

New Approach in Non-Destructive Evaluation Techniques for Automotive Castings

Thomas E. Prucha
INTERMET Corporation

Robert Nath
Quasar International

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ABSTRACT

Automotive castings are being utilized increasingly in structurally demanding and safety critical applications. The need for reduced weight, near net shape and more cost effective components has resulted in a desire by the customer to reduce the conservative safety factors previously used for design criteria. The expectation on the metal caster is to supply parts with material and structural properties verified in the product to a high statistical standard. Since the part's quality and integrity are now guaranteed, the historical approach of manual inspection, evaluation and qualitatively based acceptance decisions is being replaced with various approaches to automated evaluation. This presentation will review some of the past requirements and testing approaches used to assure part integrity and compliance. Then it will look at the work of groups like the RISC committee of USAMP/USCAR to make standards more quantitative. This discussion sets the background for introducing PCRI, an NDE (Non Destructive Evaluation) method that evaluates parts not in terms of specific indications, but rather in terms of their structural properties, which better determine fitness for use.

INTRODUCTION

Increasing demands for lighter weight, reliability and consistency have driven the substitution of new materials such as aluminum for ductile iron and also caused the redesign of ductile iron parts. As the expectations have increased so have requirements for assuring the quality and integrity of these components. The traditional approach for increasing the level of verification has been application of various aerospace standards and inspection techniques for specific attributes. Many times the evaluation criteria have been subjective and more qualitative, as has been the case for radiographic standards applied to real-time radiosopic inspection for internal part integrity and the inspection of external quality via dye penetrant techniques. Improvements were made

emanating from the cooperative efforts of the USAMP/USCAR RISC (Radioscopic Inspection Standards Committee) to move this towards quantitative standards. Still the inspection approach is based on individual tests aimed at specific attributes or indications of part quality. The PCRI (Process Compensated Resonant Inspection) method, which has been developed over the past 5 years, tests the complete part using the measurement of vibrational resonances to generate a quantitative pattern that correlates highly with the performance of the part when structurally loaded. While it is not always a direct correlation with or substitute for the traditional tests, the information obtained from PCRI can be more representative of how the part will perform and survive in service.

TRADITIONAL APPROACH TO NDE

The traditional approach to verifying the level of reliability and quality of components like an aluminum steering knuckle has been the increasing use of aerospace or premium standards and inspection techniques. Figure 1 is taken from the Aluminum Association Casting Quality Standard. It represents a listing of quality levels relating to internal integrity as defined by several ASTM standards. The intention is to specify casting integrity to a grade or quality level and then verify conformance via hard copy x-ray and a sampling plan. While this may have served the needs of commercial products, the volume levels and higher service demands on structural automotive castings soon changed the requirement from sampling plans to some form of 100% inspection.

Figure 2 was an approach initially applied to a rear knuckle made in aluminum A206 alloy for one of the first introductions of aluminum in this type of component back in late 1980's. Subsequent issues with quality and consistency have escalated the demands from the audit basis listed in the ES standard to 100% radiosopic inspection for internal quality and often 100% fluorescent penetrant inspection (FPI) for external attributes like

crack detection. Although the level of inspection increased, the level of quality measured by nonconformance encountered upon machining or

assembly did not increase in proportion to the time, effort and resources expended on these activities.

Standards For Aluminum Sand and Permanent Mold Castings

METALLURGICAL SERIES (M)
AA-CS-M5-85
ALUMINUM CASTING QUALITY STANDARD
Page 2 of 3

Quality levels as indicated in Table I and referenced in ASTM E 155 show the type of discontinuity and maximum size or degree allowed in each case.

An illustration of a typical reference radiograph as contained in ASTM E 155 is shown in Standard AA-CS-M6.

TABLE I—QUALITY LEVELS

DISCONTINUITY	REFERENCE RADIOGRAPH	QUALITY LEVELS ⁽¹⁾														NO RE OU I RE ME NT	
		I		II (AA)		III (A)		IV (B)		V (C)		VI (D)		VII (E)			
		1/4"	3/4"	1/4"	3/4"	1/4"	3/4"	1/4"	3/4"	1/4"	3/4"	1/4"	3/4"	1/4"	3/4"		
GAS HOLE	1.1	1	1	2	2	2	2	3	3	4	4	5	5				
GAS POROSITY ROUND	1.21	2	2	3	3	5	5	6	6	7	7	8	8				
GAS POROSITY ELONGATED	1.22	2	2	3	4	4	4	6	6	7	7	8	8				
SHRINKAGE CAVITY	2.1	1	N/A	2	N/A	2	N/A	3	N/A	4	N/A	5	N/A				
SHRINKAGE SPONGE	2.2	1	2	2	2	3	3	4	4	6	6	7	7				
FOREIGN MATERIAL LESS DENSE	3.11	1	1	2	2	2	3	3	5	4	6	5	7				
FOREIGN MATERIAL MORE DENSE	3.12	1	1	2	2	3	3	4	4	5	5	6	6				

*ASTM E 155 Reference Radiographs N/A—Not Available (1) Former designations shown in parenthesis

TABLE II—FREQUENCY LEVELS

Frequency Level**	Radiographic	Penetrant
1	100%	100%
2	See Table III	See Table III
3	Foundry Control	
4	Visual Inspection Only	

** Differing frequency levels for radiographic and penetrant inspection may be negotiated.

TABLE III—SAMPLING PLAN

Lot Size†	Sample Size	Acceptable Number	Rejection Number
2—50	2	0	1
51—500	8	1	2
501—Over	13	2	3

† Unless otherwise specified, a lot shall consist of all castings of a specific design of one alloy produced at one facility by the same production technique and submitted for inspection at one time.

Figure 1. Aluminum Association Standard

FRAME OF REVISED NUMBER	Test Name	Test No.	TABLE OF TESTS				Engineering Specification		
			Product Validation		In-Process IP-1			In-Process IP-2	
			Minimum Sample Size	Statistical Acceptance criteria	Minimum Sample Size	Statistical Acceptance criteria		Minimum Sample Size	Statistical Acceptance criteria
3 12 D7 Pmg ES-F99SC-5A969-AA	Casting (D2)								
	Visual Inspect.	III-D	100%	No Defects	100%	No Defects	100%	No Defects	
	Fluorescent Dye Penetrant for Surface Defects	III-E	100%	Figure IV ASTM E165 (Method A)	100%	Figure IV ASTM E165 (Method A)	1/ hour Each Cavity	Figure IV ASTM E165 (Method A)	
	Radiographic Inspection	III-F	100%	All Pass AMS 2635 see Fig. V	1/Hour Each Cavity	All Pass AMS 2635 see Fig. V	2/shift Each Cavity	All Pass AMS 2635 see Fig. V	
	Process Controls (See Control Plan)	III-G	30 pcs. from a minimum 250 pc. run	± 4 sigma	5/Batch or Lot	X Bar & R	5/Batch or Lot	X Bar & R	
	*Data reduction techniques for calculating reliability values are contained in Section IV.								
	PE K8555 specKnA12 11-17-89								

Figure 2. ES Standard for Early Aluminum Rear Knuckle

Further work was taken to improve and refine these inspection techniques, including a USCAR/USAMP effort to quantify the ASTM E155 standard used to evaluate the measurement of discontinuities. This can be seen in Figures 3-5, which is taken from the USCAR USAMP

Light Metals Division Project 110 Design and Product Optimization for Cast Light Metals. These figures and tables were prepared by LLNL.

Table 5.4. Discontinuity Analysis Results for Gas Holes - ¼ inch (6.35 mm)

Grade	Projected Area (mm ²)	Maximum Dimension (mm)	Effective Depth (mm)	Depth / Section Thickness (%)	Volume (mm ³)	Volume Fraction* (%)
1	1.0	1.4	0.7	11	0.7	0.004
2	3.9	2.6	1.0	16	3.9	0.025
3	8.2	3.9	1.1	18	9.2	0.058
4	10	4.0	1.7	27	18	0.11
5	14	5.0	1.6	26	23	0.14
6	20	6.1	1.7	27	34	0.21
7	52	11	1.6	26	86	0.54
8	72	12	2.2	34	157	0.99

* Sample size 50 by 50 mm (2 inch x 2 inch) by 6.35 mm (0.25 inch) thick

Figure 3. Table from USAMP DPO report

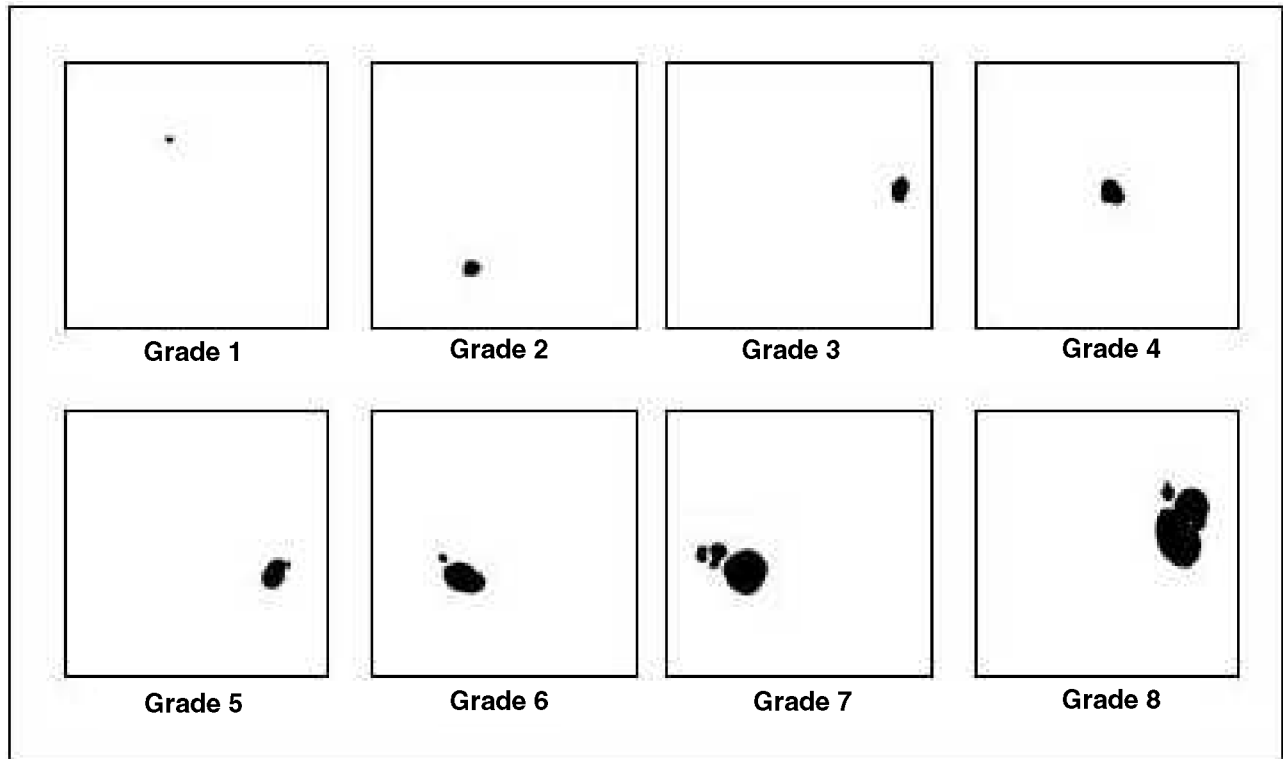


Figure 4. Reproduction of digitized radiograph of ASTM E155 in figure 5

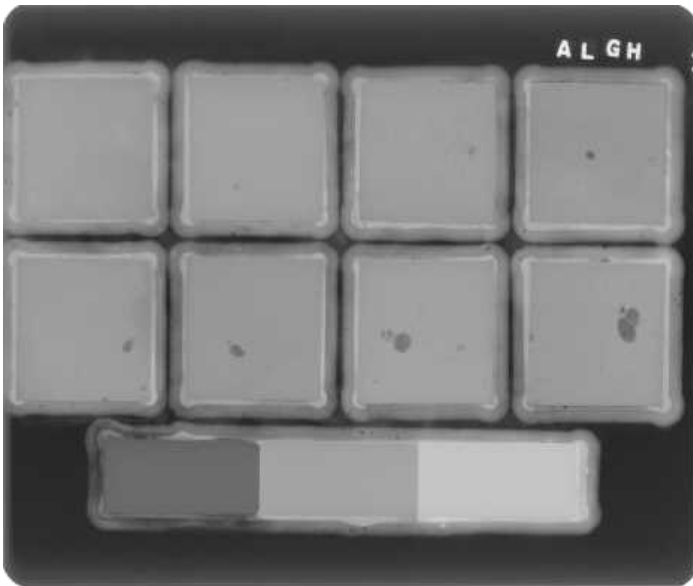


Figure 5. Digitized Radiograph of ASTM E 155 hardware for Al Gas Holes – ¼ inch showing sample array and step wedge

The ASTM E 155 Radiographic standards were digitized by Lawrence Livermore National Laboratory (LLNL) and image analysis conducted to quantify the various defect categories. These results of this analysis are starting to be incorporated into some customer standards and are being used by some NDE equipment manufacturers and casting producers as a basis for acceptance criteria. This is often integrated into some form of ADR (Automatic Defect Recognition) system that evaluates a radiosopic image.

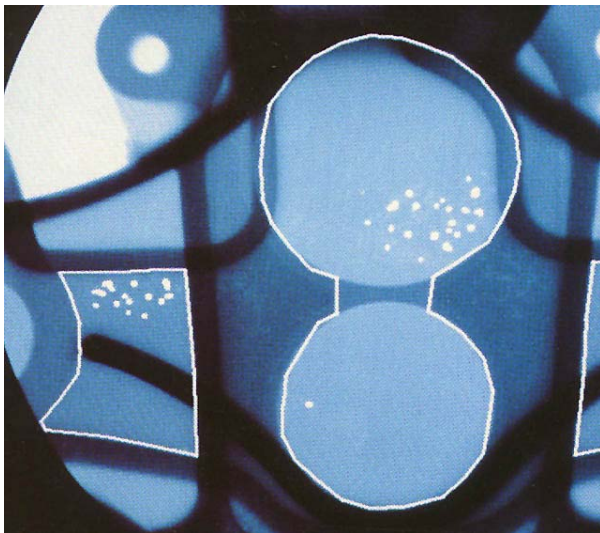


Figure 6. Radioscopic image with ROI (Region Of Interest) drawn and defects highlighted in white

These systems evaluate the gray scale part image to determine part feature compared to an anomaly and then determine the size features (size, area, aspect ratio) of these anomalies compared to accept/reject criteria in a look-up table. While these automated inspection systems have greatly enhanced the reliability

and productivity of radiosopic casting inspection, they have not increased the level of assurance of part quality at the customer to 100%. To move to the next level of PTC (Protect The Customer), an approach is needed that is not based upon a singular test for a specific attribute or “indication”, but one that is more closely related to predicting part performance in service.

RESONANT INSPECTION APPLIED TO CASTING NDT

The key to predicting in-service performance is implementing a test that is based on the structural integrity of the whole part rather than the presence of an “indication” in a particular area. The most promising technology for such a test is RI – Resonant Inspection, which is based on measurement of the resonant frequencies of a part. Resonances offer three advantages for casting NDE.

1. A part’s resonant frequency is determined by its elastic modulus, density and dimensions: parameters that correlate directly to yield strength.
2. Resonance is a whole-body phenomenon so a single measurement can detect defects at any location throughout the part.
3. A resonance test is fast and the result is quantitative so it provides immediate feedback for process control.

Against these advantages there are certain limitations that must be addressed in implementing RI. This discussion will consider RI advantages and present the approach to addressing the limitations.

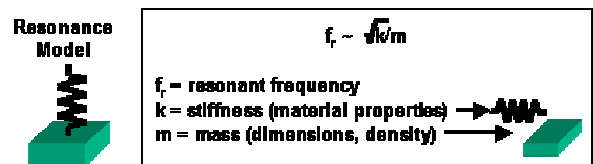


Figure 7. Resonance Model

RI works by measuring a casting’s vibrational resonances. Figure 7 shows the generally accepted physical model of resonance – a mass hanging from a spring. The model shows why RI is so powerful. The mass vibrates up and down at its resonant frequency, which is proportional to the stiffness divided by the mass. Any casting has an infinite number of resonances, each determined by a specific combination of material properties and dimensions.

The frequency of each resonance is determined by the same parameters that determine a defective part: the elastic properties (stiffness), the dimensions, and the density. Other NDT techniques measure parameters that are only analogous to part defectiveness. For example, eddy current measures the electrical impedance, which may change in the presence of a defect, but impedance

itself has no relevance to the part function. Similarly, FPI visually surveys the surface of a part for physical discontinuities, but these discontinuities do not always correlate to the presence of significant structural degradation.

Using the equation, one can see that a defect that reduces stiffness (a crack, for example) will cause the resonant frequency to shift down. So there is a quantitative mathematical relationship between the severity of the defect (in terms of the reduction in stiffness) and the size of the frequency shift.

Figure 8 shows a portion of the spectra obtained for a connecting rod in its original condition (Good1), as it was cut to simulate the effect of a typical crack (Bsmall1) and further cut to simulate a gross crack (Blarge1). This illustrates how the change in the stiffness of the part (caused by the cut) shifts the frequency and how the size of the shift is proportional to the severity of the defect.

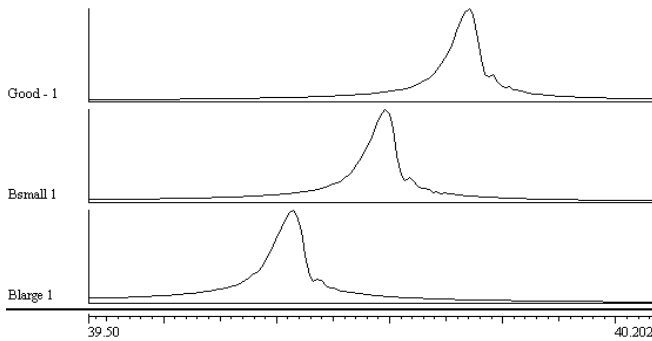


Figure 8. Defects Shift Resonant Frequency

NEED FOR PROCESS COMPENSATION

If this were the whole story, all metal casters would have adopted RI 50 years ago, when it was first introduced. Unfortunately, the changes in stiffness that shift the resonances can also be caused by acceptable process variations. Figure 9 illustrates the relative frequency shifts caused by defects and process variations. It repeats the con rod cutting experiment shown previously for three rods, all the same part number but taken from three consecutive production lots.

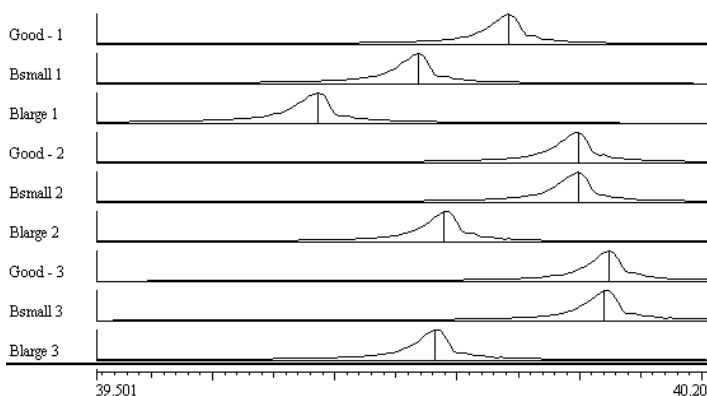


Figure 9. Process Variations also shift Resonant Frequency

Note that while the effect of the cuts on resonant frequency of each rod is similar, the frequency of the good rods varies more due to production variations than the effect of the cuts. So, the frequency of the good rod #1 is lower than the frequency of rod #2, even when a large defect is introduced into #2. So it would be impossible to detect the presence of even these large defects using frequency shifts alone.

Figure 10 summarizes the relationship between defect severity and frequency shift and compares these shifts to the range of acceptable process variations seen in typical production. Qualitative assessments are also provided based on the degradation in Yield strength. The severity data is taken from the work of Emerson.

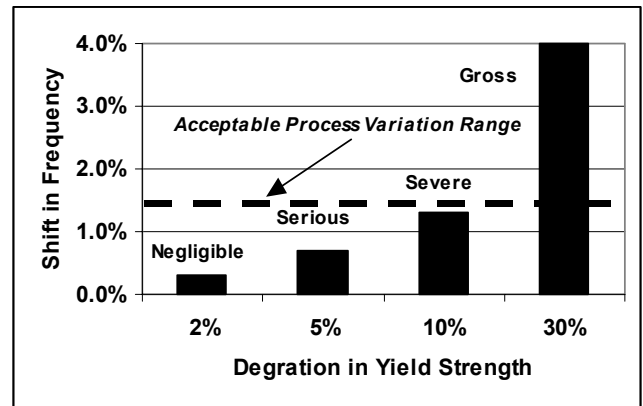


Figure 10. Summary – Defects vs. Variations

The defects that manufacturers are typically concerned with for NDE (because they are not obvious, but significantly reduce Yield strength) cause shifts in the 0.2% to 2% range. Small defects (which generally do not affect serviceability) cause shifts less than 0.2%. The dashed horizontal line shows the range of frequency shifts caused by acceptable process variations in material properties and dimensions. This data is based on measurements on approximately 300 aluminum knuckles. Nearly all castings show acceptable ranges of about 1.5%.

This illustrates why the many foundries that have been using resonance testing for years have only been able to detect grossly defective parts. The shifts caused by the normal production variations are larger than the shifts caused by all except the largest defects. To make resonance testing useful in the factory, a method is needed to compensate for the normal production variations.

PROCESS COMPENSATION RESONANT INSPECTION

The process variations mask the defects because they both arise from the same source – the dependence of the resonant frequencies on dimensions and material properties. This is the problem, but it is also the key to the solution. It means that it is theoretically possible to

work backwards and compute the effect of the production variations based on the relationships among the resonances.

This is illustrated in Figure 11, which shows a portion of the resonance spectrum containing two resonances for 4 good and 4 defective (bad) control arms. Note that it would be impossible to discriminate between the good and bad parts using either resonance because the resonances shift significantly (0.7%) due to process variations. However, the separation between the resonances is larger for the good parts than for the bad parts, even though the resonances move with production just as shown for the con rods. So we have a technique for detecting defective parts, even in the presence of significant production variation.

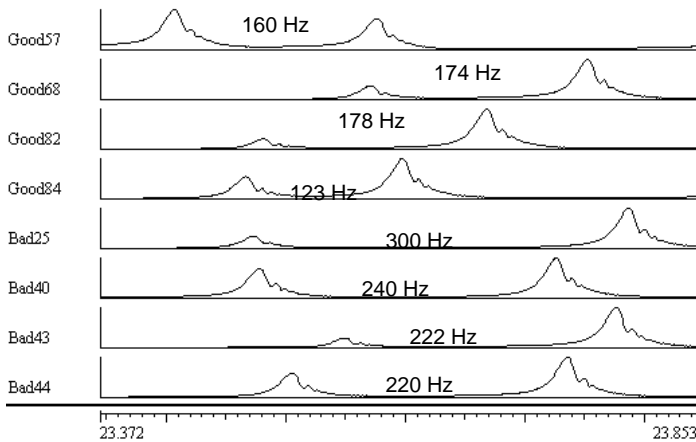


Figure 11. Two Resonances for Good and Defective Parts

This technique works because while both resonances are affected by some underlying process variable (for example, length), one of them (known as the Diagnostic resonance – the lower frequency resonance in the case shown here) is also affected by the presence of the defect. So when a defect shifts the Diagnostic resonance to a lower frequency, it moves further from the other resonance, even though they are both shifting with the process variation.

As a result, even though the resonances of the good parts are shifting due to process variations, measuring the difference between the 2 resonances compensates for that variation and allows the defects to be detected. In effect, the compensation consists of “predicting” where the Diagnostic resonance should be for a good part based on the frequency of the other resonance. If the resonance is not at the proper frequency, the part is defective.

This illustrates the fundamental concept behind Process Compensated Resonant Inspection (PCRI) developed by Quasar International. It builds on the concepts illustrated in the 2-resonance example but it is expanded to handle multiple sources of variability, so it is multi-variable compensation. (Variables are defined here as changes in a part’s material properties, dimensions or density.)

Mathematically, the compensation is governed by the following equation.

$$f_d = A * f_1 + B * f_2 + C * f_3 + D * f_4 + \dots + \Omega$$

Where: f_d is the Diagnostic frequency; A, B, C, etc., are coefficients; $f_1, f_2, f_3,$ etc., are resonant frequencies; and Ω is a measure of the uncertainty in the compensation.

To apply this general equation as an effective NDT test for a specific part, one must: determine the minimum number of resonances required, identify those resonances, and compute the coefficients A, B, C, etc., in the equation so that the Compensation Window - Ω , is minimized for good parts and maximized for defective parts.

In practice, PCRI uses pattern recognition algorithm to compute the compensating relationship based on the statistics of a training set of good and bad parts. The program combines two powerful statistical techniques.

- The MTS (Mahalanobis – Taguchi System) develops a mathematical relationship based on the resonance patterns of the good parts.
- The Bias (formally called a Quadratic discriminator) develops a relationship based on the patterns of the bad parts.

The resulting patterns can compensate for about 90% of the production variation. This reduces the 1.5% process variation inherent in the casting process to an effective variation on the order of 0.2%. Referring back to figure 10, this makes it possible for PCRI to detect virtually all structurally significant defects.

Figure 12 shows how PCRI works. A simple 2-resonance example (similar to that shown in figure 10) has been chosen to illustrate the method.

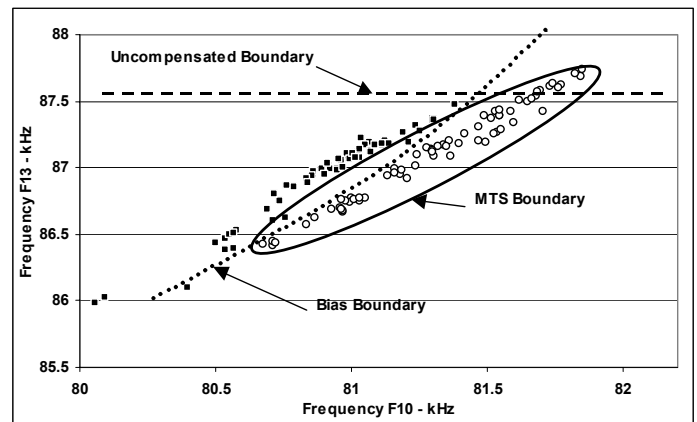


Figure 12. Pattern Recognition Example

The vertical axis is the measured frequency of a nominal 87 kHz resonance for a sample of 140 rocker arms from 15 production lots. It is designated F13 because it is the 13th resonance in the database. The circles are good parts and the squares are bad (defective) parts. Note that using uncompensated RI to measure the shift in a single resonance, rejecting all of the bad parts would reject all parts with resonances below about 87.5 kHz, as indicated by the dashed line. This would also reject most of the good parts, so it is not feasible, but it is the type of result generally obtained with uncompensated RI.

The horizontal axis is the frequency of another resonance F10, used with F13 to compensate for the process variations. As seen from the fact that the data points follow a reasonably straight line, the two resonances are mathematically correlated. The chart also shows a definite separation between the good and bad part populations. This is the separation that PCRI discovers and exploits.

The MTS boundary (the ellipse) is superimposed for illustration. All parts outside the MTS boundary are rejected. As seen, this rejects the majority of the parts. However, there are a few bad parts (those with smaller defects) that fall inside the MTS boundary. The Bias boundary (the dotted line) rejects these remaining bad parts. Thus, the PCRI pattern accepts all of the good parts and rejects all of the bad parts – the Perfect Sort.

Note, that this is a very unusual set of parts that can be sorted with only two resonances. This implies that the defects are fairly severe. Generally PCRI uses 5 to 10 resonances, but this is impossible to illustrate in a two dimensional presentation.

TYPES OF DEFECTS

PCRI rejects parts with significant structural defects. For aluminum and ferrous casting operations this includes:

- Localized defects – including shrink porosity, cold shuts, hot tears, inclusions, foil, cracks and runout
- Metallurgical defects – wrong alloys, gas porosity, nodularity, hardness, carbides and other microstructure variances.
- Mechanical defects – incorrect dimensions or missed operations.

PCRI cannot detect non-structural defects such as isolated sand pits, very small surface cracks or slight non-fill. Likewise it is not sensitive to many types of artificial defects such as EDM notches or small holes drilled into otherwise good parts.

Figure 13 illustrates the application of PCRI to ductile iron brake anchors. It is a plot showing the distribution of relative part quality score (negative scores indicate good parts). The sample included four defect types: nodularity, carbides, cracks, and shrink. The dots represent the good parts and the crosses are the bad parts. The

vertical cursor is the accept/reject cutoff. Due to the geometrical complexity of the anchor, the sorting equation required 8 resonances.

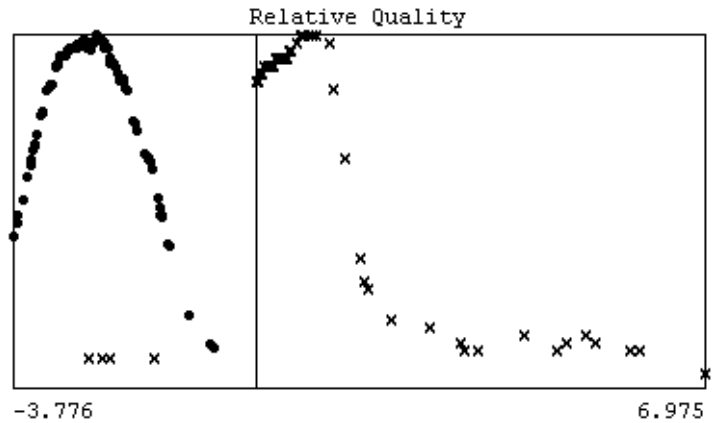


Figure 13. PCRI Parts Quality Plot

Note that the distribution of good parts (on the left) is a close fit to a normal curve. This would be expected given typical process variations.

Also, note the presence of several misclassified “bad” parts. These are parts that were rejected by magnetic particle (MPI) but were accepted by PCRI. This is a not uncommon occurrence in starting up a PCRI system. Referring back to figure 10, these are parts whose defect, while visible to the MPI inspector, is not structurally significant. Experience with other parts has shown that their Yield strength is similar to that of many of the good parts.

This misclassification problem arises because although PCRI is a superior NDE method, it depends on other, more subjective methods to provide the training sample that it uses to develop the sorting pattern. Incorrect part classification can significantly degrade the pattern because the program is searching for meaningless differences. It is critical that some structural test method be available to validate the part classification when PCRI suggests that there may be a problem with the training set. The most reliable validation method for this is destructive testing using a test with quantitative results that correlate with the part’s intended use. The need for validation testing is particularly critical when it is necessary to use artificially created defects.

PCRI CORRELATION TO DEFECT SIZE

When initially exposed to PCRI, many people with an NDE background ask, “what size defect can it detect”? The answer that it “detects defects that significantly degrade the part’s structural integrity” is not consistent with their historical focus on defects, as opposed to defective parts. An experiment was performed to provide a relative answer to the question.

It is important to recognize that the effect of a defect of a given size on a part’s stiffness, and on its Yield strength, depends on the size of the defect relative to the cross-

sectional area. So a 2 mm defect in a 20 mm² area is much more significant than the same defect in a 100 mm² area.

A set of 30 aluminum housings was cast to evaluate PCRI sensitivity to defect size. Fifteen of the housings were good and the process was modified for the other 15 to create shrink porosity defects. The resonant frequencies were measured for the housings and they were then sectioned for metallurgical evaluation. The metallurgist ranked each housing in terms of relative acceptability.

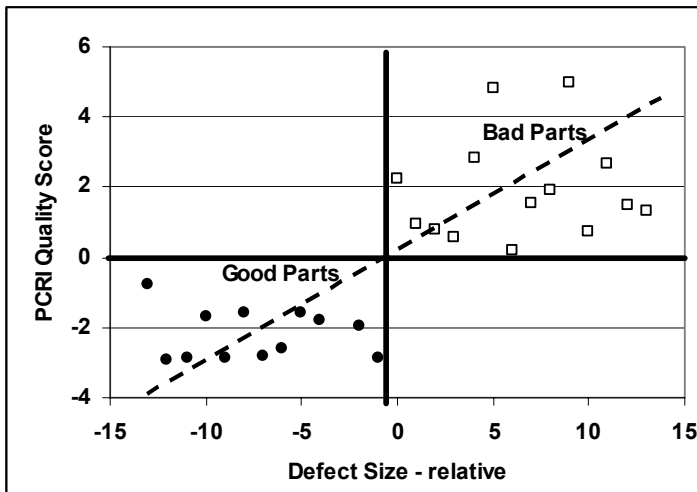


Figure 14. PCRI Score vs. Defect Size

Figure 14 compares the PCRI relative quality score (vertical axis) to the acceptability score in terms of relative defect size (horizontal axis). The vertical cursor is the accept – reject cutoff for acceptability and the horizontal cursor is the cutoff for PCRI accept – reject. The dashed line is a visual “best fit”. As seen, the accept – reject decisions made by the two methods agree perfectly. PCRI was able to detect all of the defects that the metallurgist judged would create an unacceptable part. There is considerable scatter in the “best fit” and this is due to the fact that many of the defective parts also had a flow line defect that was not included in the acceptability rating.

CONCLUSION

The casting industry has expended considerable time and resources in adapting aerospace NDE techniques to automotive requirements. PCRI is optimized for the high volume 100% inspection environment by the use of advanced software and hardware created for the automotive parts production industry. It has been shown to be much faster and more economical than most traditional methods. Since the resonances measure the parameters that determine a casting’s service performance (stiffness, dimensions and mass in all regions of the casting) it is often a better alternative to techniques that attempt to infer quality from visual assessments.

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CONTACT

Thomas E. Prucha is Vice President, Technical Services for INTERMET Corp. He can be reached at:

INTERMET Corporate Offices
5445 Corporate Drive Suite 200
Troy, MI. 48098
email: tprucha@intermet.com
website: www.intermet.com

Robert Nath is Chairman of Quasar International Inc. He can be reached at:

Quasar International, Inc.
2704 Yale Blvd. S.E.
Albuquerque, NM 87106
phone: (505) 247-9660
fax: (505) 247-9666
email: nath@quasarintl.com
website: www.quasarintl.com