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Resonant ultrasound spectroscopy for materials studies and non-destructive testing

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Abstract

The use of mechanical resonances to test properties of materials is older than the industrial revolution. Early documented cases of British railroad engineers tapping the wheels of a train and using the sound to detect cracks perhaps marks the first real use of resonances to test the integrity of high-performance alloys. Attempts were made in the following years to understand the resonances of solids mathematically, based on shape and composition. But Nobel Laureate Lord Rayleigh best summarized the state of affairs in 1894, stating 'the problem has, for the most part, resisted attack'. More recently, modern computers and electronics have enabled Anderson and co-workers, with their work on minerals, and our work at Los Alamos on new materials and manufactured components, to advance the use of resonances to a precision non-destructive testing tool that makes anisotropic modulus measurements, defect detection and geometry error detection routine. The result is that resonances can achieve the highest absolute accuracy for any routine dynamic modulus measurement technique, can be used on the smallest samples, and can also enable detection of errors in certain classes of precision manufactured components faster and more accurately than any other technique.

Keywords: Ultrasonics; Elastic moduli; Resonant ultrasound; Non-destructive testing

1. Introduction

The mechanical resonances of a freely suspended solid object are special solutions to the equations of motion that depend only on the density, elastic moduli and shape. These solutions determine all the possible frequencies at which such an object would 'ring' if struck [1]. Because a solid with N atoms in it has $6N$ degrees of freedom, there are $6N-6$ resonances (we remove six frequencies that correspond to three rigid rotations and three rigid translations). Most of these resonances cannot be detected as individual modes because dissipation in the solid broadens the higher-frequency resonances so that they overlap to form a continuum response. For a typical solid object, of the 10^{24} modes possible, perhaps the lowest 10^4 or so are very special because they are isolated from other modes and hence can be individually studied.

These special modes or resonances are not uniquely determined because there are many different solid objects that can produce identical resonance spectra [2] but in practice the resonance spectrum of an object does provide such a strongly constrained fingerprint that the information content remains important and extensive. For example, if the lowest 50 or so resonances of a single crystal solid of known shape and density are measured, even if the solid is orthorhombic with nine separate elastic moduli, all the moduli can be determined uniquely with unprecedented absolute accuracy in samples as small as 0.5 mm on a side [3]. Or, consider a solid object with nearly perfect cylindrical symmetry and constructed of an isotropic material such as a cylindrical roller bearing element. The cylindrical symmetry produces many groups of measurable modes that should be degenerate. Deviations from perfect cylindrical symmetry of as little as 1 part in 10^6 break the degeneracy to produce multiple resonance peaks where only one should be. The measurement of one such set of modes can detect this tiny cylindricity error in less than 1 second in a 1 cm diameter bearing [4].

The means to perform such powerful measurements is possible today because recent advances in electronic

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instrumentation, transducers, and computational techniques have replaced the previous century's railroad engineer, and his practised ear for a dull ring produced by a cracked train wheel, with precision, quantitative and reliable measurement systems. We descibe here the present state-of-the-art for modern mechnical resonance measurement processes, loosely called resonant ultrasound spectroscopy, or RUS.

2. Instrumentation

To use resonances in a reliable and quantitative way, it is important not to affect the resonances with the measurement system. The only successful approach must, then, involve very weak coupling to the system to be measured. This puts a great strain on the electronics, requiring thermal-noise-limited systems for millimeter-sized samples. Although, in principle, impulse excitation could be used, and the resulting response Fourier transformed to obtain the resonant frequencies, such an approach is disadvantageous for the following reasons: (a) the power per unit bandwidth is low because the impulse must spread its energy out over the full frequency range of interest; (b) the duty cycle can be very low because the system is driven only for the duration of the impulse; (c) the detection bandwidth must cover the entire frequency range of interest, so that the noise window is very large; and (d) only a very small region of the spectrum contains any useful information. In contrast, a continuous wave (CW) swept excitation of the system, shown in block form in Fig. 1, has no disadvantages whatsoever in terms of signal-to-noise ratio. Because the frequency is swept, the drive power density is essentially the full power available divided by the sweep rate, and the receiver bandwidth is determined only by the sweep rate and the Q or quality factor expected for the resonances. Thus, for a measurement covering a frequency range from 0.5 MHz to 2.5 MHz, where 50 resonances are present, and for Q of order 10^4, the swept-sine system has a S/N advantage of about 50 dB, summarized in Table 1, even with a peak power 60 dB lower than for the impulse driven system. Optimized CW/swept excitation RUS instrumentation packages are now commercially available [5].

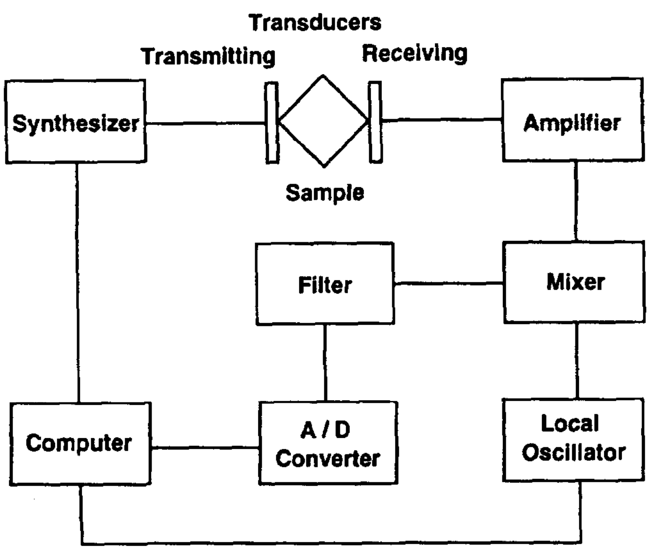

Fig. 1. Block diagram of a typical RUS CW/swept excitation measurement system.

3. Transducers

Two characteristics are important for the transducers used in RUS measurements. They are (1) lack of resonances in the region of interest, and (2) minimal noise contribution. Both characteristics are generally achievable by using undamped transducers constructed with high sound-speed materials. For measurement of the elastic moduli of millimeter-size samples, a 30 MHz $LiNbO_3$ transducer disk 1.5 mm in diameter has torsional resonances beginning below 200 kHz, and many other resonances between there and the first compressional mode at 30 MHz, making it useless for RUS. However, by making a metallic diffusion bond to a single-crystal diamond disk 1.5 mm in diameter and 1 mm thick, a structure is produced with negligible damping to minimize noise, a lowest resonance of about 4.3 MHz, and the ability to operate from below 1 K to

Table 1
Signal-to-noise comparison between impulse and swept-sine resonance measurement methods for a measurement of 50 resonances between 0.5 MHz and 2.5 MHz each with a $Q = 10^4$ covering a 2×10^6 Hz bandwidth

Parameter	Impulse	Swept sine
Drive power per unit bandwidth	peak power/full bandwidth $P/2 \times 10^6 = 0.5 \times 10^{-6}$	peak power/sweep rate $P/100 = 0.01$
Peak power	2×10^6	1
Measurement bandwidth	2×10^6	$2 \times 10^6 \times$ No. of modes/$(Q/10) = 10^5$Hz
Noise bandwidth	2×10^6	$2 \times 10^6/Q = 200$ Hz
Drive duty cycle	10^{-6}	1
Detect duty cycle	1	1
Square root of all factors, which is a measure of S/N	5×10^{-10}	3×10^{-5}

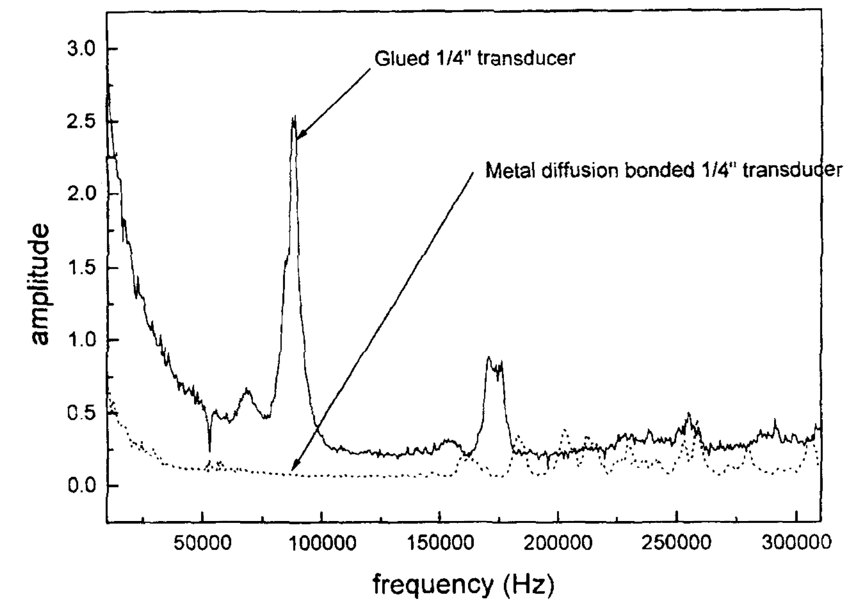

Fig. 2. Shown are the mechanical resonances of 6.35 mm diameter PZT-5A transducers with alumina backloads about 6 mm thick. One transducer is bonded with epoxy, the other with a Ag diffusion bond.

above 1000 K. Ordinary epoxy bonds can also be used, limiting the maximum temperature to about 350 K.

In Fig. 2 we show the nearly resonance free response of an epoxy bonded transducer of the type just described, and the even better response of one bonded with Ag. Using a pair of similar but smaller (1.5 mm diameter) transducers attached to thin supporting diaphragms of polymer film, the resonances of a 1 mm rectangular parallelipiped sample can be measured by contacting diagonally opposite corners using no coupling fluids. Such point contact preserves the free-surface boundary conditions to better than 1 part in 10^5 if the contact force is below 1 g. Using drive levels of less than 1 V, and electronics like that described above, S/N ratios of better than 30 dB are easily achieved.

4. Computations

Whether the goal is to measure elastic moduli or to detect flaws, RUS measurements require extensive analysis of the frequency and resonance width data acquired. Computations associated with non-destructive testing, though, are simpler and quite varied. We therefore mention here only the very interesting technique used to extract anisotropic elastic moduli from cylindrical, spherical or rectangular parallelipiped samples. The usual approach to a computation of resonance frequencies is to use a finite element code. Such a code requires that the object's volume be divided into small elements, and then equations of motion and boundary condition be applied to each element. Computation times are dependent on the number of elements, with the result that even with a supercomputer, accuracies required for the determination of elastic moduli (5 digits for 50 modes) are expensive to achieve.

A different approach, pioneered by Holland, Demarest, Ohno, Anderson, Migliori and Visscher [1,6–8] begins with a minimization of the Lagrangian for the object, then converts the resulting equations to surface integrals that are easily expanded in any complete set of functions. This makes the computation time depend on surface, not volume, but requires simple geometric shapes to be effective, Using this basic computational method, Visscher [8] developed accurate procedures to solve the very much more difficult inverse problem of determining elastic moduli from resonances. The results are codes that produce 5 digit accuracy for 200 modes and that can run on fast PCs in minutes. In Fig. 3. We show typical resonances and in Table 2 we show the result of

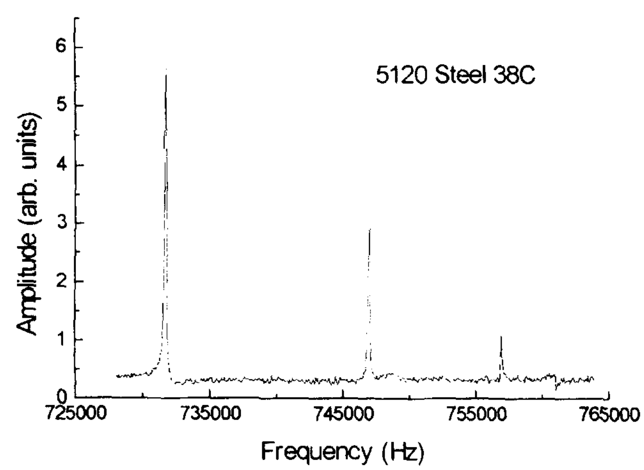

Fig. 3. Typical resonances of the rectangular parallelipiped for which an analysis for elastic moduli was performed and shown in Table 2.

Table 2
Measured and fitted frequencies for an AISI 5120 steel rectangular parallelipiped. Also shown is the dependence of each frequency on each of the two fitted elastic moduli, c_11 and c_{44}. For this sample, Young's modulus is 30.39×10^6 psi (209.55 GPa), the shear modulus is 11.82×10^6 psi (81.50 GPa) and Poisson's ratio is 0.285. The dimensions and shear modulus were determined to better than 0.1%, while Young's modulus is accurate to about 0.4%

n	f-expt	f-calc	%err	df/dc_{11}	df/dc_{44}
1	0.340010	0.339607	−0.12	0.00	1.00
2	0.447200	0.447109	−0.02	0.13	0.87
3	0.490240	0.490366	0.03	0.16	0.84
4	0.541860	0.541482	−0.07	0.02	0.98
5	0.557460	0.556663	−0.14	0.00	1.00
6	0.591740	0.592306	0.10	0.05	0.95
7	0.608670	0.608417	−0.04	0.31	0.69
8	0.615590	0.615290	−0.05	0.02	0.98
9	0.623100	0.622662	−0.07	0.07	0.93
10	0.642700	0.642897	0.03	0.12	0.88

such a computation on a 2 mm (approximate) cube of 5120 steel.

The state of the art now is such that using RUS as a laboratory tool, anisotropic elastic moduli can be measured on millimeter sampes with unprecedented accuracy over very broad temperature ranges with minimal experimental time required. In addition, the industrial applications of RUS to non-destructive testing have reached production testing of precision manufactured components in automotive and other industries.

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References

[1] W.M. Visscher, A. Migliori, T.M. Bell and R.A. Reinert, J. Acoust. Soc. Am. 90 (1991) 2154.
[2] C. Gordon, D. Webb and S. Wolpert, Bull. Am. Math. Soc. 27 (1992) 134.
[3] A. Migliori, J.L. Sarrao, William M. Visscher, T.M. Bell, Ming Lei, Z. Fisk and R.G. Leisure, Physica B 183 (1993) 1.
[4] A. Migliori, T.W. Darling, R.D. Dixon and G.W. Rhodes, Internal report #LA-UR-93-3195, Los Alamos National Laboratory, Los Alamos, NM 87545.
[5] Quatrosonics Corp., Balloon Park Rd., Albuquerque, NM (USA).
[6] R. Holland, J. Acoust. Soc. Am. 43 (1968) 988.
[7] H.H. Demarest, J. Acoust. Soc. Am. 49 (1971) 768.
[8] I. Ohno, J. Phys. Earth 24 (1976) 355.