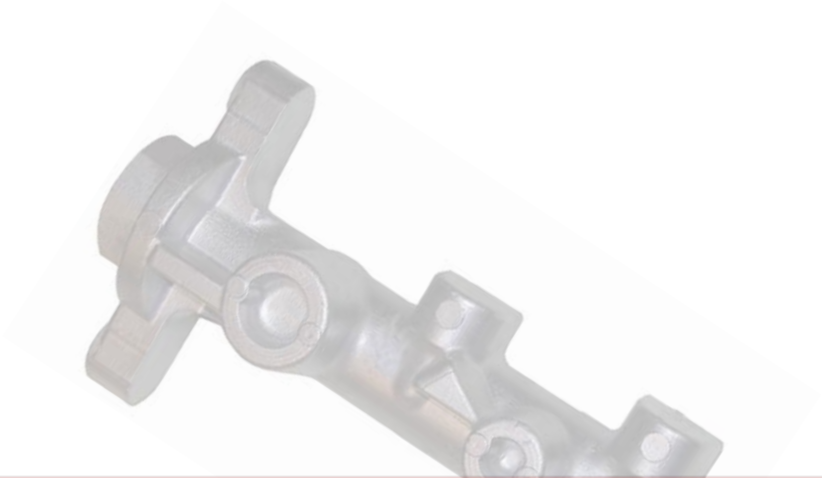
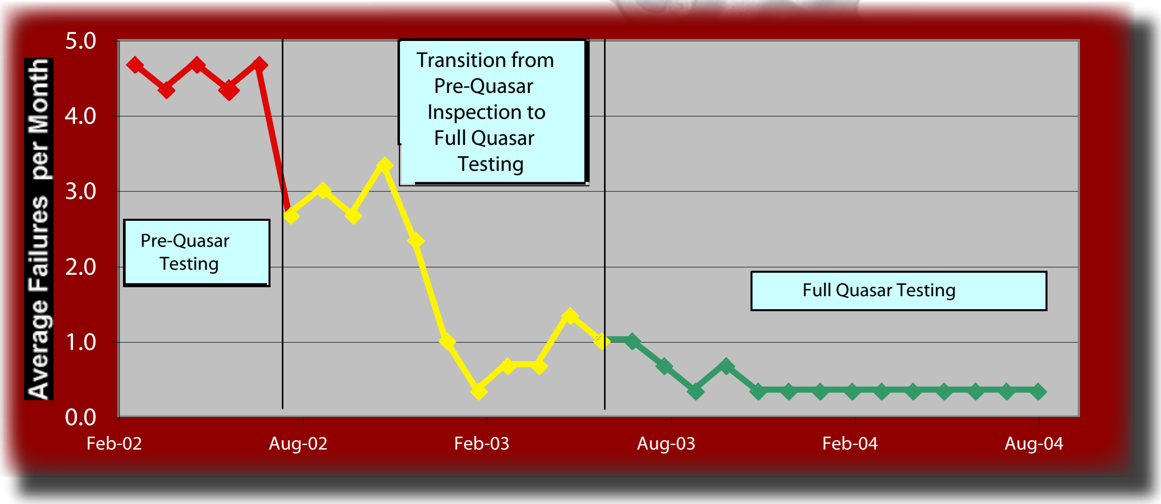
QUASAR
INTERNATIONAL, Inc.

Quasar Process Compensated Resonant Testing:

Principles of Operation





Quasar International, Inc.
5550 Midway Park Pl. NE
Albuquerque, NM 87109

Phone: 505 247-9660
Fax: 505 247-9666
E-mail: info@quasarintl.com
http://www.quasarintl.com

Process Compensated Resonant Testing – How it Works and Why It Is Needed

– Introduction –

What Will this Paper Tell You?

This document describes Quasar's Process Compensated Resonant Testing (PCRT) and how it is used to provide 100% testing of automotive and related metal and ceramic parts with nearly perfect classification. The Quasar testing directly correlates with structural integrity of the parts, and therefore directly addresses one of the key concerns of parts manufacturers: How can you detect and separate those parts which are likely to experience field failures from those parts that are not – before the parts leave the factory and with utmost confidence? Additionally, how can Quasar testing accomplish this with an average cost per part of about 10 times less than other methods, such as Magnetic Particle or dye penetrant?

This Paper is Intended to be Readable at All Levels of Technical Expertise

Even though Quasar testing contains many programming, math, and physics concepts, we work to make the system easy to operate. Equally important, we write our descriptive material so that it is conceptually easier to understand, too. We do not believe you should need a degree in physics to understand the principles of Quasar testing. Should you have any questions after reading this, Quasar staff is available to help*.

Why Should You Read this Paper?

You should read this paper to understand the basic concepts and implementation requirements of Quasar testing. Quasar testing has evolved over a number of years to be a robust, nondestructive test method that significantly outperforms all other methods on the factory floor for essentially all part types that resonate.

What Does this Paper Address?

We start with a basic look at how Quasar testing works. This begins with a model of what happens at the microscopic scale when a hard (generally metal or ceramic) substance is caused to vibrate. This leads to an explanation of what resonant frequencies are and how they come into being for any given part.

We then discuss how these resonances change in frequency when the structure is changed due to such things as a crack or inclusion. This includes a look at some actual data showing how the effect works.

Next, we briefly discuss some of the mechanics of how Quasar testing works. This includes parts placement, data collection, and software used to sort parts.

Next, we address how data are obtained for Quasar testing purposes, why uncompensated resonant data from impulse excitation is inadequate, and how the "Process Compensation" actually occurs. This is the key feature that distinguishes Quasar from other nondestructive resonance-based test methods and allows the nearly perfect results that we obtain.

We will briefly address the system startup procedures so that your theoretical knowledge and understanding of the process will be reinforced by descriptions of the applications of this theory.

When You Are through Reading This Paper, What Should You Know?

After you have read the following, you should be able to understand the fundamentals of how Quasar testing works and why it is becoming accepted as the method of choice for testing parts before shipment to avoid parts' field failures. The cover of this paper shows an example of Quasar testing based on performance data from a factory that changed from the older methods of parts inspection to Quasar testing. The graphic tells the story. Quasar testing works. Now, you can proceed to learn how.

---

* Phone 505 247-9660 and ask for technical assistance, or e-mail info@quasarintl.com.

Correlation Of Quasar's Process Compensated Resonant Testing To Structural Integrity

The way PCRT works and how it correlates with structural integrity can be understood with a molecular model based on the physical elements that actually determine the mechanical characteristics of a material. In fact, the essence of this model forms the basis for determining a material's elastic properties used for parts' design purposes (such as Young's Modulus, Shear Modulus, Poisson's Ratio, etc.). Note that elastic properties have been shown to be correlated with mechanical properties, such as tensile strength, and yield strength. The model itself provides insight into how material resonances are determined by elastic properties, and very specifically how material **flaws that adversely impact mechanical properties cause resonances to change**.

Figure 1 shows a lattice of atoms. Each atom has a certain mass, and all are connected by small springs (atomic bonds), each with a specific spring or stiffness constant. Only two dimensions are shown, but one can conceptualize parallel layers of these lattices, all of which are connected to each other by springs. This is analogous to a material (metal) that can resonate. If the lattice is pushed into the page with equal pressure on the face and suddenly released, then the lattice will resonate at some fundamental frequency (longitudinal). If it were to be pulled out of the page on one edge and pushed into the page on an opposite edge, it would resonate in a different form, or mode at a different frequency (shear). In fact, there are a number of different motion shapes (called modes) with which an object can resonate, e.g., twist it and release, squeeze it from all sides and release, etc. Additionally, there are an almost infinite number of frequency "overtones" that can be "excited" for any given resonant mode. The frequency at which each resonant mode and overtone occurs is directly related to the spring stiffness, divided by the mass of the atoms, and of course, the shape or geometry of the object. (See the sidebar on the next page that graphically illustrates the resonant mode concept for a parallelepiped and provides more detailed information about this topic.)

This simple model shows why resonant testing is so powerful. The frequency of each resonance is determined by the same parameters that determine a structurally acceptable part – the elastic properties (stiffness), the geometry (dimensions), and the density (mass). Change in any of these will change some, or all of the resonant frequencies. In particular, if a defect is introduced (crack, oxide, etc.), the net stiffness changes, and a resonant frequency change occurs.

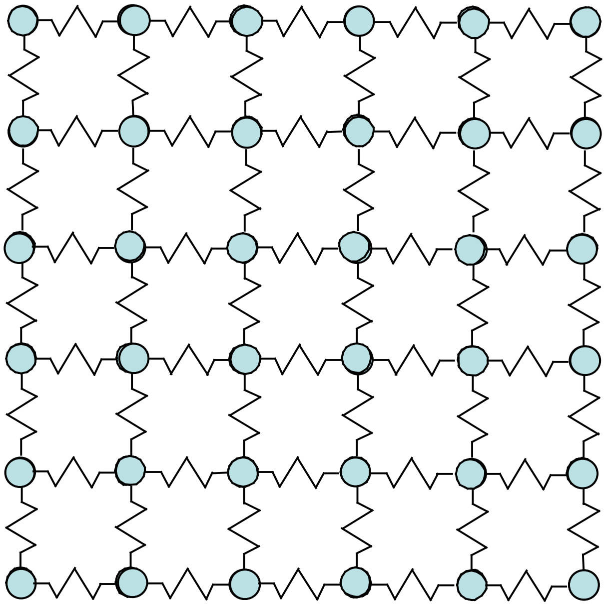


Figure 1. A lattice of atoms connected by "springs," an analogy for covalent/ionic bonding in metals. This example represents a perfect matrix, without a defect.

To visualize how a change in structure will change a resonant frequency, consider Figure 2 (next page). It is the same molecular matrix as is shown in Figure 1, but it now has two defects. One (red) is like a crack and the other (blue) is like an inclusion. The presence of either of these two defects will cause the molecular matrix to resonate at different frequencies, depending on the mode, or motion type and direction. If the stiffness changes, the resonant frequency changes. This is the key to how Quasar testing works.

Please note that this example is at the molecular level, and we must acknowledge that real metal parts are not simple crystals. They are composed of aggregate crystals and other materials. However, macroscopically, their mechanical characteristics are an "average" of their microscopic characteristics, and all the above principles still hold for PCRT. *Other NDT techniques*

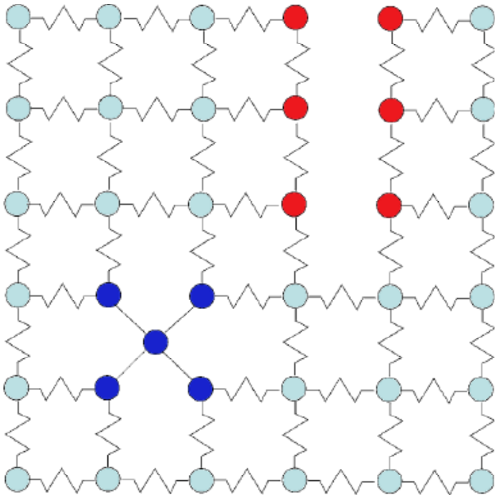


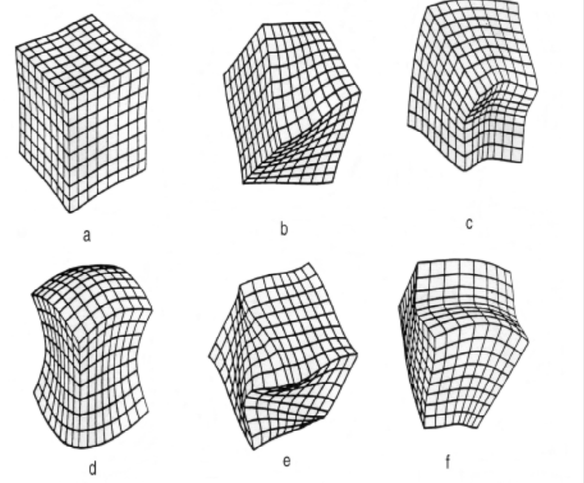
Figure 2. Atom lattice with defects.

measure parameters that are only analogous to part defectiveness. For example, eddy current measures the electrical impedance, which may or may not change in the presence of a possible defect, but impedance itself is not indicative of a part's functionality.

For structural performance, the primary relationship of interest is between a part's mechanical performance degradation (measured by Break Force, Yield Strength, etc.) and resonant frequency patterns. While a part's elastic properties are determined by its material, its potential for functional degradation also depends on the geometry and dimensions (e.g., a part's strength in tension increases as its cross sectional area increases). So degradation vs. frequency can be measured for a specific part/loading configuration. The presence of structural anomalies or discontinuities such as inclusions, cracks and voids degrades the mechanical performance of the part by interrupting the structural integrity of the bulk material and also changing the effective elastic properties of the entire part.

The graph shown in Figure 3 (next page) shows the results of an experiment to measure the Break Force versus frequency relationship for a group of powder metal exhaust flanges. These flanges were subjected to a bending force with increasing depths of cuts for each of the parts. The experimental data show an excellent quadratic fit agreeing with theoretical predictions which illustrates the ability of the resonant frequencies to predict failure level. As the part's strength is degraded (by increasing the size of a cut that was made to simulate the effect of a crack), the resonant frequency decreases. The shift in resonant frequency is roughly 10% of the degradation

What is a Resonance?



This series of illustrations amplifies on the discussion of modes and resonances associated with Figure 1 in the text. For the mode – or motion shape – associated with the cube labeled "a," one can see that by pushing on the center of each face of the cube and simultaneously releasing, the cube faces will oscillate in and out from the cube's center. This will occur at a frequency of oscillation that is determined by the cube's stiffness, mass, and dimensions.

Looking at the "b" cube, it can be seen that this motion can be caused by holding the cube by opposite faces, twisting in opposite directions, and releasing both faces at simultaneously. The resultant motion occurs about the axis connecting the opposite faces and is called the torsional mode for descriptive reasons.

Each shape shown in the figure is a unique mode. Note that not all imagined motion shapes can occur as a resonant mode. For a resonance to occur, the motion of all parts must move simultaneously in phase. There are more allowable modes for the cube that are not shown in the figure. Additionally, if the torsional mode for cube "b" occurs at a specific frequency, called the "fundamental," then there are higher frequency overtones that correspond to the same basic torsional motion but with multiple sections along the axis moving in different directions. For example, the 1st overtone of the torsional mode can be "excited" by holding the middle of the cube and twisting opposing ends in the same direction. When let go, the cube will resonate with the two ends rotating in one direction while the middle rotates in the opposite direction, then reversing, and so on. This is still the same mode, but a higher

(continued next page)

in Break Force. That is, a 15% decrease in Break Force causes a 1.5% decrease in resonant frequency for this resonance. This relationship is the basis for a resonance-based NDT method. It shows that the parameter being measured (resonant frequency) has a high correlation to the level of performance degradation that is predicted by theory and substantiated by experiment.

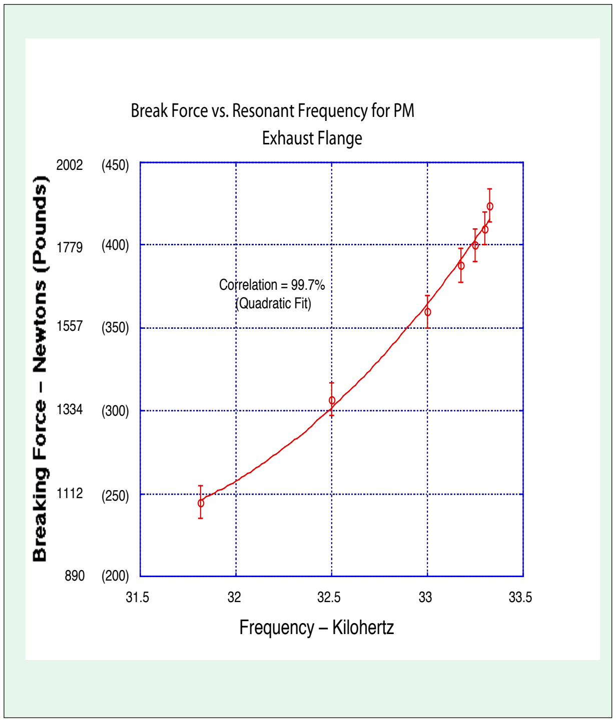


Figure 3. Correlation of Breaking Force (structural integrity) with frequency shift is essentially 100%.

Quasar testing uses multiple resonant frequencies so that normal, acceptable process variations can be accounted for. This is the most important feature that separates Quasar testing from other resonant inspection methods. Quasar testing accounts for normal frequency pattern shifts caused by acceptable variations in dimensions or material properties while also detecting those pattern changes caused by defects. Quasar is orders of magnitude better at finding the killer flaws.

(sidebar continued)

frequency resonance at a higher overtone. If we mechanically drive the cube at this frequency, it will only resonate in this mode. If we change frequency a small amount higher or lower than the 1st overtone of the torsional mode's resonant frequency, the cube will not resonate at all. It will only resonate when it is excited at one of the frequencies that allows it to move in a specific, predetermined manner.

Any change in the structure will cause a change in one or more modal frequencies, and in some cases, a perturbation of a modal shapes. Different modes will be affected differently, as will different overtones of any given mode. So, if there is a crack, incipient crack, inclusion, hole, oxide film, etc., present, there will be a change in resonant frequencies. Some will change more than others for any given type of structural change or flaw.

Generally, a flaw will cause the frequency to shift downward. This occurs because the material is generally less stiff when a flaw is present. This phenomenon is what allows the Quasar test to look at structural changes which are a direct determinant of the resonant frequencies – all fundamental modes as shown in the figure, and all of those fundamentals' overtones. And, since different modes are affected differently for any given flaw type, this also allows the Quasar method to account for process variations while still detecting unacceptable changes in structure by looking at multiple resonant mode and overtone behavior (Process Compensation).

Critical to Quasar testing, identical resonant motion can be induced by exciting the cube sinusoidally at its natural resonant frequencies with a mechanical transducer. Most importantly, it has extraordinary application in the real world. It provides the foundation for Quasar testing of parts and their sorting into structurally acceptable and structurally unacceptable groups.

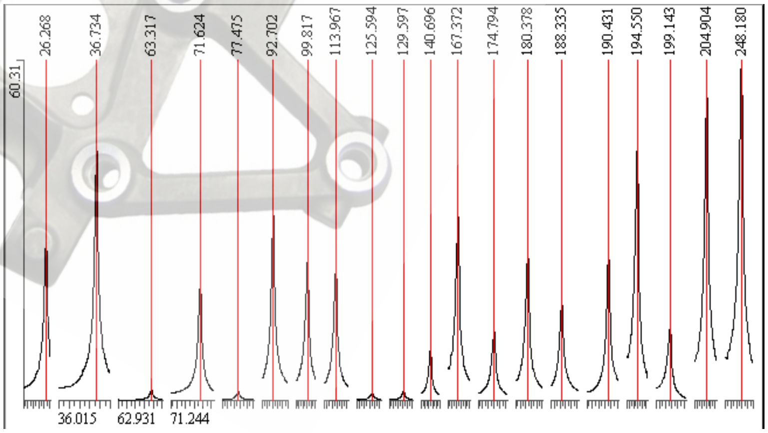
Obtaining Resonant Frequency Data

Conceptually, obtaining a part's resonant frequencies is straight forward. The part is supported by three piezoelectric transducers, one is for driving, or mechanically vibrating the part over a frequency range, and the other two are for measuring the part's response. From a practical standpoint, however, obtaining good, repeatable resonant data over the large frequency ranges needed for the Quasar testing requires highly repeatable part placement on the test station (Figure 4), temperature compensation measurement, and a suite of programs to control the data acquisition and analysis along with the mechanical aspects of the test process.

When repeatable part placement is achieved, a system operator uses the Quasar software to obtain resonant data over a broad frequency range. This is done for a set of parts containing both structurally acceptable and unacceptable or defective parts. A swept continuous wave is used to excite the part. This provides orders-of-magnitude better information to the pattern recognition software (see next section) than would an impulse FFT (Fast Fourier Transform) method. Very special attention is also paid to the selection of a Training Set of parts – both structurally acceptable and structurally unacceptable from different lots are required to reflect day-to-day process variations.

When the data are gathered, the usable resonant peaks are selected semi-automatically, and the data then form the basis for the pattern recognition analysis.

A sorting module is made using the Quasar VIPR (Vibrational Pattern Recognition) program. This program applies pattern recognition techniques using the resonant frequencies selected to allow the software to separate the acceptable from unacceptable parts. When this process is applied to the software used in production, the set of frequencies are measured and based on the pattern for any given part, the part is accepted or rejected. Typically, 3 to 7 resonant frequencies are identified that characterize the part structurally and account for its acceptable process variation. The following describes how this process works to account for process variation – the key requirement for the perfect sorting of acceptable from unacceptable parts.



Many resonant frequencies are measured from which a subset for pattern recognition based sorting is selected by Quasar software.

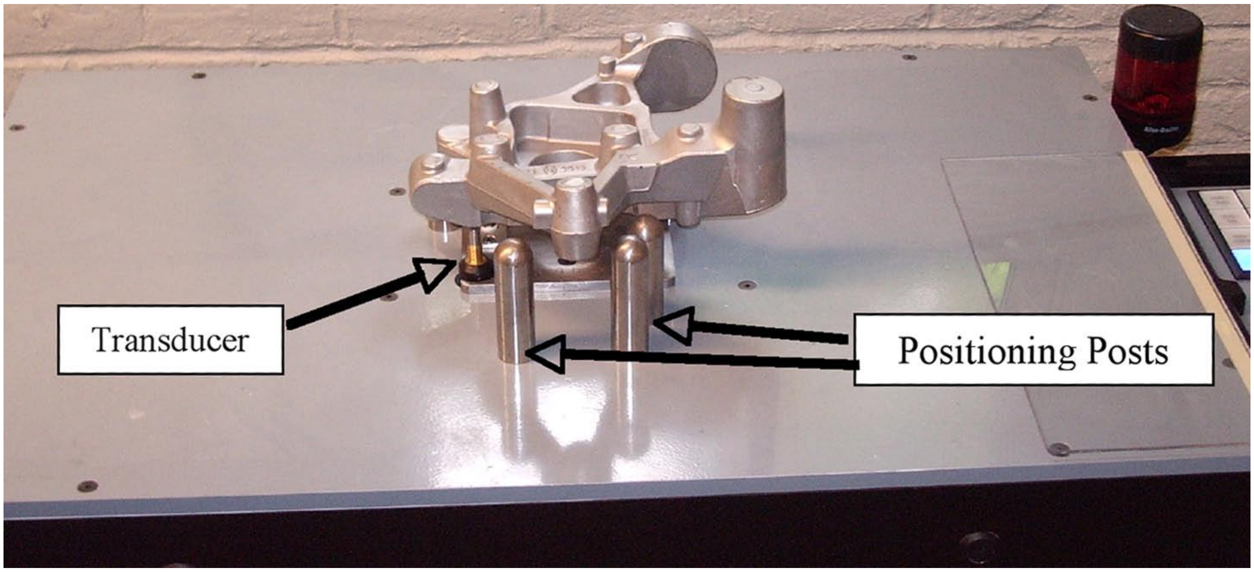


Figure 4. Test station with a steering knuckle in place. Three transducers (one excitation and two receive) are supporting it. (Only one is visible, as indicated.)

Accounting For Process Variations

The resonant frequencies of real production parts are affected by both the presence of defects and by the normal production process variations in stiffness, density and dimensions. These variations cause frequency shifts that are generally larger than the shift caused by all except the most severe defects. Therefore, the process variations tend to mask the defects when only a single frequency shift is used as a test to differentiate between acceptable and rejectable parts.

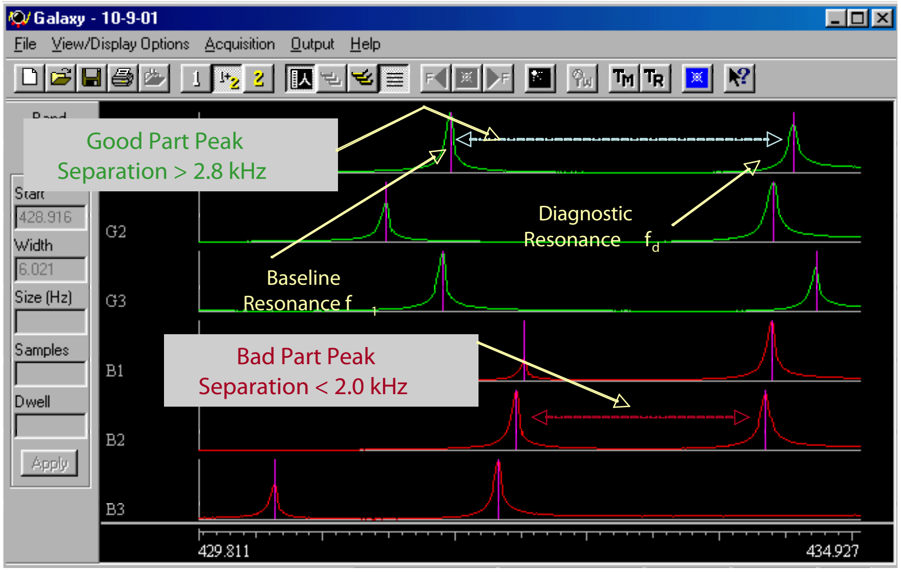


Figure 5. Relative resonant frequency shifts are used to diagnose structural flaws (simplest case of 2 resonances).

Figure 5 illustrates this point. This shows the same resonances associated with 6 different parts – 3 goods (green, top 3) and 3 bad (red, bottom 3). Note that both the left and right resonance for each part are moving in frequency and that the same resonances for the good parts can overlap the resonances for the bad parts. Using a simple resonance shift to determine if these parts are structurally acceptable is impossible. There is simply too much process variation causing the resonances to shift independently of structural flaws. But we know that not all resonances respond identically to a structural defect. If we can find two or more resonances that characterize the allowable process variation, then we can look for other resonances that are diagnostic of structural defects, also.

An example of the statistics of defect masking of the resonant frequency for a set of 200 aluminum master cylinder bodies is illustrated in Figure 6. The good part distribution is plotted in green and the bad part (oxides) distribution is plotted in red. Summary data for the good and bad distributions is provided revealing values that are similar to those observed in many manufacturing processes. The bad parts have a broader distribution – 6% range versus 1% for good parts. The average resonant frequency of the bad parts is also lower. However, the good and bad distributions overlap so there is no way to use these differences for effective sorting. While it would be possible to set a window that would reject many of the most severely shifted unacceptable parts while accepting the good parts, 70% of the bad parts would still be accepted. (It might seem surprising that some of the defective parts have higher resonant frequencies than the good parts. This occurs when the defect, such as porosity or a void, reduces the mass of the part.)

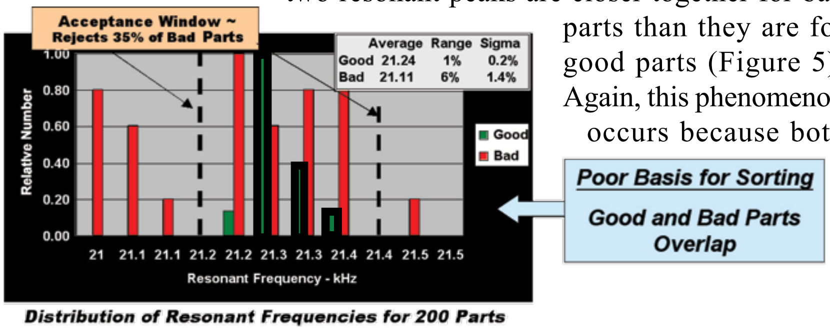


Figure 6. Acceptance window without Process Compensation

The solution to the defect masking caused by process variations is frequency compensation. In some cases, it is possible to identify defective parts because two resonant peaks are closer together for bad parts than they are for good parts (Figure 5). Again, this phenomenon occurs because both resonances are affected by some underlying process variable (e.g., length) and one of them is also affected by the presence of the defect. When a defect shifts one resonance to a lower frequency, it moves closer to the other resonance, even though they are both shifting with the process variation (again, see Figure 5).

As a result, even though the resonances of the good parts are shifting due to process variations, measuring the two resonances and quantitatively comparing the difference provides compensation for that variation and allows the defects to be detected. Most parts are complex enough, however, such that more than two resonances are required to compensate for all the process variation. Fortunately, this concept extends to using multiple resonances by using special pattern recognition software developed by Quasar.

This software program called VIPR (Vibrational Pattern Recognition) first uses a Mahalanobis-Taguchi System (MTS) based pattern recognition algorithm to separate unacceptable parts from acceptable parts. The principle is illustrated in Figure 7. The figure represents a Mahalanobis-Taguchi System pattern grouping (labeled MTS Boundary) in which acceptable parts are contained. To show the concept, only a one frequency pattern predicted and measured can be illustrated. Two frequencies may be visualized, but not drawn clearly. In reality, we never use a one frequency pattern, since that only rejects the grossly defective parts, which is not sufficient for production part testing.

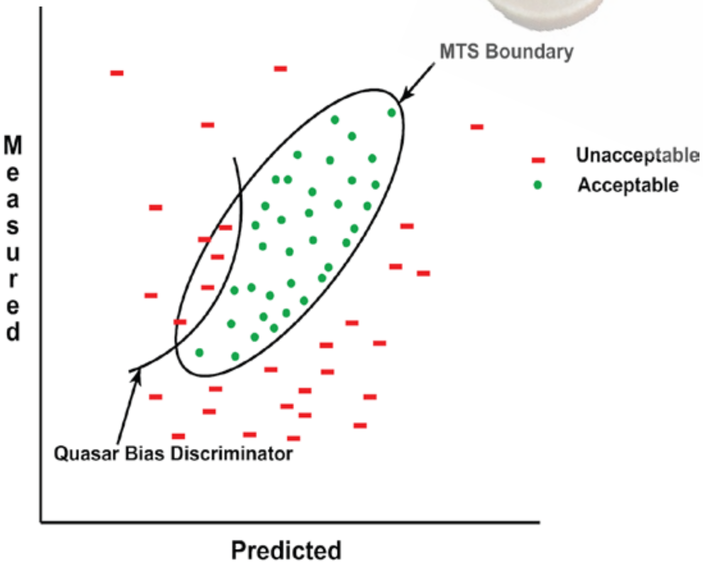


Figure 7. Quasar Pattern recognition uses the general Mahalanobis-Taguchi System and added Quasar innovation of the Bias discriminator to separate acceptable from unacceptable parts

The curve labeled “Quasar Bias Discriminator” is an innovation by Quasar that allows the software to reject unacceptable parts that fall within the Mahalanobis-Taguchi System grouping.

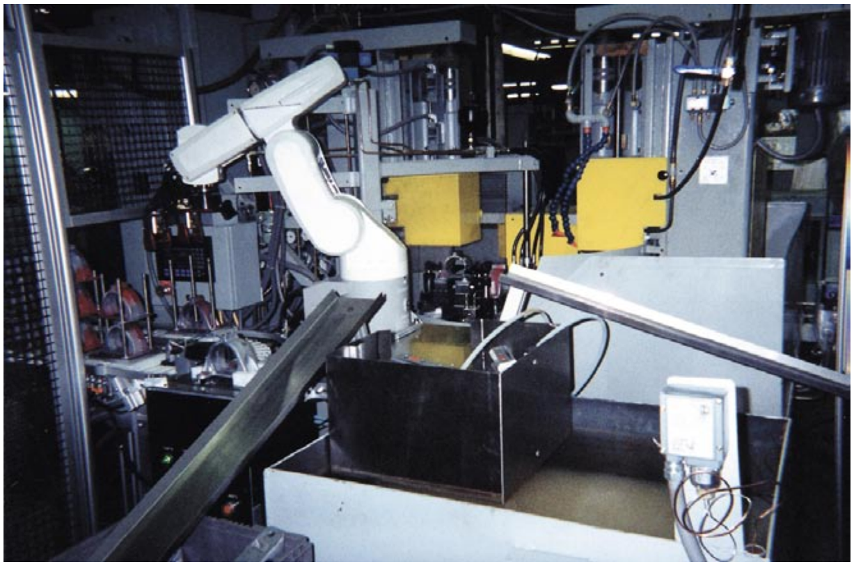
Additionally, the implementation of the pattern recognition program provides for direct correlation between the Quasar score and the degree of structural degradation. This has been demonstrated on a variety of parts, and follows from the pattern recognition math scoring algorithm.

The Quasar NDT method actually quantifies the degree of structural degradation of a part. To do this properly, it must be trained with parts that represent both acceptable structural integrity and with parts that have a known amount of unacceptable structural degradation. When the training parts are correctly classified, then the Quasar test will provide near perfect sorting. However, if the pattern recognition program is given erroneous information, then it will not find a good solution, or sort.

To expand on this very important point, the best way to train the Quasar system is to gather a set of parts with “goods” and “bads” sorted to the best of the gatherers’ abilities. The parts should be taken from different batches, shifts, days, etc., so that normal acceptable production variations are included. Then, broad windows of frequency data containing many resonances are taken for each part, and all the parts mechanically tested to structural failure. Parts that fall below a knowledgeably determined failure threshold should be designated as “unacceptable.” Also, any part that has gross visual failures (e.g., a large inclusion) should also be designated as unacceptable. The rest of the parts should be designated as acceptable. Then, the pattern recognition program (VIPR) can be run using parts that are properly classified. This will guarantee a good sort and proper in-plant operation. Typically, false accepts for structurally bad parts will drop by at least an order of magnitude when Quasar is used properly.

System Startup

On-site system startup typically requires an experienced Quasar Engineer to ensure proper installation and operation. It also requires that one or more factory personnel be trained on how the system operates and how to make appropriate decisions regarding when to add new parts to the Sorting Module database in consideration of acceptable production variations in parts. That is, over time, processes vary slightly, and this needs to be accounted for in the resonant database. After some period of time, the requirement to add new parts will decrease significantly.



Automated System in the factory

There are three options for factory use of a Quasar test system: 1) manually loaded, 2) Quasar supplies parts handling equipment for automated parts loading , and 3) a third party provides the part loading equipment to meet an interface specification. For the manually loaded system, a Quasar field Applications Engineer (AE) will set up the system and assure that the system is operating properly. This often includes adjusting the first Sorting Module. For the case in which Quasar also makes an automated parts placement system, Quasar factory engineers will set this up while the AE responsible for the client performs the normal system setup and Sorting Module development. When a third party is involved with the parts handling, Quasar will work with the parts handling manufacturer based on a predefined interface specification. Quasar will provide assistance to make sure the system is up and running, ready for the parts manufacturer to take over operations.

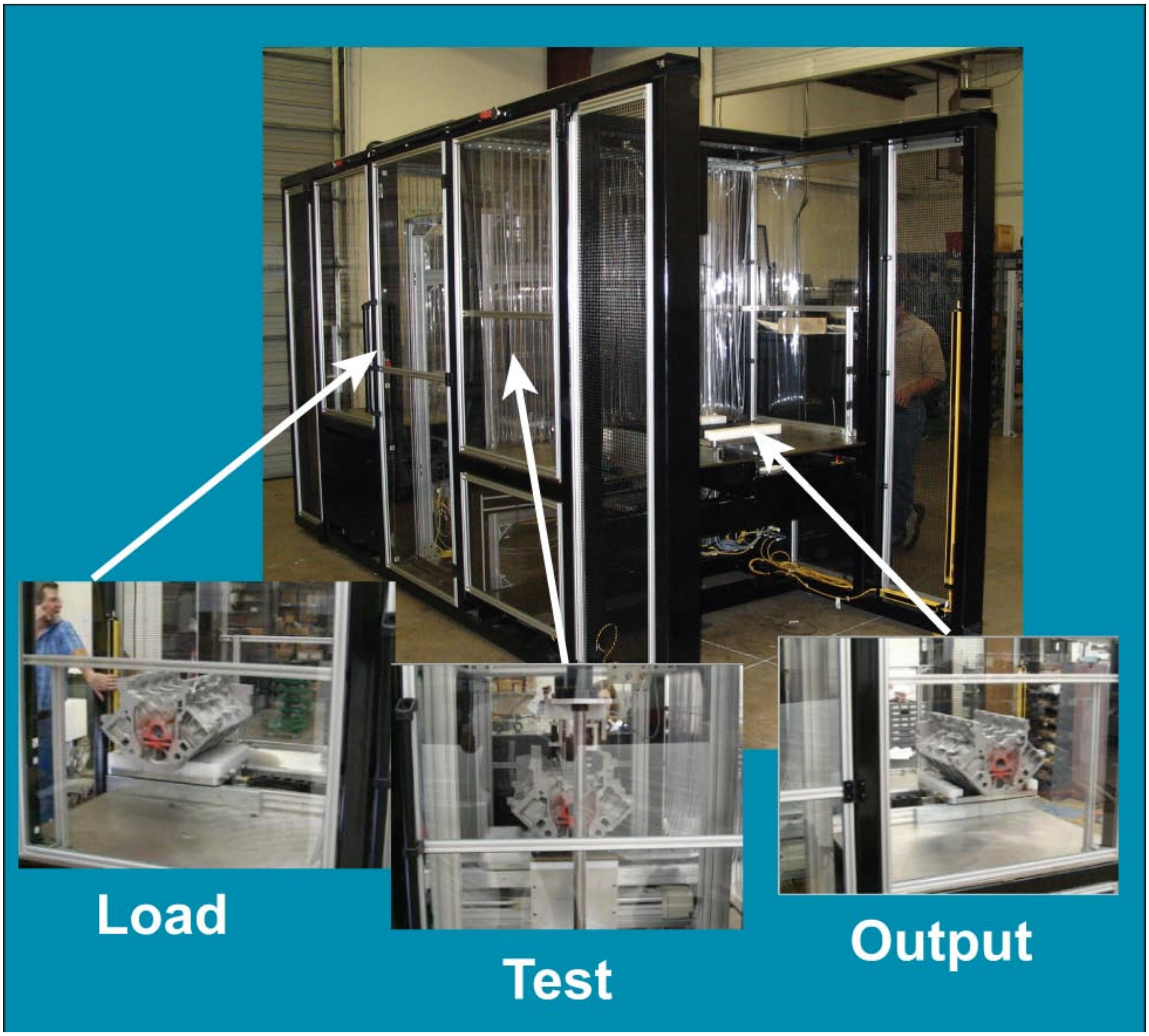
Manually Loaded Quasar System

The graph on the cover of this document illustrates the improvement that was experienced when one company adopted Quasar testing to detect brake master cylinder "leakers" caused by otherwise undetectable, randomly oriented aluminum oxides which allowed a path for high pressure brake fluids to work through to the outside. Only the worst of these are detectable by the older NDT methods. Transition to Quasar testing occurred over a year. The difference is profound when comparing the beginning part failure rate to the failure rate after Quasar was fully in place. This represents typical Quasar testing improvements.

Conclusions

Quasar PCRT offers three major benefits as a direct consequence of superior technology:

- *Quasar testing measures a property (resonances) that is directly determined by, and representative of a part's structural integrity, unlike other NDT methods which rely on "indications." This also allows Quasar testing to look inside the part for potential degradations. It is a whole body, structural test that relates directly to the strength of a part.*
- *Quasar testing is the most effective structural NDT method available for almost all metallic and ceramic parts.*
- *Quasar testing is the least expensive NDT method on a per part basis compared to other methods.*



Quasar "Flex" System designed to test aluminum engine heads, blocks, and forged crankshafts.