2010-01-1699

Automated Resonant Inspection to Validate Resonant Frequency Characteristics within Brake Components for Improved NVH Performance

Richard W. Bono
The Modal Shop, Inc.

Gail R. Stultz
The Modal Shop, Inc.

ABSTRACT

Resonant Inspection is a non-destructive test technique that measures the structural dynamic signature of an article. By comparing the resulting footprint to expected signatures, anomalous outliers are sorted due to some inherent structural defect, improving quality and consistency of manufactured components. Brake components, such as rotors and drums, are designed with specific structural dynamic properties for desired NVH qualities. Resonant Inspection via the Resonant Acoustic Method (RAM-NDT) provides a proven economical technique with the capacity for accurate, reliable and high-throughput 100% online inspection.

INTRODUCTION

Many industries, especially automotive, have used structural frequency response testing, or experimental modal analysis, as an integral part of the research and product development of components, sub-systems and complete vehicles. Over the past three decades it has become an essential tool for understanding many types of structural dynamics problems, such as noise and vibration, and the validation of appropriate solutions. Brake systems manufacturers are particularly interested in applying frequency response testing and modal analysis since the NVH (noise, vibration and harshness) quality of the sub-systems and components are very noticeable and commonly objectionable to the end customer of the vehicle.

Accordingly, many brake systems and component manufacturers are applying these techniques within the production line environment. 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 confirming the structural frequency response characteristics by “production-line” modal analysis. This type of online inspection requires accuracy, reliability, and high throughput. Resonant Acoustic Method NDT (RAM NDT) provides a proven technique exhibiting these pivotal performance requirements and automates economically. Utilizing structural dynamics and statistical variation, RAM NDT provides mature, proven technology in a robust, economical, process-friendly manner.

RAM NDT TECHNIQUE

Resonant Ultrasound Spectroscopy (RUS) [1], the general classification of Resonant Acoustic Method RAM NDT, was originally approved as an ASTM International standard in 1998, with its current edition approved July 1, 2008. In commercial nondestructive testing methodologies, RUS is also known by the terms Acoustic Resonance Spectroscopy (ARS) and, more commonly, Resonant Inspection (RI). RUS based NDT techniques all vibrate a part mechanically, measure the structural frequency response function and detect defects based upon measurable changes in the given part’s resonant frequency pattern. These techniques have become commonly used for quality inspection in the manufacture of cast, sintered and forged metal parts.

RAM NDT measures the structural frequency response as an indication of the structural integrity of each part to detect defects on a component level. Compared with traditional NDT techniques, such magnetic particle for crack detection or ultrasonics for nodularity testing, RAM NDT provides an indication of many of these types of structural defects in a single test [2], [3]. For inspecting the NVH quality of brake components on the production line, RAM NDT is ideal given that it is directly measuring the resonant frequencies of interest and sorts outliers failing to meet an appropriate template.

RAM NDT's volumetric approach tests the whole part, both for external and internal structural flaws or deviations, providing objective and quantitative results. The structural frequency 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 that can adverse affect the structural characteristics of a part are given in Table 1 for powdered metal, cast and forged applications. Many of the traditional NDT techniques 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
Low nodularity	Laps	Oxides
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 RAM NDT, complimentary traditional NDT techniques may provide a means for subjective diagnosis on the smaller subset of "rejected" parts. This is useful for determining a defect's root cause and ultimately improving the production processes. The ASME has published standards that detail each of the traditional NDT methodologies.

FUNDAMENTALS OF RAM NDT – STRUCTURAL THEORY

All structures have mechanical resonances. A resonance occurs when a structure, due to its natural, structural properties, amplifies energy imparted to it at certain frequencies. The structure itself acts like a speaker, deforming in a certain, specific pattern and radiating acoustic energy. 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. The Resonant Acoustic Method of Nondestructive Testing (RAM NDT) 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 model in Figure 1. It has one DOF because its state can be determined by 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.

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

The solution to the equation of motion produces an eigenvalue problem which yields the undamped natural frequency, see reference [4], 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 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 RAM NDT utilizes to evaluate the integrity and consistency of parts.

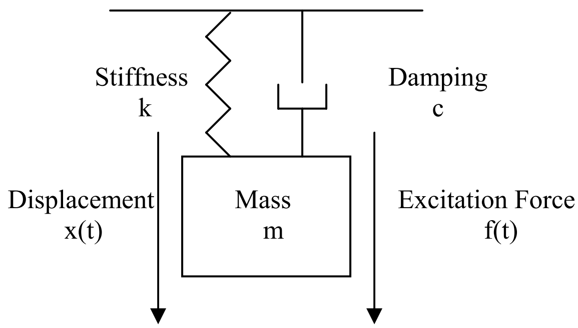


Figure 1 - Single Degree of Freedom (SDOF) discrete parameter model

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.

The Resonant Acoustic Method technique performs resonant inspection by impacting a part and "listening" to its acoustic spectral signature with a microphone as shown in Figure 2. This impulse technique provides broadband input energy to excite the part and the microphone allows for a non-contact measurement of the part's structural frequency response [5]. The part's mechanical resonances amplify the broadband input energy at its specific natural frequencies, indicated as peaks in the frequency spectrum (shown below the "black box" LanSharc smart digital controller), measured by the microphone above the background noise in the test environment. "Good" parts (structurally sound) have consistent spectral signatures (i.e. the mechanical resonances are the same among part samples) while "bad" parts (structurally different) are different. Deviations in peak frequencies or amplitudes constitute a structurally significant difference that provides a quantitative and objective part rejection. NDT-RAM processes the individual spectra, evaluating these changes compared to a baseline template for the given part. The results are displayed on the industrial PC workstation, with the pass/fail decision communicated to the system PLC. An enlarged display of a typical spectrum from 0 to 50 kHz is given in Figure 3 and a zoomed display showing a typical frequency shift is given in Figure 4.

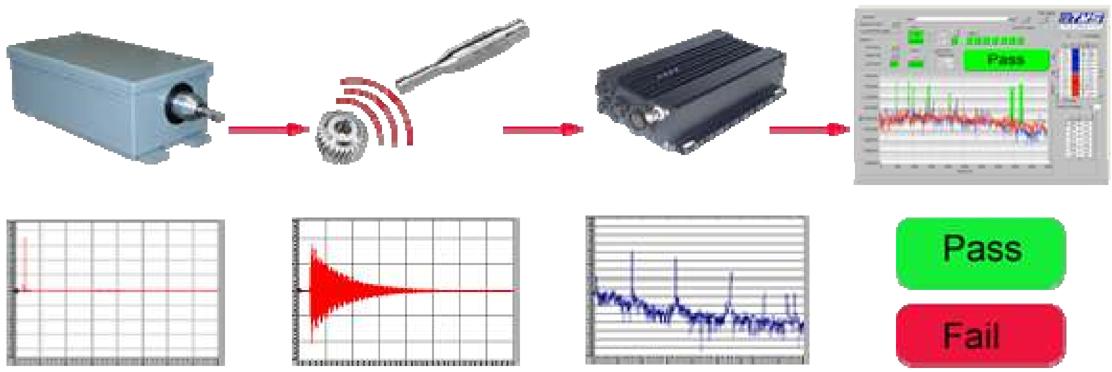


Figure 2 - NDT-RAM process flow, (a) impact part using electromechanical hammer instrumented with a force transducer, (b) measure acoustical response with an industrial microphone, (c) process structural frequency response with LanSharc smart digital controller and (d) sort part against pass/fail criteria with NDT-RAM.

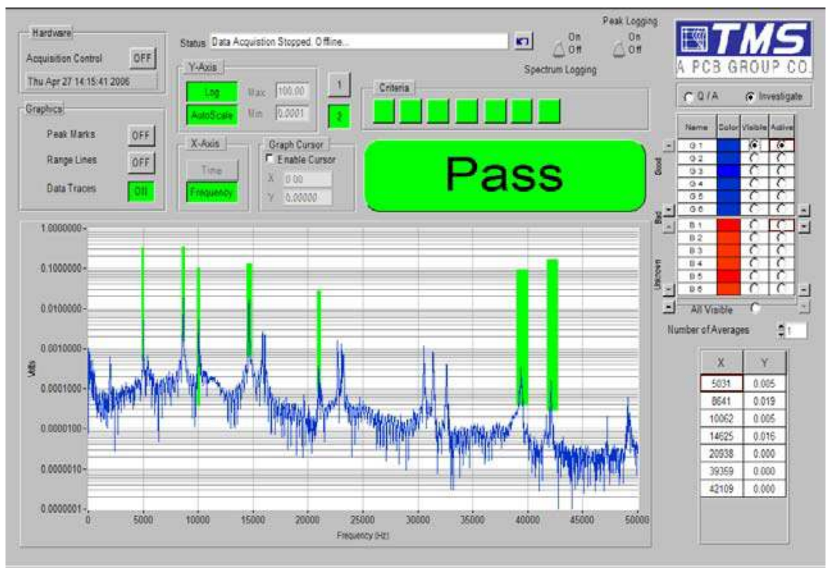


Figure 3 - Typical acoustic signature, power spectrum to 50 kHz, for a metal part, shown as processed by NDT-RAM with criteria ranges (indicated with green "boxes") at seven natural resonant frequencies.

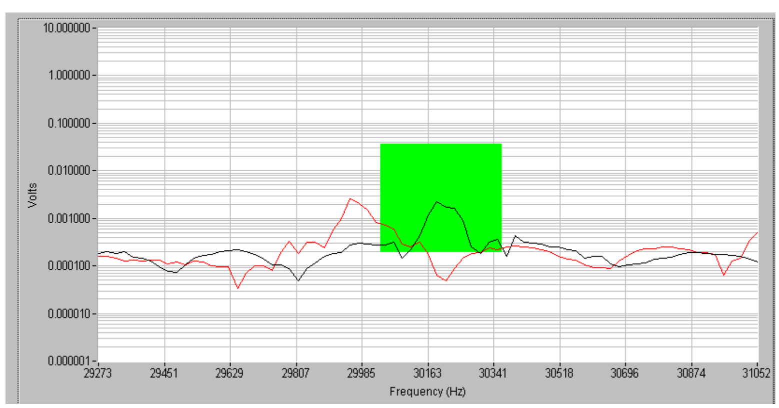


Figure 4 - Data showing a typical frequency shift detected by NDT-RAM.

RAM NDT APPLIED TO BRAKE PARTS

Brake squeals, groans and other related NVH issues have become an increasing annoyance for the more demanding automotive buyer. Market wide, warranty repairs for brake NVH claims exceed $100 million annually in the United States alone [6]. In order to meet these NVH requirements demanded by automotive OEMs for end customers, brake system suppliers and component manufacturers have implemented production-line modal analysis. Many OEMs have established specifications for the first several natural resonant frequencies which they expect their suppliers to measure and meet, often on 100% of delivered product. This includes parts such as brake rotors, drums, anchors, calipers and hubs, a selection of which are shown in Figure 5.

Figure 5 - Sample brake parts commonly inspected for first several natural resonant frequencies via RAM NDT.

One manufacturer's application required the measurement of the structural frequency response to identify and record the first five natural resonant frequencies of 100% of product delivered to a given brake system supplier as defined by the automotive OEM. Figure 6 shows the results measured for a single specimen up to 20 kHz. Depending upon the specific type of part and the OEM, as many as twenty natural resonant frequencies may be specified.

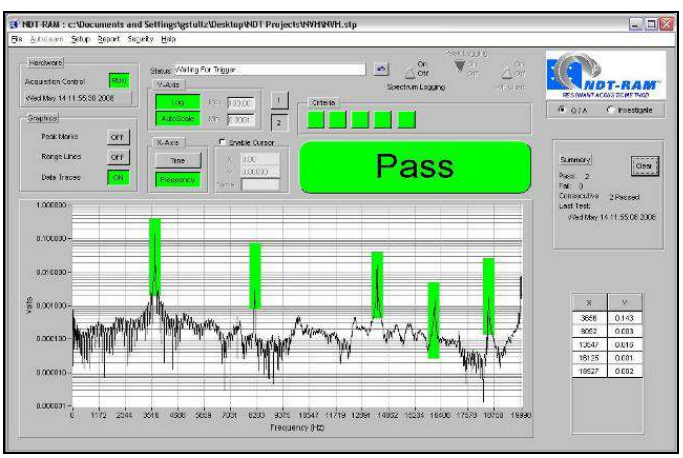
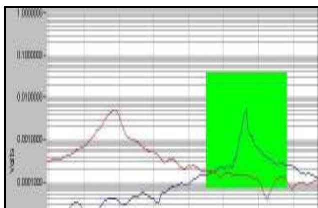


Figure 6 - The first five natural resonant frequencies measured by NDT-RAM

Typically these natural resonant frequencies are identified by the OEM or Tier One supplier based upon the results of experimental modal analysis correlated with analytical models in the lab during product development. Challenges certainly exist in the transition from development lab to production line. It is critical to understand and account for the differences in transducer selection, digital signal processing techniques and test boundary conditions. For example, it is common to use accelerometers or even scanning laser technology to perform experimental modal analysis in the product development lab. However, it is economically not feasible to implement such transducers within the production environment for 100% product inspection. Accelerometers require intimate contact for accurate measurement, while lasers are extremely expensive and not well suited for the industrial environment of a production line. Microphones, conversely, are non-contact transducers that measure the structural frequency response via the acoustic response generated by the vibrating part. This is ideal for consistent, reliable measurements while still allowing high volume throughput.

Example results for a small batch of part samples are given in Figure 7. A typical resonance shift is displayed, with resonant frequency data tabulated showing pass and fail results and standard deviation. Statistical data for each natural resonant frequency is collected and available for the process engineer to use for continuous improvement of the production line.



tatus	Part #	I	CRIT 1
AILED	1	F	3485.5
SSED	2	P	3656.2
SSED	3	P	3656.2
SSED	4	P	3656.2
ASSED	5	P	3656.2
PASSED	6	P	3656.1
PASSED	7	P	3656.2
PASSED	8	P	3656.2
D	9	F	3319.9
ED	10	P	3662.1
ED	11	P	3662.1

Pass	Freq (Hz)	Amp (volts)
Average	3658.6	0.1677
Std Dev	2.9	0.0423
Fail		
Average	3485.5	0.1331
Std Dev	117.1	0.0451

Figure 7 - Structural response test results of 3659 Hz resonant frequency for 11 samples, including statistical average and standard deviation.

SUMMARY/CONCLUSIONS

RAM NDT is an ideal solution for "production-line" modal analysis specified by automotive OEMs and Tier One brake system suppliers. This inspection technique is designed for high volume production line applications, and directly measures the structural frequency response of brake components. Objective and reliable, resonant inspection via RAM NDT ensures a simple and effective means to screen for NVH resonant frequencies, meeting supplier demands and reducing warranty claims.

REFERENCES

1. ASTM Standard E2001-08, Standard Guide for Resonant Ultrasonic Spectroscopy for Defect Detection in Both Metallic and Non-metallic Parts.
2. Bono, Richard W., and Stultz, Gail R. *"Effect of Crack Size on Natural Resonant Frequency Using Resonant Inspection"*, PM2008 Proceedings, 2008.
3. Bono, Richard W., and Stultz, Gail R. *"Resonant Inspection Applied to 100% Testing of Nodularity of Cast Ductil Iron",* SAE Brake Proceedings, 2008.
4. Ewins, D.J. Modal Testing: Theory and Practice. Research Studies Press Ltd, 1984.
5. Halvorsen, William G., and Brown, David L. *"Impulse Technique for Structural Frequency Response Testing",* Sound and Vibration, November 1977, pp 8-21.

Akebono Corporation, http://www.akebonobrakes.com/oem/engineering_tech_support/full_system_analysis.asp

CONTACT INFORMATION

The Modal Shop
3149 E. Kemper Rd.
Cincinnati OH 45241
Richard Bono
Gail Stultz
Phone - 513-351-9919
Fax – 513-458-2172
www.modalshop.com