# APPLICATION OF RESONANT ULTRASOUND SPECTROSCOPY IN DIAGNOSTICS OF RINGS

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**Abstract**

Resonant Ultrasound Spectroscopy (RUS) is a nondestructive technique originally developed for evaluating elastic constants of solids using resonance frequencies corresponding to the normal modes of vibration observed in samples with regular geometry. RUS can also be used for nondestructive evaluation of different metal or ceramic objects based on their resonance spectra. RUS allows detecting deviations, such as, variations in dimensions and hardness or flaws in the inspected objects. This paper presents an application of RUS for monitoring hardness of steel rings. Experimental results are presented that show correlation between the shift of resonant frequencies and hardness of the inspected steel rings.

## 1. Introduction

Resonant Ultrasound Spectroscopy is a nondestructive material characterization technique extracting the information contained in the mechanical resonant spectrum of an oscillating specimen. In a typical RUS configuration a small sample with simple geometry (sphere, cylinder, or rectangular parallelepiped) is placed between two ultrasonic transducers. One transducer excites an elastic wave of a constant amplitude and varying frequency in the specimen, while the second detects sample's mechanical response in an ultrasonic frequency band. The information about resonance frequencies acquired in a RUS test contains useful information about mechanical properties of the tested sample; the detected resonant frequencies generally correspond to the size, shape and elastic modula of the inspected material. More detailed description of RUS can be found in Maynar [1], Migliori *et al.* [2], [3] and Zadler *et al.* [4].

RUS is mainly used for material characterization, however it can also be successfully used for nondestructive evaluation (NDE) of different objects, e.g. metal or ceramic products. Heyliger and Ledbetter [5] applied RUS to detect surface cracks in steel blocks as well as delaminations in composite laminate. They found that RUS can be used as a NDE technique for detecting flaws in material. Adachi *et al.* [6] used RUS for the evaluation of micro-cracks in ceramic ferrules for optical fiber connectors. By comparing the differences between the resonant frequencies they could distinguish between the acceptable ferrules and the defective ones.

In this paper we present results of RUS application for hardness monitoring of steel rings. The test was performed on steel rings with well defined geometry that were prepared using thermal treatment resulting in different hardness levels. Frequency shift of a number of resonance peaks were measured in the RUS test and subsequently correlated with material hardness measured in a conventional test.

## 2. RUS theory

In this section we outline the theoretical background of RUS, the detailed presentation can be found in [2] and [3]. A free oscillation body can sustain non-attenuated vibrations at series of resonant frequencies (normal modes), $\omega_m$. Informations derived from the spectrum of modes includes the information about entire elasticity matrix as well as the information about the object's geometry and density. In theory, all of these data can be acquired from a single measurement by solving an inverse problem, that is, calculating specimen's material constants based on experimentally measured frequency spectrum. However, an exact analytic solution for a 3D object is does not exist, except some very special cases. Therefore, the usual way is to get an approximate solution by iteratively solving the forward problem. The calculation starts with the Lagrangian for a 3D elastic body,

$$L = \frac{1}{2} \int\limits_V ( \, \omega^2 \rho u_i^2 - C_{ijkl} \, \varepsilon_{ij}(u) \, \varepsilon_{kl}(u)) \, dV, \tag{1}$$

where $C_{ijkl}$ is the elastic constant tensor, $i, j, k, l = 1, 2, 3$, and $\varepsilon(u)$ is the position dependent strain tensor. Displacements $u_i$ can be expended using *Rayleigh-Ritz* approximation technique in a set of N functions $\phi_\lambda$, which should be easy to evaluate numerically

$$u_i = a_{i\lambda} \phi_\lambda, \tag{2}$$

where $a_{i\lambda}$ are the expansion coefficients. By limiting number of functions the problem is reduced to that of diagonalizing a *NxN* matrix.

Vissher *et al.* [7] discovered that the simplest choice of $\phi_\lambda$ is

$$\phi_\lambda = x^{\eta(\lambda)} y^{\zeta(\lambda)} z^{\xi(\lambda)} \tag{3}$$

where $\eta$, $\zeta$ and $\xi$ are positive integers. This solution provided basis functions that are very flexible and convenient to implement for a wide variety of shapes and symmetries. Choice of the exponents $\eta, \zeta, \xi$ is reduced to satisfy relation

$$\eta + \zeta + \xi \leq N_p, \tag{4}$$

where $N_p$ is a positive integer, higher $N_p$ values result in more accurate results.

Using estimated values for the elastic constants (from theory or literature), geometry and density of the sample, one can calculate starting resonant frequency spectrum, as decried above. A square sum function expressing the difference between the calculated frequency spectrum, $f_n^{cal}(n = 1, 2, \cdots)$ and measured spectrum, $f_n^{mea}(n = 1, 2, \cdots)$ can be formulated,

$$F = \sum_n w_n (f_n^{cal} - f_n^{mea})^2, \tag{5}$$

where $w_n(n = 1, 2, \cdots)$ are weight coefficients representing the confidence of resonance measurements [8].

Changing the elastic constants results in changes in the $F$ function and a global minimum of the function $F$ is sought. The computation is repeated until some performance criterion is met. The number of measured normal modes should be at least 5 to 10 times the number of the independent elastic constants that have to be estimated [8]. Elastic constants of a regular material sample can be estimated using the above presented RUS theory with an error less than $1\%$.

Our objective in this study is to show correlation between some preselected resonant frequencies and material hardness obtained as a result of heat treatment (tempering). Thus, our aim is not solving the strict inverse problem but establishing an experimental relation between the RUS result and material hardness.

## 3. Experiment

RUS measurements were performed in the setup shown in Fig. 1 for 34 rings divided in two batches. Each batch consisted of different number of rings that had been subjected to similar thermal treatment resulting in similar material properties. The main difference between two batches was that the first one contained finished rings (after grinding) and the second one contained unfinished rings (after turning). Hence, the size of samples in those groups was different. Hardness of tested rings for each batch is presented in Table 1. Each batch was tested separately and consisted of rings with similar hardness level.

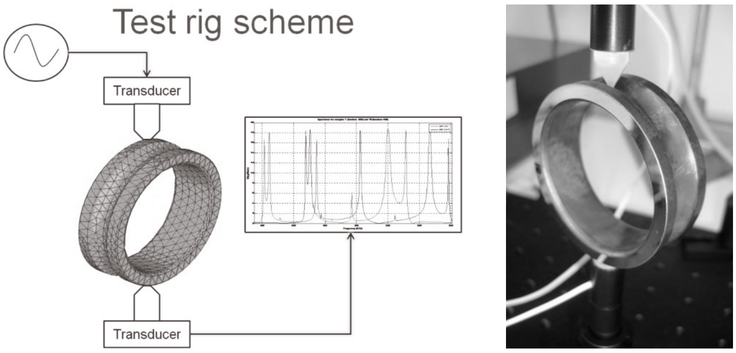


Figure 1: RUS test setup used in the experiment.

Table 1: Rings hardness level in HRC for each group

| Hardness [HRC] | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Batch 1 | 45,9 | 46,9 | 49,9 | 50,2 | 51,8 | 54,1 | 55,6 | 56,8 | 60,4 | 60,8 |
| Batch 2 | | | 51,0 | 52,3 | 54,8 | 55,7 | 55,9 | 58,6 | 59,5 | 60,7 |

The inspected rings were placed between two piezoelectric transducers; one was used to generate vibrations in the ring and the second for receiving the ring's response. The transducers were provided with conical tips that limited acoustic coupling with the inspected rings. Agilent 4385A Network Analyzer was used for the acquisition of the frequency spectrum and the data corresponding to a number of selected RUS resonance peaks were recorded. Resonance frequencies were acquired for all rings, and then the differences between them were analyzed. After preliminary test a frequency band 108-133 kHz was chosen for the subsequent analysis.

## 4. Results and discussion

The analysis of the acquired spectrums was limited to the frequency bands including resonant frequencies in the range of 108-133 kHz, which was found to be apparently sensitive to the changes in hardness.

The measured resonant frequencies were normalized to facilitate further analysis. Normalized frequency shifts were calculated with respect to the lowest measured normal mode. To get normalized frequency shifts the relative changes in resonant frequencies were calculated as

$$\Delta\bar{f}_i = \frac{\bar{f}_i - \bar{f}_1}{\bar{f}_1} \cdot 100 \ \ [\%], \tag{6}$$

where $\Delta\bar{f}_i$ denotes the averaged resonance frequency shift of the ring $i$, and $\bar{f}_1$

corresponds to the frequencies of the ring with the highest hardness level.

Correlation between the normalized frequency shifts and ring hardness for both batches is shown in Figs 2 and 3 where the standard deviations for the resonant frequencies are also indicated.

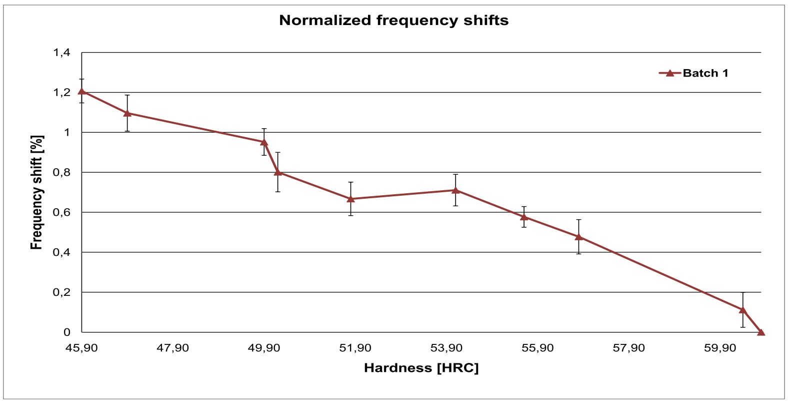


Figure 2: Relation between the relative frequency shifts and hardness for batch 1.

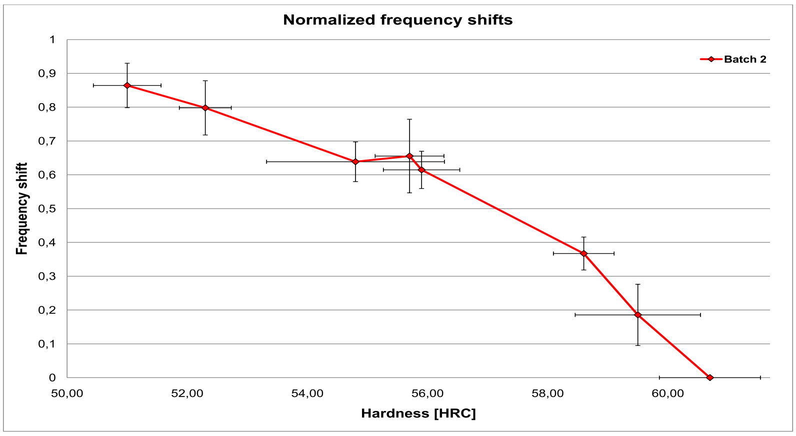


Figure 3: Relation between the relative frequency shifts and hardness for batch 2.

The data show decreasing trend in frequency for increasing hardness for both inspected batches. This trend is almost linear with only some small deviations.

Since the size of samples was different for both batches, it resulted in different resonance frequency spectrum. Hence, those two groups cannot be compared directly. However, from the above results we can say, that frequency shift is approximately 0.9% per 10 HRC for both groups.

## 5. Conclusion

It was shown that hardness of the inspected rings is clearly correlated with the resonant frequency measured in RUS tests for two batches of steel rings subjected to tempering in different temperatures.

Although the relative frequency changes may seem to be very small, it should be taken under consideration that 1% shift for the band 108-133kHz corresponds to more than 1kHz, which can be easily detected with modern instruments. It should be noted that other factors that normally affect the resonances in RUS, such as geometry and steel analysis, are at the level that does not disturb the main trend in the considered case of rings.

Thus we can say that RUS has appeared to be feasible method for the hardness inspection of rings based on the changes of the resonance frequencies. RUS could be relatively easily applied for the quality control procedure of such rings; essentially monitoring of a single resonance peak within frequency band included in our experiment would be sufficient.

## 6. ACKNOWLEDGEMENTS

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## References

[1] J. Maynard. Resonant ultrasound spectroscopy. *Phys. Today*, 49(26), 1996.

[2] A. Migliori, J. Sarrao, W.M. Visscher, T.M. Bell, Ming Lei, Z. Fisk, and R.G. Leisure. Resonant ultrasound spectroscopic techniques for measurement of the elastic moduli of solids. *Physica B*, 183(1-2):1–24, 1993.

[3] A. Migliori and J. Sarrao. *Resonant Ultrasound Spectroscopy*. Wiley, New York, 1997.

[4] B. J. Zadler, J. H. L. Le Rousseau, and J. A. Scales ans M. L. Smith. Resonant ultrasound spectroscopy: theory and application. *Geophys. J. Int.*, 156:154–169, 2004.

[5] P. Heyliger and H. Ledbetter. Detection of surface and subsurface flaws in homogeneous and composite solids by ultrasound. *J. of Nondestructive Evaluation*, 7(2), 1998.

[6] T. Adachi, Y. Kondo, A. Yamaji, S-H Yang, and I-Y Yang. Nondestructive evaluation of micro-cracks in a ceramic ferrule by resonant ultrasound spectroscopy. *NDT&E International*, 38, 2005.

[7] W. Visscher, A. Migliori, and T. Bell abd R.Reinert. On the normal modes of free vibration of inhomoheneous and anisotropic elastic objects. *J. Acoust. Soc. Am.*, 90:2154–2162, 1991.

[8] R.B Schwarz and J.F. Vuorinen. Resonant ultrasound spectroscopy: applications, current status and limitations. *Journal of Alloys and Compounds*, 310:243–250, 2000.