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DISK CRACK DETECTION AND PROGNOSIS USING NON CONTACT TIME OF ARRIVAL SENSORS

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ABSTRACT

Early detection of cracks in engine rotors can prevent uncontained engine fractures. A detection system may also reduce maintenance costs by increasing the time between inspections and reducing the number of spares required. Currently, the only method to monitor engine rotor degradation is through periodic removal of the engine from service, disassembly, and inspection of each rotor. The objective of this study was to propagate a crack in a cyclic engine test and evaluate the ability of an eddy current sensor and Reasoner software system to isolate a crack and predict its remaining useful life.

The engine used for these tests was a Spey RB168 Mk 101 engine with titanium blades. Prior to the engine test, low cycle fatigue (LCF) spin-pit testing was carried out on a pre-flawed disk to validate understanding of the disk crack growth and reduce the risk of fracture during engine testing.

Time of arrival data was collected using the QinetiQ eddy current sensor based tip timing system, to investigate the blade movement caused by crack growth in the disk. A greater understanding of the different types of faults that might exist in a rotor assembly and the ability to differentiate between them using the tip timing system is essential if the true nature of a fault is to be diagnosed and reported.

A software Reasoner, using physics-based structural transfer functions to relate blade tip timing measurements to the damage state of the disk, was validated during the spin-pit test and was subsequently used on the cracked disk test at MoD Shoeburyness. The Reasoner provided real-time monitoring of the crack growth and remaining useful life of the component.

INTRODUCTION

Materials used in aerospace gas-turbine rotating components are put through rigorous assessment and testing to reduce the risk of in-service failure. Fan and compressor disks are generally manufactured from premium grade titanium for which a mix of nominal and minimum-capability properties are assumed during the design process. However, anomalies can occasionally be introduced that pass the inspection process during and after the manufacture of the component. Many researchers have proposed several engineering models over the past decade, which address this issue with materials that exhibit large numbers of anomalies. For example Enright and Huyse [1] report a methodology for probabilistic life prediction of multiple-anomaly materials. Other researchers have considered multiple failure modes associated with these materials.

OEMs have developed extensive design systems that address these variables and factors, such as the consequences of component failure.

Given these issues, aircraft operators have to perform inspections on engines at regular intervals which are both costly and time consuming. Hence, health monitoring of critical gas turbine components has become a major area of interest for OEMs [2, 3]. As a result health monitoring systems, such as that reported by Gyekenyesi [4], rely on robust, accurate and reliable sensors as well as development and validation of algorithms for the analysis and reporting of faults. Reporting faults in error, i.e. when a fault does not exist, is costly and detrimental to aircraft availability.

The objective of this study was to propagate a crack in a cyclic engine test and evaluate the ability of tip-timing measurements from an eddy current sensor and 'Reasoner' software system to isolate a crack and predict the remaining useful life of the component. To assess these capabilities, engine trials were carried out at the UK's Ministry of Defence (MoD) engine test facility at Shoeburyness, which is operated by QinetiQ.

MOTIVATION AND APPROACH

The potential safety implications and cost of fatigue cracks in gas turbine engine disks have brought significant interest to expanding rotor life prediction and management capabilities. Blade tip time of arrival sensors in combination with physics-based modeling can be used to identify and monitor the growth of fatigue cracks in disk rim features. An integrated prognosis system incorporating these technologies has been demonstrated on component spin-pit and full engine tests under the DARPA Engine Systems Prognosis (ESP) programme.

Blade tip time of arrival (also called tip timing) sensors provide real-time (or near-real-time) streaming of blade position data to enable instant diagnosis of disk or blade damage. A software Reasoner was constructed using physics-based models of the disk and blades. Coupled with crack growth models, the Reasoner identifies the type of damage and prognoses the remaining useful life of the component. A building block approach (Figure 1) was used in the DARPA ESP programme to demonstrate the Reasoner technology first on component spin-pit tests and then on full engine tests.

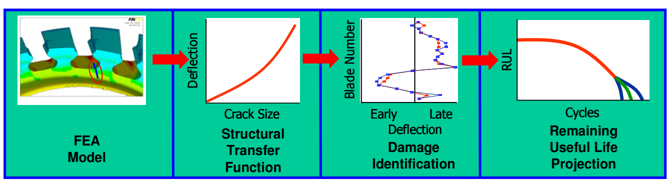

FIG 1: TECHNOLOGY APPROACH TO PREDICTING DAMAGE AND PROGNOSES FOR REMAINING LIFE.

Several retired Spey RB168 Mk 101 engines were available to QinetiQ for use in engine tests by the MoD. QinetiQ's engine asset availability, outdoor test facility in Shoeburyness, UK, and suite of tip timing sensors provided the opportunity to run cracked-disk prognosis testing in an engine environment at a low cost and with a low level of risk. Therefore, the Spey engine was selected as the demonstration vehicle for this part of the DARPA ESP programme. The first stage fan disk (made of a steel alloy) was identified for cracked disk testing, due to its accessibility for periodic inspections while installed in the engine. The blades (made of Ti 6-4) had mid-span shrouds (also called snubbers), which were removed to be more representative of modern unshrouded blade designs, and to allow for more blade deflection during cracked disk testing.

DISK MODELING AND STRUCTURAL TRANSFER FUNCTIONS

A representative first stage fan disk and blades were procured for analysis of part geometry and material properties. These enabled physics-based models of the bladed disk assembly to be created. White light scans of the parts provided their geometries, which allowed construction of computer aided design (CAD) and finite element models (FEM) of the full bladed disk. Once scans were completed, crack growth and tensile specimens were machined from the disk to characterize the material properties. A crack growth model was calibrated and used in conjunction with the FEM to determine an appropriate pre-flaw size to drive disk damage during the spin–pit and engine tests (Figure 2).

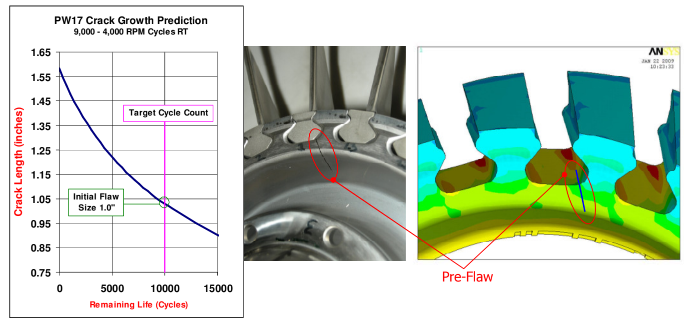

FIG 2: CRACK GROWTH MODEL AND PRE-FLAW.

Initial model investigations indicated that a test duration of approximately 10,000 cycles was required. The slot bottom feature was identified as a high-stress location on the disk. However, this high-stress region was located on the aft side of the slot bottom, which would have made periodic inspections prohibitively time-consuming, requiring disassembly of the entire compressor section of the engine. Disassembly to allow inspection of the forward side of the disk was much simpler, and therefore the pre-flaw location was moved to the forward side of the slot bottom. Due to the lower stress at this location, a pre-flaw size of 25.4 mm was selected to target the 10,000 cycle test duration. To ensure a crack initiation during the tests, a second pre-flaw was added eight slots away from the original (Figure 3).

Physics-based structural transfer functions (STFs) were built to relate time of arrival data to damage states in the engine. STFs were created for disk cracks at several locations to demonstrate the Reasoner's ability to identify the appropriate type of crack during spin-pit and engine testing. Figure 3 shows the predicted static blade positions associated with a pre-flawed disk (in pink) and a disk with critical-sized cracks in both slots (in blue). The static blade positions were calculated assuming no blade-to-blade variability in geometry due to manufacturing tolerances. Blade geometric variations generate a unique pattern associated with each blade-disk assembly. No attempt was made in this test to predict the uncracked blade stack pattern (typically done using CMM measurements); therefore, at the start of both the spin and engine tests, baseline data were collected to empirically determine this shape. This baseline data was subtracted from subsequently collected data to identify the pattern associated with the growing cracks.

It was discovered during spin testing that analysis of only a few blades in and around the pre-flawed slots was not a sufficient means of monitoring stack data for crack detection or size. STFs based on finite element analysis of the entire bladed disk assembly yielded significantly more sensitive and accurate estimates of the flaw locations and sizes than approaches based on models that only included geometry in the vicinity of the flaws. A global deformation of the disk resulted from large pre-flaws introduced at the two slot bottom locations, causing deflection of all of the blades, including those positioned far away from the pre-flawed slots.

STFs were also constructed for the first two vibratory modes for blade health monitoring during the cracked disk engine test. Blade static position and blade frequency shifts were predicted using finite element analysis for blade cracks in the two modes of interest. Crack growth analysis of the two modes was also performed, yielding remaining useful life prediction capability. Static and frequency STFs, along with crack growth models, were fed into the reasoner to ensure blade health during the engine test. More detailed information on fan and compressor blade health monitoring can be found in [5].

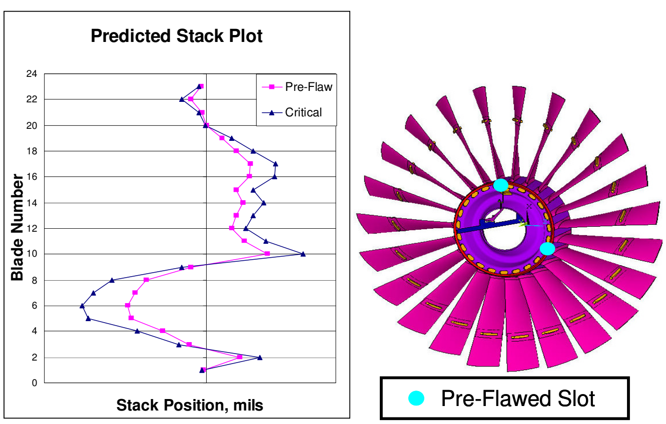

FIG 3: PRE-FLAW POSITIONS AND PREDICTED STACK.

All of the STFs were input into the Reasoner software package and used to identify and track disk and blade damage as well as predict the remaining useful life.

REASONER

During the spin-pit and engine tests, the Reasoner uses blade tip time of arrival data and physics-based models to identify the occurrence and extent of damage in the disk and blades. The measured data are compared against a baseline measurement (usually corresponding to the undamaged condition), and the deviations are subsequently compared to the physics-based model predictions to identify the damage type (or no damage). Using a combination of blade static position and blade frequency measurements, the reasoner can distinguish between disk damage and blade damage, or the reasoner can flag the user that an unknown type of damage exists, triggering an engine hardware inspection. Once a damage mode has been identified, data are used to quantify the extent of the damage (i.e., crack length) using the appropriate STF. Probability models quantify the confidence in the identified damage mode as well as the uncertainty in the crack length inference. Figure 4 gives a schematic of the procedure.

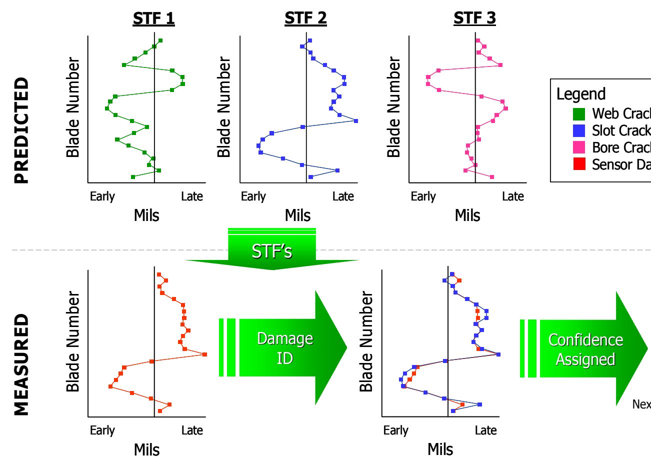

FIG 4: SCHEMATIC SHOWING THE REASONER SOFTWARE.

Finally, the current estimated crack length and crack growth rate are combined with a mission analysis algorithm to prognose the remaining useful life. The Reasoner alerts the user (engine operator) when action is required.

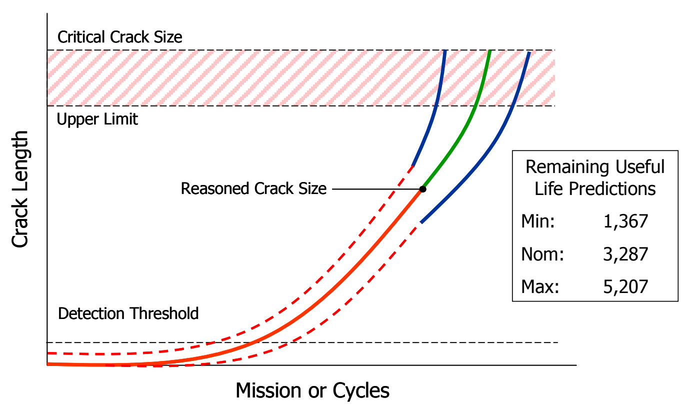

FIG 5: REASONER ALERT CRITERIA.

EDDY CURRENT SENSOR AND MEASUREMENT SYSTEM

The eddy current sensors (see figure 6) were developed at QinetiQ for low-cost, weight-neutral contamination-immune engine health management [6]. This sensor, by measuring the arrival time of individual blade tips, can be used to characterize the unsteady vibration response and determine the health of compressor blades. The sensors and system have been demonstrated and validated against industry standard optical sensors on uninstalled engines and rig tests [6]. Using these sensors QinetiQ have successfully developed a prototype FOD detection system resulting in a system capable of detecting items down to less than one gram mass [7,8].

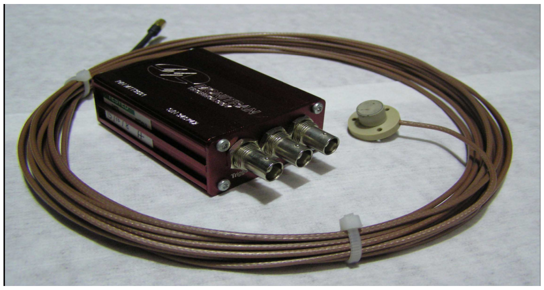

FIG 6: QINETIQ EDDY CURRENT SENSOR SYSTEM.

The sensors were flush mounted with the inner wall of the casing and the cold blade tip clearance was measured at approximately 3.5 mm. The blade tip width at the measurement point near the leading edge was approximately 3 mm. Each eddy current sensor was fitted with a 10m cable to the driver circuitry to power and condition the sensors. The electronics incorporate circuitry to remove the effect of tip clearance variation in real time. In addition to the eddy current sensors a number of industrial standard optical tip timing sensors were fitted for comparison with the eddy current sensor measurements. For an accurate measure of the LP spool speed an optical based once per revolution sensor was fitted to the first stage fan blade retainer plate.

A dedicated data acquisition system, comprising a high performance industrial PC and high speed multichannel timer card, was used for both optical and eddy current sensors.

The blade time of arrival pulses are accurately timed by the high speed timer cards at 50MHz and the time of arrival of each blade tip stored by the data acquisition system. The time of arrival data are stored to the PC hard drive. This method allows the rotors to be monitored for long periods without accumulating excessively large amounts of data. Some raw data were recorded from eddy current and optical sensors with the once per rev signal on high speed oscilloscopes to allow raw data quality checks and to allow direct comparison of the signals.

Data from the BTT system was transferred in near real time to the PC executing the Reasoner.

TECHNOLOGY DEMONSTRATIONS

A building block approach was used for technology demonstration, starting with component spin-pit tests (Figure 7) to validate STFs and Reasoner capabilities, then moving to a full-scale engine test. Two pre-flawed disks were used in the tests, as described in the following test plan:

Disk #1 – Spin-pit Test
Objective:
- Grow slot bottom cracks from pre-flaws
- Stop test just before fracture
- Update STFs and Reasoner for future tests

Test Duration: 11,500 cycles / 10 inspections

Disk #2 – Spin-pit Test
Objective:
- Grow cracks from pre-flaws
- Stop test with sufficient remaining life for two weeks worth of engine testing

Test Duration: 10,000 cycles / 5-6 inspections

Disk #2 – Engine Test
Objective:
- Grow cracks, stop test just before fracture

Test Duration: 4,000 cycles / 6 inspections

The primary objective of the first spin-pit test was to validate the prognosis approach and calibrate STFs and Remaining Useful Life predictions, as needed. Periodic inspections by acetate replication were included in both spin and engine tests to validate the Reasoner's crack growth predictions. Further crack growth model validation was performed following the first spin-pit test. Disk #1 was fractured open at both crack locations, and the crack size and crack path shape were used to validate crack growth models for the engine tests.

The second spin-pit test was performed to accumulate damage on the disk, while minimizing cost and risk. Due to the high cost of fuel and the risk associated with damaging other components in the engine, it was important to minimize the number of cycles run during the cracked disk engine test. Running 10,000 cycles in the spin-pit environment before inserting the disk into the engine allowed for a nearly 4,000 cycle engine test in which the cracks grew to near-fracture.

SPIN-PIT TEST & INSTRUMENTATION

Spin-pit testing was performed at NAVAIR's Patuxent River Maryland Rotor Spin Facility. Three QinetiQ eddy current probes were bolted to a ring and instrumented through the lid of the spin rig. Radial gaps from probe ring to blade tip were 7.4mm. Probes were attached to a BTT data acquisition system and data was transferred from the acquisition system to the PC operating the Reasoner in near real time. Figure 7 shows the Spey engine disk and fan blades fitted to the spin-pit facility.

FIG 7: SPIN-PIT FITTED WITH SPEY ENGINE HARDWARE.

SPEY ENGINE TESTS & INSTRUMENTATION

The engine used for these tests was a Spey RB168 Mk 101 engine with titanium fan blades from which the snubbers (Figure 8) were removed. Snubbers were removed from the first stage fan to make the blading more representatives of modern unsnubbered fan blades. This allowed a greater movement of the blade in the root fixing to ease crack growth detection by the time of arrival sensors. Spin-pit tests used desnubbered blades, demonstrating that such a modification to the blades would not adversely affect their mechanical integrity. Figure 9 shows the engine fitted with desnubbered fan blades and sensors.

FIG 8: FAN BLADES WITH AND WITHOUT SNUBBERS.

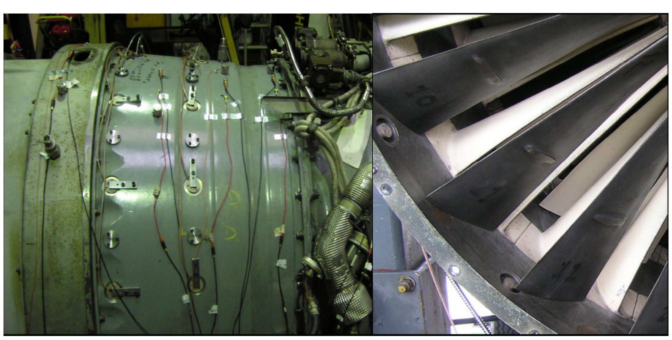

FIG 9: SPEY ENGINE FITTED WITH OPTICAL AND EDDY CURRENT SENSORS.

The first engine test was carried out with the fan disk intact, to establish a set of baseline data for the engine with the de-snubbered blades and an intact (un-cracked) disk. The engine was cycled at a variety of acceleration and deceleration rates to demonstrate the max speed capability of the engine, and to ensure both integral and non-integral vibration responses on the desnubbered blades were within allowable limits.

In the second test, the disk with two blade slot bottom cracks (previously run in the spin-pit) was installed, and the engine was run through a series of nearly 4000 cycles to promote crack growth. The tests consisted of rapid cycling of the engine between 2500 and 8000 rpm. Typical cycles are show in Figure 10 for the LP spool.

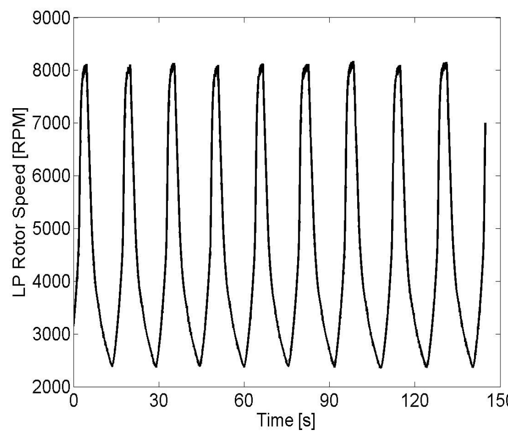

FIG 10: SPEY ENGINE LP SPOOL SPEED DURING CYCLING.

At intervals throughout the testing, crack measurements were made using acetate replication, in which an impression of the crack is made in the surface of an acetate sheet that has been softened using acetone. The crack replication is subsequently inspected under a microscope. Figure 11 shows a typical acetate replication showing the pre-flaw and crack propagation.

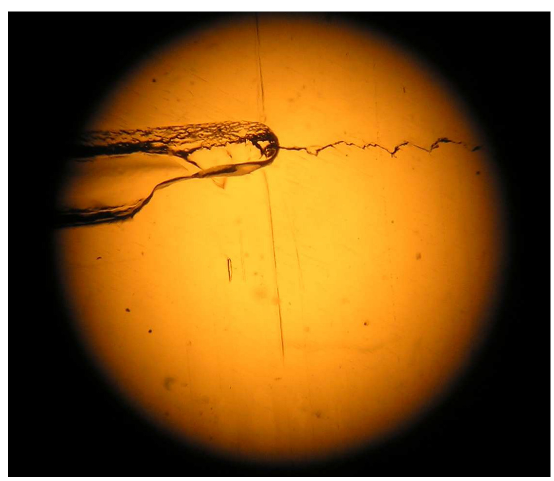

FIG 11: MICROSCOPE IMAGE OF ACETATE REPLICA SHOWING THE PRE-FLAW AND CRACK.

RESULTS & DISCUSSION

All the eddy current sensors successfully survived the spin-pit and engine running throughout the testing with no degradation of the signals becoming apparent. This shows evidence of the high mechanical integrity and immunity from contamination displayed by the sensors. Measured data from the eddy current sensor was compared with the optical sensor data and found to be in very good agreement.

<u>Spin-pit test results:</u>

The spin-pit test on the first disk was run for 11,637 cycles. Throughout the duration of the spin-pit test, the Reasoner consistently identified the appropriate crack type, matching the STF blade static position ("stack") pattern closely (see Figure 12).

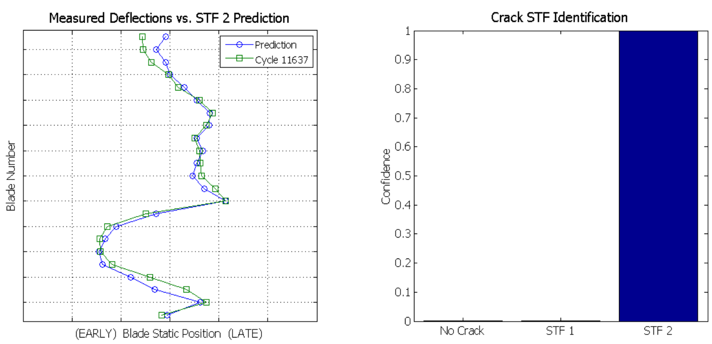

FIG 12: BLADE STATIC POSITION (STACK).

Using the slot bottom crack STF the Reasoner accurately predicted the crack size within its uncertainty bounds when compared with the inspection results (see Figure 13). The Reasoner algorithms incorporated Bayesian statistics to monitor component health probabilistically. Uncertainty from various sources, such as sensor measurements, STF and crack growth models, and run-to-run variability was propagated through the Reasoner algorithms to yield the overall system-level uncertainty shown as the black lines in Figure 13. More detailed discussion of system-level reasoner uncertainty for gas turbine engine prognosis and usage-based lifing applications is provided in [9].

The spikes in predicted crack sizes shown in Figure 13 correspond to data sets collected immediately following engine start-up, and are likely due to blades reseating in the dovetail slots. Galling patterns on the blade attachments also suggested movement of the blades within the slots. These galling patterns were particularly severe on the blades associated with the cracked slots and further suggest why approaches based on interpreting changes in individual blade stack positions are not an effective means of making inferences for disk crack prognosis. At some times during the tests, the predicted crack size decreases. These decreases reflect changes in the Reasoner's estimate of crack size based on the most recent data.

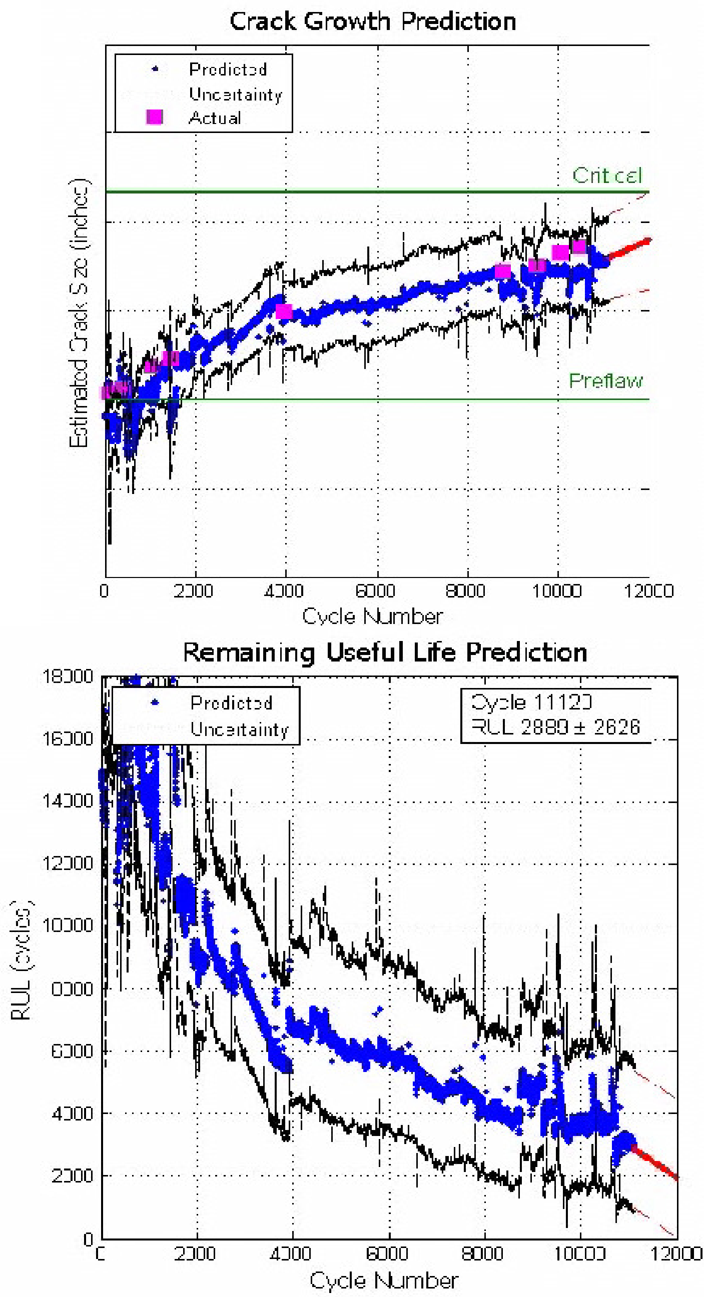

FIG 13: PREDICTED AND MEASURED CRACK SIZE AND REMAINING USEFUL LIFE PREDICTION.

<u>Engine test results:</u>

During baseline engine testing, the integral and non-integral vibration responses of the first stage fan blades were characterized (see Figures 14a and 14b). The first bending (1B) and second bending (2B) resonant responses were determined to be well within allowable Goodman limits for Ti 6-4. The non-integral order vibration (1B Async) was observed at relatively low amplitude at a transient speed, and hence was also determined to be safe.

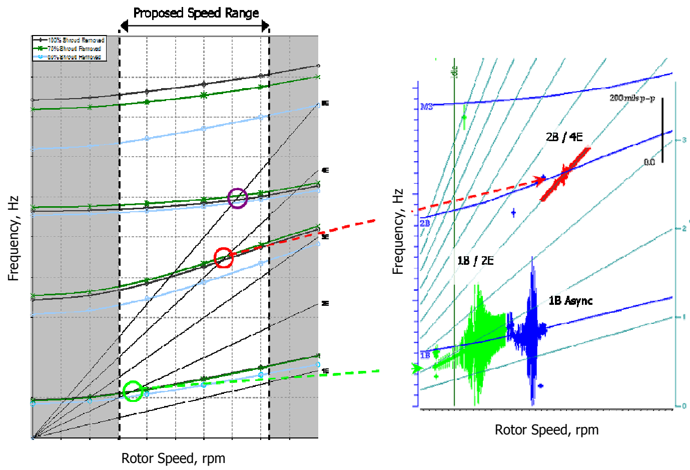

Figure 14a: Integral and non-integral vibration response of the fan blades.

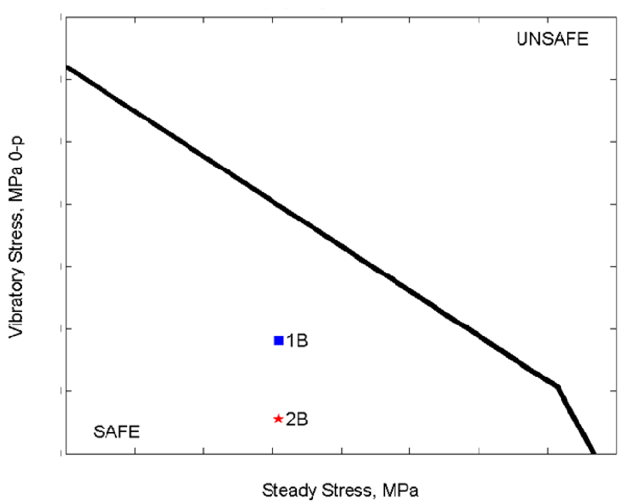

FIG 14B: GOODMAN LIMITS OF THE FAN BLADE.

During the cracked disk engine testing, the Reasoner monitored both blade static position for disk crack analysis as well as the blade vibratory responses to ensure that responses remained within allowable limits. Throughout the test, the Reasoner consistently identified the appropriate crack type, and using the slot bottom crack STF predicted the crack size in close agreement with the inspection results (see Figure 15). Intuition would suggest that blades in the cracked disk slot locations would exhibit the largest tip deflections and therefore provide the most appropriate basis for health monitoring. However, these blades exhibited significantly more variability in their static positions than did any of the other blades, therefore they alone did not provide a reliable means for crack detection and quantification. The global pattern of blade static positions remained more stable throughout engine testing; therefore a holistic approach to disk health monitoring allowed the Reasoner algorithms to accurately identify the crack locations and extent of damage.

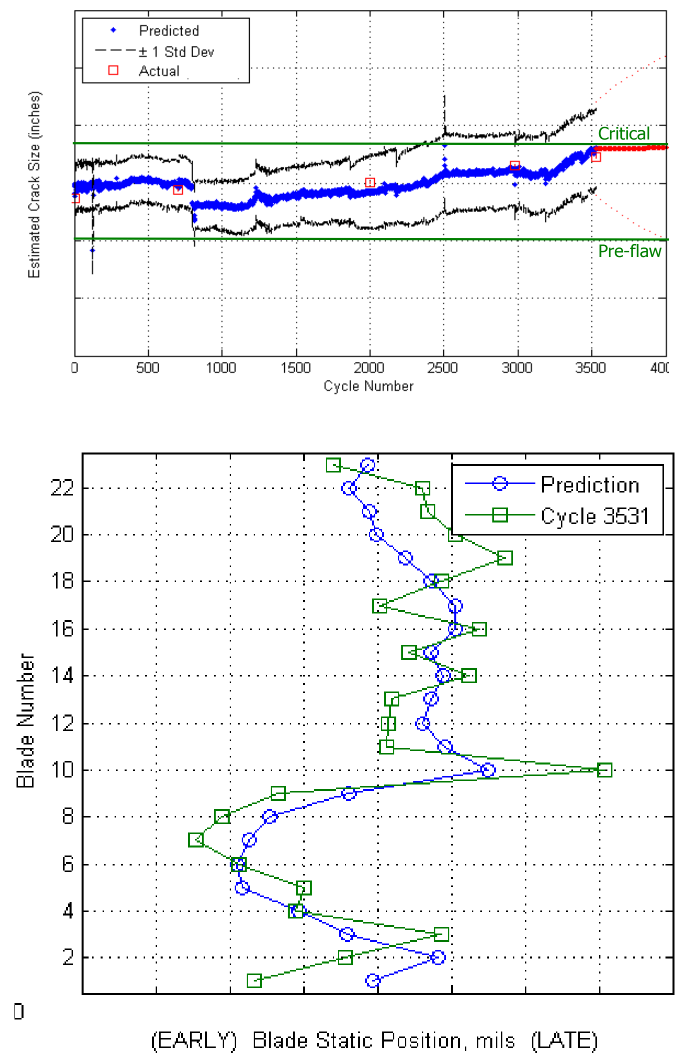

FIG 15: MEASURED AND PREDICTED CRACK GROWTH AND DEFLECTION.

Cracked disk engine testing was stopped when Remaining Useful Life predictions indicated that the engine could no longer be operated without risking rupture of the disk, see figure 16. Engine throttle movements were controlled manually at the test facility. As a result, particularly at engine start-up, some variability in the maximum speed of the engine was experienced. Due to the risk of over-speed and disk rupture, the test was suspended after 3531 cycles, with a predicted remaining useful life of less than 500 cycles.

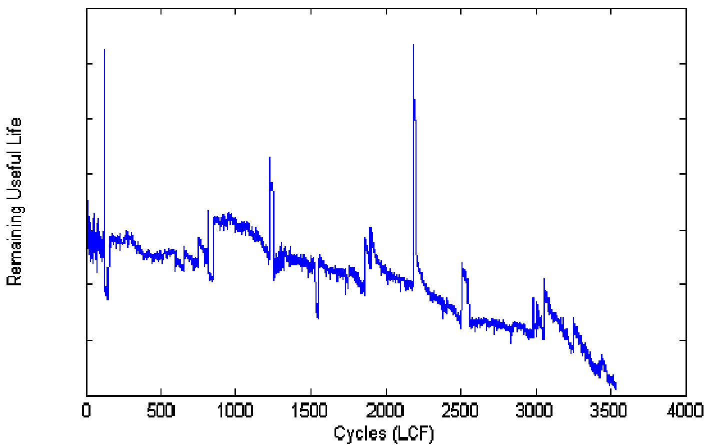

FIG 16: PREDICTED REMAINING USEFUL LIFE.

CONCLUSIONS

The Spey disk spin-pit and engine tests demonstrated the QinetiQ eddy current sensor's capability to detect tip timing movements with sufficient signal-to-noise quality and endurance throughout several thousand cycles of testing. The prognosis reasoned software combined the data from the time of arrival sensors with physics-based models to identify and monitor the growth of fatigue cracks in disk rim features in both spin-pit and engine testing. The software successfully identified the presence, location, and size of the growing cracks and calculated the remaining useful life for the component, while accounting for uncertainty in measurements and modeling probabilistically.

The technology readiness level (TRL) for damage accumulation through usage-based lifing, damage detection, and isolated and multi-mode damage prognosis were demonstrated as TRL 6 and, furthermore are ready for transition to engine programmes.

Input	Action	June 2009 TRL
Damage Accumulation (Usage Based Lifing)	Periodic Inspection (As Required)	TRL6
Damage Detection	Inspect for Cause	TRL6
Isolated Damage Prognosis	Remaining Capability & Life Extension	TRL6
Multi-Mode Prognosis	Remaining Capability & Life Extension	TRL6

TABLE 1: TECHNOLOGY READINESS LEVELS FOR DISK HEALTH MONITORING.

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