QUASAR

INTERNATIONAL INC.

Quasar
Process Compensated
Resonant Testing - PCRT

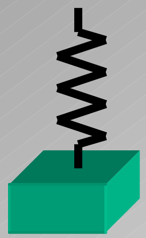
Outline

- Focus on Functional Quality
- Quasar PCRT technology
- Defect Detection sensitivity
- Examples
  - Correlation to functional performance
  - Detection of specific defect types

Functional Quality

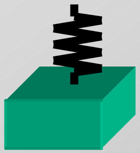
- Quality – Definition ***Visual Quality*** – rejects parts with visual indications that exceed (arbitrary) specification
  - ***Functional Quality*** – rejects parts with structural degradation that will cause *premature field failure*
- Functional Quality Requires NDT that:
  - Measures structural properties
  - Provides results that are traceable to failure levels
  - Provides quantitative and objective reject criteria
- Only Resonance NDT can meet these requirements
- Resonance *MUST* be Process Compensated
  - Uncompensated variations mask defects
- Process Compensation Requires
  - Math tools to compute compensation algorithms
  - Precision frequency measurements
  - Temperature compensation

Resonance Theory Applied to NDT



Resonant Frequencies determined by dimensions and material properties of “whole part”

$$f_r \sim \sqrt{k/m}$$



f_r = resonant frequency

k = stiffness (elastic properties e.g., Young’s Modulus)

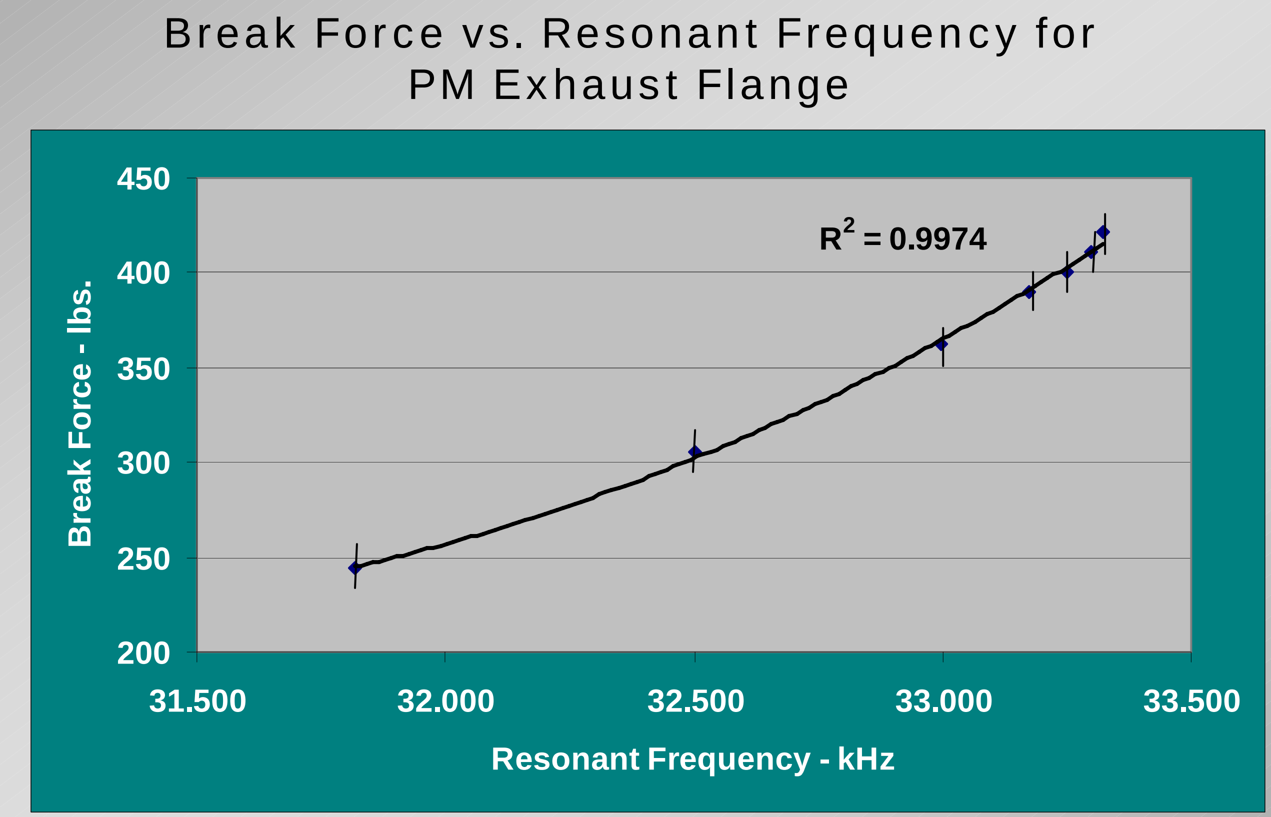
m = mass (dimensions, density)

Structural Defect = strength reduction caused by degraded material properties or dimensional variation

- e.g., a crack reduces stiffness and lowers the resonant frequency

So, resonant frequency should correlate to defect severity

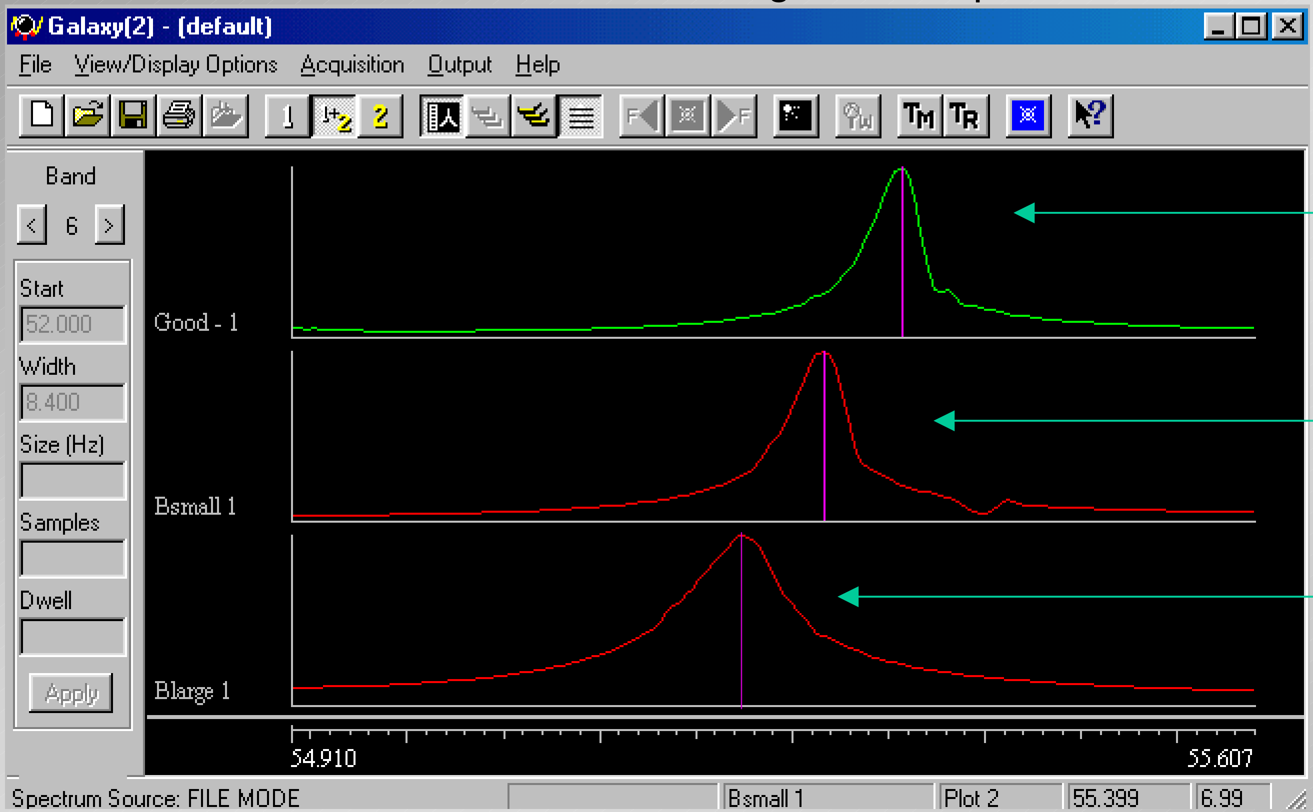
Experimental Verification Resonant Frequency Correlates to Break Strength



The high correlation between performance degradation and resonant frequency is the foundation for an NDT program

Demonstration:
Resonant Frequency vs. Defect Severity

Connecting Rod Experiment



Good Con Rod

Small Cut – Similar to Normal Production Crack

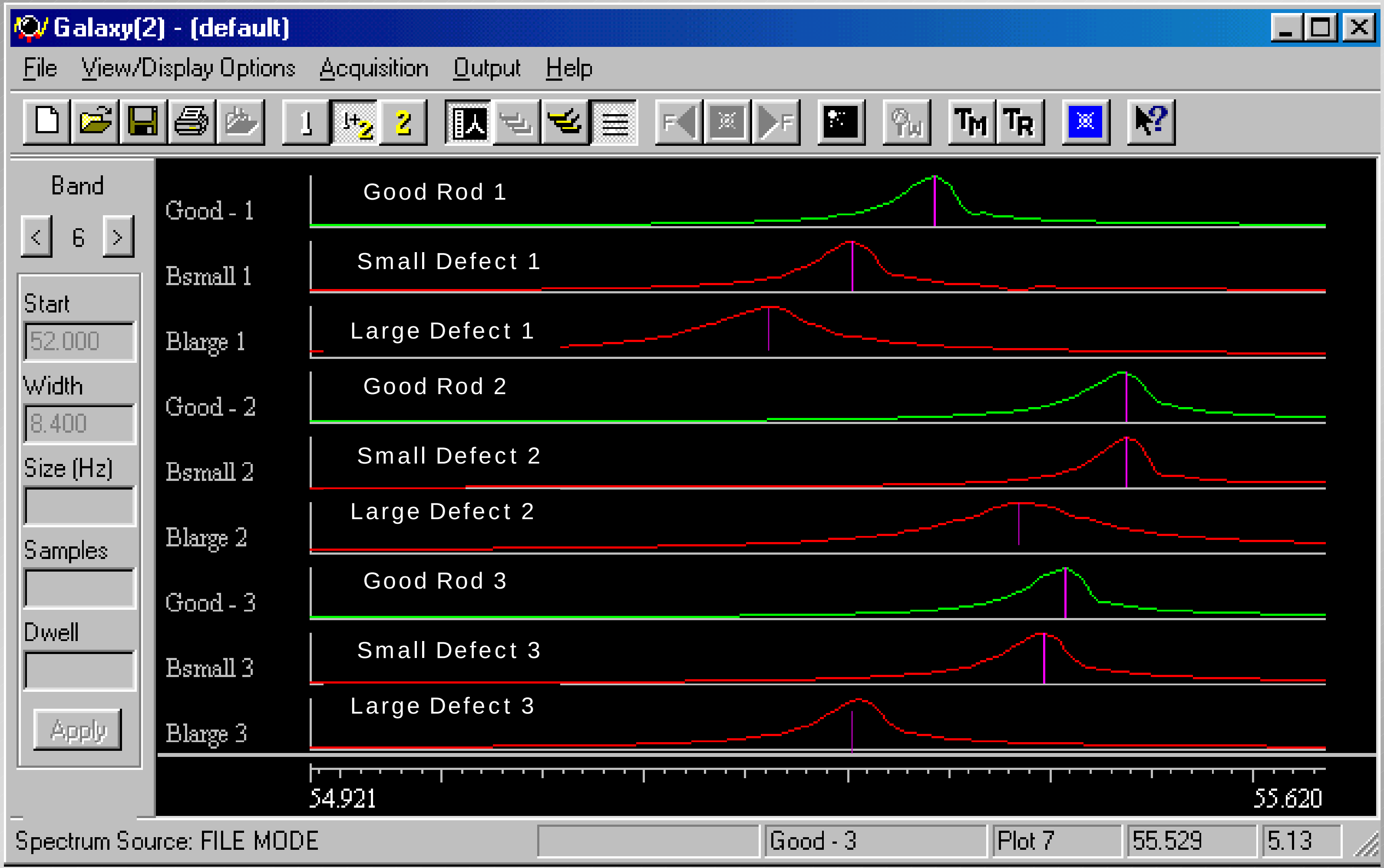
Shift = 0.9%

Larger Cut – Similar to Large Crack

Shift = 1.5%

A defect reduces the stiffness of the part and causes a proportional shift in the resonant frequency

Process Variation Mask Defects

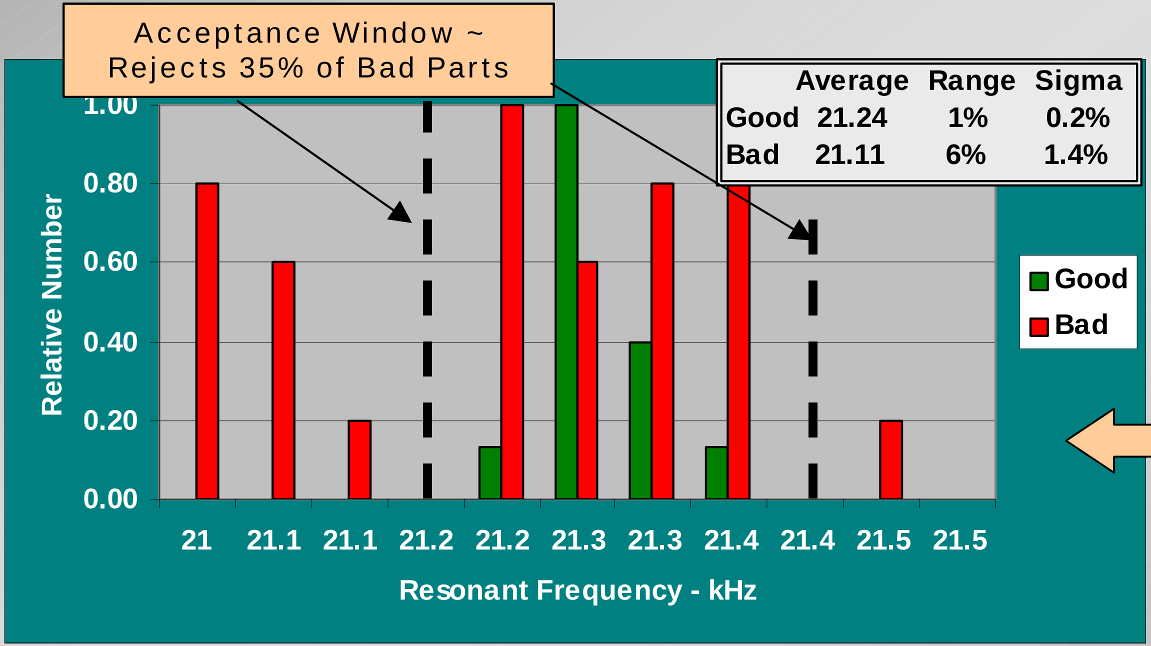


The Frequency of Good Rod #1 is lower than the frequency of Rod #2 with a large defect, due to normal process variation

Statistical Analysis of Defect Masking

Acceptable Process Variations in Dimensions and Material Properties Produce Frequency Shifts that Mask Defects

– Bad part frequency distribution overlaps good part distribution
– Some defects increase resonant frequency (e.g., reduced mass)



Distribution of Resonant Frequencies for 200 Master Cylinder Bodies

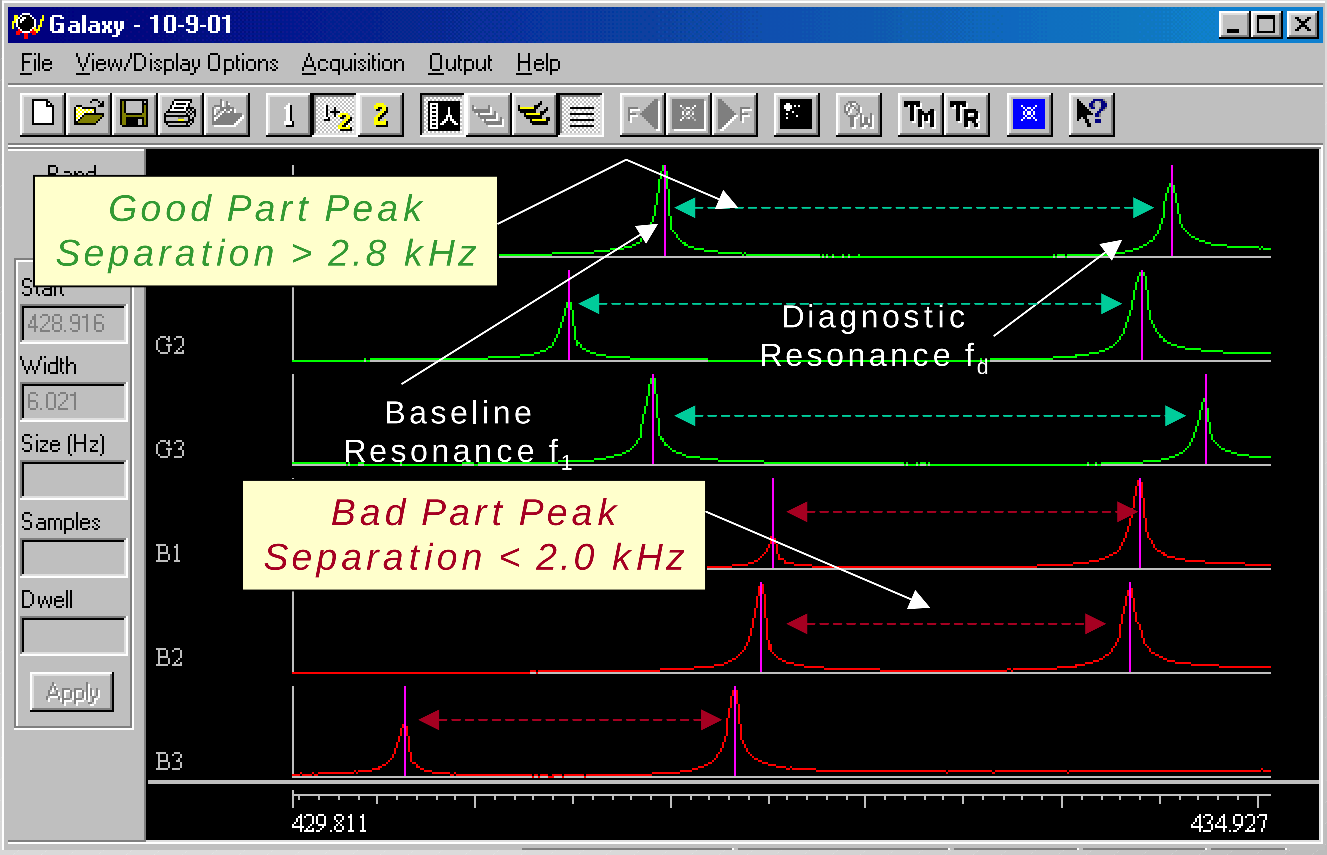
<u>Poor Basis for Sorting</u>

Good and Bad Part Distributions overlap

Result – Standard resonance testing limited to detecting gross defects

Simple Compensation

Silicon Nitride Valves



ALL resonances shift due to process variations

DIAGNOSTIC resonances also shift due to defect

Separation between resonant peaks can SOMETIMES be correlated to larger defects despite process variations

Quasar PCRT - Comprehensive Process Compensation

- Multi-frequency Process Compensation
  - Extension of Compensation to many variables
  - Measure multiple resonances
  - Predict frequency of the diagnostic resonance
  - Difference between measured and predicted frequency is the Predictor Error
  - Compute Process Compensation Equations

    $f_{dp} = A*f_1 + B*f_2 + C*f_3 + D*f_4 + \ldots$

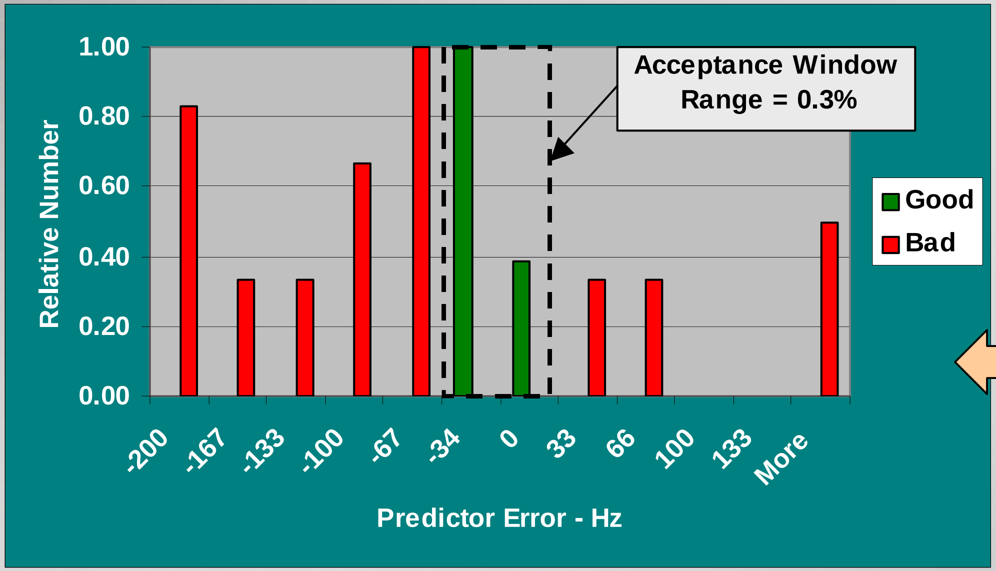
    $PE = f_{dp} - f_{dm}$

    Where: f_{dp} and f_{dm} are the Predicted and Measured Frequencies of the Diagnostic Resonance, and PE is the Predictor Error
  - Range of PE for good parts is Acceptance Window
  - Predictor Error correlates to performance degradation

- Statistical Pattern Recognition techniques develop the compensation equation
  - MTS (Mahalanobis Taguchi Score) characterizes good parts
  - Bias score characterizes bad parts

Multi-frequency Process Compensation Unmasks Defects

- Predictor Error separates Good and Bad parts
  - No overlap of Good & Bad Distributions
- Parts outside Acceptance Window are rejected



Distribution of Predictor Error for 200 Aluminum Master Cylinders

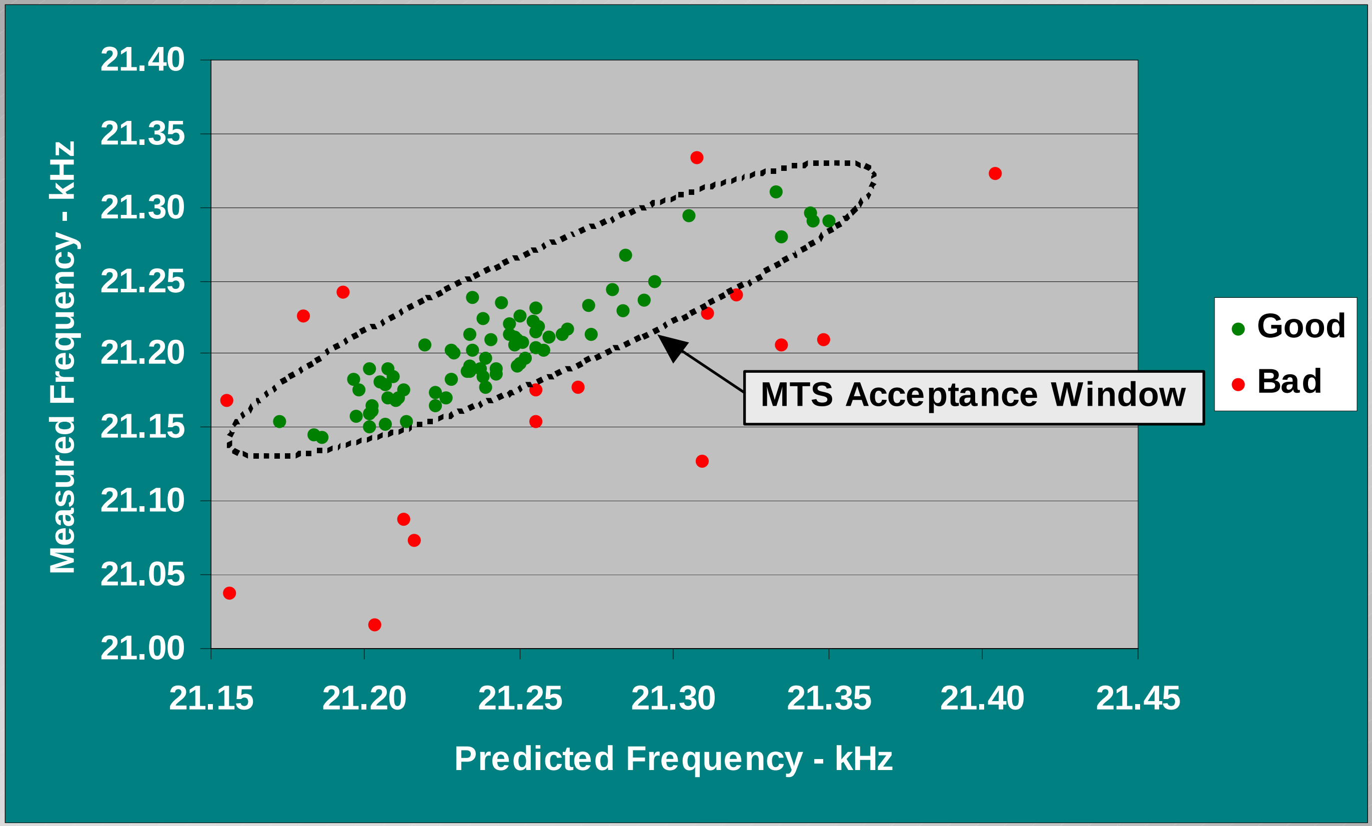
<u>Perfect Sorting</u>

All Good parts accepted

All Bad parts rejected

Process Compensation "sees through" process variation to provide effective sorting

- Graphical Illustration -
Part Sorting Using Pattern Recognition

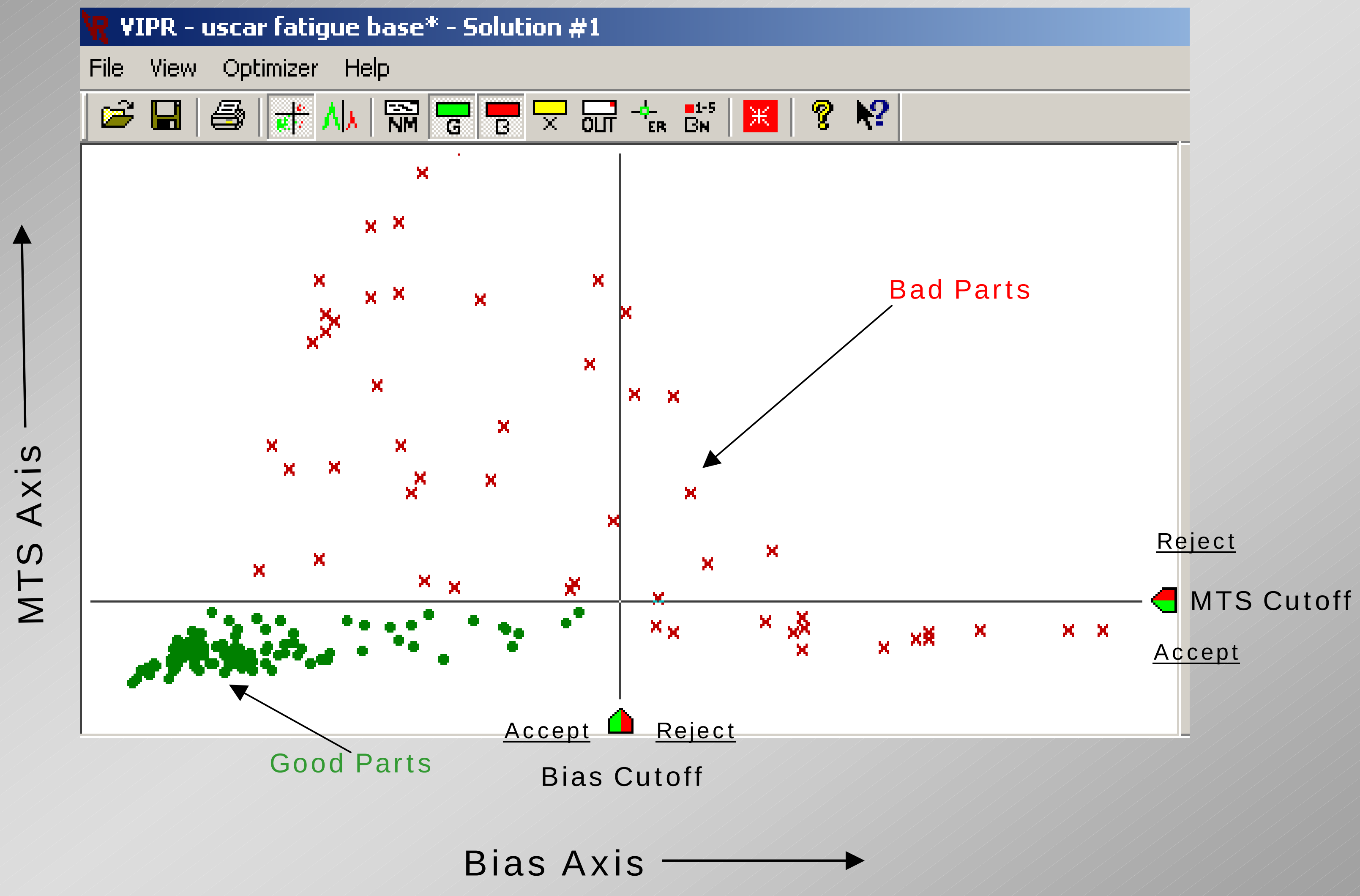


Measured & Predicted Resonant Frequencies for 200 Aluminum Master Cylinders

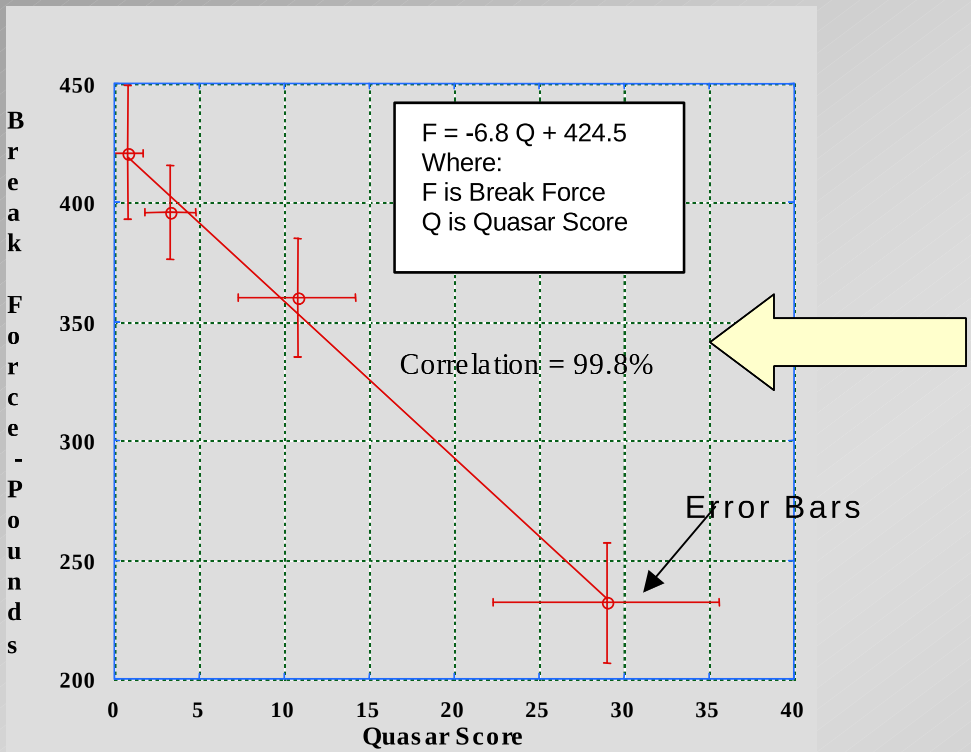
MTS = Mahalanobis Taguchi System

Quasar's VIPR program computes MTS Compensation Equations

VIPR uses both MTS & Bias Tests



Quasar Score Predicts Performance



Correlation is perfect because:

- *Quasar score is determined by <u>part strength</u>*
- *Defect size and orientation are controlled*

Perfect correlation is impossible for other NDT methods because they do not measure parameters that determine <u>Part Strength</u>

Quasar Sensitivity

- Common question:
  - What size is the smallest defect that quasar can detect?
- <u>Proper question:</u>
  - How much performance degradation can quasar detect?
- Answer – detection threshold depends on several variables:
  1. Definition of defectiveness – bad parts must be statistically weaker than good parts
     - Defects must be structural, not cosmetic
     - Failure distribution must be statistically defined
  2. Measurement R&R (i.E., Precision, temp. Comp., Tooling)
  3. Available test time vs. Weight & complexity of part

Variable 1 – Definition of Defectiveness

- Visual Definition – Parts that “look” bad - *unworkable*
- Functional Definition – Part that would fail prematurely in service
- Statistical Definition – Part that is statistically weaker than minimum failure level of good parts

Sample Quasar Severity Definitions

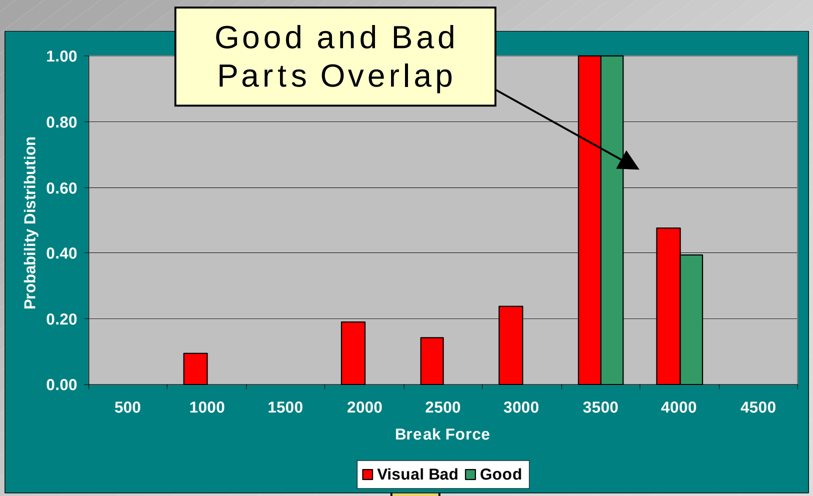
Based on Minimum Acceptable (Good) = Mean – 3 sigma

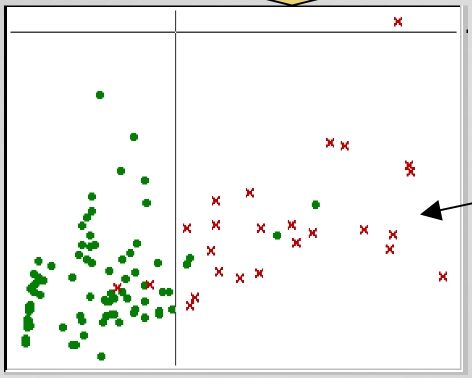
Severity Rating	# of Standard Deviations below Mean Good Part Failure Level
Good	< 3
B1	3 to 4
B2	4 to 5
B3	5 to 6
B4	6 to 7
B5	> 7

Initially these rating may be subjective based on other NDT

Visual Classification Provides Poor Basis For Sorting

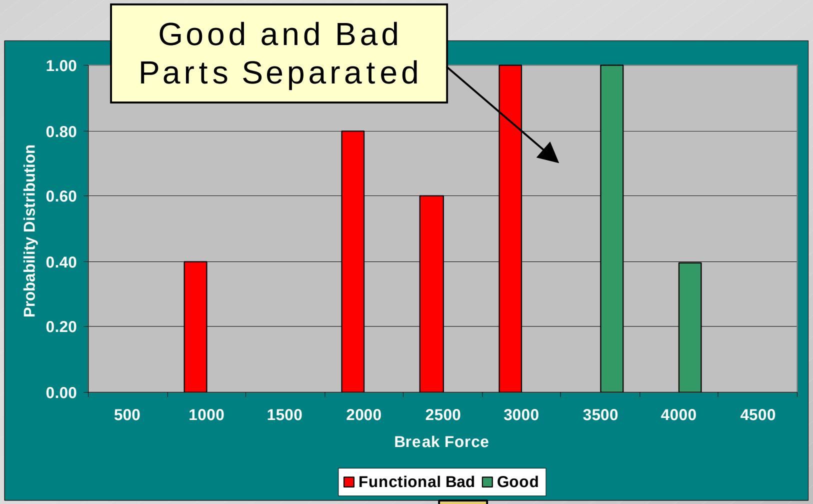
Visual Classification

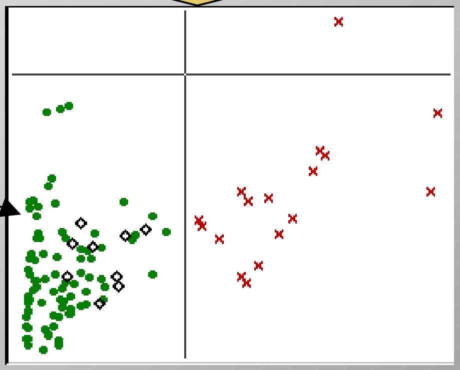




VIPR Sorting = 95%

Functional Classification





VIPR Sorting = 99.7%

Legend

Good Parts - ●

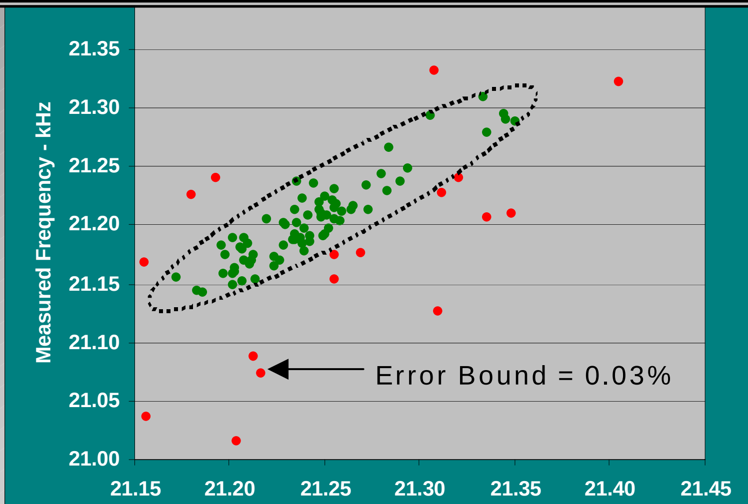
Bad Parts - x

Reclassified Parts - ◇

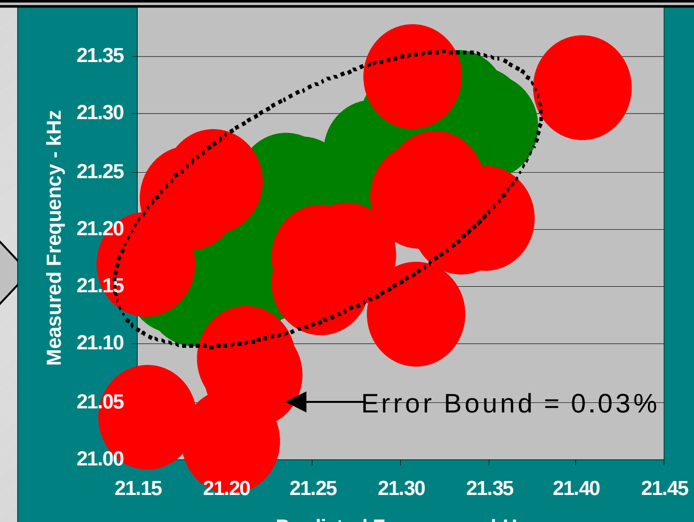
Bottom Line: Defects must degrade part strength to be detected with Quasar

Variable 2 – Resonance Measurement Reliability and Repeatability

EFFECT OF MEASUREMENT ERROR ON SORT PERFORMANCE



Measurement Error = 0.03%
Parts Can Be Sorted



Measurement Error = 1%
Parts Cannot Be Sorted

Performance Comparison

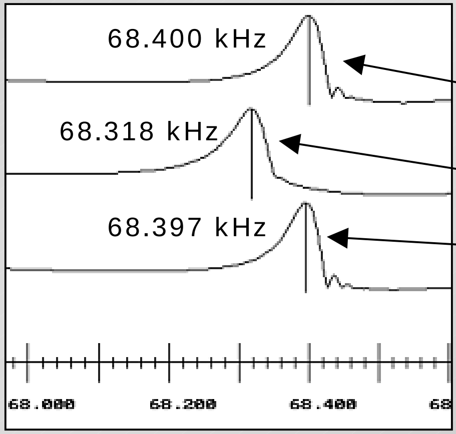
Quasar Swept Frequency Method
vs.
Impulse Method (hammer & microphone)

	Quasar	Impulse
Precision	0.001%	1%
Placement	0.005%	?
Temp Comp	0.015%	?
Total	0.03%	1+%

Bottom Line: Effective detection requires precise measurements

Temperature Compensation

- Temperature Compensation is critical to accurate resonance measurements
  - Quasar total error budget is 0.03%
  - Resonant frequency varies with temperature
    - Ferrous – 0.015% per degree Celsius
    - Aluminum – 0.025% per degree Celsius
- Compensation measures part temperature (+/- 0.5 degrees Celsius) and computes equivalent frequency at baseline temperature



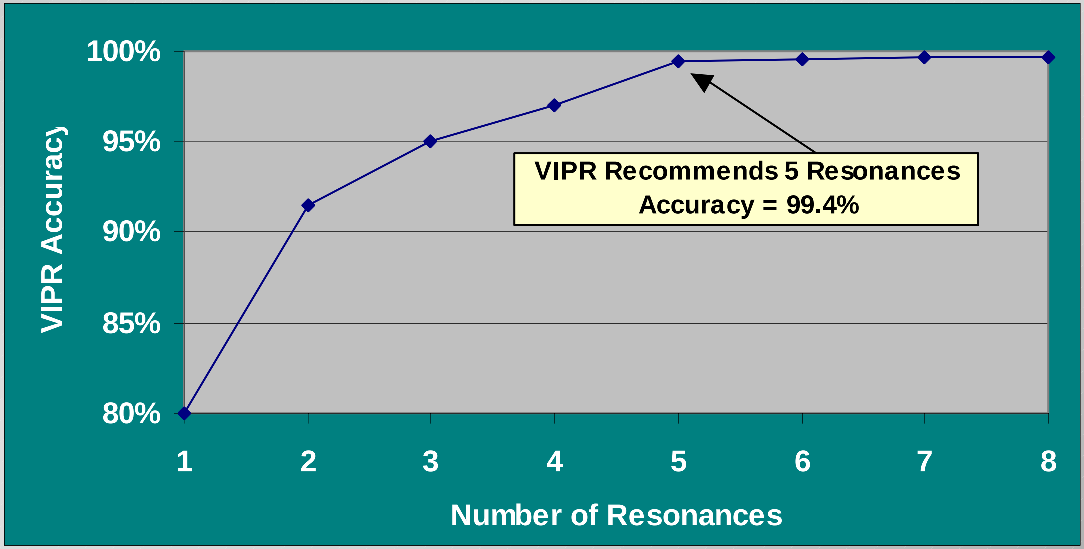
<u>Temperature Compensation Example</u>

- Part measured at 23 C
- Repeat measurement at 31 °C
- Repeat measurement compensated to 23 °C baseline
- Compensation Accuracy = 99.995%

Bottom Line: Effective detection requires temperature compensation

Variable 3 - Test Time

- Required Test Time determined primarily by Part weight and complexity
  - Heavier parts use lower frequencies – longer measurement time
  - Complex geometry requires more resonances for compensation
- Number of resonances also increases with:
  - Amount of Process Variation
  - Statistical overlap between Good and Bad part failure levels
  - Required sort accuracy



VIPR Accuracy vs. # Resonances

PM Sensor - 86 goods, 32 bads

Bottom Line: Effective detection requires sufficient time

Severity Detection Threshold Determines Test Time

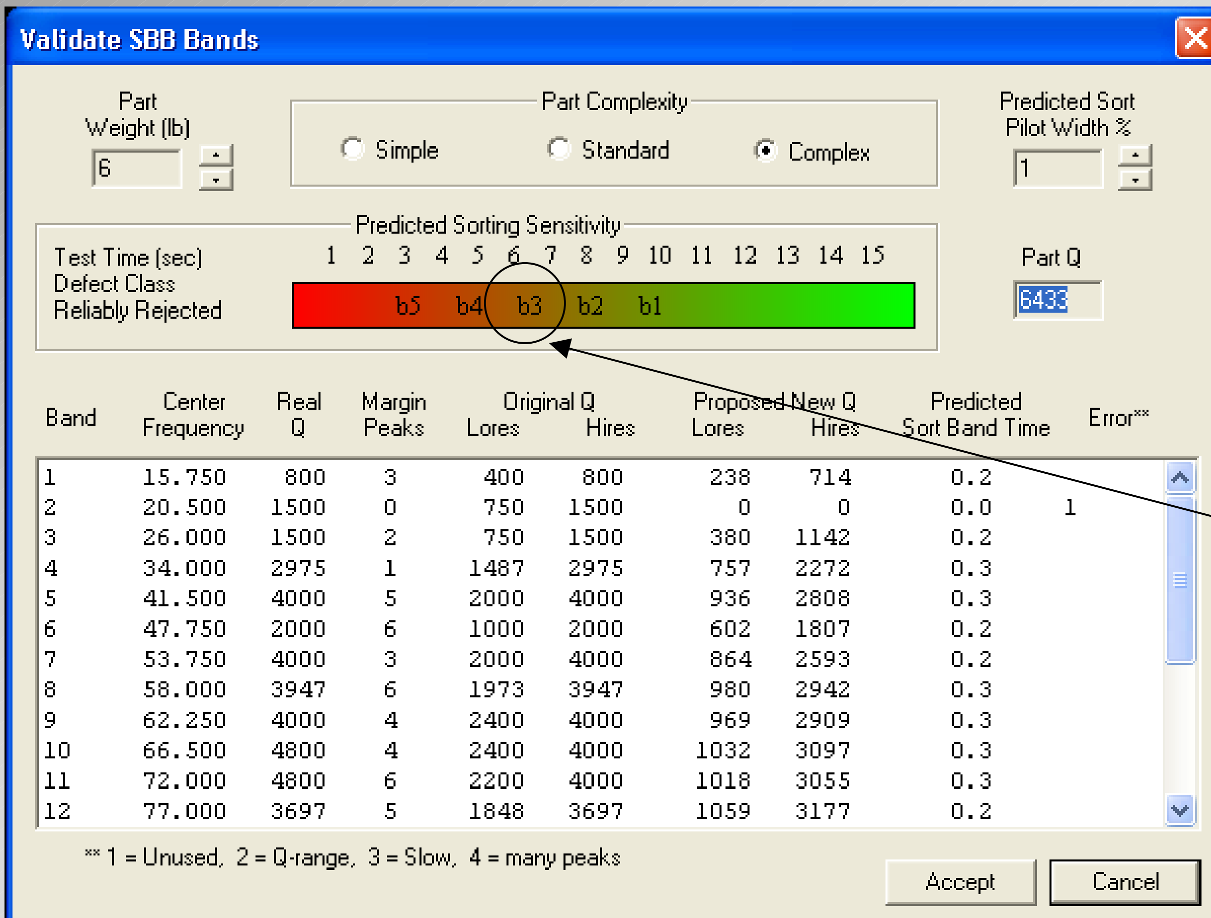
	Weight/Complexity Factor (lbs)						
Time - sec.	0.25	0.5	1	2	4	8	16
1	*B4*	*B4*	*B5*	*B5*	*B5*	*B5*	*B5*
2	*B3*	*B3*	*B4*	*B5*	*B5*	*B5*	*B5*
3	*B2*	*B3*	*B4*	*B4*	*B5*	*B5*	*B5*
4	*B2*	*B2*	*B3*	*B4*	*B4*	*B5*	*B5*
5	*B1*	*B2*	*B2*	*B3*	*B4*	*B4*	*B5*
6	*B1*	*B1*	*B2*	*B3*	*B3*	*B4*	*B4*
7	*B1*	*B1*	*B1*	*B2*	*B3*	*B3*	*B4*
8	*B1*	*B1*	*B1*	*B2*	*B2*	*B3*	*B3*
9	*B1*	*B1*	*B1*	*B1*	*B2*	*B2*	*B3*
10	*B1*	*B1*	*B1*	*B1*	*B1*	*B2*	*B2*

Minimum Detectable Degradation - typical Q = 2000

Example: 2 pound simple part requires 5 - 6 sec. To reliably detect degradation of B3 and above

Minimum defect severity threshold can be traded vs. test time for a given part weight, stiffness & complexity,

Galaxy Projects Timing vs. Weight & Complexity Tradeoff



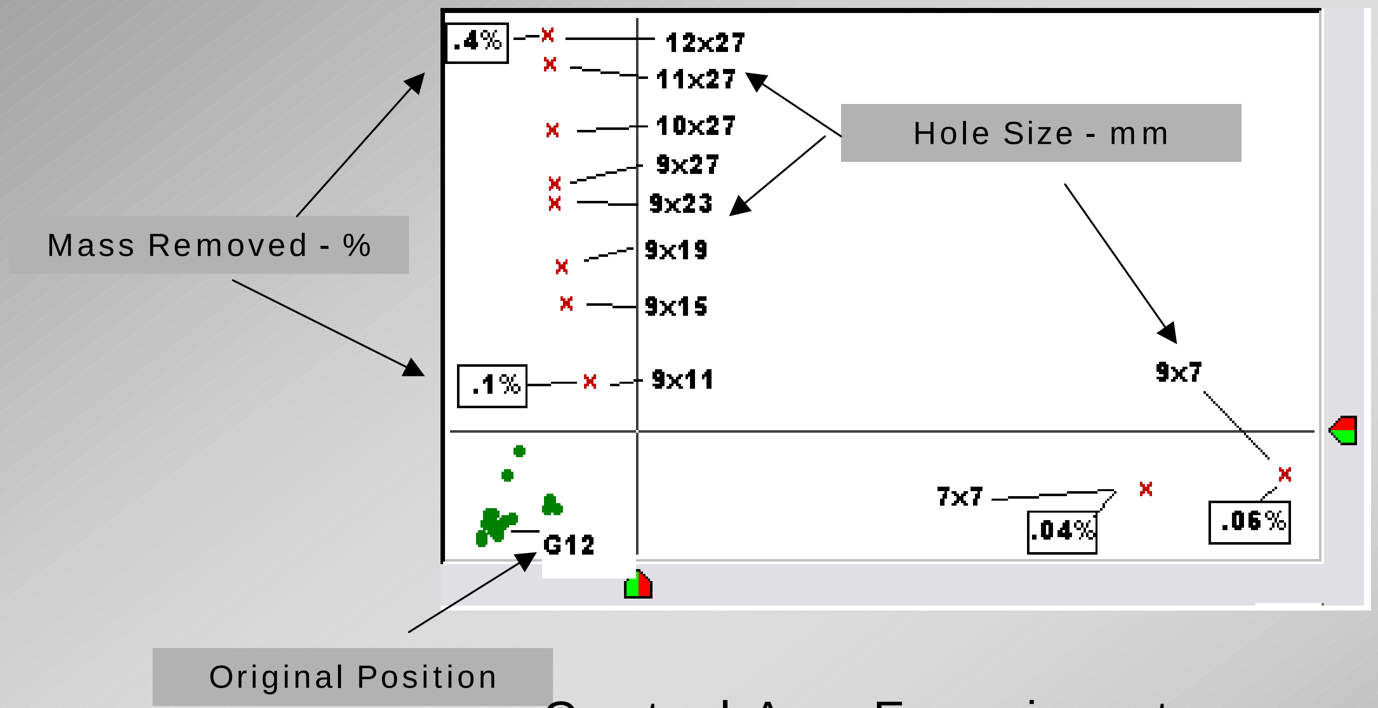
Band	Center Frequency	Real Q	Margin Peaks	Original Q Lores	Original Q Hires	Proposed New Q Lores	Proposed New Q Hires	Predicted Sort Band Time	Error**
1	15.750	800	3	400	800	238	714	0.2	
2	20.500	1500	0	750	1500	0	0	0.0	1
3	26.000	1500	2	750	1500	380	1142	0.2	
4	34.000	2975	1	1487	2975	757	2272	0.3	
5	41.500	4000	5	2000	4000	936	2808	0.3	
6	47.750	2000	6	1000	2000	602	1807	0.2	
7	53.750	4000	3	2000	4000	864	2593	0.2	
8	58.000	3947	6	1973	3947	980	2942	0.3	
9	62.250	4000	4	2400	4000	969	2909	0.3	
10	66.500	4800	4	2400	4000	1032	3097	0.3	
11	72.000	4800	6	2200	4000	1018	3055	0.3	
12	77.000	3697	5	1848	3697	1059	3177	0.2	

Process feedback example – reliable detection of B3 severity will require 6 to 7 seconds for this part.

Examples

- Correlation to functional performance
  - Quasar score vs. defect size
  - Quasar score vs. fatigue life
- Detection of specific defect types
  - Cracks
  - Nodularity

Quasar Score vs. Defect Severity

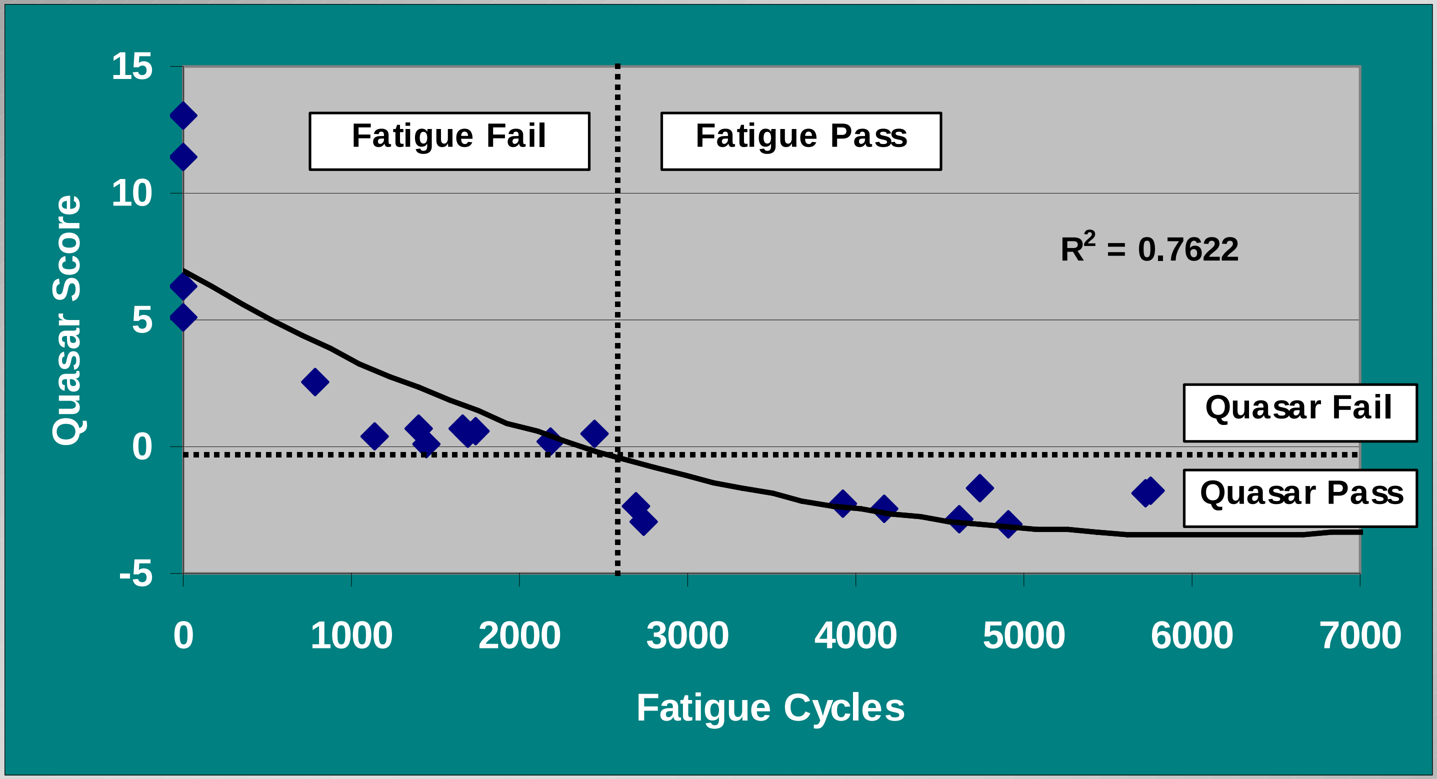


Control Arm Experiment

Correlation of Quasar Score to hole size as Good Part (G12) drilled out

Conclusion: Quasar Score correlates to defect severity even for complex parts

Quasar Score Vs. Fatigue Life



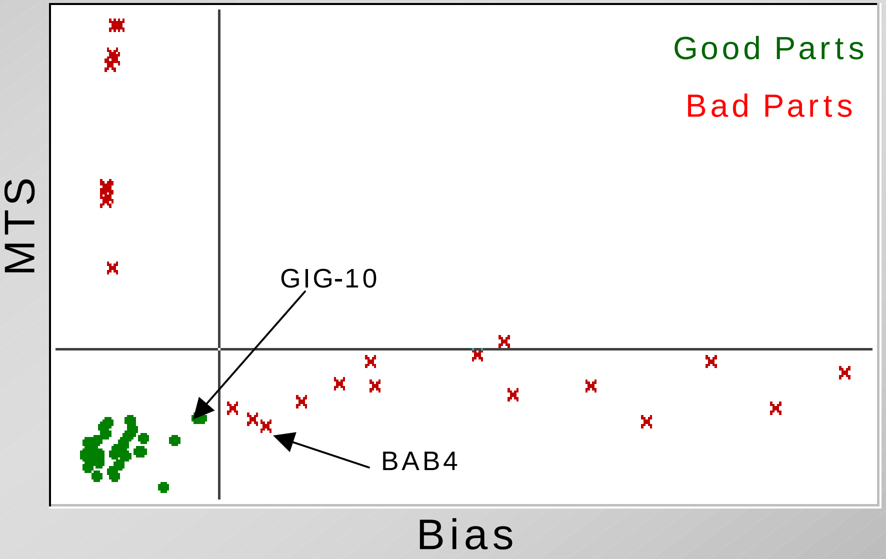
Accelerated Fatigue Test of Aluminum Knuckles

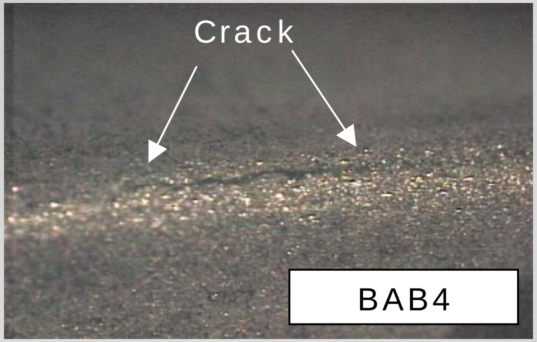
Fatigue Pass > 2500 cycles; Quasar Score Pass < 0

Correlation is apparent, but imperfect, because fatigue loading did not uniformly stress entire part

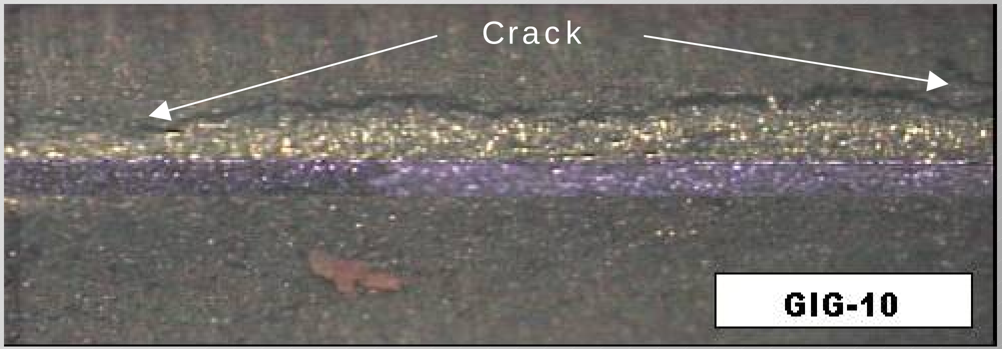
PCRT Application Example - Cracks

- Sample: 140 Hubs
  - 71 good, 69 bad
- Develop Sorting Module
  - 40% train, 60% validate
- Result: 1 “good” part – GIG-10 rejected in validation
- Microscopic exam - 40X





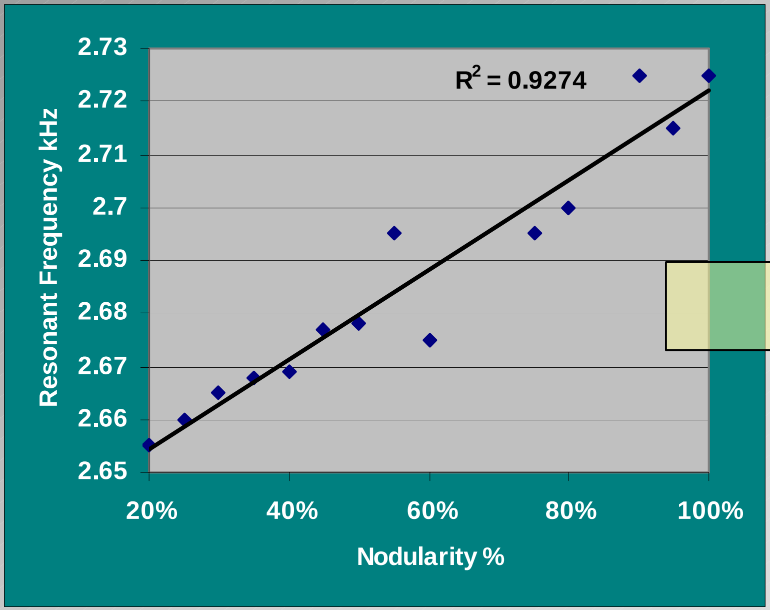
MPI Bad



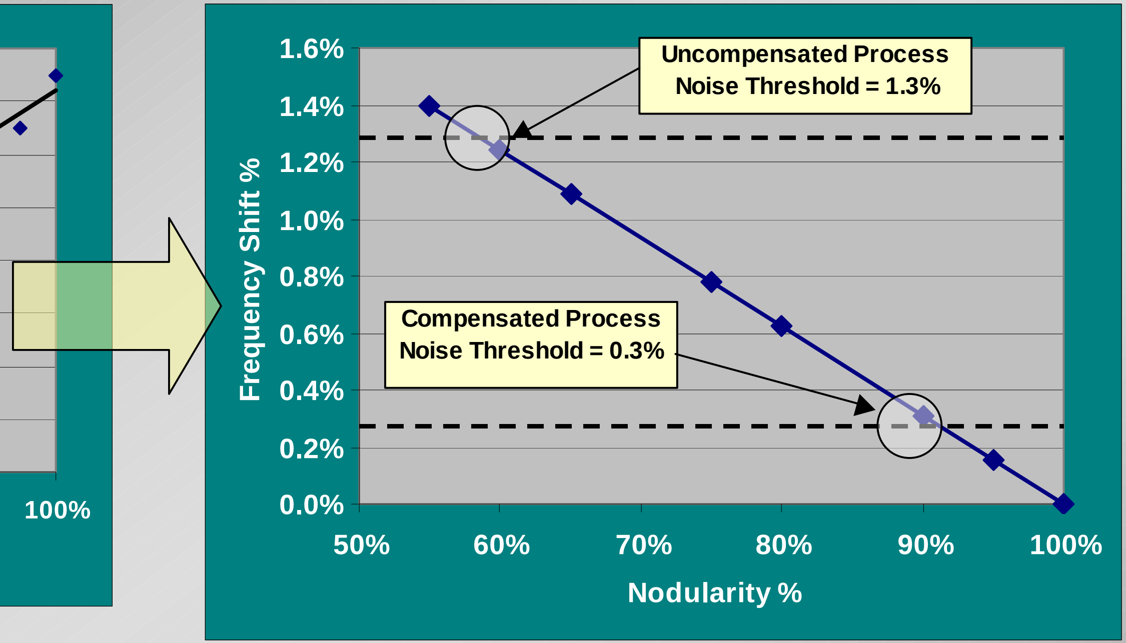
MPI Good

Conclusion: Some MPI “Goods” have larger cracks than MPI “Bads”. Quasar produces consistent results

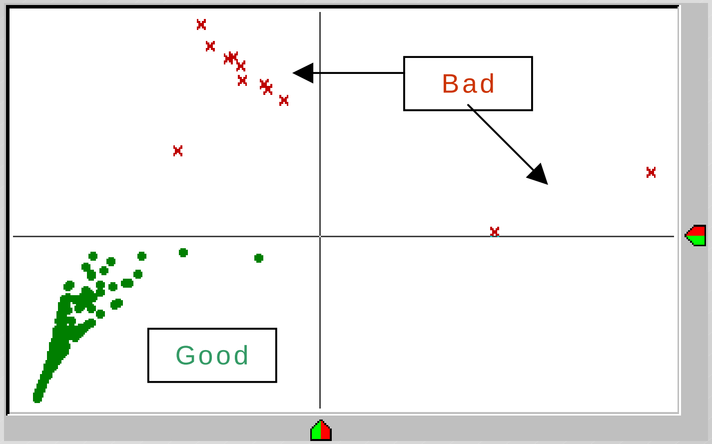
Application Example - Nodularity



Data Source: *Emerson – British Cast Iron Research Assoc. - 1974*



Sensitivity: Frequency shift vs. Nodularity



Ductile Iron Brake Anchors
Defective = Average nodularity 70%

	Nodularity Detection Threshold
Uncompensated	< 60%
Compensated	< 90%

Quasar PCRT Provides Functional Quality

- Resonance tests complete part for *ALL* structural defects
- Resonance Pattern determined by material properties (e.g., Young's Modulus)
- Quasar Score correlates to structural performance (e.g., Yield Strength or Fatigue Strength)
  - Detects differences in materials or processes
  - Detects discontinuities (cracks, inclusions, etc.) that affect Strength
  - Insensitive to superficial indications
- Compensates for acceptable process variation
- Management sets Reject limits based on objective criteria - no operator judgment

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First in
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