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Non-Contact Resonant Ultrasound Spectroscopy for Elastic Constants Measurement

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Abstract

Resonant ultrasound spectroscopy (RUS) is a technique for investigation of elastic properties of solids based on the inversion of natural frequencies of free elastic vibrations of a small simply shaped specimen. In the presented contribution, authors modified the standard RUS experimental setup replacing the piezo-crystal transducers by pulse-laser as the source and scanning laser interferometer as the receiver, which brought the following improvements:

i) The scanning laser interferometer provides information about eigenmode shapes, which improve mode identification and thus considerably stabilize the inversion calculation.
ii) There is not any mechanical coupling between the specimen and transducers, which improves resonance quality and measurement reproducibility.
iii) We can observe the temperature evolution of one individual mode, which allows evaluation of elastic constants and their temperature derivatives.
iv) The measurement is more appropriate to carry out in a temperature or vacuum chamber.

Keywords: Laser ultrasound, non-contact resonant ultrasound spectroscopy (RUS), modal vibration analysis, crystal acoustics

1. Introduction

The classical scheme of RUS was adopted by the pioneering works [1-3] following the setup used in the RPR (Rectangular Parallelepiped Resonance) measurements in geophysics. In Fig.1, the main idea of this scheme is outlined: The specimen (parallelepiped, sphere, or any other bulk shape [4]) is placed between two transducers such that the contact area between the specimen and the transducers is minimal (e.g. a cube is placed such that it touches the transducers by two opposite corners only) to ensure the best possible approximation of fully free vibrations. Then, one of the transducers is used as a generator of ultrasonic waves (either scanning slowly the frequencies within a chosen range, or generating a broadband pulse), whereas the second as a detector. Obviously, the main disadvantage of such method lies in the fact that the vibrations are not purely free, as the specimen is restricted by the contact forces from the transducers. This effect was repeatedly shown to be negligible [5,6], but for bulk specimens only. Nevertheless, it introduces a systematic error in detection of the peak position and embarrasses attenuation measurements. For thin plates or shells, which have bending stiffness in some directions comparable to the forces applied by the contact of the transducers, the classical scheme becomes unsuitable.

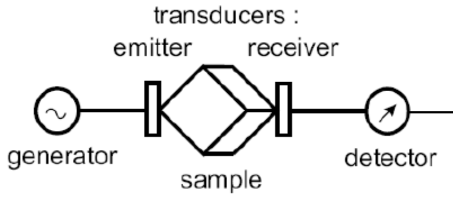

Figure 1. Classical experimental arrangement of the RUS method

Elastic constant evaluation is an inverse problem consisting in finding the optimal set of constants C_k, such that it minimizes the error function

$$F(C_k) = \sum_p w_p \left(f_p^{cal}(C_k) - f_p^{\exp} \right)^2, \tag{1}$$

where f_p^{cal} and f_p^{exp} are corresponding calculated and measured resonant frequencies and w_p are some properly chosen weights .

The assignment of experimental and calculated modes is a source of many errors in classical RUS measurement, where the resonance response is detected on a single position on the sample, and simple ordering of the calculated and measured frequencies is performed to associate corresponding modes. If either the initial guess of the elastic constants is too inaccurate, or some resonance during measurement is lost, such simple ordering leads to an incorrect matching of frequencies and affects the resulting constants.

The problem of the mode identification may be successfully solved by measurements of the vibrating specimen by a scanning laser interferometer [7,8]. However, such arrangement does not solve the problem of contact forces, as the transducer used as generator of vibrations is still in a mechanical contact with the specimen.

In this paper, we describe a fully non-contact modal RUS technique, utilizing pulse excitation by impact power laser. Such scheme fully avoids the effect of the clamping forces, and enables, thus, more accurate measurements of both the elastic coefficients and the attenuation.

2. Non-contact Modal RUS

2.1 Experimental setup

The experimental setup for RUS experiments is outlined in Fig.2. It consists of a National Instruments PXI high speed digital I/O system including the waveform generator (5421, 16bits/100MS/s/80MHz) and the two-channels digitizer (5122, 14bits/100MS/s/100MHz) which enables synchronized sampling of both output and input cards. The elastic vibrations in the specimen are excited by sequences of pulses of a focused infrared laser beam (pulse duration 8ns, energy 25mJ , Quantel ULTRA Nd:YAG Laser system, equipped by fiber optic - FOLA options) from the side of the specimen opposite to detected one. The displacement response is detected in a mesh of points on the sample surface by means of the laser interferometer (Polytec OFV-2570, phase detection in the frequency range 50kHz - 24 MHz) equipped with an original scanning unit consisting of two dielectric mirrors on motorized positional stages. The unit is used for equidistant scanning of the specimen's surface with precision up to 1.25μm. The frequency responses in individual points of the mesh are acquired automatically. Resulting spectrum in each measured point of the sample surface is obtained simply by standard FFT procedure applied on signals detected in time domain. The specimen is laid on a soft underlay made of a material with extremely low acoustic impedance (e.g. cork wood). The vibrations here are both generated and detected by lasers, contacts with the transducers or a stage are fully avoided.

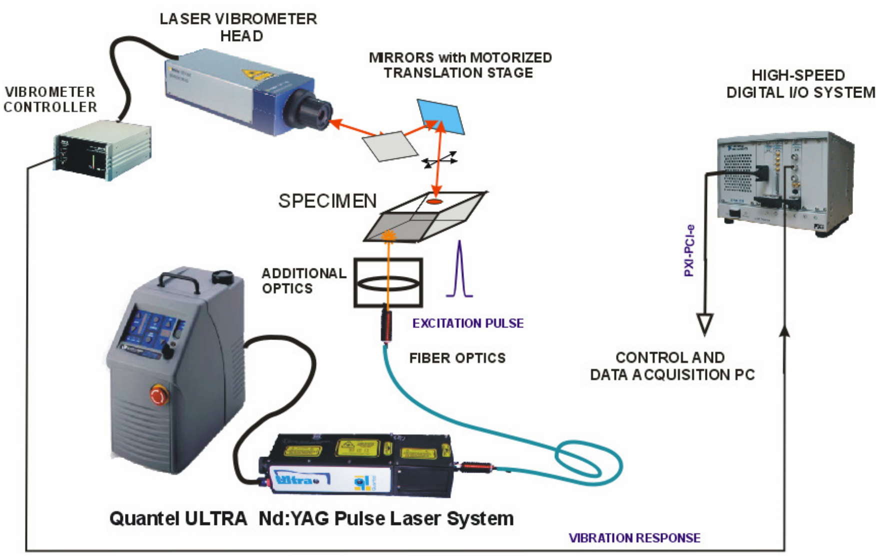

Figure 2. Non-contact Modal RUS with laser pulse excitation

2.2 Inversion procedure for evaluation of elastic constants

A new architecture of the inversion procedure was created ([10]) to incorporate the additional information of eigenmode shapes to the classical inversion scheme. It was considerably complicated by the fact that the eigenmodes form a system of orthogonal vectors, but their surface projections do not (only these projections are provided by the measurement). Hence, one should be aware that identical projections may belong to different modes.

The following architecture of the inversion procedure was found as the most suitable:

1) We take a first estimation of the elastic constants $C^{(0)}_k$ (from pulse-echo measurement or from literature) and calculate eigenfrequencies and eigenvectors of the given sample by the Ritz method.
2) We plot surface distributions of displacement corresponding to each mode and manually associate computed and experimentally measured modes by comparison of their distributions. This manual association allows us to consider also peak position in spectrum and quality of measured distribution. If our constants are far from the correct one then we normally reach to associate only a few first modes.
3) We minimize the error function (1), where the summation is performed only over the associated modes. The minimization is performed by the gradient (Levenberg Marquardt) method, which provides fast and straightforward convergence. The robustness of this inversion can be considerably improved by the reformulation of the problem from the original C_k elastic constants to some properly chosen linear combinations of C_{k} ,[11].
4) Then we return to the 2. step with new constants $C^{(1)}_k$ and repeat this process until we match all the measured resonances and fit their frequencies.

2.3 Comparison to the classical RUS scheme

Efficiency of the described technique may be illustrated on the example in Fig.3, where the first three resonances of the single crystal specimen of CuAlNi are compared. The resonances obtained by contactless technique are of higher quality (sharper) and shifted to lower frequency values in the comparison with the contact excitation. The contact and necessary clamping force increase stiffness of measured samples and they are the cause of biased identification of the first resonances mentioned in literature [3].

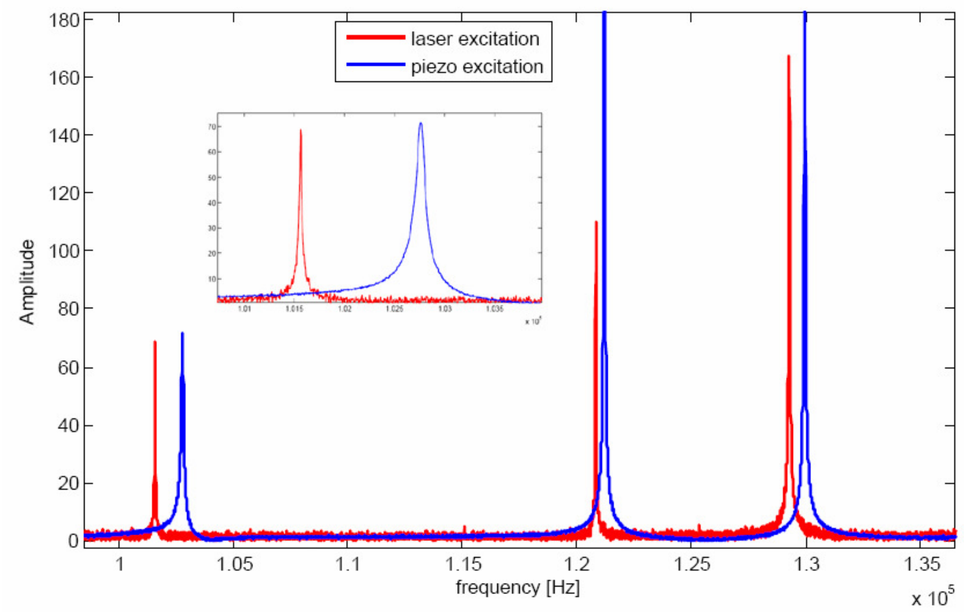

Figure 3. Comparison of the first tree resonances of the CuAlNi alloy single crystal excited by pulse laser (red) and by PZT transducer (blue). The zoomed area shows the first resonance.

2.4 Attenuation measurement for detection of magnetic transition in NiMnGa

In the following example, the change in ultrasound attenuation associated with para- to ferro-magnetic transition was investigated for NiMnGa alloy [12]. NiMnGa alloy exhibits extremely strong magneto-elastic attenuation increase below the Curie point (T_c ~ 385K) which complicates the use of the classical RUS scheme for investigation of this alloy.

Above the Curie point, the spectrum (Fig.4) has a good quality and all the resonant frequencies can be reliably determined. Below the Curie point, the quality of the spectrum significantly decreases. Individual peaks start overlapping and merging, and are also drifted with the temperature (see six selected modes). The non-contact modal RUS method enabled quantitative evaluation of temperature dependences of elastic coefficients and attenuations (Fig.5). Details and physical interpretation may be found in [12].

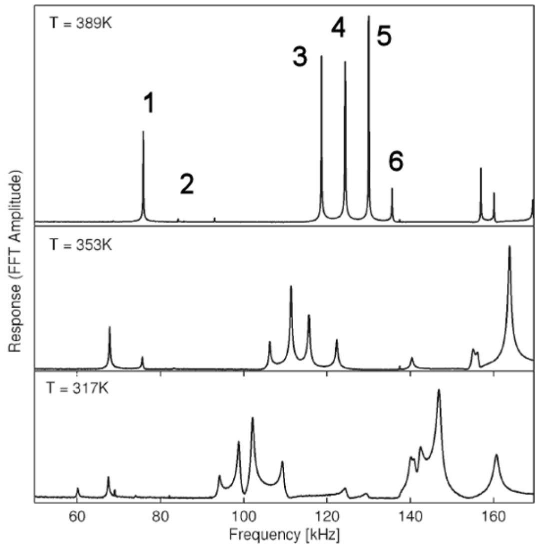

Figure 4. Part of the resonant spectra of NiMnGa in the vicinity of the Curie temperature. The numbers 1-6 denote particular modes.

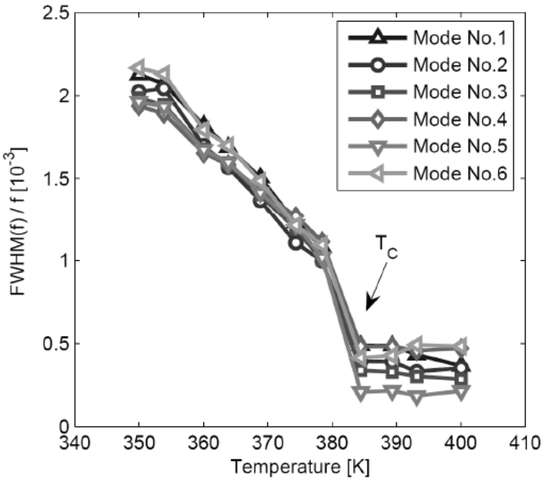

Figure 5. Changes of attenuation in NiMnGa single crystal in the vicinity of the Curie temperature

3. Conclusion

A novel RUS scheme was proposed based on the combination of pulse laser excitation and laser scanning interferometer detection. The main advantages of this new scheme are:

a) Detection of high quality resonances without influence of any additional clamping force.
b) Reliable mode identification by measuring of eigenmode shapes.
c) Measurement of the temperature evolution of one individual mode, which allows evaluation of elastic constants and their temperature derivatives with high accuracy.
d) Quantitative measurement of attenuation (damping, internal friction, etc.)
e) Suitability for measurement under various conditions (vacuum, high/low temperatures, high hydrostatic pressure, etc.)

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References

1. I. Ohno , J. Phys. Earth 24, 355-379. 1976
2. H. H. Jr. Demarest, J. Acoust. Soc. Am. 49, 768—775, 1971
3. A. Migliori, J.L. Sarrao, Resonant Ultrasound Spectroscopy, J.Wiley and Sons,Inc., NY 1997.
4. W.M. Visscher , A.Migliori , T.M. Bell, and R.A. Reinert, J. Acoust. Soc. Am. 90 , 2154 , 1991
5. A. Yoneda, Earth Planets Space 54, 763-770, 2002
6. J. Tian, J., H. Ogi, M. Hirao, Appl. Phys. Lett. 87, 204107-1 - 204107-3, 2005

7. H. Ogi, K. Sato, T. Asada , and M. Hirao , J. Acoust. Soc. Am. 112, 2553-2557, 2002
8. H. Seiner, P.Sedlák, M. Landa, In: Proceedings of 2006 IEEE International Ultrasonics Symposium, October 3. – 6. 2006, Vancouver (Canada), CD-ROM
9. M. Landa, P. Sedlák, H. Seiner, L. Heller, L. Bicanová, P. Šittner, V. Novák, Accepted to Applied Physics A (2008).
10. P. Sedlák , Elastic properties of CuAlNi shape memory alloy, PhD. Thesis, FNSPE, CTU 2008
11. M. Landa, H. Seiner, P. Sedlák , L. Bicanová,L. Heller, Resonant ultrasound spectroscopy close to its applicability limits, the chapter in the prepared book "Acoustic Properties of Solids", Nova Publishers, (accepted)
12. H. Seiner, L. Bicanová, P. Sedlák, M. Landa, L. Heller, S.P. Hannula, submitted to Mater. Sci. Eng. A. (special issue 'Proceedings of 15th ICIFMS 2008').