Effect of Crack Size on Natural Frequency Using Resonant Inspection

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Resonant Inspection is commonly used by powdered metal part manufacturers to sort quality components from those with structural defects. One of the more common structural defects found in powdered metal parts are cracks, often produced while in the green state. A controlled experiment was designed to investigate the sensitivity of resonant frequency shifts to crack size. This evaluation was intended to generalize and quantify the effectiveness of resonant inspection by generating a variety of crack sizes within a tightly controlled set of production parts. Although data was acquired to quantify how small of a crack the resonant inspection technique can detect, it is important to recognize that these results cannot be applied across all powdered metal parts due to differences in part geometry, mass and stiffness as well as control of production process variations.

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, 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 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 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.

DESIGN OF EXPERIMENT

A powder metal part supplier and their customer were interested in evaluating very precisely the sensitivity of resonant frequency shifts to crack size in a given part. A large number of production lots were evaluated for extensive baseline setting. Eighteen lots of approximately 5000 parts each were 100% inspected using the Resonant Acoustic Method (RAM NDT). The statistical results of this testing created a master template of resonant frequencies as shown in Table 2. A typical frequency spectrum with the acceptance criteria limits is shown in Figure 1. The consistency of the production parts is very good, with relatively tight criteria limits (set at approximately twice the standard deviation) and standard deviations also shown in Table 2.

Table 2. Baseline resonant frequencies determined for master NDT RAM template

Nominal Resonant Frequency (Hz)	Criteria Limit Width as Percentage of Nominal Resonant Frequency (%)	Standard Deviation of Actual Resonant Frequency (%)
4857	0.58%	0.29%
6223	0.45%	0.23%
6748	0.39%	0.34%
7782	0.44%	0.22%
19040	0.44%	0.23%

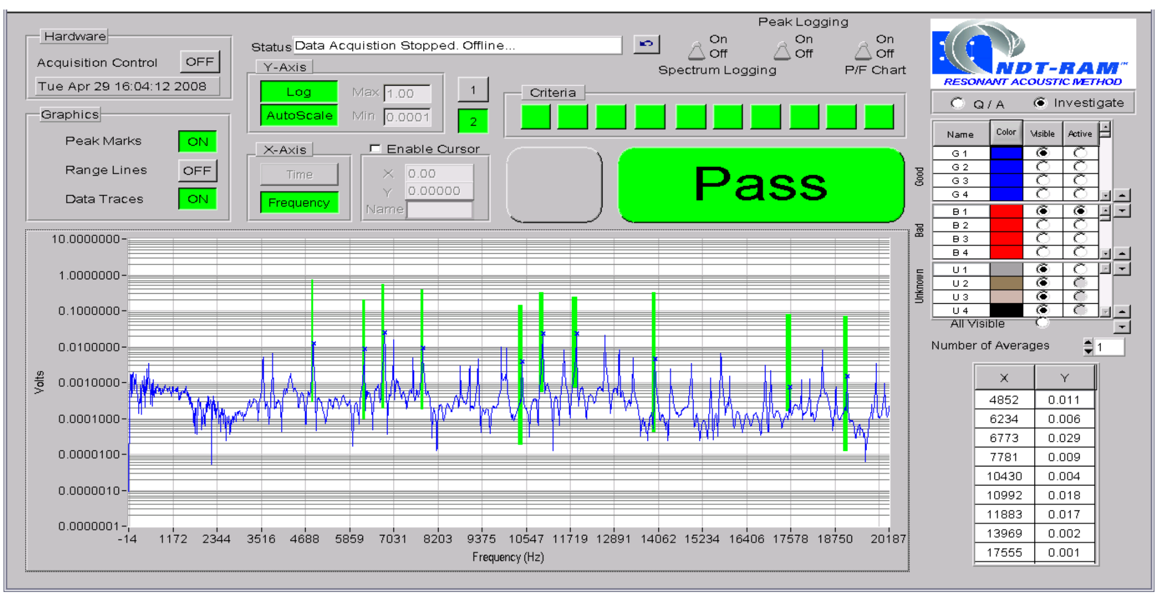

Figure 1. Typical frequency spectrum with acceptance criteria ranges/limits as displayed with NDT RAM

A control set of 18 production parts were tested using the NDT-RAM system. These parts were labeled for trending purposes throughout the experiment. The parts were then subjected to fatigue testing as shown in Figure 2. Given the application of a forcing function at the top corner of the part's vane, cracks of various sizes were manually created at the base of the part's vane. These cracks were visually inspected with a 400x microscope to estimate the crack length along the inner and outer portions of the base of the vane. Note that two of the parts, labeled H and P, were not subjected to any fatigue cycling and served as a "placebo" of sorts to monitor overall stability during the study. The parts were then retested using the NDT-RAM system to evaluate the shift in resonant frequency characteristics. The resulting data for three of the selected resonant frequencies (4857 Hz, 7782 Hz, 19040 Hz) is shown in Tables 3, 4 and 5, with an overlay of one part's before/after frequency spectra shown in Figure 3.

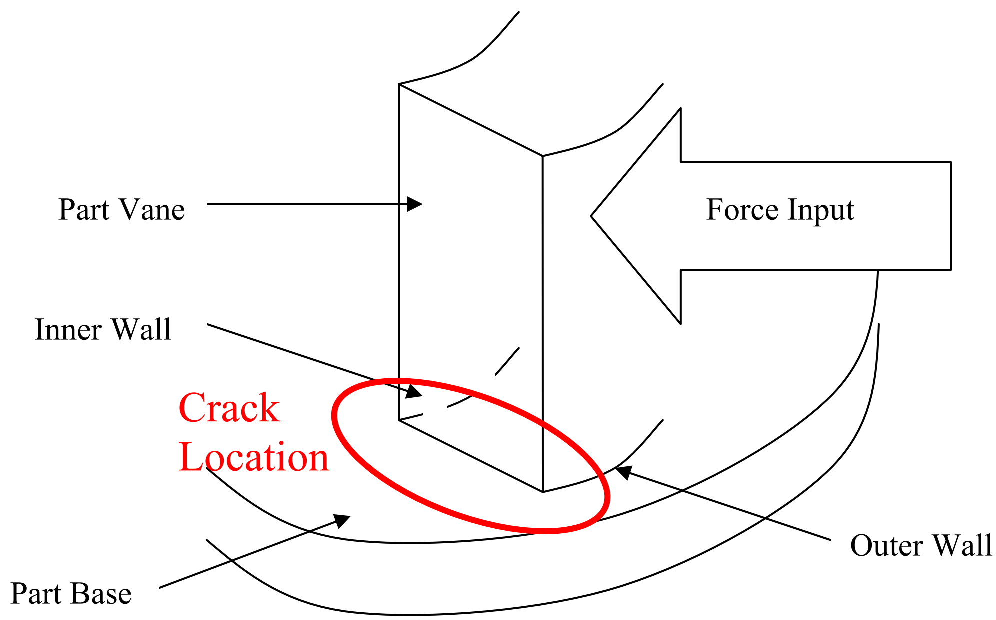

Figure 2. Simple schematic showing fatigue test configuration on part vane with indication of crack location.

Table 3. Frequency shift data at 4857 Hz from before/after crack

Part Identification	Measured Crack Length, OD (mm)	Measured Crack Length, ID (mm)	Original Resonant Frequency (Hz)	Altered Resonant Frequency (Hz)	Percent Shift (%)
A	1.0	0.5	4886.7	4851.6	0.72%
B	1.5	1.5	4851.6	4816.4	0.73%
C	1.0	0.5	4875.1	4839.8	0.72%
D	1.5	1.5	4863.3	4839.8	0.48%
E	1.0	0.5	4839.8	4804.7	0.73%
F	0.5	0.5	4863.3	4839.8	0.48%
G	1.0	0.5	4851.6	4816.4	0.73%
H	No crack	No crack	4851.6	4851.6	0.00%
I	0.5	0.5	4863.3	4839.8	0.48%
J	1.5	1.5	4851.6	4804.7	0.97%
K	2.5	1.0	4886.7	4804.7	1.68%
L	2.0	1.0	4875.0	4793.0	1.68%
M	2.0	1.0	4851.6	4769.5	1.69%
N	3.0	1.5	4851.6	4781.2	1.45%
O	4.0	3.0	4828.1	4722.7	2.18%
P	No crack	No crack	4851.6	4851.6	0.00%
Q	0.5	0.5	4851.6	4781.2	1.45%
R	3.0	2.0	4875.0	4781.2	0.72%

Table 4. Frequency shift data at 7782 Hz from before/after crack

Part Identification	Measured Crack Length, OD (mm)	Measured Crack Length, ID (mm)	Original Resonant Frequency (Hz)	Altered Resonant Frequency (Hz)	Percent Shift (%)
A	1.0	0.5	7804.7	7781.2	0.30%
B	1.5	1.5	7769.5	7746.1	0.30%
C	1.0	0.5	7787.1	7769.5	0.23%
D	1.5	1.5	7781.2	7757.8	0.30%
E	1.0	0.5	7734.4	7722.7	0.15%
F	0.5	0.5	7781.2	7757.8	0.30%
G	1.0	0.5	7757.8	7734.4	0.30%
H	No crack	No crack	7746.1	7757.8	-0.15%
I	0.5	0.5	7781.2	7757.8	0.30%
J	1.5	1.5	7757.8	7734.4	0.30%
K	2.5	1.0	7816.4	7781.2	0.45%
L	2.0	1.0	7816.4	7769.5	0.60%
M	2.0	1.0	7769.5	7722.7	0.60%
N	3.0	1.5	7746.1	7710.9	0.45%
O	4.0	3.0	7746.1	7699.2	0.61%
P	No crack	No crack	7757.8	7757.8	0.00%
Q	0.5	0.5	7757.8	7722.7	0.45%
R	3.0	2.0	7781.2	7734.4	0.60%

Table 5. Frequency shift data at 19040 Hz from before/after crack

Part Identification	Measured Crack Length, OD (mm)	Measured Crack Length, ID (mm)	Original Resonant Frequency (Hz)	Altered Resonant Frequency (Hz)	Percent Shift (%)
A	1.0	0.5	19078.1	19054.7	0.12%
B	1.5	1.5	19019.5	18996.1	0.12%
C	1.0	0.5	19054.7	19031.2	0.12%
D	1.5	1.5	19031.2	19007.8	0.12%
E	1.0	0.5	18996.1	18972.7	0.12%
F	0.5	0.5	19066.4	19054.7	0.06%
G	1.0	0.5	18984.4	18972.7	0.06%
H	No crack	No crack	19054.7	19054.7	0.00%
I	0.5	0.5	19031.2	19019.5	0.06%
J	1.5	1.5	19043.0	19019.5	0.12%
K	2.5	1.0	19089.8	19043.0	0.25%
L	2.0	1.0	19066.4	19007.8	0.31%
M	2.0	1.0	19007.8	18960.9	0.25%
N	3.0	1.5	19043.0	18984.4	0.31%
O	4.0	3.0	19031.2	19054.7	-0.12%
P	No crack	No crack	19031.2	19031.2	0.00%
Q	0.5	0.5	19007.8	18949.2	0.31%
R	3.0	2.0	19066.4	18996.1	0.37%

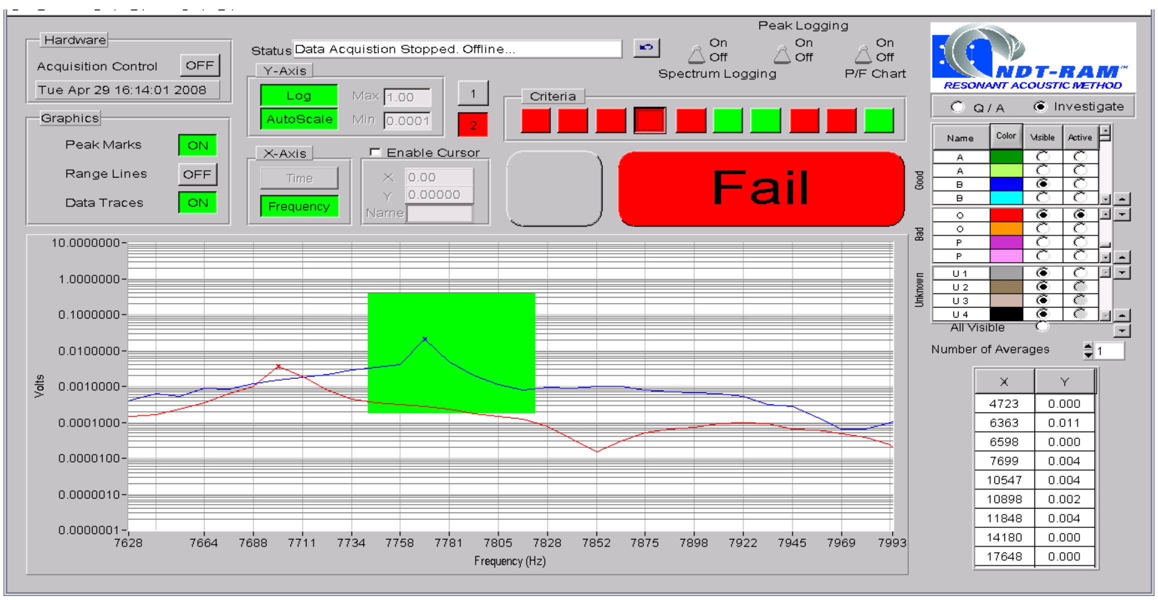

Figure 3. NDT-RAM display showing frequency shift resulting from fatigue crack testing, acceptable criteria limit shown as green box.

After the control set of parts were retested to measure the shift in resonant frequency characteristics due to the induced crack along the base of the vane, the parts were sectioned to confirm accurate visual inspection of the crack damage using the microscope. The cracks tended to propagate only along the edge of the inner or outer diameter, never cracking all the way through the vane.

EXPERIMENTAL RESULTS

The general trend of the data shows a direct correlation between the size of the observed crack and the resulting shift to resonant frequencies evaluated. Figure 4 shows this trend, plotting the percentage shift in resonant frequency from Tables 3-5 against a crack magnitude indicator. This indicator was calculated by taking the square root of the sum of the squares of the inner and outer wall crack length. Also note that a linear fit trend line from each data set plots through zero, indicating the expected result of 0% frequency shift from no crack.

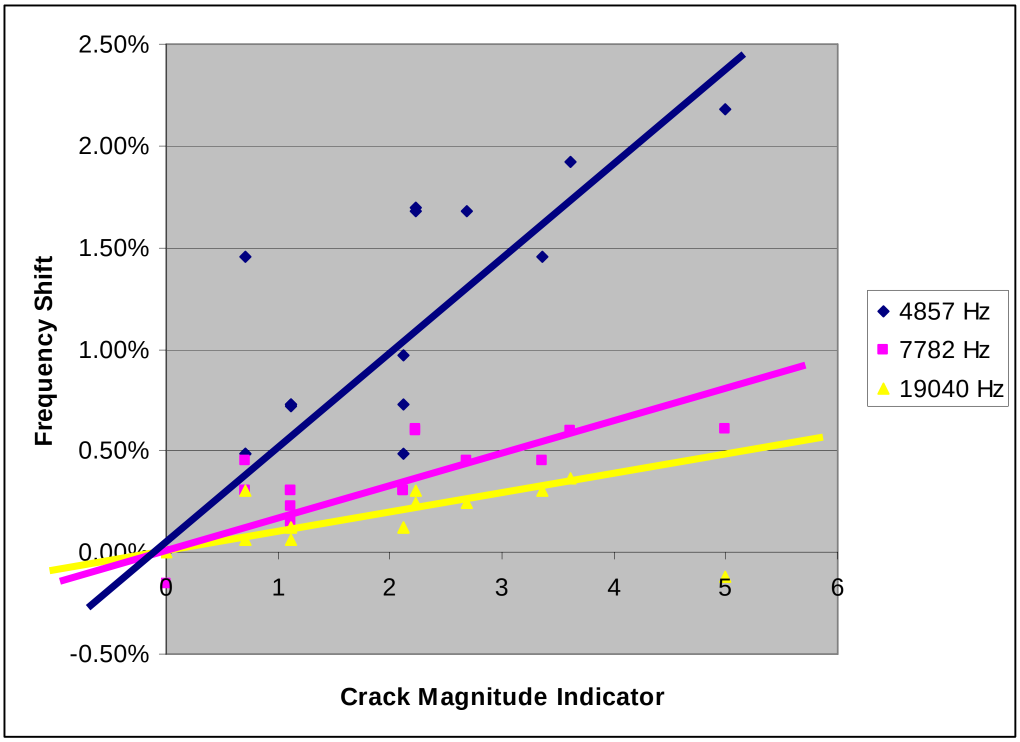

Figure 4. Correlation between resonant frequency shift and crack magnitude, displayed with linear fit trend line for three resonant frequencies

Comparing the width of the criteria limit, set at approximately twice the standard deviation (see Table 2), to the actual percent shifts in resonant frequency due to the induced cracks, the 4857 Hz range effectively sorts parts that exhibit measured cracks of at least 1.0 mm at either the inner or outer wall. In these cases, the measured frequency shift was at least 0.72% (see Table 3), larger than the 0.58% criteria limit width. Therefore, any shift in resonant frequency results in a peak lower than the specified criteria limit, similar to what is shown in Figure 3. Part D, however, exhibited anomalous results and, without determining root cause, was considered an outlier in this study. It should be noted though that the part manufacturer was targeting 2.0 mm cracks or larger for reject based upon other independent, destructive fatigue studies.

Similar results were seen based upon data at 7782 Hz. As before, by comparing the width of the criteria limit (Table 2) to the actual percent shifts at this particular nominal resonant frequency (Table 4), parts with induced cracks greater than the targeted 2.0 mm were effectively sorted from the batch given shifts of at least 0.45% (greater than the 0.44% criteria limit width). In this case, if it was necessary to sort parts exhibiting smaller cracks, the width of the criteria limit could be set closer to the standard deviation rather than conservatively set about twice the standard deviation. The effective result of this would be a slightly higher "scrap rate" of approximately 5% instead of approximately 2% (1σ vs 2σ).

The placebo parts (the two parts H and P that did not undergo fatigue crack testing mixed in with the other 16 parts of the control group) showed perfect repeatability between before and after resonant frequency measurements in all cases except one. At the 7782 Hz nominal resonant frequency, as shown in the table above, the placebo labeled H did indicate a shift between before/after data, but of just a single spectral line. All other data at all other nominal frequencies show no shift. This is likely due to the specific part H having its resonant frequency very close to the FFT spectrum bin edge. As such, the resonant frequency doesn't actually shift but the measurement of the resonant frequency may tend to "flip-flop" between spectral lines depending upon small variances in test parameters or boundary conditions.

It is also important to note that some resonant frequencies measured were very insensitive to the particular induced crack defects. For example, data at the nominal resonant frequency of 6736 Hz showed little to no frequency shift. This is important because defects do not affect all resonant frequencies the same. As a result, multiple criteria ranges are generally needed to reliably evaluate and sort parts.

CONCLUSION

The powder metal part manufacturer from this study successfully implemented RAM NDT for 100% inspection of the given part. No part failures have been reported to date.

It has been shown that resonant frequency shifts are sensitive and have a correlation to crack size. RAM NDT can be an effective tool in sorting powder metal parts based upon crack defects. It is important to note, however, that the correlation between crack size and frequency shift is dependent upon part material and geometry, and the resulting interaction with the resonant frequency mode shape. The specific experimental results from the data presented in this paper should in no way be applied to other part geometries.

REFERENCES

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