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.