WHITE PAPER

Fundamentals of Resonant Acoustic Method NDT

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Abstract

Rapid conversion of machined parts to powdered metal and cast is driving industries, especially automotive. Due to the high expectations of both primary manufacturers and end consumers, defects cannot be tolerated even in million piece quantities. There is, in effect, a growing requirement for zero defect supply chain commitments. To achieve zero defect output, manufacturers are making the commitment to move to online NDT. This type of online inspection requires accuracy, reliability, and high throughput. Resonant Acoustic Method NDT (NDT-RAM^{TM}) provides a proven technique exhibiting these pivotal performance requirements and automates economically. NDT-RAM tests, reports and screens for most common part flaws in a manner similar to the way NASA tests flight hardware and automotive manufacturers validate their new car designs. Utilizing structural dynamics and statistical variation, NDT-RAM provides mature, laboratory proven technology in a robust, economical, process-friendly manner.

1. Motivational Example

As with most powdered metal component suppliers, Company ABC is already doing spot magnetic particle testing on batches of parts from a given production run. The problem starts when a customer, say an automotive manufacturer, experiences field failures. The result is that Company ABC is put on parts-hold and has to pay for both containment and 100% field inspection on the customer site. At the risk of permanently damaging the company's reputation and losing both existing and new business, significantly larger part batches are subjected to magnetic particle inspection, with 100% of the production lots inspected via a 300% visual part sort – where each part is visually inspected by three separate technicians. Everyone who can be pulled from another job is pulled in to help out during this time of crisis. To ensure necessary quality, 100% end-of-line part inspection must be implemented; traditional NDT techniques such as magnetic particle, liquid penetrant, eddy current and X-ray, or purely visual inspection, are painstaking, subjective manual processes. As a result, rarely does the 100% inspection continue, and the cycle of "flawed-parts roulette" continues.

Providing relief and security for the high volume manufacturer, NDT-RAM offers reliable inspection, with quantitative, objective results. This technique is easily automated to eliminate human error with fast throughput for cost effective 100% inspection, simple and straightforward with minimal disruption to production. NDT-RAM is a volumetric, resonant inspection technique that measures the structural integrity of each part to detect defects on a component level. With a large number of successes on the production lines of powdered metal, cast and forged parts, NDT-RAM is the simple, effective solution to this common problem.

2. History

The history of NDT techniques used for quality control testing in part manufacturing dates back to the beginning of the industrial manufacturing era. Initially, the basic visual inspection of the operators themselves served as the primary means of monitoring part acceptability. More sophisticated NDT techniques evolved, and magnetic particle inspection eventually became the de facto standard for testing ferrous metallic components such as castings, forgings and, more recently, powdered metals. This subjective and visual technology has remained essentially unchanged for the past 50+ years, yet continues to be the most common inspection tool for such parts.

Traditional NDT techniques focus on detecting and diagnosing defects. They use visual techniques or imaging to scan for any indication of defects. For the case presented in our motivational example, identifying the type of defect itself is secondary to identifying the defective parts. While diagnosing specific defects is applicable when evaluating and inspecting some systems, such as gas pipelines or similar, it is not appropriate for high volume 100% manufactured part inspection. For these components it is of primary importance to detect *if* a part is non-conforming rather than *why*. Therefore, an end-of-line "go/no go" objective inspection, such as by NDT-RAM, is preferred here to a subjective diagnosis.

Scanning methods include magnetic particle testing (MT), ultrasonic testing (UT), eddy current/electromagnetic testing (ET), dye penetrant testing (PT), X-ray/radiographic testing (RT) and visual testing (VT). The fundamental difference between these traditional NDT techniques and resonant inspection (RI) is this scanning methodology. Scanning methods are manual and require subjective interpretation by an operator. As a result, the operator requires a certain level of technical training and/or certification to properly diagnose such indications of defect and infer the effects on the functionality of a part. Additionally, whenever such a technique requires the judgment of an operator, overall reliability suffers. In *Juran's Quality Handbook*, Juran states that operators average only 80% reliability – this statistic is a reflection of the human interpretation factor, not the accuracy of the techniques themselves, see ref 1. None of these scanning techniques allow for efficient, cost effective or reliable quality control testing of 100% of manufactured parts of any appreciable volume. It should be noted that in some cases eddy current techniques can be implemented as a "whole part" test by using an encircling coil, easily automated with high throughput. However, in these cases the effectiveness of ET's flaw detection is reduced, limited to detecting on certain types or configurations of surface flaws.

Resonant inspection, conversely, measures the structural response of a part and evaluates it against the statistical variation from a control set of good parts to screen defects. Its volumetric approach tests the whole part, both for external and internal structural flaws or deviations, providing objective and quantitative results. This structural response is a unique and measurable signature, defined by a component's mechanical resonances. These resonances are a function of part geometry and material properties and are the basis for RI techniques. By measuring the resonances of a part, one determines the structural characteristics of that part in a single test. Typical flaws and defects adversely affecting the structural characteristics of a part are given in Table 1 for powdered metal, cast and forged applications. Many of the traditional NDT techniques previously discussed can detect these flaws as well, but often only RI can detect all in a single test, throughout the entire part (including deep sub-surface defects), in an automated and objective fashion.

Table 1. Typical structural defects detectable by resonant inspection.

Cast	**Forged**	**Powdered Metal**
Cracks	Cracks	Cracks
Cold shuts	Missed or double strikes	Chips
Porosity	Porosity	Voids
Hardness/density	Hardness	Hardness/density
Inclusions	Inclusions	Inclusions
Heat treat	Heat treat	Heat treat
Compressive & residual stress	Quenching problems	Decarb
Nodularity	Laps	Oxides
Gross dimensions	Gross dimensions	Gross dimensions
Raw material contaminants	Raw material contaminants	Raw material contaminants
Missed processes/operations	Missed processes/operations	Missed processes/operations

After defective parts have been sorted with RI, complimentary traditional NDT techniques may provide a means for subjective diagnosis on the smaller subset of parts. This is useful for determining a defect's root cause and ultimately improving the production processes. Table 2 provides a generic NDT selection table stating the capabilities of the various methods. The ASME has published standards that detail each of the traditional NDT methodologies mentioned here, see ref 2-8.

Table 2. General overview of common NDT techniques.

	ET	**MT/PT**	**UT**	**RT**	**RAM**
Defect Type					
Cracks/chips/porosity/voids	Yes	Yes	Yes	Yes/No	Yes
Missed processes/operations	Yes/No	No	Yes/No	Yes/No	Yes
Material property	Yes/No	No	No	No	Yes
Structurally significant	Yes	Yes	Yes	Yes	Yes
Production lot variations	Yes/No	Yes	Yes	Yes	Yes/No
Defect Location					
Surface (external)	Yes	Yes	Yes	No	Yes
Internal	No	No	Yes	Yes	Yes
Brazing/bonding/welding	No	No	Yes/No	Yes/No	Yes
Speed/Training/Cost					
Part throughput	Medium	Low	High	Low	High
Training requirements	High	High	Medium	High	Low
Overall inspection costs	Medium	Medium	High	High	Low
Automation Capacity					
Quantitative results	Yes/No	No	Yes/No	No	Yes
Automation requirements	Medium	N/A	Complex	Complex	Easy
Automation cost	Medium	N/A	High	High	Low/Medium

3. Theoretical Background

Modal analysis is defined as the study of the dynamic characteristics of a mechanical structure or system. All structures, even structures such as metal gears or similar parts that are apparently rigid to the human eye, undergo deformation. These deformations can be described using modal analysis. Specifically, all structures have mechanical resonances, where the structure itself amplifies any energy imparted to it at certain frequencies. For example, tuning forks or bells will vibrate at very specific frequencies, their natural frequencies, for long periods of time with just a small tap. The sound that is made is directly due to these natural frequencies. In fact, any noise generated by a structure is done so by vibration, which is simply a pattern of summed sinusoidal deformations. NDT-RAM utilizes this structural dynamic behavior to evaluate the integrity and consistency of parts.

For illustrative purposes, consider the single degree-of-freedom (SDOF) mass, spring, damper system in Figure 1. It has one DOF because its state can be be determined b one quantity (x), the displacement of the mass. The elements of this simplified model are the mass (m), stiffness (k) and damping (c). The energy imparted into the system by the excitation force (f) is stored in the system as kinetic energy of the mass and potential energy of the spring and is dissipated by the damping. The mathematical representation of the SDOF system, which is called its equations of motion, is given in Equation (1) below.

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = f(t) \tag{1}$$

The solution to the equation of motion produces an eigenvalue problem which yields the undamped natural frequency as

$$\omega_n = \sqrt{\frac{k}{m}} \qquad (2)$$

Equation (2) reveals the natural frequencies, or resonances, of a system that are determined by its mass (i.e., volume and density) and stiffness (i.e., Young's modulus and cross-sectional geometry). While in Equation (2) holds only for an SDOF system, the underlying relationship of mass and stiffness can be generalized for more complex systems. That is, an increase in stiffness will increase the natural frequency and an increase in mass will decrease the natural frequency. For example, consider the strings on a guitar. The larger diameter strings (more mass) produce lower tones than the smaller strings (less mass). Also, a string has a higher pitch when tightened (increased stiffness) than when loosened (decreased stiffness). It is these fundamental properties of the resonances of a system that NDT-RAM utilizes to evaluate the integrity and consistency of parts.

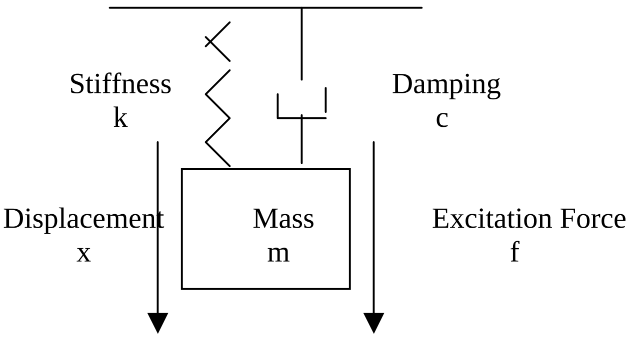

Figure 1. Single Degree of Freedom (SDOF) discrete parameter model

The natural frequencies are global properties of a given structure and the presence of structural defects causes shifts in these resonances. For example, a crack will change the stiffness in the region near the crack and a variation in density or the presence of porosity will change the mass. A crack defect typically reduces the stiffness in the material, thus decreasing the natural frequency. Similarly, porosity in a cast part reduces mass, thus increasing the natural frequency. These shifts are measurable if the defect is structurally significant with respect to the either the size or location of the flaw within a specific resonance mode shape. With some defects, a shift in resonant frequency can also be noticed audibly, such as a cracked bell that does not ring true.

4. Resonant Acoustic Method (NDT-RAM)

An introductory overview of the resonant inspection technique and theoretical background has previously been presented in Sections 2 and 3, respectively. This portion of the paper discusses in more detail the specific implementation of resonant inspection and the associated advantages of the Resonant Acoustic Method.

RI is basically experimental modal analysis simplified for application to high volume production manufacturing and quality control testing. The generic, step-by-step procedure is as follows:

1. Excite the part with a known and repeatable force input. This force is typically generated by a controlled impact or actuator providing broadband or sinusoidal energy over the appropriate frequency range of analysis.
2. Measure the structural response of the part to the applied input force using a dynamic sensor such as a microphone or accelerometer (vibration pickup) and a high-speed analog to digital converter (ADC) with appropriate anti-aliasing filters.
3. Process the acquired time data with a Fast Fourier Transform (FFT) for analysis in the frequency domain.
4. Analyze the consistency of the frequency spectrum from part to part by comparing to a spectral template created from known good parts. Mechanical resonances are indicated as peaks in the frequency spectrum of the response. "Good" parts (structurally sound) have consistent spectral signatures (i.e. the mechanical resonances are the same among parts) while "bad" parts are different. Generally these templates are setup to evaluate the consistency of the frequency and amplitude of ten or fewer peaks. Any deviation in (a range of) peak frequency or amplitude constitutes a structurally significant difference that provides a quantitative and objective part rejection.

The Resonant Acoustic Method technique performs resonant inspection by impacting a part and "listening" to its acoustic spectral signature with a microphone. The controlled impact provides broadband input energy to excite the part and the microphone allows for a non-contact measurement of the structural response. The part's mechanical resonances amplify the broadband input energy at its specific natural frequencies, measured by the microphone above the background noise in the test environment. An example of such a spectrum from 0 to 40 kHz is given in Figure 2.

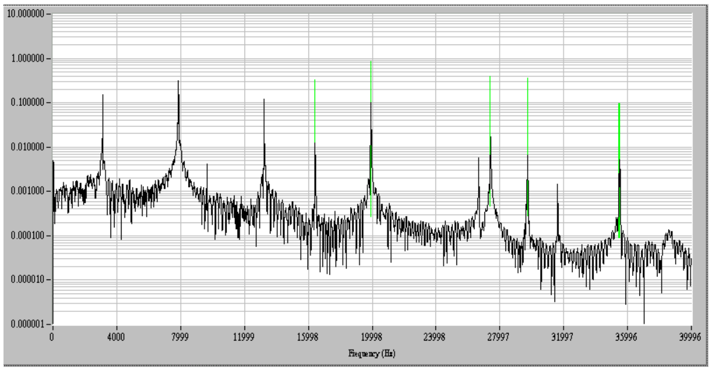

Figure 2. Typical acoustic signature for powdered metal part.

Gross defects can often be distinguished directly by the human ear, but human hearing is subjective and limited to approximately 20 kHz maximum. By analyzing data beyond 20 kHz, to upwards of 50 kHz, much smaller defects can be detected, even across production lots given reasonable process control. Typically, these defects cause frequency shifts as shown in Figure 3. These shifts are a function of how the specific defect affects the mechanical resonance, which is dependent upon the specific defect location with respect to the deformation pattern of the resonance. Fortunately, mechanical resonances are global properties of a structure, and generally a defect will alter at least one resonant frequency. For this reason, it is good practice to set up multiple criteria ranges for analysis.

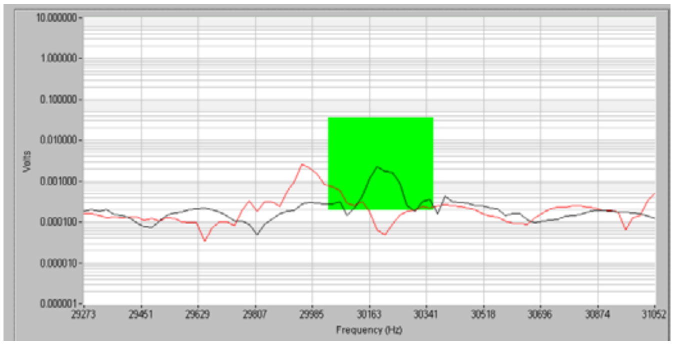

Figure 3. Data showing frequency shift due to structural defect in part.

An additional signal processing tool for improving analysis and sorting of good parts versus defective parts is implemented with a time delay function. Often times a defect may not cause a substantial shift in resonant frequency, but instead reduces the structure's capability to "hold its tone" over time. By delaying the structural response measurement (many times just milliseconds) the resonant peak is not measurable from defective parts because the energy decays too rapidly. The peak in the frequency spectrum disappears, shown in Figure 4. A practical example of this is a cracked bell – when struck, it does not ring for an extended period of time as a "good" bell would.

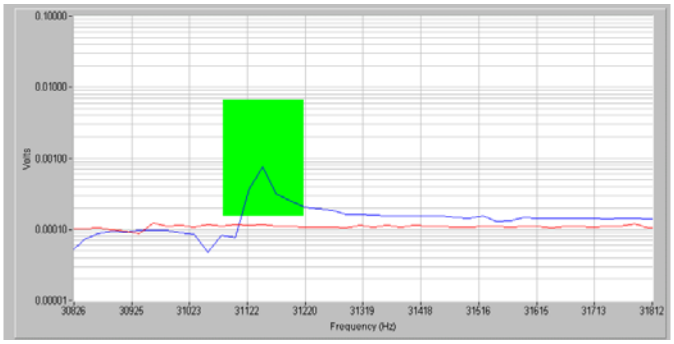

Figure 4. Data showing resonance of good part against defective part, processed using time delay technique causing the peak to "disappear".

NDT-RAM's basic measurement procedure allows for easy automation and very high part testing throughput. There is no part preparation required – no magnetizing, cleaning, immersion, etc. Expendable costs associated with such preparation, such as chemicals and waste removal, are eliminated. The single impact and non-contact response measurement (via microphone) can be made as a part is moving down a conveyor, often as fast as a part per second. The parts do not need to be physically stopped; nor are they required to be precisely located with expensive robotics on contact actuators and vibration pickups. Simple guides are typically adequate to rotate/position the part for impact and allow flexibility to test many different types of parts or geometries. Given this capacity for automation and throughput, and its quantitative analysis with objective results, NDT-RAM is ideal for plant floor, high volume quality control test applications.

The core system components are shown in Figures 5 and 6. From the rugged microphone and industrial electric impactor to the NEMA 4 smart digital controller, the packaging is ideally suited for dirty, plant environments such as ductile iron foundries. A typical conveyor system for fully automated testing is shown in Figure 7.

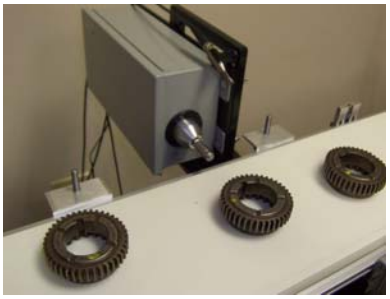

Figure 5. Industrial electric impact hammer designed for millions of impacts and rugged microphone for non-contact response measurement, shown mounted on conveyor section.

Figure 6. Smart digital controller measures signals and processes data, independent of PC, with internal digital relay outputs.

Figure 7. Fully automated system on 6 ft conveyor section, shown with acoustic chamber for testing parts.

Successful implementation of NDT-RAM depends upon proper setup of the accept/reject criteria ranges in the part template. Each type and/or geometry of part requires a separate template. Parts need to be tested in the same manufacturing state. Typically, templates can be setup quickly with just a few dozen parts in less than a ½ hour. This sample set should include both good parts (ideally with at least several from different production batches) and parts with the expected variety of flaws. It is recommended to validate the template and resulting part sort with a larger statistical data set of a few hundred pieces. Often other NDT techniques, for example magnetic particle inspection, are complimentary in this regard, or destructive evaluations are commonly used for correlation as well. Once the specific part's template is verified for accuracy, large volumes of parts can be 100% tested quickly and reliably.

System validation can be performed using a controlled set of known parts. Parts of a given type, both good and defective, are kept as “standards” and run through the automated system for validation on a regular basis. Across batches over time, signatures often show trends where mechanical resonances shift due to acceptable variations in material properties (density, etc.) or process variations (heat treatment, etc.) By investing time upfront with this type of system validation procedure, process engineers and technicians have a better understanding of their parts and manufacturing processes and ensure the reliability of their inspection system.

5. Case Study: Powdered Metal Sprocket

The manufacturer of the powdered metal sprocket shown in Figure 8 below needed to automate inspection, primarily for cracks and flawed teeth. The initial part template was set up using 70 samples. 30 of these were visually inspected as good parts, while the remaining 40 were determined to have a variety of flaws such as broken, chipped and cracked teeth as shown in Figure 9. Typical data from several parts is shown in Figure 10, where frequency shifts down from cracks (two blue traces left of acceptance box) and up from broken teeth (red, pink and olive traces right of box) are clearly displayed against the two good samples (black/gray traces peak within box). These physical flaws correlate nicely with the theory presented in Section 2. A crack is simply a weaker spring (lower stiffness, k, in Eq. 1) and a broken tooth reduces mass (lower mass, m, in Eq. 1) which affects the resonant frequency accordingly.

Figure 8. Powdered metal sprocket.

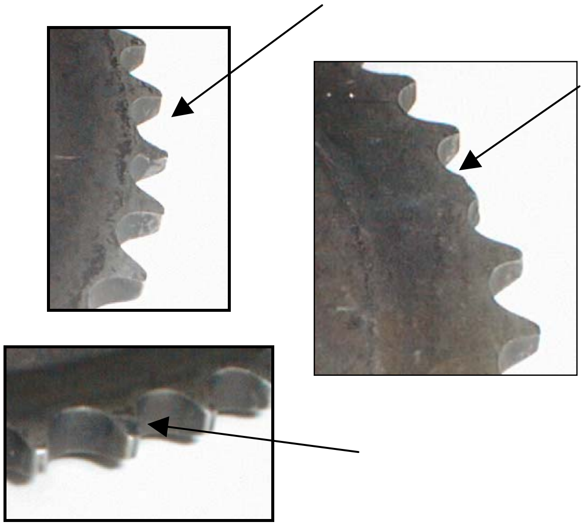

Figure 9. View of powdered metal sprocket with chipped, broken and cracked teeth, as indicated, clockwise from top.

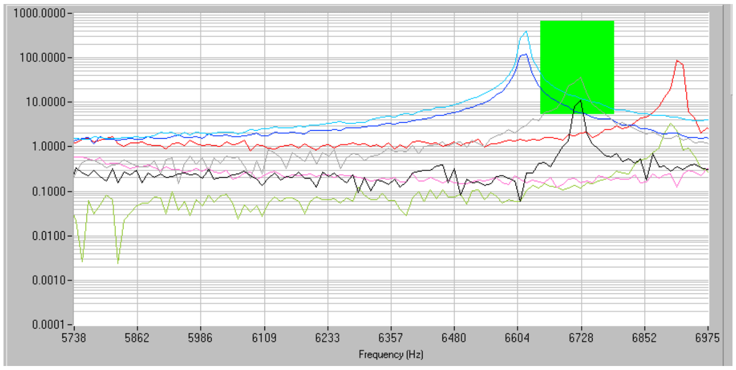

Figure 10. Data at 6700 Hz resonance from 7 samples.

Results of this evaluation showed that the flawed samples could be reliably sorted from the good parts. Of note, one of the “good” samples had significant shifts in resonances, indicating the presence of structural defects. (This is common, often related to the inability of visual scanning techniques such as magnetic particle testing to detect internal flaws.) Given the volumetric, whole-part testing by RAM, this part was successfully sorted and contained where subjective, visual inspection failed.

The resulting template configured for this sprocket was implemented successfully in production, with millions of parts reliably tested per year. Prior to NDT-RAM, the facility was scrapping 6-8% of production parts and still had field failures returned by their customers, all while trying to keep up with 100% inspection via magnetic particle testing. NDT-RAM reduced this scrap rate to under 2% by eliminating false rejects (for example, a part that has a flaw indication on its surface yet is structurally sound.) Additionally, and more importantly, NDT-RAM has prevented any defective parts from shipping to customers.

6. Conclusion

The NDT-RAM technique serves quality minded manufacturers who are dissatisfied with visual detection techniques such as magnetic particle, liquid penetrant, or X-ray, which are time consuming, costly and subjective. NDT-RAM allows for simple integration of a turnkey system that is a reliable, fully automated method for quality control and process improvement. This rapidly growing technique creates an economical, on-line inspection system that provides for zero defect product supply. Unlike previous implementation of resonant inspection which are excessively complicated and costly to automate, NDT-RAM is fast, simple and reliable, and easily re-configurable. As a result, powdered metal and casting manufacturers around the world have proven the benefits of NDT-RAM resonant inspection over their traditional inspection techniques.

7. References

[1] Juran, Joseph M. and Godfrey, A. Blanton, Fifth Edition, *Juran's Quality Handbook,* McGraw-Hill.
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[7] ASTM D4086-92a (1997) e1 Standard Practice for Visual Evaluation.
[8] ASTM E165-02 Standard Test Method for Liquid Penetrant Examination.