Resonant Ultrasound Spectroscopy Offers Unique Advantages as a **Nondestructive Test Method**

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Resonant ultrasound spectroscopy is making headway as a fast and nondestructive measurement technique. Thanks to advances in computer technology, codes and software are now available for data reduction, analysis, and interpretation.

Resonant ultrasound spectroscopy (RUS) is an emerging ultrasonic measurement technique. By measuring the natural vibrational frequencies of test samples, RUS can determine the full set of elastic constants. For example, RUS can obtain Young's modulus, shear modulus, and Poisson's ratio for isotropic materials. By comparing the vibrational spectra of a test sample to those obtained from a standard, it is possible to infer the causes of the differences (if any) and detect various part defects, such as size variations, cracks, and pores.

RUS first appeared in the second half of the 20th century with its development fueled by advances in computing power. In 1964, Frasier and LeCraw performed one of the earliest RUS measurements on spheres of isotropic materials[1]. After this initial success, much improvement was made in the geophysics community, where RUS was used by Anderson and coworkers to measure the elastic properties of spherical lunar samples in the 1970s[2]. After the late 1980s, RUS was adapted by some physicists and materials scientists including Migliori and coworkers, who began to examine high-temperature superconducting materials[3]. Current research uses of RUS include a wide range of topics in physics, geophysics, and materials science, where elastic constants are being accurately measured on samples as small as 70 μg[4].

Industrial applications of RUS appeared around the beginning of the new millennium, used for quality control of manufactured parts. Among the first commercial RUS units in the U.S. were those made by Quatrosonics[5] in the 1990s based on technology developed at Los Alamos National Laboratory. However, due to the hardware and software complexity, commercial RUS units are still only available from a few sources[6,7].

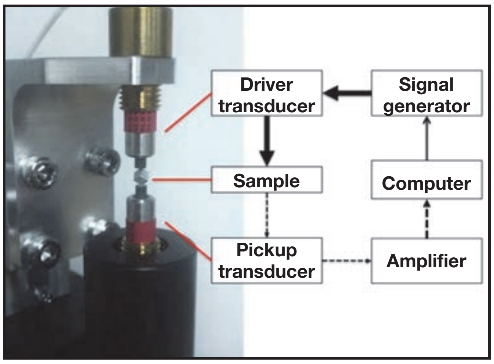

Fig. 1 — *Typical resonant ultrasound spectroscopy (RUS) measurement in a two-transducer setup.*

RUS is attractive because measurements are fast and nondestructive, and can also be automated. But data interpretation could be challenging due to the complicated nature of the theories. Thanks to advances in computer science and technology, codes and software are now available for data reduction and analysis, as well as interpretation.

Resonant ultrasound spectroscopy fundamentals

All RUS-related applications start with measuring the vibrational response of test samples when subjected to mechanical stimulation. For a piece of solid material, the natural mechanical vibrational frequencies (i.e., eigenfrequencies), which correspond to specific vibrational modes such as bending and torsion, are solely determined by the material's mass density, geometric parameters, and elastic constants. Because mass density and geometric factors are easy to obtain, if one could measure the natural vibrational frequencies of a test sample, its elastic constants could be back calculated—an inverse mathematical problem. In practice, due to the constraints of computing power, some simple geometry (such as spheres, cubes, and prismatic bars) is often used in actual measurements.

An example of measuring a cube sample using a two-probe RUS is shown in Fig. 1. The sample, approximately 2 mm wide on each side, is sandwiched between two piezoelectric transducers. One of the transducers (the driver transducer) is used to apply mechanical stimulation provided by a signal generator to the test sample; the other transducer (the pickup transducer) *listens* to the response from the sample and feeds it back to the data acquisition module. Input signals are usually a series of mechanical waves with a wide band of frequencies in the ultrasonic range (a few hundred kHz to MHz). Only those waves with frequencies matching the natural vibrational frequencies of the test sample can be detected by the pickup transducer. The resulting spec-

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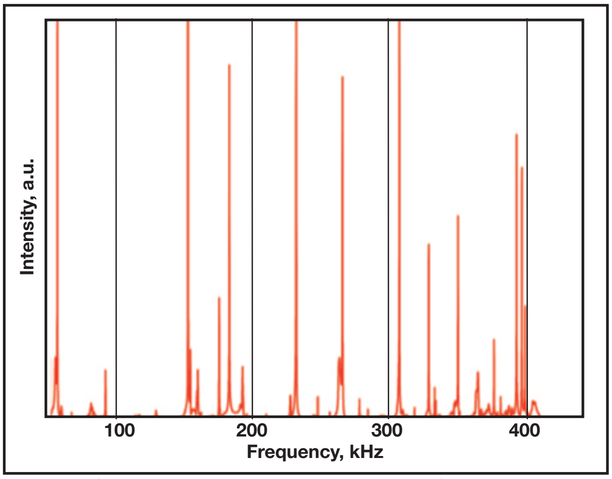

Fig. 2 — *Sample spectrum obtained from RUS measurement.*

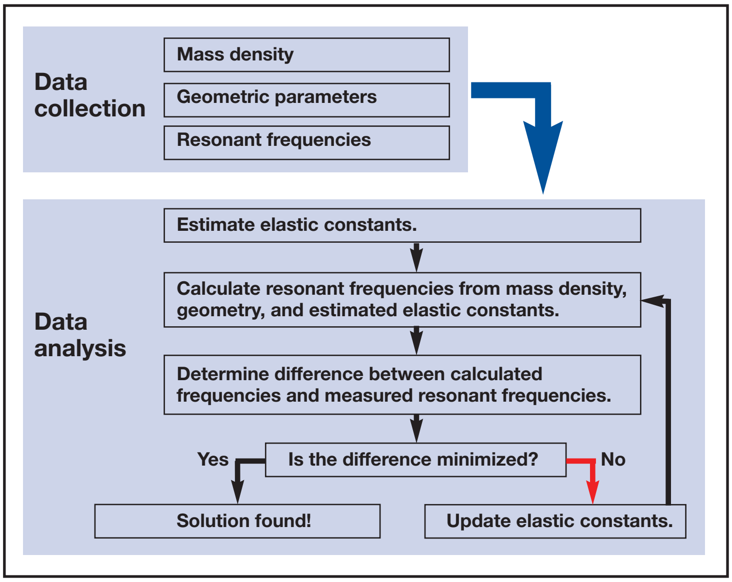

Fig. 3 — *Schematic of data collection and analysis steps involved in RUS.*

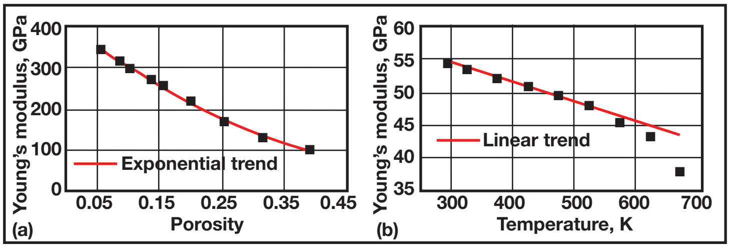

Fig. 4 — *RUS is used to determine (a) porosity effect on Young's modulus of alumina (after[10]), and (b) temperature effect on Young's modulus of PbTe-based thermoelectric materials (after[11]).*

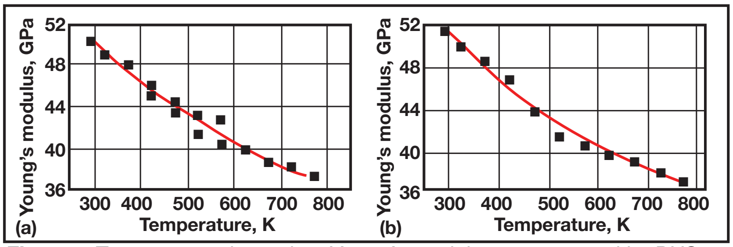

Fig. 5 — *Temperature dependent Young's modulus as measured by RUS reveals a diffusion controlled order-disorder phase change: (a) heating/cooling rate = 5 K/min, (b) heating/cooling rate = 2 K/min[12].*

tra are peaks at various frequencies as shown in Fig. 2. The positions of the peaks correspond to the eigenfrequencies of the test sample.

After collecting the resonant frequencies, determining the elastic constants involves a fairly complicated procedure. Because this is an inverse problem, one must first provide an initial "guess" regarding the unknown elastic constants from other means, such as existing knowledge of similar materials or theoretical modeling. Using these estimated elastic constants, along with sample geometry and mass density, the eigenfrequencies of the test sample can be estimated and compared to the measured data. If these two sets of frequencies are identical—or the difference is small enough—then the predicted values can be regarded as the sample's true elastic constants. Otherwise, the predicted values must be modified and the above steps repeated. This procedure usually requires a number of iterations and is affected by the quality of both the measured data and initial estimates.

A key step in this data analysis is to find an appropriate algorithm to modify the elastic constants based on differences between measured and calculated frequencies. This is often realized through computer codes and software. One common process is the Levenberg-Marquardt algorithm[8], which is a nonlinear least-squares scheme that uses Taylor's expansion to linearize the difference between measured and calculated frequencies. This data analysis procedure is illustrated in Fig. 3. RUS theories are explained further in a textbook by Migliori and Sarrao[9].

Resonant ultrasound spectroscopy research applications

As previously mentioned, RUS is used to measure the elastic constants of solid materials in various research areas including metals, alloys, ceramics, glasses, concretes, and rocks. Compared to many static testing methods, such as tensile and bending tests, RUS is nondestructive and can work with small samples. Compared to other ultrasonic techniques such as the pulse echo method, RUS features less preparation and faster sample installation.

Because elastic constants are influenced by other physical and chemical properties, RUS can be used to explore many related phenomena, including structural phase changes, superconducting transitions, magnetic transitions, and damage accumulation due to microcracking. For example, RUS is used to measure the influence of porosity on the elastic constants of alumina at different sintering stages. Young's modulus as a function of volume fraction porosity is shown in Fig. 4a[10]. This information can facilitate a deeper understanding of porosity evolution during sintering and its effect on mechanical properties—key aspects in the design and fabrication of engineering ceramics.

Further, RUS measurement can be made under some extreme conditions such as high and low temperatures. Figure 4b shows the measurement of Young's modulus of a PbTe-based thermoelectric material between room temperature and 673 K (400°C)[11]. In this case, Young's modulus initially decreased nearly linearly and then exhibited a rapid drop beyond 573 K (300°C) due to the creep of grain boundary phases. Because the target application for these thermoelectric materials is waste heat recovery, detection of the onset temperature of grain boundary sliding can help determine the safe operating temperature range, which in this case is up to 300°C.

Another example of applying RUS in materials research is shown in Fig. 5, where Young's modulus is again measured as a function of temperature[12]. In contrast to seeing a downward trend as shown in Fig. 4b, an upward trend is observed in the Young's modulus of a different PbTe-based thermoelectric material. The turning point around 523 K (250°C) in the curve indicates a change in bonding strength. Further analysis confirms the change is likely due to an order-disorder phase transformation: This transformation is controlled by the diffusion of doping elements such that when the heating/cooling rate is high, a hysteresis occurs (Fig. 5a), while no hysteresis is observed when the heating/cooling rate is reduced (Fig. 5b).

Resonant ultrasound spectroscopy industrial applications

In contrast to research uses of RUS that mainly focus on material property measurements, industrial applications primarily reside in nondestructive evaluation (NDE) of precision components. The basic configuration of an industrial RUS unit is similar to its research counterpart, although the sample stage and transducers may be modified to accommodate larger and more complicated parts. Figure 6 shows an example of a commercial RUS unit with integrated testing and online analysis capabilities.

A major difference between industrial and research applications involves data usage. Instead of calculating the elastic constants, measured ultrasonic spectra (Fig. 2) are directly used as input for analysis. Defects that result in variations in vibrational modes (eigenfrequencies) will lead to changes in RUS spectra. By comparing measured spectra with standards, it can be determined whether a part should be accepted or rejected, and potential defects in the bad parts can be explored.

A general guideline for using RUS to evaluate the integrity of metallic and nonmetallic (i.e., ceramics and composites) components is provided in ASTM standard E2001-98[13]. According to this standard, a *fingerprint*—usually a few characteristic resonant peaks—must first be established. Then, sorting criteria for acceptance/rejection should be determined. In practice, establishment of sorting criteria is often realized by examining a large number of good and bad parts and analyzing the data in a statistical manner. Typical criteria include the following aspects in measured spectra: *peak shifts,* or changes in peak positions; *peak splitting,* where a single peak splits into two or more due to symmetry imperfection; and a combination of peak shifts and splitting. Other considerations include changes in peak amplitudes, peak broadening, and phase changes[14].

Summary

Successful RUS applications include identifying various types of defects including cracks (on the order of millimeters or submillimeters), cavities, geometrical imperfections, compositional inhomogeneity, and hardness variations[13,14]. Compared to traditional NDE methods, such as dye penetration, magnetic particle method, and eddy current testing, RUS possesses some unique advantages. One is the ability to examine parts with both external and internal defects, compared to dye penetration and magnetic particle methods that can only be used to detect external defects. Another is the ability of RUS to evaluate both conducting and nonconducting components; in contrast, the eddy current method does not work with nonconducting materials. In addition, RUS measurements can be made very quickly (on the order of minutes or less) if a good testing procedure is developed.

Nevertheless, RUS has drawbacks. For example, it requires special equipment and software, which are not yet widely available. Further, establishing sorting criteria often involves extensive efforts in terms of testing and data analysis. Because it is an emerging technology, the learning curve for adapting RUS to existing industrial facilities may be steep. However, once these initial obstacles are cleared, RUS will serve as a fast and reliable NDE technique in many manufacturing settings.

Fig. 6 — *Commercial RUS unit. Courtesy of Magnaflux.*

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