Process Compensated Resonance Testing (PCRT) for Aerospace Components

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<u>Process Compensated Resonance Testing</u>

Capabilities Overview
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. It has been commercialized successfully in the automotive manufacturing sector by Albuquerque based Quasar International, Inc. Vibrant, a division of Mechtronic Solutions, Inc. has acquired the rights to commercialize PCRT for aircraft NDT applications. 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. Resonance Spectroscopy, the analysis of the resonate 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 analytic tool of Resonance Spectroscopy coupled with advances in computer based analytic software has resulted in PCRT, an analytical tool of great power. The technology is achieving growing acceptance (over 100,000,000 automotive parts tested with PCRT in 2005) in inspection of manufactured components such as connecting rods, crank shafts, suspension arms, etc. Proprietary software algorithms developed to compensate analysis for normal manufacturing parameter 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. The differences between PCRT and NDT methods currently in use may seem small at first glance, but deeper investigation reveals that PCRT can increase production yield, optimize the useful life, and prevent field failures of aerospace components cost effectively.

System Overview
The PCRT system uses one transducer that excites the component through a range of frequencies from a few hundred Hz to over 5 MHz, depending on a part's size and elastic properties. Two additional transducers then measure the frequency response of the component to the excitation. ***The inspection process requires only seconds to accomplish for individual component parts and to about three minutes for more complex assemblies*.** PCRT has the ability to carry out a superior inspection with no paint stripping, no chemicals, and with no sensitivity to paint chips or surface cleanliness. The realization of significant reductions in Total Ownership Costs (TOC) is anticipated with the implementation PCRT. Eliminating the labor intensive cleaning processes and subjective inspection can save hours on a given inspection routine. ***The***

hardware measures the resonances, and the software analyzes the resonance pattern to determine the structural integrity of the part. The software is based on a patented technique using genetic pattern recognition algorithms and is able to detect relevant frequency shifts that occur when the part's material properties change due to work hardening, cracking, material loss, or other defects. It is important to note that ***if cracking is detected, component failure has already begun***, the material has been fatigued to the point at which crack initiation and propagation have already taken place, and the aircraft has been flying with a component that is failing. ***None of the current NDT technologies in use today can detect the onset of fatigue before cracking begins.*** PCRT has demonstrated the ability to detect fatigue failure prior to crack initiation and propagation.

PCRT uses patented genetic pattern recognition algorithms to develop sorting modules that evaluate the frequency responses of tested components. With the sorting modules developed the software ***eliminates the need for costly training of technicians because the algorithms make the real-time assessment of the part not the technicians***. Below are highlights of PCRT algorithm capabilities:

- Contains built-in pattern recognition which performs data analysis while the software's cross-validation capability compares patterns with those in the part database.
- Optimizes the number of resonances necessary for part evaluation
- Provides optimization and selects relevant frequencies for detection of desired defects
- Can compensate for normal part variations by using only selected resonances sensitive to the typical defects encountered

Examples of Aerospace applications

The following sections present examples of aircraft components and assemblies that have been evaluated using PCRT technology.

Defect Identification in Flight Control Linkage

PCRT testing was conducted on aircraft flight control linkages provided to Vibrant by the FAA Airworthiness Assurance NDI Validation Center (AANC) in Albuquerque, NM. Two like Input Rod Assemblies were removed from an elevator actuator assembly on a narrow body commercial airliner. Using PCRT techniques to generate comparative waveforms, a linkage with a known crack and an identical part exhibiting no indications were tested. The crack in the defective component was induced during normal aircraft operation and was verified by AANC visually and through the use of eddy current testing. Crack dimensions: approximately 1 inch in length and 0.0525 deep. Setup and test of the part with the PCRT system was completed in **less than 5 minutes**.

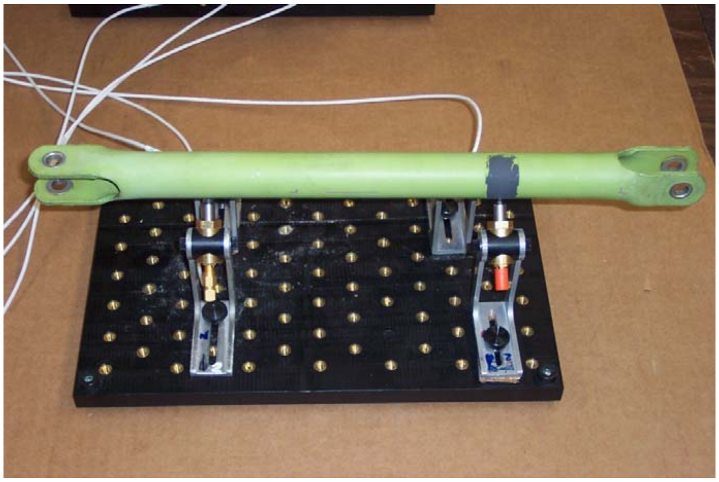


Figure 1 - Input Rod Assembly

Results showed a clear difference between the cracked part and the good part. In Figure 2 below the top wave form is of the good Input Rod Assembly in a painted state, the middle wave for is from the good assembly stripped of paint, and the bottom wave for is of the defective assembly in a painted state. Note that the defective part is clearly differentiated, yet the presence of paint makes almost no difference in the analysis of the good component.

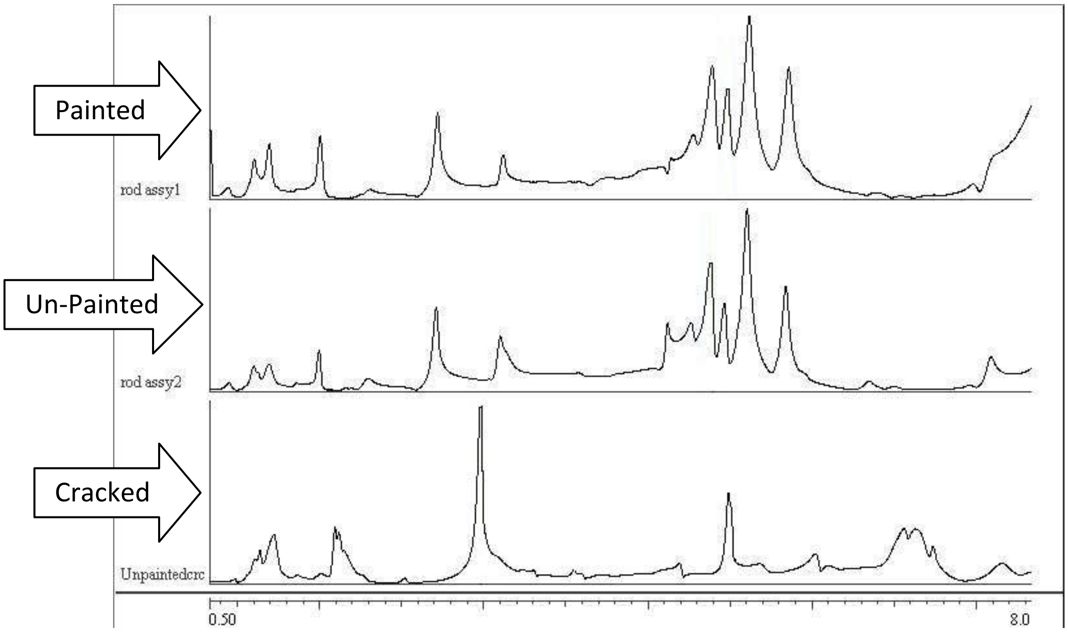


Figure 2 - Waveform Output - Input Rod Assemblies

Flight Control Assembly

Two additional assemblies were provided to MSI by AANC for PCRT testing. These assemblies did not exhibit any indications of flaws or failures and were only tested to show the similarity of frequency responses for identical assemblies. Figure 3 shows the flight control assembly and PCRT test setup.

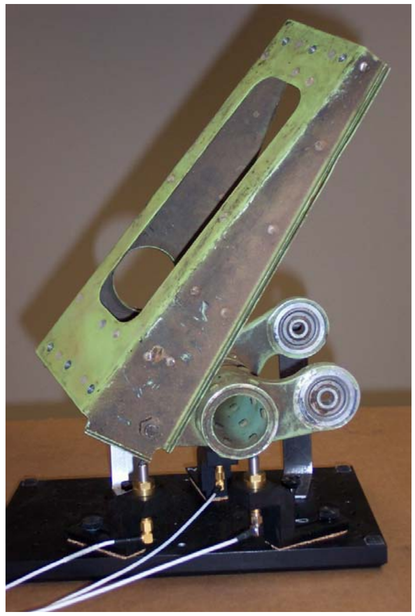


Figure 3 - Bracket Assembly

Waveforms shown in Figure 4 demonstrate the similarity of frequency response for each assembly. As can be seen in Figure 4, the wave forms are very similar. The pattern recognition algorithms at the heart of the PCRT technology are able to determine the similarities and differences of the waveform resonance patterns based on resonant frequencies, not amplitudes. The example (figure 4) actually shows aligned resonances that the computer can easily detect, but require close scrutiny for the human eye to discern. This allows for the elimination of operator judgment in determining the state of a given part being tested.

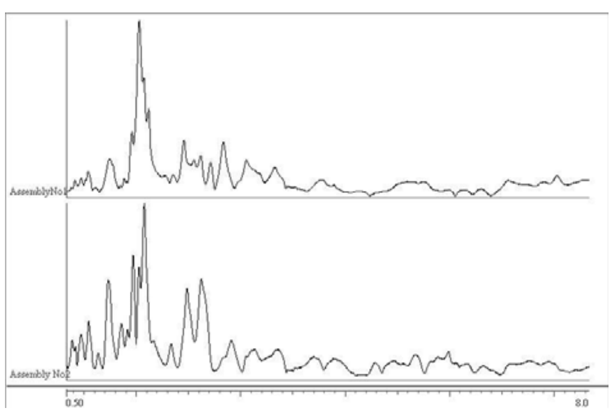


Figure 4 - Waveforms for Identical Bracket Assemblies

Helicopter Spindle Fatigue Testing

In May of 1996 a Sikorsky CH-53E, destined for HMX-1 for presidential transport, suffered a catastrophic main rotor failure during a test flight. The subsequent inspection led the manufacturer to investigate the capabilities of PCRT for the monitoring of high stress components with these components still installed in assemblies and subassemblies. A titanium spindle was mounted in a fatigue test fixture, and PCRT transducers were attached.

Process Compensated Resonant Testing data were acquired from 500 Hz to 78 kHz. The data was acquired in 14 separate frequency bands. These bands were chosen so that resonant peak amplitudes of similar height were captured in each band and so that reasonable sized data packets could be used to isolate the minimum data set needed to detect flaws. As it turned out, band 4 (12 to 18 kHz) and band 8 (34 to 40 kHz) provided the best diagnostic features. Strain gauge data were digitized and compared to the Process Compensated Resonant Testing data. Figure 6 shows this comparison for Band 4. Changes in strain gauge readings correspond to changes in the Process Compensated Resonant Testing data, except the PCRT data were much more sensitive to structural changes.

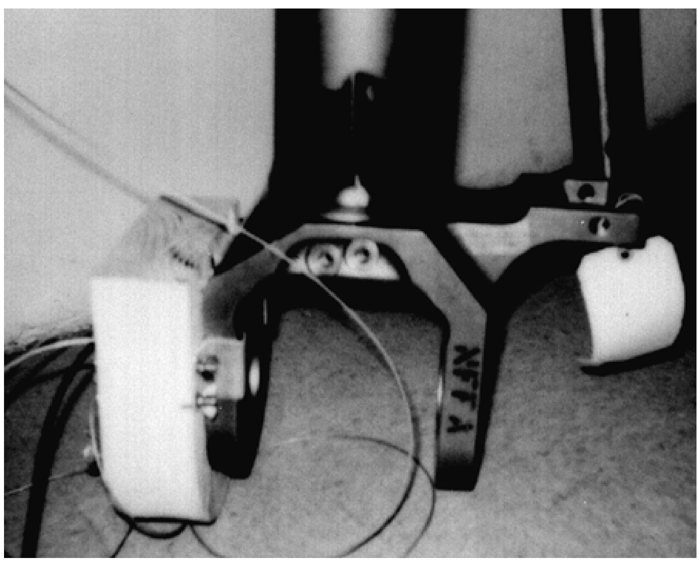
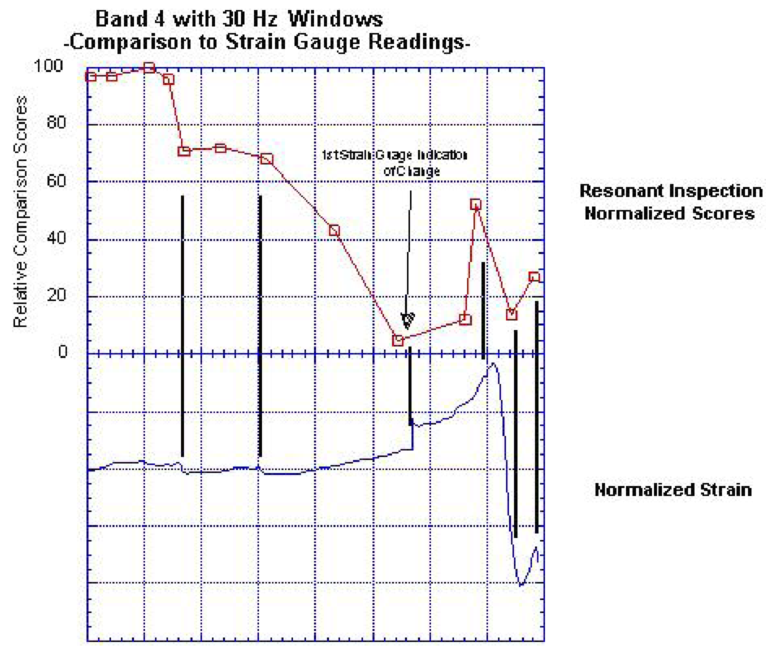


Figure 5 - Helicopter Spindle Test Setup



Vertical dark lines show correlation of Resonant Inspection results with changes in strain gauge readings

Figure 6 - PCRT vs. Strain Gage

The testing showed clear indication of crack initiation and growth. In addition, there was significant, **prior warning** of impending failure as the PCRT frequency response begins to shift long before the strain gage data picked up the crack propagation. The processed data showed a change in the frequency response until the moment where the crack was first detected. This is indicative of an overall decrease in the spindle stiffness. After the crack appeared, the PCRT data indicated that an apparent increase in stiffness occurred (about 800,000 cycles) prior to catastrophic failure. This indicates that localized weakening and then stress (work) hardening occurred and was caused by the greater motion excursions when the stiffness initially decreased. It is presumed that the hardness increased to a certain point in the presence of an initiated crack, initially following a ductile fracture process and then began to follow the more catastrophic brittle fracture process. This is clearly indicated by strain gauge data which show increased excursion after crack formation while the PCRT data show an apparent increase in stiffness during the same period. Both the strain gauge and PCRT data exhibit drastic change just before the spindle broke completely. Figure 7 shows the frequency response shift during crack propagation.

The key point is that **PCRT provided clear indication of impending failure** long before strain gage indications or visual inspection did.

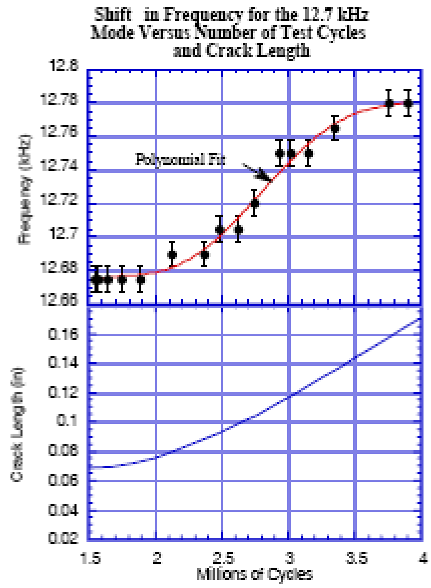


Figure 7 - Frequency Shift vs. Crack Length

Turbine Blade Testing

Testing was conducted on super alloy turbine blades provided by a major aircraft gas turbine engine manufacturer. Superalloys have been developed for use in elevated temperature applications in which the structural materials must have high strength, excellent corrosion resistance, and good resistance to creep and fatigue. When these superalloys are exposed to higher than normal operating temperatures, permanent metallurgical changes such as gamma prime solutioning and rafting can occur in the microstructure.

The objective of the testing was to determine if PCRT could detect metallurgical change such as gamma prime solutioning. A new set of turbine blades (30) named “good” and a set of unserviceable blades (57) rejected for gamma prime solutioning named “bad” were used for the exercise. Frequency shift and resonance patterns were used to separate the new from the unserviceable blades. PCRT inspection was able to detect easily the differences between the “good” and the “bad” blades. The frequency responses in Figure 8 show the frequency shifts of the known bad blades (B) to the right, while known good blades (G) are to the left.

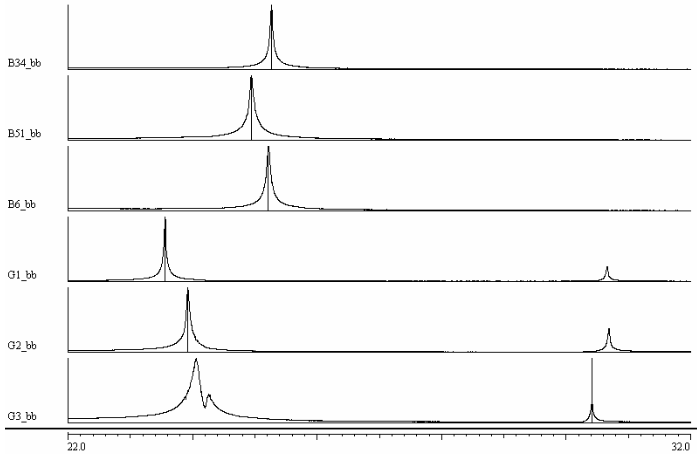


Figure 8 - Turbine Blade Frequency Shift

Figure 9 shows the results of the genetic pattern recognition sorting module for the entire set of tested blades.

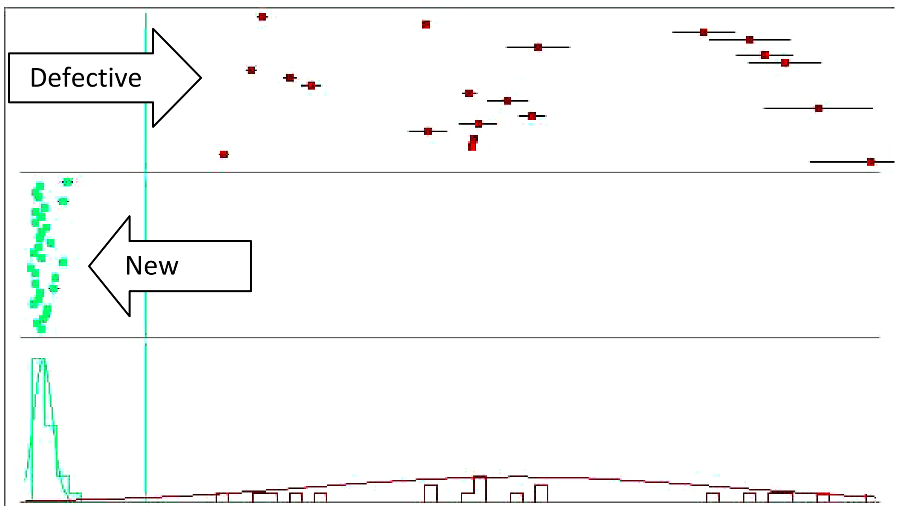


Figure 9 - Genetic Algorithm Sorting Of Good/Bad Turbine Blades

The results shown in this preliminary study are very encouraging since PCRT technology has demonstrated that it can detect the presence of metallurgical changes through frequency shifts in the blades affected with gamma prime solutioning.

Effect of Various Surface Conditions on PCRT Results

Testing and experience in the automotive industry indicates that PCRT results are not affected significantly buy the presence of non-structural coatings or contamination. This allows for the reduction or elimination of cleaning and stripping operations currently required by most NDT technologies, saving time and avoiding hazardous chemicals

Paint-

A test was performed with the Input Rod Assembly outlined in section 1.1.1.1 above. An unpainted Input Rod Assembly was tested using PCRT and the waveform captured. The same part was then painted to an average thickness of about 0.005 inches. The painted part was tested and an equivalent waveform was captured (see Figure 2).

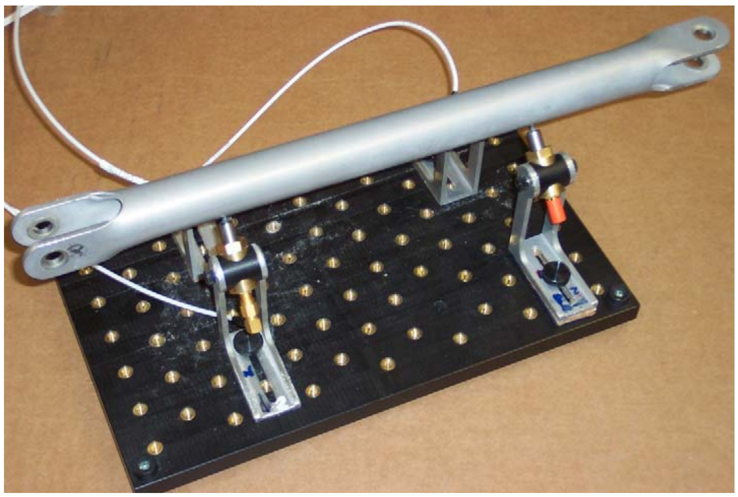


Figure 10 - Unpainted Rod Assembly

Grease-

Extensive practical experience in the automotive industry with during PCRT evaluations indicate that no significant effects result from the presence or absence of grease and oils on inspected parts. During the test outlined in section 1.1.1.2, one assembly was clean and the second assembly had significant grease/dirt coating and no significant change in frequency response was observed (see Figure 4).

Candidate Component Characteristics

PCRT can accurately detect typical flaws in parts ranging in sizes from a few millimeters to meters in the longest dimension and hundreds of pounds in weight. Typical minimum detectable flaw sizes are those that cause structural integrity variation from optimum that are on the order of 0.1% or less. The threshold can be set higher, depending on the normal and acceptable part-to-part variations. Complex geometries are also readily handled by PCRT pattern recognition algorithms. Small light components such as turbine blades and larger heavier components such as aircraft wheels have been successfully tested using PCRT.