Acoustic Resonance Analysis Using FEM and Laser Scanning For Defect Characterization in In-Process NDT

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Abstract. This contribution describes the theoretical and practical approach of acoustic material testing for defects under the ancillary conditions of production variation with multiple defects and structural properties in the whole specimen.

Acoustic Resonance Testing (ART) is a NDT method that enables fast and low cost 100 % testing of components and materials in the ceramic and metal industry. A crack in a component causes certain resonances displaced to low frequencies whilst others remain the same. This qualitative method differentiates between defective and non-defective parts for quality assurance in volume productions. Combining the results of the theoretical (FEM) and practical (resonance frequency measurement) approach allows a fast and low-effort evaluation of the classification reliability. The FEM results are used to set up the test characteristics for the inline test system and allow an estimation of the detectable deficiency size. The part vibrations can be measured contactless by laser scanning or with a microphone.

This contribution presents the method and application for automotive components like conrods within the sonic and ultrasonic range (up to around 50 kHz). The high degree of resolution down to less than one Hertz enables the detection of very small defects.

1. Introduction

Resonances characterize the structure and properties of the material of a work-piece with extreme high precision like a fingerprint. After excitation a body vibrates in specific characteristic frequencies, which depend on the material, internal structure and the geometry. The oscillations directly represent the mechanical properties of the specimen. These vibrations can be measured in the sound and ultrasound range using a microphone or a laser.

Acoustic resonance analysis [1] can detect defects such as cracks, defective microstructure, shrinkage cavities, exfoliation, material spalling and fluctuations in density. In the whole body longitudinal and transverse waves are formed, which are influenced by cracks, structure and density changes, porosity, dimensional and weight differences, binding defects or also over-folding. The defect classification takes place by comparison of the measured resonance effects with defined "good" samples.

To apply acoustic air-borne or structure-borne noise sensors and determine the different wave forms it is necessary to know

- which wave forms are present?
- which resonance frequency is associated with which wave form?
- which sensor type can measure the resonance?

and so on.

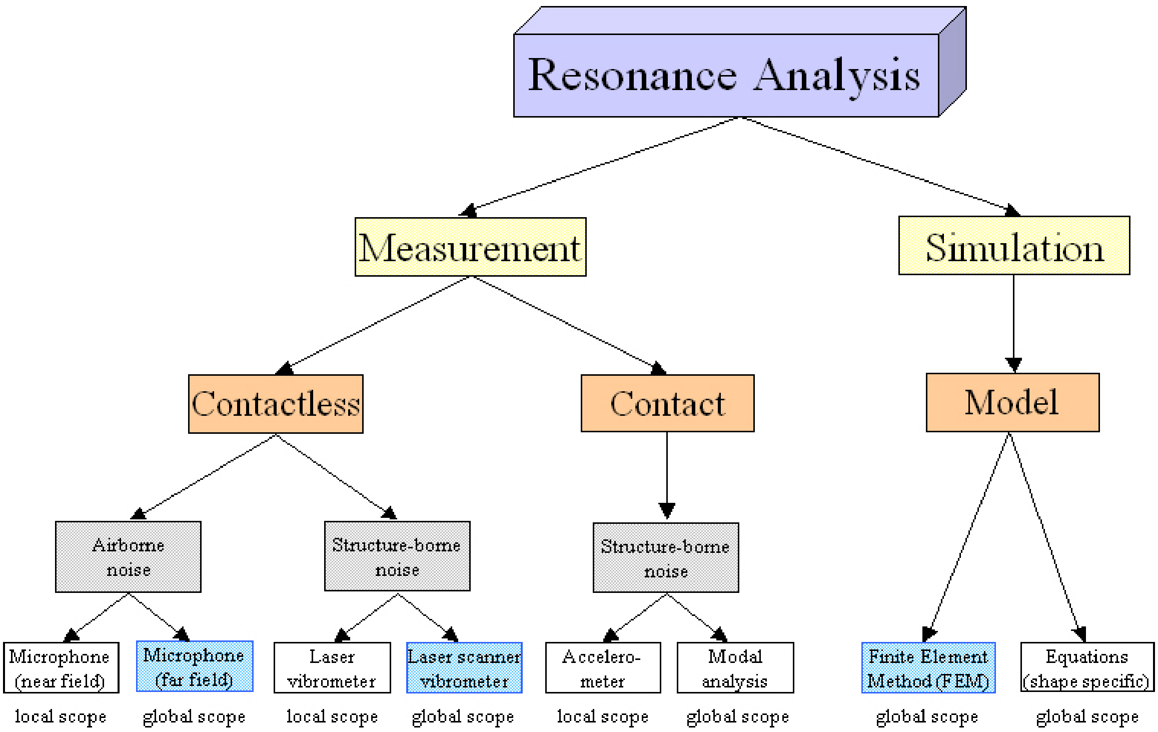

Figure 1: Methods for the determination of resonance frequencies

Figure 1 shows how resonance frequencies can be determined and with which sensor this can be done. It is important to remark that the different sensors and usage lead to different statements. The retrieved values cover only local information at the sensor position or give a global scope and include the resonance frequencies of the whole specimen. The boxes marked blue in Figure 1 were applied to conrods and are described in chapter 2.1.2 (FEM), 2.2.1 (structure-borne noise measurement) and 2.2.2 (airborne noise measurement) in more detail.

2. Resonance Determination

2.1 Simulation / Model Based Approach

A „perfect" body can be described as an unambiguous system of natural frequencies ω_i and natural shapes ϕ_i. The natural frequencies $\omega_i = (\omega_1, \omega_2, \omega_i, .., \omega_m)$ describe it acoustically. The sound velocity c depends on the medium through which the sound waves pass. In a solid there is a non-zero stiffness for both volumetric and shear deformations:

$$c_{solids,longitudinal} = \sqrt{\frac{E(1-\mu)}{\rho(1-\mu-2\mu^2)}}$$

with *E* Young’s modulus (elasticity), ρ density and μ Poisson’s ratio. Sound waves are generated with different velocities dependent on the deformation mode.

The natural shapes $\phi_i = (\phi_1, \phi_2, \phi_i, .., \phi_m)$ describe the specimen geometrically. A “disturbed” or defective body is characterised as well by a natural frequency and natural shape vector as also by the sum of permissible and non-permissible geometry and structure changes (defects).

2.1.1 Calculation

For bodies of a very simple geometry, such as rods, pipes, rings or a bar, a set of mathematical equations and thus a model can be drawn up [2]. Applying a mathematical model and calculating the multitude of characteristic oscillations takes a great deal of time and effort or is even impossible. The results of simplified models, however, are helpful for the interpretation of the measured frequencies and to assign them to their kind (longitudinal waves, transverse waves, etc.).

These are the basis for modeling programs as the FEM (refer to 2.1.2), but with the disadvantage that you cannot directly visualize the different vibration modes.

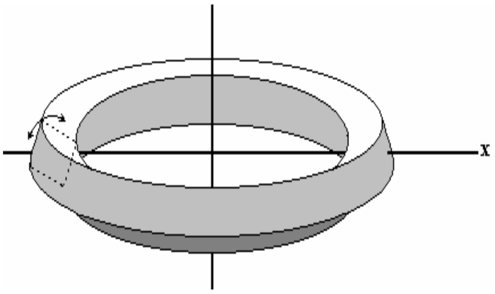

Figure 2: Schematic view of a torsion vibration

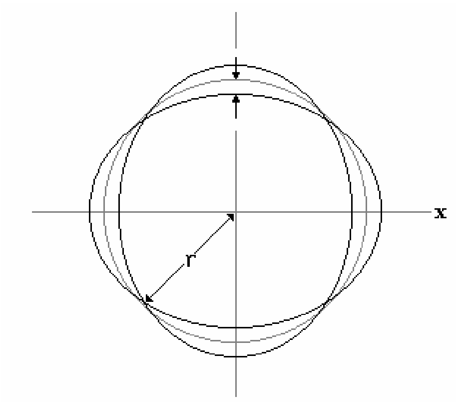

Figure 3: Schematic view of a transversal vibration in ring level

2.1.2 Finite Element Method

Finite Element Method (FEM) can provide accurate vibration models of a specimen without any constraints (“ideal excitation”) on basis of CAD drawings. Computer simulation software generates the theoretical resonances and vibration modes based on longitudinal and transversal waves.

By means of a FEM, based on the geometrical data, the natural frequencies can be calculated and the impact of changes and disturbances can be simulated. Defects in the model at specific positions will result in frequency changes. The model-supported calculation gives the following results:

- Identification of the resonant modes,
- Simulation of volume and bonding defects,
- Prediction of the consequence of defects,
- Identification of the concerned modes,
- Prediction of the needed measuring ranges,
- Prediction of the criteria for classification.

The FEM of an airbag cap calculates and visualizes, for example, 17 resonance frequencies up to 22 kHz. At 3300 Hz the work piece oscillates according to Figure 4 exclusively in a large diameter (light colours), but not, however, in a small diameter. This behaviour is different at e.g. 13900 Hz (Figure 5): defects in this area influence this resonance frequency, but not the 3300 Hz.

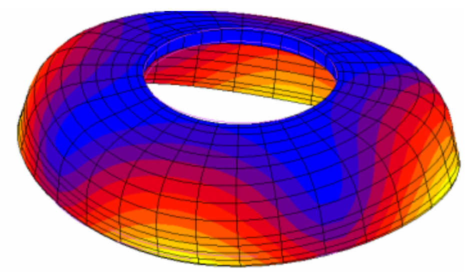

Figure 4: Airbag oscillation 3300 Hz

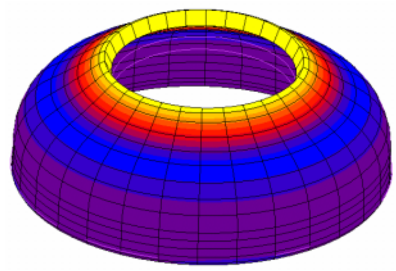

Figure 5: Airbag oscillation 13900 Hz

Artificial defects or variations of the dimensional properties can be inserted into the model (Figure 6) to calculate the impact on the resonance positions. The result is a positive of negative shift of single frequencies. Through the behaviour of certain effects it is possible to distinguish between the standard production variation and defects like cracks.

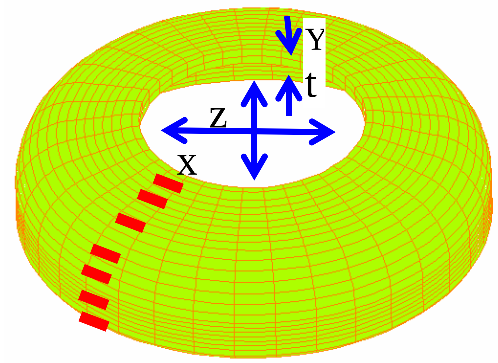

Figure 6: Defect simulation

The FEM was applied on conrods to evaluate the different vibration modes and to correlate them with practical measurements (see chapter 2.2). Vibration modes were calculated up to 50 kHz. Figure 7 shows the modes up to 20 kHz [3].

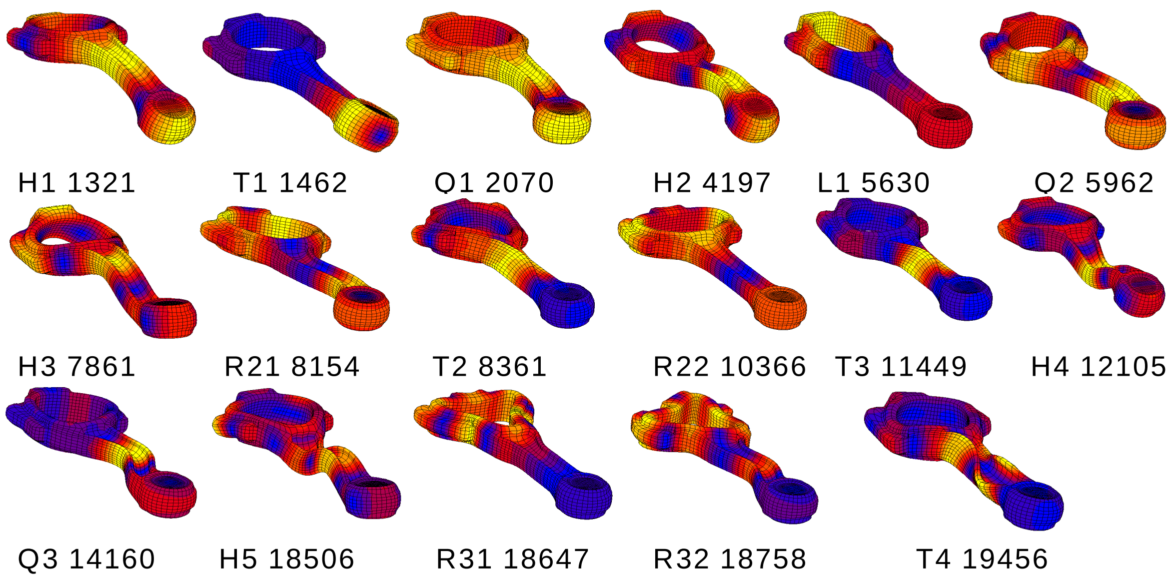

Figure 7: FEM of a conrod up to 20 kHz (colours: light is high amplitude, dark is low amplitude. Denotation: the alphanumeric is the mode (see below), the following number the frequency)

The following basic modes and (non-harmonic) overtone modes of a conrod can be identified:

H	vertical bending	pure transversal wave mode
Q	cross bending	pure transversal wave mode
T	torsion	combination longitudinal / transversal mode
L	length bending	pure longitudinal wave mode
R	ring bending	longitudinal wave mode

2.2 Measurements / Practical Test Approach of Conrods

For an experimental procedure, it is necessary as described above to stimulate the body, to measure the structure-borne vibration or airborne sound by suitable sensors and to process them with a computer.

2.2.1 Structure-borne Vibration Measurement

Structure-borne measurements could be done by contacting the specimen with a piezo sensor like an accelerometer to the specimen or contactless with a laser vibrometer. In both cases the wave propagation is measured at a single position. This disadvantage can be compensated using a scanning method. In this case a laser vibrometer performs a series of measurements, stores the vibration values of different positions and merges them by the computer.

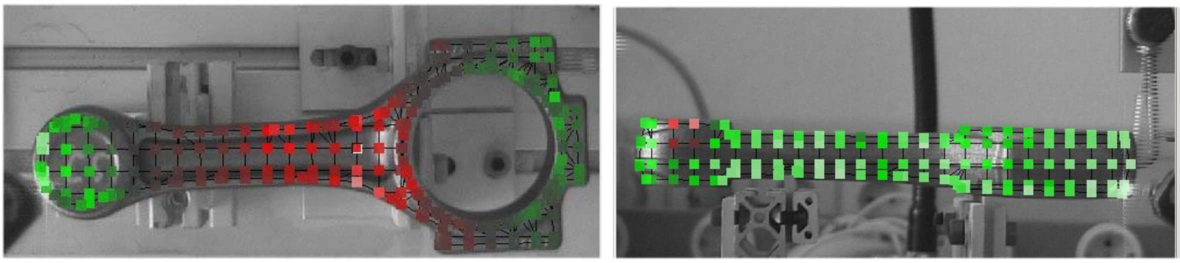

Figure 8: Laser scan of conrods (green: low vibration   red: high vibration)

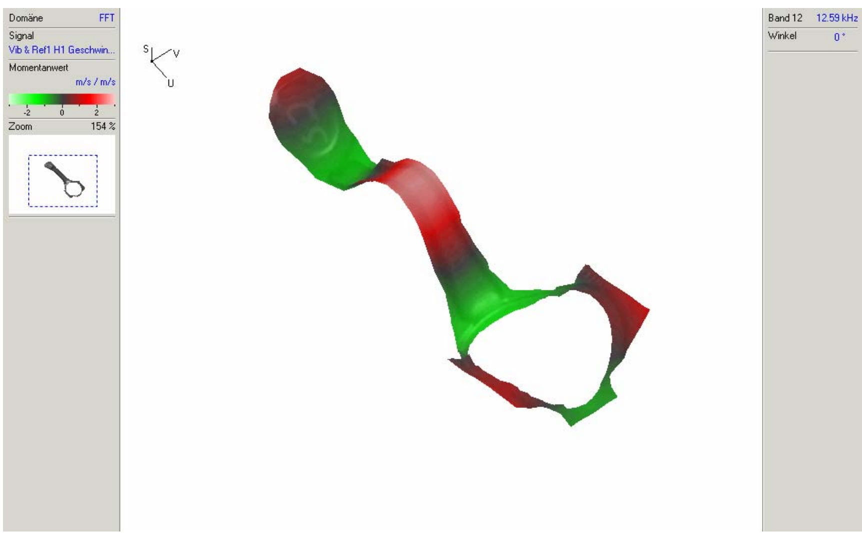

Figure 9: 3-D view of a conrod at 12590 Hz

2.2.2 Airborne Sound Measurement

Airborne sound has its source in structure-borne vibrations. The following steps have to be carried out successively:

1. Support, stimulation and measuring position must be determined,
2. Natural frequencies have to be measured of exemplary good work-pieces (geometry, material, hardness, structure are known),
3. Characteristic frequencies must be analysed in terms of direction (spectral-line displacement), level and presence,
4. Characteristic frequencies must be compared with typical bad workpieces and their effects,
5. An algorithm for classification has to be set up.

Acoustic measurements using a microphone can be done in the near field or the far field of a specimen.

In the near field the microphone is very close to the specimen and measures only parts of the vibrations. Although resonance frequencies are a mechanical characteristic of the part and exist wherever you hit the part, the amplitude depends on the excitation position and the distance between specimen and microphone. Vibration modes of remote areas in the near field will only generate resonances with low amplitudes.

In the far field the microphone position is located at a position where it can measure the vibrations of the whole body, for example in a distance half the length of the part.

Figure 10 shows the spectrum measured with a microphone in the far field of the same conrod that was used for the FEM and the laser scan. The different vibration modes can be clearly assigned to the resonance peaks in the spectrum.

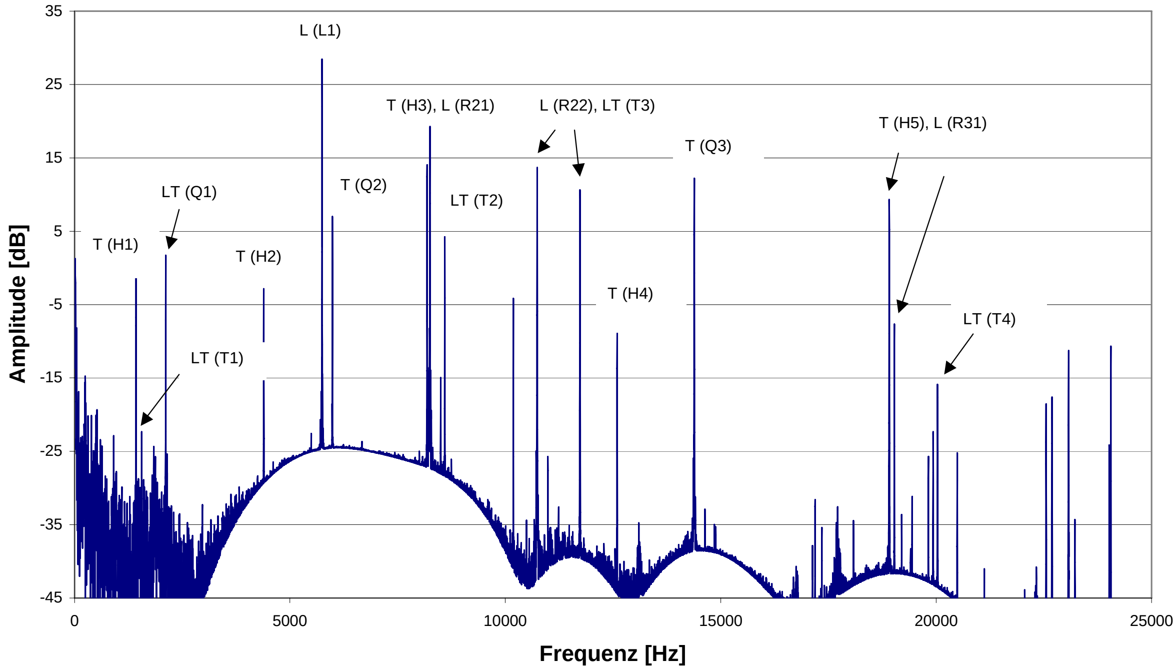

Figure 10: Microphone spectrum of a conrod (far field)
(L: longitudinal, T: transversal, LT: longitudinal/transversal. modes see Figure 7)

3. Results and Conclusion

The FEM calculated wave modes up to 50 kHz reveal that the massive small eye of the conrod have only low vibration amplitudes, even in the high frequency range. The acoustically contribution of this part of the specimen to the resonance spectrum is therefore very low. Cracks or structural changes in this area have only a negligible effect on the resonance frequencies. Resonance analysis cannot be used to evaluate deficiencies in the small eye. If it would be drilled before testing it would be another story! The big eye and the shank are vibrating in a lot of modes with high amplitudes. The resonance analysis method can be used to find deficiencies in this area, because the vibration modes will have an impact on resonance frequencies.

The measurements corroborate the theory. The resonance frequencies measured with the microphone align with the FEM modes (Table 1). The calculated FEM values are always lower than the measured values with the microphone or the laser. Microphone and laser of course measured identical resonance frequencies (mechanical property, only the way of the data acquisition is different).

Table 1: Vibration modes and resonances of a conrod

	Basic wave modes	Resonance frequencies [Hz]		Deviation FEM to laser / microphone		Formation of resonances	
		FEM	Laser / microphone	[Hz]	[%]	Laser	Microphone
1	T (H1)	1321	1406	85	6,23	++	+
2	LT (T1)	1462	1543	81	5,39	++	-
3	T (Q1)	2070	2109	39	1,87	+	+
4	T (H2)	4197	4359	162	3,79	++	+
5	L (L1)	5630	5754	124	2,18	0	++
6	T (Q2)	5962	5981	19	0,32	+	+
7	T (H3)	7861	8144	283	3,54	++	+
8	L (R21)	8154	8230	76	0,93	+	++
9	LT (T2)	8361	8609	248	2,92	+	+
10	L (R22)	10366	10738	372	3,53	+	++
11	LT (T3)	11449	11734	285	2,46	+	++
12	T (H4)	12105	12594	489	3,96	++	+
13	T (Q3)	14160	14406	246	1,72	+	++
14	T (H5)	18506	18875	369	1,97	++	++
15	L (R31)	18647	19187	540	2,85	-	+
16	L (R32)	18758	19930	1172	6,06	-	-
17	LT (T4)	19456	20031	575	2,91	+	0

(basic modes: see Figure 7 and Figure 10
++: vibration mode very strong formed;
+: vibration mode good formed;
0: resonance exists, vibration mode not so clearly formed;
-: resonance exists, vibration mode not so clearly formed;
--: resonance does not exist / cannot be measured)

The deviation between calculated FEM and measured resonance peaks is on average 3 %. Due to simplifications in the underlying model of the specimen all FEM calculated values are smaller than the measured ones.

4. Summary

A detailed analysis and comparison of laser spectrum and microphone spectrum reveals that the microphone measures additional resonance at about 10 kHz and 20 kHz. The reason is due to differences in the signal chain, characteristic of the aliasing filters, excitation / microphone position and the laser reflection orthographic to the surface of the specimen.

Up to 20 kHz laser sensors are not necessary if the measurement conditions are appropriate to measure also low amplitudes. This may require an anechoic shelter in a production environment to allow a good signal-to-noise ratio.

In principle laser scan or the microphone can measure all theoretically calculated measured resonances. Improvements to measure the longitudinal wave modes LT (T1), L (L1), L (R21), L (R32) and LT (T4) could be made if an additional excitation direction and / or microphone location were used. The laser scan does not give an additional information or advantage, but proves the values acquired by the microphone.

The frequency deviation between calculated and measured values is low. The different percentage is caused by deficiencies and simplification of the modelled conrod.

The approach to model the specimen using FEM and to compare the results with contactless measurements is the appropriate approach to understand the measured spectrum and to find out, which locations of the specimen can be analysed by the acoustic resonance analysis method.

5. References

[1] Hertlin, Ingolf: Acoustic Resonance Analysis. NDT compact and understandable – Vol. 5. Castell-Verlag, Wuppertal 2003

[2] Kleiner, Helmar; Kotterba, Benno: Vergleich der Messung und Berechnung der Klänge von Metallringen. 20. Deutsche Jahrestagung für Akustik der DEGA (DAGA 1994, Dresden)

[3] Arnolds, Georg; Hertlin, Ingolf: FEM-Analyse und Laser-Scan von Pleuelstangen. Untersuchungsbericht. RTE Akustik+Prüftechnik GmbH, Pfinztal 2003