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Contactless Mode-Selective Resonance Ultrasound Spectroscopy: Electromagnetic Acoustic Resonance

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Abstract

We describe a novel method for measuring elastic constants and internal friction in electrically conductive solids: electromagnetic acoustic resonance (EMAR). Contactless coupling based on the Lorentz-force mechanism is achieved by permanent magnets to supply the static magnetic field and a solenoidal coil surrounding a rectangular-parallelepiped specimen. Because the direction and symmetry of the Lorentz forces can be easily changed by changing the geometrical configuration of the static field and the coil, we can select a single vibration group of interest, filtering out the other vibration groups. In principle, seven vibration groups can be independently excited among eight possible vibration groups of a rectangular-parallelepiped specimen. This provides a big advantage in mode identification. The EMAR method is much less sensitive than the RUS method to the initial (guessed) C_{ij} for the inverse calculation. For a copper monocrystal, we reached the same C_{ij} with 100 %-varied guessed values. For silicon-carbide-fiber-reinforced titanium-alloy composites, we could vary the guessed values up to 20 %. We used a free-decay method to measure internal friction Q_{ij}^{-1}. The contactless EMAR method enables one to measure intrinsic internal friction, free from energy loss into transducers and grips.

Transcript

This paper describes a new RUS (Resonance Ultrasound Spectroscopy) method to selectively and independently cause one particular vibration group, using electromagnetic acoustic transducer, EMAT.

The RUS method is a powerful tool to determine all independent C_{ij} for a small specimen with a single frequency scan. One measurement provides a complete set of C_{ij}. However, successful use of the RUS method needs exact correspondence between measured and calculated resonance frequencies, that is mode identification. For this, we need to know the elastic constants for the inverse calculation that are not far from the true values. For making exact mode identification, several methods appeared, but they are inapplicable to the material of large internal friction, because of resonance-peak overlapping. The best way to make an exact mode identification is to produce the RUS method for one particular vibration group independently.

As well as the difficulty of making mode identification, mechanical contacting causes a problem in the RUS method. Coupling force is not very large compared with the conventional contacting methods such as the pulse-echo method, but, still acoustic energy goes into the transducers that causes extra energy loss and increase the as-measured internal friction.

In this study, we develop a new contactless resonance method to selectively and independently select one vibration group among eight groups of free vibration of rectangular parallelepipeds, and apply it to determining C_{ij} and Q_{ij}^{-1}, which is internal friction tensor, of the silicon-carbide-fiber reinforced titanium alloy composite. Then, we use this method at elevated temperatures to measure the temperature dependence of C_{ij} and Q_{ij}^{-1}, which is easily realized by the EMAR feasibility at elevated temperatures.

[Transparency 1]

Figure 1 shows a typical measurement setup of EMAR, which includes a solenoid coil and permanent magnets providing the static magnetic field. The specimen is inserted in the coil. Because the coil is very loose and never tight, no external forces are applied to the specimen, except for gravity, realizing an acoustically-noncontacting situation.

We drive the solenoid coil with high-power burst signal to induce eddy currents on the specimen surface. Eddy currents interact with the magnetic field and generate the Lorentz forces that cause mechanical vibration. The same coil detects the deformation of vibration after the excitation. By sweeping the frequency of the driving bursts and getting the amplitude spectrum as a function of the frequency, we obtain the resonance spectrum.

[Transparency 2]

We can select a vibration group just by changing the geometrical configuration between the static magnetic field and the coil. Figure 2 explains the mode-selective principle with EMAR. For example, in the measurement configuration of Fig. 2 (a), the magnetic field is applied in the axial direction of the coil. In this case, we expect the Lorentz forces occurring normal to the specimen surfaces. By focusing w, which is the deformation on the x_1-x_2 plane, we easily find, that to detect w with the same coil via the reversed Lorentz-force mechanism, w must be an even function about x_1 and x_2, and an odd function about x_3. Among eight vibration groups of rectangular parallelepipeds, only OD group (breathing vibration) satisfies this condition, meaning that only OD group is excited and detector, filtering others out, in this configuration. Similarly, in Fig. 2 (b), only the OY group and, in Fig. 2 (c), only the OX group are detected and excited. Thus, we can select the vibration group by changing the measurement configuration. In principle, with this method, we can independently cause seven vibration groups among eight groups. We found these three groups are enough to reduce all C_{ij} even for orthorhombic symmetric crystal.

[Transparencies 3 and 4]

We used copper monocrystal specimens and also silicon-carbide-fiber-reinforced titanium-alloy composite as shown in Fig. 3. Both are rectangular parallelepipeds with a few millimeter dimensions. Figure 4 shows a microstructure of the composite material, the silicon carbide fiber and the matrix. This material is a candidate for the aerospace structures and jet-engine components and it is expected to be used at elevated temperatures. Therefore, we need to know the elastic behavior at elevated temperatures.

[Transparencies 5 and 6]

First, we show a couple of the copper monocrystal results and then show the composite results. Figure 5 compares the EMAR and RUS resonance spectra. We used broken line for the RUS spectrum and solid lines for the EMAR spectra. There are many resonance peaks in the RUS spectrum, because all vibration groups are excited simultaneously. But in the EMAR case, we observe just one particular vibrational group with different measurement configuration as expected. Thus, it is much easier to make the exact mode identification. For example, OY_2 and OX_2 appeared at almost the same frequency as shown in Fig. 6. In the RUS measurement, these two modes overlap each other and it is quite difficult to identify them. However, because EMAR can excite independently these two modes, mode identification is clear, including no ambiguousness.

[Transparency 7]

Concerning internal friction, we used a free-decay method with EMAR. We drive the coil with the resonance-frequency bursts, turn off the excitation, and measure the amplitude of vibration with time. By fitting an exponential function, we obtain internal friction from the decay constants. Figure 7 shows the amplitude decay with logarithmic scale, which shows a good agreement with the fitted function. We measure internal friction for all resonant peaks and determine internal friction tensor, Q_{ij}^{-1}, through the inverse calculation.

[Transparency 8]

Table I shows thus determined elastic constants and internal friction. We also used the RUS method to determine the C_{ij} and Q_{ij}^{-1}. Elastic constants between EMAR and RUS agreed well, but EMAR C_{ij} were relatively smaller than RUS C_{ij}. We attribute this to restriction of vibration by sandwiching transducers in the RUS measurement, although we tried to minimize the coupling force. This effect was found remarkably in the internal friction tensor. Internal friction for shear moduli were comparable between the two methods, but internal friction for the vibration mode accompanying volume change, EMAR internal friction was considerably smaller than RUS internal friction, especially for bulk modulus. In this frequency range, 1 MHz or less, the main contribution to the internal friction is dislocation damping. And the bulk-modulus internal friction should be very small, because, in principle, dislocation can not move with hydrostatic oscillation. EMAR measurement provided such a physically reasonable result. RUS methods provided smaller internal friction for the bulk modulus, but it is considerably larger than EMAR. Thus, we consider that this is caused by the energy loss into the transducers because of the volume-changing oscillation in the RUS method.

[Transparency 9]

Next, we will move to the composite material. Figure 8 compares the resonance spectra measured by RUS and EMAR. RUS spectrum consists of large number of peaks, especially in the higher frequency region, and some peaks overlap, making mode identification difficult. In the EMAR case, because we can detect only one vibration group, mode identification is clear.

[Transparency 10]

Table II shows the determined C_{ij} and Q_{ij}^{-1} for the composite material. We again used the RUS method to reduce C_{ij}, but in this case we employed the EMAR C_{ij} as initial values for the inverse calculation. Otherwise, inverse calculation failed to converge or converged to the false minimum. The RUS method is sensitive to the initial C_{ij}.

Note that internal friction for the wave modes propagating to the thickness direction were larger than those for other modes; internal friction for C_{33}, C_{44}, and E_{33} were larger than others. We attribute this to imperfect bonding between ply layers. This composite was fabricated by foil-fiber-foil technique at 1173 K and imperfect bonding could occur because of the mismatch in the thermal expansion coefficient between the fiber and matrix.

[Transparency 11]

Finally, We describe the EMAR measurement at elevated temperatures. For this, we locate the solenoid coil within the stainless-steel cylinder vessel, which is surrounded by the heater. We set the permanent magnets outside the vessel (Fig. 9). This permanent magnets can rotate about the axial direction of the cylinder vessel, so that we can change the field direction and then select the vibration group. With this method we can increase the temperature as long as the specimen possesses electrical conductivity.

[Transparencies 12, 13 and 14]

Figure 10 shows the EMAR spectra of the OY group at various temperatures. Even at 1000 K, we obtained good signal-to-noise ratio of the spectrum. We determined the temperature dependence of each C_{ij} for the crossply composite as shown in Fig. 11. We found anomaly in the temperature dependence around 700K. Also we measured the temperature dependence of internal friction (Fig. 12). Internal friction considerably increased from 700 K. After heating, the internal friction failed to return to the initial value. We attribute the anomaly of the C_{ij} and increase of internal friction at 700 K to disbonding between silicon carbide fiber and the matrix. Indeed, we observed such disbonding after the heart treatment.

Here is the conclusion. We could select the vibration group by just changing the geometrical configuration between the coil and static field.

We observed some effect of the coupling force in the RUS measurement, especially, for the internal friction measurement.

EMAR showed good feasibility at elevated temperature and high-temperature measurement.

DR. SACHSE: Most of the EMATs are narrow-band devices and yet you show a pretty broad range of frequencies.

DR. OGI: No, I understand most EMATs have broadband frequency range. I just have to change the matching network.

DR. LEISURE: The EMAR technique must also be affected by energy loss outside. Do you have any idea how much that would be, what would be the limiting Q you might be able to measure?

DR. OGI: Please repeat.

DR. LEISURE: You have energy loss in the EMAR technique as well affecting Q coupling to the external source. Do you have an estimate of how much that would be?

DR. OGI: I do not know. I think it highly depends on the specimen size.

DR. ANDERSON: I noticed the elastic constants were consistently lower for your magnetic method compared to the RUS method. I do not understand why they are consistently lower.

DR. OGI: We actually observed smaller C_{ij} with the RUS method than with the EMAR method. For example, RUS provided a little bit higher resonance frequency, I do not know why exactly. There is a paper studying the coupling-force effect on the resonance frequency. In that paper, by increasing the force, the resonance frequencies shift to higher region, and then they provide a little bit higher C_{ij}.

DR. ANDERSON: Maybe the difference in Q is related, too.

DR. OGI: Yes. The difference is larger for the bulk-modulus internal friction, while almost no difference occurred for the internal friction of shear moduli. These observations suggest energy loss into the sandwiching transducers for the volume-changing vibrations.

DR. ANDERSON: Perhaps in the breathing mode you see that. ___________ of the air on the specimen, so perhaps the magnetic field situation creates a different loading --

DR. OGI: I see.

DR. ANDERSON: It is very curious. But it is systematically lower and then you say it is contactless. We are interested in the loading of air on specimens, but you have to be very careful in calling it resonant frequency versus pressure.

DR. MARSTON: If you could repeat your description of how the sample was mounted, how do you support the weight of the sample?

DR. OGI: There was a plastic plate on the inside the coil and we just inserted the specimen. Just putting it on the plastic plate, only gravity is applied to the specimen because the coil is very loose and never tight. Of course, there is some coupling between the specimen and the plastic plate, but maybe the acoustic impedance between the plastic plate and metal is quite different, and little energy loss occurred.

DR. MARSTON: You might try some time just holding it like a fishing line, the corners, or some thin filaments.

DR. ISAAK: Do you ever have a problem with this method of maybe not seeing some of the modes that you expect to be there from RUS or is it usually -- if there are 12 RUS modes in this range, you ultimately will see 12 as you do all the orientations?

DR. OGI: I am sorry, I do not understand.

DR. ISAAK: When you compare the modes that you see with the EMAR and RUS, do you generally see all the modes?

DR. OGI: No. We could not observe all modes, even if the detection condition is satisfied. Around here some modes were missing. Because this method detects integrated deformation on the specimen surface, if the integrated value is very small, it fails to detect such a vibration.

Also, another disadvantage of this method is it is applicable to the material having electrical conductivity or magnetostriction.

Thank you.