Designation: E 2001 – 98 (Reapproved 2003)

Standard Guide for
Resonant Ultrasound Spectroscopy for Defect Detection in Both Metallic and Non-metallic Parts[1]

This standard is issued under the fixed designation E 2001; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide describes a procedure for detecting defects in metallic and non-metallic parts using the resonant ultrasound spectroscopy method. The procedure is intended for use with instruments capable of exciting and recording whole body resonant states within parts which exhibit acoustical or ultrasonic ringing. It is used to distinguish acceptable parts from those containing defects, such as cracks, voids, chips, density defects, tempering changes, and dimensional variations that are closely correlated with the elastic properties of the material.

1.2 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

E 1316 Terminology for Nondestructive Examinations[2]

3. Terminology

3.1 *Definitions*—The definitions of terms relating to conventional ultrasonics can be found in Terminology E 1316.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *resonant ultrasonic spectroscopy (RUS), n*—a nondestructive examination method, which employs resonant ultrasound methodology for the detection and assessment of variations and mechanical properties of a test object. In this procedure, whereby a rigid part is caused to resonate, the resonances are compared to a previously defined resonance pattern. Based on this comparison the part is judged to be either acceptable or unacceptable.

4. Summary of the Technology (1)[3]

4.1 *Introduction*:

4.1.1 In addition to its basic research applications in physics, materials science, and geophysics, Resonant Ultrasound Spectroscopy (RUS) has been used successfully as an applied nondestructive testing tool. Resonant ultrasound spectroscopy in commercial, nondestructive testing has a few recognizable names including, RUS Nondestructive Testing, Acoustic Resonance Spectroscopy (ARS), and Resonant Inspection. Early references to this body of science often are termed the "swept sine method." It was not until 1990 **(2)** that the name Resonant Ultrasound Spectroscopy appeared, but the two techniques are synonymous. RUS based techniques are becoming commonly used in the manufacture of steel, ceramic, and sintered metal parts. In these situations, a part is vibrated mechanically, and defects are detected based on changes in the pattern of vibrational resonances or variations from theoretically calculated or empirically acceptable spectra. RUS measures all resonances, in a defined range, of the part rather than scanning for individual defects. In a single measurement, RUS-based techniques potentially can test for numerous defects including cracks and dimensional variations. Since the RUS measurement yields a whole body response, it is often difficult to discriminate between defect types, that is, cracks or other discontinuities. Nevertheless, on certain types of parts, it can be accurate, fast, inexpensive and require no human judgment, making 100 % inspection possible in selected circumstances. Many theoretical texts **(3)** discuss the relationship between resonances and elastic constants and include the specific application of RUS to the determination of elastic constants **(4)**. The technology received a quantum increase in attention when Migliori published a review article, including the requisite inexpensive electronic designs and procedures from which materials properties could be measured quickly and accurately **(5)**. The most recent applications include studies in ultrasonic attenuation, modulus determinations, thermodynamic properties, structural phase transitions, superconducting transitions, magnetic transitions, and the electronic properties of solids. A compendium of these applications may be found in the Migliori (**1**) text. Resonant ultrasound spectroscopy also found use in the study of the elastic properties of the Apollo moon rocks **(6)**.

4.1.2 This guide is intended to provide a practical introduction to RUS-based nondestructive test (NDT), highlighting successful applications and outlining failures, limitations, and

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[1] This guide is under the jurisdiction of ASTM Committee E07 on Nondestructive Testing and is the direct responsibility of Subcommittee E07.06 on Ultrasonic Method.

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[2] *Annual Book of ASTM Standards*, Vol 03.03.

[3] The boldface numbers in parentheses refer to the list of references at the end of this guide.

potential weaknesses. Vibrational resonances are considered from the perspective of defect detection in 4.2. In 4.3 and 4.4, a review of some of the types of RUS measurements are presented. In 4.5, some example implementations and configurations of RUS systems and their applications are presented. Finally, the guide concludes with a discussion of constraints, which limit the effectiveness of RUS.

4.2 *Mode Shapes and Defects*:

4.2.1 Resonant ultrasound spectroscopy/NDT techniques, operate by driving a part at given frequencies and measuring its mechanical response (Fig. 1 contains a schematic for the RUS apparatus). The process proceeds in small frequency steps over some previously determined region of interest. During such a sweep, the drive frequency typically brackets a resonance. When the excitation frequency is not matched to one of the part's resonance frequencies, very little energy is coupled to the part; that is, there is essentially no vibration. At resonance, however, the energy delivered to the part is coupled generating much larger vibrations. A part's resonance frequencies are determined by its dimensions (to include the shape and geometry) and by the density and the elastic constants of the material. The required frequency window for a scan depends on the size of the part, its mechanical rigidity, and the size of the defect being sought.

4.2.2 Vibrational resonances produce a wide range of distortions. These distortions include shapes, which bend and twist. It is known that increasing the length of a cylinder will lower some resonant frequencies. Similarly, reducing the stiffness, that is, reducing the relevant elastic constant, lowers the associated resonant frequency for most modes; thus, for a given part, the resonant frequencies are measures of stiffness, and knowledge of the mode shape helps to determine what qualities of the part affect those frequencies. If a defect, such as a crack, is introduced into a region under strain, it will reduce the effective stiffness, that is, the part's resistance to deformation, and will shift downward the frequency of resonant modes that introduce strain at the crack. This is one basis for detecting defects with RUS-based techniques.

4.2.3 The torsional modes represent a twisting of a cylinder about its axis. These resonances are easily identified because their frequencies remain constant for fixed length, independent of diameter. A crack will reduce the ability of the part to resist twisting, thereby reducing the effective stiffness, and thus, the frequency of a torsional mode. A large defect can be detected readily by its effect on the first few modes; however, smaller defects have much more subtle effects on stiffness, and therefore, require higher frequencies (high-order modes) to be detected. Detection of very small defects may require using the frequency corresponding to the fiftieth, or even higher, mode. Some modes do not produce strain in the end of the cylinder, therefore, they cannot detect end defects. To detect this type of defect, a more complex mode is required, the description of which is beyond the scope of this specification. A defect in the end will reduce the effective stiffness for this type of mode, and thus, will shift downward the frequency of the resonance. In general, it must be remembered that most modes will exhibit complex motions, and for highly symmetric objects, can be linear combinations of several degenerate modes, as discussed in 4.3.2.

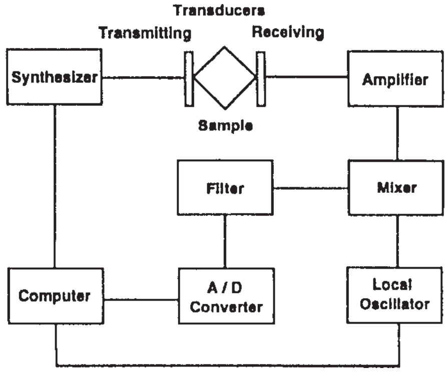

FIG. 1 Schematic of the Essential Electronic Building Blocks to Employ RUS in a Manufacturing Environment

4.3 *General Approaches to RUS/NDT*:

4.3.1 *Test Evaluation Methods* **(1)**—Once a fingerprint has been established, for conforming parts, numerous algorithms can be employed to either accept or reject the part. For example, if a frequency ±50 Hz can be identified for all conforming parts, the detection of a peak outside of this boundary condition will cause the computer code to signal a "test reject" condition. The code, rather than the inspector, makes the accept/reject decision. The following sections will expand on some of these sorting criteria.

4.3.2 *Frequency Shifts*:

4.3.2.1 Resonant ultrasound spectroscopy measurements generally produce strains (even on resonance) that are well within the elastic limit of the materials under test, that is, the atomic displacements are small in keeping with the "nondestructive" aspect of the testing. If strains are applied above the elastic limit, a crack will tend to propagate, causing a mechanical failure. Note that certain important engineering properties, for example, the onset of plastic deformation, yield strength, etc., generally are not derivable from low-strain elastic properties. Sensitivity of the elastic properties of an object to the presence of a crack depends on the stiffness and geometry of the sample under test. This concept is expanded upon under 4.4.3.

4.3.2.2 Fig. 2 shows an example of the resonance spectrum for a conical ceramic part. Several specific types of modes are present in this scan, and their relative shifts could be used to detect defects as discussed above; however, the complexity is such that, for NDT purposes, some selections must be made so that only a portion of such a large amount of information is used. For simple part geometries, the mode type and frequency can be calculated, and selection of diagnostic modes can be based on these results. For complex geometries, empirical approaches have been developed to identify efficiently diagnostic modes for specific defects. In this process, a technician measures the spectra for a batch of known good and bad parts. The spectra are compared to identify diagnostic modes whose shift correlates with the presence of the defect. The key is to isolate a few resonances, which differ from one another, when known defects are present in the faulty parts.

4.3.3 *Peak Splitting*—One of the techniques employed for axially symmetric parts is identified in texts on basic wave

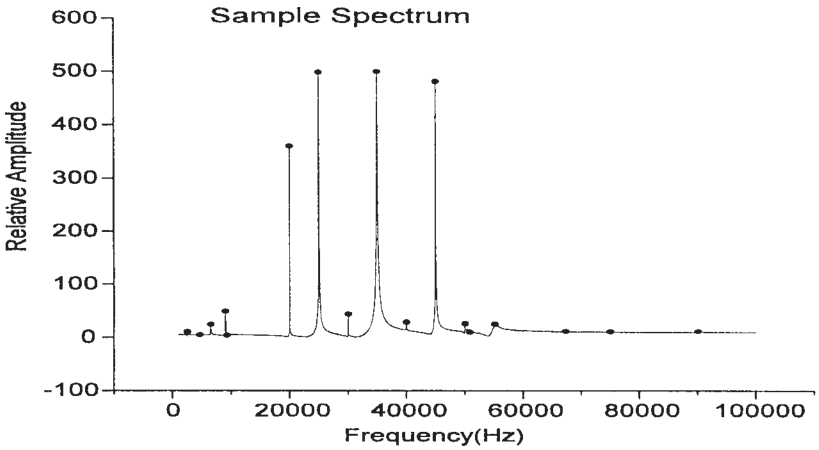

FIG. 2 Typical Broad-Spectrum Scan

physics **(7)**. Some test procedures are based on simple frequency changes while others include the recognition that symmetry is broken when a defect is present in a homogeneous, isotropic symmetrical part. These techniques employ splitting of degeneracies or simply "splitting." A cylinder actually has two degenerate bending modes, both orthogonal to its axis. The bending stiffness for both of these modes, and therefore their resonance frequency, is proportional to the diameter of the cylinder. Because the part is symmetric, both modes have the same stiffness, and therefore, the same frequency (the modes are said to be degenerate and appear to be a single resonance). When the symmetry is broken by a chip, however, the effective diameter is reduced for one of the orthogonal modes. This increases the frequency for that mode, so both modes are seen. In addition, a crack or inclusion affects the symmetry. This splitting of the resonances is illustrated in Fig. 3, which shows spectra for a good part and two defective parts. The part is a steel cylinder. Fig. 3 also demonstrates a useful feature of this particular technique, that is, the size of the splitting is proportional to the size of the defect. It is important to recognize that not all resonance peaks are degenerate. Pure torsional modes, for example, are not degenerate, so they cannot be used for splitting.

4.3.4 *Phase Information and Peak Splittings*:

4.3.4.1 In practice, the same empirical approach described for frequency shifts is used to identify diagnostic modes whose

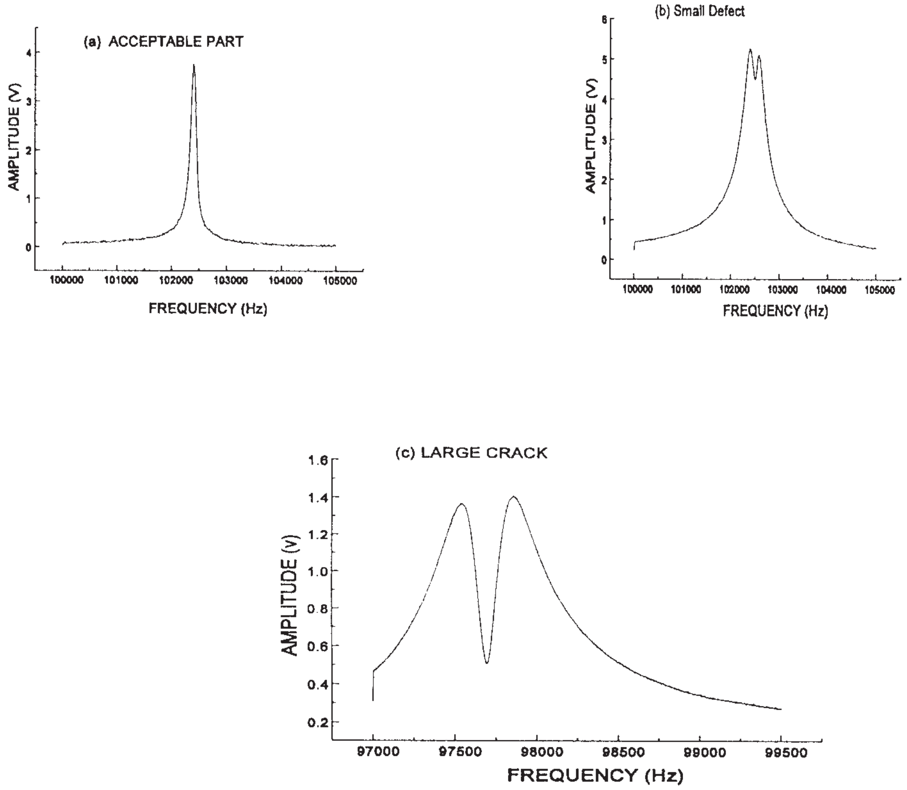

FIG. 3 Shown is a Bending Mode Within a Resonance Spectrum of an Acceptable Steel Cylinder (a), One With a Small Defect (b), and One With a Large Crack (c).

splittings correlate with the size of a defect of interest. The sensitivity of this type of measurement is enhanced by the interference, which occurs between closely-spaced peaks. The destructive interference develops into a visible spectral splitting which would not be noticeable with the amplitude spectrum (the real and quadrature components add to form the amplitude response). Most commercial systems function reasonably well without this attribute, but the problem can be exacerbated when the material exhibits resonance line widths which are greater than 1 % of the frequency. Under such circumstances, it may be impossible to detect splittings without phase information.

4.3.4.2 Degenerate modes all have the same phase at low-symmetry points; therefore, if one mode is shifted slightly destructive interference occurs between them, showing up as a splitting if the sample rigidity is sufficient. The frequency difference between the two resulting peaks increases in direct proportion to the defect size. This does not hold for accidental degeneracies, which are modes that by coincidence rather than by symmetry have the same frequency. The actual shift in frequency is no more than would be expected for an isolated mode, but the interference enhances the visibility.

4.3.5 *Dimensional Measurements*:

4.3.5.1 Industrial sorting of parts often occurs in two sectors: defect detection and dimensional inspection. Ceramic plants often spend more resources on the latter than crack and chip investigations. It is a relatively simple matter to use RUS techniques to measure physical parameters, such as weight, density, and dimensions. In practice, one measures all the physical attributes possible. For a ring, these would include weight, thickness, outer diameter, and inner diameter. It is imperative to use “good”, that is, as free of defects as possible, parts in this study. One measures a suitable number of the lowest resonances and either plots each resonance frequency as a function of each parameter or uses the correlation feature of standard spreadsheet programs. The best results are obtained when singlets (single resonances) or nondegenerate modes are used. Statistical analysis will reveal which resonances have significant correlations with the desired physical attribute.

4.3.5.2 Usually, these measurements are performed in conjunction with crack/chip/seam detection. Resonant ultrasound spectroscopy techniques often have to accommodate shifts in resonance frequencies associated with density differences in addition to those resulting from dimensional variations with sintered parts (ceramics and powder metals). As long as the part is within the tolerance limits, and no other critical defect is present, it is acceptable to pass the item. This is accomplished by varying the frequency window that is scanned. Fig. 4 illustrates the ability to determine the thickness of an alumina washer. Twenty washers were measured with an accuracy of ~1 µm and the results are plotted against the frequency of specific resonances.

4.4 *Practical Considerations*:

4.4.1 *Implementation*:

4.4.1.1 An integration of RUS techniques into a manufacturing process is illustrated in Fig. 5 as an example of how the ideas of 4.3 are integrated into a commercial product. The key element is the synthesizer/receiver of which several commercial instruments exist. It generates a swept sine oscillation over a defined range as a continuous wave (CW) electrical signal, and then moves to the next defined range. This pattern is replicated until the scan is completed. Either a piezoelectric or an EMAT **(8)** transducer converts the electrical signal into a mechanical vibration which excites the part. A second transducer senses the vibration and converts it back to electrical energy. The receiver detects the signal and performs an analog to digital conversion. Then, a computer processes the signal and displays the frequency spectrum. If the measurement is being performed in a laboratory, the spectrum is analyzed visually to observe shifts, splits, or other phenomena of interest. In a production environment, a display is neither required nor even desirable under some circumstances. The computer applies an algorithm that passes or rejects the part based on predetermined criteria as described above. The time required for a measurement depends on the size of the part and the mechanical attenuation (defined by the resonance line width) of the material, as discussed in Migliori’s textbook **(1)**. Mode measurement times in some particular systems may typically range from 0.25 to 2 s/mode (depending on their stiffness) and a particular part may require two to five modes to check for all types of defects, as shown in Fig. 5.

4.4.1.2 A specific application requires the development of a complete NDT system. This system is defined by measuring the part for all of the types of defects of interest and integrating the RUS measurement system with materials handling equipment and with appropriate control hardware and software. Fig.

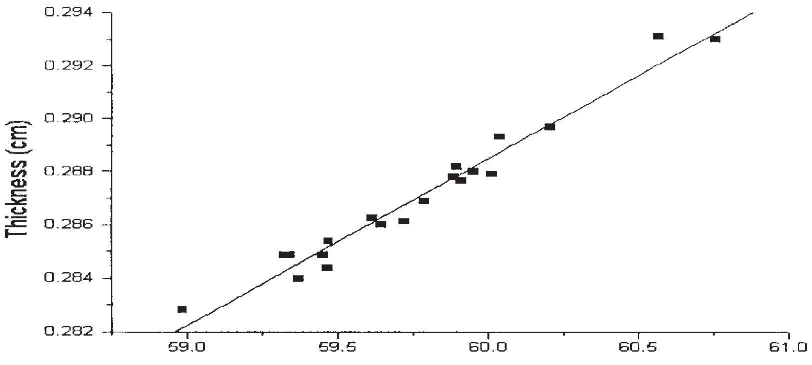

FIG. 4 Illustrates the Result of Measuring Ceramic Washers With a Digital Micrometer and Plotting the Thickness Against a Specific Resonance Mode

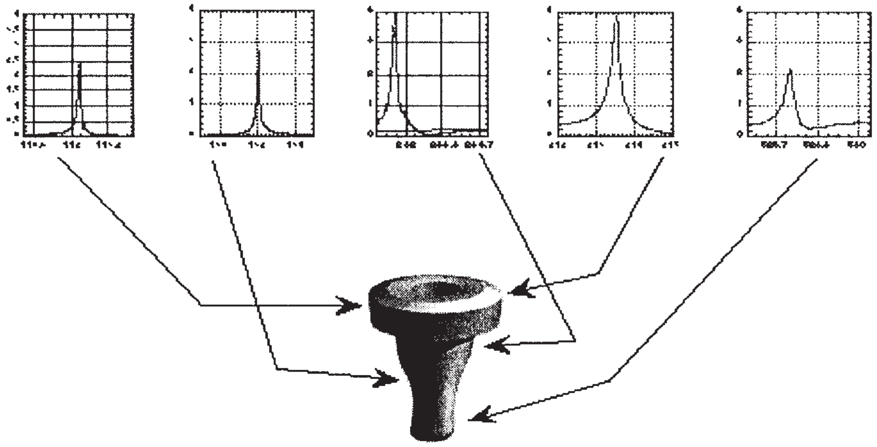

FIG. 5 RUS Techniques Applied to a Complex Ceramic Part in Which Many Different Defects Might Be Present

5 illustrates the type of defects, which can be found using RUS **(9)**. Five modes are used to detect the various defects of concern. The first mode is a bending mode, which measures the top, washer-shaped section of the part. The second mode is a bending mode for the lower, rounded conical section of the part. It is sensitive to circumferential defects. The third mode is a breathing mode for the conical section. It is sensitive to axial defects. The fourth mode is a transverse bending mode for the washer section, particularly sensitive to gross cracks in the section that move the first mode outside the measurement window. The fifth mode is a bending mode for the tip. The frequencies of the three higher modes all shift considerably due to standard dimensional variation, so information from the two lower modes is used to dynamically set the frequency windows for the higher mode scans. The five measurements require a total of 5.6 seconds.

4.4.1.3 If a calibration is performed, the following procedure is recommended. The RUS apparatus can be calibrated using a combination of a signal generator and a defined part. Upon initial electronics checkout, a known calibrated signal is inserted from a signal generator, and the response recorded. Some manufacturers require a ±2 Hz accuracy from a 1 MHz signal. Following the electronics acceptance, the simplest calibration technique is to employ a standard part. These parts can be of any geometry, but a small (≤50-g) cylinder is recommended. This part is unit specific and is delivered with its spectra to the user concerned with calibration, both in hard copy and as a digital file stored in the software. The spectra is recorded over a broad range and compared with the file frequencies, for a defined temperature.

4.4.2 *Application Examples*:

4.4.2.1 The detection of defects using RUS-based techniques has been demonstrated successfully for numerous types of parts. Four examples will be cited here to show the range of applications. These examples highlight some attributes of RUS techniques for nondestructive evaluation. They also illustrate some technical considerations that impact the implementation of RUS for a specific part.

4.4.2.2 Fig. 3 illustrates one application of RUS to the detection of defects in solid cylinders. For a homogeneous, isotropic part, Fig. 3 is applicable; however, steel parts usually are anisotropic because their forming process usually introduces texture. All conforming parts, therefore, will have split degeneracies, as well as those containing defects of interest. The figure shows a diagnostic mode for a conforming part, for a part with a small crack, and for a part with a large crack. The defect of interest here is a small circumferential crack. The sorting of parts is accomplished by documenting the normal, acceptable split and discarding parts which exhibit larger ones. The existence of this effect places a lower bound on the size of a crack that can be detected. The defects that are of most interest almost always produce spectral shifts well above this lower bound. Depending on the materials properties, frequency shifts can be used for the same purpose.

4.4.2.3 Setting the rejection criteria is the primary task in the engineering effort required to customize RUS techniques to a given part. For the example discussed above, this approach is able to detect reliably cracks as small as 0.3 mm × 1 µm × 0.8 µm in roller bearing elements. The test also is able to detect heat-treatment failures and inclusions, and is applied successfully to both polished and rough finished parts.

4.4.2.4 In 4.3.5, the application of RUS to measuring the length of similar parts is discussed. This application depends on identifying modes that vary with the dimension of interest. To measure length, a torsional mode is used because its resonance frequency varies inversely with length and it does not split. The mode selected must be of sufficiently high order to provide the required accuracy, but not so high that the measurement is complicated by the presence of other modes within the frequency window. For the example in Fig. 4, a measurement precision of ±5 µm is required.

4.4.2.5 Resonant ultrasound spectroscopy-based techniques also have been used to detect chips and cracks in ceramic parts. Successful implementations find chips, which cover only 0.01 % of the surface area of the part. In a typical example, the spectrum of the chipped part shows a 20 Hz split of 240 kHz (about 0.008 %), a good approximation to the size of the chip. In addition, the resonance frequency for conforming parts usually is lower than that for those containing chips (because chips usually reduce only the inertia of the object as they occur at relatively lightly strained edges and corners). Note that cracks have a much more severe effect on the strength of the part, and thus, produce much larger resonance shifts than do chips.

4.4.2.6 Resonant ultrasound spectroscopy techniques also have been applied to the measurement of the mass of ceramic parts where the density of the part varies substantially from batch to batch. All of the parts are within acceptable production dimensional variations but monitoring the change in average mass provides useful insights for controlling other production variables and can be done faster than by weighing. This approach involves developing a parameter that combines modes that vary with dimensions and correcting for density variations. This parameter is accomplished by noting that density variations affect all modes in the same direction; thus, the frequency measurements can be combined mathematically to define a suitable parameter.

4.4.2.7 Finally, when sorting parts by a RUS-based inspection system, data on all failures can be stored. While the data can be analyzed in detail, it is available also for statistical process control. For example, a protocol can be established to alarm the system if three consecutive parts fail for any reason or can be limited to notify the operator in the case of part height exceeding the established limit for more than ten measurements. This rapid feedback can be used to control manufacturing parameters, as well as to determine which process stage is responsible for a given defect. Significant savings in waste accrue when a process error is found early in the manufacturing cycle.

4.4.3 *Constraints*:

4.4.3.1 In principle, a large enough set of the resonances of any object measured sufficiently accurately would enable detection of the smallest elastic or dimensional anomaly; however, often there are practical constraints limiting the instances in which RUS/NDT techniques can be applied successfully. Properties common to objects successfully tested by RUS/NDT techniques are: small size and weight (preferably less than 2 kg and .5 m with any maximum dimension), however one manufacturer claims to have success with parts over 20 kg and exceeding 1 m in some dimension; precise dimensions and high homogeneity. The more precise and homogeneous a part, the smaller the defect that can be detected; highly symmetrical shapes or simple shapes; and, resonances from hard (acoustically responsive) samples. These parameters may give limitations to the size, shape, and location of the minimum detectable defects.

4.4.3.2 In general, objects that do not meet at least three of these conditions produce difficulties, which in practice often require too many resources to eliminate. A discussion of each condition is provided in more detail below.

4.4.3.3 A major problem encountered with large objects is their weight. The support points are places of large strains in the object and a place of solid contact with some support structure. This problem may cause a plastic deformation in the object and, for calculable objects, violates the requirement for a free boundary. Precisely reproducible support of heavy objects is difficult to achieve although supporting the weight over a large area on foam rubber or another soft material may be successful. If the transducer mass is negligible, solid bonding of the transducers to the object will not affect the resonances but may produce reproducibility problems. Large objects, of course, will have low-frequency resonances, necessitating special instrumentation. Because the detection limit for a defect is set by the size of the defect compared to the size of the object, the ability to detect a small defect in a large object becomes severely limited by the overall sensitivity, noise, and reproducibility of the measuring system.

4.4.3.4 Resonant ultrasound spectroscopy measures many properties simultaneously. In fact, unless the nature of the modes is known, it is very difficult to tell whether a frequency shift is due to a dimensional change, an elastic modulus change, or a homogeneity change without analyzing the spectrum using parts with known, quantified defects. The changes in the frequency pattern may be related to different defects, dimensional changes or differences in materials properties. These must be studied carefully using a sufficiently large batch of representative samples. Fig. 5 shows an example where evaluating five separate frequency windows can detect different defects at different locations.

4.4.3.5 The breaking of a degeneracy by changing the symmetry of an object produces peak splitting which, with interference effects described in 4.3.3, provides the most sensitive detection of cracks, chips, and the like. The nature of many machining and grinding operations means that precision components usually are of high symmetry, and obversely, it is difficult to mass-produce precision parts of low symmetry. The complexity of a shape will affect the mixing of the mode types and the density of modes per unit frequency of the object. With simple geometries, it becomes easier to find diagnostic resonances for sorting conforming and nonconforming parts than with complex shapes. In the event that a part has a complex shape or is inhomogeneous, different software tools may be able to enable RUS testing.

4.4.3.6 The dissipation or internal friction in a material determines the width of the resonance peaks. With soft materials (copper, carbon composites, etc.) the amplitude of the peaks is low, introducing noise problems, and the width reduces the precision with which the peak center-frequency can be determined.

4.5 *Summary*—Resonant ultrasound spectroscopy is a new NDT technique. Although, as with any technique, RUS has limits, when properly implemented, a wide range of parts and defects can be examined. RUS can be applied to metal, ceramic, and composite parts. Because it is a whole body measurement, RUS determines the structural integrity of a part rather than scanning for "indications" of the location of individual defects.

5. Significance and Use

5.1 The primary advantage of RUS is its ability of making numerous measurements in a single test. In addition, it can examine rough ground parts. It requires little sample preparation, no couplants, and generally will work with soiled items; however, it has no capability with soft materials. Soft metals, polymers, rubbers, and wood parts are not viable candidates for this technology.

6. Apparatus

6.1 A generic schematic apparatus for applying RUS/NDT is shown in Fig. 1.

7. Keywords

7.1 acoustic resonance spectroscopy; elastic properties; modes; nondestructive test; peak shifting; peak splitting; quality control; resonance inspection; resonance ultrasound spectroscopy; resonances

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