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Standard Practice for Part-to-Itself Examination Using Process Compensated Resonance Testing Via Swept Sine Input for Metallic and Non-Metallic Parts[1]

This standard is issued under the fixed designation E3213; 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 covers a general procedure for using the Process Compensated Resonance Testing (PCRT) via swept sine input method to perform Part-to-Itself (PTI) examination on populations of newly manufactured and in-service parts. PCRT detects resonance pattern differences in metallic and non-metallic parts. Practice E2534 for Defect Detection with PCRT and Practice E3081 for Outlier Screening with PCRT cover the development and application of PCRT sorting modules that inspect a part at a single point in time. These methods use the resonance frequency spectra recorded from test parts and perform different statistical analyses to compare test parts to reference populations. These comparisons include, and must compensate for, the normal geometric, material, and processing variations present in any population of parts. In many applications, however, the user may need to evaluate the effects of a single processing step or in-service load in isolation from other sources of variation. For example, a manufacturer may want to perform process monitoring and control on a heat treatment or hardening process. A maintainer may want to evaluate the effect of service cycles in an engine. A PCRT PTI examination measures the resonance frequency spectrum of a part at two points in time, such as before and after a manufacturing process step, and calculates the change in resonance frequencies to evaluate the effect of the intervening process. Control limits can be set on the frequency change to field a PTI PASS/FAIL inspection capability. The limits may be based on training populations of parts with acceptable and unacceptable levels of change, model predictions of the effects of part changes, or criteria derived from process control practices. Manufacturing processes and in-service loads that can be evaluated with a PCRT PTI inspection include, but are not limited to heat treatment, hot isostatic pressing (HIP), shot peening, induction hardening, carburization, coating, thermal history changes, residual stress changes, creep, plastic deformation, corrosion, and fatigue. 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 *Units*—The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.4 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E1316 Terminology for Nondestructive Examinations

E2001 Guide for Resonant Ultrasound Spectroscopy for Defect Detection in Both Metallic and Non-metallic Parts

E2534 Practice for Process Compensated Resonance Testing Via Swept Sine Input for Metallic and Non-Metallic Parts

E3081 Practice for Outlier Screening Using Process Compensated Resonance Testing via Swept Sine Input for 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.

[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.

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[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.

3.2 *Definitions of Terms Specific to This Standard:*

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

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

3.2.3 *diagnostic resonance mode, n*—a resonance mode of vibration that is sensitive to the change in material state produced by a manufacturing process or in-service damage.

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

3.2.5 *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.

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

3.2.7 *Part-to-Itself (PTI) examination, n*—a PCRT PTI examination uses the resonance spectrum recorded for a part in two different states, such as before and after a manufacturing process like heat treatment or hardening, or after the accumulation of in-service loads/damage.

3.2.7.1 *Discussion*—The change in resonance frequencies is used to evaluate the change in material state. The frequency changes can be compared to acceptability limits to evaluate manufacturing processes and the effects of accumulated in-service damage.

3.2.8 *Process Compensated Resonance Testing (PCRT), n*—PCRT is a nondestructive examination method that enhances RUS with pattern recognition capability.

3.2.8.1 *Discussion*—PCRT effectively discriminates 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 ultrasonic resonance frequency patterns, or both. PCRT pattern recognition tools identify the combinations of resonance patterns that most effectively differentiate acceptable from unacceptable components. In PTI applications, the change in resonance frequencies for diagnostic modes is used to evaluate the material state change produced by manufacturing processes, repair processes, or in-service loads/damage and determine whether a part is acceptable.

3.2.9 *quality factor (Q factor), n*—dimensionless property of resonance peak that describes the peak shape, that is, width at full width at half maximum (FWHM) divided into the peak center frequency; peaks with higher Q factor values are narrower and sharp.

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

3.2.11 *Resonant Ultrasound Spectroscopy (RUS), n*—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.

3.2.11.1 *Discussion*—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. 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.

3.2.12 *sorting module, n*—for PCRT PTI applications, a software program that records diagnostic resonance modes in two or more material states of a part, calculates the frequency changes for those modes between the material states, compares the frequency changes to acceptability limits, and classifies a part as acceptable or unacceptable.

3.2.13 *teaching set, n*—for PCRT PTI applications, a group of parts identical to normal production or in-service parts (with normal part-to-part variation) subjected to the process or in-service load(s) of interest to identify diagnostic resonance modes and quantify the frequency changes produced by the material state changes resulting from the process or loads.

3.2.13.1 *Discussion*—An effective teaching set includes examples of acceptable and unacceptable material state changes.

3.2.14 *work instruction, n*—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 Resonance 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 variations from normal and acceptable process variation 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

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

frequencies determined by the mass, geometry, and material properties of the part. In Part-to-Itself (PTI) applications, the resonance spectrum for a part is recorded for the part in two or more different material states. The resonance spectrum recorded at each material state is stored in a database organized by component serial number. For non-serialized components, a temporary serialization scheme is implemented to track parts through a manufacturing or repair process. The PCRT measurement yields a whole-body response, finding structurally-significant material state variations anywhere within the part, but it is generally not capable of determining the type or location of the anomaly.

4.1.4 PCRT PTI examination can be applied to new parts in the manufacturing environment, to parts currently in service in a maintenance environment, or in a combined program in which PTI examinations are conducted from new manufacture throughout the part service life. In a manufacturing application, material state changes resulting from manufacturing processes can include heat treatment, hot isostatic pressing (HIP), induction hardening, carburization, and many others. The change in frequency of diagnostic resonance modes is used to evaluate the change in the material state of the part. This evaluation can include a comparison of the frequency changes to acceptability limits for monitoring and control of the manufacturing process and for nondestructive testing (NDT) of 100 % of the part population to determine whether the final parts are acceptable. In a maintenance application, material state changes resulting from the accumulation of in-service loads and damage are evaluated by measuring the frequency changes between service intervals. The frequency changes are compared to limits to determine if the accumulated damage has rendered the part unserviceable, enabling a condition-based maintenance approach. A second maintenance application is the evaluation of repair processes that change the part material state. The changes in frequencies measured before and after the repair process are compared to acceptability limits to determine if the repair process was performed to specification, and for NDT of 100 % of the post-repair population to determine if the repaired parts are acceptable. One example of a PCRT PTI manufacturing application is induction hardening of steel gears. The gears are measured before and after induction hardening, and the frequency change is calculated and compared to acceptability limits to determine if the case depth and hardness are within specification. An example of a maintenance PTI application is an aircraft engine turbine blade at an engine overhaul facility. Blades are measured in the as-new condition when they are purchased as spares, again when the blades return to overhaul after a service interval, and finally after a rejuvenation repair process. The as-new to service interval frequency change is used to determine if a part has accumulated unacceptable levels of damage. The frequency change from the repair process is used to determine if the repair has been performed to specification.

4.1.5 This practice is intended to provide a practical guide to the application of PCRT PTI examination of 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 schematic for one 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 resonance frequencies of the part, 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. The resonance frequencies of a part are determined by the 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 Material state changes from a manufacturing process, accumulated damage, or a repair process will change the effective stiffness of a part. That is, the resistance of the part to deformation will change and will shift the resonance frequencies of resonance modes that are sensitive to that material state change. 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.

4.2.3 For example, the resonance mode for a turbine blade shown in Fig. 3 features significant bending deformation in the airfoil section. Material state changes that affect the airfoil section, such as a diffusion heat treatment in a coating process, will cause frequency changes in airfoil-centric modes that correlate to the magnitude of the material state change. In the case of diffusion heat treatments during coating, this will tend to reduce the overall stiffness of the airfoil material, producing a decrease in frequency for mode shapes that feature airfoil deformation. Other resonance modes with deformation in areas that are masked during the coating and heat treatment process, like the fir tree, will be affected much less or not at all.

4.2.4 Another example is induction hardening of steel gears. The induction hardening process reduces the stiffness of the material in the case-hardened region, typically the gear teeth (**6**). The reduction in stiffness causes a decrease in resonance frequencies. The magnitude of the decrease correlates to the case depth and hardness of the hardened region.

5. Significance and Use

5.1 *PCRT Applications and Capabilities*—PCRT PTI examination has been applied successfully to a wide range of

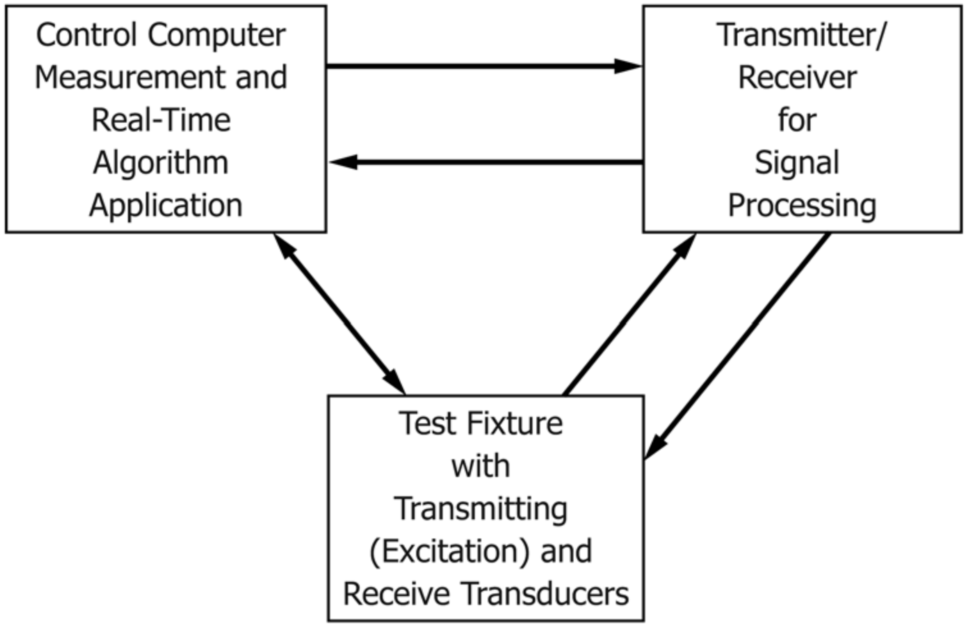

FIG. 1 PCRT System Schematic

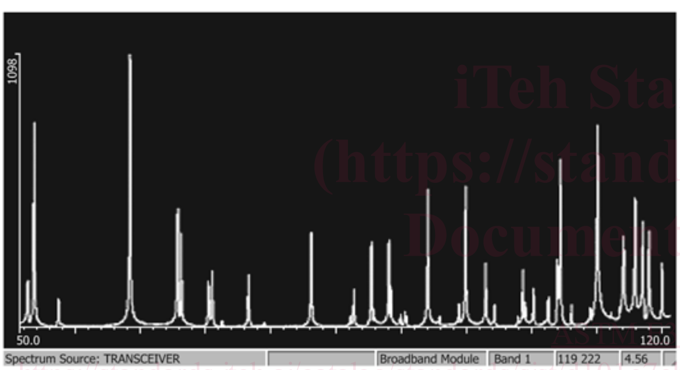

FIG. 2 Resonance Spectra (50 kHz to 120 kHz)

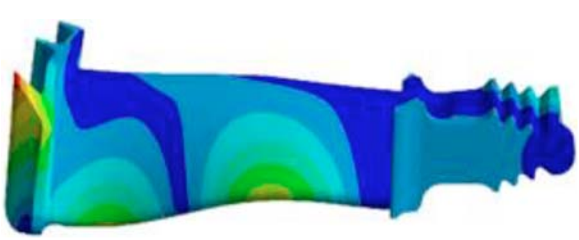

FIG. 3 Airfoil Bending Mode for Turbine Blade

parts in manufacturing and maintenance environments. Examples of manufacturing processes, repair processes, and in-service damage mechanisms evaluated with PTI are discussed in 1.1. PCRT has been shown to provide cost effective and accurate PTI-based NDT, process monitoring, and life monitoring 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) Heat treatment operations:

(a) Aerospace gas turbine engine components (blades, vanes, disks)

(b) Additively manufactured components

(c) Steel mechanical components

(d) Industrial gas turbine blades

(2) Induction hardening and carburization (both case-hardened and through-hardened parts):

(a) Gears

(b) Ballnuts

(3) Hot Isostatic Pressing (HIP):

(a) Gas turbine engine components (blades, vanes, disks)

(b) Additively manufactured components

(4) Shot peening:

(a) Steel mechanical components

(5) In-service thermal history, aging, creep damage, fatigue:

(a) Gas turbine engine components (blades, vanes, disks)

(b) Industrial gas turbine blades

(c) Aircraft landing gear wheels

(6) Maintenance repair/rejuvenation processes:

(a) Gas turbine engine components (blades, vanes, disks)

(b) Industrial gas turbine blades

(c) Aircraft landing gear wheels.

5.2 *General Approach and Equipment Requirements for PCRT via Swept Sine Input:*

5.2.1 PCRT systems comprise hardware and software capable of inducing vibrations, recording the component response to the induced vibrations, and analyzing the data collected. Inputting a swept sine wave into the part has proven to be an effective means of introducing mechanical vibration and can be achieved with a high-quality signal generator coupled with an appropriate active transducer in physical contact with the part. Collection of the part's resonance response is achieved by recording the signal received by an appropriate passive vibration transducer. The software required to analyze the available data may include a variety of suitable