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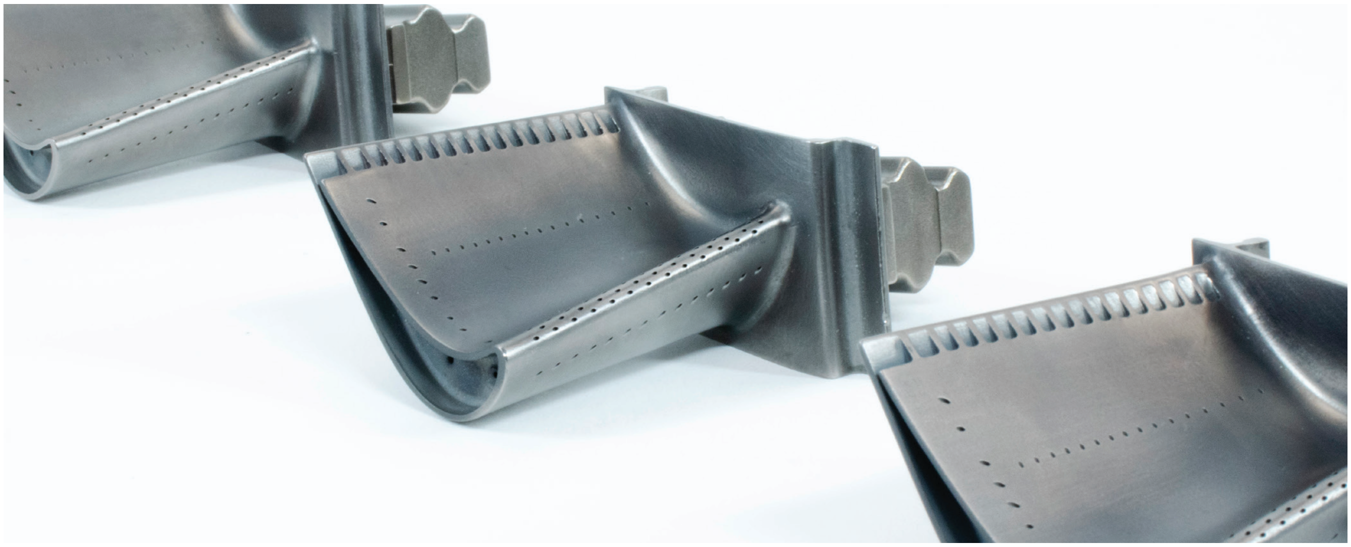

GAS TURBINE BLADE QUALITY INSPECTION

USING NDT RESONANT ACOUSTIC METHOD

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Quality Inspection of Gas Turbine Blades Using NDT-RAM

Abstract: High pressure gas turbine blades are complex components that operate in the harshest environment within the turbine and are subjected to extreme temperatures. These conditions require that the blades be thoroughly inspected at multiple stages of their lives. In this paper we will provide evidence that an additional non-destructive examination, NDT-RAM, could greatly aid in improving the inspection practices of gas turbine blades. Implementing NDT-RAM as an inspection method for turbine blades can not only reveal defects and lifecycle fatigue that may be missed by other NDT inspection methods, but it can also reduce the time and cost of inspecting these critical and complex components.

Introduction: High pressure turbine blades are critical components of gas-turbine engines. These blades are the heart of the creation of the engine's mechanical power, and they operate in the hottest and highest-pressure environment. During operation, these components are surrounded by combustion gases that can exceed temperatures approaching the substrate melting point.[1] These blades also are subjected to stresses resulting from the centrifugal force and fluid forces during operation.[2] All these things in combination present very difficult design, manufacturing, and inspection criteria that if not followed properly can lead to early engine failures. Due to the reality of these failures occurring and the likelihood that they will happen again, acceptance and implementation of more sensitive and structural based non-destructive testing methods is critical.

The Aerospace and Power Generation industries perform multiple inspections using a variety of NDT inspection methods on every turbine blade that is manufactured and/or repaired. These inspections include fluorescent liquid penetrant for the exterior surfaces, radiography for the interior structure, ultrasonic inspection to verify wall thicknesses, Laue x-ray diffraction for the single crystal grain structure, and redundant visual inspection. These are all excellent inspections, and each serves a specific focus. When applied properly, each can identify defects on the blades, but they are not capable of detecting metallurgical issues or any blind defects that exist outside their specific focus area.

Resonant Acoustic Method (NDT-RAM) is a non-destructive testing technique that can aid in these critical inspections. NDT-RAM is a Resonant Ultrasound Spectroscopy (RUS) inspection method which uses the natural frequencies of a component to assess its quality. These natural frequencies are not only impacted by defects but also by structural issues such as variations in mechanical properties, metallurgical consistency, and material stress state. These structural issues are not currently inspected by the Aerospace and Power Generation industries.

Sensitivity to these issues would allow for a substantial improvement in the quality and consistency of the components and provide improved risk avoidance.

Resonant Acoustic Method (NDT-RAM): NDT-RAM is an impulse Resonant Ultrasound Spectroscopy (RUS) method described and governed by ASTM E2001. It is a volumetric approach that tests the whole part, both for external and internal structural flaws or deviations, providing objective and quantitative results. [3]

NDT-RAM compares the frequency spectrum of mechanical resonances of parts under test to the frequency spectrum of mechanical resonances of a reference set of parts or to a modelled set of resonance values. Objects that are similar will have comparable resonant frequency spectra. Objects that are not similar will have a shift in frequency or multiple frequencies when compared to the reference data. The reference data should always include every possible normal and acceptable variation to ensure no false positive results. The differences a part has that fall outside criteria will be the indicator of a structural change for the part under test (e.g., defects in parts/or material properties associated with the mass, stiffness, and damping). So, since the frequency differences are driven by any structural change, this method can be used to inspect external, internal, and metallurgical structural flaws or deviations. Simply put, NDT-RAM is a volumetric resonant inspection technique that measures the structural integrity of each part to detect defects, anomalies and inconsistencies on a component level. [4]

NDT-RAM systems come in several different configurations that range from the simple single piece load system with manual impulse excitation (RAM-TEST Manual), shown in Figure 1 to fully automated testing systems that provide sorting of acceptable and unacceptable products (RAM-AUTO & RAM-DROP) like those shown in Figure 2.

Figure 1 – RAM-TEST Manual system

Figure 2 – RAM-AUTO and RAM-DROP Systems

To create a test setup using NDT-RAM (or any type of resonance inspection technique), a set of reference data must be created from a set of known good parts by:

- Identifying repeatable and consistent resonant peaks based on testing all the reference parts or as provided by a modelled digital twin
- Selecting a subset of the identified resonant peaks that have adequate separation within the spectrum of peaks
- Adjusting the selected peak ranges to ensure testing reliability and to finalize the testing “criteria”
- Testing parts against the developed criteria to evaluate the quality of the parts under test

Once a reference data set has been established, the system is most often used in a pass/fail mode, following a simple process:

- **First,** a mechanical impulse is applied to the test part, exciting its natural resonant frequencies
- **Second,** a sensor captures the frequency responses of the test part
- **Third,** a Fast Fourier Transform (FFT) is performed and the system displays the resonant frequency spectrum of the part under test
- **Fourth,** this resonant frequency spectrum is compared with the spectra of the reference data set

Impact

An industrial impactor taps each part with a measured and repeatable force, producing sound.

Measure

A microphone is used to transform the parts' response into electrical signals for analysis.

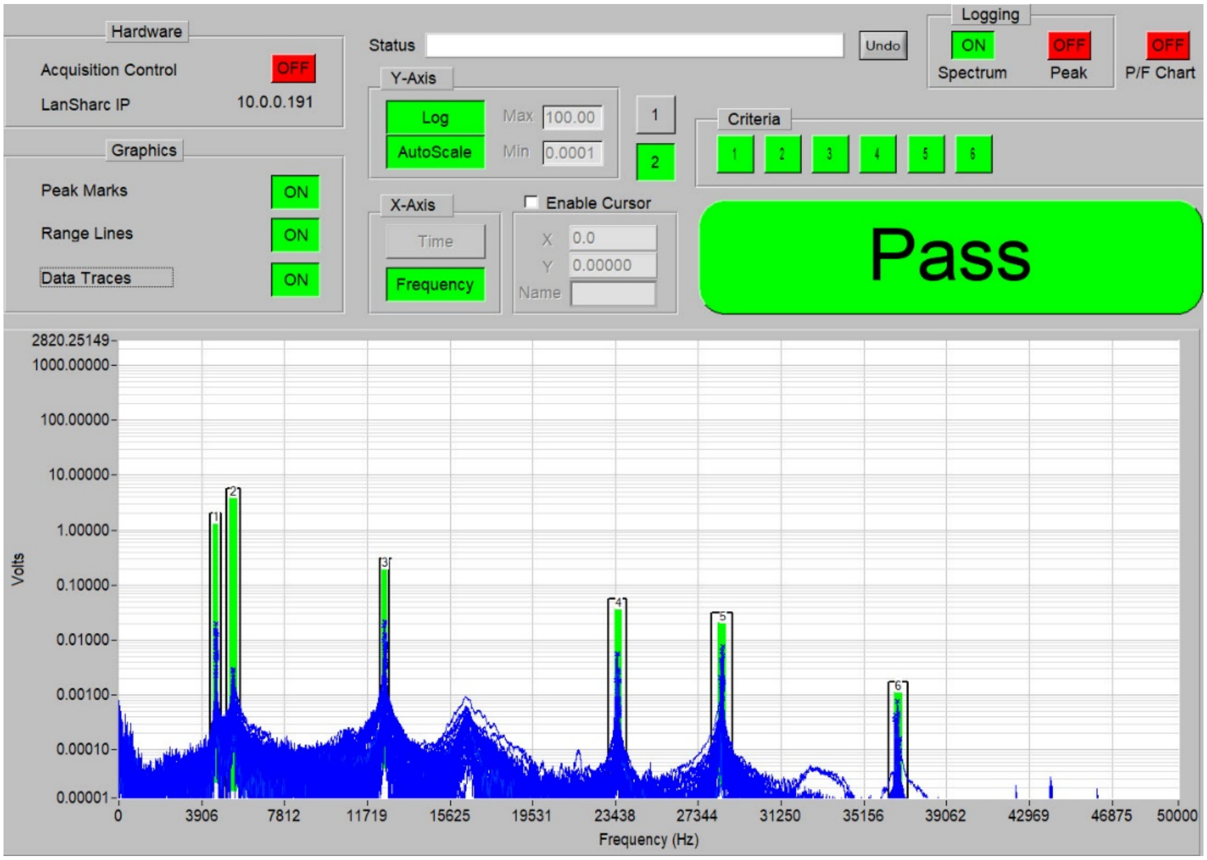
Process

The smart digital controller uses a Fast Fourier Transform (FFT) method to determine frequency characteristics.

Quantify

NDT-RAM software compares the results to criteria limits and accepts or rejects the part accordingly.

All test parts with frequency peaks outside of the defined boundaries (criteria) are rejected as unacceptable parts. See Figure 3 for an example frequency spectrum of a passing part.



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Criteria: 1 2 3 4 5 6

Pass

Figure 3 – NDT-RAM Software showing criteria

The more definition within the reference parts, the clearer the criteria and the more useful the inspection.

When performing NDT-RAM testing, no preparation or fixturing of the test parts is required. For pass/fail testing, the NDT-RAM software performs a standard statistical analysis that reveals whether or not the test parts fall within the defined criteria. Beyond the standard pass/fail testing, the test data for each individual part can also be used for additional statistical analysis, such as population investigations or batch processing variations (i.e., heat treatments). The data can also be used for comparison to either previous or future tests of the same parts.

Current Turbine Blade Inspection Methods: All turbine blades are inspected using various NDT methods at manufacture and at each repair interval. All of the following inspections are applied to each blade: fluorescent liquid penetrant for the exterior surfaces, radiography for the interior structure, and visual inspection for any obvious damage.

Other inspections, such as Laue x-ray diffraction and ultrasonic inspection only occur during manufacturing. These inspections will be required for all blades. Some inspections, such as a metallurgical evaluation or dimensional validation, can also be performed on a sampling plan, but the frequency of this depends on the original engine manufacturer's (OEM) specifications.

At manufacture, the required inspections effectively weed out the majority of defective parts. The inspections are well thought out and can be relied upon to identify nearly all defects in the inspection's area of interest. However, there is always a risk of hidden metallurgical anomalies and defects that are beyond the current inspection capabilities. There is also the possibility of human error in the form of a missed operation or an inspector miss.

After engine service and prior to repair, blades are inspected for stress rupture cracks and deformation of the leading edge. [5] They are also categorized into the level of repair needed. These inspections do not consider any metallurgical or stress state issues. This inspection is only visual.

At the repair stage, various processes are completed, but each of these repairs can include coating removal, welding of cracks, reestablishment of tip height dimensions with weld, tip grinding, opening of cooling holes with electrical discharge machining (EDM), and finally either a partial or full recoating of the blade. All these repair operations are critical and if not controlled properly can damage a blade's structural integrity. It is also very important to note that many turbine blades can be repaired multiple times at various cyclic intervals.

To reiterate, at each repair cycle, the inspections performed are liquid penetrant (see Figure 4) for the exterior surfaces, radiography (see Figure 5) for the interior structure, and finally visual inspection for any obvious damage. These methods are all well established and have been performed on these types of components for many decades. They require trained and certified operators as well as controlled processes. There are currently no NDT processes performed to validate the condition of the microstructure or if blades have an elevated level of stress. Instead, a random blade is selected and destructively tested to confirm if the microstructure is acceptable. This blade is considered representative of the entire blade population, even though it could have been a newer or older blade that was replaced during the last repair cycle.

This entire inspection scheme is reliant upon the individual inspector's acuity and adherence to the inspection procedures.

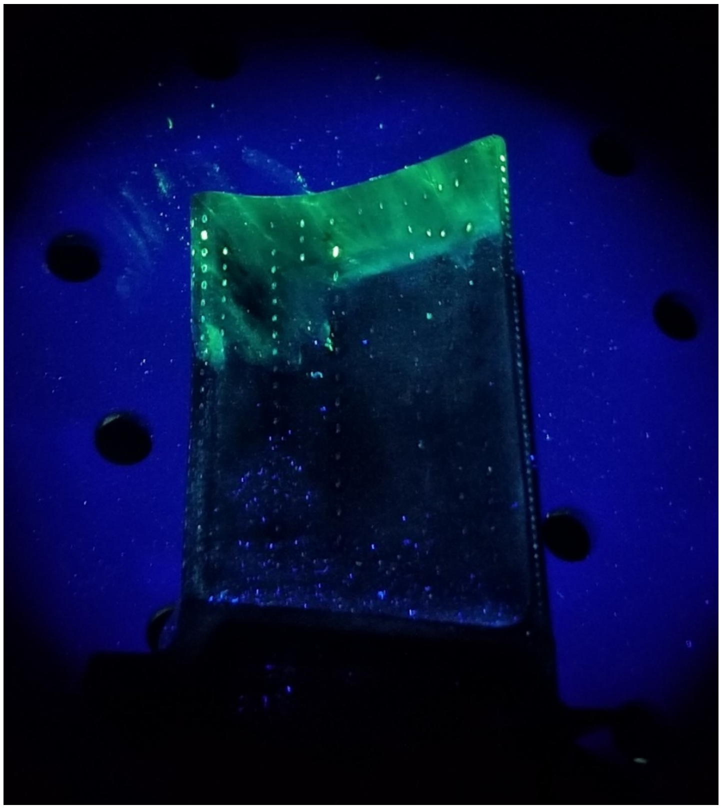


Figure 4 – HPT Blade at liquid penetrant

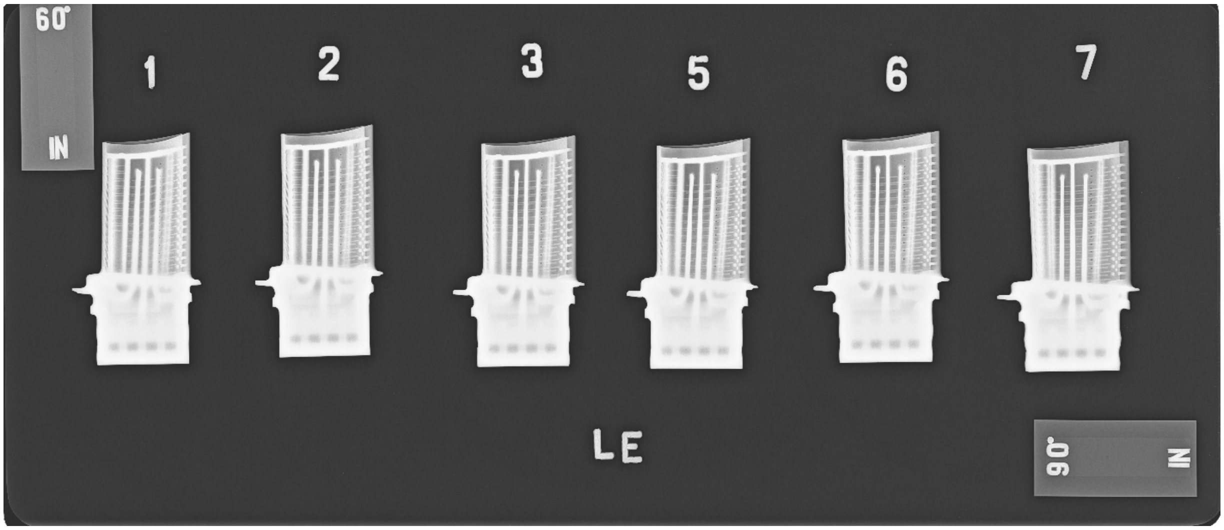
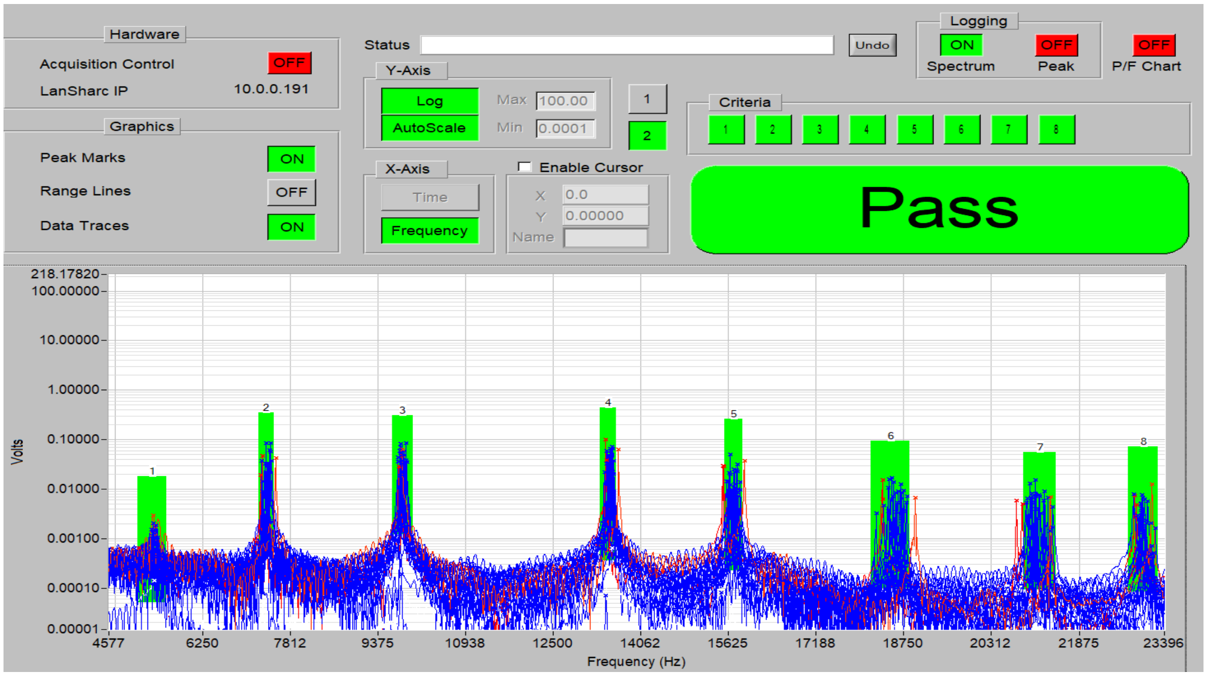


Figure 5 – HPT Blade x-ray image

NDT-RAM Turbine Blade Inspection Benefits: Implementation of RUS testing via NDT-RAM, in conjunction with the current conventional NDT methods, will provide both the Aerospace and Power Generation industries with a more complete and thorough inspection process. Natural frequencies are directly related to the overall structural integrity of a component - for turbine blade inspections they provide a test result based not only on the presence or lack of defects, but also on the part’s metallurgical properties.

The test data is a physics-based, digital result, free of operator interpretation, storable, and repeatable. NDT-RAM testing is also a fast inspection process with most tests requiring less than 0.1 seconds for data collection and typical throughput rates around 3 seconds per part. This frequency information goes beyond an operator’s interpretation and is valuable for much more than just pass/fail testing.

In Figure 6 below, the resonance spectra of CFM56-3 HPT blades is shown. The individual natural frequency responses are easily identified, distinguishable from each other, and repeatable.



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Criteria
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Figure 6 – NDT-RAM frequency spectrum of HPT blades

In Figure 7, three individual frequencies are zoomed in to show the individual blade responses. The acceptable blades are represented by the **blue** spectra and the unacceptable blades are represented by the **red** spectra. The unacceptable blades have a significant shift in their natural frequencies from the acceptable blades.

Deviant blades can fall outside the acceptable tolerance criteria at multiple frequencies. Some of the unacceptable parts fall on the high side of the criteria, while others fall on the low side. There are many factors that can cause the frequencies to shift lower or higher. Variations in a defect's location, size, and severity or material issues like grain size, hardness, and residual stresses will cause a shift in the natural frequencies. Parts that are defect-free are more repeatable in their responses from part to part, where the ones with unwanted conditions are much more variable.

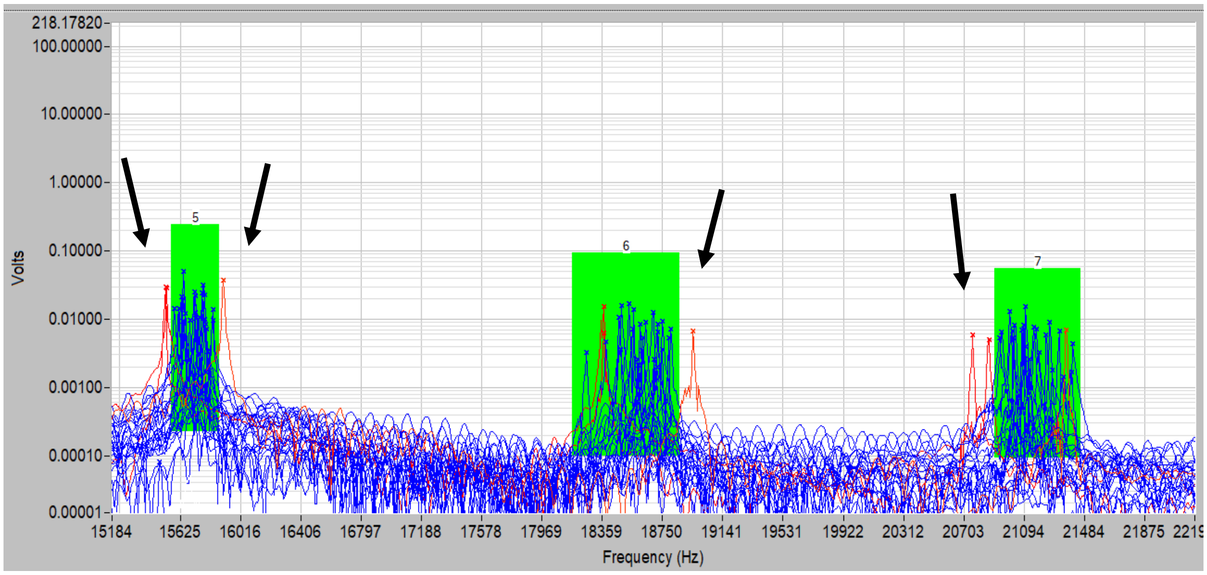

Figure 7 – Zoomed in portion of HPT Data

It can also be noted in Figure 7 that some of the **red** spectra fall inside some of the acceptable criteria ranges. This is a normal result, as not all defects or material issues will impact ALL frequencies.

The specifics with the parts shown are confidential - these issues are material based and are blind to the standard NDT inspections performed on these parts.

To highlight how frequencies can be affected by different defects, the following figures show the useable testing frequencies of several different components coupled with images of how individual frequencies can be impacted by defects.

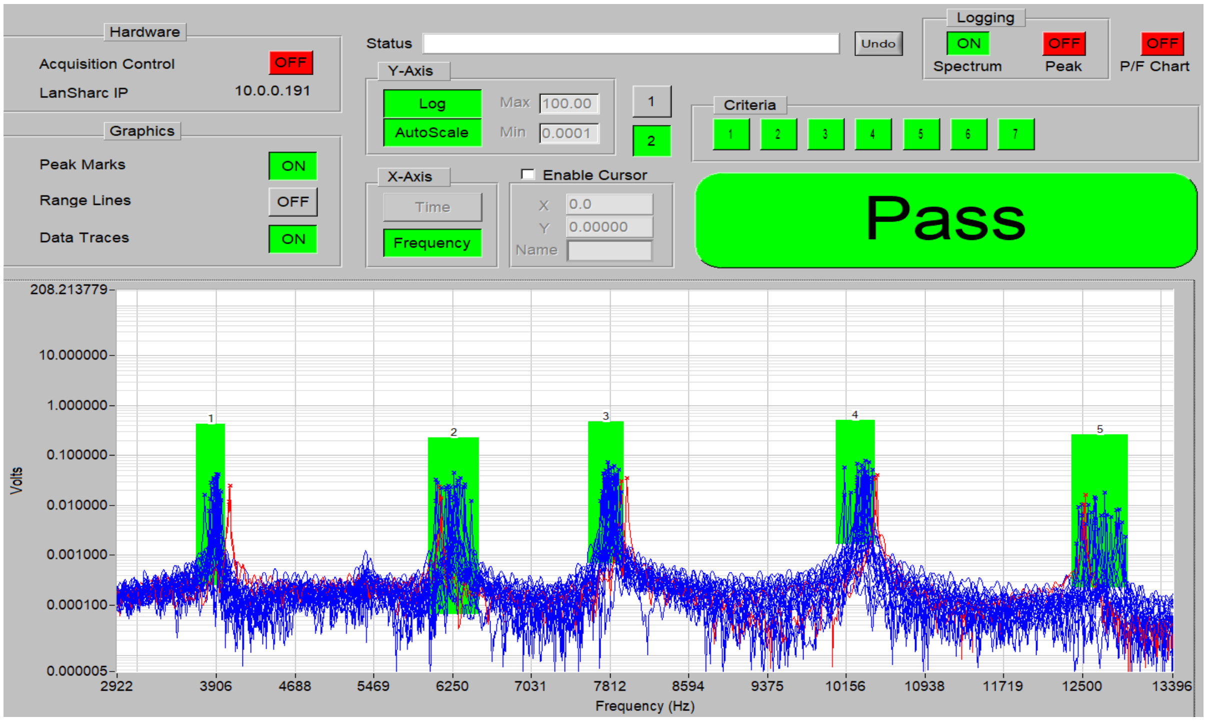
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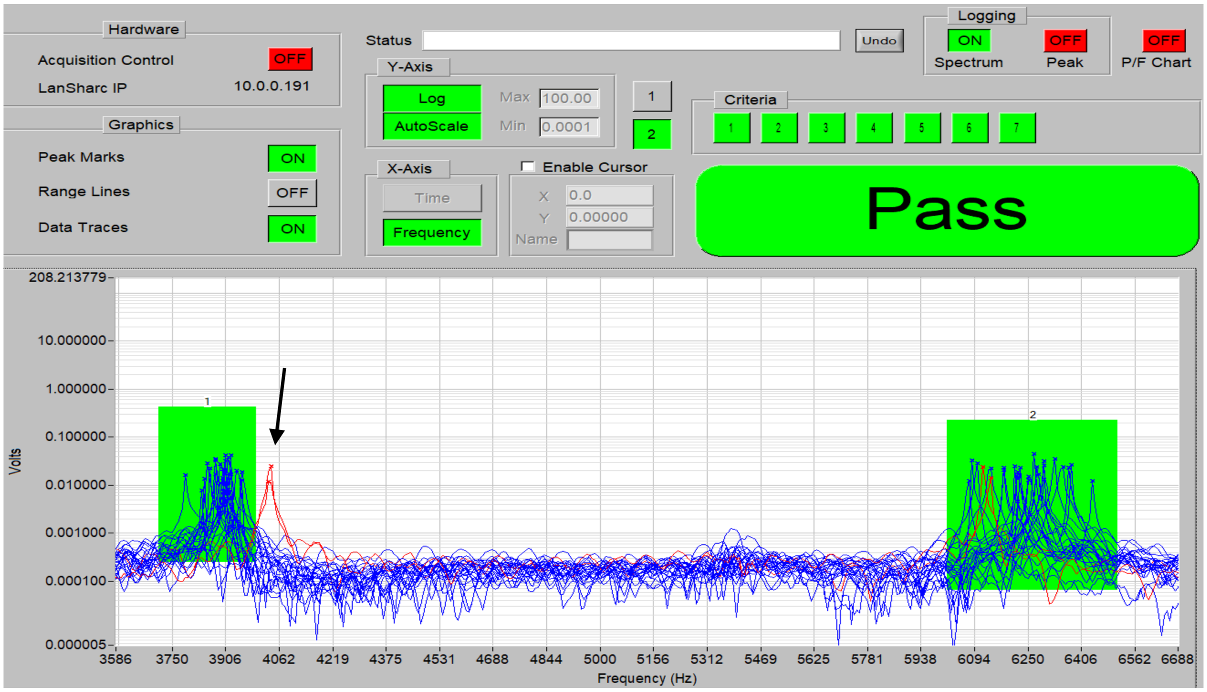
Figure 8 – HPT 1 blade frequency spectrum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Criteria
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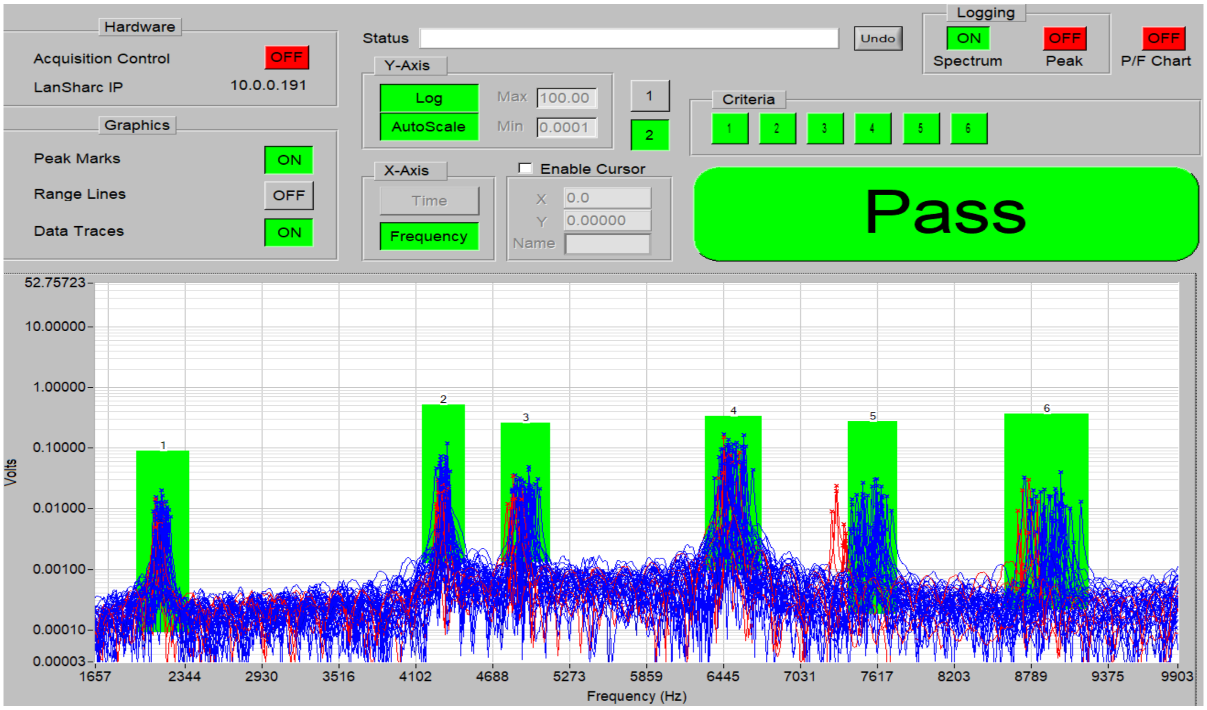
Figure 9 – HPT 1 blade frequency 1 zoomed to show deviation from criteria



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Criteria 1 2 3 4 5 6
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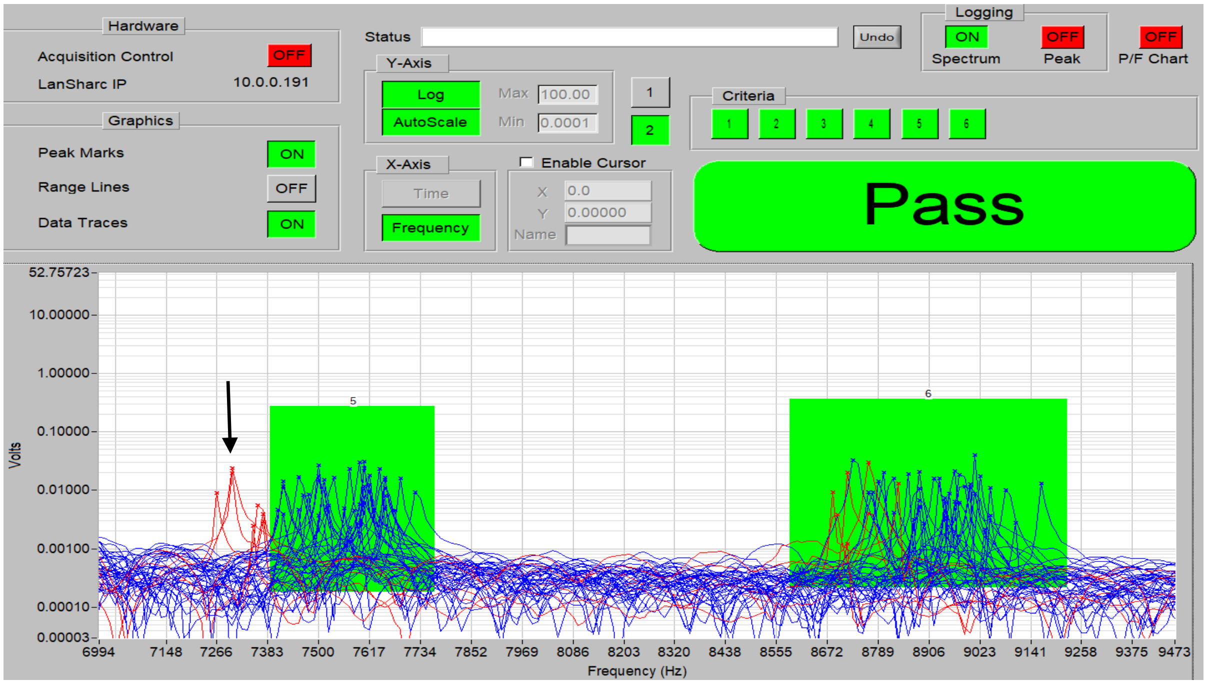
Figure 10 – HPT 2 blade spectrum



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Criteria 1 2 3 4 5 6
Pass

Figure 11 – HPT 2 blade frequency 5 zoomed to show deviation from criteria

The images provided all show the type of impact that different defects and material issues may have on the natural frequencies of turbine blades. The variation that these issues create is detectable using NDT-RAM. The changes in the natural frequency response of the turbine blades can be caused by many structural differences that are not detected by current inspection methods as well as defects that the current inspection techniques are able to detect.

Material aging is yet another relevant factor in the lifecycle and quality of turbine blades. As mentioned previously, some turbine blades may undergo multiple repairs during their lifecycle. These repairs sometimes come early in the life of a turbine blade due to unexpected engine removal. Normally, however, the repairs are scheduled based on programs called Service Management Plans (SMPs). Every engine operator has an SMP that considers part attributes that engineering has identified as significant for part life and should not be changed by the processes applied to the part during service.[6] The plan provides time or cycle intervals at which critical components are to be evaluated and repaired. For high pressure turbine blades, cycle intervals vary from engine to engine and from material to material, but they usually take place somewhere between 8,000-12,000 cycles. As the engine operates, the turbine blades are cyclically loaded and subjected to enormous stresses. The blades are designed to withstand a certain “lifetime” of these cycles, but eventually, the material elements will begin to segregate or breakdown, and the blades will become weaker and weaker.

NDT-RAM can be used to evaluate the occurrence material segregation or breakdown. Figure 12 and 13 show three different groups of blades. The blue spectra were collected from a newer set of blades, the black spectra from a set of blades in the middle of the lifecycle, and the red spectra from a set of blades nearing the end of their acceptable lifecycle. It is very important to note that ALL blades came from a single engine.

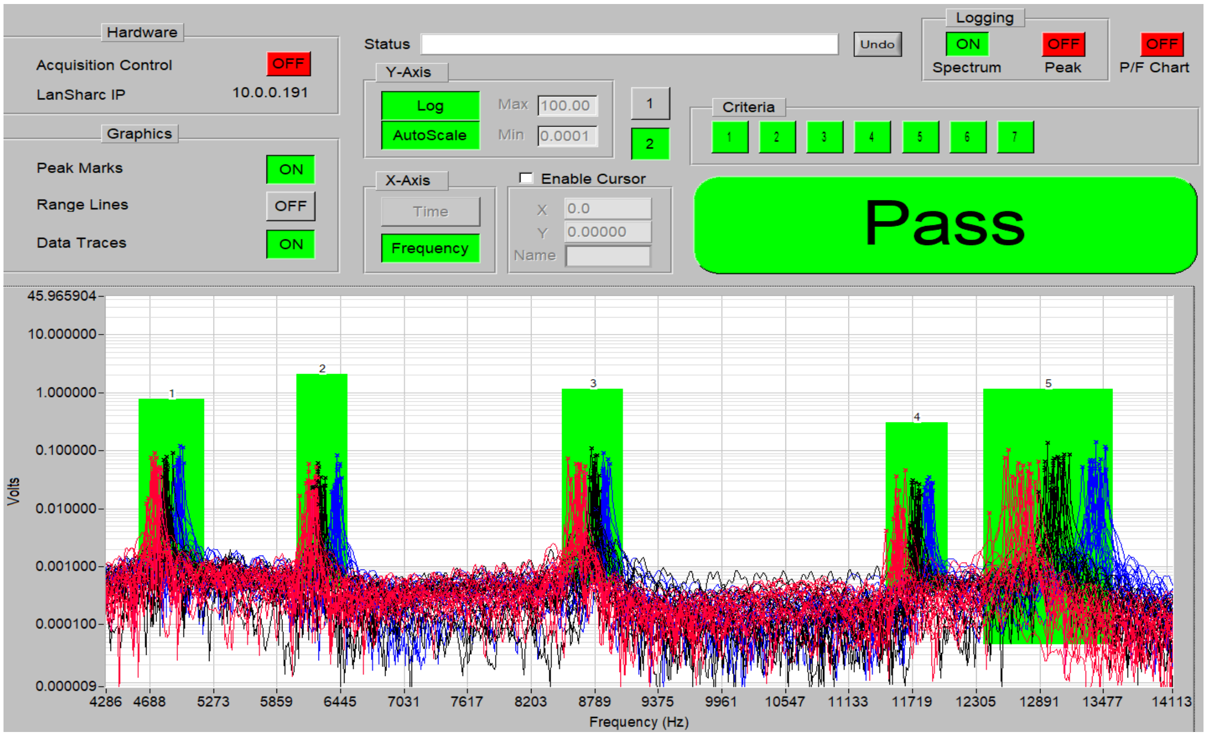
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Figure 12 –HPT 1 blades with various levels of age and repairs

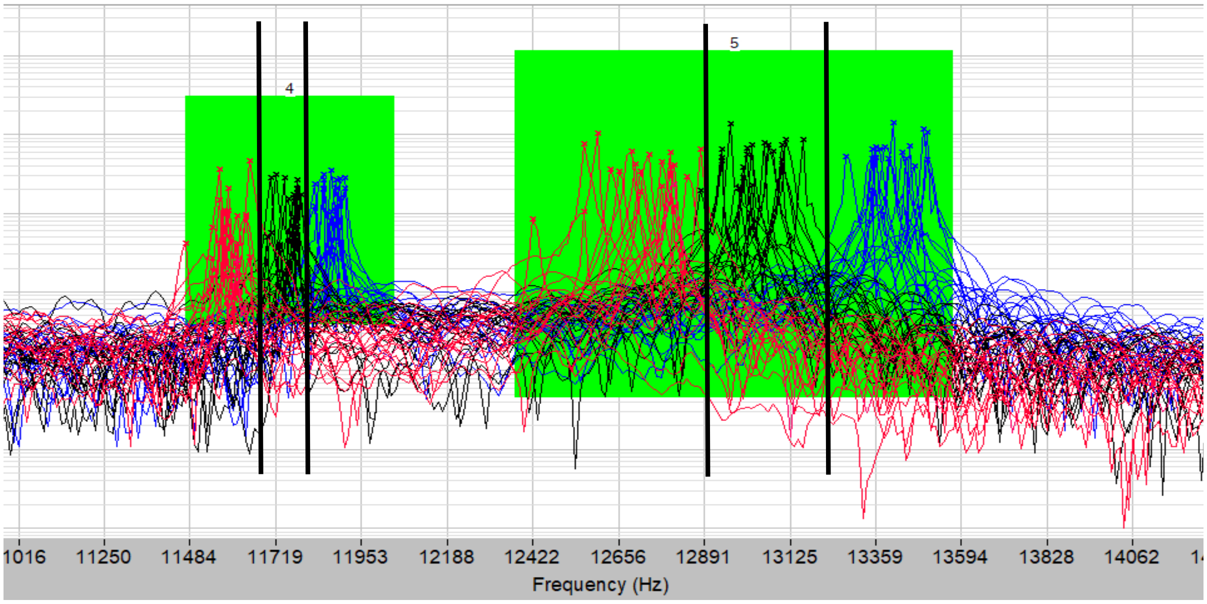

Figure 13 – Clearly different spectra for aged blades

The frequencies trend lower with age, but just when do these blades become unsafe to repair? This data is even more clearly separated when we look at all the frequencies of the single parts using a different statistical analysis. In Figure 14, the blades are plotted using a standard Z-score. Each dot represents a single blade's combined frequencies. All the blades were used to determine the statistical mean and standard deviation.

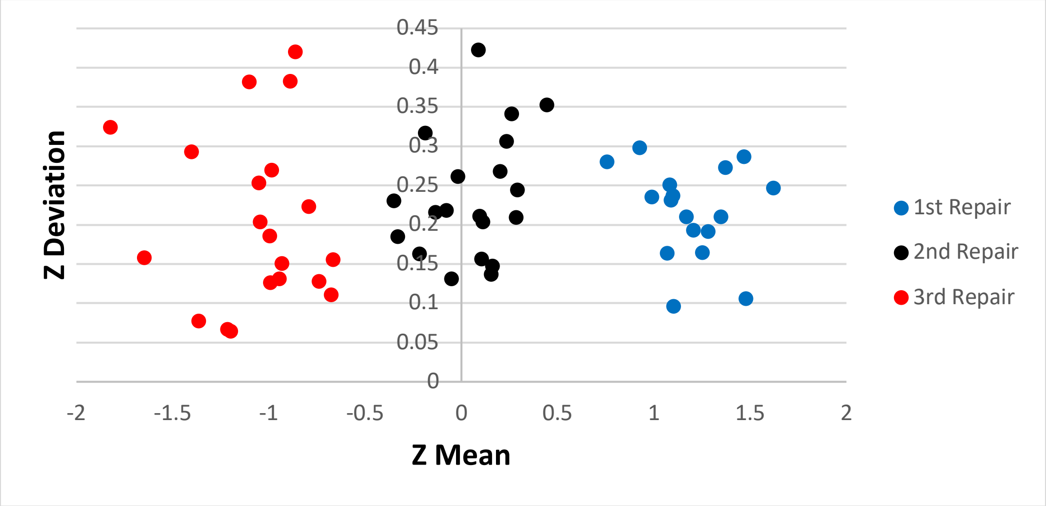

Figure 14 – Blade frequencies grouped by age (repair)

In addition to defect, material property, and lifecycle stress detection, the data collected by NDT-RAM systems is retained and can be put to use for further statistical analysis on the life of individual parts or populations of parts. The data captured during NDT-RAM testing can be stored permanently and recalled for further evaluations. As shown in Figure 14, all the frequencies of a single part can be plotted and used for other purposes. This type of data is typically used to understand mold to mold, batch to batch, and other variation and changes in practices over time. These types of evaluations can easily be accomplished by using either a Median Absolute Deviation (MAD) Z-score calculation when data is skewed or by using a standard Z-Score calculation for more normal data.

MAD Z-score = (frequency - column median)/column median absolute deviation

Z-Score = (frequency - column average)/column standard deviation

Both calculations are a measure of a component's location within a given population. A component having a score of +2 deviations above the median for MAD Z or the mean for Norm Z will have a Z-score of +2.0. Parts that have more variation will have either higher or lower Z-scores.

As an example, the red parts in Figure 15 and Figure 16 can be identified as outliers because of their low average Z-scores and/or high Z-score variation. On occasion, when a blade population has very tight population averages and deviations, parts can be identified as different or suspect merely from there visual separation from that population. Statistical evaluations can be performed on entire groups of part numbers or for just the individual engine sets.

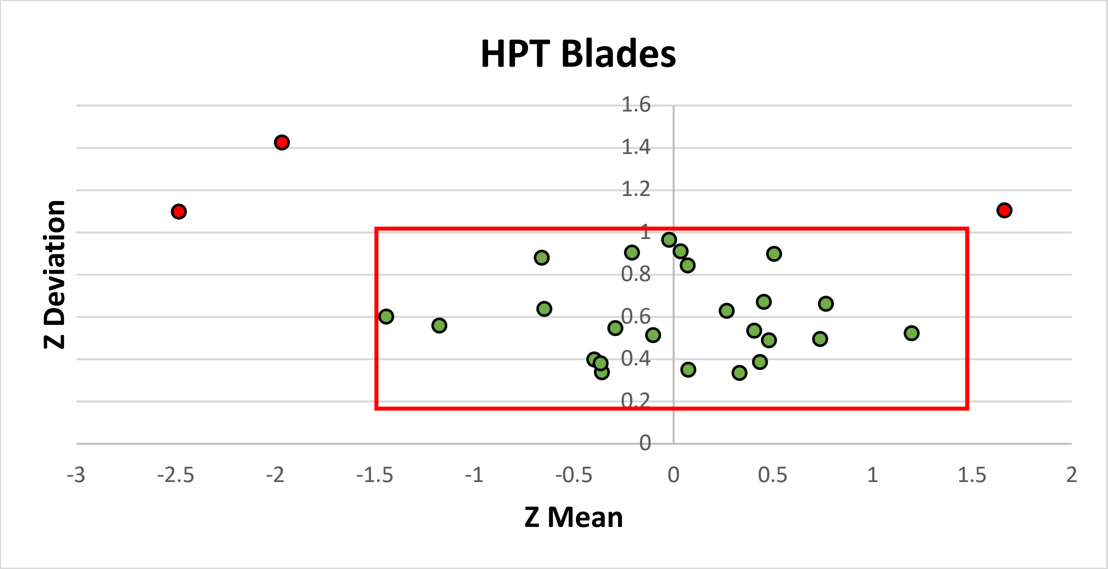

Figure 15 - Z-Score of HPT blades

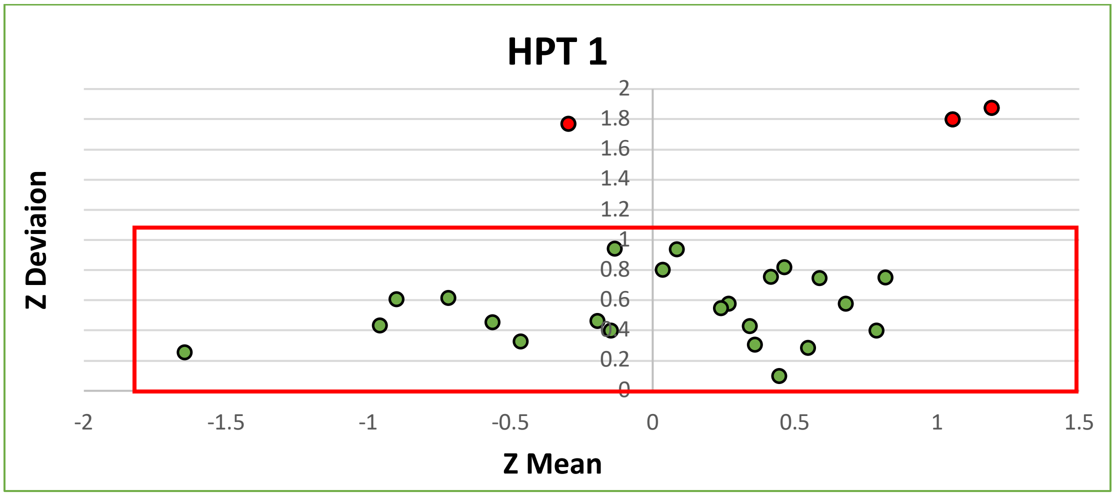

Figure 16 - Z-Score of HPT 1 blades

Another plot that can be created from the frequency data is a standard bell curve. Bell curves have many statistical uses, but are used heavily in population studies and in Six Sigma reports.

Figure 17 shows some of the population data from the previous blades discussed in a bell curve plot. For turbine blades specifically, bell curves can be used to evaluate incoming material integrity, heat treatment batch variation, vendor consistency, and other relevant parameters.

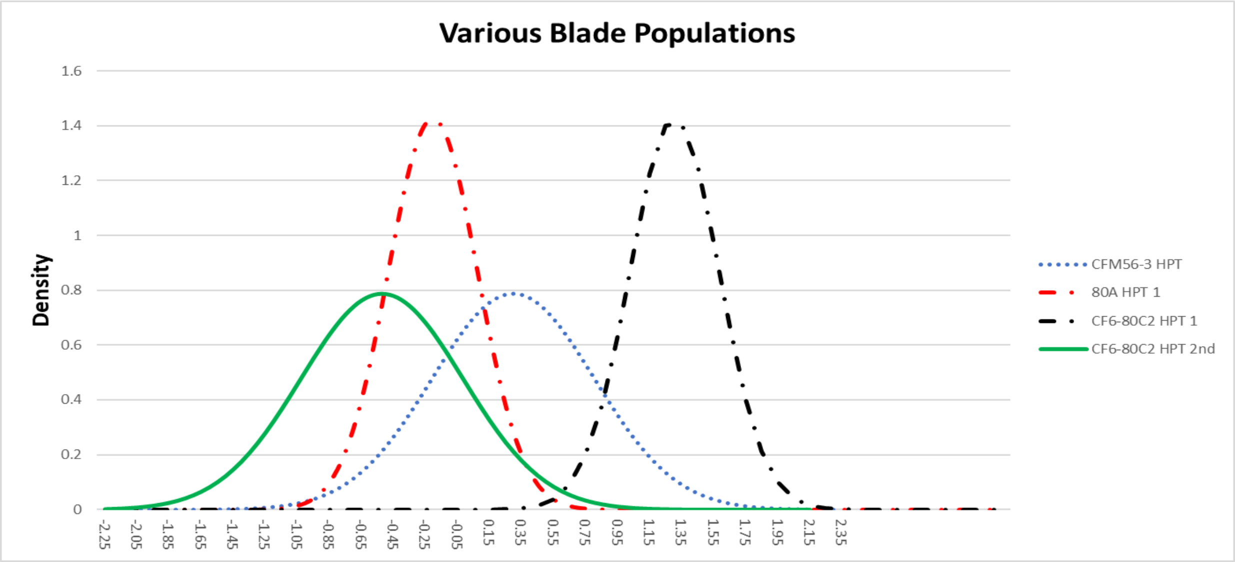

Figure 17 – Bell curve plot showing multiple blade populations

Current Turbine Blade Inspection Review: Nearly all turbine blade inspections are all visually interpreted. None of these inspections are directly related to the material condition of the blades and all of them rely on the interpretation by a certified inspector. Fluorescent liquid penetrant provides an enhanced indication under black light, a radiographic latent image provides a visual of the internal structure, and the visual inspection is a direct eyesight (possibly enhanced) process. Only the radiography data is retained. Finally, all these inspections are only as good as the inspector’s sensitivity to a particular indication.

Benefits of Using NDT-RAM: The NDT-RAM inspection is based on the natural frequency data collected from the component. The data is directly tied to the material and structural integrity of the component. The inspection information is digitally recorded and can be recalled for analysis whenever desired. The system can be run by nearly any operator after a brief training session. The data from the inspections can be used for many different purposes. The capital equipment cost is affordable and every system comes with training and a full year of support.

References:

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