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Resonant Ultrasound Spectroscopy and Non-Destructive Testing

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The use of mechanical resonances to test properties of materials is perhaps 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 mark 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 the 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 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.

Introduction

The mechanical resonances of a freely suspended solid object are special solutions to the equations of motion in the absence of energy loss mechanisms that depend only on the density, elastic moduli and shape. These solutions determine all the possible frequencies at which such an object would "ring" at if struck[1]. Because a solid with N atoms in it has 6N degrees of freedom, there are 6N-6 resonances (we remove 6 frequencies that correspond to 3 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 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 in the sense that there are many different solid objects that can produce identical resonance spectra[2]. However, 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 0.5mm 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

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

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 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 MHZ, where 50 resonances are present, and for Q of order 10^4, the detector noise bandwidth can easily be of order 100Hz, $2x10^4$ narrower than for the pulsed system. Taking data within a few khz of each resonance requires a total of about 100kHz of measurement bandwidth, compared to 2MHz for the pulsed system(20 times better), with a noise bandwidth of 100Hz, compared to 2MHz (20,000 times better), and with a spectral power density about 2MHz/200 or about 10,000 times higher than for the pulsed system assuming equal peak power. The duty cycle for the swept measurement is roughly the resonance width over the region swept, while for the pulsed system it is near 1/Q providing another factor of about 10^3. Thus the S/N can be $(10^{17})^{1/4}$ or about 10^8 better for the swept system. Of course, in the swept system, much lower peak power (perhaps 10,000 times lower) would be used, reducing the actual advantage of the swept system to more like 10^6 or so. Nevertheless, it is clear that the swept system enables very much weaker excitation of resonances to be used. Optimized CW/swept excitation RUS instrumentation packages are now commercially available.

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 30MHz $LiNbO_3$ transducer disk 1.5mm in diameter has torsional resonances beginning below 200kHz, and many other resonances between there and the first compressional mode at 30Mhz, making it useless for RUS. However, by making a metallic diffusion bond to a single-crystal diamond disk 1.5mm in diameter and 1mm thick, a structure is produced with negligible damping to minimize noise, a lowest resonance of about 4.3MHz, and the ability to operate from below 1K to above 1000K. Ordinary epoxy bonds can also be used, limiting the maximum temperature to about 350K. Using a pair of such 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 gram. Using drive levels of less than 1 volt, and electronics like that described above, S/N ratios of better than 30db are easily achieved.

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 [1,5-7] 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 result are codes that produce 5 digit accuracy for 200 modes and that can run on fast PC's in minutes.

The state of the art now is such that using RUS as a laboratory tool, anisotropic elastic moduli can be measured on millimeter samples 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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