



Standard Practice for Process Compensated Resonance Testing Via Swept Sine Input for Metallic and Non-Metallic Parts¹

This standard is issued under the fixed designation E2534; 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 practice describes a general procedure for using the process compensated resonance testing (PCRT) via swept sine input method to detect resonance pattern differences in metallic and non-metallic parts. The resonance differences can be used to distinguish acceptable parts with normal process variation from parts with material states and defects that will cause performance deficiencies. These material states and defects include, but are not limited to, cracks, voids, porosity, shrink, inclusions, discontinuities, grain and crystalline structure differences, density-related anomalies, heat treatment variations, material elastic property differences, residual stress, and dimensional variations. This practice is intended for use with instruments capable of exciting, measuring, recording, and analyzing multiple whole body, mechanical vibration resonance frequencies in acoustic or ultrasonic frequency ranges, or both.

1.2 This practice uses inch pound units as primary units. SI units are included in parentheses for reference only, and are mathematical conversions of the primary units.

1.3 *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:²

E1316 Terminology for Nondestructive Examinations

E2001 Guide for Resonant Ultrasound Spectroscopy for

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

Current edition approved Dec. 1, 2015. Published December 2015. Originally approved in 2010. Last previous edition approved in 2010 as E2534-10. DOI: 10.1520/E2534-15

² For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

Defect Detection in Both Metallic and Non-metallic Parts

3. Terminology

3.1 Definitions:

The definitions of terms relating to conventional ultrasonic examination can be found in Terminology **E1316**.

3.2 Definitions of Terms Specific to This Standard:

3.2.1 *broadband*—the range of frequencies, excitation parameters, and data collection parameters developed specifically for a particular part type.

3.2.2 *classification*—the labeling of a teaching set of parts as acceptable or unacceptable.

3.2.3 *false negative, n*—part failing the sort but deemed by other method of post-test/analysis to have acceptable or conforming specifications

3.2.4 *false positive, n*—part passing the sort but exhibiting a flaw (either inside the teaching set of flaws or possibly outside the teaching set range of flaws) or nonconforming to specification.

3.2.5 *margin part*—a single part representative of a part type that is used to determine measurement repeatability and for system verification.

3.2.6 *Process Compensated Resonant Testing (PCRT)*—a nondestructive examination method that enhances RUS with pattern recognition capability. PCRT more effectively discriminates between resonance frequency shifts due to unacceptable conditions from resonance frequency shifts due to normal, acceptable manufacturing process variations. The process employs the measurement and analysis of acoustic or ultrasound resonance frequency patterns, or both. PCRT pattern recognition tools identify the combinations of resonance patterns that most effectively differentiate acceptable and unacceptable components. Statistical scoring of the resonance frequencies is used to compare components to known acceptable and unacceptable populations, quantify process variation, and characterize component populations.

3.2.7 *resonance spectra*—the recorded collection of resonance frequency data, including frequency peak locations and the characteristics of the peaks, for a particular part.

3.2.8 *Resonant Ultrasound Spectroscopy (RUS)*—Basic RUS (1)³ was originally applied in fundamental research applications in physics and materials science. Other recognizable names include acoustic resonance spectroscopy, acoustic resonant inspection, and resonant inspection. Guide E2001 documents RUS extensively. RUS is a nondestructive examination method that employs the measurement and analysis of acoustic or ultrasonic resonance frequencies, or both, for the identification of acceptable variations in the physical characteristics of test parts in production environments. In this procedure an isolated, rigid component is excited, producing oscillation at the natural frequencies of vibration of the component. Diagnostic resonance frequencies are measured and compared to resonance frequency patterns previously defined as acceptable. Based on this comparison, the part is judged to be acceptable or, if it does not conform to the established pattern, unacceptable.

3.2.9 *sort*—a software program capable of classifying a component as acceptable or unacceptable.

3.2.10 *teaching set*—a group of like components including examples of known acceptable and known unacceptable components representative of the range of acceptable variability and unacceptable variability.

3.2.11 *work instruction*—stepwise instructions developed for each examination program detailing the order and application of operations for PCRT examination of a part.

4. Summary of Practice

4.1 Introduction:

4.1.1 Many variations on resonance testing have been applied as nondestructive examination tools to detect structural anomalies that significantly alter component performance. The details of this basic form of resonance testing are outlined in Guide E2001.

4.1.2 Process Compensated Resonant Testing (PCRT) is a progressive development of the fundamental principles of RUS, and can employ various methods for enhancing the discrimination capability of RUS. Throughout the 1990s, application of RUS for production NDT led to better understanding of the challenges associated with differentiating resonance variations caused by structural anomalies from resonance variation from normal and acceptable process variations in mass, material properties, and dimensions (2,3). PCRT first became commonly used in the production examination of metal and ceramic parts in the late 1990s (4). By the early 2000s, PCRT had essentially developed into the robust NDT capability it is today (5).

4.1.3 PCRT is a comparison technology using a swept sine wave to excite the components through a range of resonance frequencies determined by the part's mass, geometry, and material properties. The resonance spectrum is then compared to resonance spectra for known acceptable components and unacceptable components. The database of known acceptable and unacceptable components is established through the col-

lection of a teaching set of components that represent the range of acceptable process variation and the unacceptable conditions of interest. PCRT applications are *taught* to be sensitive to resonance variations associated with unacceptable components and also *taught* to be insensitive to variations associated with acceptable components. PCRT pattern recognition tools identify the combination of resonance frequencies that most effectively differentiate the acceptable and unacceptable components. Statistical tools score each component based on its similarity to the known acceptable and unacceptable populations, and establish scoring PASS/FAIL limits for each criteria. A component with resonance frequencies sufficiently similar to the acceptable components and different from the unacceptable components will pass the PCRT inspection. A component that fails either criteria will be rejected. In one examination cycle, PCRT-based techniques can test for a single anomaly, or for combinations of anomalies, as listed in 1.1. The PCRT measurement yields a whole body response, finding structurally-significant anomalies anywhere within the part, but it is generally not capable of determining the type or location of the anomaly. A teaching set of parts must contain both acceptable and unacceptable samples as determined by someone knowledgeable of the design, validation testing, and minimum functional requirements of the part.

4.1.4 PCRT can be applied to new parts in the production environment, to parts currently in service, or in a combined program in which parts are initially classified as free of substantial anomalies in production, and then periodically re-examined with PCRT in order to monitor for the accumulation of fatigue and damage resulting from use. One example of a PCRT application is gas turbine engine blades. Application of PCRT to the blades in the production environment can detect manufacturing and material defects such as casting shrinkage, cracks, voids, shifted cores, heat treatment irregularities, and other material variation. Since turbine blades are periodically inspected throughout their useful lives, PCRT can be applied during these in-service inspections to accept only parts that are free of service induced defects such as gamma prime solutioning, rafting, creep, cracks, inter-granular attack, and excessive wear and fatigue.

4.1.5 This practice is intended to provide a practical guide to the application of PCRT-based nondestructive testing (NDT) to metallic and non-metallic parts. It highlights the steps necessary to produce robust and accurate test applications and outlines potential weaknesses, limitations and factors that could lead to misclassification of a part. Some basic explanations of resonances, and the effects of anomalies on them, are found in 4.2. Some successful applications and general description of the equipment necessary to successfully apply PCRT for classification of production parts are outlined in 5.1 and 5.2, respectively. Additionally, some constraints and limitations are discussed in 5.3. The general procedure for developing a part-specific PCRT application is laid out in 6.1.

4.2 Resonances and the Effect of Anomalies:

4.2.1 The swept sine method of vibration analysis operates by driving a part at given frequencies (acoustic through ultrasonic, depending on the part characteristics) and measuring its mechanical response. Fig. 1 contains a summary of the

³ The boldface numbers in parentheses refer to a list of references at the end of this practice.

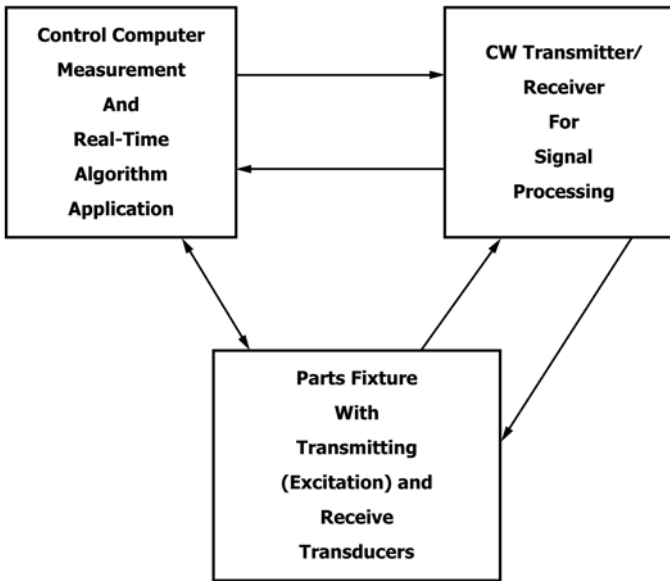


FIG. 1 PCRT System Schematic

embodiment of a PCRT apparatus. The swept sine wave proceeds in small frequency steps over a previously determined broadband frequency range of interest. 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 geometry, density, and material elastic constants (mechanically equivalent to mass, stiffness, and damping) of the material. An example of the resonance spectra for a part is shown in Fig. 2 for reference.

4.2.2 If a structural anomaly, such as a crack, is introduced into a region under strain, it will change the effective stiffness of a part (decrease stiffness for a crack). That is, the part's resistance to deformation will change and will shift some of the part's resonant frequencies (downward for decreasing stiffness). Voids in a region can reduce mass and increase certain resonant frequencies. In general, any change to a part that alters the structural integrity, changes a geometric feature or affects the material properties will alter its natural resonance frequencies. Graphic examples of the effects of various anomalies on resonances are presented in Guide E2001.

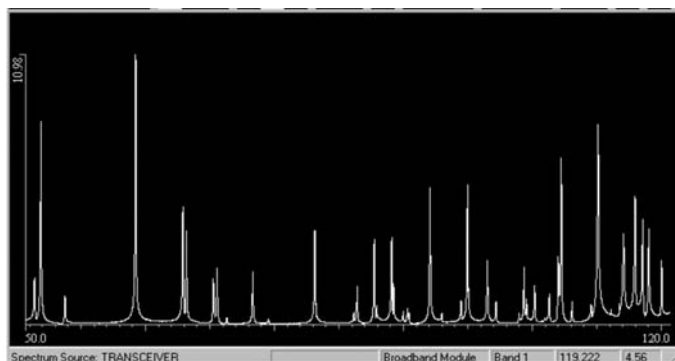


FIG. 2 Resonance Spectra (50 kHz – 120 kHz)

4.2.3 For example, the torsional (twisting) (Fig. 3) resonant modes represent a twisting of a part about its axis. In the simple example of a long cylinder, these resonances are easily identified because some of their frequencies remain constant for a 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 both shifts to a lower value and then alters the mode shape. Other resonances representing different resonance mode shapes of the part will not be affected in the same manner. Also, a large structural anomaly can be detected readily by its effect on the first few resonant frequencies. However, smaller structural anomalies have much more subtle and localized effects on stiffness, and therefore, often require higher frequencies (high-order resonant modes and harmonics) to be detected. In general, it must be remembered that most parts will exhibit complex motions when resonating. Analyzing the relationship between the resonant frequencies provides one way to generate the information necessary to interpret the data resulting from measuring the frequencies of the various resonant modes. These relationships form one basis for detecting the difference between normal, expected variations and variations indicating significant structural or geometric differences from one part to another. A broad body of research is available describing various other nonproprietary approaches to identifying significant features (flaws, damage, etc) from changes in their vibration characteristics in the presence of environment or process variation.(6)

5. Significance and Use

5.1 *PCRT Applications and Capabilities*—PCRT has been applied successfully to a wide range of NDT applications in the manufacture and maintenance of metallic and non-metallic parts. Examples of anomalies detected are discussed in 1.1. PCRT has been shown to provide cost effective and accurate NDT solutions in many industries including automotive, aerospace, and power generation. Examples of successful applications currently employed in commercial use include, but are not limited to:

- (1) Silicon nitride bearing elements
- (2) Steel, iron, and aluminum rocker and control arms

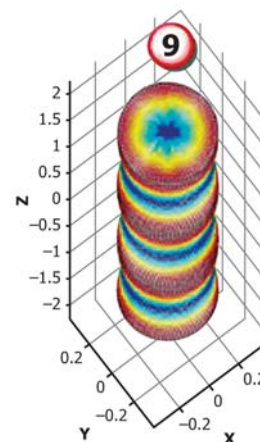


FIG. 3 Torsional Mode for a Cylinder