SIMULATION OF REFRACTORIES RESONANCE FREQUENCY

Dietmar Gruber*, Thomas Auer, Harald Harmuth
Chair of Ceramics, University of Leoben, Austria

ABSTRACT

The resonance frequencies of a system are the frequencies in which it oscillates after external excitation. The excited resonance frequencies depend on the location of the excitation and on the properties of the specimen, which are shape, density defects and elastic modulus.

Corresponding to the excitation different resonance frequencies and their harmonics can be observed, which are called Eigenmodes. If the shape and density of a sample are known E, G and ν can be evaluated from the frequency spectrum generated in a laboratory experiment. For common shapes the relation between linear elastic material properties and resonance frequencies is documented in [1].

It seems resonable to use resonance frequencies for performing quality control in the production process in a non-destructive way. The applicability of this testing method can be tested by simulating the influence of inhomogenieties.

Simulations with ABAQUS have been carried out to enhance and expand the evaluation of laboratory experiments. Results show high accordance between ASTM formulas and simulation results for geometries covered by ASTM. For other shapes the simulation can provide a relation between elastic properties and the resonance frequencies. Further simulations show the influence of inhomogeneities on elastic properties, densities and cracks on the Eigenmodes and the dependency of the sample oscillation from the loading point.

EVALUATION OF LABORATORY EXPERIMENTS

In laboratory experiments the frequency spectrum of a sample can be detected after mechanical excitation. For instance this can be done with a resonant frequency and damping analyser (RFDA) [2]. In figure 1 a typical frequency spectrum of a ordinary ceramic refractory can be seen [3]. Two peaks were detected with the RFDA system and were evaluated. In the current case the required relation between resonance frequency and Young's modulus (E) and shear modulus (G) can be taken from the ASTM standard [1]. The Young's modulus is determined using the resonant frequency in the flexural or longitudinal mode of vibration. The shear modulus is found using torsional resonant vibrations.

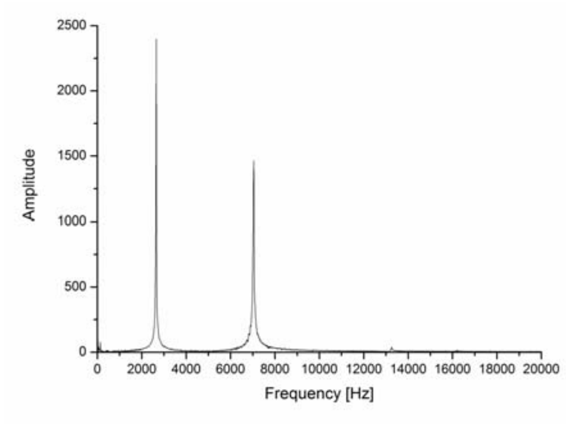


Fig. 1. Recorded frequency spectrum from an ordinary ceramic refractory

CONTRIBUTION OF THE SIMULATION TO THE EVALUATION OF LABORATORY EXPERIMENTS

In case of evaluating geometries covered by ASTM the simulation of resonant frequencies can contribute to assign the peaks of the frequency spectrum to characteristic modes of flexural, torsional or longitudinal oscillation. Therefore a simulation was carried out with the testing samples geometry. The calculation delivers the resonance frequencies and the corresponding deformation of the sample.

From the frequency spectrum in fig. 1 the Young's modulus can be calculated using the ASTM formulas. If this Young's modulus is compared with the simulation result for the recorded frequencies the difference between the Young's moduli is very low and only 0,27‰. Observable is a high accordance of the results obtained by ASTM and simulation.

For specimen geometries which are not within the validity of ASTM the relation between elastic properties and resonance frequency can be calculated. The example shown here is an industrial brick with a length and width of 198 and 180 mm and height of 65mm. On the cold end the height is 78mm.

Two reasons prevent the validity of the ASTM formulas. One of them is their restriction to rectangular cross sections. Moreover they are valid only for a length-width ratio greater than five. Both are not satisfied here. A simplified geometry with rectangular cross section and height of 71,5 mm was evaluated with the ASTM formulas. The obtained result is 104,23 Hz/GPa. For the simplified geometry the simulation delivers 99,58 Hz/GPa and for the real geometry 99,62 Hz/GPa.

It can be observed that small deviations of the shape from the area of validity of ASTM cause a significant difference between the simulated and ASTM results. The difference between the real and the simplified case is small in the simulation. Therefore the inaccuracy of the ASTM formula is more influenced by the smaller length/width ratio than by deviation from rectangular shape. For a possible evaluation of the spectrum of a commercial available brick the relation between elastic properties and resonance frequencies have to be simulated.

Dependence on location of excitation

Additionally to the simulation of the Eigenmodes the oscillation amplitude generated by the excitation in two points (A, B, fig. 2) was simulated. In this case vibrations in the frequency range from 100 to 15000 Hz are applied in point A or B on the sample defined in table 1. The amplitude of the oscillation in a selected point was simulated, and evaluated for point C (fig. 2). As result a diagram of amplitude versus frequency is obtained and shown in figure 3 for loading point A of fig. 2 and figure 4 for loading point B of fig. 2.

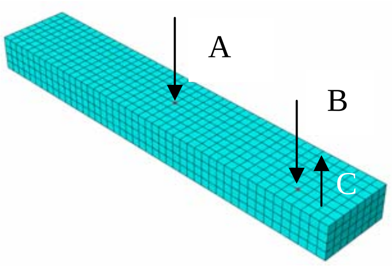


Figure 2. Geometry with loading points A, B and evaluation point C.

Tab. 1: Shape and properties of investigated specimen

Height [mm]	12,5
Length [mm]	140
Width [mm]	25
Young's modulus E [GPa]	50
Poisson ratio ν	0,2
Density ρ [kg/m^3]	3000

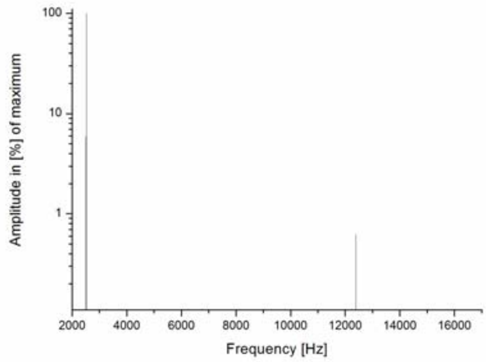


Fig. 3. Amplitudes in point C in dependence of excitation frequency for loading point A

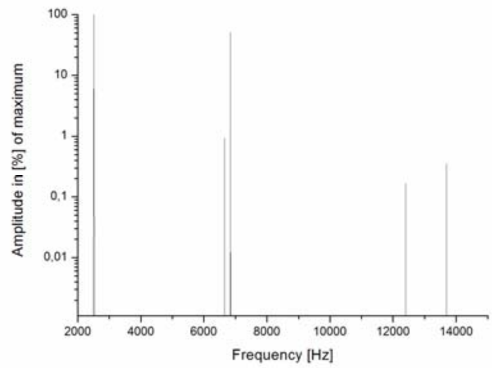
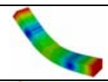
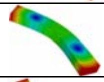
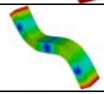
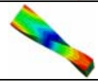
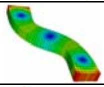
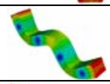
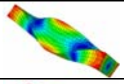
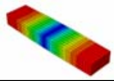
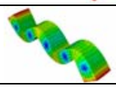


Fig. 4. Amplitudes in point C in dependence of excitation frequency for loading point B

For interpretation of results the Eigenmodes in table 2 can be applied. In both diagrams (fig. 3, 4) the peak for the first Eigenmode can be observed, which is assigned to the out of plane flexure. The in plane flexure (Eigenmode 2, 5) and the longitudinal wave are not excited in both cases. Eigenmode 4 is the lowest torsional resonant frequency and can only be observed in case of loading point B because this loading point is not in the samples symmetry axis.

Table 2. Eigenmodes of the sample described in table 3.

Eigen-mode	Frequency [Hz]		
1	2518,5	Out of plane flexure	
2	4859,4	In plane flexure	
3	6661,2	Out of plane flexure	
4	6834	torsion	
5	11709	In plane flexure	
6	12378	Out of plane flexure	
7	13707	torsion	
8	14571	Longitudinal	
9	19726	Out of plane flexure	

THE EIGENMODES IN DEPENDENCE OF MATERIAL INHOMOGENIETIES

From the ASTM formulas [1] it can be observed that the square of the resonance frequency increases with the Young's modulus and decreases with the density. For prediction of the selectivity of the method for industrial quality control simulations of materials with heterogeneous densities and Young's modulus have been performed.

The shape of the models is the same as described in table 1. The Young's modulus and the density are reduced by 25 % in 1/2 and 1/8 of the sample volume. The volume with the reduced material property is situated at one end of the sample. The border between the two material definitions is perpendicular to the sample length.

In table 2 and 3 the results for the simulation with Young's modulus and density reduction of 25 % are listed. Noticeable is the very low influence on the reduction of the Eigenmodes if the Young's modulus reduction is only in an eighth of the sample. Furthermore the influence on the reduction of the Eigenmodes depends on the location of the reduction. If, as simulated, the volume with the reduced Young's modulus is on one end of the sample the Eigenmode 9 will show the highest decrease, because in Eigenmode 9 this volume has the highest stresses. If the whole samples Young's modulus and density are decreased by 25% the frequencies decrease by 13,4% in case for the Young's modulus reduction and increase by 15,4% in case of the density reduction, respectively.

Tab. 2. Results for the simulation of lower Young's modulus

	Fraction with lower Young's modulus		
Eigenmode	1/8	1/2	1
1	-0,06%	-7,51%	-13,4%
2	-0,12%	-7,52%	-13,4%
3	-0,32%	-6,84%	-13,4%
4	-0,26%	-7,61%	-13,4%
5	-0,47%	-7,00%	-13,4%
6	-0,79%	-7,30%	-13,4%
7	-0,93%	-6,76%	-13,4%
8	-0,21%	-7,65%	-13,4%
9	-1,30%	-6,97%	-13,4%

The result for the simulation with reduced density can be seen in table 3.

Tab. 3. Results for the simulation of lower density

	Fraction with lower density		
Eigenmode	1/8	1/2	1
1	3,84%	7,07%	15,4%
2	3,73%	7,07%	15,4%
3	2,59%	7,63%	15,4%
4	3,14%	7,71%	15,4%
5	2,56%	7,60%	15,4%
6	1,94%	6,95%	15,4%
7	2,88%	6,65%	15,4%
8	3,12%	7,73%	15,4%
9	1,72%	7,54%	15,4%

Influence of cracks

The influence of cracks on the frequency was simulated for cracks with a length of 5 and 10 mm, respectively. The samples geometry is the same as in the investigations described before. The distance of the crack from the end surface is denoted by x (x = 0-70 mm) (fig. 5). The cracks are modelled as two parallel faces without any interaction between the crack faces.

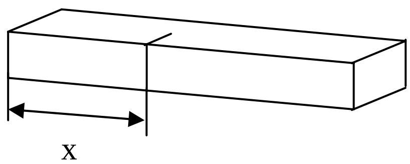


Fig. 5. Position of the crack

In fig. 6 the frequency reduction of the Eigenmodes 2, 5 and 9 in % can be seen in dependence of x in case of crack length of 5mm. The Eigenmodes 2, 5 and 9 are chosen because they show the highest decrease with increasing x. Up to approximately x=25mm Eigenmode 9 shows the highest decrease. From 25 mm to 50 mm Eigenmode 5 and for x > 50 mm Eigenmode 2 has the highest decrease. The frequencies for Eigenmodes 5 and 9 show an increase after minimum. This can be explained with the crack position and deformation in different Eigenmodes. If the cracked region shows relatively low stresses influence on the frequency will be low. This is especially the case for Eigenmode 2 and low values of x.

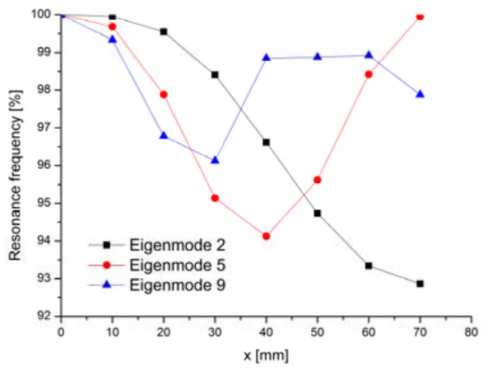


Fig. 6. Frequency dependence from the crack distance x in case of 5 mm crack length

In case of 10 mm crack length the reduction of the Eigenmodes is higher (fig. 7).

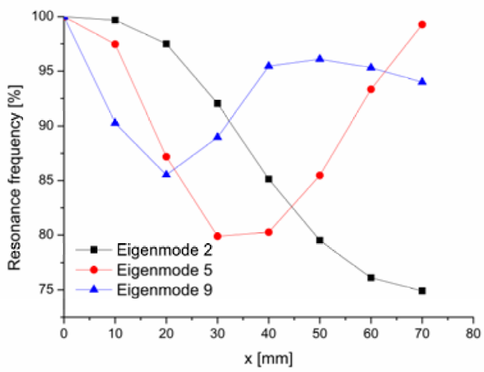


Fig. 7. Frequency dependence from the crack distance x in case of 10 mm crack length

Summary

The simulation of resonance frequencies can support the evaluation of laboratory experiments by forecasting the Eigenmodes. Furthermore the oscillation amplitude in each sample point can be simulated for arbitrary location and direction of excitation. This facilitates the selection of an hammer impact point for the laboratory investigations.

The sensitivity of the Eigenmodes on material inhomogeneities was also simulated. The location of the inhomogenieties determines the effect on the single Eigenmodes.

ACKNOWLEDGEMENT

Financial support by the Austrian Federal Government (in particular from the Bundesministerium für Verkehr, Innovation und Technologie and the Bundesministerium für Wirtschaft und Arbeit) and the Styrian Provincial Government, represented by Österreichische Forschungsförderungsgesellschaft mbH and by Steirische Wirtschaftsförderungsgesellschaft mbH, within the research activities of the K2 Competence Centre on “Integrated Research in Materials, Processing and Product Engineering”, operated by the Materials Center Leoben Forschung GmbH in the framework of the Austrian COMET Competence Centre Programme, is gratefully acknowledged.

REFERENCES

[1] American Society for testing and Materials (ASTM), Dynamic Young’s Modulus, and Poisson’s Ratio for AdvancedCeramics by Impulse Excitation of Vibration, C 1259-94, 1994

[2] IMCE nv, Slingerweg 52, B-3600 Genk, Belgium.

[3] Chr. Manhart, H. Harmuth: Resonant frequency and damping analysis of refractories with and without reduced brittleness, UNITECR’09