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Process Compensated Resonance Testing – Whole Body and Surface NDT for Ceramic Balls

Prepared by Vibrant Corporation – August, 2012

Contents

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1. Purpose

Hybrid bearings, using silicon nitride ceramic rolling elements, are a critical technology for future high-performance gas turbine engine applications. While they offer significant performance benefits over conventional steel balls, ceramic balls with critical defects suffer from high rates of infant mortality leading to catastrophic failure. Ceramic balls rely on nondestructive evaluation to certify them for use, but legacy inspection methods do not offer the accuracy, high throughput and affordability required for widespread hybrid bearing application.

Process Compensated Resonance Testing (PCRT) is a nondestructive evaluation method for ceramic balls. PCRT uses measured resonant frequencies of parts to detect surface and internal flaws. For ceramic balls, internal defects and bulk material property variations are detected by measuring shifts of resonant peaks to lower or higher frequencies. Surface defects are detected by measuring degeneracy in surface acoustic waves. A PCRT inspection detects both internal and external defects in a single sweep, and returns an automated pass/fail result.

1.1. PCRT

The connection between material vibrations and material properties is based on the fundamental physical observation that the resonance responses of an object are related to its stiffness and mass:

$$\mathbf{f} = \sqrt{\frac{\mathbf{k}}{\mathbf{m}}} \qquad \textbf{(1)}$$

where *f* represents frequency, *k* is stiffness, and *m* is mass. Most resonance NDE methods focus mainly on the basic characteristics of the response, such as the frequency and amplitude. PCRT uses additional information provided by highly capable hardware and proprietary analysis algorithms.

Vibrant’s PCRT system makes extremely repeatable frequency measurements, which contribute to detection of much smaller variances than other resonance inspection systems. Repeat measurements for a given component are generally within 0.02 percent (standard deviation). The quantitative results provided by the PCRT sorting system can be used for supplier comparison, process control feedback, and sliding scale acceptance criteria for applications with varying degrees of criticality.

PCRT uses genetic pattern recognition algorithms and resonant ultrasound spectroscopy (RUS) modeling software developed at Los Alamos National Labs (LANL) by Dr. Albert Migliori and the LANL resonant ultrasound group 8. PCRT proprietary software algorithms compensate for normal manufacturing variations to permit focused detection of material alterations, process deviations, raw material inputs, defects and service-related deterioration.

PCRT methods can be applied to silicon nitride spherical bearing elements, e.g. SiN balls, for a variety of outputs. PCRT measurements can be used to determine elastic material properties, such as Young's modulus. They can also be used for process control monitoring, evaluation of supplier consistency, and detection of surface defects.

Low-frequency resonance modes, mainly influenced by the bulk properties of the ball, identify differences in the material properties due to raw material supply and manufacturing conditions. Measurement of only the first few modes of the resonating sphere can identify even small changes in material properties such as density or Young's modulus (+/- 1 percent or less). Using Vibrant RUS modeling capabilities, the Young's modulus, Poisson's ratio, and individual elastic moduli (C_{11} through C_{66}) of a ball can be quickly determined.

Higher frequency resonance responses in SiN balls, correlating to surface acoustical waves (SAWs), and other modes restricted to the outer shell of the ball, are influenced by surface damage, and can be used to detect surface cracks and other flaws. Hardware developed at Vibrant specifically for generating and detecting SAWs on SiN bearing surfaces extended PCRT capabilities for detection of flaws generated in commercial manufacturing processes, and artificially induced surface defects.

1.2. Hardware

The PCRT system consists of a transceiver, two or three transducers in a part fixture, and control software. A fixture developed for hybrid bearings is shown in Figure 1. The transceiver is a specialized combination of a waveform generator that drives resonance in the part sample and an oscilloscope that measures the part response.

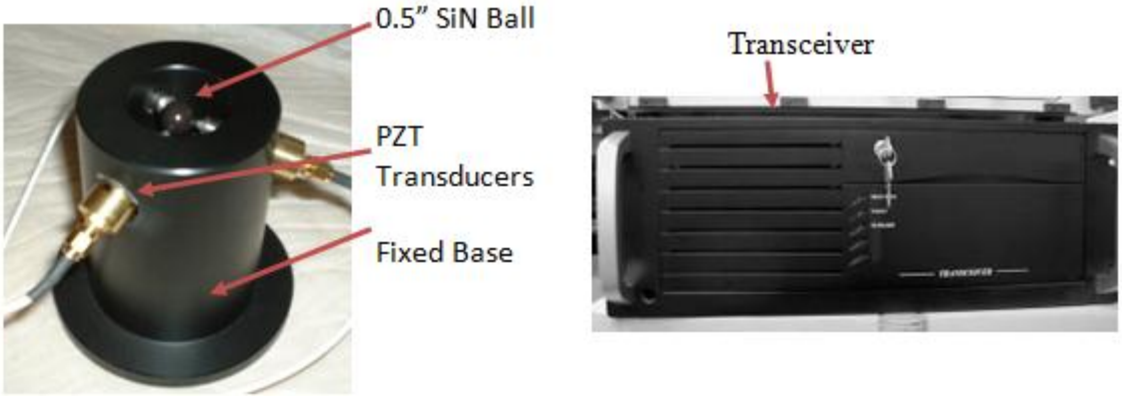

Figure 1 – PCRT fixture for hybrid bearings (left). PCRT transceiver (right).

The transducer is a custom piezo-electric device optimized for resonance testing across a wide frequency range. The tip of the transducer is silicon carbide, designed to be wear-resistant and to present a common contact surface to the parts to be tested over a high volume of production tests. The functional element is lead zirconate titanate (PZT), a material that expands when a voltage is applied, and produces a voltage when compressed. The deflection at the tip of the transducer is very small, on the order of tens of nanometers. The resulting deflection of the test part is also very small, measureable only with laser devices.

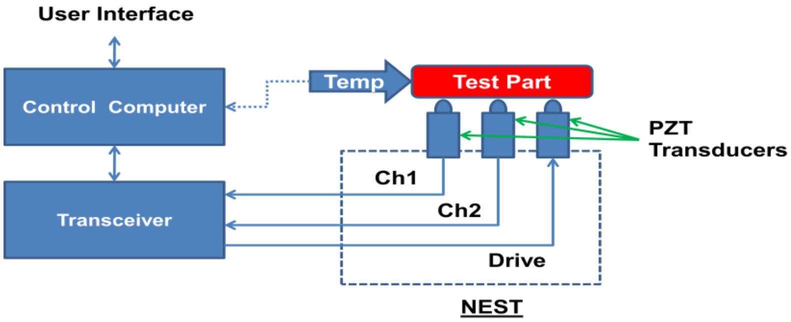

Figure 2 – Functional schematic of a PCRT system.

The transducer design has a lifetime of at least a million cycles, i.e. part tests, must remain dry, and cannot withstand significant shear loads. The transducer is a low-voltage device, and is not a safety concern. PCRT systems are compatible with the environment that eddy current inspection machines for steel balls typically operate in.

2. Application Modes/Methods

PCRT methods are unique among other NDT options in that they allow a quick inspection of both the bulk properties and the surface quality of the ball, without special sample preparation, excessive scanning, or highly trained inspectors. PCRT installations are robust and require little maintenance or space. The following sections give some detail on the manner in which the PCRT measurements may be used.

2.1. Bulk Property Measurements / Internal Defects

When a component has a basic material difference, or internal flaw that significantly affects its structural integrity, this manifests itself in a frequency shift (Figure 3). For the ceramic balls, this type of shift is seen due to density difference (Figure 4), modulus difference, i.e. lot-to-lot raw material variation or raw material supplier difference, and to some processing defects such as inclusion effects, gross porosity and missing material.

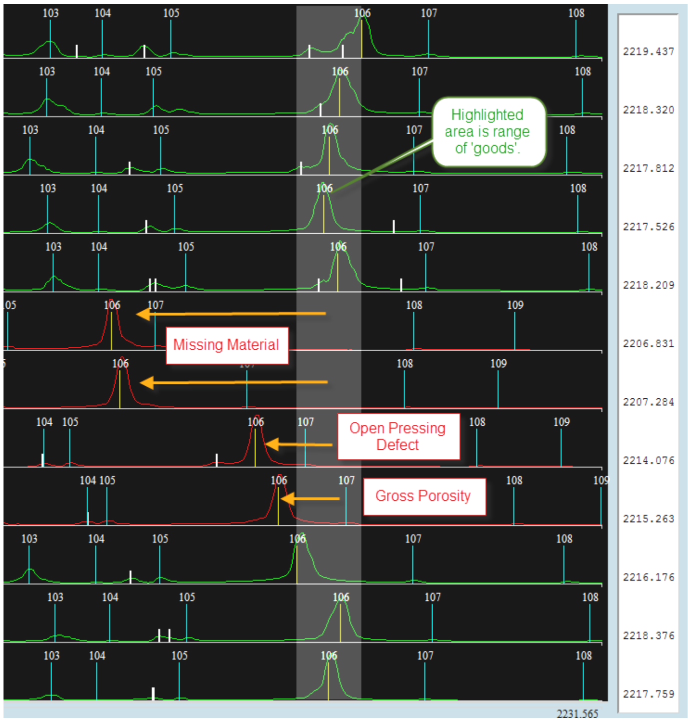

Figure 3 - Resonance spectra showing shifts due to missing material, open pressing defect, and gross porosity. [> 1" ball, 2200 kHz]

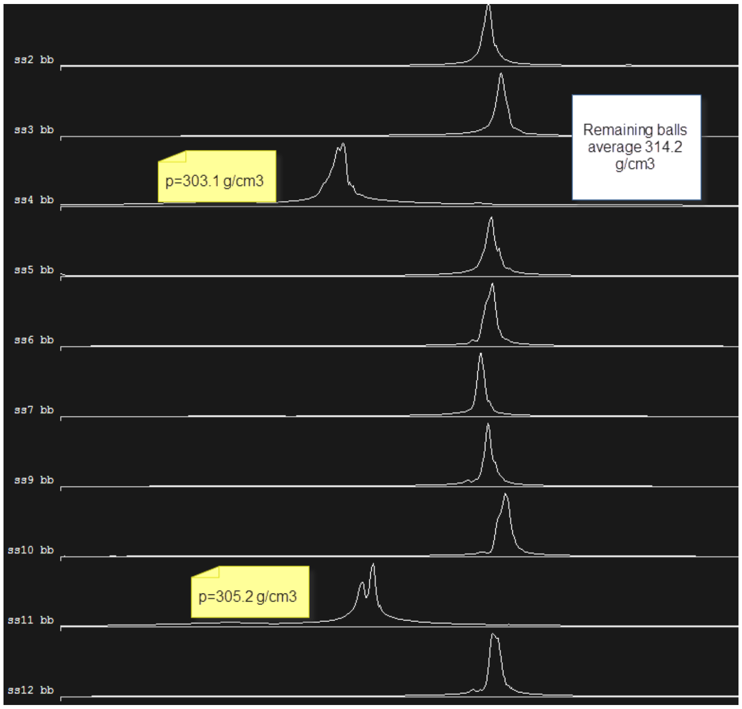

Figure 4 - Resonance data for parts displaying density variation. Density variation is about 0.3%. Resonance shift is 1.1% compared to variation within other samples of 0.07%.

2.2. Process Monitoring

Consider the data presented in Figure 5 for balls from three different manufacturing lots from a common supplier. The three lots were easily distinguished from each other via bulk frequency shifts visible across the spectrum. Lots 1 and 3 are relatively close to each other in frequency, while Lot 2 is shifted higher. This effect can be quantified in a Z-score analysis that statistically evaluates all of the frequencies in the spectra for each lot. Figure 6 shows the Z-score plot, and highlights the quantitative difference between Lot 2 and the other lots in terms of average Z-score.

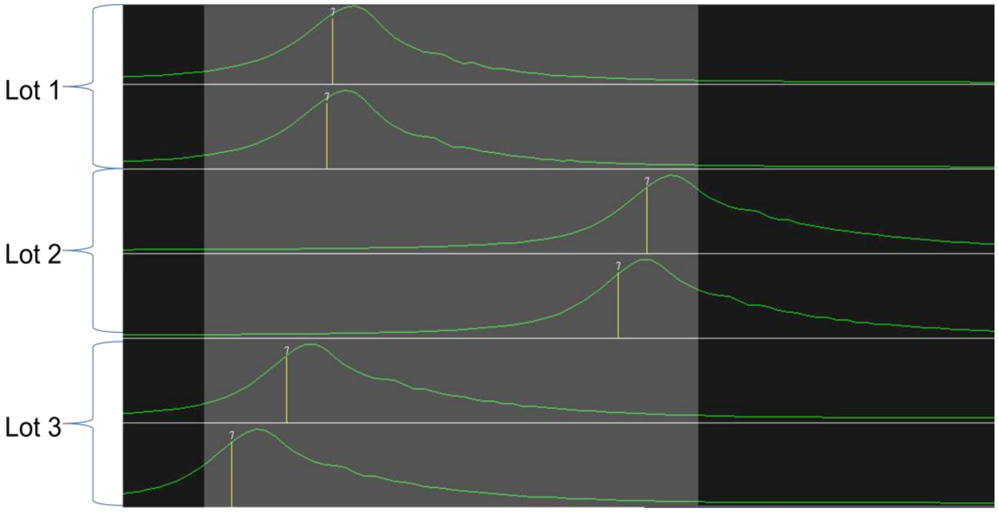

Figure 5 – Lot-to-Lot Variation in 1" Balls.

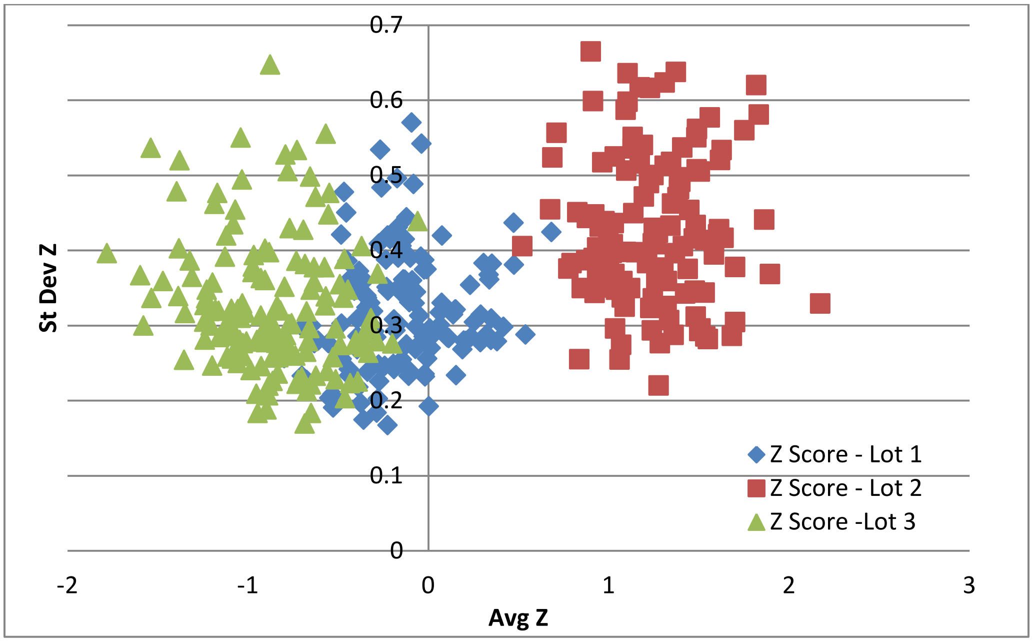

Figure 6 – Z-Score analysis for 1" ball lot-to-lot variation.

Vibrant’s Resonant Ultrasound Spectroscopy (RUSpec) capability was used to determine the Young’s Modulus for a subset of each of these lots. Figure 7 shows a plot of Young’s modulus versus density for the three lots. While the balls within a given lot are very self-consistent, measurable modulus and density differences are apparent.

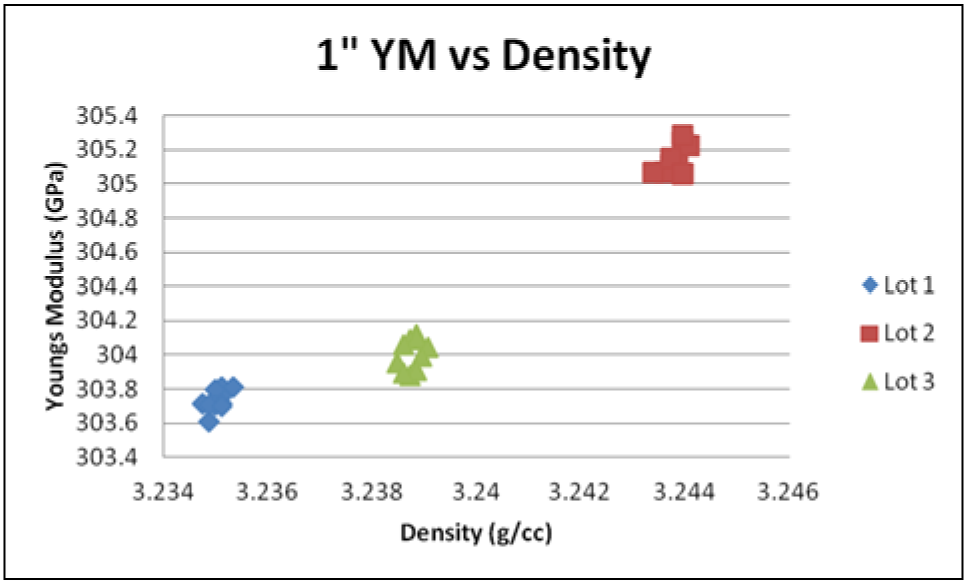

Figure 7 – RUSpec material property characterization of 1” sample lots.

It should be noted that the variations seen here fall within the material property specifications for this grade of SiN material (TSN-03NH, Class 1, Grade 5), and that the effect of these variations on structural performance will depend on the specifics of the bearing application. Material variations that fall outside of the specifications will stand out even more, and will be easily detected by the RUSpec system.

The Young’s modulus may be of interest as a quality control measure of the received ball material. Very small differences in modulus are detectable with the PCRT data. While the amount of variation in the samples may be acceptable, it may not be desirable to mix balls of varying material within the same bearing for optimal performance. Measurement of the Young’s modulus may also be effective in evaluating suppliers and manufacturing process changes. The Young’s modulus results for the sample in Figure 8 demonstrate that some batches (process variations) produced much more consistent results than others. PCRT evaluation of material lots could be used in process and quality control at the material manufacturer, or at incoming inspection at the ball finisher, to validate manufacturing process capability.

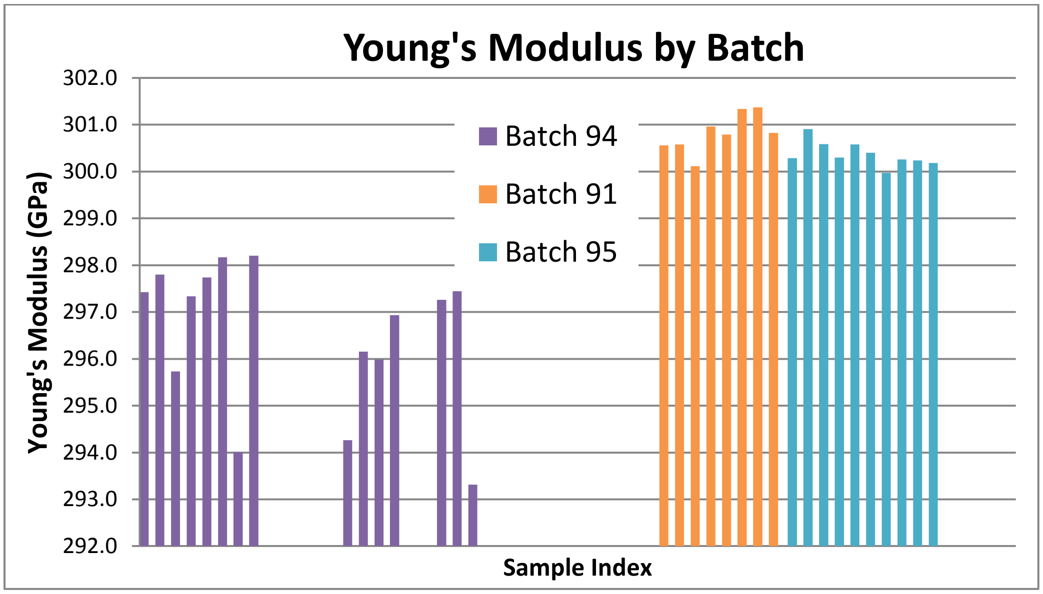

Figure 8 - Young's modulus data for various batches of 9/16" balls. Batches 91 and 95 have very similar modulus values, and show very consistent values from sample to sample. Batch 94 shows a lower nominal modulus, and significantly more variation.

2.3. Detection of Surface Defects

Surface Acoustical Waves (SAWs) are a specialized type of resonance vibration that moves only at the surfaces of materials. Generally speaking, they penetrate the material only a single wavelength. SAWs propagate on the surface of the SiN ball at a speed slightly slower than a shear wave. The frequency of such vibrations can be calculated by the following:

$$v_{shear} = \sqrt{(C_{66} / \rho)} \tag{2}$$

$$v_{surf} = A * v_{shear}, \text{ where } 0.9 < A < 0.95 \tag{3}$$

$$f_{SAW} = v_{surf} / \lambda, \text{ where } C / \lambda = \text{integer} \tag{4}$$

where v_{shear} is the shear velocity, C_{66} is an elastic modulus, ρ is the density, f_{SAW} is the SAW mode frequency, v_{surf} is the surface velocity, λ is the wavelength of the SAW, and C is the ball circumference. While Equation (3) provides an estimate of the surface velocity, the actual surface velocity is determined from the empirical data.

SAW responses are clearly seen across a range of ball sizes, in good accordance with theory, and the formulas presented above (Figure 9).

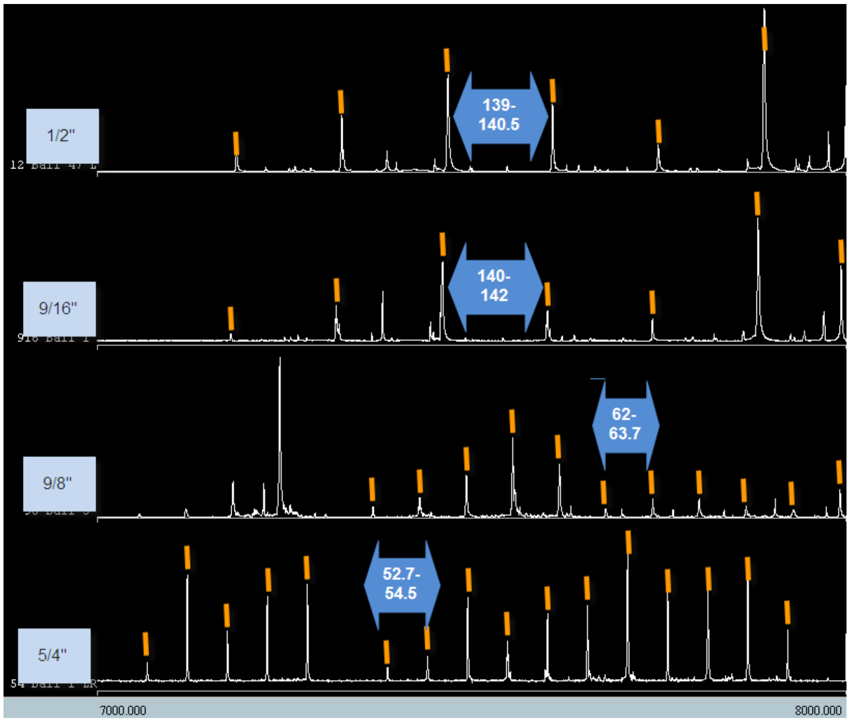

Figure 9 - Measured SAW intervals for a variety of ball sizes. The 9/16" balls are a different material than the others, leading to slightly different SAW separation, based on different material properties (C_{66}) and resulting surface velocity.

SAW modes degenerate significantly when a surface defect is present. Figure 10 shows these changes as Vibrant cracked a ball multiple times via ball-ball impact. The first crack produces a single additional response to the left of the main SAW response. The second crack adds an additional response to the left of that, and the third crack adds more and more responses. The defects cause the waves to slow as they move around the ball, resulting in resonances occurring at lower frequency. The frequency of these additional responses is consistent from measurement to measurement, and is related to the effect the defect has on the integrity of the ball. Larger defects move the additional responses to lower and lower frequencies.

PCRT inspections are automated, and do not require human interpretation. In sorting mode, the detection of the additional responses (“peaklings”) that represent the unwanted surface defects is automatic, and tuned to the customer’s desired sensitivity.

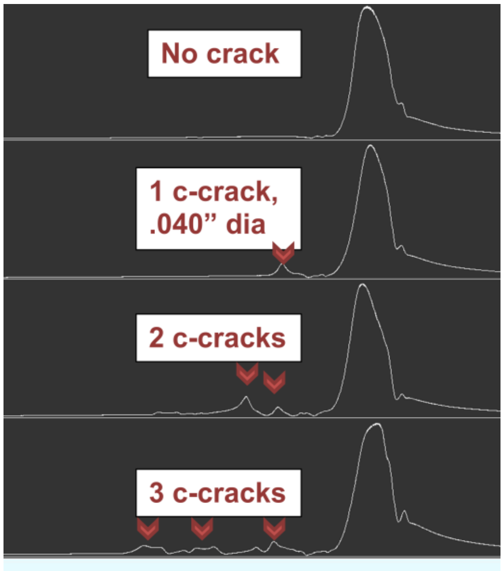

Figure 10 – SAW response resonance data for a ball with increasing C-cracks inflicted. Note the additional responses measured in the cracked sample, and the spread of these responses further to the left. [9/8" Ball, 2MHz]

Figure 11 shows an example of a combination of peaks that may be used for sorting. Three peakling zones are indicated in the top image. For the ball with no damage, the peakling zones are empty; the PCRT software passes this ball. For the impact crack ball, each peakling zone has at least one peakling present. The PCRT software flags the presence of those peaklings and rejects the ball. For a large laser-etched notch, the peakling count and distribution of the peaklings i.e. shifting to the left, towards lower frequencies, within the zone increases. These indicate a correlation between greater defect size/severity and higher peakling count/distribution. This is further demonstrated by Figure 12, where laser notches of various dimensions were studied. Increasing either the length or the depth of the notch produced a noticeable trend with the separation of the peaklings from the main SAW response.

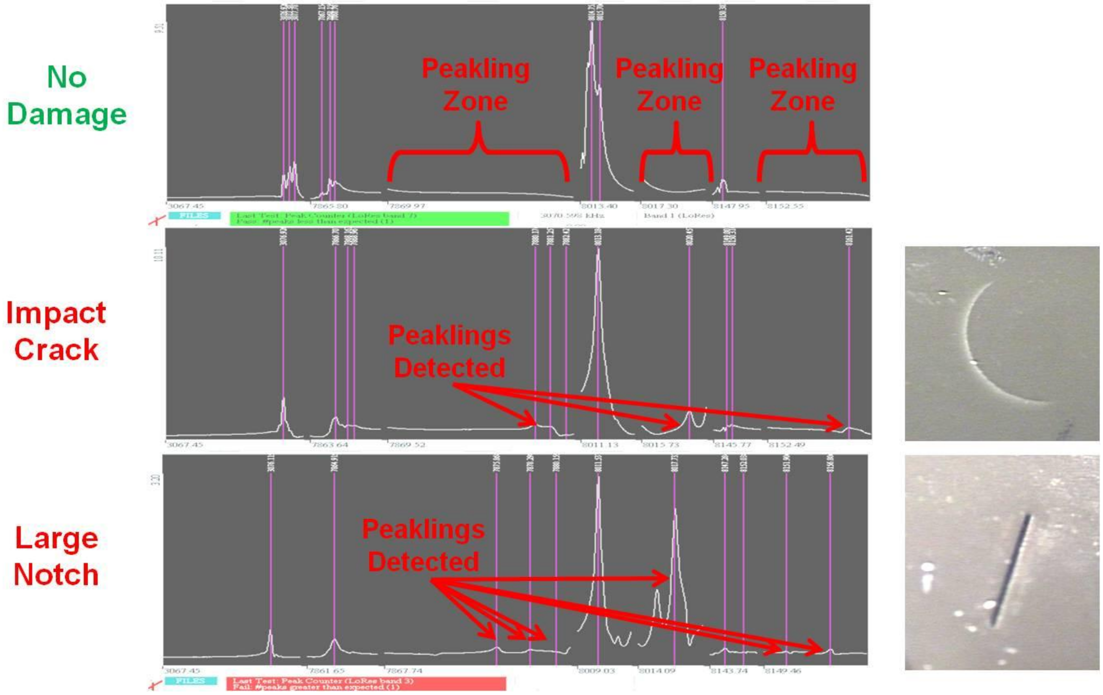

Figure 11 - Peakling sorting module examples.

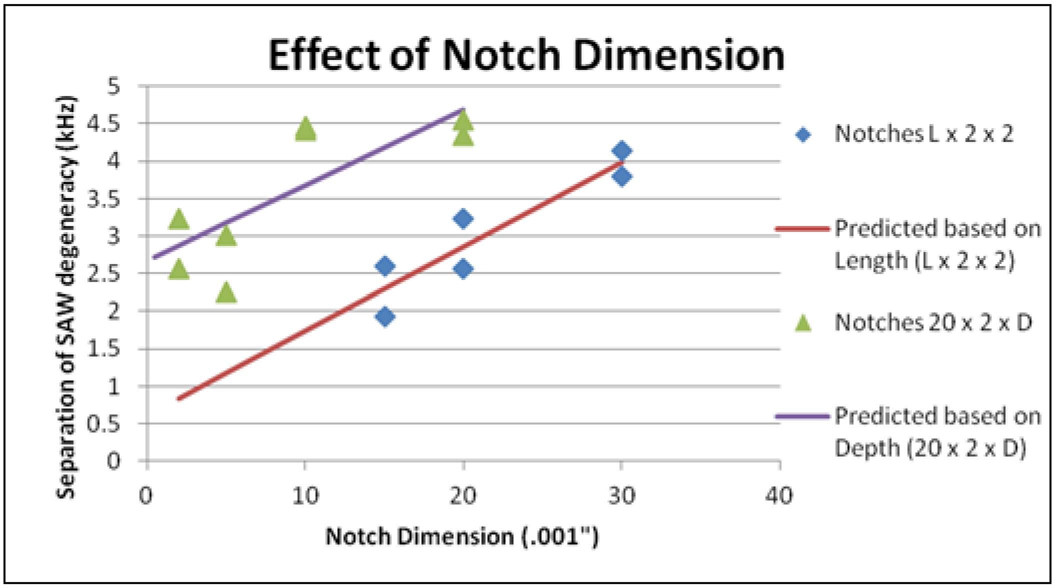

Figure 12 - Effect of notch dimensions on response.

3. Probability of Detection (POD)

Vibrant has done a number of studies related to POD of various surface defects on various sizes of ceramic balls. These include study of cracks and notches in 1/2” and 1” balls and an analysis of paired data, i.e. taken for the same balls before and after notching.

The 90 percent POD for 1/2" notch and impact samples was 0.012" (Figure 13). This is accompanied by a 17.5 percent false reject rate. The 90 percent POD for the cracked ½" samples is about 0.040" (Figure 14), but the uncertainty is higher in these, because of the variable response.

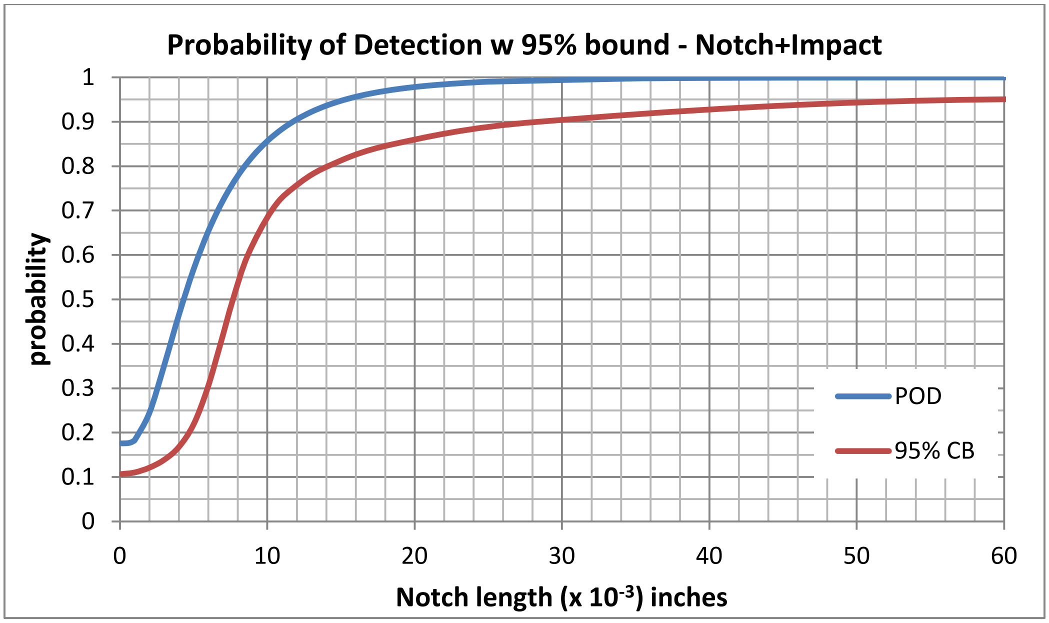

Figure 13 - POD curve for 1/2" balls, notch and impact defects only.

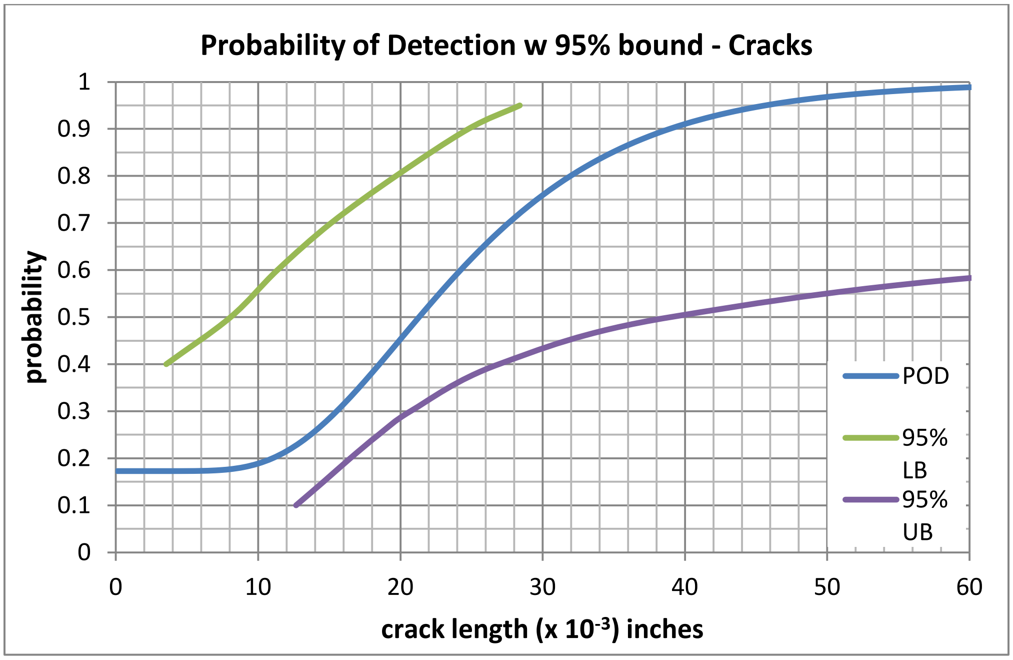

Figure 14 - POD curve for 1/2" balls, crack defects only.

Figure 15 shows the estimated POD curve based on the 24 notched balls (three repetitions of each). The notch length with a probability of being detected of 0.9 is estimated to be 0.0268” in length. With 95 percent confidence the notch length yielding a 0.9 probability of detection should be no larger than 0.044”. It is obvious that a smaller defect is more readily detected on a smaller ball.

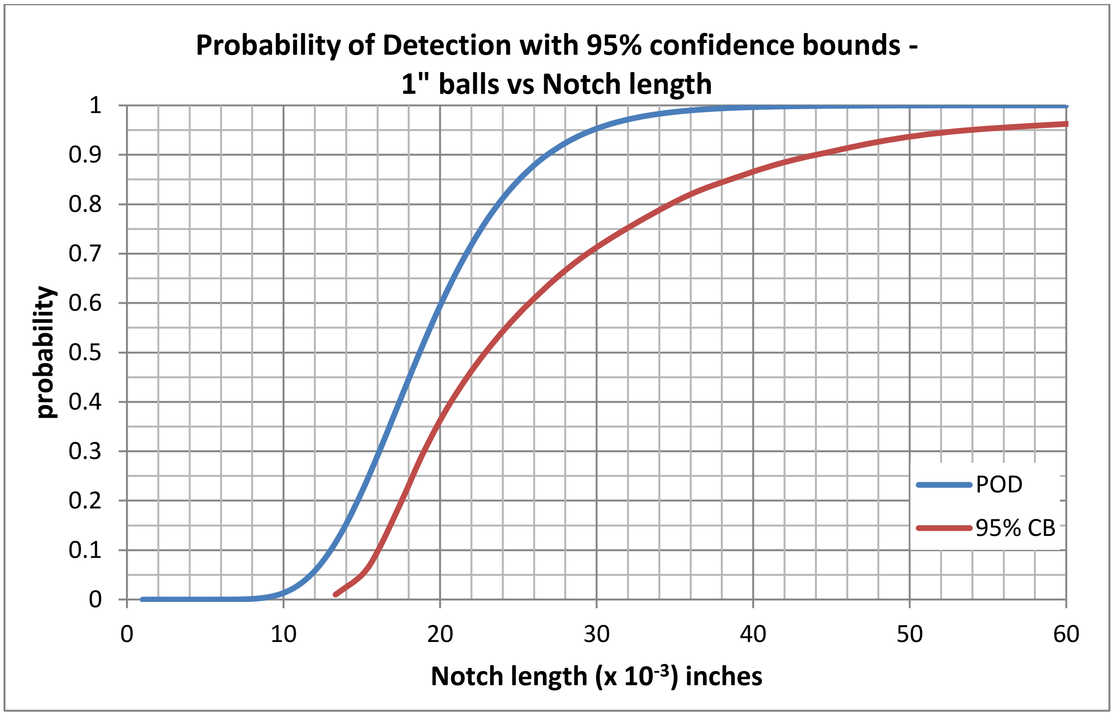

Figure 15 - Hit/Miss POD for 1” balls based on presence of peak in the [2.5 kHz, 6 kHz] zone with confidence bound versus notch length.

PCRT sorting modules are adjustable to suit the needs of an application. Conservative sorting criteria can be set for some applications, and can be relaxed for others, depending on customer needs.

4. Comparison to other NDT methods

Vibrant compared PCRT inspection results with other NDT methods for detection of surface defects. The other methods included visual, focused FPI, and immersion UT inspection. The 1/2” ball sample included 64 balls;

- Five balls with single c-cracks, ranging in chord length from 11 to 44 mil.
- Nine balls with laser notches, ranging in size from 5 x 2 x 2 to 30 x 2 x 20 (l x w x d, mil)
- Six balls with impact damage from a Vickers micro-hardness tester.
- The remaining 44 balls were considered to be ‘good’.

FPI performed by a seasoned Level III FP professional at an OEM partner had no false rejects, and rejected the cracked samples, but missed some of the largest notch defects and an impact defect. The FPI inspection took 6-7 hours for a single inspection of the ball set. As ball size increases, FPI time also increases.

The visual inspection had a yield of only 30 percent (compared to 65-75 percent for the other methods). While no defective balls were accepted, some of the balls were rejected for reasons other than the master result – for example two notched balls were rejected for scratches. One impact defect was rejected for the same. It should be noted that some of the balls in this set had already passed the same visual inspection before being included in the co-inspection set.

The UT inspection had a false reject rate of zero percent. One notch and two (of five) cracks were missed. The 64 balls were inspected in about 30 minutes. As ball size increases, inspection time also increases.

The PCRT run had a false reject rate approaching 10 percent, and missed one crack defect. A single PCRT test of the ball set was performed in about 30 minutes. As ball size increases, PCRT inspection time is virtually constant for ball sizes up to 9/8”.

5. Automated Ball Testing

Vibrant maintains an automated ball tester that combines a PCRT system for ceramic balls with automated part handling (Figure 16). The system provides the following capabilities:

- Accommodates balls from 1/2” and 5/4” in diameter
- Tests > 75 balls per hour
- No ball-to-ball contact during operation
- Fully automated PCRT testing requiring no operator interpretation
- Meet all safety requirements for operating on production and inspection floors at ball finishers or bearing manufacturers

The testing sequence is as follows:

1. Lift one ball via suction from the feed tray.
2. Move the ball to the temperature measurement fixture.
3. Record the temperature of the ball.
4. Move the ball to the test transducer fixture.
5. Measure resonant responses, determine test result.
6. Move the ball to the appropriate accept/reject tray.
7. Return to the feed tray for the next test ball

Figure 16 - Automated Ball Testing System

6. Additional Applications

PCRT and RUSpec have additional hybrid bearing applications beyond finished, spherical rolling elements. The bulk property/internal defect detection, process monitoring, material property characterization and surface defect detection capabilities can also be applied to cylindrical ceramic rolling elements. Balls and cylinders in the unfinished blank stage can be inspected for bulk property/internal defects, process variation and have their material properties characterized by the blank manufacturer on outgoing material or the ball finisher on incoming material. The advantage of blank inspection is the detection of defective balls before hours of surface finishing is performed.

Vibrant has a broad base of experience with other aerospace components. In propulsion, Vibrant has implemented commercial PCRT inspections for gas turbine engine blades, including blades for the JT8D and CFM56. In those inspections, PCRT detects cracks, geometrical variation and microstructural changes due to overtemperature exposure. In landing gear, Vibrant has applied PCRT to detection of cracks, voids and porosity in carbon brake disks and cracks, corrosion, and fatigue in wheel tie bolts.

7. Conclusions

PCRT offers fast, accurate and affordable defect detection for ceramic rolling elements for hybrid bearings. PCRT has demonstrated capabilities for bulk property/internal defect detection, process monitoring, material property characterization, and surface defect detection. In co-inspection comparison, PCRT demonstrated superior defect detection and/or throughput vs. visual, FPI, and UT methods. Vibrant's automated ball testing system tests more than 75 balls per hour with no ball-to-ball contact.

8. References

[1] “Resonant Ultrasound Spectroscopy “, Migliori, A., Serrao, J.L., 1997, Wiley Interscience.