

Application of resonant ultrasound spectroscopy in diagnostics of rings

T Łukomski and T Stepinski

Submitted 15.12.10

Accepted 09.03.11

Resonant ultrasound spectroscopy (RUS) is a non-destructive 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 non-destructive evaluation of various metal or ceramic objects based on their resonance spectra. RUS can be used to detect deviations, such as variations in dimensions and hardness or flaws in the inspected objects. This paper presents an application of RUS for monitoring the hardness of steel rings. Experimental results are presented that show a correlation between the shift of the resonant frequencies and the hardness of the inspected steel rings.

1. Introduction

It has been known for a long time that differences in the shape, size and material of an elastic object result in different resonant frequency spectra; for example, the sound of a bell differs whenever its size, shape or material is different. Imperfections, inclusions or cracks can also influence the bell's sound. The resonant spectrum is unique for each elastic object and can be used as its fingerprint. A comparison between the frequency spectra of two elastic bodies can reveal deviations in their mechanical parameters. The relation between the resonant frequencies and the object's features can be revealed either theoretically, by solving the so-called inverse problem, or experimentally, by correlating measurement results.

Resonant ultrasound spectroscopy (RUS) is a non-destructive material characterisation technique using the information contained in the ultrasound frequency band of the mechanical resonant spectrum of an oscillating specimen. In a typical RUS set-up, a small sample with a simple geometry (sphere, cylinder or rectangular parallelepiped) is placed between two ultrasonic transducers. One transducer excites an elastic wave of a constant amplitude and a varying frequency in the specimen, while the second detects the sample's mechanical response in an ultrasonic frequency band. The information about the resonance frequencies acquired in an RUS test contains useful data about the mechanical properties of the tested sample; the detected resonant frequencies generally correspond to the size, shape and an elastic modulus of the inspected material. A 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 characterisation. However, it can also be successfully used for the non-destructive evaluation (NDE) of various objects, for example metal or ceramic products. Heyliger and Ledbetter^[5] applied RUS to detect surface cracks in steel blocks, as well as delaminations in a composite laminate. They found that RUS can be used as an NDE technique for detecting

flaws in materials. Adachi *et al.*^[6] used RUS for the evaluation of micro-cracks in ceramic ferrules for optical fibre connectors. By comparing the differences between the resonant frequencies they could distinguish between acceptable ferrules and defective ones. The same method was used for the quality assessment of varistor ZnO structures by Hasse *et al.*^[7].

In this paper we present the results of an RUS application for hardness monitoring of steel rings. We report the results of tests performed on steel rings with well-defined geometry, which were prepared using thermal treatment (tempering), resulting in different hardness levels. Frequency shifts of a number of resonance peaks were measured in the RUS test and subsequently correlated with the material hardness measured in a conventional indentation test. Rings were chosen due to their regular geometry and their common occurrence in industry, for example in the production of bearings, where hardness is an essential parameter.

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 oscillating body can sustain non-attenuated vibrations at a sequence of resonant frequencies (normal modes), ω_m . Data derived from the spectrum of modes includes information about the entire elasticity matrix as well as information about the object's geometry and density. In theory, the complete elastic parameters can be acquired from a single measurement by solving an inverse problem, that is, calculating the specimen's material constants based on an experimentally measured frequency spectrum. However, an exact analytical solution for a 3D object does not exist, except in some very special cases. Therefore, the usual approach is to get an approximate solution by iteratively solving the forward problem. The calculation starts with the Lagrangian for a 3D elastic body:

$$L = \frac{1}{2} \int_V (\omega^2 \rho u_i^2 - C_{ijkl} \varepsilon_{ij}(u) \varepsilon_{kl}(u)) dV \dots\dots\dots(1)$$

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 expanded using the Rayleigh-Ritz approximation technique in a set of N functions ϕ_λ , which should be easy to evaluate numerically:

$$u_i = a_{i\lambda} \phi_\lambda \dots\dots\dots(2)$$

where $a_{i\lambda}$ are the expansion coefficients. By limiting the number of functions, the problem is reduced to that of diagonalising an $N \times N$ matrix.

Vissher *et al.*^[8] discovered that the simplest choice of ϕ_λ is:

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

where η , ξ and ξ 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 η , ξ , ξ is restricted to those satisfying the relation:

$$\eta + \xi + \xi \leq N_p \dots\dots\dots(4)$$

Tomasz Łukomski is with AGH – University of Science and Technology, Kraków, Poland. Email: lukomski@agh.edu.pl

Tadeusz Stepinski is with Uppsala University, Uppsala, Sweden. Email: tadeusz.stepinski@angstrom.uu.se

where N_p is a positive integer. Higher N_p values give more accurate results.

Using estimated values of the elastic constants (from the theory or literature), together with the geometry and density of the sample, an initial resonant frequency spectrum can be calculated as described above. A square sum function expressing the difference between the calculated frequency spectrum, f_n^{cal} ($n = 1, 2, \dots$), and the measured spectrum, f_n^{mea} ($n = 1, 2, \dots$), can be formulated:

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

where w_n ($n = 1, 2, \dots$) are weight coefficients representing the confidence in the resonance measurements^[9].

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 resonance modes should be at least 5 to 10 times the number of independent elastic constants that have to be estimated^[9]. The elastic constants of a regular material sample can be estimated using the RUS theory presented above with an error of less than 1%.

Unfortunately, material hardness does not depend only on the elastic constants. It also depends on the material microstructure, including grain size and orientation, and also on other factors, such as the tempering temperature. Hence, it is probably impossible to calculate the hardness directly by solving the inverse problem. However, we are able to do it indirectly by applying empirical correlation.

Our objective in this preliminary study is to show, experimentally, a degree of correlation between some preselected resonant frequencies and material hardness variations resulting from the parameters of the tempering process. Thus, our aim is not to solve the strict inverse problem but to establish an experimental relation between the RUS result and the material hardness.

3. Experiment

RUS measurements were performed for 61 rings in the set-up shown in Figure 1. The rings were divided into three batches and each batch consisted of a number of groups with three rings in each (triplets). These groups had been subjected to different thermal treatment resulting in different material properties.

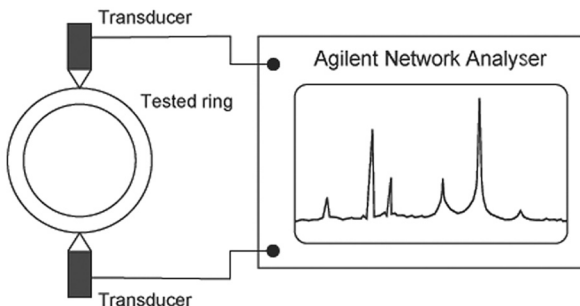


Figure 1. RUS test set-up used in the experiment

The main difference between the batches was that the first one contained finished rings (after grinding), the second one contained unfinished rings (after turning) and the third one, also unfinished,

had slightly different material parameters which resulted in a higher hardness level, both before and after the thermal treatment. Hence the size and hardness of samples in those batches were different. The hardness of each ring was measured at five points and then averaged for a whole triplet. The results are presented in Table 1 with tempering temperature as a parameter. The specimen's hardness was evaluated using a Vickers hardness tester and then the results were converted to the Rockwell scale. All values referring to the hardness in this paper are presented in the Rockwell scale C – HRC. The relation between the hardness and the temperature of the tempering process for all three batches can be seen in Figure 2. From Table 1 and Figure 2 it can be seen that, due to different material analysis, the result of the tempering process for batch 3 was slightly different from that for batches 1 and 2.

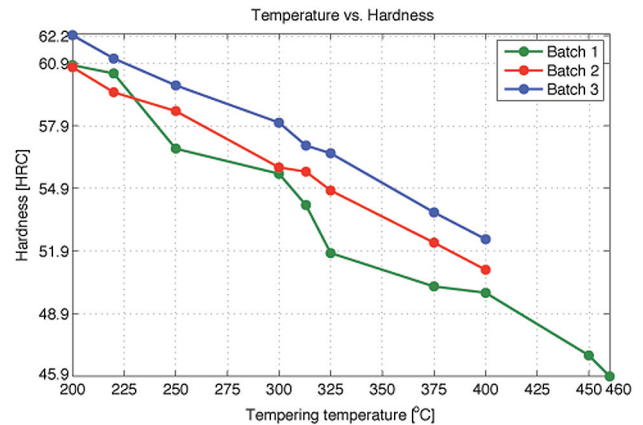


Figure 2. Averaged hardness of rings as a function of tempering temperature (N.T. means no tempering, i.e. the hardness of the hardest rings in batch 3 before tempering)

For RUS spectrum acquisition the inspected rings were placed between two piezoelectric transducers, as shown in Figure 1. One transducer 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 (to minimise the mechanical load that could influence the measurement result). An Agilent 4385A Network Analyser was used for the acquisition of the frequency spectra. Initially, frequencies corresponding to a number of selected RUS resonance peaks were recorded and evaluated. After this preliminary test the frequency band 108-133 kHz was chosen for subsequent analysis and resonant frequencies in this band were acquired for all rings.

Also, it should be noted that the temperature at which the tests are performed has an influence on the elastic constants and thus the RUS. Although the elastic constants might not vary much for temperature changes of a few degrees Celsius, it is not recommended to do tests at varying temperature since this can produce errors in the resonant frequencies. That is why all experiments were performed at a constant temperature of 22°C in an air-conditioned laboratory.

Another factor that affects the frequency shifts are variations in sample size and geometry. The inner diameter of all rings was 50 mm, and the outer diameter was 62 mm for batch 1 and 63 mm for batches 2 and 3. Differences between the diameters of the tested rings were smaller than 0.1 mm for each batch. Thus

Table 1. Ring hardness level in HRC for each group and for each tempering temperature

		Tempering temperature										
		460°C	450°C	400°C	375°C	325°C	313°C	300°C	250°C	220°C	200°C	N.T.
Hard	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	–
	Batch 3	–	–	52.5	53.7	56.6	56.9	58.0	59.8	61.1	62.2	63.6

this did not have a significant influence on the frequency shifts of the tested rings. However, rings from batch 1 (after grinding) and from batches 2 and 3 (after turning) had about 1 mm difference in diameter. Although this resulted in totally different (shifted) frequency spectra, it did not influence the general trend, which is shown in the next section.

4. Results and discussion

Normal modes in the range of 108-133 kHz were easy to identify and also appeared to be sensitive to changes in hardness. An example of the frequency spectra measured for two rings with different hardness levels is shown in Figure 3.

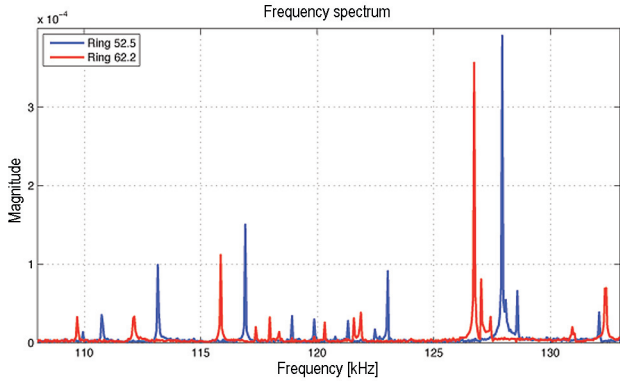


Figure 3. Example of frequency spectra of two rings with different hardness levels

The measured resonant frequencies were normalised separately for each batch, due to differences in geometry (batch 1) and material properties (batch 3) between batches. Normalised frequency shifts were calculated with respect to the rings tempered at 200°C. To get the normalised frequency shifts, the relative changes in the resonant frequencies were calculated as:

$$\Delta \bar{f}_{in} = \frac{\bar{f}_{in} - \bar{f}_{1n}}{\bar{f}_{1n}} \cdot 100 [\%] \dots\dots\dots (6)$$

where $\Delta \bar{f}_{in}$ denotes the resonance frequency shift of mode n for the ring i , and \bar{f}_{1n} corresponds to the frequency of mode n of the ring tempered at 200°C for the specific batch.

Results presenting the shifts in four selected resonant frequencies for batch 3 after normalisation are shown in Figure 4. It can be seen that the normalised frequency shifts were quite similar for all four modes. Therefore, the frequency shifts for all modes were averaged and standard deviations were calculated.

Correlation between the averaged normalised frequency shifts and the averaged ring hardnesses for all batches is shown in Figure 5. The standard deviations for the resonant frequencies and

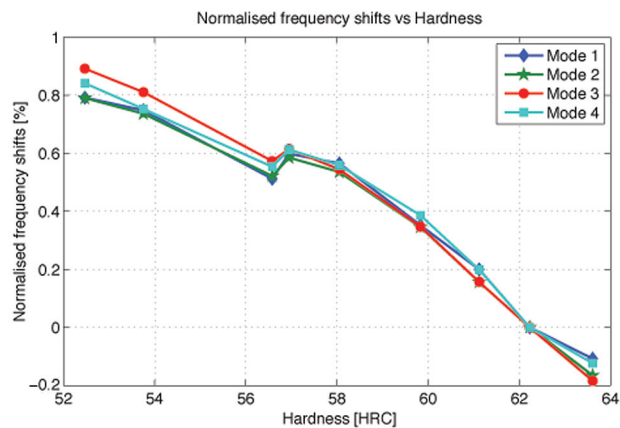
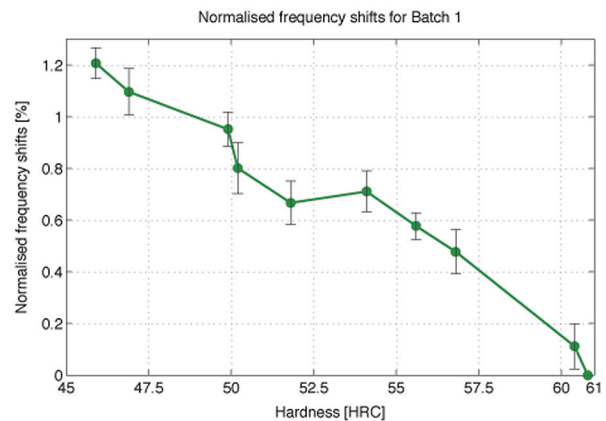


Figure 4. Frequency shift of four normal modes for batch 3 after normalisation

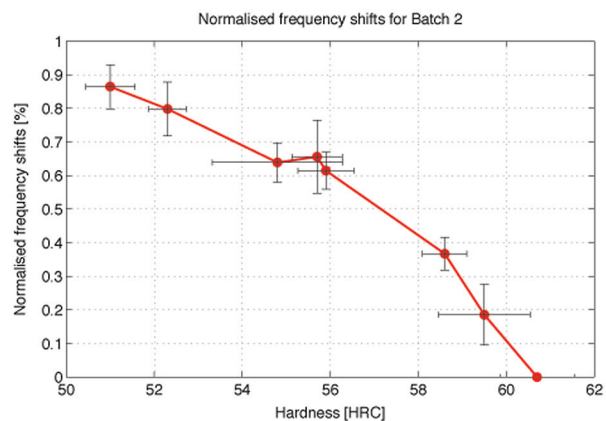
hardnesses are also indicated, with the exception of batch 1, where only one hardness value was known for each tempering step.

The data shows a decreasing trend in frequency shift for increasing hardness for all the inspected batches. This trend could be well represented by a linear function. However, after further analysis the trend appeared to be better fitted with a parabolic function.

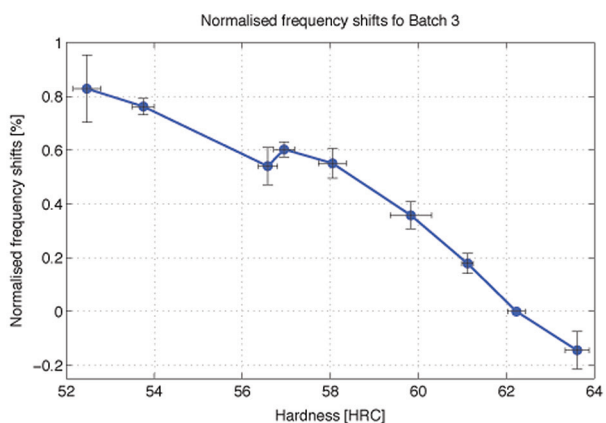
When we compare all batches together, as shown in Figure 6(a), it can be seen that batches 1 and 2 overlap each other due to their similar hardness level. Batch 3, however, had different material properties, which resulted in higher initial hardnesses of the rings. Hence, its graph is slightly shifted to the right. The frequency shift estimated from the results presented in Figure 5 is approximately 0.9% per 10 HRC for all groups.



(a)



(b)

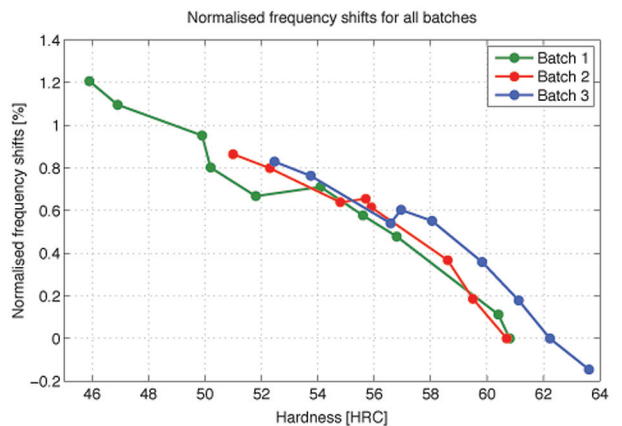


(c)

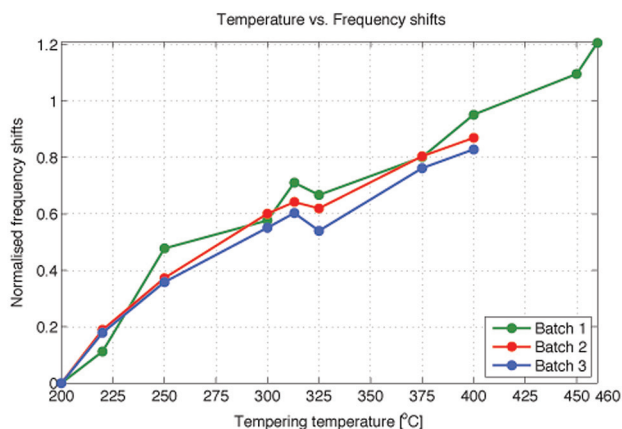
Figure 5. Relation between the relative frequency shifts and hardnesses of rings in batches 1 to 3

Also, knowing that hardness changes linearly with temperature for all batches (Figure 2), and that they were tempered at the same temperatures, it is possible to correlate frequency shifts with temperature. The result is shown in Figure 6(b). Note that the rings from batch 3 that had not been tempered are removed in this plot.

From Figure 6(b) it can be seen that all rings tempered at a temperature of 325°C show a clear drop in the frequency shift. This decrease might be caused by a change in the steel structure that appears for tempering temperatures above 300°C.



(a)



(b)

Figure 6. Normalised frequency shifts for all batches in function of hardness (a) and tempering temperature (b)

5. Conclusion

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

Although the relative frequency changes may seem to be very small (0.9%/10 HRC), it should be borne in mind that a 1% shift for the band 108-133 kHz corresponds to more than 1 kHz, 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 chemical analysis, are at a level that has not disturbed the main trend in the case considered of rings.

As mentioned in Section 1, resonances depend on the material shape and the elastic constants. In spite of the fact that hardness does relate directly to the elasticity matrix, it is possible that in this specific case hardness is correlated with elasticity as well as with the structure changes that occur during the tempering process. Unfortunately, data about the material structure and elasticity were unavailable to the authors and it is impossible to verify this conclusion. That is why the authors focused exclusively on the hardness evaluation of the tested specimens.

In summary, we can say that RUS appears to be a feasible method for the hardness inspection of rings based on changes of shifts in the resonance frequencies. RUS could be relatively easily applied in quality control procedures for such rings; essentially, monitoring of a single resonance peak within the frequency band of our experiment would be sufficient.

6. Acknowledgements

This work was supported by JERNKONTORET's (The Swedish Steel Producers' Association) Committee TO44 in the project 44030 financed by Vinnova (The Swedish Governmental Agency for Innovation Systems) as part of its Strategic Steel Research Programme, which is gratefully acknowledged.

References

1. J Maynard, 'Resonant ultrasound spectroscopy', *Physics 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) pp 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, J A Scales and M L Smith, 'Resonant ultrasound spectroscopy: theory and application', *Geophys J Int*, 156, pp 154-169, 2004.
5. P Heyliger and H Ledbetter, 'Detection of surface and subsurface flaws in homogeneous and composite solids by ultrasound', *Journal of Non-Destructive Evaluation*, 7 (2), 1998.
6. T Adachi, Y Kondo, A Yamaji, S-H Yang and I-Y Yang, 'Non-destructive evaluation of micro-cracks in a ceramic ferrule by resonant ultrasound spectroscopy', *NDT&E International*, 38, 2005.
7. L Hasse, M Kiwilszo, J Smulko and T Stepinski, 'Quality assessment of varistor ZnO structures by resonant ultrasound spectroscopy', *Insight - Non-Destructive Testing and Condition Monitoring*, 51, pp 262-265, May 2009.
8. W Visscher, A Migliori, T Bell and R Reinert, 'On the normal modes of free vibration of inhomogeneous and anisotropic elastic objects', *J Acoust Soc Am*, 90, pp 2154-2162, 1991.
9. R B Schwarz and J F Vuorinen, 'Resonant ultrasound spectroscopy: applications, current status and limitations', *Journal of Alloys and Compounds*, 310, pp 243-250, 2000.