Monitoring of the Structural Integrity of Wheelset Axles Using Guided Waves

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ABSTRACT

The structural integrity of wheelset axles of high speed trains as well as freight wagons is of major importance for safety of rail transport. Up to now the inspection of wheelset axles is part of a periodic maintenance which is expensive due to long inspection times and highly influenced by the human factor, especially if those inspections are carried out during night time. Permanently installed SHM-systems at each axle would be able to monitor the structural integrity and could reduce the maintenance effort. However due to mechanical constraints, requirements and regulations the mounting options of such SHM-systems are limited. Approaches with ultrasonic transducers mounted at one end face of the axle can excite guided waves and could be able to monitor the entire component from only one sensor position.

The geometry of the axle with many cross-sectional variations results in reflections and changing dispersion relations along the wave propagation direction and lead to complex wave propagation problems hiding flaw echoes. Thus, echo signals are difficult to interpret and correlations between echo signals and flaws are hard to reveal.

In the presented paper we show a signal processing approach to extract information on the structural integrity from ultrasonic guided wave echo data. On a mock-up we could show, that the suggested method is able to detect a crack growth reliably. Based on the knowledge of wave propagation and on results from numerical simulations, classification algorithms are developed and applied to additionally enhance the prediction accuracy of crack size and position.

KEYWORDS : *ultrasonic inspection, guided waves, monitoring, classification.*

1 INTRODUCTION

Cracks in wheelset axles of high speed trains could lead to serious accidents. Also the wheelset axles of freight wagons are safety relevant structures particularly if the wagons are loaded with dangerous freight, e.g. fuel or gas. To guarantee the reliability and integrity of the components, non-destructive inspections are necessary. Currently, the operating railway companies inspect the integrity of the axles at regular intervals using ultrasonic inspection techniques to detect cracks in an early stage. The maintenance cost for the regular ultrasonic inspections and the downtime of the trains and wagons are comparatively high.

Permanently installed structural health monitoring (SHM) systems could not only reduce the maintenance cost but might also limit the influence of the human factor on the inspection reliability. However, practical applications of SHM-systems on trains are not yet available. Approaches assessing the vibration pattern of the bogie were tested in laboratory but suffer from long transfer paths and are disturbed by the rolling noise of the axle's ball bearings. Hence, promising approaches should use sensors directly mounted on the monitored rotating structure to omit the influence of long transfer paths. Permanently installed ultrasonic inspection systems could be used to monitor the condition of the structure. Due to mechanical constraints and regulations the mounting options of SHM-systems directly on the wheelset axle are limited and ultrasonic transducers could only be mounted at the end faces of the axle. For an integral assessment of the entire axle with transducers mounted at the end faces two different approaches a possible (i) a conventional inspection technique using high frequency ultrasound with wavelength much smaller than the diameter of the axle or (ii) low frequency ultrasound with frequencies between 50 and 400 kHz. Using high frequency signals, the pulse propagates mainly as longitudinal wave with diverging sound fields, where the diameter of the sound field is smaller than the diameter of the structure. A high number of permanently installed ultrasound transducers on both end faces are required to illuminate the entire structure and omit dead zones where flaws cannot be detected. The seatings for wheels and brake discs change the axle cross section and generate additional echo signals disturbing the monitoring results. Contrary to using conventional testing techniques, the application of ultrasonic guided wave, excited in a low frequency regime is very promising. The guided wave strongly interacts with the boundaries of the structure and floods the entire volume of the axle, omitting dead zones. The main drawback of guided waves, however, is their multi-modal and dispersive propagation properties. To overcome this problem, most state-of-the-art textbooks [1] suggest using only the first few fundamental modes with known wave speed to allow an easy interpretation of the received echo signals. The diameter of the wheelset axle, however, would demand very low frequencies to meet this requirement. On the other hand, a high number of propagating modes is expected to increase the probability of very strong mode-flaw-interactions with any flaw type, and thus, to increase the reliability of the method. The most important challenge of using guided waves for an SHM-system is the analysis of the complex echo signal, merging the contributions of all propagating modes. Due to their dispersive behaviour, a direct correlation between arrival times and defect location is hardly to determine. However, for SHM-systems only assessing the integrity of the structure such detailed information is not necessary. The aim of the SHM-system for trains and wagons is only to signal the maintenance staff the necessity of maintenance work in near future, considering that the remaining operating time of a wheelset axle with initial cracks with crack depth of few millimetres is at least a few thousand kilometres. As direct approaches interpreting the multi-modal echo signal, such as mode separation or back propagation, are difficult to handle, the application of classifying approaches was the aim of the subsequently presented investigations.

In our investigation we could demonstrate the applicability of classifiers to interpret the received signals from an ultrasonic SHM-system using guided wave for assessing the integrity of a wheelset axle. As test structures we used true-to-scale-models of a real wheelset axle. As the dispersion curves scale with the model, we had to increase the excitation frequencies along with the scaling factor, to exhibit the same wave pattern inside the structure as in the real component. Piezo-ceramic transducers mounted at only one end face of the axle excite guided waves and receive the echo signals. The classifier was not only trained for the detection of defects but also for a rough determination of crack depth and location.

2 DISPERSIVE PROPAGATION PROPERTIES

With the aim of getting a reliable classification of cracks in a wheelset axle regarding their size and location, it is essential to extract characteristic features from the ultrasonic measurement results obtained by the SHM-system. The effective feature extraction, however, demands for a comprehensive *a priori* knowledge of the physics of wave propagation in the axisymmetric waveguide and the mode-flaw-interaction, i.e. the influence of a crack on the propagating elastic wave, their modal components and their dispersive properties. Consequently, the main goal of our investigation is to find features which are highly correlated with the depth and location of any crack. To meet this requirement initially we developed a theoretical description of the dispersive wave propagation.

The equation of motion in an elastic, isotropic medium [1] as basis of further calculations is given in many textbooks as

$$(\lambda+\mu)\nabla(\nabla\cdot u)+\mu\nabla^2 u=\rho\frac{\partial^2 u}{\partial t^2}.$$

With the Helmholtz-decomposition the displacement vector u can be expressed as u_r, u_φ and u_z using cylindrical coordinates (r,φ,z). The displacement vector u is decomposed through the gradient of the scalar ϕ and the curl of the divergence vector H. This leads to the equations of motion

$$c_L\nabla^2\varphi=\frac{\partial^2\varphi}{\partial t^2}, \qquad c_S\nabla^2 H=\frac{\partial^2 H}{\partial t^2}$$

where c_L is the longitudinal wave velocity and c_S the shear wave velocity. Utilizing the rotational symmetry the longitudinal elastic waves are independent of the angle φ which reduces the number of independent equations. Substituting possible solutions of ϕ and H into the equations of motion leads to Bessel differential equations. Introducing the boundary conditions at the cylinder surface and applying further simplifications leads to a system of two uniform equations. To get a nontrivial solution the condition of a non-zero determinant of the given system of equations has to be fulfilled. This leads to a frequency equation, firstly derived by Pochhammer in 1876 [2]. The final solution for the displacement vector u can be calculated through root finding of the Pochhammer frequency equation. The second wave type important for our problem is the flexural wave. In comparison to the already derived longitudinal waves, flexural waves depend on the circumferential angle φ. Therefore all three components of the displacement vector are nonzero. To find the displacement vector field for flexural elastic waves a similar method is used to solve the respective equations. The introduced boundary conditions and a wavelength in the order of magnitude of the diameter lead to guided waves, which also satisfy the governing equations.

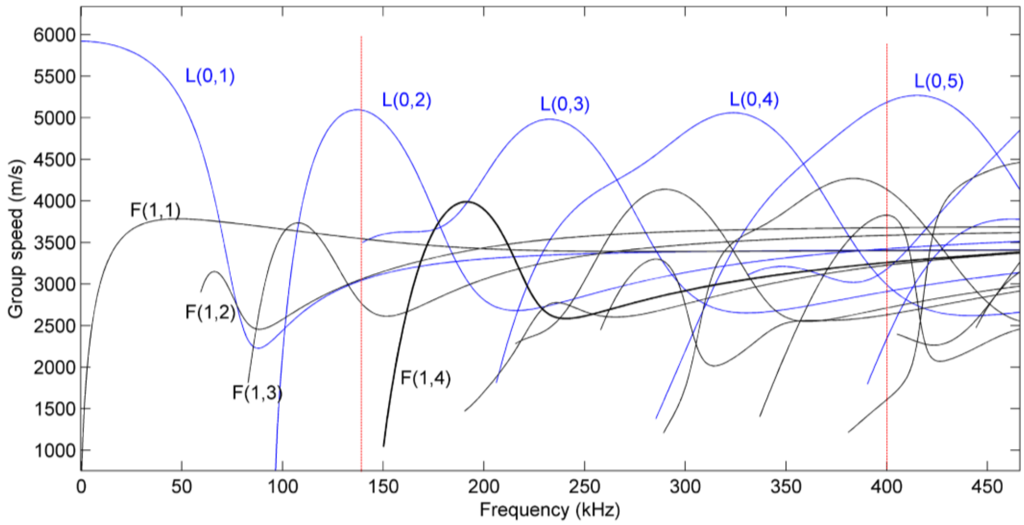

Figure 1: Group velocity dispersion curves for the longitudinal and flexural modes calculated with PCdisp. Red vertical line marks the selected excitation frequencies.

For our investigations we computed the dispersion curves for a homogeneous isotropic elastic cylinder using the free Matlab toolbox PCdisp [3]. Figure 1 shows the group velocity dispersion curves calculated for cylindrical waveguide with an assumed constant, averaged diameter of 42.75 mm. As the diameter varies in the real component, the calculated dispersion relations are only rough approximations without considering reflections at the cross-sectional variations. With every change in diameter the dispersion curves shift along the frequency axis, as the x-axis of the diagram is

controlled by the frequency-thickness-product. A complete solution of the dispersion properties containing the influence of the cross-sectional variations is not yet available. Due to their symmetry the variations only lead to a coupling between either symmetric modes or asymmetric modes. A cross coupling does not occur. Thus, symmetric longitudinal modes only couple with another symmetric longitudinal mode [4]. This specific feature allows the utilization of the approximated dispersion relation for an averaged diameter without loss of generality. One main idea of our approach is to concentrate on the axisymmetric modes for assessing the structural integrity and evaluating the increasing contribution of asymmetric modes in the echo signal which corresponds to the increasing crack depth.
Another assumption is adapted from the results of Puckett [5]. In his work he reveals that the dominant mode at a given frequency has a group velocity close to the longitudinal wave speed in unbounded media. For this reason, we selected excitation frequencies of 140 kHz and 400 kHz to get maximum displacement values for the u_z component.

3 FEATURE EXTRACTION

To recognize cracks with different depth and at different locations using a classifying method we tested various approaches to extract the required information from the measured ultrasonic echo signals. The extracted information is mapped onto a feature vector in a way that the values of the feature vector correlate with either crack depth or crack location. Only the normal displacement component of the echo signal u_z at one of the end faces is evaluated by the piezo-ceramic transducer. To simplify the interpretation of the measurements, all calculations include at least two measurements, one for the flawless state (zero measurement - ZM) and one for the case of an introduced crack (error measurement - EM). That means, for every test run of the SHM-system the current condition of the structure will be compared with a measurement where the structural integrity could be guaranteed, e.g. the quality check after manufacturing.
Using the described transducer arrangement and an in-phase excitation of all transducers, axisymmetric longitudinal modes will be excited. The Hilbert-method considers the symmetry relations between transducers pairs. In this method the difference is calculated between time signals of opposite transducer pairs (1 – 3 or 2 – 4, see Figure 4). The processing of the Hilbert-method for transducers 1 and 3 is given as

$$h_{z,1,3}(t) = \left| \frac{\partial H\{u_{z,1}(t)\}}{\partial t} - \frac{\partial H\{u_{z,3}(t)\}}{\partial t} \right| .$$

This value has to be integrated over the inspection time interval and the results for the ZM as well as for the EM are compared against each other and represent the feature value. Hence, depending on the increasing asymmetric vibrations caused from an asymmetric crack, the feature value is assumed to correlate with crack depth.
Another technique for the crack recognition was developed using wavelet transform. This transformation exhibits a high signal-to-noise ratio due to convoluting the mother wavelet with the reflected signal. The aim of this signal-processing is to apply an appropriate mother wavelet to detect changes between the wavelet coefficients calculated from ZM and EM in the time-frequency-domain. In our investigation we used the Morlet wavelet as mother wavelet. This wavelet possesses a high correlation coefficient between excitation signal and wavelet and emerged as the best candidate. In the first step of our Wavelet-method a threshold calculation is done on the basis of at least two ZMs. The threshold contains the information about vanishing variations of the wavelet coefficients between two or more ZMs and helps to decide whether or not a crack is present. Only wavelet coefficients greater than this threshold are used in next steps. Hence, the threshold makes this method more robust against noise. Figure 2 shows the variations in the coefficients between

ZM and EM with 1 mm and 2 mm crack depth. For this calculations the transducer were excited at the frequency of 140 kHz. With the use of appropriate processing a feature value can be gathered. This method shows a distinctive correlation between the position of the first local maximum in the spectrogram and the crack location in axial direction. The maximum value in the spectrogram also coincides with the crack depth.

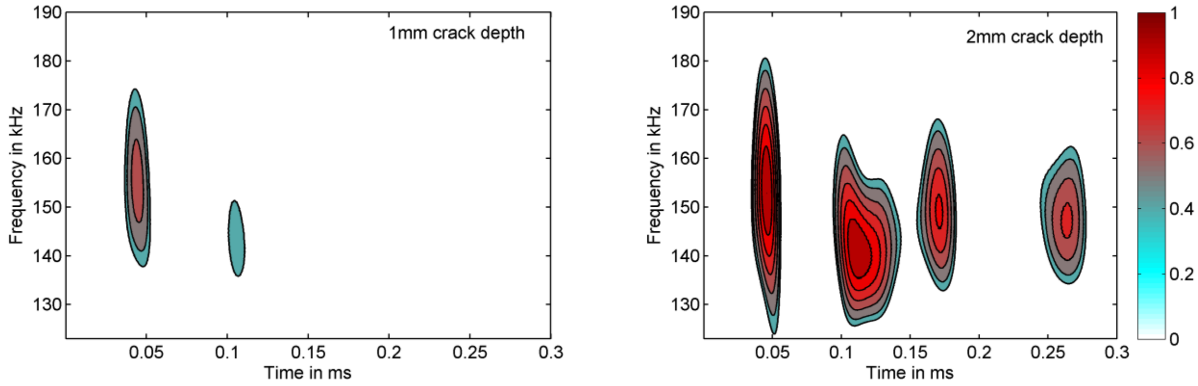

Figure 2: Illustration of the capability of the wavelet method: Normalized spectrogram of the difference wavelet coefficient matrix for 1 mm crack depth (left). Normalized spectrogram of the difference wavelet coefficient matrix for 2 mm crack depth at the same crack position (right).

Besides the above mentioned method in time-frequency domain, implementations in the time domain were also considered. The time domain features often have advantages in terms of computational costs compared with feature gathering methods using transformations. Hence, especially for online SHM-systems time domain methods should be preferred. In the following we briefly present two approaches for calculating robust feature values, (i) the integration method and (ii) the histogram method.

The integration method pre-processes the data and again determines difference signals between the ZM and the EM signal. The integral of these signals defines the feature value and contains all amplitude variations during the measurement interval, while the wave propagates along the waveguide. Hence, the result of this method highly depends on the length of the time interval. Additionally, this method yields another feature value representing the crack location in the axial direction.

In the first step the histogram method counts the number of amplitude values u_i that matches to the amplitude range of one out of 32 bins. Afterwards a kernel density estimator

$$g(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x - x_i}{h}\right)$$

with a Gaussian kernel function $K(x)$ and a bandwidth parameter h is convolved with the amplitude distribution gained from the histogram. This approximated density function can now be subtracted from the ZM reference density function. In Figure 3 is shown an overview of five data sets with increasing crack depth. The left diagram represents the amplitude ranges with most significant variations. A feature value for this method can be generated using the maximum of the cumulative density function. This method achieves a good separability as shown in Figure 3 (right). This is a great benefit compared with other features especially for small crack depths.

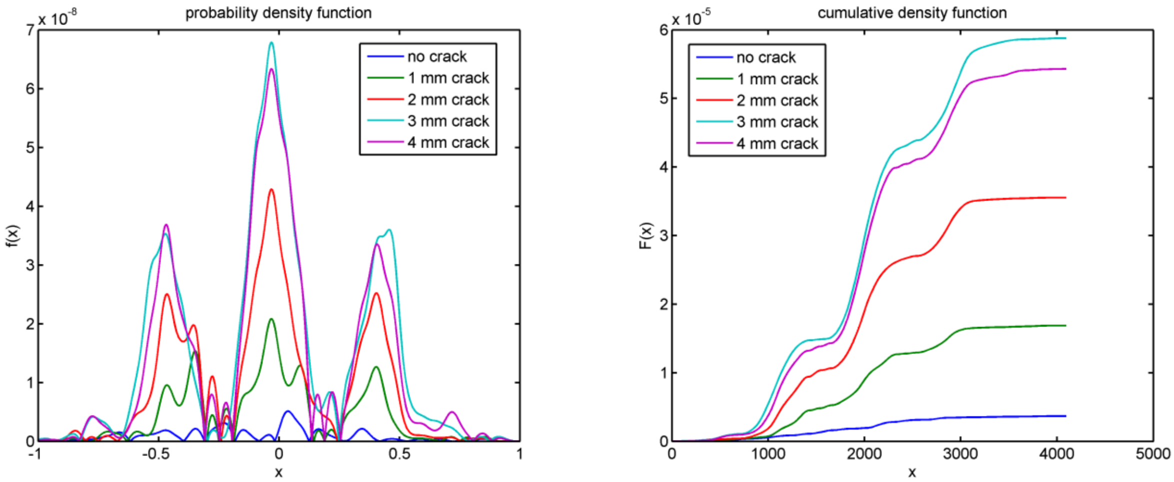

Figure 3: Probability density function (left) and cumulative density function (right) are calculated of variations within a specific amplitude range for four crack depths.

4 Classification Process

The stability and accuracy of a classifier strongly depends on the quality of the class-specific separation between feature values. For a finite training data set the feature distributions $p_n(x)$ are not exactly known. For the reason that our feature characteristic has a multimodal distribution, a maximum likelihood prediction cannot estimate the real *a-priori* distribution $p(x)$ for a given feature. Therefore the non-parametric estimation is used with the kernel density estimation presented above. For this type of prediction it is very important to choose an appropriate window length for the kernel density estimator. If the window is too long, a rough estimation falsifies the density function. After approximating the feature density function the interclass-covariance is calculated to obtain a rating of the efficiency of the feature. Only those features with the best rating were chosen for subsequent calculations.

In the next step the features are whitened using the principal component analysis (PCA). This statistical procedure finds the eigenvectors of the feature covariance matrix and diagonalizes the covariance matrix. The PCA decorrelates the data and is able to reduce the dimension of the feature space, and thus, accelerates the computational time of the subsequent algorithms. Finally all events from the feature space are assigned to a defect class calculated by an appropriate clustering algorithm. In this process the algorithm finds the nearest mean value between every event in the feature space and the centroid locations of a class.

5 EXPERIMENTAL RESULTS

In the following we explain the experimental setup and present some results from the training process. The classifier was trained using measurement data from the setup illustrated in Figure 4 using a small-scale model of a wheelset axle (scale 1:4). At the beginning of the experiment a defect-free axle assures structural integrity and reference measurements were done to obtain the ZM data. Afterwards a sickle crack with a defined depth was inserted at one of the illustrated positions and the measurements were repeated to get the EM data. This procedure was done for every new crack depth and for different crack locations. An axisymmetric arrangement of four transducers was used to excite the ultrasonic pulses. The transducers were excited in phase. Hence, the sensor array mainly excites axisymmetric longitudinal waves. This constraint plays an important role for some of the applied feature extraction algorithms such as the Hilbert method. Respective the scaling of the model, mainly the L(0,2)-mode is excited at an excitation frequency of 140 kHz. At this frequency only a few modes can propagate along the waveguide. This allows an easy interpretation of the received echo signal. This fact has to be taken into account for the development of the feature extraction algorithms, working with a decomposition of the multimodal displacement field of the echo signal.

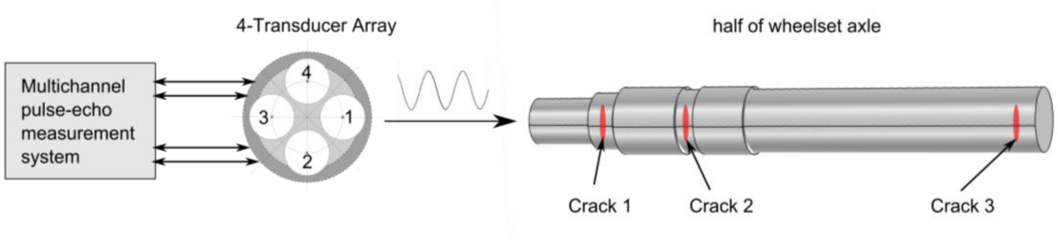

Figure 4: The experimental setup for crack detection of a test wheelset axle using a transducer array of 4 piezo-ceramic transducers.

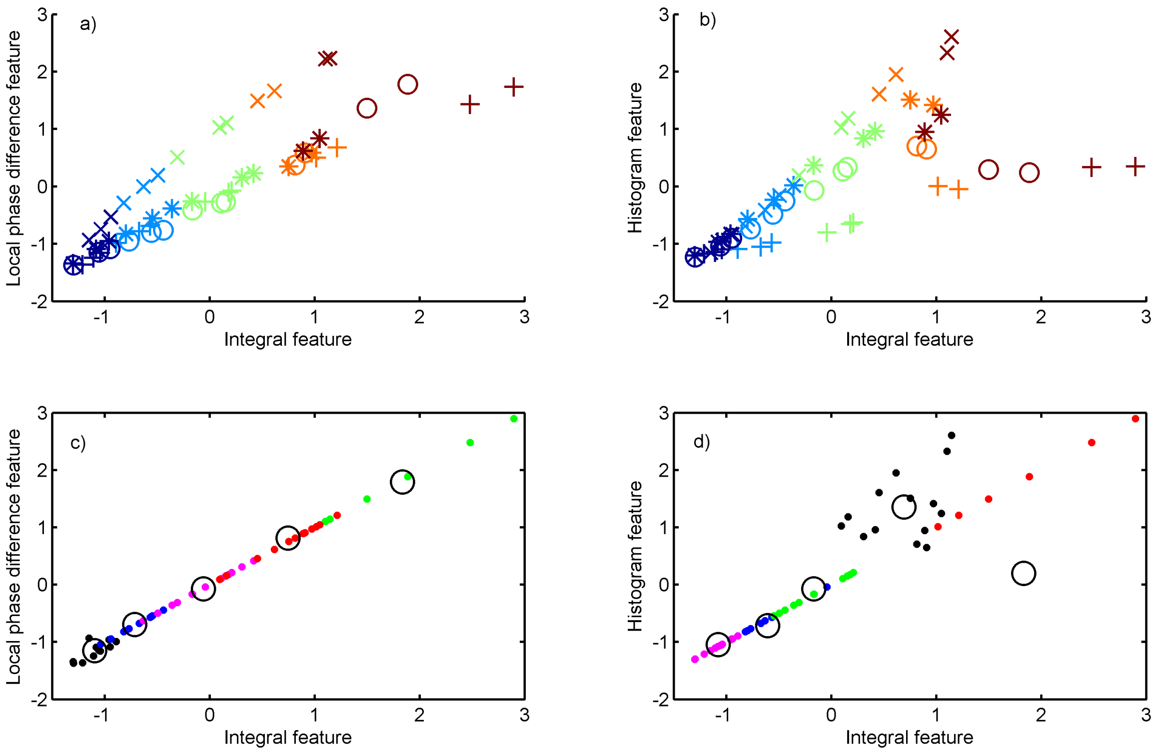

Figure 5: (a) and (b): Measured feature values with increasing crack depth: dark blue – no crack, light blue – 1 mm crack, green – 2 mm crack, orange – 3 mm crack, dark red – 4 mm crack. Different markers denote the four different transducers: plus sign – transducer 1, circle – transducer 2, asterisk – transducer 3, cross – transducer 4. (c) and (d) shows the result from the clustering algorithm. The cluster-centroids are marked with black circles.

Excitation frequencies of 140 kHz and 400 kHz with varying number of excitation bursts were used for the pulse-echo method. Figure 5 shows selected results of feature extraction and classification. In (a) and (b) the crack depth is colour coded and the markers represent the number of the transducer. The integral feature provides the classifier with a good correlation between the feature and the crack depth. A determination is difficult only for 3 and 4 mm depth. The feature characteristics plotted on the y-axis in (a) were calculated from the phase variations which occur at every transducer pair with increasing crack depth. A good sensitivity of the considered feature can

be observed. The feature recognizes the crack orientation in circumferential direction, visible due to higher feature values at transducer 1.
The results from the classification process are exemplary shown in the diagrams (c) and (d). Measurements were grouped into five classes. This allocation allows discrimination between one class for every crack depth and one class for structural integrity of the wheelset axle. The results denote a more stable classification with the integral feature and local phase difference feature than with the histogram feature.

6 CONCLUSION

In this paper, we demonstrated a SHM-system for wheelset axles, able to monitor the entire component from only one sensor position. With this sensor arrangement the mechanical constraints and requirements are fulfilled and the wheelset axles of trains could be monitored during operation. This would reduce the downtime of the trains and wagons, because regular inspection intervals could be omitted or at least increased. A reliable excitation using the transducer array is essential for the online monitoring to provide the classifier with echo signals which can be compared to zero measurements obtained from the flawless component. We could demonstrate the advantage of guided waves, where lower excitation frequencies can be used and propagating wave flood the entire volume of the axle.
The application of appropriate feature extraction methods enhances the reliability of the crack prediction and algorithms working in time domain reveal reliable information about the structural integrity of the axle. The applicability of time domain algorithms could be an important advantage compared with more complex algorithms requiring transformations which increases the effort of computational power. An additional extraction of features with uncorrelated values between adjacent transducers would allow a determination of the crack location in circumferential direction.
In future works the theoretical knowledge should be extended to a better understanding of wave propagation in cylindrical waveguides with variations in cross-section. This would provide a fundament for developing algorithms which decompose the multimodal echo signal to improve the reliability of the SHM-systems. More convenient features would be the result of this approach and could lead to algorithms more stable against noise and other distortions.

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