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Real-time Detection of Developing Cracks in Jet Engine Rotors

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Abstract -Test Devices has developed a unique method for detecting the existence of dangerous cracks in turbine engine disks. The system uses the data from two distinct sensors, a radial position sensor and an angular position reference signal. By combining these two data into a vector quantity, the system measures the displacement of the principal mass axis of the rotor. A reasoner system uses the change of principal mass axis to infer the presence of cracks. It does so by tracking changes in the unbalance as a function of the operating cycle count. The rate of change is compared with the known patterns of change produced by cracks as opposed to those produced by normal wear phenomena and other benign effects.

1. INTRODUCTION

Jet engine disks operate under high centrifugal and thermal stresses. These stresses cause microscopic damage as a result of each flight cycle as the engine starts from the cold state, accelerates to maximum speed for take-off, remains at speed for cruise, then spools down after landing and taxi. The cumulative effect of this damage over time creates a crack at a location where high stress and a minor defect combine to create a failure initiation point. As each flight operation occurs, the crack is enlarged by an incremental distance. If allowed to continue to a critical dimension, the crack would eventually cause the burst of the disk and lead to catastrophic failure (burst) of the engine. Engine burst in flight is rarely survivable.

To prevent burst in flight, periodic inspections are conducted. During scheduled major overhauls, the engine is disassembled and each disk is inspected carefully using one or more NDE processes to discover any cracks that might have formed. Inspections are conducted by immersing the disks in a liquid doped with fluorescent dye, cleaning the disk, then manually inspecting under UV light. If a crack exists, the fluorescent liquid that remains in the crack after cleaning becomes visible as a bright line where the crack meets the disk surface. Additional or alternative inspections are sometimes conducted using a probe with a high frequency RF coil on its tip. The coil induces eddy currents in the disk material, and the presence of a crack in the eddy current field is detectable as a change in the effective impedance of the coil. The Fluorescent Penetrant Inspection (FPI) technique is the lowest cost approach, with no special tooling required, but it can fail to disclose cracks that are tightly closed when the disk is at rest. FPI is also unable to find sub-surface cracks. The eddy current system is more effective at detecting both of these problematic cases, but it requires careful setup and operation. It is impractical to inspect more than a small portion of the surface of the disk with the eddy current probe, and any cracks in the areas not inspected would, of course, not be detected.

These methods only work by tearing down the engine and inspecting each piece. There is currently no effective system for detecting cracks in service and so the life of each disk must be predictable, to be certain that no failures occur between inspections. Reliable understanding of both phases of the crack formation and growth process is necessary for success. The number of cycles than can be run before a detectable crack will form is the first measure of the life of a disk. That number sets the acceptable number of operations before first inspection, and has a very large impact on the economics of operation of the engine, since inspections are very expensive. The second important issue is the crack growth life of the disk. The geometry, material, and stress level in the rotor determine the rate of progression of the crack as it extends during each cycle of operation. Some materials (titanium as an example) are very strong, but very brittle, and sometimes show limited crack growth life. Others are more ductile, and offer lower performance per pound, but give longer crack growth lives and therefore more robust and reliable operation. Balancing off the higher performance and longer crack initiation life of high performance materials against the short crack growth life and its concomitant higher level of risk, is one of the challenges that faces the disk designer.

Fatigue life is an uncertain characteristic, describable only in terms of the probability of failure after a certain stress history. Further, the detailed stress history of a particular engine part at a particular point in its life is very difficult to know. Each engine operation produces a different combination of thermal and mechanical stress as a result of differences in ambient temperature, load, and pilot inputs. The combined effect of uncertainty of the response of the disk and the uncertainty of its stress, makes it impossible to establish a safe life in a deterministic way. The best that can be done is to establish the probability of crack initiation and growth for the most severe stress that can be expected, and to retire disks well before the probability of failure becomes unacceptable. This, of course, leads to retirement of expensive disks well before they approach their average life. A method or technique that could reduce the uncertainty of disk life could have powerful economic consequences in addition to its safety improvement implications.

As part of the life management process, each new design or design modification is tested to measure cyclic fatigue life, often called “low-cycle” fatigue life (LCF). Just as in flight operation, the test needs to establish two numbers. The first is the number of cycles of operation that occur before the first detectable crack forms. The second, and equally significant, is the number of cycles between the first detectable crack and the burst failure of the disk. Engine designers spend substantial time and money on computer simulations (“finite element models”) of rotors to predict LCF life, but these simulations are not sufficiently reliable, however, to be the sole tool in managing design life. After design and before extensive field use, it is important to measure the LCF life of a new or modified design in a spin test machine. These machines (called “spin pits”) are designed to cycle the rotor from some low speed to operational speed then back again. Spin pits are heavily armored and are designed to contain the fragments of burst if it should occur. Such burst events do, however cause some damage to the test equipment, and more seriously, destroy the evidence necessary to understand the origin and growth rate of the crack. It is therefore highly desirable to be able to stop a life test just prior to burst, preserving the test rotor for analysis and saving substantial facility repair cost.

Just as in the operating engine, it is important to know both the initiation and the growth life of cracks. Although tear-down and inspection are easier in the case of the spin pit than in the engine, such interim inspections add substantially to the cost of the test, and avoiding them is desirable. This is particularly true in he case of elevated temperature tests, where cool-down and heat-up must be conducted carefully and isothermally, and thus consume a lot of time. A method to detect cracks in the spin pit and to observe their growth can substantially improve the value of the test. If cracks can be detected on-line, during the test operation, interim inspections can be reduced or even eliminated. If crack growth can be tracked reliably, the test can be allowed to proceed to the point of rapid crack growth, but stopped just before burst. A disk with a crack of near critical length is much more valuable to the designer than a collection of broken pieces. Micrographs of the fracture surface reveal initiation sites and phenomena. “Beach marks” are visible under ultra high magnification and can be counted to reveal growth rate, since each beach mark indicates a single cycle of crack growth.

The crack detection system described in this paper was initially developed for use in LCF tests as cracks form and grow. It has been shown to be a reliable indicator in the restricted case of a single disk operated in a spin pit. The system has been sufficiently useful in that application to justify work to extend its application to operating jet engines and other advanced performance machinery, including high performance energy storage flywheels. A patent covering the apparatus and methodology is pending.

2. DETECTION OF CRACKS BY MEASURING VIBRATION

Jet engine rotors are highly symmetric about their operating axis. They are subject to highly symmetric stress, and so their expansion in response to the stress (“strain”) is also symmetric and the part remains well-balanced despite very significant changes in its dimensions. When a crack is introduced into the disk, the symmetry is broken, and the strain is no longer uniform. This dimensional asymmetry is reflected in the mass distribution of the disk, creating a measurable unbalance, which in turn causes vibration that can be measured. In the spin pit this vibration measurement has been used for many years as a diagnostic tool, but it has often been ineffective. Spin pit operators routinely measure part vibration, but often report that there was no vibration increase prior to burst.

The observation that a vibration monitor is only occasionally effective in preventing burst led to a further investigation of the phenomena of disk unbalance created by cracks. The first issue revealed by that investigation was that the vibration of the shaft in the test machine was broad spectrum. There are multiple vibration modes in a complex assembly, and many of these modes are excited by the drive motor and by the residual aerodynamics in the spin chamber. Although the chamber is evacuated to reduce drag horsepower, the atmosphere that is left is sufficient to interact with the rotor and excite many modes of vibration. Unbalance, on the other hand, causes single frequency vibration, exactly equal to the shaft rotation frequency. Our first attempt at improving crack detection was to use a spectrum analyzer to separate out the synchronous vibration from the other frequencies, and monitor that. Our ability to detect cracks improves significantly with that simple technique, but we continued to observe that synchronous vibration did not always increase before burst. In a significant number of cases, in fact, the vibration level decreased progressively over time, and that improvement increased sharply just before burst.

Finally the mental fog cleared and we realized that we were looking at only half the information that was available to us. The vibration level information contains no phase angle information. Measuring changes in the unbalance of a rotor requires the fusion of two streams of data: amplitude and phase of synchronous vibration. Neither half of the fused information is useful by itself, but taken together and combined properly, the two information streams create information that is a powerful diagnostic tool.

Measuring amplitude and phase is relatively easy if the signal of interest is monochromatic and at a single frequency, but it is substantially more difficult when the signal of interest is obscured by high amplitude noise at other frequencies. Conventional filter implementations are quite able to extract the synchronous component of the signal, allowing accurate measurement of the amplitude of that signal. In the spin pit and in the operating engine, however, the fundamental operating speed is often changing rapidly. Conventional filters shift the phase of the synchronous signal by an amount that depends on the rate of change of the frequency. This is a particularly serious problem in the spin pit because rapid acceleration and braking are necessary to achieve reasonable rates of accumulation of cycles. The drives used in the spin pit are, by their nature, non-constant torque devices, so the rate of change of frequency changes continuously, making the measurement of the phase angle of the synchronous frequency very difficult.

The signal processing system developed to solve this problem (patent pending) is currently implemented in an analog fashion. A synchronous tracking filter, narrow band, with a proprietary phase-compensation system is used to extract the amplitude and phase of the synchronous vibration of the disk being monitored. The two signals are conveniently handled as a vector quantity. The system monitors the synchronous vibration vector of the rotor as it cycles, and compares that vector with the original vibration. The difference vector reflects the change in vibration over time. As a crack develops, the vector changes in a characteristic way, and cracks as small as 0.15” have been clearly indicated during LCF tests in the spin pit. This is much smaller than the cracks that have caused air transport fatalities in the recent past, so there is reason to believe that the system has the potential to show direct benefit immediately as a flight safety enhancement.

With this technology it is has been consistently possible to terminate tests just prior to disk burst, preserving the entire disk for analysis. Preventing a burst allows the metallurgist an opportunity to view the disk with no collateral damage and to determine the crack initiation site with complete certainty. Preventing a burst also reduces the cost of the test by eliminating the high costs associated with facility repair after a failure; and further savings are realized by preserving arbors, blade sets, and other associated tooling and attachments.

Unbalance has been shown by analysis and experience to be a sensitive measurement of changes in the imbalance of the test article. When a crack develops in a high-speed spinning disk, it causes a significant distortion of the symmetry of the strain field in the disk. Contrary to the intuitive belief that cracks near the rim are more significant that those near the bore, the most important issue is the stress level at the crack location.. Rim, bore and blade cracks produce measurable imbalance changes. Rim cracks produce less distortion of the mass distribution but are at a relatively large radius and thus produce significant imbalance. Bore cracks are at a small radius, but because of the high stress in the bore produce very significant mass distribution changes. Blade cracks produce a very small amplitude reading (compared to rim and bore cracks), but the phase indication is identical.

The developed method has been proven reliable in the testing application. It has allowed a significant reduction in the need for interrupting the test for interim inspections. The benefits of the system include early warning of the existence of cracks and a significant reduction in test program cost.

3. SYSTEM DESCRIPTION

In the spin pit, the system uses an eddy-current proximity probe to measure the instantaneous position of the shaft on which the test rotor is mounted. Because the spin pit drive uses a flexible shaft running above its first resonance, the part runs about its principal mass axis (axis of balance). The deviation of that axis from the geometric axis of the shaft is a direct measure of the unbalance of the rotor.

The spindle vibration signal is processed through the proprietary tracking filter, and the synchronous amplitude and synchronous phase angle are measured. A once-per-revolution signal is generated by a reluctance pickup or an optical probe, and used as the zero phase reference. The filter provides amplitude and phase fidelity despite the rapidly changing rate of speed and rate of acceleration. Most commonly, the system is set up to record amplitude and phase at a specific speed point during acceleration of the rotor. The amplitude and phase values measured during the early period of the test, when the rotor can be assumed to be uncracked, are taken as the baseline unbalance of the system. Subsequent amplitude and phase data are combined and a vector subtraction is performed to compute a change vector. Both amplitude and phase of the change vector are plotted and displayed in real time, allowing the test engineer to observe the unbalance change. Monitoring the rate of growth is particularly important in determining the point at which the test must be halted to prevent burst.

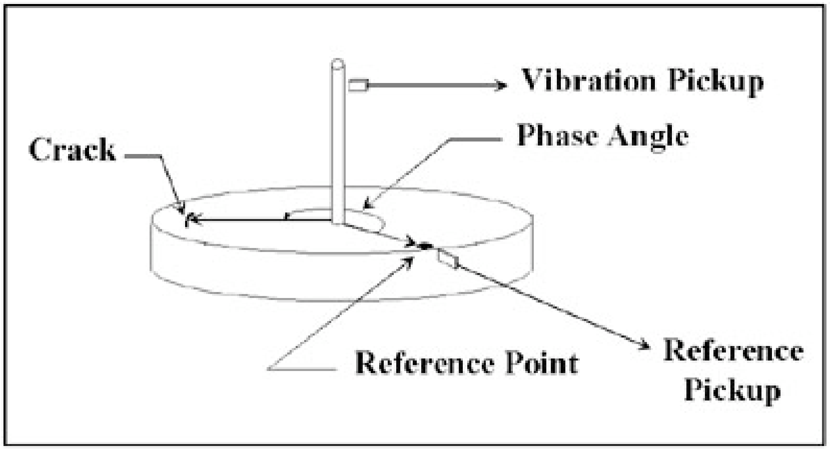


Figure 1 - Crack Detection System
Functional Measurement & Reference Diagram

Referring to Figure 1: a reference point is established on the rotor (or its supporting shaft). The initial unbalance of the part is measured and recorded. The amplitude and phase of vibration is measured at the same speed in each subsequent cycle and vectorially subtracted from the initial vibration. The vector difference is taken as the unbalance induced by a crack.

The crack detection system does not require that the article under test be rotating at a constant speed before a valid measurement can be taken. The crack detection system provides an accurate indication of crack-induced amplitude and phase changes at any time and speed, whether accelerating or decelerating. The system has an additional use in dynamic balancing a test article while installed in the test facility. Because it measures vibration amplitude and phase, the crack detection hardware can be used to trim-balance the test rotor, which can even further improve the sensitivity of the system to detect small, incipient cracks.

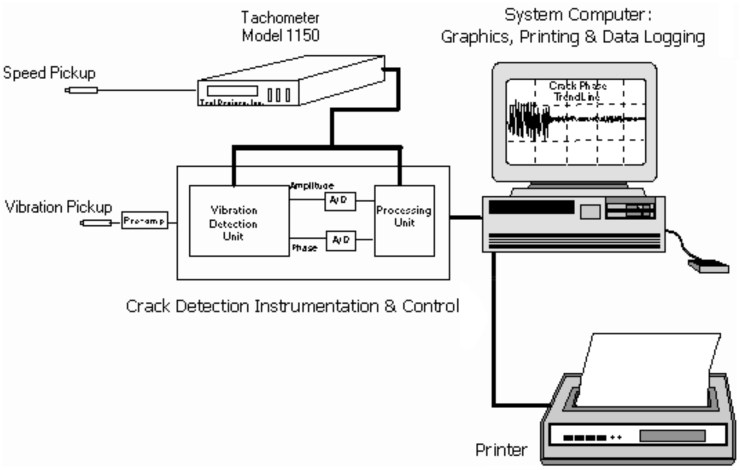
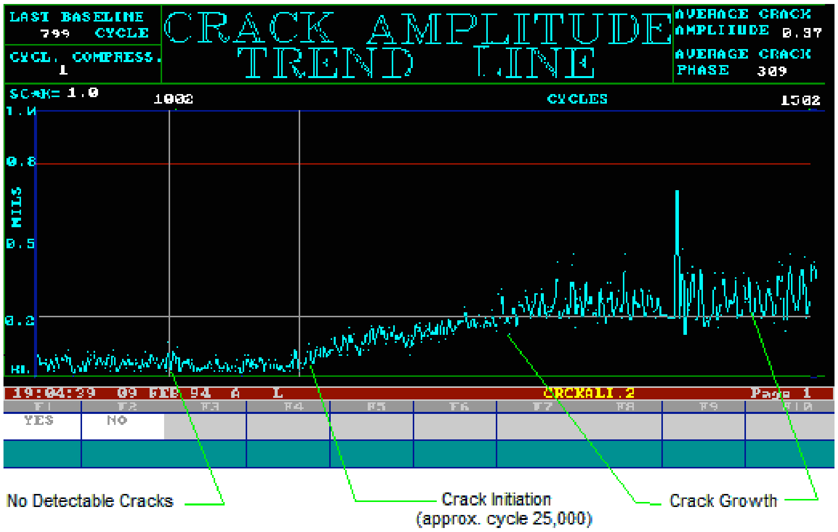


Figure 2 - System Block Diagram

4. APPLICATION EXAMPLES

The crack detection system is a sophisticated, real-time analysis tool that processes the vibration and speed signals, and provides direct information about the vibration and unbalance of the rotating parts. This information is available at all times throughout the transient (i.e. cycling) mode or during constant speed, steady state conditions. The information is graphically displayed on a computer screen in real-time using three basic graphs: crack amplitude, crack phase and vibration amplitude. These graphs are continuously available during the test and show a trend line over time, correlated to the number of cycles (see Figures 3 - 6 for graphs of crack amplitude and crack phase).

These graphs continuously display vibration and crack propagation during each cycle in transient mode. Alarm monitoring functions are included in the software and the system can be shut down automatically if selected thresholds are exceeded. The data can be plotted on a graphics printer, logged on a data printout and can be written to disk in a standard format for transfer to external data analysis programs. The system has repeatedly proven its ability to provide an early warning of potential component failures. The performance of the crack detection system has been demonstrated in many different testing applications. Without exception the system has given excellent results with various rotating part configurations and with different materials, including both metals and composites.



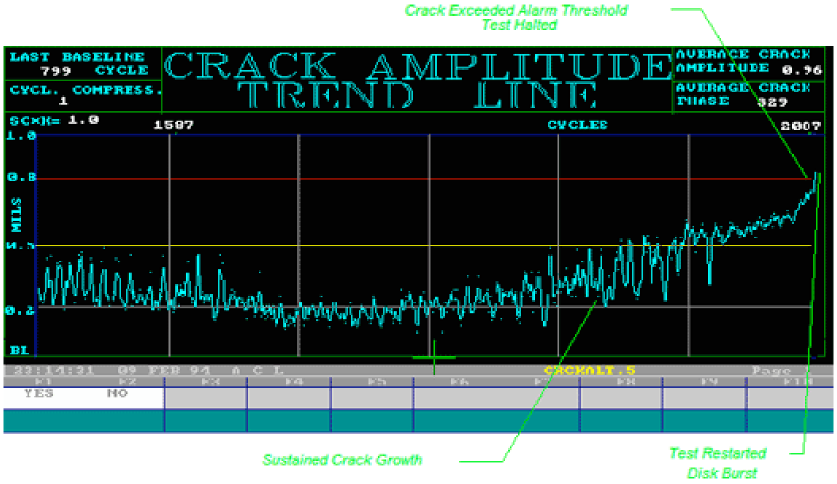
No Detectable Cracks

Crack Initiation
(approx. cycle 25,000)

Crack Growth

Figure 3 Crack Amplitude - Bladed Turbine Assembly
(cycle range: 24,802 - 25, 402)

High Pressure Turbine *(bladed disk assembly)* An example application is shown in Figures 3 - 6. This was a low cycle fatigue test for life certification of a bladed turbine assembly for a jet engine gas generator. The disk was about eight inches in diameter and weighed 15 lb. The test specification called for 30,000 cycles between minimum and maximum speeds of 2,500 RPM and 48,000 RPM. The crack detection system monitored the vibration and crack development, and up through 25,000 cycles (1100 on Figure 3) the system indicated an insignificant crack amplitude and the crack phase was random (see Figure 5), a clear indication that no crack had been detected. Beyond 25,000 cycles the initiation of a crack is indicated, as demonstrated by the trend of the crack amplitude (see Figures 3 & 4) and crack phase curves (see Figures 5 & 6).



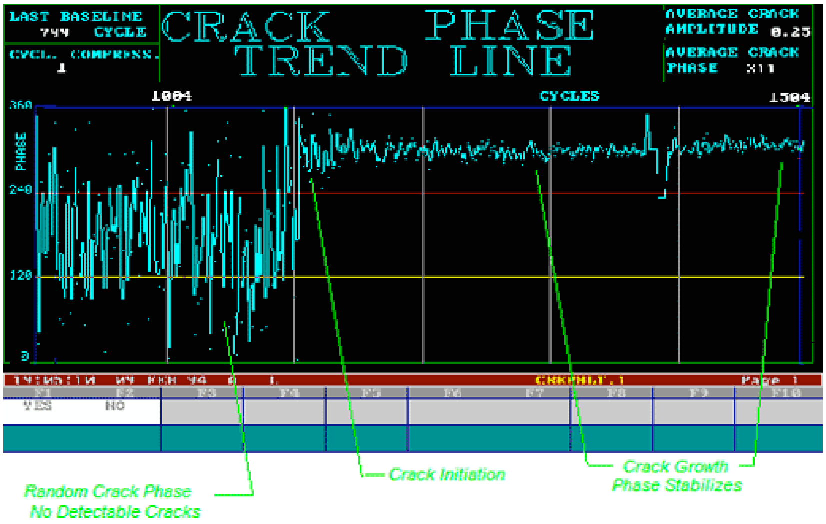
Crack Exceeded Alarm Threshold
Test Halted

Sustained Crack Growth

Test Restarted
Disk Burst

Figure 4 Crack Amplitude - Bladed Turbine Assembly
Final 600 cycles (25,387 - 25,987

As the amplitude of the crack grew, the phase stabilized around a particular angle. During the next 1000 cycles the crack propagation continued, confirmed by the crack amplitude and phase stability trend. At 25,987 cycles (2087) on the graph in Figure 4, the crack amplitude grew to a reading of 0.83 mils, which exceeded the alarm level set at 0.8 mils, and shut down the test (note: the crack amplitude is relative indication of crack size compared to a previously set baseline, not an absolute indication). The alarm level was reset and the test was continued. The next cycle indicated 0.96 mils of crack amplitude, and the disk burst on the following cycle.



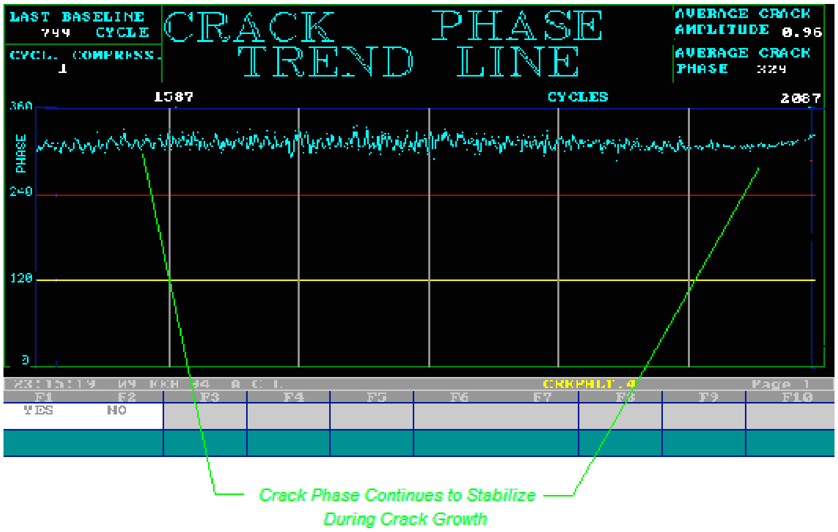
Crack Initiation

Crack Growth
Phase Stabilizes

Random Crack Phase
No Detectable Cracks

Figure 5 Crack Phase - Bladed Turbine Assembly
(cycle range: 24,804 - 25,404)

Near the end of the test, the unprocessed vibration amplitude actually decreased as the crack grew in size. This somewhat surprising phenomenon happens when the imbalance caused by a crack acts in opposition to the initial imbalance of the assembly. As this crack grew it began to counteract the fundamental system imbalance and as a result actually improved the state of balance of the assembly. After the burst, investigation showed that the crack phase information correlated exactly with the actual fracture point.



Crack Phase Continues to Stabilize During Crack Growth

Figure 6 Crack Phase - Bladed Turbine Assembly
Final 600 cycles (25,387 - 25,987)

A visual inspection of the disk showed three main post fractures. Other cracks were evident but were very small and tightly closed. The metalurgical analysis showed microscopic crack initiation at approximately 20,500 cycles. The disk was inspected for cracks using Fluorescent Penetrant Inspection at cycle 23,750, and no indications were found. The crack detection system detected the crack after approximately 4,370 cycles from microscopic crack initiation.

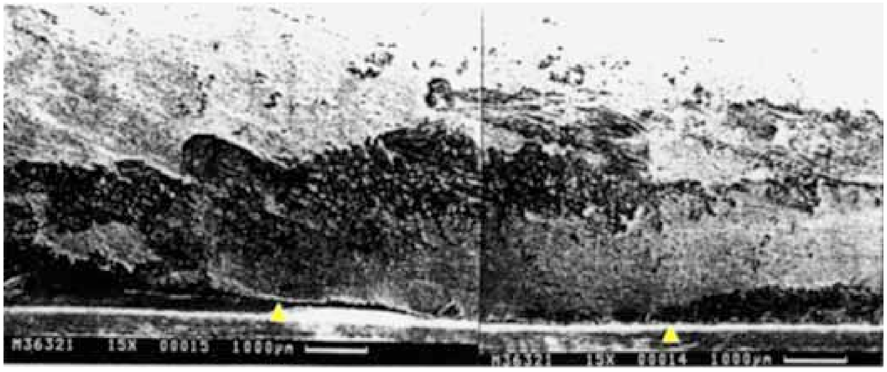


Figure 7 Scanning Electron Microscope photograph of fracture origin area (located between triangles).

Examination of fracture surfaces with a scanning electron microscope (SEM) showed fatigue had initiated from multiple origins as shown in Figure 7. Striations are clearly visible to within 0.005-in. of the surface (see Figure 8). Figure 9 is a micrograph showing one of the cracks detected in an intact post.

Figure 8 Scanning Electron Micrograph showing striations detected near a crack origin in the HPT assembly.

In this test the crack detection system successfully detected and tracked the primary crack in this rotor for the last 990 cycles. In the next example the system detects and tracks a series of cracks in another bladed disk assembly for over 17,000 cycles.

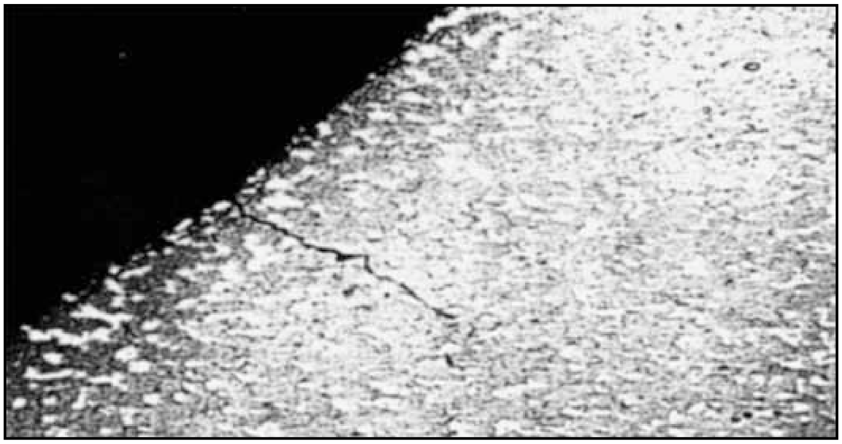


Figure 9 Micrograph showing one of the cracks detected in the HPT assembly

Power Turbine (bladed disk assembly) This was a Low Cycle Fatigue test performed on a series of power turbine disks. The test was performed in a degraded vacuum which eliminated fretting as an issue during the spin test. A number of tests were run and different failures were recorded and observed with the crack detection system as listed below:

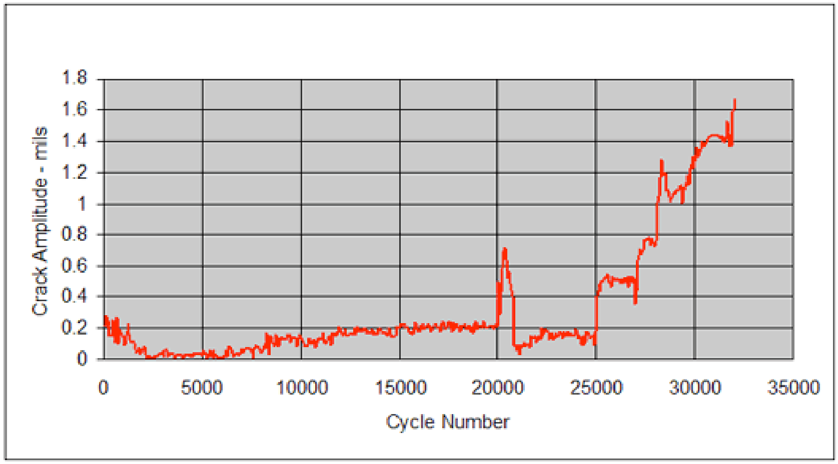


Figure 10 Crack Amplitude Graph of Power Turbine (tenon crack)

Figure 10 is a plot of crack amplitude plot for one of the power turbine disks. This disk developed cracks in blade tenons. At test termination (approximately 32,000 cycles) this disk had 16 cracks approximately 0.200 inches in size. At approximately cycle 14,000 it was estimated by metalurgical analysis that the largest crack was on the order of 0.015 inches in size. The crack detection system successfully picked up the initial crack and was able to track crack growth through multiple crack initiations for over 17,000 LCF cycles. Figure 11 shows the phase plot of the crack detection system for this test. It is clear from the undulations in the graph that past cycle 15,000 the system was tracking multiple cracks, growing at different rates. Figure 12 shows a view of the cracked tenon after the Power Turbine test.

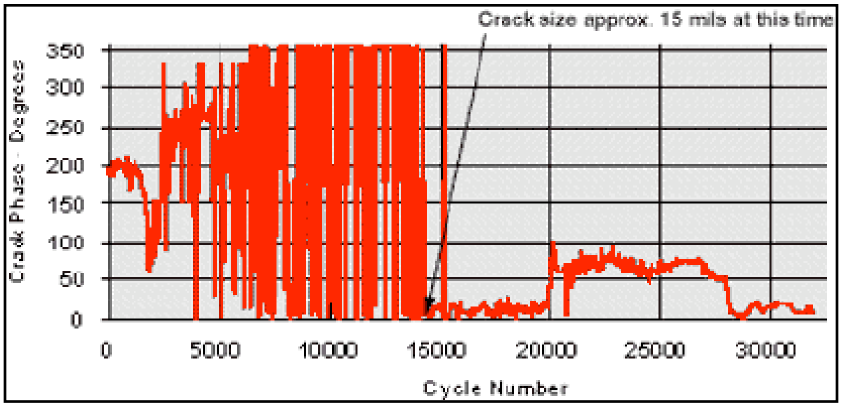


Figure 11 Phase Plot

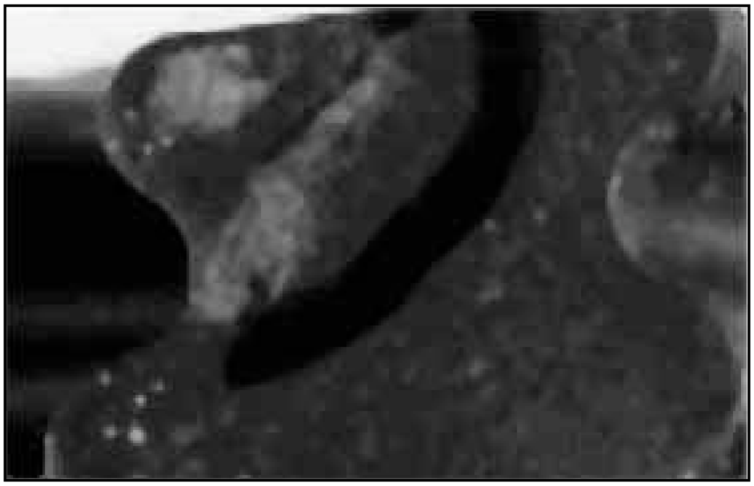
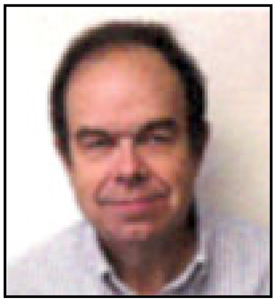


Figure 12 View of Tenon Crack and Blade Interface Surface
After Power Turbine Test)

5. SUMMARY

A non-destructive system has been developed that can detect and track cracks in jet engine rotors in real time during low cycle fatigue testing in a centrifugal stress testing facility. The system has been successfully tested on numerous rotor types including jet engine hardware, medical centrifuge rotors, and energy storage flywheels. The system has already contributed significantly to the knowledge base of fatigue life of spinning rotors, and ultimately to the safety of the systems these rotors are installed in. The system has broad application outside the spin pit including use inside an operating jet engine or other system as a diagnostic tool to detect potentially hazardous conditions.



Eric Sonnichsen is Founder and Chairman of Test Devices Inc., *a manufacturing and service company that specializes in the measurement of physical effects and phenomena in high speed machinery. He has developed test machinery for rapid evaluation of the cyclic fatigue life of jet engine rotors and has been a consultant on the safety of centrifugal stress test facilities. He is co-chairman of an industry consortium that is working to develop containment and safety systems and protocols for very high speed energy storage flywheels. He holds a BSME from Northeastern University.*

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