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Standard Practice for
Resonance Testing Using the Impulse Excitation Method[1]

This standard is issued under the fixed designation E3397; 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 Impulse Excitation Method (IEM) to facilitate natural frequency measurement and detection of defects and material variations in metallic and non-metallic parts. This test method is also known as Impulse Excitation Technique (IET), Acoustic Resonance Testing (ART), ping testing, tap testing, and other names. IEM is listed as a Resonance Ultrasound Spectroscopy (RUS) method. The method applies an impulse load to excite and then record resonance frequencies of a part. These recorded resonance frequencies are compared to a reference population or within subgroups/families of examples of the same part, or modeled frequencies, or both.

1.2 Absolute frequency shifting, resonance damping, and resonance pattern differences can be used to distinguish acceptable parts from parts with material differences and defects. These defects and material differences include, cracks, voids, porosity, material elastic property differences, and residual stress. IEM can be applied to parts made with manufacturing processes including, but not limited to, powdered metal sintering, casting, forging, machining, composite layup, and additive manufacturing (AM).

1.3 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. This practice does not provide inspection acceptance criteria for parts. However, it does discuss the processes for establishing acceptance criteria specific to impulse testing. These criteria include frequency acceptability windows for absolute frequency shifting, scoring criteria for statistical analysis methods (Z-score), Gage Repeatability & Reproducibility (R&R) for diagnostic resonance modes, and inspection criteria adjustment (compensation) for manufacturing process and environmental variations.

1.4 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.

1.5 *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.*

1.6 *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

2.2 *ISO and Other International Standards:*

EN 1330-2 Non-destructive testing — Terminology — Part 2: Terms common to the non-destructive testing methods[3]
ISO 12680-1:2007 Methods of test for refractory products — Part 1: Determination of dynamic Young's modulus (MOE) by impulse excitation of vibration[4]
ISO 22605:2020 Refractories — Determination of dynamic Young's modulus (MOE) at elevated temperatures by impulse excitation of vibration[4]

3. Terminology

3.1 *Definitions:*

3.1.1 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 *bandwidth, n*—the range of frequencies excited and recorded in the inspection.

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[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] Available from European Committee for Standardization (CEN), Avenue Marnix 17, B-1000, Brussels, Belgium, http://www.cen.eu.

[4] Available from International Organization for Standardization (ISO), ISO Central Secretariat, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, https://www.iso.org.

3.2.2 *broadband, n*—the bandwidth, excitation parameters, and data collection parameters developed specifically for a particular part type.

3.2.3 *classification, n*—the labeling of a training set of parts as acceptable or unacceptable or the labeling of different sets of parts according to their manufactured, maintenance, or repair process parameters.

3.2.4 *compensation, n*—the adjustment of inspection criteria to accommodate variation in part characteristics caused by manufacturing processes or environmental conditions. Compensation requires the correlation of characteristics to resonance responses. Examples of variations that can require compensation include part mass (caused by manufacturing process variation) and part temperature during the test caused by either process or environmental conditions, or both. Various statistical tools can identify combinations of resonance patterns that are influenced by process variations, and they can accommodate for these differences.

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

3.2.6 *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.

3.2.7 *family, n*—part with supposed same geometry, size, mass, material.

3.2.8 *Fast Fourier Transform (FFT), n*—an algorithm that calculates the discrete Fourier transform (DTF) of some sequence. The discrete Fourier transform is a tool to convert specific types of sequences of functions into other types of representations. Another way to explain discrete Fourier transform is that it transforms the structure of the cycle of a waveform into sine parts.[5]

3.2.9 *impulse excitation method, n*—a resonance inspection method that involves striking an object with a mechanical impact causing multiple resonances to be simultaneously excited.

3.2.10 *lot, n*—a quantity of parts consecutively made under the same manufacturing conditions using qualitatively homogenous materials, usually identified on the parts with a unique number/letter or combination thereof. This number may be referred to as a lot code, batch code, or date code depending on the manufacturer's preference.

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

3.2.12 *resonant inspection (RI), n*—any induced resonant nondestructive examination method that excites mechanical resonances of a part for the purpose of identifying a part's conformity to an established acceptable pattern.

3.2.13 *resonant ultrasound 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.

3.2.14 *sort, n*—a software program or data analysis method capable of classifying a part as uniquely different from other parts. A productionized sort could identify parts as acceptable or unacceptable.

3.2.15 *training set, n*—a group of like parts including examples of known acceptable and known unacceptable components representative of the range of acceptable variability and unacceptable variability.

3.2.16 *work instruction, n*—a document with stepwise instructions developed for each examination program detailing the order and application of operations for IEM examination of a part.

3.2.17 *Z-score, n*—a statistical analysis that describes the position of a part's distance from the calculated mean, when measured in standard deviation units.

4. Significance and Use

4.1 *IEM Applications and Capabilities*—IEM has been successfully applied to a wide range of NDT applications in the manufacture, maintenance, and repair of metallic and nonmetallic parts. Examples of anomalies detected are discussed in 1.1 and 6.2. IEM has been proven to provide fast, cost-effective, and accurate NDT solutions in nearly all manufacturing, maintenance, or repair modalities. Examples of the successful application focuses include, but are not limited to: sintered powder metals, castings, forgings, stampings, ceramics, glass, wood, weldments, heat treatment, composites, additive manufacturing, machined products, and brazed products.

4.2 *General Approach and Equipment Requirements for IEM:*

4.2.1 IEM systems are comprised of hardware and software capable of inducing vibrations, recording the component response to the induced vibrations, and executing analysis of the data collected.

4.2.2 *Hardware Requirements*—Examples of a tabletop impact excitation system and a production-grade drop excitation system are shown in Fig. 1 and Fig. 2, respectively. IEM systems include: an excitation device (for example, modal hammer / impact device / dropping system) providing an impulse excitation to the object, a vibration detector (for example., microphone), a signal amplifier, an Analog-to-Digital Converter (ADC), an embedded logic, and a data User Interface (UI). Tested parts can typically be on any surface type, but they can also be supported (for example, foam support, held with an elastic) in consideration of possible damping influences. The following schematics show the basic parts for an impact excitation approach (Fig. 3) and a drop excitation approach (Fig. 4).

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[5] https://www.techopedia.com/definition/7167/fast-fourier-transform-fft.

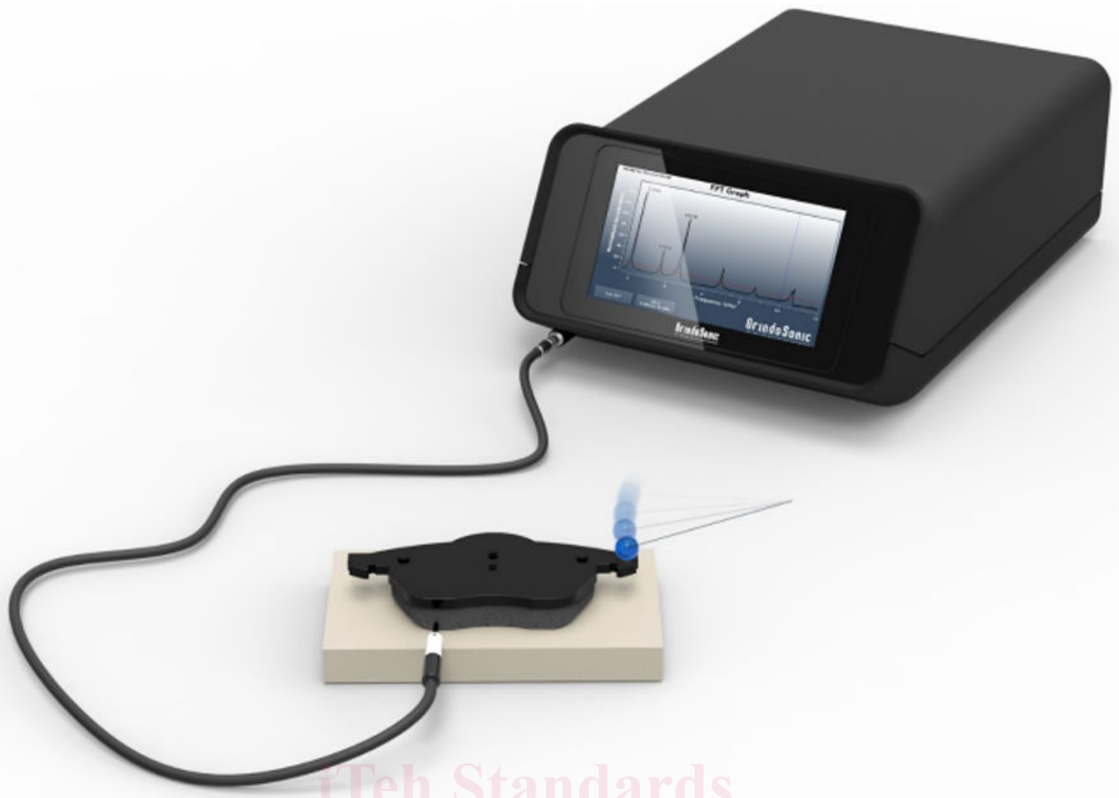

FIG. 1 IEM Tabletop Testing System Using a Non-Instrumented Impactor

4.3 *Constraints and Limitations:*

4.3.1 IEM needs a change in structural integrity to properly sort different parts. This means that parts with only cosmetic issues, such as a visual surface anomaly would still need be inspected with a focused visual inspection.

4.3.2 The location of a flaw or specific flaw type characterization is challenging. As IEM measures the whole-body response of a part, location and categorization of defects usually requires additional data (such as additional nondestructive and destructive evaluation) and analysis.

4.3.3 Large raw material or process variation, or both, may limit the sensitivity of IEM without some method for compensating for those variations.

4.3.4 Groups of parts with a wide range of physical temperatures are not good subjects for IEM without some method for compensating for those variations. Temperature affects the natural frequencies, so stabilization of temperature is desired for parts testing. Data can be taken over a large range of temperatures, as long as the parts are stable during the testing.

4.3.5 IEM is a volumetric inspection method. Sensitivity to defects will be driven by the size of the defect relative to the size and mass of the part. For example, a small hairline crack of a certain length that may be detectable in a 0.5 lb part may not be detectable in a 100 lb part.

4.3.6 The expected useful frequency range of the part to be tested must be considered when selecting and configuring an IEM examination. Many IEM systems are limited to detecting frequencies up to 50 kHz, but more modern systems have demonstrated detection of frequencies up to 150 kHz on some parts. Parts with small dimensions or parts made from certain materials, or both, may have resonance spectra that fall partially or entirely outside of the frequency range of some IEM systems. The physics of energy distribution from the impulse and attenuation from interfering harmonic modes can also cause a reduction in signal-to-noise ratio at the higher end of IEM frequency ranges.

4.3.7 Materials that resonate poorly or dampen vibrations are typically not good candidates for IEM examination.

5. General Practice

5.1 Impulse Excitation Method (IEM) is the oldest form of resonance testing. It has been applied as nondestructive examination tool for over a century to detect structural anomalies that significantly alter part performance. Many modern improvements in hardware and software have significantly increased the method's repeatability and sensitivity. The range of frequencies IEM systems can excite and record has expanded into the ultrasonic range, with some systems reaching close to 150 kHz. These improvements have also allowed IEM the capability of segregating parts based on fine process control variations. IEM has demonstrated detection of very small defects and material property changes. The details of this form of resonance testing are outlined in Guide E2001.

5.1.1 IEM is a correlation technology using an impulse to excite and record all of a part's resonance frequencies. These frequencies are determined by the part's mass, geometry, and material properties. The resonance spectrum is then either analyzed compared to a training set of resonance spectra for known acceptable parts and unacceptable parts, statistically evaluated, or compared to modeled data. For statistical testing,

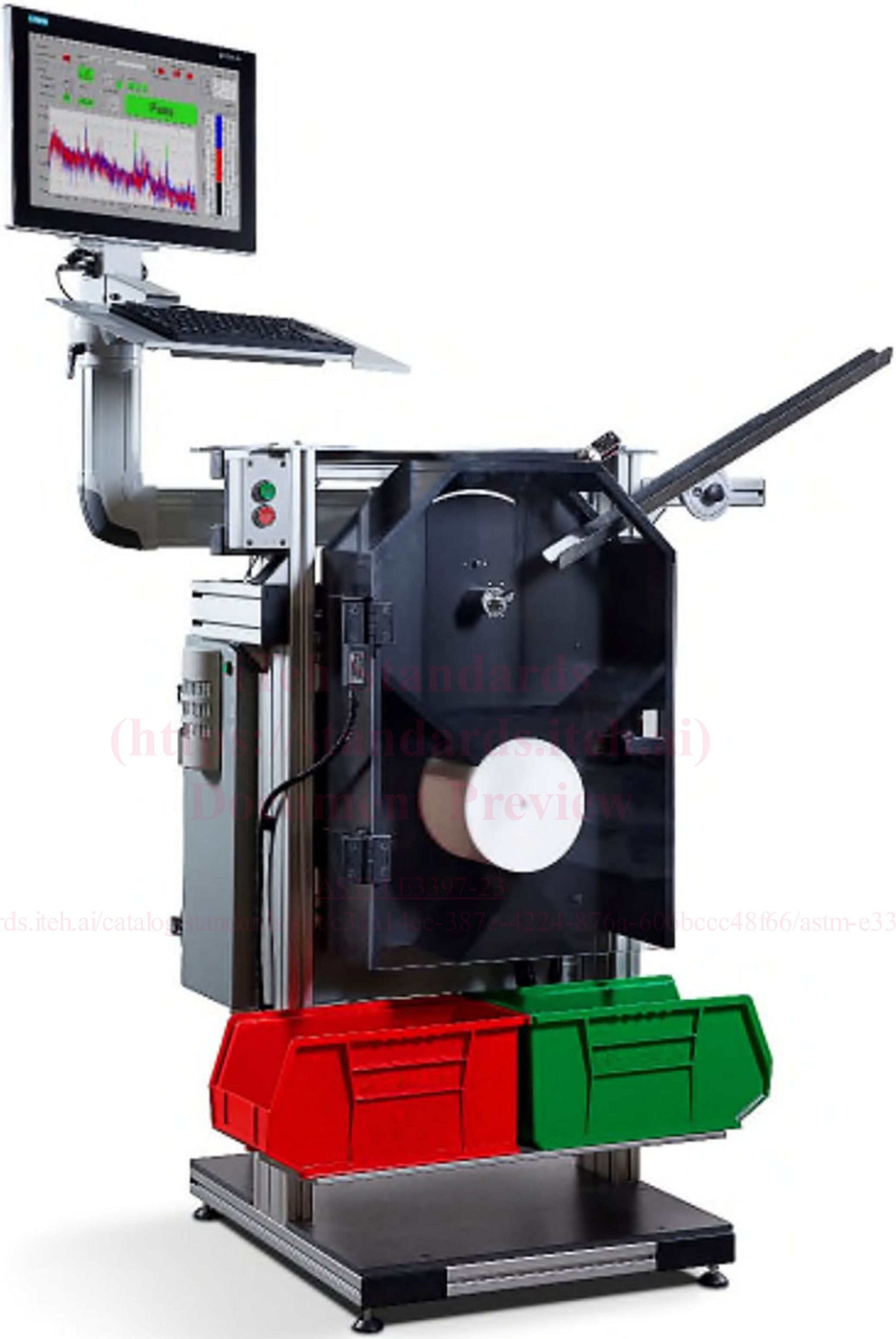

FIG. 2 Production-Grade Drop Excitation System

many methods of analysis can be used on the obtained resonance data set. Simple individual frequency relationships, complex covariance matrix relationships, and Z-score analysis are commonly used. For comparable training set testing, a database that is representative of the total variation range of established known acceptable and unacceptable parts is used. Finally, for modeled data testing, predicted resonance data is

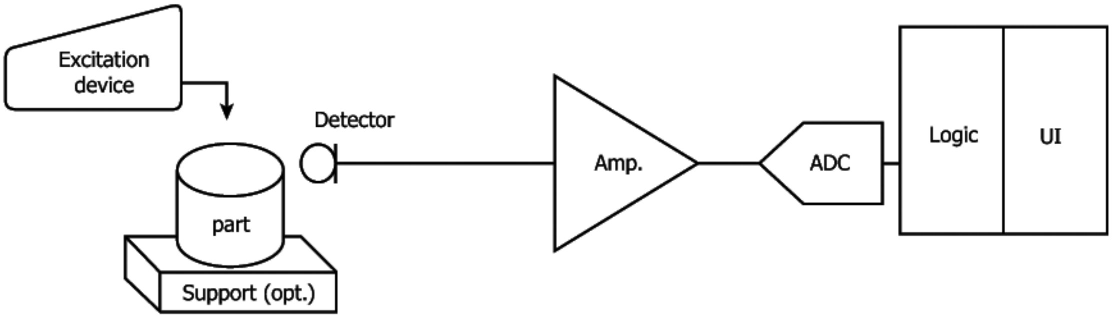

FIG. 3 Schematic of Impact Excitation Approach

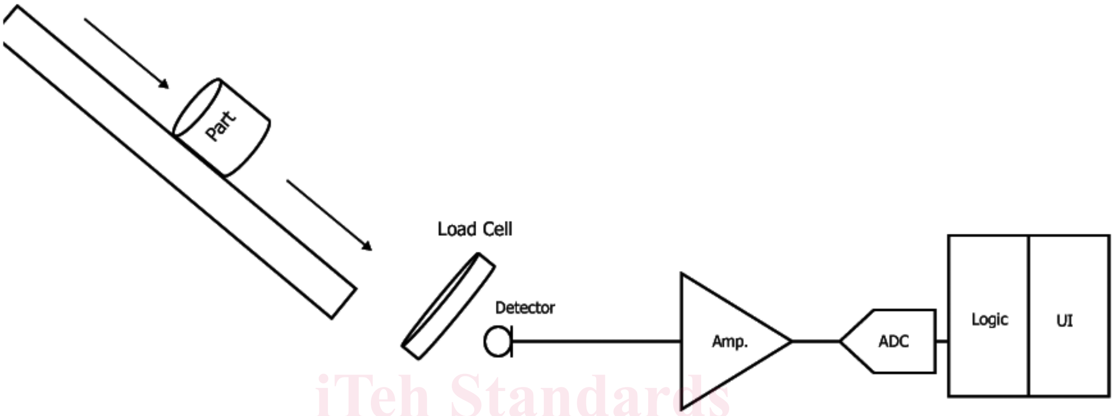

FIG. 4 Schematic of Drop Excitation Approach

provided from a valid design model and the raw IEM resonance data is compared and evaluated.

5.2 Fig. 5 shows a collection of typical resonance spectra for multiple parts with resonance peaks indicated.

5.2.1 IEM Equipment typically has four main components, an impactor, a measuring device, a data acquisition device/analyzer, and software. The impactor and measuring device come in several different varieties. The impactor options are typically a manual or automated "hammer" instrumented with an embedded force sensor, a non-instrumented hammer, or a fixed impact surface with a load cell (for small parts). A microphone, piezoelectric transducer, accelerometer, and laser vibrometer are the typical measurement device options. Selection of the impactor and measurement device will be application driven. The data acquisition device and software work together to collect the data from the measuring device and impactor (if using an instrumented impactor), process the data, make a decision on the test result, and display the data. Fig. 6 shows an example of manual operation of an IEM system. Fig. 7 shows an automated IEM system feeding parts to the impactor via a conveyor.

5.3 Fig. 8 shows a heavy duty automatic system with an integrated scale for part mass measurement.

5.4 Common test surfaces for part placement during testing (should be low-friction, anti-static). Be sure that surface chosen is appropriate to the environment (laboratory or production).

5.4.1 Acetyl (or other hard plastic) test surface (should be connected to direct earth ground);

5.4.2 Conveyor (polyurethane, plastic, other non-metallic surfaces);

5.4.3 Wood;

5.4.4 Hard or soft foam;

5.4.5 Metallic impact surface (drop test).

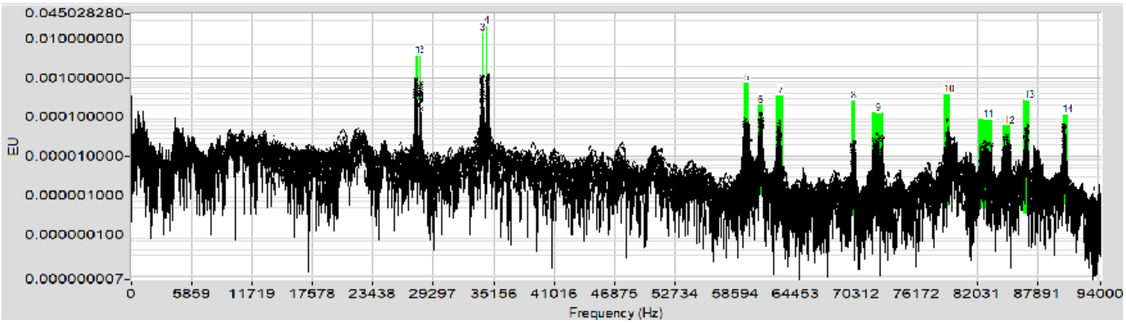

FIG. 5 Typical Resonance Spectrum (0 Hz to 94 kHz)

FIG. 6 Manual Operation of IEM System for AM Part Inspection

FIG. 7 Production-Grade Automatic IEM System

5.5 The part to be tested should be positioned on the test surface in a way that it is free to move after impact and has limited surface contact to minimize damping. Constricting the movement of the part during IEM testing will typically result in decreased amplitude of the resonant frequencies and possibly affect the frequency response of the part.

5.6 While IEM is a whole-body testing method, meaning that the entire structure is excited and tested in a single impulse, it is important to determine the optimal impact location on the part in order to elicit a repeatable response from the part across the range of frequency measurements. To find the optimal impact location, impact one part in multiple

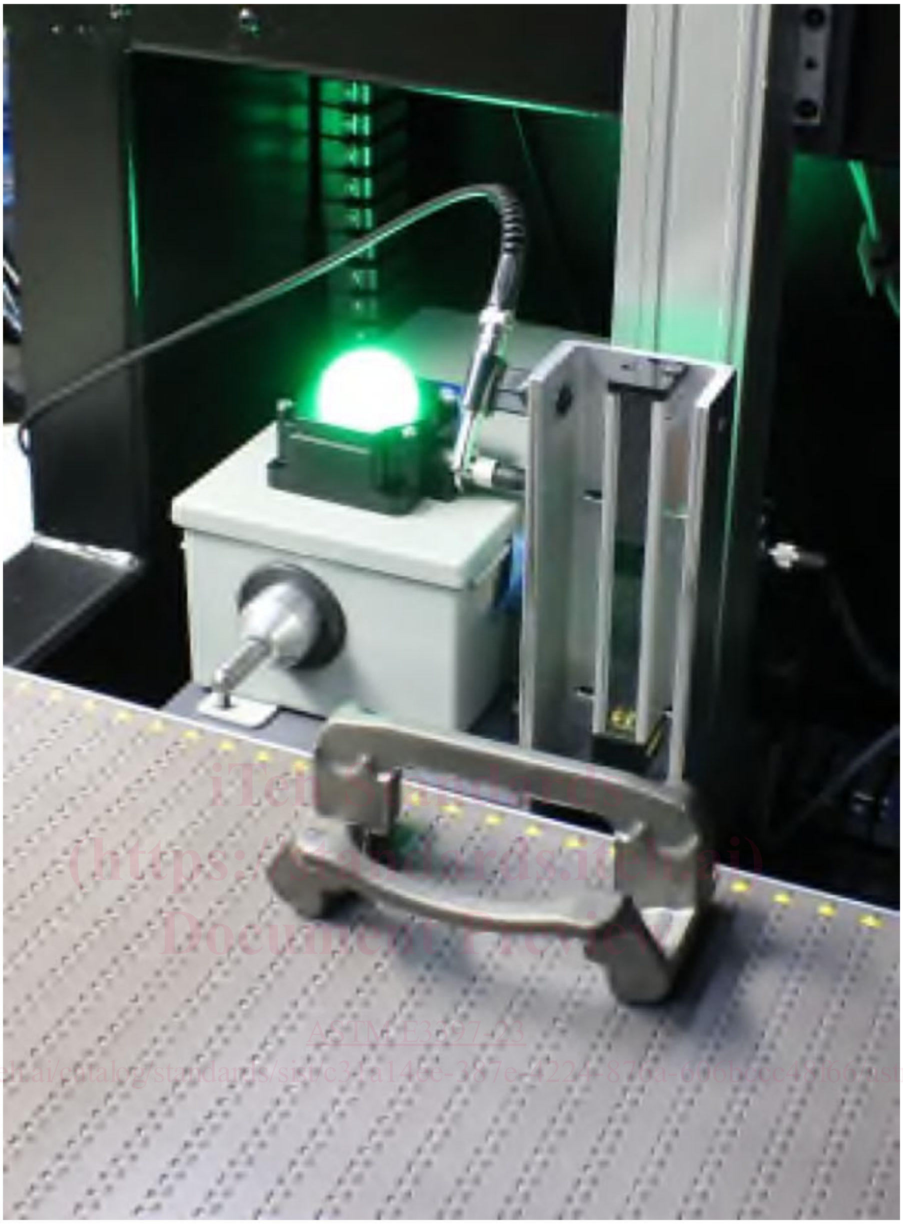

FIG. 8 Heavy-Duty IEM Automatic System with Integrated Scale to Measure Part Mass

locations and compare the results. The ideal scenario of a part being tested would be that the frequency and amplitude response are repeatable regardless of impact location on the part. In practice, most parts have areas of the structure that are naturally damped and do not conduct the resonance energy from the impact (non-symmetrical parts may have a case where a resonant frequency peak will split at certain impact locations and not at others). Most areas of a part will sufficiently conduct resonance energy through the part. An impact location on the part that provides a repeatable response spectrum with isolated, single peaks that have sufficient amplitude for measurement (separation between peaks and noise floor), should be chosen for IEM testing of all pieces of that same part type. For production testing, the impact location should be documented in the work instructions for the part.

5.7 The quality of the impact and response signals should be evaluated to ensure quality data results at the determined location on the part. Evaluate the time response (Fig. 9) of impact channel to ensure a single impact on the part. To achieve high quality, repeatable results, the impulse device should only contact each part one time for a single test. Evaluate the time response (Fig. 10) of the measurement channel to ensure there is a clean signal. If using a microphone, look for a complete ring-down without evidence of modulation. Modulation indicates over-driving the part at excitation.