce SIR effectiveness simply from constraint of the specimen. In fact, this task was eliminated from the program, preferring to perform a thorough test of surface finish effect. (4) Task 4 included design and testing of unique, attractive features for a prototype disk inspection system. These included a practical way to fixture the disk and insert energy into the part, improvements to the defect recognition algorithm (DRA), a practical disk handling device, automated indexing subsystem (to be used on blade slots, etc.), and automated IR camera positioning. These fed into the conceptual prototype system design. (5) Task 5 identified a path to MRO shop implementation. Delta Tech Ops engineers participated to provide expertise that isn't available at FTT.

2.2 Objectives and Success Criteria of the Project

The basic objective of this program was to conduct research necessary for the continued development of the SIR inspection method for flight engine disks, leading to a field-implementable state of readiness. Accomplishments included: (1) produced and refined an SIR disk inspection system requirements document, (2) investigated factors unique to turbine disks that may reduce inspection reliability, such as compressive surface and bulk residual stresses, (3) continued refinement of defect-recognition algorithms (DRAs), to enable flaw-detection reliability exceeding that of unaided inspection by a trained technician, (4) designed selected subsystem concepts, with the goal of improving the reliability, throughout, and cost of these inspections, and (5) identified a path to MRO shop implementation. Throughout the duration of this research, FTT collaborated with FAA engineers and Delta Tech Ops (a commercial engine maintenance shop) to iterate on this design document, as well as to generate a plan for implementing a production inspection system.

3 Background - The Original Breadboard System

This section provides a description of the major components of a basic breadboard system that was used for future design and development of subsystems for a production prototype disk-inspection system. This information forms the basis for a listing of requirements for a viable prototype system. The breadboard system was originally produced during the original precursor program.

3.1 Ultrasonic Excitation Source

The Branson excitation subsystem provides a 20 KHz vibration into the test article. The current, simple configuration allows the flexibility needed for inspecting various disk geometries, but adjustment is slow and not suitable for a production environment.

3.2 System Base

The SIR breadboard system base is a rigid, versatile bed which provides the basis for numerous experiments with subsystems, without making expensive, time-consuming modifications.

3.3 Infrared Camera

The camera is a state-of-the-art FLIR IR camera. A high-end, complex camera is required to detect the subtle, fleeting signals that are characteristic of crack-like indications that are emitted by engine parts. IR cameras continue to evolve, so it is likely that the same, or better, capability will be available sometime in the future at lower cost.

3.4 Inspection Fixture

The original fixture subsystem comprised all the supporting hardware including a "tee fixture" support mount that allows a disk to be mounted vertically or horizontally. The fixture was subsequently scrapped, and a new concept was developed that is more practical for the MRO environment.

3.5 Setup Standards

Setup standards are used for all nondestructive testing (NDT) systems to ensure consistent system performance at startup, reconfiguration, and between shifts. The signals on known defects are examined, recorded, and compared to legacy data. This provides the inspector insight into whether the system is performing consistently. The precursor program and a parallel USAF program funded research into optimal artificial defects for SIR testing standards. These probably will be used as models for setup standards for generations to come. Development seems adequate for some applications but lacking for others. It is anticipated that a multi-level hierarchy of standards, much like the standards for eddy-current inspection used for USAF engine disk inspection, will be developed.

4 Prototype System Conceptual Design

4.1 Overview

The following subsections provide a view of mechanical and software components of a suitable prototype SIR disk-inspection system that would fit into the MRO shop environment to test concepts for a production unit. Other scenarios certainly are possible, as well as design variations on the described system.

4.2 Prototype System Mechanical Requirements Routine Protocol

Design of a suitable prototype SIR disk inspection system may be compatible with the following standard steps that are taken when a component is inspected on existing equipment.

A. System Setup Procedure

1. Turn on electronics
2. Load software
3. Load configuration parameters for the setup standard in the software
4. Bolt any special fixture onto bed. This may be the same fixture that is used for the disk to be tested. (For blade inspection, this is called a "pinch block". Ideally, a similar fixture could be designed for disk inspection, thus stabilizing the process and eliminating the need for a coupling material such as paper card stock.)
5. Load setup standard onto fixture
6. Securely tighten the standard and fixture
7. Align and focus the camera to show the desired inspection surface of the setup standard
8. Create a grid pattern over setup standard image in software
9. Align Branson horn with the fixture impact location
10. Close door on system enclosure
11. Execute excitation and recording with the software
12. Playback recorded inspection and evaluate the signal to assure that the signal is within prescribed limits
13. Document results
14. Remove setup standard. The use of a setup standard may be required post-test as well as prior to disk inspection. Also, multiple setup operations and independent inspection processes may be required for a single disk.

B. Repeated SIR Inspection of disks

1. Using an overhead crane, load disk into appropriate fixture, upon assuring proper identification
    1.1. Be sure to meet all alignment requirements for optimal imaging
2. Torque down the fixture
3. Close door on system enclosure
4. Execute excitation and recording with the software
5. Playback recorded inspection and evaluate the signal
6. Document results
    6.1. Identify if an indication is present

6.2. If an indication is identified to be a crack, document disk location and estimated amplitude

7. Repeat inspection of multiple features on the disk. Conduct multiple setup and inspection operations as required for various geometries associated with each disk design. Then, remove disk.
8. Repeat Steps 1-7 for all disks to be inspected
9. Many disks are heavy, so special handling subsystems may be required to install and remove each disk. If possible, the disk will not have to be removed and replaced on the fixture multiple times.

4.2.1 Platform

The lead-in program focused upon conceptual design of various subsystems that could be included in the category of "platform" considerations. Those considerations included system flexibility, user ergonomics, part loading and mounting, a programmable turntable, exciter orientation, and robotic manipulation of the IR camera. Numerous brainstorming sessions were conducted with designers and SIR testing experts. Final configuration and supporting data were then produced for presentation in this conceptual design document.

Delta Tech Ops, the intended first implementation site for the prototype disk inspection system, provided a data sheet for the eddy-current-testing ETC 2000 automated system as a template for use by the team to size and scope out the SIR system. This has been very useful; however, there are several significant size and capacity options with the eddy-current system. Upon asking for clarification, the primary Tech Ops team member stated that the team should consider smaller, lighter parts for the first prototype, because the majority of Delta parts can be handled with that version. A larger, more expensive system could be considered as a second system later in the implementation process.

The following basic design factors for the system conceptual design were established:

1. The maximum part diameter to be considered is 32 inches. A minimum diameter of 1 inch is planned. Vertical translation will be 22 inches "usable".
2. Assure that enclosure size accommodates the above dimensions with some room to spare.
3. The disk inner diameter may be used for clamping and energizing, as well as outer diameter features. This is because history dictates that clamping and energizing should not be done in the same locality.
4. Assume that the entire disk needs to be inspected, since SIR will be replacing FPI.
5. Disk may need to be manually (with assist from an overhead crane, if necessary) turned over for inspection of both sides.
6. Disk positioning and clamping will be manual.
7. An enclosure is required for safety and noise isolation. It will have an open roof to accommodate the Tech Ops overhead transport crane.
8. The open roof may not be acceptable to Tech ops, due to sound level issues. A roll-back roof may be required.
9. Axial and radial positioning of the Branson energizer are required.
10. Weight capacity will be 200 pounds.
11. The USAF production blade system robot and camera configuration are suggested for this system.
12. Basic system subassemblies will be portable on tracks to accommodate a variety of engine component sizes, while assuring that the platform is stable.
13. Angular location information is needed from the turntable.

14. Concentricity is important for image quality.
15. A 3-point support with nylon tips, 120 degrees apart, will be basic for the system.
16. Part/Fixture configuration must overhang so the Branson and camera have maximum access.
17. Three points of excitation may be necessary for each disk to assure adequate excitation.
18. A spoke-type "steering wheel" concept is suggested for maximum access to the bottom of a component.

As more brainstorming sessions were conducted, a final concept for the prototype system took shape. The fact that a prototype blade-inspection system and a fully automated blade-inspection module have already been produced, enabled many concrete suggestions regarding the final design of a disk inspection system. Figure 1 displays the suggested configuration of the prototype system, considering all input.

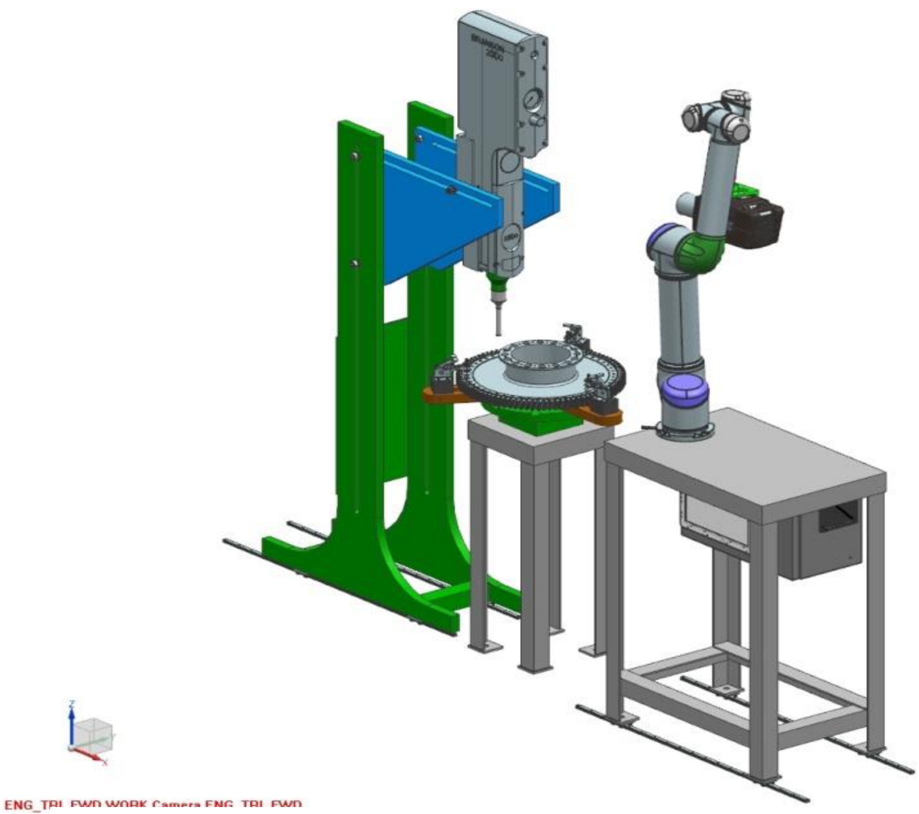

Figure 1. Anticipated Prototype Disk Inspection System Configuration.

Although not shown, the system will be mounted within an enclosure to protect the part from reflected heat and for sound suppression. The Branson exciter is on a rotator so that it can be used for axial or radial excitation. Experience from the lead-in program revealed that both are necessary. Access to the system for incoming disks will be via the overhead crane system that is currently in place at Tech Ops. The robot-mounted IR camera will be capable of viewing both disk faces, although the lower face would require disk rotation to view some regions. The exciter and camera subsystems will be mounted on tracks so that they can be manually adjusted for a range of disk sizes.

4.2.2 Ultrasonic Excitation Subsystem

An ultrasonic excitation source is required to transmit energy into the inspected component. Examples of these systems include a piezoelectric shaker and an ultrasonic welder system. This includes the power supply and the housing or fixtures that complete the system. Typical power ratings for a piezoelectric shaker system range from 800W – 4000W, with typical frequencies ranging from 14,000 Hz – 100,000 Hz. The excitation subsystem must be mobile to enable a variety of disk geometries to be excited. The optimal excitation orientation is vertical, with the component in a horizontal position. Typically, a Branson ultrasonic welder is used for this function, but a custom subsystem that is designed strictly for SIR testing may be a worthwhile investment.

4.2.3 Infrared Thermal Camera and Manipulation Subsystem

An infrared-thermal-camera subsystem is required to view the inspected component while it is excited with the ultrasonic excitation subsystem. The infrared-camera subsystem must be sensitive enough to detect the thermal signals generated from typical defects of interest. The camera must have the sensitivity to achieve the specified defect Probability of Detection (POD) for those defects of interest. Cooled MWIR (InSb) thermal cameras usually provide the best sensitivity (around 20 mK or better), whereas LWIR microbolometers are generally less sensitive but may be adequate in many applications. Frame rates 30 Hz or faster are generally sufficient for SIR measurements. Any resolution is adequate as long as the camera is close enough to the specimen to resolve defect indications. Considering that typical SIR testing systems are used at least part of the time as exploratory tools, it is recommended that the most sensitive camera at an affordable price should be selected.

Combined with the rotary-indexing-table concept being considered in Subtask 3.2.5, the camera must be positioned at discrete locations along a path from bore to rim using a robotic arm. The view angle would be close to parallel to the disk axis for much of the inspection, but it must tilt in-plane to assure line of sight for several typical views. At the blade-broach slots, circumferential view angles are needed. Automated rotary indexing of the disk must be included. Otherwise, a great many more unique camera positions are needed, and the robotic mechanism must have a much greater reach. The favored robot is the Universal Robots Model UR5-AE3, which is the same robot that is integrated into the automated blade inspection module. By the time the prototype disk inspection system program is initiated, new models may be available, but much of the software and programming that have been done for the blade system will transfer directly to the disk system, thus providing a cost saving and de-bugged package.

The suggested infrared camera for this task is the FLIR Model A8303sc. This is the camera that is used for the production blade inspection system that has been fabricated and delivered to USAF. The documentation associated with that program is extensive, right down to nuts-and-bolts level in a detailed bill-of-material listing. It can be consulted for most basic components that could be considered for the disk system. However, infrared-camera technology is advancing rapidly. By the time this program starts, there may be a better camera option available from FLIR or one of its competitors. It would be worthwhile to perform a study before buying the system IR camera.

4.2.4 Component Rotation/Indexing Subsystem

One possible scenario for the system would be to perform virtually all manipulations with the robotic camera system; however, it was determined to be more practical to incorporate an automated indexing rotary table. The additional cost and complexity will be offset the reduction in the functional requirements and size of the robot. Automated turntables are readily available and competitively priced. The industry continues to evolve. A short study at the inception of the prototype program to select an optimal turntable would be worth the effort expended.

Figure 2 shows a typical disk mounted on the turntable. It is set up for axial excitation and reasonably unobstructed view of the top face. The disk will have to be rotated within the fixture for two reasons: to access areas under the clamps with nylon cushions, and excitation at significantly different locations to assure complete coverage of excitation. When a disk is excited at one location, it is not necessarily

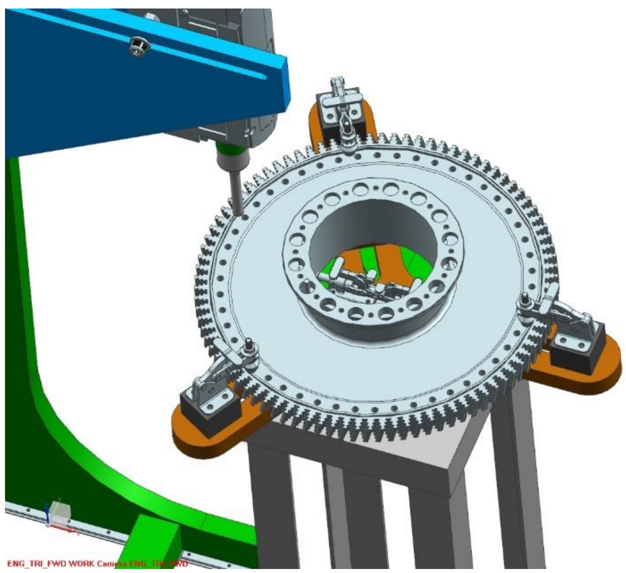

Figure 2. Disk in Clamping Arrangement

intuitive regarding which locations may not be adequately excited. The figure shows direct coupling to a disk. This will not be conducted on the prototype system unless contact is on a zero or low-stress location, such as on the outer tip of a blade fir tree. The figure also shows a three spoke arrangement for the disk holding fixture. This will provide maximum access for the exciter and the IR camera, potentially to avoid having to flip the disk during inspection.

4.2.5 Coupling or Fixture for Energy Transfer

A coupling medium or component fixture is generally required to transfer the energy from the ultrasonic excitation system to the inspected component. The coupling or fixture must not damage the component (see next subsection). Historically, business card stock has been found to be the best coupling medium in a laboratory setting. However, this approach is not acceptable for typical production inspection scenarios. For blades, specialized “pinch blocks” have been implemented to avoid the use of a coupling medium like card stock. In this scenario, the ultrasonic-excitation subsystem transfers energy into the fixture, and then into the component. The presence of a tight, hardened fixture prevents damage that could occur from being in direct contact to the excitation system. This approach has been so successful with the USAF inspection systems that a goal for the lead-in program was to design and test a similar concept for disk inspection. The first test of a “reverse-pinch block” concept that incorporated modified blade stubs was unsuccessful. Although the scrap blades were modified to fit tightly within blade slots and act as the coupling mechanism for the Branson, insufficient energy was transmitted to the cracked regions of interest. Hopefully, minimum design modifications can be made to achieve success with this approach.

4.2.6 Damage Avoidance Requirements

The inspection system and procedure must be designed in such a way that the component being transferred and tested does not incur any damage during inspection. Coupling media, such as a hardened, tight fixture, should be used to avoid direct contact damage. The ultrasonic excitation parameters must be set to not induce damage during the inspection. Parameter optimization tests or strain-gauge testing of the component during the pre-production phase can be used to verify damage avoidance. The fixture that holds the part in the system must not be capable of damaging a part. This fixture may be the same fixture that transfers excitation energy, as is the case with blade inspection. The only exception to these guidelines that may be proposed is a possible direct contact of the exciter to the disk at a location that experiences very low or zero in-service stress, such as the “dead rim”, or ends of blade retention posts.

4.2.7 Setup Standards and Hierarchy

For calibration of the SIR system, setup standards are required which emit infrared radiation in a measurable response to acoustic excitation. It is best that the infrared emission increases monotonically and linearly with acoustic excitation amplitude. Setup standards should conform as closely as possible to the characteristics of the parts being inspected by the system, (part geometry, weight, and material properties). In some cases, it may only be possible to simulate local disk characteristics. The recommended approach for artificial defects in setup standards is to use those that were developed during the USAF prototype blade inspection system program, or use artificial defects that were developed during the precursor FAA program. These are generally pressed-fit pins of prescribed sizes and interference fit, or small set screws in drilled and tapped holes. It is best if the defect can duplicate the infrared signal from defects of interest in amplitude and time evolution of the thermal signal. Setup standards should be created only using a method that is highly reproducible. Also, they must be capable of many calibration operations without any noticeable change in SIR signal.

In order to maintain functional integrity of the system of setup standards, a hierarchy is required that will include “grand masters”, “transfer masters”, and “working standards” that are used in conjunction with each inspection run. This type of hierarchy has been used for automated eddy-current inspection for decades and its use for SIR standards mitigates concerns that continued excitation of a standard will likely cause the IR signal response to change over time. For this reason, a grand master standard is needed which is seldom be used, so the signal is always the same. Transfer masters are then periodically checked against this grand master. The working setup standards are more frequently checked against the transfer masters. The working standards are used several times a day to ensure consistent operation of the SIR inspection system. Much like eddy-current setup standards, they will eventually change and be replaced.

The latest experiments with press-fit pins in relatively thick-blade and disk sections have shown them to be unacceptable due to lack of significant excitation. Set screws drilled and tapped into the standard may be the preferred approach for the time being. However, endurance tests should be conducted to look for signal "drift" as the screws possibly loosen. The latest method uses a staking process to keep the screws from rotating.

4.2.8 Ergonomics and Human Engineering

Operators will be constantly tending to the system so it should reflect common sense ergonomic features in the design; however, some are not intuitive, such as whether the operator should normally be standing or sitting. Several Military documents are available to assist with design when necessary. For example, MIL-STD-1472, Rev. G contains much detailed applicable information concerning virtually every aspect of a system such as an NDT module.

4.2.9 Part Handling and Transport

4.2.9.1 Identification

The system protocol will define a method for identifying disks, even if it is as simple as manual reading and entering the disk serial number. More automated approaches, such as barcode ID and RFID, could be used.

4.2.9.2 Batching

Batch processing of components based on testing multiple parts of the same geometry is much more practical for engine blades than disks. It is under consideration for the USAF blade program but will not be considered at this time for the FAA disk program.

4.2.9.3 Transport

Transport of components to and from the inspection system, as well as installing disks onto the system, are to be achieved using an available overhead crane system and some simple fixtures at the depot. It also must be assumed that a large variety of disks will be tested in a single shift, so design of transport fixtures should be sympathetic to that fact. Safety for personnel and disks is an important aspect of transportation.

Due to the size and weight of some of these components, access to mechanical lifting assistance is advisable to both avoid workplace injuries and reduce the likelihood of damaging the parts while preparing them for inspection. The parts must be manipulated onto the inspection fixture at a prescribed location and fastened in place, which may require some minor additional lifting and rotating.

A commercially available lifting device with little modification was used at FTT during the lead-in program; however, some special fixtures may be required to compliment the overhead crane capability at the overhaul center when the prototype system is put in place.

4.2.9.4 Mechanical Points of Contact

For the breadboard inspection system, an interface layer such as paper card stock is used to prevent any possible contact damage to an engine component during excitation using an ultrasonic welder. This isn't realistic for the production prototype system. Direct contact of the vibration source with the component or holding fixture is preferred. Fixture concepts will be suggested that only contact the disk on surfaces that experience zero stress or very-low-stress during engine operation, such as the outer ends of blade attachment features. Features such as integral bolted-rotor flanges; bolted-on labyrinth-seal flanges; cover-plate snap diameters; and blade attachments (fir trees, dovetails and slots) can be considered and submitted for approval by appropriate structural analysts. Fixture concepts may also be designed to provide surfaces where the ultrasonic excitation horn can contact and efficiently transfer energy into the disk. In order to accomplish a "whole field" SIR inspection, it is anticipated that more than one fixture attachment/excitation scheme may be needed for a given part or assembly to ensure that excitation energy is locally sufficient to induce activation of a crack. A single-fixture/excitation concept was designed and tested for a USAF compressor spool during the lead-in program. It was quite successful. However, test cases have been limited, and there are many more basic designs to be considered at an overhaul facility.

Earlier work by FTT using a rotary table has shown there can be a measurable loss in excitation and resulting crack signal, depending upon the setup. Therefore, it is important to test a concept thoroughly before spending much time and money to complete the task.

The inspection fixture must be compatible with the overhead crane system. Safety is critical, because many disks are heavy. Ideally, the part holding fixture could be double purposed as the energy transfer fixture. It may also be the fixture that holds the setup standard.

4.2.10 Enclosure Requirements

The system enclosure serves multiple functions, including ambient-light shielding, sound proofing, personnel safety, and shielding of hardware from some environmental dust. Although there is a desire to make it as compact as possible to minimize the footprint, the designers must be sympathetic to the fact that new, unanticipated components will probably be tested on the system. Generally, it is relatively inexpensive to select a larger enclosure than is currently needed to meet the known requirement. The enclosure must be robust and be capable of being moved numerous times around the shop. Figure 3 shows a concept of the system with a suitable enclosure. Current preference is to not have a roof on the enclosure; however, safety requirements related to noise level may force a design change to include a portable roof that can be opened to move components in and out via overhead crane.

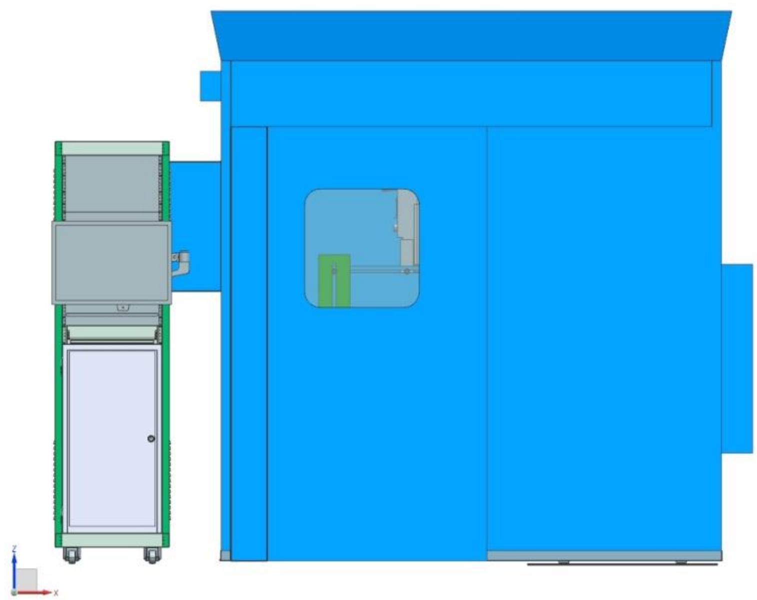

Figure 3. Prototype SIR Inspection System Enclosure and Rack

4.2.11 Usability

4.2.11.1 Manual and Automatic Operation

The prototype disk inspection system will have a variety of automated features. In general, some manual overrides should be included, wherever practical.

4.2.11.2 Access based on Inspector Certification Level

The system will have the ability to limit features and/or data access based upon the user's NDE Level certification.

4.3 Prototype System Software and Computer Requirements

4.3.1 Operating System Software

Operating software for this system may be largely derived from the operating system for the SIR blade inspection system that has been produced for USAF/Tinker AFB. It will have the distinct advantage of being produced, debugged, and used for a significant period on a related system. Appropriate permission should be requested from USAF to copy and use the operating system.

The software will provide a method for manipulating the turntable and IR camera robot, triggering the excitation of the component, and recording the part response. The system software will provide a method for reviewing and analyzing the results, as well as provide a method to manage the inspection data and subsequent post processing.

4.3.2 Defect Recognition Algorithm (DRA)

For the prototype system, the latest update of the DRA will be tuned for disk application and applied to assist with noise rejection and defect recognition.

To meet the demands of a production-inspection environment, the DRA will be configured to process inspection data within a reasonable time. One of the challenges of the SIR inspection data is processing all the data quickly, since the amount of recorded data is large (ex: 640x512 pixels recorded at 60 FPS for 2 seconds -> 39.3 million time-points of information). The DRA addresses this challenge through a series of data-filtering and data-reduction methods. These methods have been shown to reduce the full-processing time of the DRA, but enhancements and optimizations can still be made. Work during the lead-in program demonstrated that enhanced methods could be developed to augment or replace current methods to make the overall algorithm faster and smarter. Examples of enhancements and new methods that could be explored are faster data-vector operations, new parameterizations of signals for enhanced thresholds, and improved noise-reduction methods. These enhancements would help the DRA scale to the newer high-definition IR cameras (ex: 1280x720 pixel array) since the time-point information would nearly triple for the same time of inspection.

While the DRA, in its current state, can identify relevant indications as small as one pixel, the algorithm still lacks knowledge of size, location, or the state of surrounding pixels. Incorporating this information would enhance the interpretation capabilities of the program.

Potential enhancements to the presentation and reporting of the DRA results have been developed and documented. Examples of the enhancements for results presentation and reporting include but are not limited to generating easy-to-see boxes around relevant indications, numbered list of relevant indications with meta-data, high-contrast color mapping, and detailed inspection reports. Concepts like these enhancements should make digesting the DRA information easier and provide improved reporting documentation for record keeping.

A significant study was conducted during the lead-in program. Numerous enhancements show promise to further enhance a tool that has been shown to be valuable in the production blade inspection system. For that system, the current version of the DRA in a decision-making mode was shown to compare favorably with inspector results during a formal reliability demonstration. Still, more can be obtained, depending upon customer desires.

Monthly status reports from the lead-in program provide details regarding potential enhancements to the DRA, as it is currently implemented in the USAF production blade-inspection module. This section provides a summary of steps that can be taken to provide those enhancements, including prioritization.

Work was performed in the following areas:

- DRA algorithm flow was established
- Watershed transform used for separation of close ROIs (only if needed)
- Final characteristics chosen to use with a neural network
- Preliminary results demonstrated using an enhanced DRA

The "watershed transform" can be used when defects are too close together to detect and characterize individually. It will separate indications into individual regions of interest (ROIs); however, it will it will decrease the overall size of ROIs and increase the number of ROIs to analyze along with a possible higher false-call rate. This method may be valuable if estimates of defect size are desired for SIR testing.

An "area coefficient" also has potential. After applying binary thresholding based on heating intensity, the area of the resulting particle is measured throughout the time series. Area, or size and intensity of crack indications should grow throughout excitation and then decrease in size as they decay. A correlation coefficient can be applied to a series of numbers that represents the average defect. Figures 4 and 5 shows that such an approach could be used to pick out crack signatures accurately, as well as signatures from artificial defects.

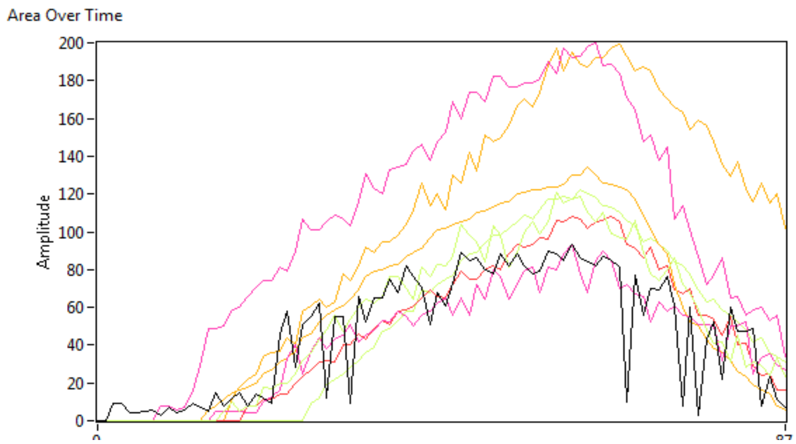

Figure 4. Various Crack / Pin Area Measurements from JT8D Disk

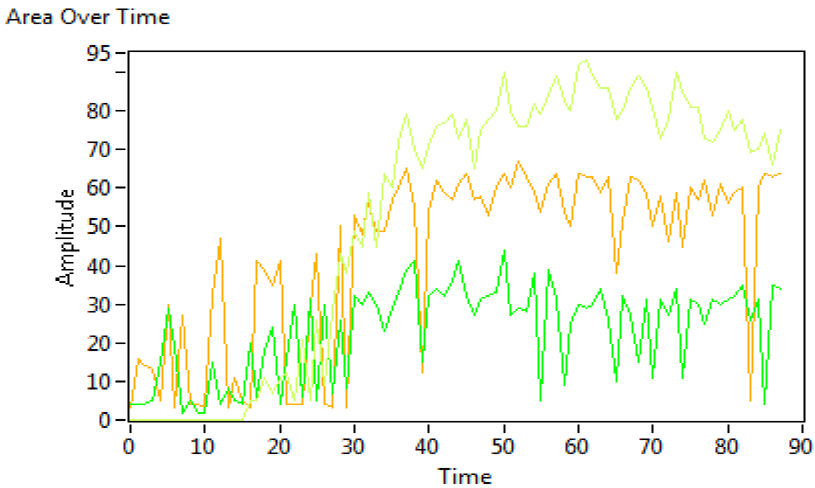

Figure 5. Non-Crack / Pin Area Measurements from JT8D Disk

"Heating falloff correlation" also shows promise. After excitation, cracks typically have the highest intensity of heat at their centers with Gaussian falloff. A plot of distance from crack center versus heat intensity could be approximated and correlated by a logarithmic function. Figures 6 and 7 show that a clear distinction could be made between crack and non-crack signals, based upon limited testing with available hardware at this time.

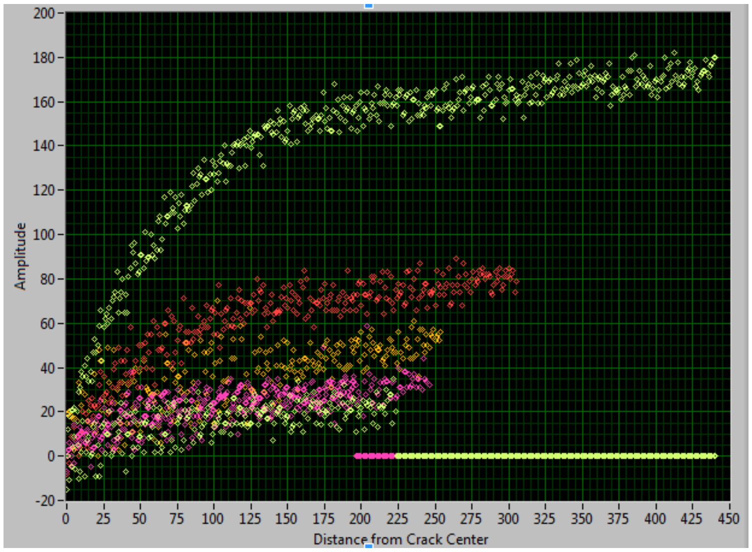

Figure 6. Various Crack / Pin Area Measurements from JT8D Disk

"Principal component analysis" (PCA) allows compression of the time variable in infrared data using singular value decomposition (SVD). The resulting data and images are like original DRA results. Results show cracks and other areas of progressive contrast. Subtraction based around the transition of heating to cooling allows for signal measurement use throughout full recording. These images or their underlying data could be saved to serve as an efficient recording means for

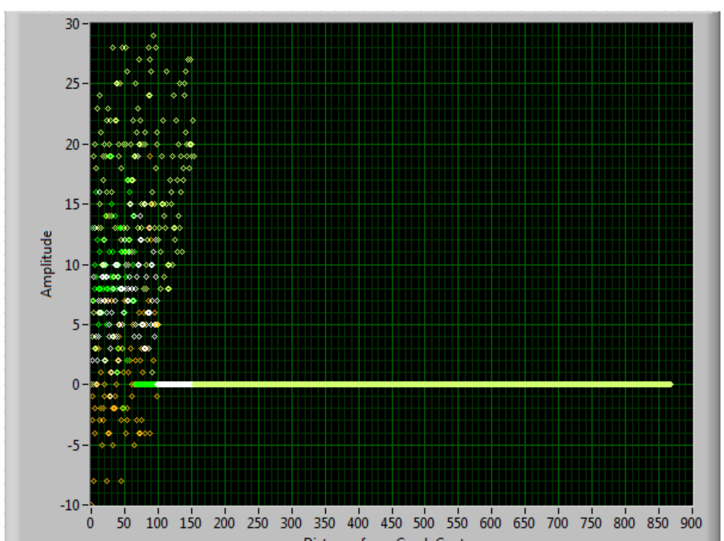

Figure 7. Non-Crack / Pin Area Measurements from JT8D Disk

IR results. This allows for extremely small storage volume at maximum frame size (326,400 doubles ~ 2.6 MB or 16-bit ints ~ 0.6 MB). Using this approach, 3 TB HD could store over a million full frame results. Data storage for a full range of information has been a concern for SIR testing since discussions began with USAF and the FAA.

"Crack Likeness" is another approach that shows promise. A trained particle classifier is developed, based on ROIs generated from original DRA with a low threshold for minimum peak size. ROIs are re-sampled to correct size (32 pixels by 32 pixels). In the test case, 88 crack ROIs and 225 non-crack ROIs were obtained to train the LabView particle classifier. The resulting classifier is a tool that measures the distance to the sample that closest resembles a crack. Lower numbers represent closer resemblance to cracks.

Other analysis options are available, perhaps to the extent that this subject deserves its own small contract or separate task to exploit the potential fully. The other approaches include:

- Elongation Factor (maximum "feret" diameter divided by minimum "feret" diameter)
- Compactness Factor (area divided by the product of bounding rectangle width and height)
- Heywood Circularity (perimeter divided by the circumference of a circle with the same area)
- Type Factor (factor relating area to the moment of inertia)
- Particle Frame Persistence (the number of frames that a particle is visible)

Looking at relative potential for the various approaches in light of current experiments, neural-network-learned weights show particle compactness has greatest weight in the answer, followed by area coefficient, particle frame persistence, crack likeness and heating falloff correlation

Surprisingly, the original DRA values contribute only 6% of the NN's answer, but this could be because of pre-filtering of ROIs based on the original DRA output. Table 1 shows relative advantages, based upon current testing and available data.

Table 1. Relative Observed Advantages of Signal Processing Approaches

Compactness factor 33%

Area coefficient 15%

Particle frame persistence 14%

Crack likeness (particle classifier) 13%

Heating falloff correlation 12%

Original DRA mean value 4%

Original DRA max value 2%

Elongation factor 2%

Heywood circularity 2%

Type factor 2%

Linear signal mean 2%

Linear signal max 0%

Bias 1%

Going forward with enhancement-method selection, obtaining more suitable crack samples would make training the neural networks more accurate. If more samples are obtained, separating data into a training-sample set and a validation-sample set would ensure the neural network is not over-trained. A convolutional deep neural network should provide a more accurate image-classification system. TensorFlow by Google provides the framework for such a neural network.

There are so many potential options for signal enhancement and data management using the above approaches and others that a very productive SBIR program could be assembled and proposed. This could include generation of additional relevant crack specimens.

4.3.3 Computer Minimum Requirements

The suggested computer for the prototype system is the superlogical Model SL-4U-C7H61-HA. This is a 19-inch rack mount computer, so assumptions have been made regarding physical size of the computer and how the system will be configured. This is the same computer that is used for the production blade-inspection system for USAF. It has been shown to be adequate for that scenario. The documents associated with that program contain extensive bill-of-material listings, so they can be consulted for suggested components all the way down to nuts-and-bolts level.

4.4 Basic Ancillary Requirements

4.4.1 Reliability, Accuracy and Consistently Meeting Requirements

4.4.1.1 Probability of (Flaw) Detection (POD)

Capability of the inspection system must be demonstrated once the final configuration is achieved. Any significant change to the system after demonstration is cause for a retest. The system should be able to support a POD study in accordance with USAF MIL-HDBK-1823 Rev A. This requires a mixture of defective components or subcomponents with a known variety of defect sizes mixed with non-defective parts and run through the entire inspection process under production conditions, using multiple inspectors. USAF has produced many disk specimens that simulate local geometries, but no intact disks have ever been cracked for demonstration purposes. Time and expense have been prohibitive. For SIR testing, the design of specimens must be revisited, because global geometry is more important for this technique than any other that has ever been tested. This was not an issue for blades, because they are small and relatively easy to approach as intact specimens.

4.4.1.2 Ensure Inspection to Manufacturers' Specifications

The manufacturers' inspection and repair documents may be required for SIR process development. These specifications are typically known as Technical Orders (TOs) for Department of Defense systems. They directly provide the technical requirements for all inspection processes of a part number. The TOs are broken down into subsections known as Work Processes (WPs), which detail various technical procedures for groups of similar parts. The WP breaks down the component inspection into discrete zones and specifies the required inspection process, service limit, repair limit, and repair process for various specific defects in each aforementioned zone. Inspection results reporting is tied back to these documents and the respective zones that are called out for each part number. It is anticipated that commercial engine manufacturers will provide similar documents; however, in some cases the OEM will not be involved, and inspection requirements may come directly from the operator, the FAA or other regulatory agency.

Interpretation of inspection results by the SIR "Defect Recognition Algorithms" (DRAs) is to be consistent with current acceptance standards applied by the MRO operation. Input from inspection personnel is to be incorporated to create the most representative inspection process. Significant differences in acceptance and rejection rates between current inspection practices and SIR testing may occur and should be investigated. For this reason, it will be advantageous to save as much raw data as can be done in a practical sense, at least until the new SIR inspections are proven to be compatible with desires of the MRO engineers.

4.4.2 Performance

4.4.2.1 Rate of inspection

Inspection rate should be as fast as possible without compromise to inspection reliability or system integrity. Although disk inspection has not been developed to the point where subcomponent inspection times can be estimated, the time to complete an automated SIR inspection of blades using the USAF system is approximately two minutes per airfoil. This inspection-time estimate includes component loading/unloading, inspection actuation, infrared-data recording, and post-processing. Using SIR testing, supervision will be able to prove that every critical region of a part has been inspected, as opposed to most manual processes where an inspector may forget to view a region and no verification exists. Through the system-development process, it has become obvious that multiple excitation locations around a disk will probably be required to deal with possible "dead zones". This may also necessitate multiple positions of a part on the holding fixture. These operations certainly will impact inspection speed and must be minimized without sacrificing inspection reliability.

4.4.2.2 Defect detection and false calls

The single, quantitative design criterion for the USAF prototype blade inspection system was a mean 90% POD at 0.040 inch crack length, using MIL-HBK-1823, Rev. A guidelines. In fact, a demonstration using skilled operators on the USAF prototype blade system showed a mean POD much smaller than 0.040 inch for the selected components. It is anticipated that the same smallest-crack-size criterion will hold for SIR inspection of some engine disks and spacers. Thresholds may vary for each part location, thus the processes are to be tailored to minimize the false-call rates, while maintaining inspection-reliability requirements. It must be emphasized that some components will fall into this category, while others may range from “easy” to “impossible” to inspect using SIR technology. Inexpensive early assessments should be conducted before any new component is considered being a candidate for SIR testing. Along with basic suitability for inspection, use of a finely tuned DRA will be critical to consistent achievement of the goals.

4.4.3 Supportability

4.4.3.1 Support Staffing

The target staffing requirement for the production SIR disk inspection system is one Level II certified inspector per shift. Loading of components will be assisted by a device that will be designed and tested during the current program. Ultimately, it may be possible for one operator to run multiple machines simultaneously.

4.4.3.2 Adaptation to Future Parts

This prototype SIR NDT system is designed to accommodate engine disks and spacers within a practical size and range. Future adaptations to allow inspection of other components having various sizes, weights, and complexity is anticipated, but not within the scope of the current program.

4.4.3.3 Training

A training program will be offered for the system. The system will be designed so that basic operation can be mastered in just a few days, as demonstrated during the USAF prototype blade SIR system on-site task at Tinker AFB. It is recommended that the owner of the system use Level II inspectors who have certifications in infrared NDT. As mentioned above in this document, various levels of interaction with the system will be available according to levels of personnel certification.

4.4.3.4 Inspection Methods and Hardware

Specific formal inspection methods are recommended for each part number, as specified by the responsible department at the overhaul center. Key parts of the method may come from depot engineering, the OEM, or a skilled subcontractor such as the supplier. Regulatory agencies also may provide guidance. It is the intention of the supplier to make the system simple enough to accommodate new parts of reasonably similar design, so that the owner can produce his own inspection fixtures, optimization tasks, and processes. Fixture design for the SIR system must promote camera access, limit vibration damping, and facilitate transport. The supplier will remain available to perform any and all operations required to implement the system for new part designs, but that will not be essential.

4.4.3.5 Inspection Requirements and Limits

Specific inspection requirements and limits are to be provided by the OEM, regulatory agency, or system owner. Those physical requirements will be converted to appropriate signal limits in the DRA. In some instances, the inspection limits may be derived from formal NDT reliability demonstrations that convert desired physical-inspection limits to indicated flaw criteria in the SIR system; however, it must be recognized that there is currently no verified correlation between SIR signal strength and flaw size. In the future this may be possible with additional specimens, testing, and development of the DRA.

4.4.3.6 User Guide

A detailed user guide or manual will be provided for the SIR Inspection System, including hardware, software and any peripheral devices. The supplier will also remain available to assist when questions arise. The user guide for the USAF blade inspection system is a good starting point for this document.

4.4.3.7 Recommended Spare Parts List

The customer will be provided with a recommended spare-parts list. The list will maintain a balance between the need to have on hand any critical part that has a potential to fail in-service at any time versus the economic impact of purchasing parts that probably will never fail. For example, the end effector of the Branson subsystem can fail in-service if the operator makes a serious mistake. It isn't very expensive, but failure could shut down an operation for days if the replacement isn't in hand.

4.4.4 Interfaces

4.4.4.1 Facility Connection – Power, Air, Cleanliness, Lighting, Noise, Vibration

Interface planning should be coordinated with the appropriate facility group at the MRO shop; a tentative list of necessary interfaces includes:

1. 208-240V and 110V power source; powers Branson and electronics.
2. Shop air (<100 psi); supplies Branson actuation system and auxiliary items like articulating arm.
3. System enclosure; prevents incident thermals from reflecting off the components and maintains a safe workplace. (The enclosure is generally provided with the system.)
4. Low vibration, level environment; prevents equipment (most importantly IR camera) from shaking.
5. Reasonable range of temperature and humidity for typical system electronics.

4.4.4.2 Operator Interface

Physical interfaces will include but not be limited to a keyboard, a mouse, and a scanner. At least one red "Stop" button will be strategically placed for easy access by the operator.

4.4.4.3 Customer Interface – Reports, Data, Return of Parts, Parts Disposition

Reporting may be achieved on a "per part number" basis, but virtually any arrangement is possible and only limited by the input descriptions of the components to be inspected. As noted, reports will tie back directly to the technical orders for a given component. Data will be stored in a database structure, with the reports and raw data saved in the same location. The data will be stored locally on the contractor-supplied system and the data can be accessed by management personnel as needed.

Parts should be segregated after inspection, based upon preliminary disposition. Additional work may be required, repair may be required, rejection may be necessary, or user input may be required and noted in a reporting summary, with more detailed results included in subsequent sections of the report. Clearly separated holding areas will be designated for each population of components, providing maximum assurance that rejected parts will not mistakenly find their way into the acceptable population or any other population.

4.4.4.4 Disposition of Inspected Parts

As components leave the active system, they will receive a preliminary disposition of "Pass" or "Fail". Parts entering the "Fail" area may later be found to be acceptable, but only after appropriate review. Any component that fails will immediately be segregated from other components and placed in a special secured location for engineering review and final disposition.

4.4.5 System Envelope and Packaging

4.4.5.1 Floor space

All floor space requirements will be communicated from the supplier to the appropriate MRO facilities representatives early in the manufacturing program. Changes in "footprint" will quickly be communicated if they occur. A typical prototype SIR system will require a space of about 4 feet by 8 feet. Additional space is required for receiving and outgoing areas, as well as secure locations for parts marked with "Fail". Total floor space required may be approximately 20 feet by 20 feet.

4.4.5.2 Weight

The prototype system may weigh approximately 500 lbs. Its load bearing and dimensional capacity should accommodate most fan disks, turbine disks and spacers that frequent the MRO shop.

4.4.5.3 Portability

The prototype SIR disk inspection system will be designed to be portable. A typical system has heavy-duty locking wheels.

4.4.5.4 Enclosure requirements for inspection

The prototype SIR disk-inspection system will have a thermal enclosure to prevent incident thermal energy reflecting off the component and attenuating the inspection results. The enclosure will ensure that the operator and bystanders cannot be injured during active system operations. The enclosure also reduces dust and debris that might interfere with or damage sensitive electronic devices. It will be sized with some anticipation that relatively large parts may be inspected in the future. More detail is included in Section 4.2.10, Enclosure Requirements.

4.4.6 Safety

4.4.6.1 User protection – Physical Separation and Pinch-Point Avoidance

Any automated operation will integrate physical separation whenever the hardware used does not already include user safety protocols or process control, such as an enclosure to protect the user from the moving Branson end effector, or any other automated operation that may be selected for use with the system. Any lifting or positioning of components heavier than 30lbs should follow generally accepted protocols.

In the event of a sudden power failure, the system must be designed to shut down gracefully. Once power is restored, the system may easily be rebooted, and operation may continue. There will be no battery backup to provide normal system operation during a power failure. The system must comply with all user health and safety requirements.

4.4.6.2 E-stops

Manual E-stop is required for stopping the ultrasonic excitation source or any other automated movement.

4.4.6.3 In-use warnings

The system will be capable of providing in-use warnings to alert the user of any issues or errors. These alerts may come in a visual and/or audible form.

4.4.6.4 Electrical codes

All electronics, cabling, connectors, etc. should follow NEC and OSHA guidelines, as well as state and local codes.

5 Bibliography

Human Engineering, Ergonomic Design Standard. (n.d.). US Department of Defense - MIL-STD-1472G.

Standard Practice for Crack Detection Using Vibrothermography. (n.d.). ASTM Standard E3045-16.

Implementation Plan

for a Prototype Sonic Infrared Engine Disk Inspection System

1 Introduction

1.1 Background and Purpose of this document

Reducing sustainment costs while extracting the maximum worthwhile life from turbine engine components is a need recognized by the Federal Aviation Administration and the U. S. Air Force. Florida Turbine Technologies, Inc. (FTT) anticipates being tasked to use the technical advancements from several recently completed FAA and USAF programs to move forward with fabrication of a prototype sonic infrared (SIR) disk inspection system. A production blade inspection module has already been implemented at Tinker AFB, so much has been learned from that effort, as well as the conceptual design project for this prototype.

The detection of surface-breaking defects in critical engine components using fluorescent penetrant inspection (FPI) has been a well-established technique in the aerospace industry for many years. However, production FPI processes have shortcomings that still remain, despite many years of use and process improvements. One of the most critical shortcomings is the high variability in inspection capability due to human factors. It is also well recognized that surface preparation and surface opening of crack-like defects strongly influence performance. Although still a relatively new method, SIR inspection technology has shown the potential to be a replacement for FPI in many scenarios, with less time consumed by inspection, thorough documentation of each inspection, higher inspection reliability, less surface preparation, and (perhaps most importantly) no environmental concerns. This is the basic purpose for the envisioned SIR disk inspection system. Based upon previous FAA funded research and complimentary research funded by the USAF, SIR demonstrations in a production environment have now shown statistical evidence of the ability to detect reliably cracks in military compressor blades. Furthermore, an automated production blade inspection system has been produced for USAF depot inspections. For more massive components such as engine disks, practical implementation questions still need to be addressed through prototype system testing before SIR can be commercially viable. The implementers will be the first to state that SIR testing will not replace other NDT methods for every engine component. This is universally true for every inspection technology. Specific applications require the thorough knowledge of the physics and limitations of SIR testing.

The purpose of this document is to provide the framework for the optimal transition of the prototype system from the laboratory at FTT to a manufacturing or depot floor. This document assumes that a prototype system will be ordered based upon lead-in work associated with FAA contract DTFACT-16-C-00003. The best implementation will be one where each critical technical and programmatic question has been answered before the system is delivered.

1.2 Scope of the system design

The basic capability of the SIR disk inspection system will be to perform rapid, accurate crack inspections for a variety of disks in an engine overhaul shop. The scope of the initial system design will cover most of the possible commercial engine disk designs, but boundaries have been established, leaving off some of the more massive and exotic engine components and assemblies. Once a prototype system has been thoroughly proven, it may be possible to develop several versions of the inspection system to accommodate easily radically different disk designs and envelopes. This isn't a unique idea. Automated eddy current inspection systems have been produced for various special applications.

There were five technical tasks defined in Contract DTFACT-16-C-00003 in order to achieve the stated objectives: (1) Task 1 involved generating a complete conceptual prototype system design and selecting a specific disk of interest. Delta TechOps provided two disks of their choice, the PW2037 high-pressure turbine disk. (2) Task 2 included re-assembly of the breadboard disk SIR inspection system from the lead-in program and experimental verification that the system produced identical results to the initial assembly. It was tested using a disk containing artificial defects from the lead-in program to verify that inspection sensitivity for those defects had not changed. This formed the baseline for additional experimental activities. (3) Task 3 included the assessment of the impact of residual compressive stress on the sensitivity of disk SIR testing. This phenomenon can be divided into two categories. The first is residual compressive stress caused by media finish, localized to a few mils beneath the surface of the part. The second is compressive bulk stress caused by manufacturing or operational stresses. This would be much harder to define and test than media finish effects, because any special constraining fixture to simulate bulk stress will reduce SIR effectiveness simply from constraint of the specimen. In fact, testing of this phenomenon was eliminated from the program, preferring to perform a thorough test of surface finish effect. (4) Task 4 included design considerations for various important subsystems of a prototype disk inspection system. These include a practical way to fixture the disk and insert energy into the part, improvements to the defect recognition algorithm (DRA), a practical disk handling device, automated indexing subsystem (to be used on blade slots, etc.), and automated IR camera positioning. These all feed into the conceptual prototype system design. (5) The purpose of Task 5 was to identify a path to MRO shop implementation. Delta TechOps engineers participated to provide unique expertise that isn’t available at FTT.

The scope of a system design program must consider formal contractual documents that are specific to the customer. For USAF, these are “CDRL” items. They include detailed software documentation and a bill of material list. These are often ignored or given little notice as a program is being negotiated, but history indicates that they can be expensive and time consuming.

1.3 Relationship of this plan to Conceptual Design Document

The basic objective of Contract DTFACT-16-C-00003 was to conduct necessary research to continue development of the SIR inspection method for flight engine disks toward a field implementable state of readiness. The Implementation Plan must be used in conjunction with the Conceptual Design to achieve a complete understanding of the intent of the overall effort to implement SIR technology. Details of the system concept are not repeated in the Implementation Plan.

FTT collaborated with FAA engineers, USAF, and Delta TechOps throughout the performance of Contract DTFACT-16-C-00003 to generate both the Conceptual Design and Implementation Plan.

2 Engineering Requirements

2.1 Use of Guiding FAA and Delta TechOps Documents

A robust Conceptual Design document has been completed for the prototype disk inspection system. Review and acceptance of the design by the MRO facility managers and engineers is a prerequisite prior to implementation.

In order to implement SIR disk inspection at TechOps, specific technical requirements and verification documents, following the Code of Federal Regulations (CFR), were identified as key elements to be addressed for this process change. Areas of technical concern are listed below, along with a listing of the supporting data necessary for compliance. In order to achieve compliance, it is recommended that each requirement listed below be satisfied. The technology is novel, so any short-cut could lead to suspicion and rejection of the technology.

The specific documents provided by TechOps addressed another novel NDT technology that has been successfully implemented at TechOps. This “template” was a significant starting point. However, details of the narratives for the other NDT technology cannot be included herein, in order to protect the proprietary nature of TechOps information.

2.2 Suitability and Durability of Inspected Engine Components

This recommendation addresses CFR No. 33.15, “Materials - Compliance by Analysis”. Suitability and durability of any inspected engine component are not affected by proper implementation of SIR NDT. Three aspects of the inspection are critical: (1) high statistically based NDT reliability and documentation of the inspection, (2) no direct contact between the SIR exciter and any surface of the component that experiences significant in-service stress, and (3) verification that excitation levels are far below any possible fatigue threshold.

Assurances are in place to either eliminate any direct contact between the Branson titanium “exciter” and surface of the part, or make direct contact at locations with zero-to-minimum operating stress (such as the “dead rim”) and prior approval by Engineering. Therefore, the mechanical strength and other properties assumed in the design data of the materials are unchanged by contact of the Branson titanium exciter with a component.

Engineers will define and conduct an appropriate theoretical and experimental task to verify that excitation stress levels and durations are significantly below known fatigue thresholds, thus assuring that SIR testing will not degrade mechanical properties. The results of this task will be subject to periodic review. Typically, excitation levels are less than 10% of any level of concern.

It is also recommended that evaluation by high magnification optical microscopy be conducted to verify that no surface damage has been imparted to any part surface receiving vibratory energy during the inspection process.

2.3 Statistically based Verification for NDT Method Substitution

This recommendation addresses CFR No. 33.19, "Durability - Compliance by Analysis". NDT method substitution must be done in a purely objective manner, based upon a proven verification process. Statistically based inspection reliability demonstration testing and analysis according to USAF MIL-HBK-1823, Rev. A is used by the USAF and is recommended for use as the guideline to compare directly the FPI method of current use to the SIR method that will be implemented. Historical testing and comparison has shown SIR testing to produce superior inspection reliability, along with imaged records of test results and various forms of advanced signal processing. For example, USAF blade testing has shown that comparable tests for compressor blade inspection revealed 90% mean POD at 0.028 inch crack length for SIR testing, when the comparable figure for FPI was 0.040 inch crack length under ideal conditions. However, it must be fully appreciated that changing the inspection system or the subject engine component necessitates a new demonstration to estimate accurately the inspection effectiveness.

Both the SIR and FPI demonstrations must be performed under realistic production inspection conditions. Often, when an inspection reliability demonstration is conducted on FPI, the conditions are not comparable to the actual production conditions. During the demonstration, pristine materials are used, processing may be different, inspectors may be hand-picked, and inspectors take much more time to evaluate specimens. Detailed demonstration procedures must be developed for both NDT methods to be compared, and supervision of the demonstrations by an objective expert must be performed. Historical studies indicate clearly that in most cases SIR testing provides superior statistically based inspection reliability when properly applied to suitable engine components.

Production of the most suitable specimen set to perform the NDT reliability demonstration may require some engineering design work, and agreement among all parties affected by the demonstration results.

2.4 Influence upon On-wing Monitoring Programs or Engine Inspection intervals

CFR 33.4 Instructions for Continued Air Worthiness- Compliance by Analysis

This recommendation addresses CFR No. 33.4, "Instructions for Continued Air Worthiness - Compliance by Analysis". No operational on-wing monitoring program is affected as a consequence of following this proposed change in general surface inspection procedure used at the depot. The change does influence maintenance practices but not engine inspection intervals and does not influence life limits for any critical rotating parts. This change in maintenance practice is only the alternate inspection when instructions indicate that proper verification has been performed, and SIR testing may be used for a particular application. In those instances, SIR testing is a valid substitute for any call-out of FPI in an engine manual. Thorough evaluation and comparison of SIR testing to FPI using USAF MIL-HBK-1823, Rev. A as the basis is a requirement.

It is possible that at some future date implementation of SIR testing in a widespread manner could impact engine overhaul intervals, based upon a smaller screened crack size than inspection performed by FPI. This would be a result of cooperation between structural engineers, product support experts, and the depot inspection team.

2.5 One-to-one Correlation of SIR Testing with FPI

This recommendation addresses CFR No. 33.53, “Engine Component Tests - Compliance by Analysis”. Effectiveness of SIR testing must be compared one-to-one with the state-of-the-art specified FPI process. SIR testing must show comparable or superior statistically based inspection reliability when compared to the exact FPI process used on any specified engine component. Demonstration, analysis and presentation should be performed in compliance with USAF MIL-HBK-1823, Rev. A. Furthermore, preliminary testing must be performed when considering substitution of SIR to assure that the technique is suitable, producing excellent results with a reasonable level of false inspection calls.

2.6 Vibration Characteristics of Components Tested by SIR

This recommendation addresses CFR No. 33.63, “Vibration”. It is recommended that verification of zero surface damage to any location on a component surface that receives vibratory energy through a coupling device be verified with optical microscopy for the first part and any instances where there is a method change. Alternately, in the case of direct energy application at a zero or minimal operating stress location, such as the outer surface of a blade slot “steeple”, the optical analysis must show that any surface disturbance is negligible simply as final proof.

Engineering personnel must also receive quantitative proof that the level and duration of excitation energy associated with SIR testing is far below any fatigue threshold (LCF or HCF) of concern for each candidate component. Typically, excitation levels are less than 10% of any level of concern. Several experimental methods exist to perform this evaluation and produce undeniable proof.

2.7 Influence on Surge and Stall Characteristics

This recommendation addresses CFR No. 33.65, “Surge and Stall Characteristics”. Flight operating conditions remain unchanged. There is no influence upon surge or stall characteristics. However, in the future, implementation of SIR testing can potentially lead to extended operating time between overhauls for the engine, based upon improved statistically based inspection reliability for smaller screened fatigue crack lengths and imaged inspection records. Such proof is derived using well-known and trusted demonstration, analysis and presentation methods contained in USAF MIL-HBK-1823, Rev. A. For such to take place, Engineering must be educated and totally buy in to the USAF experimental processes and analysis methods. If operational lives are based upon fracture mechanics analysis, then a case may be made for life extension.

2.8 Safety Analysis

This recommendation addresses CFR No. 33.75, "Safety Analysis - Compliance by analysis". It is anticipated that implementation of SIR testing will provide an additional level of safety that is associated with screening of smaller potential active defects and production of an imaged record of inspected surfaces, much like eddy current or radiography inspections.

Effectiveness of SIR testing must be compared one-to-one with the current specified FPI process. SIR testing must show comparable or superior statistically based inspection reliability when compared to the exact FPI process used on any engine component. Demonstration, analysis and presentation should be performed in compliance with USAF MIL-HBK-1823, Rev. A. Furthermore, initial testing must be performed when considering substitution of SIR testing to assure that the technique is suitable, producing excellent results with a reasonable level of false inspection calls.

It is recommended that absolute verification of zero surface damage to any part surface that receives vibratory energy be verified with optical microscopy. Alternately, in the case of energy application at a zero or minimal operating stress location, such as the outer surface of a blade slot "steeple", the optical analysis must show that any surface disturbance is negligible simply as final proof.

Engineering personnel must also receive quantitative undeniable proof that the level and duration of excitation energy associated with SIR testing is far below any fatigue threshold (LCF or HCF) of concern for each candidate component. Typically, excitation levels are less than 10% of any level of concern.

2.9 Major Alterations, Major repairs, and Preventive Maintenance

This recommendation addresses CFR No. 43.14, "Appendix A, Major Alterations, Major Repairs, and Preventive Maintenance". There will be no required component alterations, changes in special repairs or preventive maintenance. For the vast majority of engine disk inspections, any detection of a possible active crack is cause for a status of "Reject/Scrap". Detection of more and smaller cracks than FPI may lead to some additional disk rejections, but there exists no current data to confirm or refute that postulate.

The inspection of the whole field surface inspection of engine components using SIR testing does deviate from most engine manuals, where FPI has been the indicated method for decades. Therefore, this alternate whole field inspection procedure must be approved by Engineering and QA Management.

3 Packing, Shipping, and System Location at Customer Facility

3.1 Custom Crate

The prototype system will be shipped in a custom crate, or set of crates. Obviously, safety for the system will be a prime consideration.

3.2 Coordination with Customer for Shipping and Set-up

Contract coordination with receiving personnel is important from early stages of the program. The design document specifies utilities requirements and footprint. Packaging, shipping, receipt, supplier set-up of the system, and functional testing must be closely coordinated. Fortunately, in the past, it has been easy to set up implemented systems and initiate testing.

4 Customer-required Contract Data Requirements

Each customer has its own set of contract data requirements. These constitute another important part of the implementation program, and the scope of the activity to satisfy the requirements is often underestimated, resulting in cost and schedule overruns.

5 NDT Reliability Demonstration on Fully Implemented System

Details of the statistically based capability demonstration of the implemented system are contained in the design document. Supplier and receiver must appreciate that any modification of the system after completion of the demonstration invalidates the results of the demonstration. Demonstration should be performed using USAF MIL-HBK-1823, Rev. A.

6 Customer Meetings and On-site Support

The customer should schedule regular meetings with the supplier to discuss all aspects of the inspection system. Additional meetings may be required to coordinate transportation and set-up of the system. A kickoff meeting with the system supplier following installation and check-out is required prior to formal acceptance of the system. Several weeks of familiarization and inspector training will be required. It is the responsibility of the customer to provide properly certified inspectors for the training phase of this implementation. When the system is fully implemented, and the customer has begun inspection operations, it is important for the supplier to appoint a focal point who will remain available for some period to answer questions and travel back to the customer's facility if a major issue arises.

7 Fixtures and Set-up Standards (Kits)

The conceptual design document addresses these hardware items in detail. It is anticipated that each part number disk will have its own particular "kit", containing software, set-up standards, and special fixtures. Several kits may be ordered with the system to assure that it addresses an adequate number of components when it is implemented. Sufficient training should be provided by the supplier so that the customer is fully capable of generating their own "kits" for new part configurations.

8 Health and Safety Considerations

Any automated operation will integrate physical separation to avoid pinch points whenever the hardware used does not already include user safety protocols. This would include features such as an enclosure to protect the user from the moving Branson end effector, or any other automated operation that may be selected for use with the system. Any lifting or positioning of components heavier than 30lbs should follow generally accepted protocols.

In the event of a sudden power failure, the system must be designed to shut down gracefully. Once power is restored, the system may be re-booted easily, and operation may continue. There will be no battery back-up to provide normal system operation during a power failure. The system must comply with all user health and safety requirements.

Manual 'E-stop' is required for stopping the ultrasonic excitation source or any other automated movement.

The system will be capable of providing in-use warnings to alert the user of any issues or errors. These alerts may come in a visual and/or audible form.

All electronics, cabling, connectors, etc. should follow NEC and OSHA guidelines, as well as state and local codes.

The enclosure and system operation should be designed to eliminate any hearing issues as defined by local health and safety regulations. However, it is possible that design of the system to not have a roof on the enclosure, or some other factor may necessitate hearing protection in the final analysis.

9 Summary and Recommendations

It is anticipated that implementation of SIR testing will provide an additional level of safety that is associated with screening of smaller potential active defects and production of an imaged record of inspected surfaces, much like eddy current inspection.

Statistically based inspection reliability demonstration testing and analysis according to USAF MIL-HBK-1823, Rev. A will be used to compare directly the FPI method of current use to the SIR method that will be used. Historical testing and comparison have shown SIR testing to produce superior inspection reliability, along with imaged records of test results and various forms of advanced signal processing. For example, USAF blade testing has shown that comparable tests for compressor blade inspection revealed 90% mean POD of approximately 0.028 inch crack length for SIR testing, when the comparable figure for FPI was approximately 0.040 inch crack length under ideal conditions.

Effectiveness of SIR testing must be compared one-to-one with the current specified FPI process. To be acceptable, SIR testing must show comparable or superior statistically based inspection reliability when compared to the exact FPI process used on any engine component. Demonstration, analysis, and presentation must be performed in compliance with USAF MIL-HBK-1823, Rev. A. Furthermore, initial testing must be performed when considering substitution of SIR testing to assure that the technique is suitable, producing excellent results with a reasonable level of false inspection calls.

Caution should be exercised when comparing results from the production implemented form of SIR testing to the currently applied FPI process. Often, an attempt is made to compare SIR testing with non-production FPI results relative to specimen processing times, inspection times, or use of non-production test specimens. Care should be taken to avoid comparing a production SIR inspection with a laboratory FPI inspection process. Prior inspection demonstrations of realistic FPI processes performed by independent contractors have shown the effective flaw size to be much larger than 0.040 inch, and much closer to 0.13 inch at best. In some cases, this is not a concern, but in other instances, flight safety may be impacted.

Further benefit of SIR testing will be derived from the proven facts that there is zero environmental impact from SIR testing, and limited surface preparation is required when compared to that used for FPI.