Detection of Core Fracture in Inorganically Bound Cast-in Sand Cores by Acoustic Microphony

Florian Ettemeyer[1(✉)], Florian Steinlehner[2(✉)], Philipp Lechner[2(✉)], Wolfram Volk[1,2(✉)], and Daniel Günther[1(✉)]

[1] Fraunhofer Research Institution for Casting, Composite and Processing Technology IGCV, Walther-Meißner-Straße 4, 85748 Garching, Germany
{florian.ettemeyer, daniel.guenther}@igcv.fraunhofer.de, wolfram.volk@utg.de

[2] Chair of Metal Forming and Casting, Technical University of Munich (TUM), Walther-Meißner-Straße 4, 85748 Garching, Germany
{florian.steinlehner, philipp.lechner, wolfram.volk}@utg.de

Abstract. This article suggests a new method to detect the fracture of cast-in sand cores. The goal of this approach is to reduce the time and efforts as well as increase the stability of the decoring process. A testing geometry and a test rig were built to explore the decoring process in the laboratory in order to test this approach. The proposed method is based on acoustic microphony to determine any fractures and loss of contact between a casting part and the cast-in sand cores that shall be removed by a mechanical decoring process. By the use of numerical tools a prediction of the occurring eigenmodes of theoretical decoring states is possible. This method is particularly suitable for cast-in geometries that can-not be monitored by visual inspections, such as cooling channels in the cylinder heads of combustion engines.

Keywords: Casting · Process control · Decoring

1 Introduction

Casting is the preferred economical and energy-efficient way to produce complex and functionally-integrated components compared to competing manufacturing processes. On the whole, the casting process is mainly characterized by the possibility of producing complex, near-net shape geometries with significant inner structures. The cavities are realized using sand cores [1].

Cores are shaped as the cavities in the casting part. One example for a casting part in which cores are needed are cooling channels in a combustion engine's cylinder head. The cores are usually constructed of resin or water glass bounded sand-binder-systems and are lost components. Hence, cores have to be produced for each cast component and placed in a mold. After the casting process, the already weakened cores are

disintegrated by mechanical energy and removed from the cast component. This process is named decoring.

There are different approaches to decore casting components. The most commonly used method is mechanical decoring. Initial cracks are induced in the cores by the impact of hammer-like pulses onto the cast component. This so-called pre-decoring is the most time-consuming process step and therefore most relevant in economic terms. During the following process step, the cast component with the cracked core is shaken to crush individual core fragments by inertia and interaction. The dissolved sand can then be removed through openings in the cast component via pivoting movements.

Today the efficiency of the decoring process is often based on the worker's experience. This means that in order to ensure that all cavities are free of sand after the decoring process, this often includes idle decoring time to ensure a clean casting part without any sand residues.

2 Basics

Eigenfrequencies and Eigenmodes of Mechanical Structures. Eigenfrequencies are discrete frequencies that represent mechanical deformation modes of a structure. The vibrating response of a system after stimulation is a composite of a superposition of an infinite number of eigenfrequencies. Depending on the mechanical properties and the geometry of a mechanical structure eigenfrequencies can vary. Acoustic resonance testing methods are state of the art in many industries for quality control [2], e.g. in the automotive industry. There are also research approaches that use acoustic methods to detect failures, as described by Levikari et al. [3] for multilayer ceramic capacitors and by Zhang et al. [4] for composite beams. Acoustic signals can be converted from a time-based scale to a frequency-based description by applying a fast-Fourier-transformation (FFT). With finite element solvers, it is possible to calculate the discrete eigenfrequencies of a mechanical structure without experimental effort.

Recipe of the Sand-Cores. To predict the eigenfrequencies of the specimens by a virtual method, the material properties have to be defined correctly. The sand cores used in this article are produced by a core-shooting process on a Loramendi SLC2-25L core-shooting machine. Silica sand type H32 from Quarzwerke with a medium grain size of 320 µm is used as base material. All sand cores are inorganically bound with 2% (by mass) of sodium silicate water glass (Inotec EP 4158) and the reaction is accelerated by 1.6% (by mass) of a promotor (Inotec TC 4500).

3 Experimental

Testing Geometry. A cylindrical aluminum casting part is chosen as a specimen. Figure 1 shows the process chain for the manufacture and design options for the specimen. The casting box is a 3D-printed sand mold into which the inorganically-bound sand cores (cylinders with 50 mm diameter and height) are inserted. By varying the opening angle and the wall thickness of the casting part, it is possible to induce different stress states into

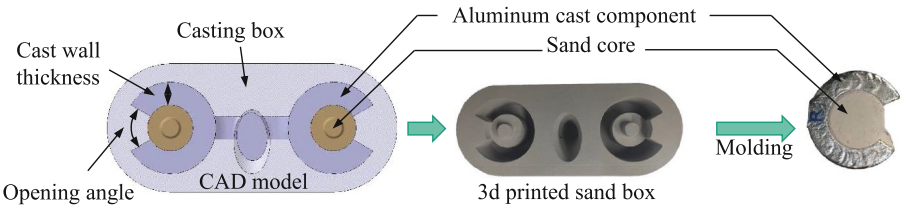

Fig. 1. Illustration of the process chain to produce the specimen

the cast-in sand core geometry due to shrinkage of the casting part during cooling. With the cylindrical shape, the decoring behaviour can be directly correlated to the mechanical properties of the sand cores, since standardized tests like the compression test or the so called Brazilian-disk-test [5] already exist for this kind of specimen.

Test Rig. Two different test rigs are used for the experimental investigation in this article: one is based on a hammer fall and the other on a pendulum. The related engineering principals are illustrated in Fig. 2.

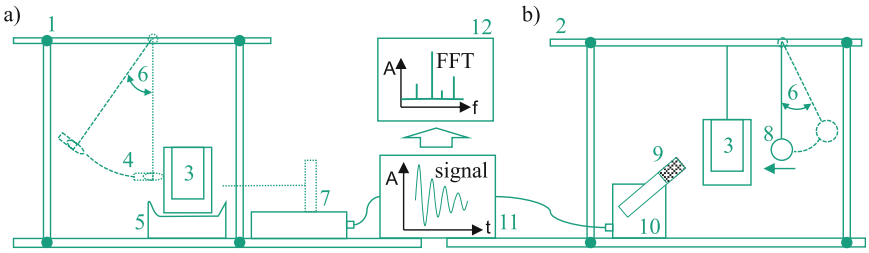

Fig. 2. Test rig number one: hammer fall test rig for inducing damage in the specimen (a) and test rig number two: pendulum test rig for acoustic frequency measurement of the specimen (b)

Test rig number one (1) is shown in Fig. 2a. It is based on a hammerfall method and induces damages and core-fractures in the specimen (3). In accordance with the process of industrial decoring machines, a hammer (4) is used to induce an impulse into the specimen. The specimen is fixed by its base on a specially designed vice (5) with four fixing points evenly distributed over the diameter. Varying impulse energies can be induced depending on the displacement angle (6) of the pendulum arm and the weight of the hammer head that is used. Velocities and accelerations of the chimed test geometry can be measured with a laser vibrometer (7) on the opposite side.

Test rig number two (2) is shown in Fig. 2b. It is needed for an acoustic measurement of frequencies before and after the decoring process. The main goal of test rig two is to record the frequency spectrum of the stimulated specimen and to detect variations of the eigenfrequencies as a function of the level of damage from test rig one.

Whereas the laser vibrometer used in test rig number one measures the velocities of the specimen at one point, the acoustic method allows the measurement of the complete vibration state. Due to the clamping in test rig number one, the frequencies of the test

geometry may vary. In order to reduce this influence, the specimen is suspended differently to test rig number one for the acoustic measurement. The impulse for the acoustic signal is provided by a hanging bullet (8) that can be deflected. The response signal of the swinging specimen is recorded with a microphone (9) and transmitted via a signal amplifier (10) to an oscilloscope (11), which processes the data for a computer (12). The time-based signal from the oscilloscope is converted in a frequency-based signal by a Fourier-transformation and the characteristic eigenfrequencies of the specimen can be extracted. These measured eigenfrequencies vary depending on the factor of the damage and the design options of the specimens used. The technical properties of the devices used in the two test rigs involved are shown in detail in Table 1.

Table 1. Technical properties of the measurement equipment in the test rigs

Device	Producer	Model	Frequency range [Hz]	Additional information
Microphone	Superlux	ECM 888B	20–20,000	Sensitivity: –3 dBV/Pa (7.1 mV/Pa) ±3 dB
Amplifier	ART (Applied Research and Technology)	Tube MP	10–20,000	Maximum Amplification: 70 dB
Oscilloscope	RS Pro	RSDS 1102CML +	100,000,000	Maximum sampling rate: 1 GSa/s
Laser vibrometer	Polytec	OFV-3001	100,000	

4 Simulation

The specimen is modeled up with the simulation software Abaqus for the numerical investigations. The test geometry is meshed with tetraedical elements that have an edge length of 3 mm and a deviation factor of 0.1. The test geometry has a height of 70.4 mm and a wall-thickness of 5 mm. The sand-core has a diameter of 50 mm and a nominal height of 45 mm. The difference of 5 mm between the shot sand core geometry and the cast-in geometry is due to the need for clamping to position the core in the casting box.

Material Parameters of Aluminum Component. The near eutectic aluminum alloy AlSi10 Mg is used to cast the aluminum component. Young's modulus is set to 70 GPa and the Poisson's ratio is set to 0.3. The density of the aluminum alloy is considered to be 2.7 g/cm^3.

Material Parameters of Sand-Core. According to Levy et al. [6] elastic properties of materials can be determined by acoustic techniques, for example, by measuring the speed of propagation in a material. For this article, the Young's modulus of the sand core is determined by an acoustical method, too. The eigenfrequencies of a sand bar with a cross section of 22.4 mm edge length and a height of 170 mm are determined with an acoustic test rig similar to that shown in Fig. 2b. Performing a numerical finite-element parameter study, Young's modulus is varied between 5 GPa and 12 GPa and the first eigenfrequency of the simulation is compared with the eigenfrequencies produced in the experiment. A Young's modulus of about 7 GPa is determined for the used recipe of the sand core. The result of the measurements with the acoustic method and the validation by varying the modulus in the simulation is consistent with the Figures found by Griebel et al. [7]. They measured the modulus of elasticity with two optical systems and calculated a modulus for comparable silica-sand and sodium silicate binder of 7.02 ± 0.45 GPa and 7.37 ± 0.70 GPa, respectively. In the work of Schneider et al. [8], a Young's modulus of 7.55 ± 0.17 is stated by measuring the speed of propagation of elastic waves.

The density for the sand core is set to 1600 kg/m^3 in accordance to the work of Schneider et al., who identified a density of 1558.08 ± 8.98 kg/m^3 for the same recipe of inorganically-bound sand cores [8].

The Poisson's ratio of the sand core is set to 0.3 [9].

Eigenfrequencies of the Test Geometries. Within a virtual modal analysis eigenfrequencies of the testing geometry were calculated, compare to [10] and [11]. Figure 3a shows the test geometry with a wall thickness of 5 mm and no opening angle with inserted sand core. The filling level of the specimen is varied in the virtual study, see Fig. 3b. Furthermore, a delamination of the sand core is simulated. This is done by two different damage states: On the one hand, a segment with a delamination angle α is cutted out of the core, see Fig. 3c. On the other hand, the contact between the sand core and aluminum part is interrupted on a segment of the border of the sand core, see Fig. 3d. The dimension of the interrupted contact segment is characterized by the angle β. Larger values for the angles α and β mean a more damaged core. The three cases shown here represent different core damage levels during the process of decoring.

Figure 4 shows the evolution of the first eight eigenfrequencies for all three damage states. The calculated eigenfrequencies are shown on the ordinate. The level of damage, represented by filling level, segment angle and delamination angle, is plotted on the abscissa axis.

The virtual analysis predicts that the first eigenfrequency for this specimen with a fully filled sand core will be at 13.8 kHz. The first eigenfrequency for the same specimen with no sand core is predicted to be at around 5.7 kHz. The eigenfrequencies number one and two develop in the same way and decrease in value the greater the damage to the sand core is. Because of the characteristic behaviour, the first two eigenfrequencies are the focus of further investigations in this article.

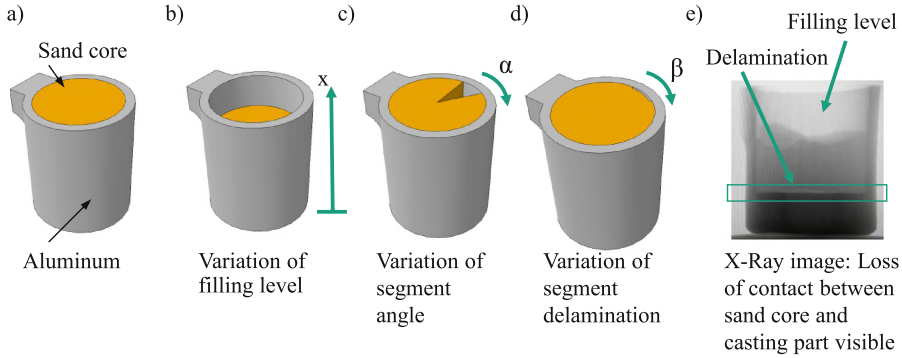

Fig. 3. Specimen modelled in CAD (a), specimen with 10% filling of sand-core (b), specimen with cut-out segment (c), specimen with interrupted contact (d), X-ray image (e)

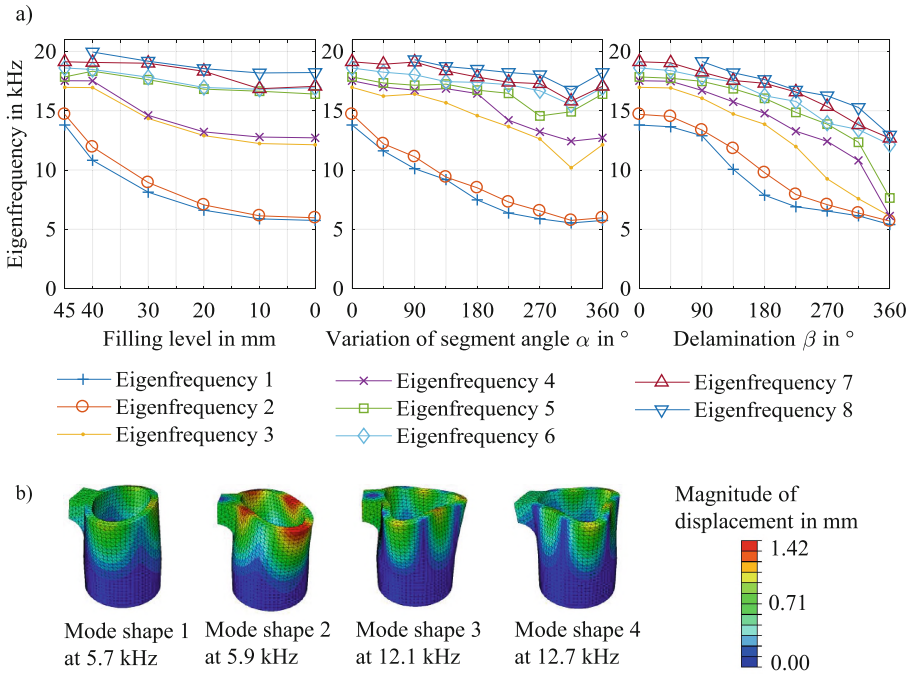

Fig. 4. Results of the numerical simulation: evolution of the first eight eigenfrequencies of the specimen depending on different representations of the level of damage of the sand core (a) and shaping of the first four eigenmodes for a specimen with no sand core (b)

5 Validation

By fixing the specimen on test rig number one and exposing it by several impacts from the fall hammer, emerging eigenfrequencies can be observed from the fast-Fourier-transformation of the laser vibrometer signal due to the increasing level of damage to the sand core. Figure 5 shows the measured signal from the laser vibrometer and the frequencies calculated by a fast-Fourier-transformation. After several impacts of the fall hammer, a frequency amplitude of around 6 kHz develops. This frequency can be compared to the result of the virtual analysis. The first bending eigenfrequency also shifts to this range for a higher degree of delamination. This effect can be explained by the loss of contact between the sand core and casting part. This can be confirmed visually by comparing this theory to the X-ray image in Fig. 3e. Due to the position of the laser-point of the vibrometer in the plane of the fall hammer, the laser vibrometer mainly measures the first bending frequency. The frequencies that occur in the range of 2-3 kHz can be explained by the clamping situation in test rig number one.

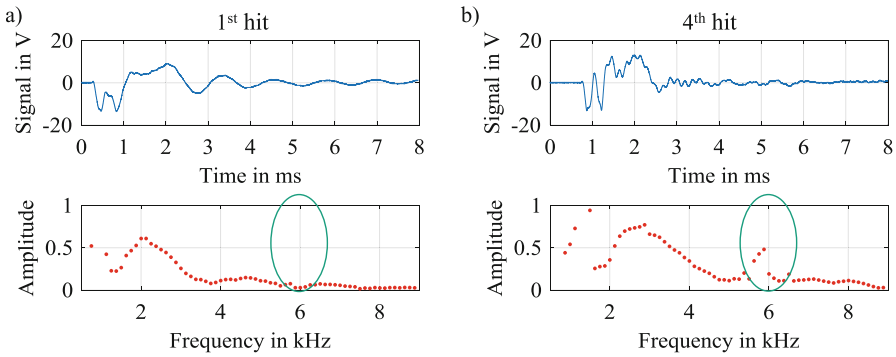

Fig. 5. Measured displacement of the test geometry with laser vibrometer and fast-fourier-transformation of the signal. Specimen after the first hit (a) and partially decored specimen after the fourth hit (b)

A specimen with a complete sand core (height 45 mm), with a delaminated sand core with $\beta = 200°$ and one without a sand core is measured on test rig number two as a second stage to validate the results of the virtual analysis. The stimulation impulse for the acoustic measurement has a value of 0.02 Ns. Because of the acoustic measurement, more than one eigenmode can be detected. Figure 6 shows the fast-Fourier-spectrum for the three testing-scenarios in the range of 0.5 kHz to 20 kHz. Each specimen was measured ten times and the enveloping curve for all values is plotted. The amplitudes for every measurement were normed to its maximum value. The numerically calculated values of the first two eigenfrequencies for every damage scenario are plotted, too.

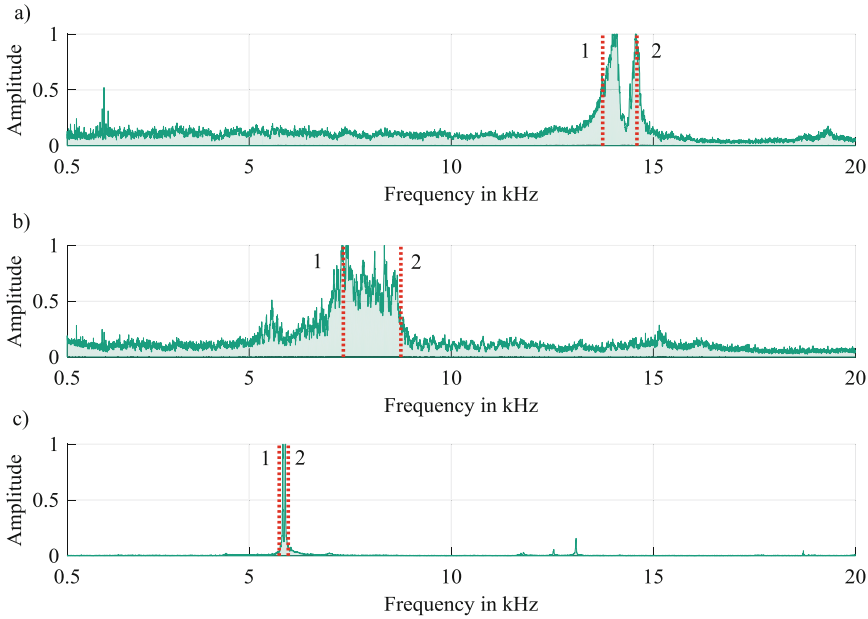

Fig. 6. Fourier-spectrum for specimen fully filled with complete sand core (a) with delaminated sand core (b) and without sand core (c). The calculated first and second eigenfrequencies are marked by the dotted line.

6 Discussion

The first two eigenfrequencies represent an oval deformation of the cylindrical geometry of the specimen, compare Fig. 4b. The eigenfrequencies only differ in a certain kind of phase shift. As a result of the non-symmetric geometry in this case, the two eigenfrequencies differ in terms of their absolute values. The first two eigenfrequencies would match for a rotation-symmetric specimen. The higher the level of damage to the sand core, the less the first two eigenfrequencies differ. This effect is predicted in the virtual analysis and is confirmed by the experimental investigations. Whereas the first two eigenfrequencies have a value of 14.0 kHz and 14.6 kHz respectively for the specimen with a complete sand core, the eigenfrequencies of the empty specimen have values of 5.8 kHz and 5.9 kHz respectively in the experiment.

A significant shift in the frequencies from higher to lower values depending on the damage to the sand core is confirmed in both the virtual analysis and the experiment. Deviations between the simulation and experiment can be explained by geometrical imperfections of the specimen, by inhomogeneities of the material of the casting and the sand-core part as well as uncertainties in the material definition for the simulation.

7 Summary

This article introduces an acoustic method to detect core fractures in cast-in structures. This method is based on the theory that after decoring, the residual core is no longer part of the resonant system and thus eigenfrequencies tend to shift. Two test rigs were used for the experimental validation of the virtual investigations. One test rig was used to induce core fractures in cast-in structures. The other is designed to measure the acoustic system response of a specimen after stimulation.

Three different abstractions for partially decored castings were proposed: core height, segment loss and segment delamination. The eigenfrequencies that occur for these three cases of damage of the cast-in sand cores were calculated in a virtual analysis. The experimental validation of the results of the virtual analysis indicates a good correlation for the first two eigenfrequencies. Both the simulation and the experiment show a significant frequency shift from higher to lower values the greater the damage to the specimen is. Therefore, the loss of contact between the aluminum casting part and the sand core can be reliably detected by the acoustic method presented here.

8 Outlook

The next step within this research is to adapt the method that has been introduced to more complex geometries and stress states of the sand cores. Furthermore, the results should be verified by a larger number of experiments to improve the statistical value. For an industrial application, this method has to be resistant to ambient conditions such as noise or clamping effects. Therefore, the effects of clamping have to be analyzed more thoroughly in further investigations.

As a key goal, the research will be adapted in future to not only detect but also predict core-fracture. The aim is to link the detection of core fractures to mechanical properties of the sand cores as a function of the previous history of impacts to the sand core.

References

1. Günther, D., Mögele, F.: Additive manufacturing of casting tools using powder-binder-jetting technology. In: New Trends in 3D Printing. InTech (2016)
2. Heinrich, M., Rabe, U., Grabowski, B., Valeske, B.: Methodische Entwicklung der akustischen Resonanzanalyse zur zerstörungsfreien Erkennung von ur-oder umgeformten Serienteilen mit unzulässigen Geometrieabweichungen – simulationsbasierte Modellüberlegungen. DGZfPProceeding BB, 152
3. Levikari, S., Kärkkäinen, T.J., Silventoinen, P., Andersson, C., Tamminen, J.: Acoustic detection of cracks and delamination in multilayer ceramic capacitors. In: IEEE 11th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED) 2017, pp. 622–627. IEEE, August 2017
4. Zhang, Z., Shankar, K., Morozov, E.V., Tahtali, M.: Vibration-based delamination detection in composite beams through frequency changes. J. Vib. Control **22**(2), 496–512 (2016)

5. Li, D., Wong, L.N.Y.: The Brazilian disc test for rock mechanics applications: review and new insights. Rock Mech. Rock Eng. **46**(2), 269–287 (2013)
6. Levy, M., Bass, H., Stern, R.: Modern Acoustical Techniques for the Measurement of Mechanical Properties, vol. 39. Elsevier (2001)
7. Griebel, B., Brecheisen, D., Ramakrishnan, R., Volk, W.: Optical measurement techniques determine Young's Modulus of sand core materials. Int. J. Metalcast. **10**(4), 524–530 (2016)
8. Schneider, M., Hofmann, T., Andrä, H., Lechner, P., Ettemeyer, F., Volk, W., Steeb, H.: Modelling the microstructure and computing effective elastic properties of sand core materials. Int. J. Solids Struct. **143**, 1–17 (2018)
9. Voß, R.: Toleranzanalyse komplexer Gussbauteile mittels stochastischer Simulation der Fertigungseinflüsse. epubli (2012)
10. Xu, W., Lai, C., Sun, X.: Identify structural flaw location and type with an inverse algorithm of resonance inspection. J. Vib. Control **21**(13), 2685–2696 (2015)
11. Zheng, Y., Heinrich, M., Osman, A., Valeske, B.: Automated detection of geometric defects on connecting rod via acoustic resonance testing. In: 25th European Signal Processing Conference (EUSIPCO) 2017, pp. 1868–1872. IEEE, August 2017