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Modern NDT for Aging Aircraft

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Abstract

Modern nondestructive testing (NDT) is applied increasingly for improving the reliability and lifespan of aging aircraft. One method, Process Compensated Resonance Testing (PCRT) has recently seen increased implementation in the Aerospace Industry. In cooperation with Vibrant, Delta and Honeywell have largely been involved with the development of PCRT for aerospace applications. PCRT is a long proven NDT method and has been fully implemented and integrated into the automotive industry. The Aerospace and Power Generation Industries are now discovering the benefits that this inspection has to offer. PCRT provides a quick, easy, operator independent method for determining the structural acceptability of parts based on whole body resonance analysis.

This technical paper covers the background of the PCRT technology and capabilities as it relates to specific applications for aerospace components. Highlighted are specific details for the application and validation of PCRT for in service testing of JT8D 1st stage high pressure turbine (HPT) blades to improve engine reliability. Experimental information pertaining to high temperature exposure and fatigue are also included. Additional information, related to defect detection in the CF6-80A 1st stage HPT blade and ceramic rolling elements used in hybrid bearings, is included as well.

Overall it is clear that PCRT is emerging as a practical and inexpensive (compared to existing inspection methods) technology to use for defect detection, process control, and life monitoring of new and in-service components.

1. Introduction to PCRT and Vibrant

Process Compensated Resonance Testing (PCRT) is a relatively new approach in NDT. The underlying technology was developed in the late 1980's at Los Alamos National Laboratories. PCRT is based on the physics fundamental that any hard component will resonate at specific frequencies that are a function of its mass, shape, and material properties. Material changes or flaws change the normal resonant pattern.

Resonant Ultrasound Spectroscopy (RUS), the analysis of the resonant frequencies of a component, has been used to detect major flaws in metal components for decades. This technique lacks the resolution to find small defects and cannot effectively be used to qualify production parts or detect the onset of fatigue.

However, the analytical tool of RUS, coupled with advances in computer based analytical software, has resulted in PCRT, an analytical tool of great power. The technology is achieving growing acceptance (over 150,000,000 automotive parts tested with PCRT in 2006) in inspection of manufactured components such as connecting rods, crank shafts, suspension arms, etc.

Proprietary software algorithms, developed to compensate for normal manufacturing variations, and novel algorithms for monitoring structural changes in a part over its life, are combined into PCRT Systems that can increase production yield, optimize part life, and significantly reduce field failures of components.

PCRT is a fundamental shift in NDT philosophy and applications. Current technologies strive to highlight indications that could represent structural deficiency in a component. PCRT accurately measures the structural similarity of a component to known good parts, and is also able to measure the structural changes in a single part throughout its useful life. Proprietary pattern recognition software algorithms, called Sorting Modules, are developed to compensate for normal manufacturing variations. These Sorting Modules, and novel algorithms for monitoring structural changes in a part over its life, are the basis of PCRT systems. These rapid, accurate, and operator independent PCRT systems can increase production yield, optimize part life, and significantly reduce field failures of components.

Vibrant was formed in early 2006 and licensed the PCRT technology from Magnaflux-Quasar for application in the aerospace and power generation industries. Vibrant has been AS 9100 & ISO 9000 certified since March of 2008. Vibrant is committed to maintaining a strong quality system and meeting or exceeding the needs of its customers.

2. Configuration of a PCRT System

The PCRT System must be configured for a given component prior to testing. Typical configuration of a PCRT system is shown schematically in Figure 1.

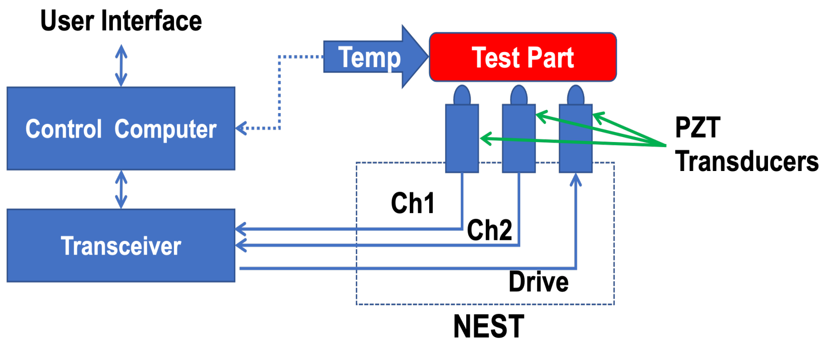

Figure 1 – Typical PCRT System Schematic

To configure a PCRT System Vibrant performs the tasks outlined in the following sections.

A. Hardware Development

For each component to be tested, Vibrant develops a unique locating fixture, called a nest. The nest acts as the interface between the part to be tested and the PCRT software. Each nest has three PZT transducers, one acting as the driver and two for measuring the response signals. Each nest also has locating mechanisms to ensure accurate and repeatable part placement. The automated nest shown in Figure 2 was created for testing the JT8D-T1 blades.

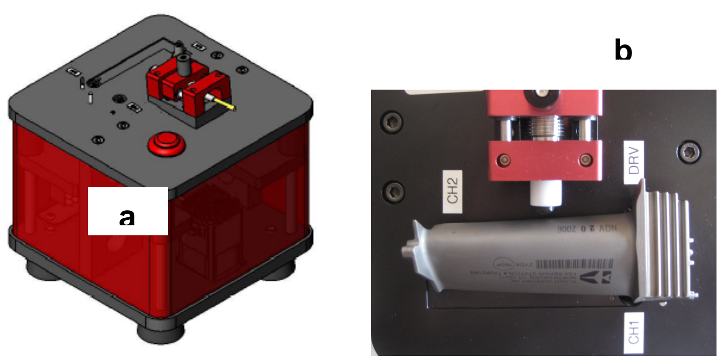

Figure 2 – Automated Nest for JT8D-T1 Blades
a) Model of Automated nest
b) Nest with Blade positioned

The nest is then connected to a high frequency signal generator (transceiver), a host computer running the PCRT software, and a temperature meter. A sample PCRT system setup is shown in Figure 3.

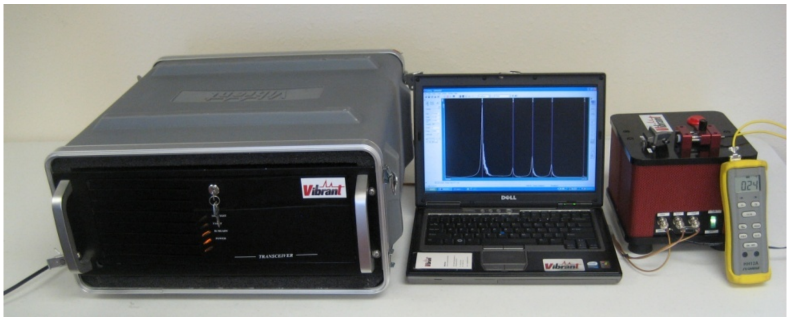

Figure 3 – Sample PCRT System Setup
(From left to right: transceiver, host computer, automated nest, temperature meter)

B. Temperature Compensation Characterization

Changes in a part's temperature can cause resonance frequency shifts that affect the PCRT process. A standard procedure, protected under US patent 5965817, is followed to generate a characterization to compensate for part temperature changes. This characterization is then applied, based on part temperature as measured with the temperature meter, each time a part is tested.

C. Development of Broadband

The PCRT System can vibrate a part over a very wide range of frequencies (1 Hz - 3000 kHz). However, the resonances that can be used for production sorting of parts typically reside in a much smaller frequency range and are dependent on the mass, geometry and material properties of a part. For each type of part a unique broadband must be established. The full broadband spectrum, ranging from 3– 80 kHz, for a JT8D-T1 blade is shown in Figure 4.

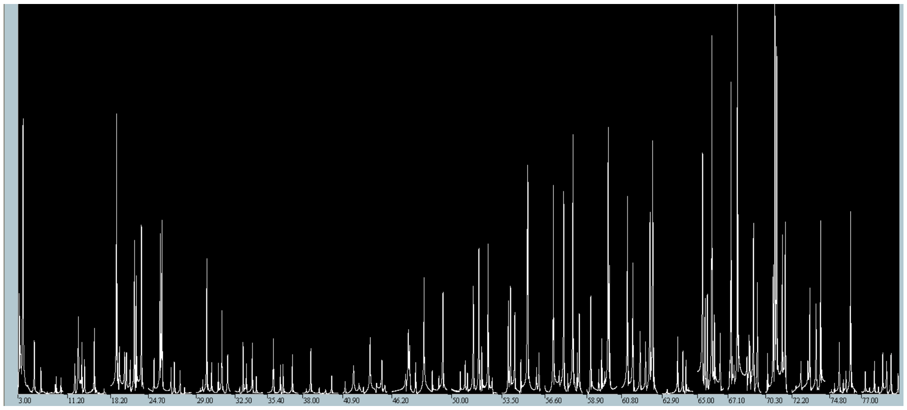

Figure 4 – Full Broadband Spectrum (3-80 kHz) of JT8D-T1 Blade

The broadband parameters (including but not limited to step size, dwell time, and quality characteristics) are optimized to ensure the resonance peaks of interest are sampled and selected appropriately. The process of collecting the full broadband spectrum for a part is referred to herein as logging.

D. Creation of Design Database

A design database comprised of part spectra is used to analyze resonance data. Creation of the design database involves 2 components; the Margin Library and the Parts Library. The Margin Library is built by logging a single part 30 times under various conditions. The Margin Library is used to estimate the error involved with part placement and other minor effects. This error is mathematically taken into consideration during the construction of the Sorting Module. A subset the JT8D-T1 Margin Library is shown in Figure 5; observe the consistency of the resonance peaks.

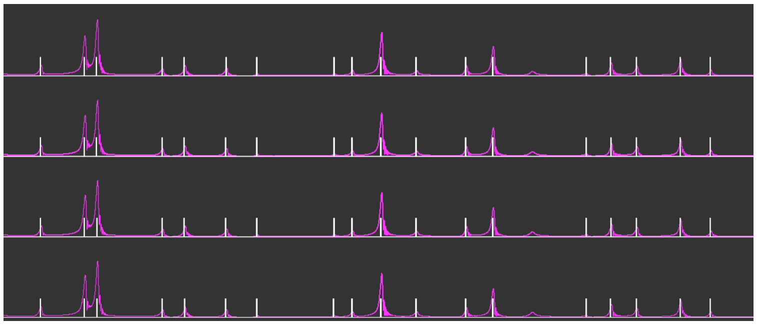

Figure 5 – Subset of JT8D-T1 Margin Library

The Parts Library is built by logging all parts available in the Teaching Set. The teaching set parts should include acceptable and unacceptable components at a recommended ratio of 2 to 1, respectively. The acceptable components should cover the entire range of process variation (multiple batches, operators, dies, molds, etc.). The unacceptable components should contain only the defects of interest. Unacceptable parts can be classified by severity over a range of 1-5. This severity is used by the PCRT System to focus detection on the most critical defects.

The records logged in the Parts Library are then used to build the Design Database. The records are stacked and the resonant peaks of interest are identified using a combination of built-in software analysis and detailed visual inspection. The screenshots in Figure 6 from the PCRT software illustrate the results of this process. Notice the differences in the resonances of the bad parts compared to the good parts.

Figure 6 – PCRT Screenshots of Subset of Blades in JT8D-T1 Design Database
(Top green are good, bottom red are bad)

E. Creation of Sorting Module

The Design Database is then analyzed by the PCRT software to identify patterns in the resonant frequency peaks that are able to distinguish the good parts from the bad. The patented PCRT software utilizes a Mahalanobis-Taguchi System (MTS) statistical analysis to identify a multi-frequency central tendency or pattern that groups the good parts, and excludes many types of defects. Defects with a lesser effect on the resonant spectra are excluded with a secondary discriminator known as the Bias. This is all determined in 'n-dimensional' space; however, a simplified output graphic of the software for JT8D-T1 is shown in Figure 7. Parts in the lower left region would be passed; parts in all other quadrants would fail. In this figure the goods are identified by green dots (mostly located in pass region with small percentage of those rejected in the other quadrants) and the bads are identified by red Xs (notice there are no bads in the pass region). The black diamonds represent parts that are considered 'unknown'. These parts do not affect the final algorithm; results are based only on 'good' and 'bad' parts, but the display shows how these parts would be sorted.

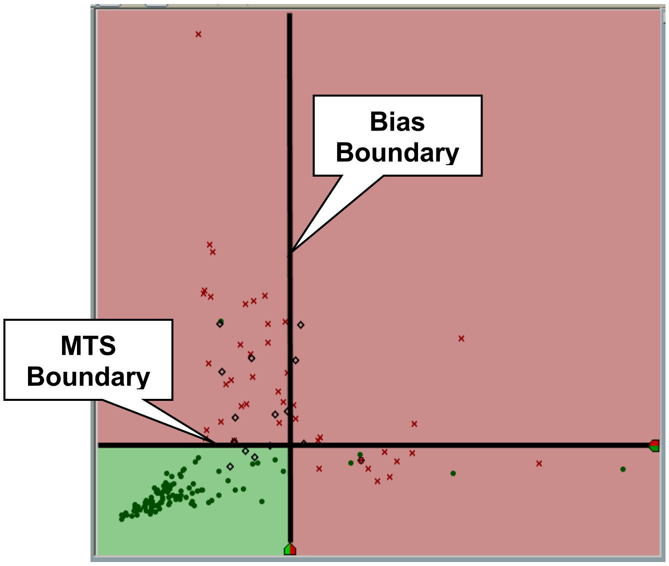

Figure 7 – Simplified Sorting Solution Output for JT8D-T1

The software generates several possible sorting solutions based on the number of resonances used by the pattern-recognition algorithm. The number of resonances used in the sorting solution, generally 2-9, depends on a number of variables including the complexity of the part, the resonance variation, and number of defect types in the population.

The sorting solutions generated are analyzed to select the best solution to use for the Sorting Module. The Sorting Module is the set of resonances and data sampling parameters necessary for classifying the tested parts as pass or fail. Each resonance in the Sorting Module is measured in 0.5-3 seconds and test results are provided subsequent to measuring the last resonance. A sample test output, for a JT8D-T1 blade, is shown in Figure 8.

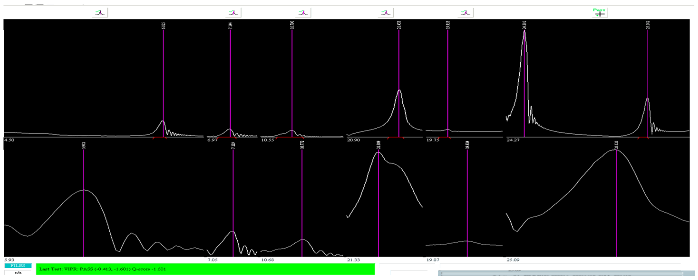

Figure 8 – PCRT Screenshot of Sample Test Output

Prior to implementation the Sorting Module is validated to see if it can run in an automated, objective fashion. The validation assures that the system will interpret the test results properly in an unsupervised (no operator interpretation) test.

3. Applications of PCRT

PCRT has been applied as a viable NDT technique on many different components. PCRT can be used on a wide range of materials, including but not limited to: steel, aluminum, composites, ceramics, and superalloys. Also, the size and geometry of components does not limit the application PCRT.

The majority of the technical information contained in this report is pertinent to the application of PCRT to the JT8D 1st stage turbine blade; however additional information, pertaining to the application of PCRT to silicon nitride ceramic rolling elements, CF6-80A 1st stage HPT turbine blades, is also contained herein. The results of several studies involved with the application of PCRT for fatigue and life monitoring are also included.

4. JT8D 1st Stage Turbine Blade Project

A. Overview

The JT8D 1st stage turbine blade, used in the 217C and 219 engines on the MD-88 aircraft, has had in-service challenges for some time. This has primarily been attributed to multiple failure mechanisms, which often intertwine to produce unscheduled engine removals (UER), in-flight shut downs, and failures. The main contributors are overtemp, intergranular attack (IGA), thin wall, cracking, and/or stress rupture. Over 150 blade fracture events in industry have been reported by Pratt & Whitney (P&W) since 1990. Inspections currently performed on these blades include UT for wall thickness, visual/dimensional, FPI for cracking, and overtemp analysis.

The current method of determining whether a blade is overtemp is somewhat subjective and very time consuming. The metallographic result for a single sectioned blade is the basis for scrapping or returning to service the entire blade set. No inspection method or criteria for IGA currently exists; however, limits of 24,000 hours and 2 ‘strip and recoat’ repairs were previously in place to avoid future failures. Even still, no lifetime tracking, serialization, or consistent method of marking service life exists; which made it difficult to ensure the limits were adhered to. These inspections, and correspondingly engine performance have been proven to be unreliable.

In an effort to develop an improved non-destructive testing (NDT) method, Delta engineering provided Vibrant with a “teaching set” of 89 JT8D-T1 blades in various conditions.

The teaching set blades were analyzed by Vibrant and were used to form an initial sorting algorithm. Information obtained from the Overtemp Study detailed in section 4.B. was also used. During the six-month trial, the majority of the teaching specimens were sectioned in Delta’s Maintenance Lab and examined for overtemp, wall thickness, cracking, and IGA, using the methods detailed in section C. Metallographic Analysis of Blades. Simultaneously, the PCRT system collected data from production blades passing through the Delta Blade and Vane Shop. Data from the sectioning and PCRT spectra were then used to refine the algorithm before a critical design review and blind study (detailed in section E) were successfully passed in November 2008. The six-month trial ended in early December 2008, and in-service testing was implemented in January 2009.

B. Overtemp Study

In order to learn more about the effect temperature exposure has on resonant frequencies, spectra was captured for 10 blades before and after exposure to a range of temperatures. 5 of the blades were newly manufactured (blades 1-5) and 5 were previously serviced (blades 80-84) with approximately 7,000 hours.

I. Exposure of Blades

The 10 blades were subjected to exposure cycles reflective of operating and suspected overtemp temperatures provided by Delta. For each cycle, the blades were placed into a room temperature furnace, brought up to temperature, and soaked for 30 minutes. The exposure cycles for the overtemp study are detailed in Table 1.

Table 1 – Exposure Cycles for Overtemp Study

Cycle	Blades Exposed	Exposure Temperature (°F)
1	1, 2, 3, 4, 5 80, 81, 82, 83, 84	1800
2	2, 3, 4, 5 81, 82, 83, 84	1950
3	3, 4, 5 82, 83, 84	2000
4	4, 5 83, 84	2050
5	5 84	2100

II. Microstructural Analysis of Overtemp Study Blades

The exposed blades were cut-up and analyzed using the methods detailed in section 4C and results are listed in Table 2.

Table 2 – Delta Lab Results for Overtemp Study

Exposure Temperature (°F)	Blade	Delta Lab Result	Blade	Delta Lab Result
1800	**1**	no- no evidence of elevated temperatures	**80**	no- approached 2050
1950	**2**	no- approached 2050	**81**	no- 2050
2000	**3**	no- approached 2050	**82**	yes- 2050
2050	**4**	yes- 2050	**83**	yes- 2050
2100	**5**	yes- 2100	**84**	yes- 2100

The differing lab results for parts 3 and 82, which were treated identically in the study, could come from previous temperature exposure to blade 82, or could demonstrate subjectivity in the current overtemp inspection methodology.

III. PCRT Analysis of Overtemp Study Blades

The data gathered during the overtemp study shows clearly that increased temperature exposure causes the resonances to decrease in frequency (shift left). This trend is evident for all blades used in the study. Figure 9 shows this trend; note that the largest visible shifts occur initially and due to the 2100°F exposure cycle.

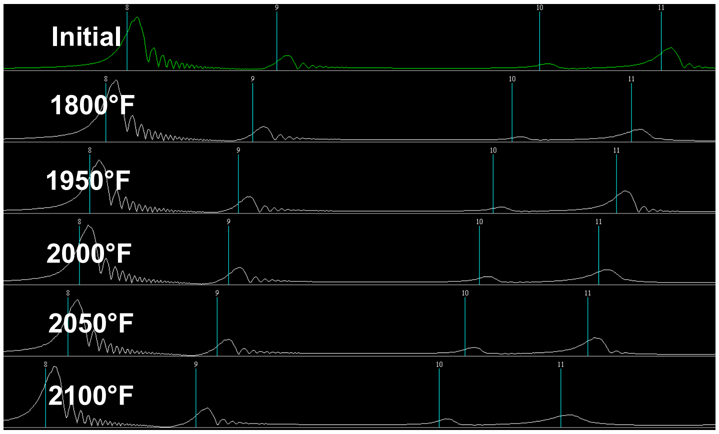

Figure 9 – Stacked Spectra (19-21.5 kHz) of Blade 5

On average, the resonances decreased approximately 1.5% on exposure to 2100°F. A large shift also occurred upon initial exposure to elevated temperatures. Overall the resonance shift was consistent for all resonances evaluated, but the resonances did not all shift by identical amounts. This represents a pattern shift, where the relative spacing of resonances is affected. The percent shifts and the relative spacing effects are used by the PCRT System to set up the pass/fail criteria for testing.

C. Metallographic Analysis of Blades

Metallographic analysis was utilized to add confidence to the blade classifications in the PCRT database. Blades were examined via sectioning, as in Figure 10, per P&W SPM 70-36-20-280-100, which is referenced in P&W JT8D Engine Manual 72-52-01.

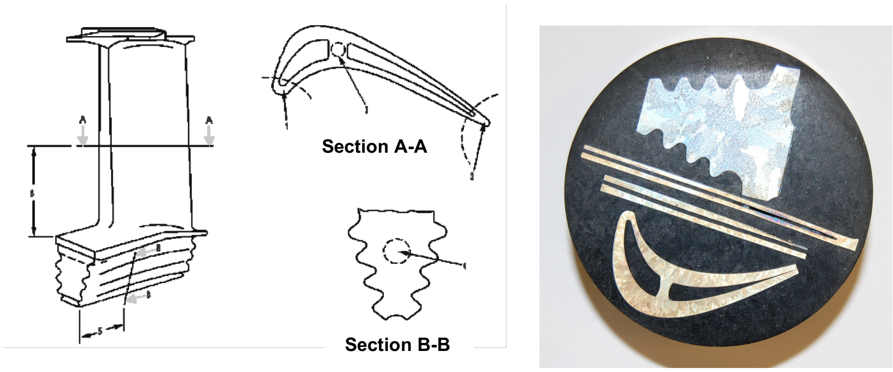

Figure 10 – Schematic and Photograph Showing Blade Sections

To date, a more than one-hundred (100) blades have been sectioned, mounted, etched, and analyzed in support of this study. All blades were characterized for overtemp, thin wall, IGA, having a combination of those defects, or as acceptable. This characterization information was used to further validate the PCRT system. The methods used for each of these characterizations are discussed in the following sections.

I. Overtemp Analysis

The P&W Manual includes very specific instructions for conducting a turbine blade overtemp analysis. These procedures dictate that one blade (of the 64 blades in a set) shall be sectioned and analyzed and the result determines the serviceability of the entire set. This method may be flawed as an overtemp event can result in local hot spots, where some blades may be overtemp, and others may not. Thus, some serviceable blades may be scrapped as a result of analyzing one blade which is determined to be severely overtemp. Likewise, some overtemp blades may be passed into the serviceable pool after analyzing one good blade. Neither conclusion produces a result that is considered reliable or acceptable.

The overtemp inspection is performed by using an optical microscope, up to 1000x, to evaluate the sectioned microstructure (Figure 11).

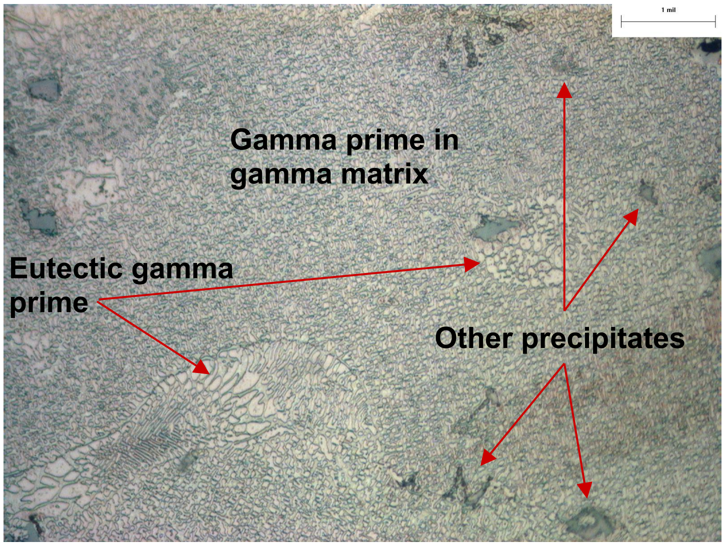

Figure 11 – 500x Micrograph with Basic Metallurgy of JT8D-T1 Blade

The initial microstructure is determined by analyzing the root section of the blade; the microstructure of this section is not typically affected except in extreme cases. The initial microstructure is then compared to the hot sections (leading and trailing edges; respectively LE & TE), specifically identifying three main gamma prime effects; coarsening, solutioning and rafting [4].

Per the P&W Manual, the inspected blade and entire blade set is rejected if the microstructural inspection shows solutioning (with or without rafting) of the gamma prime.

II. Thin Wall Analysis

Prior to cut-up the blades were subjected to an ultrasonic (UT) inspection for wall thickness measurement. A modified version of the ultrasonic thickness procedure found in the P&W JT8D Engine Manual 72-52-01, Inspection -07 and Inspection -08 was utilized. The modified method was used to prevent the need to strip the blade coating.

The P&W engine manual specifies twenty-nine (29) points to measure UT thickness for the JT8D-T1 blade. These points are shown schematically in Figure 12. The minimum specification for wall thickness, as specified by the engine manual, for the main area of concern (points 3, F, and 4 in Figure 12) is 0.022”.

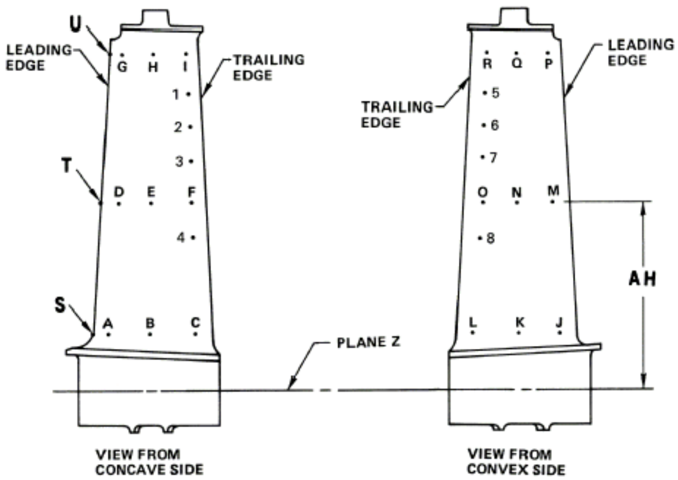

Figure 12 – Ultrasonic Wall Thickness Measurement Locations
(From P&W Manual)

UT measurements were verified by measurements obtained during microscopic evaluation. An example of the microscopic evaluation is shown in Figure 13.

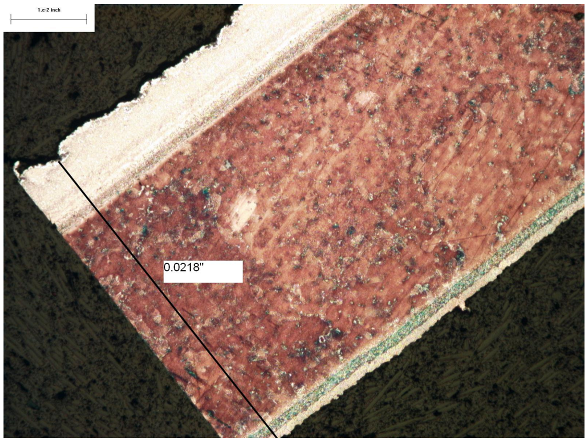

Figure 13 – Image of Microscopic Evaluation of JT8D-T1 Blade Wall Thickness

III. IGA Analysis

No IGA inspection method is currently documented. Magnetoscope can be used for the inspection of internal corrosion, but it tends to be inconsistent and unreliable for detecting IGA. Only gross amounts of IGA would likely be detected. Therefore, sectioned blades were examined for the presence of IGA on the internal cavity walls and the associated crack depths were documented.

As no inspection method is available for IGA, neither is a reject limit, although it is clear some amount of IGA is considered minor and acceptable. To estimate a reject limit, blueprints and QED (Quality assurance documents) for several part numbers were examined. These outline radiographic, FPI, and visual specifications for reject criteria of the castings during manufacture. For this study, rejection limit for IGA was set at a depth of 0.003". A micrograph showing significant IGA is shown in Figure 14.

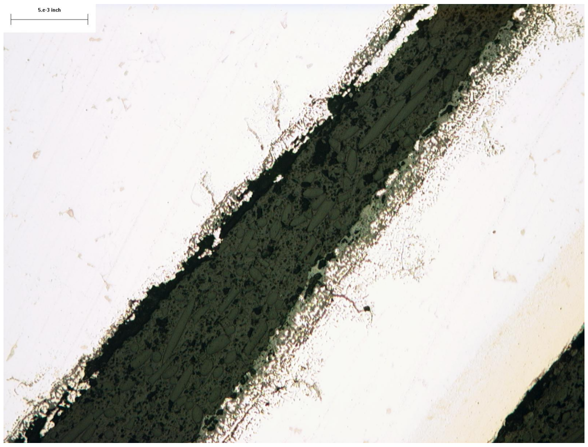

Figure 14 – Micrograph of Blade Showing Significant IGA

IV. Metallographic Results

Metallographic results were separated into "buckets", shown in Table 3, to illustrate how many examples of each defect were obtained. The number shown in the bucket is the number of examples identified to date. Additional work is being performed to add examples to the buckets and build the robustness of the PCRT System.

Table 3 – Buckets for JT8D-T1 Metallographic Results
(Number reflects number of examples provided to date)

IGA	Overtemp	Thin Wall	Cracking	None Present
4	36	8	0	44 (also have 140 assumed good)

IGA and Overtemp	IGA and Thin Wall	IGA and Cracking	Overtemp and Thin Wall	Overtemp and Cracking	Thin Wall and Cracking
8	1	0	11	1	1

IGA, Overtemp and Thin Wall	IGA, Overtemp and Cracking	IGA, Thin Wall and Cracking	Overtemp, Thin Wall and Cracking
4	1	0	2

IGA , Overtemp and Thin Wall and Cracking
0

D. PCRT of In-Service Blades

For a six month period, data was collected on blades pulled from the scrap area and on in-service blades in conjunction with normal inspections and suspected overtemp events. During this period, blades were sent to the Delta lab for metallographic analysis (detailed previously) to classify the blades as good or bad. All of this data was crucial to building the information on good and bad blades in the design database.

Some initial Delta assumptions about the blades were shown to be incorrect upon PCRT evaluation and sectioning. Two (2) blades taken from the serviceable pool, and assumed to be good stood out as outliers in the PCRT population of goods. Upon cut-up, both blades were found to be overtemp.

Vibrant then provided full training to five (5) Delta employees. The PCRT inspection procedure was implemented in January 2009. The implemented sorting module was based on 6 resonances. This sorting module correctly sorted 100% of the characterized (to-date) bad blades and 95% of the goods. Further work is being performed to investigate the remaining 5%.

Post implementation, the PCRT Sorting Module has been updated and re-evaluated based on new information. This new information includes the ongoing cutup of blades, observations of spectra, information on part numbers and repair processes, and other further analyses. This update process will continue until a satisfactorily robust Sorting Module is developed.

E. Blind Study

At the conclusion of the six month data collection phase, a 'blind study' was conducted as part of a critical design review. Delta selected 16 blades representing the target defects, and good parts, for this review. After analysis by Vibrant, the blades were sectioned to determine the actual blade classification. The results of this study are shown in Table 4.

Table 4 – Results for Blind Study Blades

Blade Letter	Comment	PCRT Result	Metallographic Result
A	Suspect good	Pass	N/A
B	Suspect IGA & OT	Fail	Coating cracks
C	Suspect good	Pass	Good
D	Suspect OT, IGA & Thin wall	Fail	OT, IGA, & Thin wall
E	Cracked	Fail	Cracked, OT, IGA
F	Suspect OT	Fail	OT
G	Suspect good	Fail	Good
H	Suspect IGA & OT & Thin wall	Fail	IGA, OT
I	Suspect good	Pass	Good
J	Cracked	Fail	OT, Cracked, Thin wall
K	Suspect OT	Fail	OT
L	Suspect good	Pass	Good
M	Suspect good	Pass	Good
N	Suspect good	Pass	Good
O	Suspect IGA & OT	Fail	OT, Thin wall
P	Suspect good	Pass	OT

The blind study results revealed PCRT provided excellent correlation with the actual condition of the blades supplied. 2 of the 16 blades were classified differently by the Delta Lab and PCRT. This has been attributed to the metallographic overtemp analysis being conservative and somewhat subjective. PCRT provided a nearly instant result, while metallographic sectioning took approximately 6 weeks. Blade A was not sectioned and is to be used by Vibrant as a good blade in a study of transducer consistency.

F. Results Discussion and Path Forward

The number of blades found with an overtemp 2050°F condition was significant, approaching 50% of the blades examined. Further investigations are underway to quantify the degree of overtemp and its role on the life of the blade.

Delta will continue to perform the PCRT inspection on JT8D-T1 blades and perform metallographic analysis as needed. Vibrant will continue to provide testing support and data analysis. Upon obtaining a statistically satisfying set of blades (for each defect), the individual defect POD limits and classifications may be possible. After a period of time in which successful testing has occurred, the joint team will begin to compile the necessary information to seek FAA Certification.

5. Hybrid Bearing Rolling Element Project

Vibrant teamed with Honeywell Engine Systems in 2008 to evaluate PCRT's ability to identify defects in Hybrid Bearing Rolling Elements (ceramic balls). Honeywell successfully implemented PCRT for inspecting 0.5-in. production ceramic balls and is currently pursuing additional applications and further defining validation processes.

A. Overview

New developments in gas turbine engines are driving the requirements of current bearing technology to its design limits in terms of material performance, capability and reliability, as well as affordability. Hybrid ceramic rolling element\metal race bearing technology has proven itself to be a valid candidate to meet the needs of the growing engine technology requirements. These new bearings provide much better properties than the all-steel components they are designed to replace. These properties include increased load-carrying capability, decreased friction and heat generation, greater stiffness and corrosion resistance, lower coefficients of thermal expansion, and increased thermal stability characteristics. The ceramic balls of this new generation of bearing have proven to be robust in use provided that they are free of manufacturing defects. However, NDE techniques applied to ceramics for this class of bearing have proven to be ill suited for quality-assurance inspections for typical rates of manufacturing production. The slow inspection rate and high inspection costs of the current ceramic NDE methods may prevent hybrid bearings from being widely used in current or future fleets. Figure 15 shows examples of C-spall and crack defects found in ceramic balls. A distinct advantage of the PCRT process is the ability to detect internal defects that cannot be detected by any surface measurement technique.

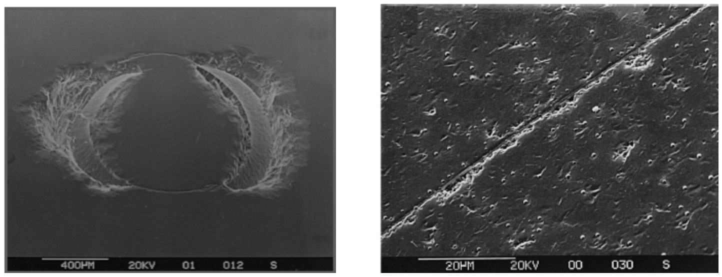

Figure 15 – Examples of C-Spall and Crack Defects in Ceramic Balls [9]

Lower-frequency resonances can be used to evaluate the spherical symmetry and identify bulk-body defects. Higher-frequency resonances, where surface or Rayleigh waves dominate, propagate without dispersion in an isotropic media and therefore, any distortion in the measured Rayleigh wave may be attributed to near surface flaws [6,7]. An example of this distortion is shown in Figure 16. The resonances exhibit peak splits and shifts in frequency and these are key characteristics that the PCRT System uses to classify a part as acceptable or unacceptable.

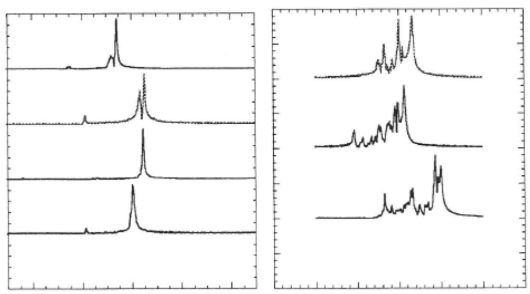

Figure 16 – Resonances of Good Samples and SAW-Like Modes Caused by Surface Defects

B. PCRT System Configuration

The nest designs for some of the ceramic balls studied are shown in Figure 17. The nest for the 0.5-in diameter ball is a fixed nest that improves the repeatability of the PCRT system.

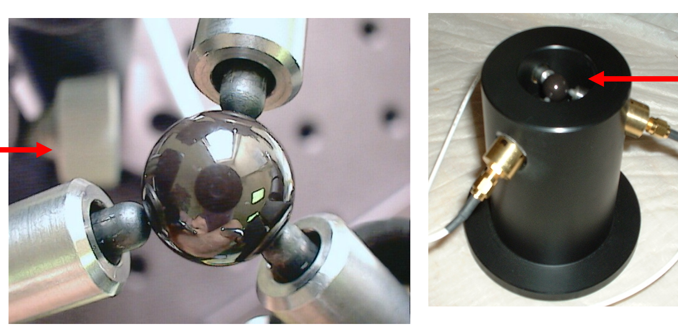

Figure 17 – Nest Designs for Ceramic Balls

C. Defects Detected

Relatively low frequency resonances (first 10-15 modes) for the ceramic balls proved capable of detecting a number of whole body and surface defects such as:

- Microstructure Differences
- Surface Chemistry / Reaction Layer Defects
- Metallic Inclusions
- Density Variation
- Heat Treat Variation

An example of a reaction layer defect is presented in Figure 18 and Figure 19.

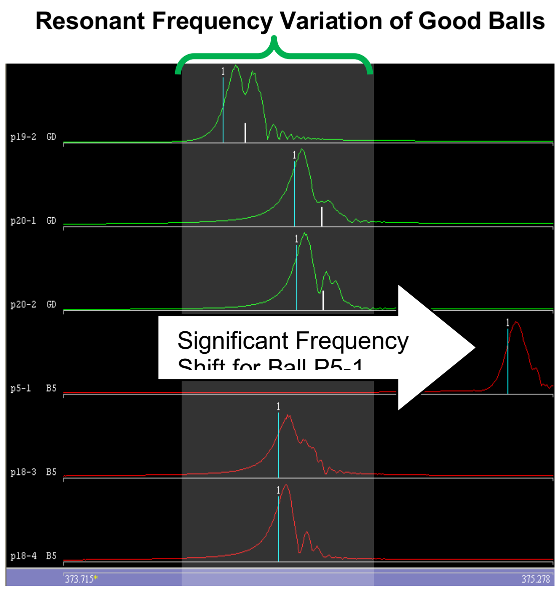

Figure 18 – Close up of first resonant peak for 3 good and 3 defective balls

Figure 19 – "Reaction Layer" Defect in Ball P5-1

Significant surface scuffs and gouges were also detectable by these lower modes. For repeated samples, it was found that PCRT sorting methods could reliably detect a scuff or gouge representing about a .02% volume effect, and/or about a 1% effect on the surface area. Figure 20 shows the increased effect (frequency splitting) as a 'scuff' defect was created and increased in size to approximately 0.130" x 0.170". The size of the frequency split is proportional to the size of the 'asymmetry' imparted to the ball, as shown in Figure 21. Opportunities to detect smaller defects of these types are currently being investigated at higher frequencies.

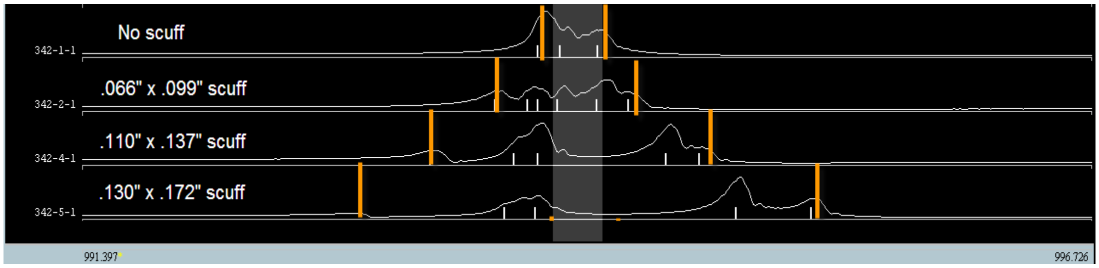

Figure 20 – Increased 'splitting' of 994 kHz resonance due to increased surface scuffing.

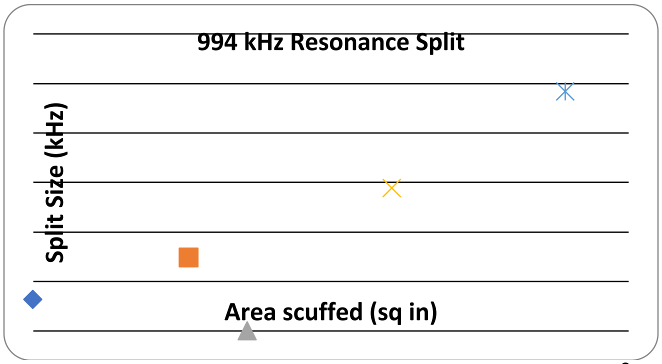

Figure 21 – Plot of Split Size vs. scuffed area (in^2).
The split size is proportional to the size of the defect.

Smaller surface damage is detectable by higher order surface resonance. Figure 22 shows peak splitting around 2.6 MHz due to a C-spall crack introduced into a 1.125-in. ball (via impact with a 0.375-in. ball).

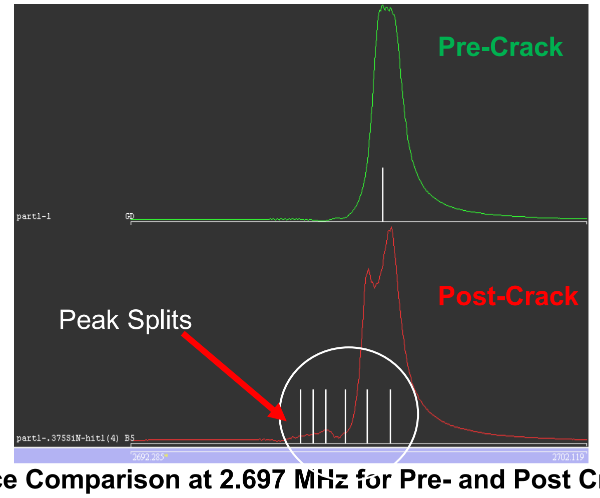

Figure 22 – Resonance Comparison at 2.697 MHz for Pre- and Post Crack 1.125-in. SiN Ball

The 2.697 MHz resonance in Figure 22 has the characteristics of peak splitting with the formation of many new resonances as indicated by the white vertical lines. These characteristics were evident on many other resonances over the broadband range. The peak splitting characteristics were expected based upon the surface acoustic wave behavior described by Migliori [6].

6. CF6-80A 1st Stage HPT Turbine Blade Project

A. Overview

The CF6-80A Stage one blade is unique in design, manufactured with a brazed-in inverted tip cap that has led to several service failures and numerous in flight shutdowns. After an undetermined and unpredictable amount of cycles the braze diffusion line is weakened by service stresses. This weak area is a prime location for crack propagation when the part is under load. Once a crack is present, it grows along the diffusion line in an axial direction using the parent material and braze interface as a guide. The cracks will grow towards the leading edge until they break out to the surface. After breakout, the crack and surrounding parent material is subjected to the harsh operating environment of the high pressure turbine. This allows the corrosive elements to attack the exposed material and eventually a complete tip separation can occur. These failures have occurred at unpredictable cycles and hour intervals. This unpredictability lead Delta Airlines to self impose an 11,000 hour life limit on the blades, resulting in a sequestering of over 1,500 possibly serviceable blades.

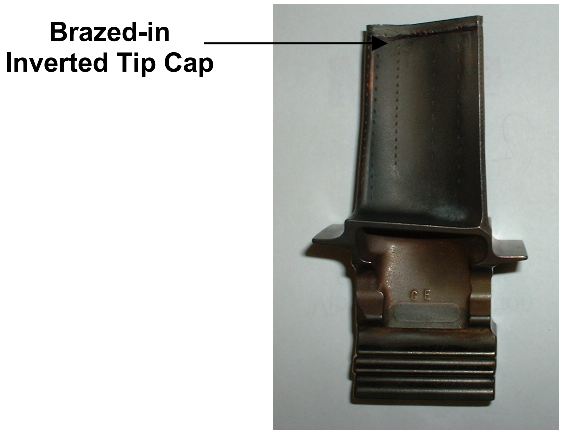

Figure 23- Image of CF6-80A Turbine Blade

The currently used inspection methods, repair and overhaul X-ray and FPI, have proven to be inconclusive in detecting braze interface cracking. Delta and Vibrant jointly participated in an evaluation of PCRT for the inspection of the CF6-80A Stage 1 HPT Turbine Blades.

B. PCRT System Configuration

As discussed previously, PCRT Systems must be uniquely configured for each component. For the CF6 1st stage HPT blade, Delta provided Vibrant with one hundred seven (107) blades to be used as the teaching set. The serviceability of these blades was unknown and all blades met or exceeded the life limit imposed by Delta.

Analysis of the spectra was used to determine which fixturing orientation produced the best quality and most repeatable resonance data. The transducer location was optimized and used to create an automated nest for this component, shown in Figure 24.

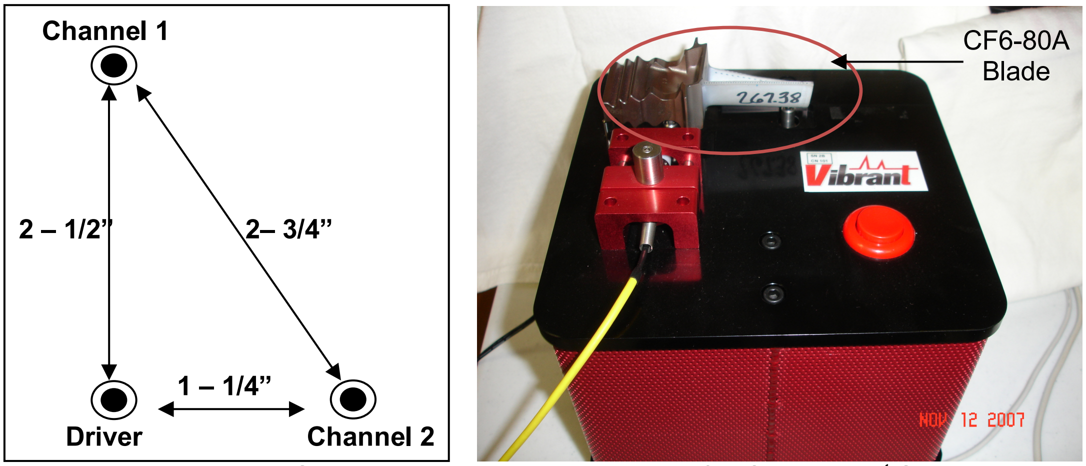

Figure 24- Transducer Schematic and Automated Nest for CF6-80A 1st Stage Turbine Blades

The temperature compensation characterization and broadband were then developed. The broadband for this component ranged from 1-143.6 kHz.

The spectra for all the blades were logged into the database and the resonances were analyzed for patterns or indications of differences. In order to aid in the classifications of these unknown teaching set parts, various techniques were utilized. Several of these techniques are discussed in the Classification of CF6-80A Blades section.

The blades were then categorized in the PCRT software and a sort between the "good" and "bad" blades was built and validated. This sort, shown in Figure 25, was based on 17 good and 10 bad blades. The pink diamonds represent measured, 'unknown' parts that would pass the PCRT inspection.

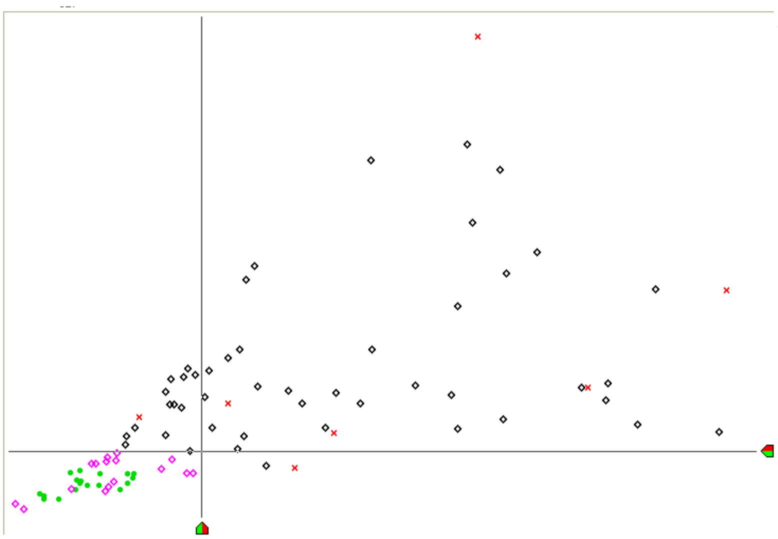

Figure 25- Sorting Solution Output for CF6-80A 1st HPT Blade

To validate the results of this sort, Vibrant subjected 10 of these 'good' blades to a magnified digital radiographic inspection. These magnified digital radiographs showed that the blades had no indication of braze joint cracking. The entire airfoil area was also examined to ensure that the blades met all repairable X-ray requirements. Additionally the radiographs showed that the blades had consistent tip cap placement in both the radial and axial orientations. These radiographs were practical to use as a validation method, but due to high costs it is not practical to inspect all the blades with this method.

C. Classification of CF6-80A Blades

All of the blades Vibrant received from Delta were of unknown classification. In order to build a database with robust classifications, various methods of classifying the blades were evaluated.

One method was to have blades X-ray inspected, limited to the leading edge portion of the brazed-in cap. 10 parts were inspected by an ASNT Level III in Radiography and the results were recorded. This provided initial sorting results that were inconclusive in detecting both a crack indication and a correlation to the spectra groupings.

Further classifications were gained by providing 30 blades to Sandia National Laboratories for Computed Tomography Inspection (CT). The CT scan was collected approximately 0.400 inches below the brazed-in cap and entirely through the squealer tip. The 30 parts were inspected by an ASNT Level III in Radiography and the results were recorded. The CT scan results provided a 3-D view of the entire brazed joint. The reject criteria for a brazed tip cap gap were as follows:

- A gap of .005 inch is permitted between the tip cap and blade ribs 3, 5, & 7. A gap of .010 inch is permitted between the tip cap and rib 1 of the blade.
- Braze alloy must not flow into cavities beyond .100 inch from the bottom of the tip cap. Braze is not permitted around the trailing edge pin fins which are more than .050 inch from the bottom of the tip cap

Of the blades inspected, 4 blades were identified as having crack indications that appeared to have propagated from the braze interface and 3 additional blades were noted as having suspect density variation within the braze, but no confirmation of a crack indication. A gapped braze example and an example of a crack identified using CT are shown in Figure 27 and Figure 26, respectively.

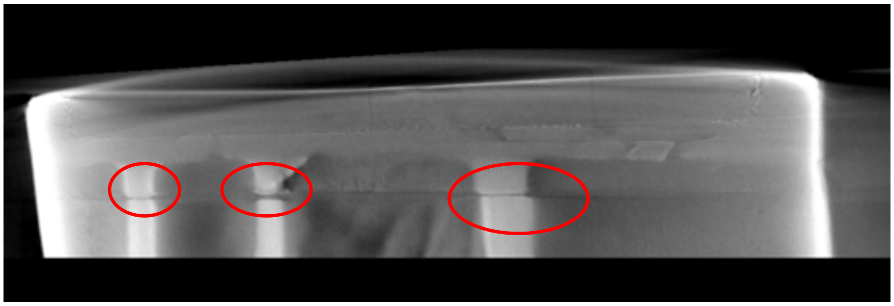

Figure 26 - CT Gapped Braze example

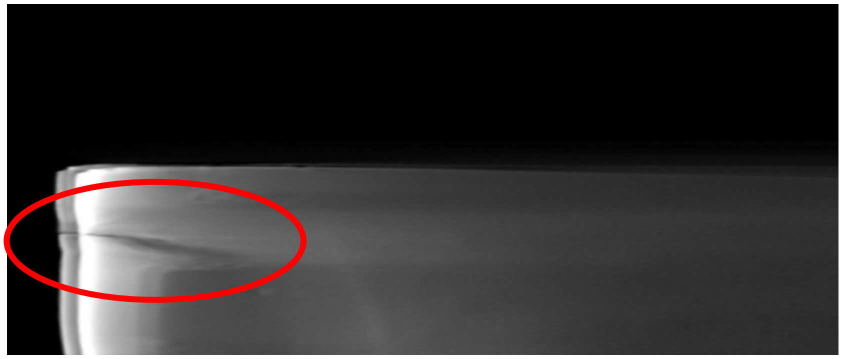

Figure 27 - CT crack example

Another inspection method, a 10X visual inspection, was performed on all blades. The visual inspection provided 4 additional blades with surface cracks at the suspect area as well as 2 blades with very minor crack like indications that required a 50X visual inspection. Examples of both a surface crack and a minor crack indication are shown in Figure 28.

PCRT was then used as another method of classification. The resonance spectra from all blades were evaluated for pattern similarities and statistical variations from the normal distribution. The data was analyzed and the 10 most similar parts were selected as the sample of good parts. After spectrally grouping the selected assumed good parts, a correlation with the previous inspections was identified. Specifically, 4 of these 10 "good" parts had previously been inspected and none of the parts had failed the other NDT evaluations.

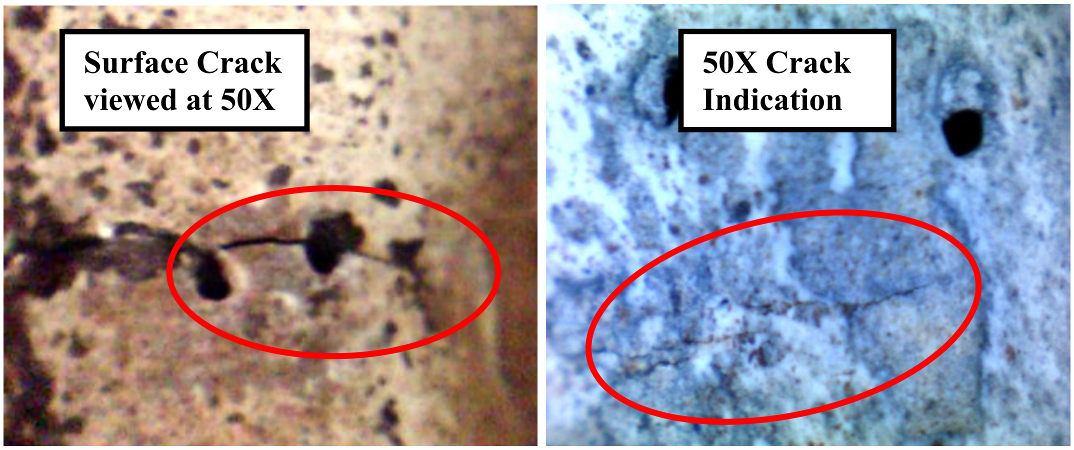

Figure 28 - Visual Crack Examples

The correlation of each inspection and the spectra evaluations lead Vibrant to categorize a grouping of 10 blades as "good" and a grouping of 7 blades as "bad".

D. Path Forward

Vibrant has created a sorting module they are confident will properly identify CF6-80A 1st stage blades that have been structurally affected by a braze breakdown at the leading edge braze joint. The sorting module has been developed to "look" specifically for parts that have resonance spectra that are most similar to parts without this defect. In addition, other structural defects that have a similar influence on the resonance patterns will be rejected by the sorting module.

Based on the blades Vibrant tested, a nearly 40% accept rate is predicted. This is assumed to be a statistically significant representation of the entire population of sequestered blades at Delta. This is potentially a significant cost savings in parts for Delta. Additional cost savings would likely be in the form of reduced unscheduled engine removals and failures.

7. Fatigue and Lifing Projects

The increasing age of aircraft in service has lead to research of new requirements for life monitoring and fatigue life predictions. The PCRT technology has been shown to be a valuable tool for this process. Studies have shown that resonances shift due to fatigue; whether thermal, mechanical or thermal-mechanical. This information can be used to monitor the state of the health of a component.

A. Al 6061-T6 Coupons

In order to generate a correlation between the resonance shifts and fatigue life a study using Al 6061-T6 coupons was conducted in cooperation with the AANC Validation Center at Sandia National Labs. The coupons were placed into the fatigue fixture, in Figure 29, and subjected to loading cycles.

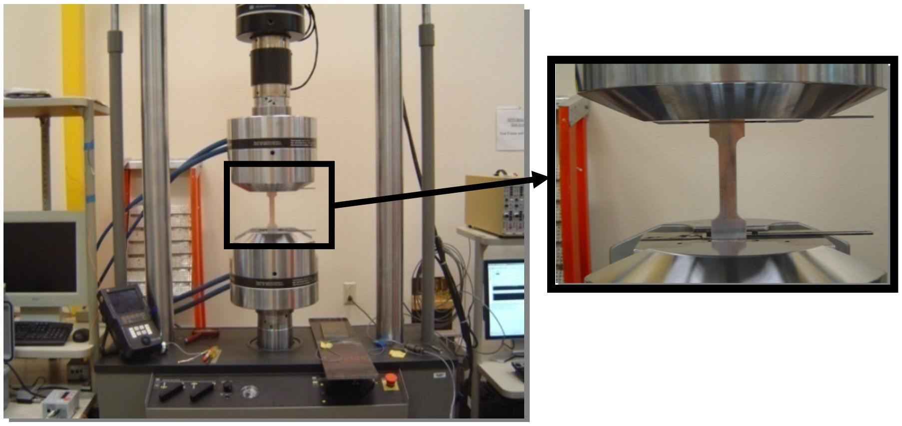

Figure 29 – Fatigue Fixture and Al 6061-T6 Coupon

Spectra was captured between load cycles at regular intervals. A portion of the spectra from a coupon is shown in Figure 30.

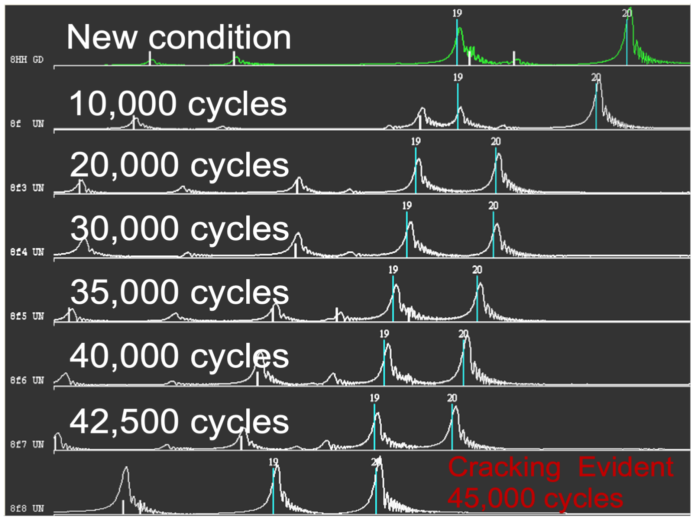

Figure 30 – Spectra of Al 6061-T6 Coupon Showing Shifting due to Fatigue

The coupon elongation was monitored along with the resonances. Data from the two are presented in Figure 31. The frequency shift was not due to elongation alone, as while the elongation was roughly linear up to about 40,000 cycles, frequency shift was non-linear throughout the test range.

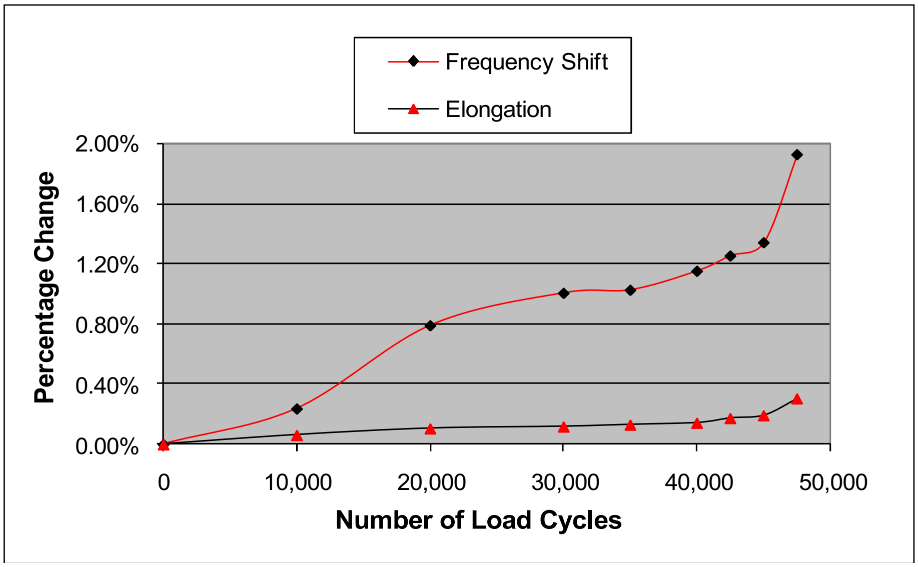

Figure 31 – Comparison of Frequency Shift and Coupon Elongation due to Fatigue

B. TMF Rene 80 Coupons

Additional studies have been conducted to analyze the effects of thermal and thermal-mechanical fatigue (TMF). Rene 80 superalloy coupons were machined and subjected to thermal and mechanical cycling. The semi automated cycling sequence was: initial heating, heating retention, and cooling. As the coupon was heated (using an induction heater), the tensile load decreased as the temperature was increased. As the coupon was force-air-cooled, the tensile load steadily increased back to the starting point. A digital record of the load cell pressure, coupon temperature, and amperage output from the induction heater was captured for each cycle. The test setup is shown in Figure 32.

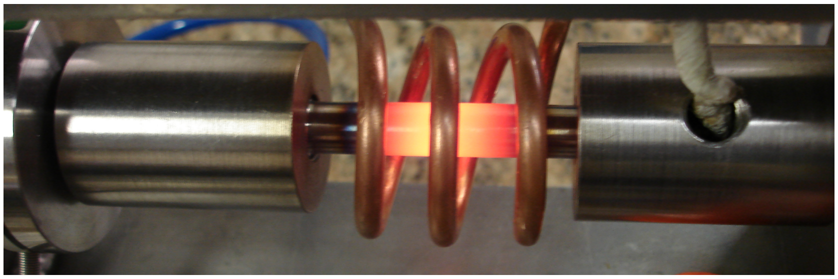

Figure 32 – Rene 80 Coupon Under Load and at 1500°F

Periodically, the coupon was logged with the PCRT System. It was also inspected for any geometrical changes and discontinuity nucleation or propagation. Dimensional, visual, and fluorescent penetrant inspections were performed to correlate the resonance spectra to physical changes. A typical test is demonstrated in Figure 33. The crack is indicated through PCRT by the increased frequency shift and change in relative spacing (peak convergence). Notice that PCRT has the capability of detecting cracking prior to FPI indication.

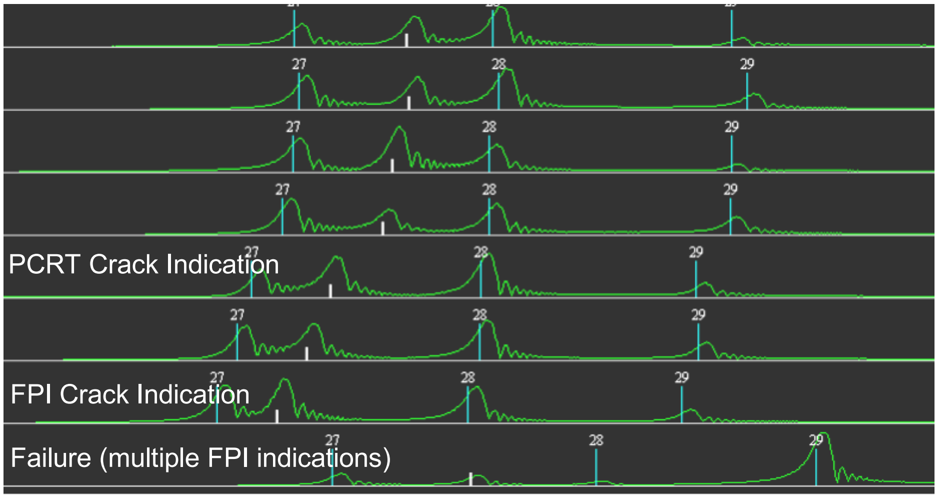

Figure 33 – Rene 80 Coupon Resonances Indicating Fatigue

8. Summary and Conclusions

A growing need for the use of modern NDT in aerospace has led Vibrant and several partner companies, largely Delta and Honeywell, to develop Process Compensated Resonance Testing. PCRT stems from resonance based technology combined with advanced computational mechanisms. The development of PCRT has been validated through other methods including legacy NDT and destructive analysis. PCRT has been proven to have good correlation to existing inspection techniques. PCRT has many advantages, and few disadvantages, compared to current inspections. The key benefits of PCRT include:

- Characterizing Mature, Well-Controlled Manufacturing Processes
- Sorting for Structural Integrity with a Single, Whole Body Test for Multiple Defects
- Digital Historical Record of Resonant Spectra for Life-of-Part Surveillance
- Elimination of Operator Error

Various experimental studies have been conducted to learn more about the capabilities of PCRT. These studies provided information on temperature and fatigue as they relate to resonance frequencies. PCRT has proven to be effective for detecting overtemp conditions and fatigue related issues (such as cracking). The PCRT cracking indications have been identified prior to indications provided by FPI.

PCRT has been successfully applied to a wide range of components. Delta implemented a PCRT inspection for detecting overtemp, thin wall, IGA and cracking in the JT8D 1st stage turbine blade. Other applications include detecting multiple surface and internal defects in ceramic rolling elements of various sizes, detecting problems with the brazed-in tip cap on the CF6-80A 1st stage HPT turbine blade, and detection of various other defects in a wide range of aerospace components.

9. References

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