Enhanced Resonant Inspection Using Component Weight Compensation

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ABSTRACT

Resonant Inspection is commonly used for quality assurance testing of powder metal components, providing a volumetric whole body approach that detects both external and internal structural flaws or anomalies. This technique measures the structural response, a unique and repeatable signature dependent upon the component's mechanical resonances. Since these resonances are a function of the material properties, certain process variations such as powder density can contribute to uncertainties in the testing technique. This paper presents the results of an enhanced resonant inspection technique, called Adaptive Resonant Acoustic Method, that allows for adaptive, intelligent data processing providing improved quantitative results.

INTRODUCTION TO RAM NDT

The Resonant Acoustic Method of NDT (RAM NDT) is a volumetric resonant inspection technique that measures the structural integrity of each part to detect defects on a component level. This technique is easily automated to eliminate human errors with fast throughput, providing cost effective 100% inspection with minimal disruption to production. With a large number of successes on the production lines of powder metal and cast parts, RAM NDT is the simple and effective solution to manufacturers' zero PPM challenge.

Traditional NDT techniques, for example magnetic particle or dye penetrant testing, focus on detecting and diagnosing defects. They use visual or imaging techniques that scan for indications of specific defects. For production line quality inspection, 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 using ultrasonics to inspect gas pipelines, it is not appropriate for high volume 100% inspection of manufactured metal parts. For these production lines 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 RAM NDT, is preferred here to a subjective diagnosis, perhaps useful in defect root cause analysis.

Resonant inspection (RI), the general classification of RAM NDT is described in the ASTM E2001-8 standard. RI 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 that can adversely 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 commonly detectable by resonant inspection technique for powder metal, cast and forged processes.

Powder Metal	Cast	Forged
Cracks	Cracks	Cracks
Chips	Cold shuts	Double strikes
Voids	Nodularity	Porosity
Hardness	Porosity	Hardness
Inclusions	Hardness	Inclusions
Heat treatment	Inclusions	Heat treatment
Decarb	Heat treatment	Quenching
Oxides	Stresses	Laps
Contaminants	Contaminants	Contaminants
Missed ops	Missed ops	Missed ops

After defective parts have been sorted with RI, 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.

SCIENCE OF RESONANT INSPECTION

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 as a result of applied forces. The structure itself deforms in a distinct, specific pattern. This structural dynamic behavior is defined by the mass, stiffness and damping of a given part's material properties and geometry. The deformations are described using modal analysis, see reference [1]. 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. The Resonant Acoustic Method of Non-destructive Testing (RAM-NDT) utilizes this structural dynamic behavior to evaluate the integrity and consistency of parts.

The natural frequencies are global properties of a given structure and the presence of structural defects causes shifts in some or all of these resonances depending upon how the flaw interacts with the specific deformation pattern. 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 obviously does not ring true.

<u>PRACTICAL APPLICATION OF RESONANT ACOUSTIC METHOD</u>

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 1. The controlled impact provides broadband input energy to excite the part and the microphone allows for a non-contact measurement of the part's structural response. 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" signal processor), 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 2.

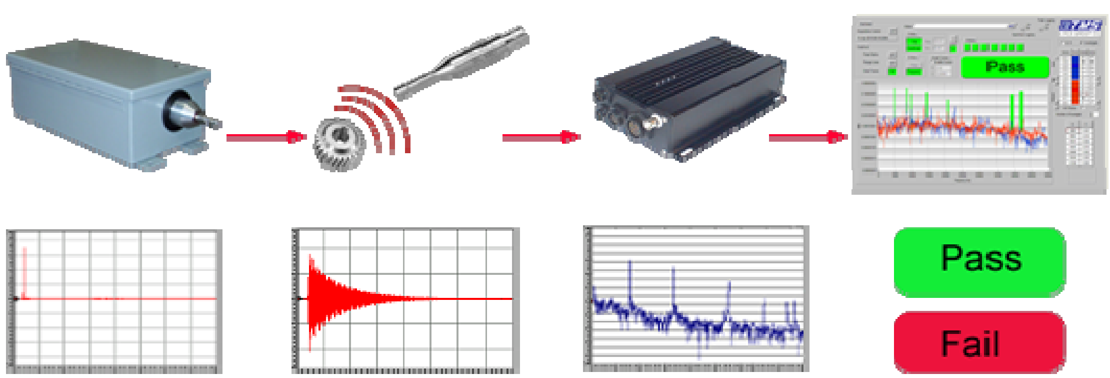

Figure 1. NDT-RAM process flow.

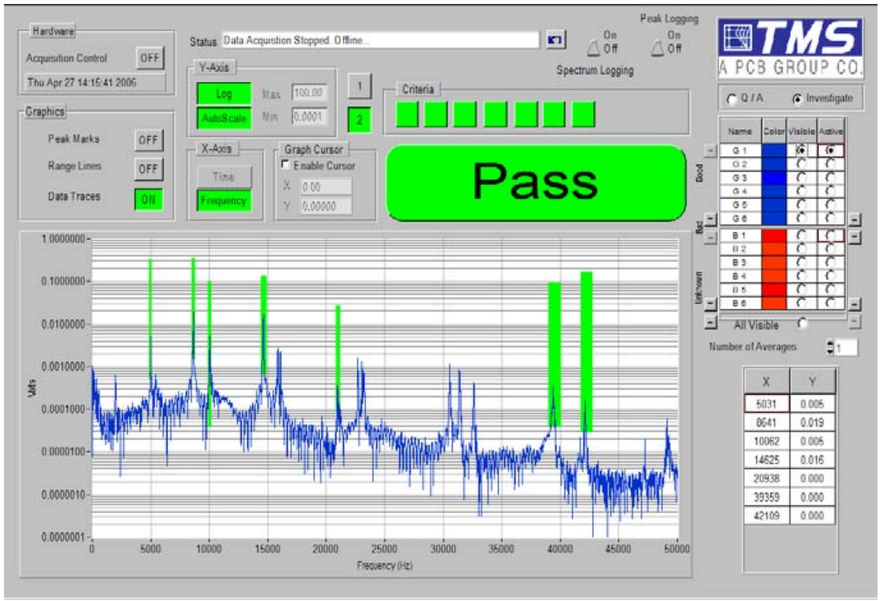

Figure 2. Typical acoustic signature, power spectrum to 50 kHz, for a metal part, shown as processed by NDT-RAM with criteria ranges (indicated with green "boxes") at seven natural resonant frequencies.

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. However, certain variations in production processes may also cause frequency shifts. For example, part density, dependent upon consistency and quantity of powder mixture in a fixed part geometry, has a direct linear affect on the structural resonant frequencies. When production variations cause resonant frequency shifts on the same order of magnitude as the structural defects themselves, differentiating acceptable process variation from actual flaws becomes more challenging. By monitoring certain additional production parameters such as component weight, on a real-time per part basis, and adapting the NDT-RAM template accordingly, enhanced quality control testing may significantly improve the inspection results.

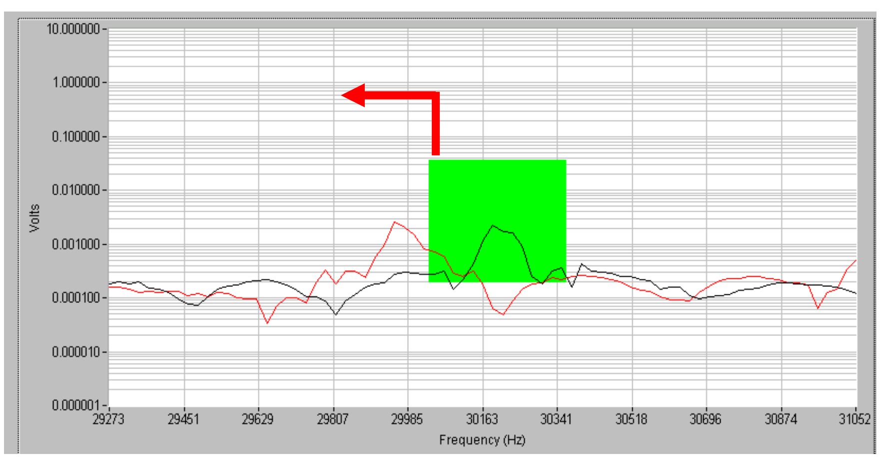

Figure 3. Data showing a typical frequency shift detected by NDT-RAM.

ADAPTIVE RESONANT ACOUSTIC METHOD

One of the common challenges to successful implementation of resonant inspection is the ability (or rather, inability) to distinguish resonant frequency shifts due to acceptable variations in production processes from unacceptable structural flaws. Examples of such process variations in powder metal parts include the amount or consistency of powder material, the alignment and pressure of the press, as well as the temperature and atmosphere within the sintering furnace. The resonant frequency profile of a given component may be sensitive to these types of process variations, which can mask smaller defects and complicate the deployment of resonant inspection as an effective quality control inspection.

An Adaptive Resonant Acoustic Method (ARAM) has been developed that interrogates process variation and adjusts the normal criteria limits set within the NDT-RAM software. Given any variation in the production process that results in a linear frequency shift of mechanical resonances, like component weight or temperature, a compensation factor can be established that correlates with this variation. The result automatically adjusts the NDT-RAM criteria limits accordingly while maintaining high throughput and logging additional valuable data that can be used to improve process and quality.

A block diagram illustration showing the flow of ARAM implemented for automatic weight compensation is provided in Figure 4. The component under test is weighed using a scale integrated within the conveyor system automation, as shown in Figure 5. The component weight is communicated to the system controller PC via USB, and the NDT-RAM software applies a compensation factor to the given master setup template to create a dynamic setup template for the given component under test. The resulting dynamic setup template is transferred via Ethernet to the LanSharc "black box" analyzer (shown previously in Figure 1) which acquires and process data, applies the appropriate dynamic setup template, and switches output relays to communicate pass/fail status to the PLC controller. The PLC then sorts the parts using an ejector cylinder as the final stage within the conveyor automation as shown in Figure 6.

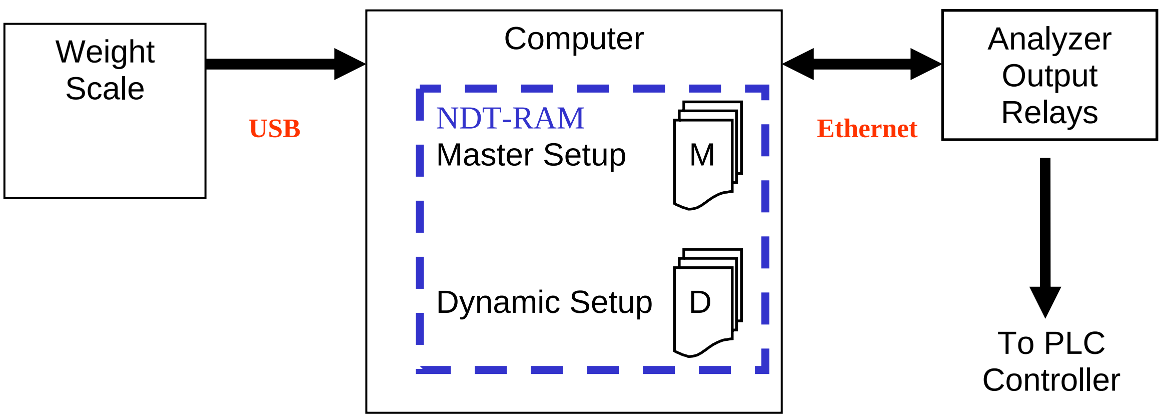

Figure 4. Block diagram implementation of ARAM

Figure 5. Part scale within conveyor system provides simple automation with high throughput

Figure 6. Final part sorting within conveyor system

A powder metal rotor component was tested. NDT-RAM was used to measure the parts' resonant frequency characteristics. Additional weight data was acquired for each part. Figure 7 plots the resonant frequency data near 6500 Hz against the individual part weight in grams. Figure 8 shows the individual component weight data for the parts. Using standard NDT-RAM processing, the criteria limits for this resonant frequency would need to be set as indicated by the green box in order to include all the "good" parts, as indicated with blue marks. Unfortunately, all of the "bad" parts, as indicated with red marks, are inclusive to this same criteria limit, and therefore, would not be sorted correctly.

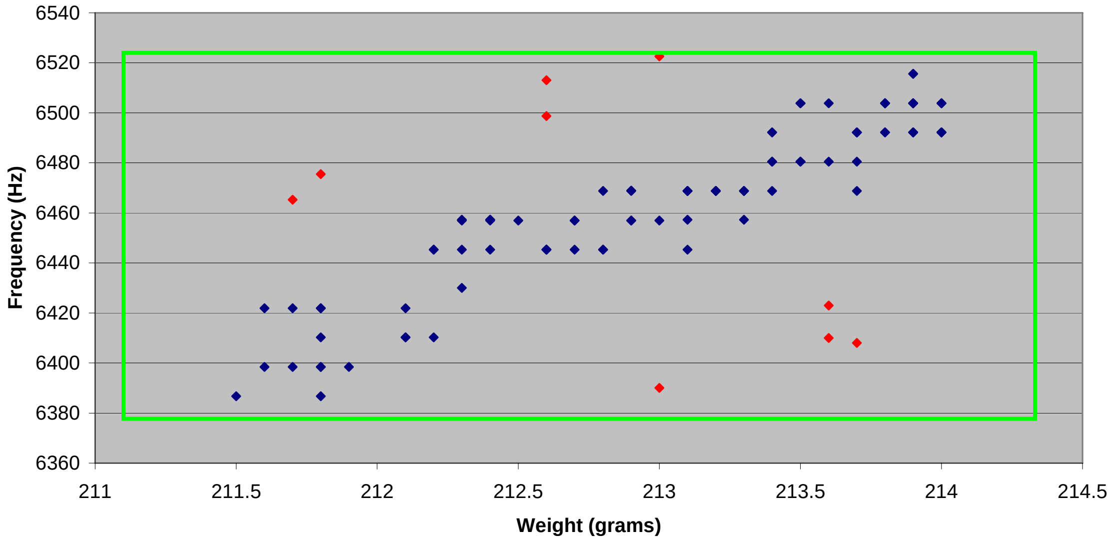

Figure 7. Resonant frequency data plotted against individual component weight.

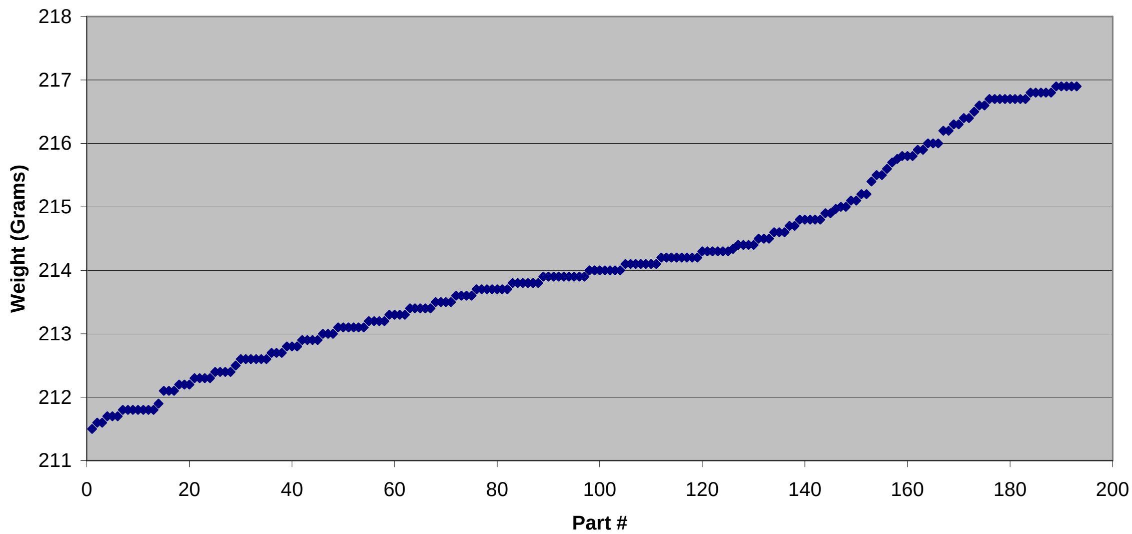

Figure 8. Weight data acquired on the rotor parts used in this experiment

By implementing the enhanced processing capability of ARAM, NDT-RAM effectively allows skewed criteria limits, shifting a tighter criteria limit by a compensation factor determined with the individual part weight. An additional software interface to NDT-RAM called NDT-ESP (External Setup Program) , shown in Figure 9 interrogates alternative sensor inputs, like for example from an in-line scale to monitor and record individual part weights. Based upon the weight, a compensation factor is applied to the master setup file shown above in Figure 4, which creates an individual dynamic setup file sent to the LanSharc for processing each part individually. The result is a skewed criteria limit shown graphically in Figure 10. Additionally, since these types of process variations cause a global linear shift of mechanical resonances, the same compensation factor is applied across the entire frequency range. Data acquired about the 12,500 Hz resonance is displayed in a similar manner in Figure 11.

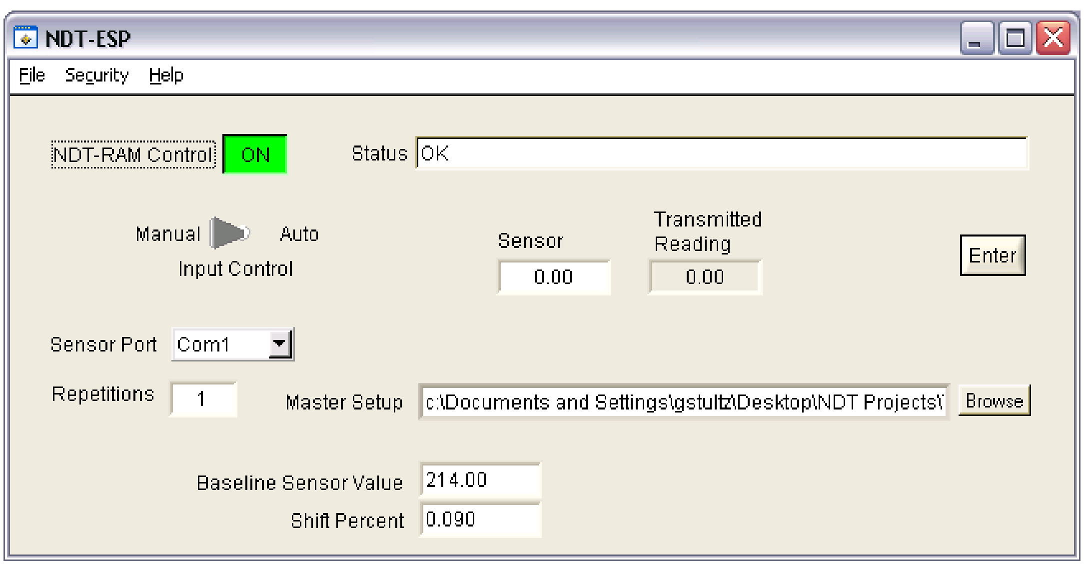

Figure 9. NDT-ESP External Setup Program interrogates alternative sensor inputs to the NDT-RAM processing software

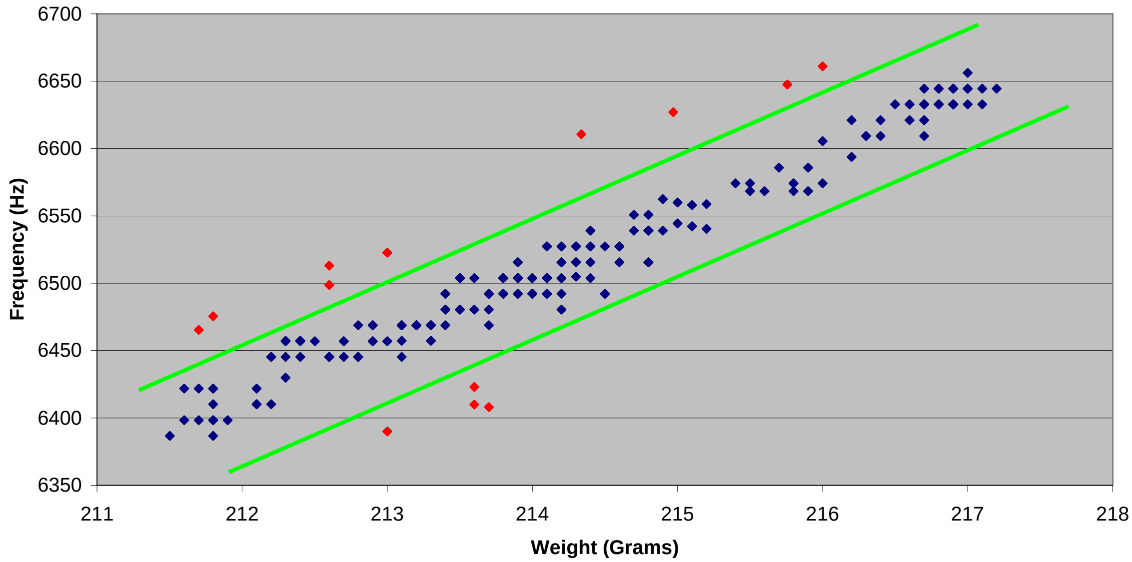

Figure 10. Skewed criteria limits set using ARAM about the 6,500 Hz resonance

Figure 11. Skewed criteria limits set using ARAM about the 12,500 Hz resonance

CONCLUSION

The Adaptive Resonant Acoustic Method enhances the capabilities of standard NDT-RAM quality inspections by allowing adaptive, intelligent data processing using alternative sensor inputs, such as individual part weight or temperature. These alternative sensor inputs are interrogated through an external setup program (NDT-ESP) which applies a resulting global compensation factor to the NDT-RAM template file. Such a methodology results in the ability to set tighter criteria limits, greatly improving scrap rates and overall quality, as well as recording additional process variables resulting in better feedback control improving overall process consistency.

REFERENCES

[1] Ewins, D.J. Modal Testing: Theory and Practice. Research Studies Press Ltd, 1984.