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## Investigations to introduce the probability of detection method for ultrasonic inspection of hollow axles at Deutsche Bahn

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### Abstract

The vast experience with the automated, ultrasonic system for the inspection of hollow railway axles used by Deutsche Bahn shows that much smaller flaws are detectable than required. This results in a number of false calls. False calls lead to unnecessary demounting and disassembling of wheelsets, which generates unnecessary additional costs. In order to adjust the sensitivity of the inspection system to reduce the number of false calls without compromising safety, the capability of the system to detect cracks needs to be comprehensively established. This capability can be quantified by using probability of detection (POD) curves for the system. The multi-parameter POD model makes it possible to include several factors that influence the crack detection in the analysis. The analysis presented in this paper shows that crack position, orientation, depth extension, and shape as well as the geometry of the axle all have influence on the ultrasonic response amplitude. For future work, calculation of the POD using multi-parameter POD model with these parameters is planned.

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### 1. Introduction

Deutsche Bahn uses mechanized ultrasonic inspection systems to inspect hollow railway axles. Currently, about 140 devices are used to inspect more than 130,000 axles per year. Current testing results show that the devices detect even smaller flaws than required by the standard. This oversensitivity is resulting in a number of false calls.

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The sources of false calls are various. Accumulations of dirt, press fits and flawed coatings can all generate ultrasonic indications. False calls lead to unnecessary demounting and disassembling of the wheelsets which generates unnecessary additional costs. The goal of the joint project between DB-Sytemtechnik and BAM is to determine the capability of the ultrasonic system to detect flaws. Once determined, the sensitivity of the inspection can be adjusted so that the number of false calls is reduced.

Indications from non-destructive testing (NDT) systems, especially when trying to detect very small defects, are inconsistent. Therefore, in applications where a missed flaw can have catastrophic consequences, the reliability of the system has to be established. The probability of detection (POD) curve is considered to be a standard tool to quantify the reliability of NDT [1]. A signal response model [2] assumes that the response signal from the defect is linearly correlated with the flaw size with normally distributed deviations. Setting the decision threshold, the POD and a lower 95% confidence bend are calculated from this correlation. The  $a_{90/95}$  point determines the limit of reliable use of the NDT system. When there are more factors that influence the POD of the flaw significantly, the signal response model is not applicable any more. The multi-parameter POD model, allows several influencing factors to be included in the analysis and enables the POD to be expressed as a function of these factors [3].

## 2. Automated system for the inspection of hollow axles

One of the ultrasonic inspection systems for the inspection of hollow railway axles used by Deutsche Bahn is shown in Fig. 1. The system is docked to the side of the axle and the probe module is pushed into the borehole. The axles are inspected from the bore surface.



Fig. 1. Example for a mechanized ultrasonic inspection system for the inspection of hollow axles used by Deutsche Bahn

The section view of the axle with the probe module inside is illustrated in Fig. 2. The ultrasonic transducers are located in the probe module. The electro-mechanical drive moves the probe module in the axial direction and at the same time it rotates around the longitudinal axis, so that the transducers describe a helical path. The electro-mechanical drive also delivers coupling oil to the probe module and transfers the signals from the transducers to the control unit. Several transducers with different angles of incidence are mounted in the probe head with the aim of detecting cracks on the outer surface of the axle. The detection of the planar, surface breaking flaws that are perpendicular to the surface is mainly based on the corner reflection effect. The ultrasonic wave that hits the back surface of the inspected component under a favorable angle is reflected to the flaw and then back to the transducer. Since the outer surface of the axle has a variable diameter, the cracks which propagate perpendicular to the surface of the axle, will have a  $90^\circ$  angle to the axis only in the regions of the axle where the diameter is constant. The angle between the flaw and the ultrasonic wave will have an influence on the corner reflection effect and therefore also on the detectability of the flaw. The transition region between the wheel seat and the body of the axle is considered particularly susceptible to cracking. The investigation of the detectability of cracks by the ultrasonic inspection system was concentrated in this region.

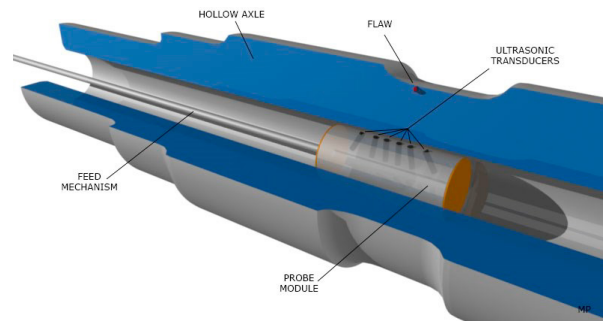


Fig. 2. Section view of the axle with the probe module

### 3. Investigation of the influencing factors on the response amplitude

To properly assess the reliability of the inspection system, several factors that influence the response amplitude, have been investigated. As a first, relatively fast and inexpensive tool for investigation, ultrasonic simulation of the inspection was used. Simulations were performed with software CIVA 2015 (11.1). The exact geometry and material of the axle, the geometry of cracks and the properties of ultrasonic transducers were defined in CIVA. The sound field was calculated and response amplitudes analyzed. In Fig. 3. the sound field generated in the axle by one of the transducers is shown.

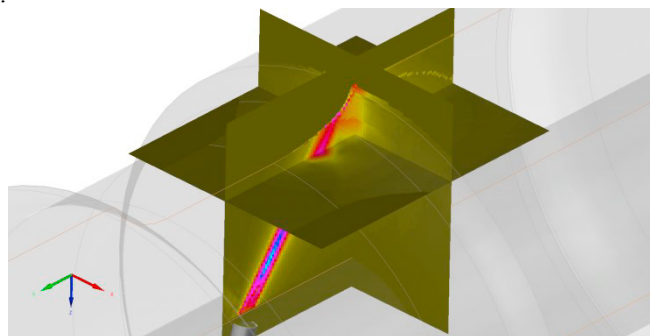


Fig. 3. Simulation of the ultrasonic inspection of the hollow axle

#### 3.1. Crack position

The first factor whose influence has been investigated was the position of the crack in the axle. The response amplitudes from the crack, plotted against the position of the crack in the axle for a  $35^\circ$  transducer are plotted in Fig. 4 a). The position of the crack in the transition region from the shaft to the wheel seat is illustrated in Fig. 4 b). It can be seen that the crack of the same size will have a different response amplitude depending on its location. The highest response amplitude is at the position 485 and the smallest at the position 465.

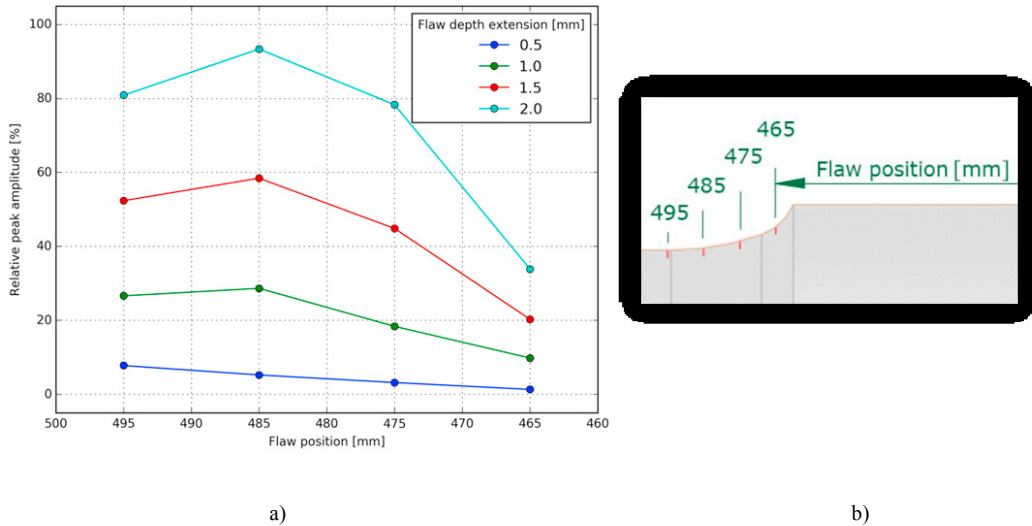


Fig. 4. a) Maximum response amplitude as a function of the flaw position in the axle; b) Position of the crack in the transition region from the free shaft to the wheel seat

### 3.2. Crack orientation

As a next factor, the influence of the orientation of the crack on the response amplitude was investigated. The detection of the cracks is primarily based on the corner reflection effect. If the angle between the crack and the ultrasonic wave generated by the transducer is changed, it will influence the corner effect and hence the response amplitude. In Fig. 5 a) the response amplitudes for the crack oriented perpendicular to the surface and a crack oriented perpendicular to the longitudinal axis are plotted for four transducers with different angles. It can be seen that the maximum response amplitude is higher for the cracks oriented perpendicular to the surface in all four cases. In Fig 5 b) the influence of the change of orientation on the corner effect is illustrated.

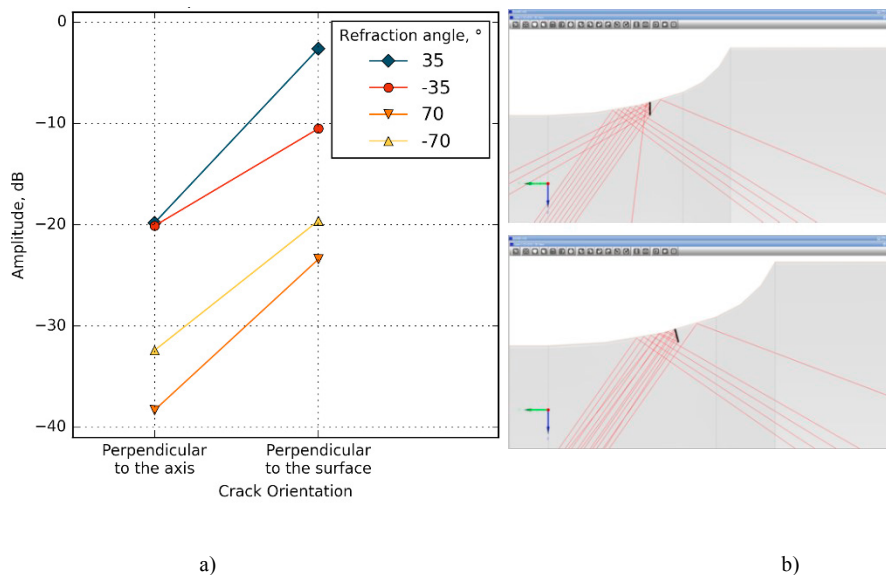


Fig. 5. (a) Maximum response amplitude for different orientations of the crack; (b) Influence of the crack orientation on the corner reflection effect.

### 3.3. Crack depth extension

The crack depth extension, considered as the size of the crack, is usually seen as the most influencing factor on the response amplitude. In Fig. 6., the diagram from Fig. 4 a) is shown again, this time with two significant points marked with dashed circles. It is normally assumed that the response amplitude will be higher for larger cracks. Here it can be seen that the smaller crack with the depth extension 1.5 mm at the position 495 will have a larger response amplitude than the larger flaw with depth extension 2.0 mm at the position 465. Obviously, it is not enough just to consider one influencing factor i.e. the size of the crack when calculating the probability of detection. Other important influencing factors also have to be considered.

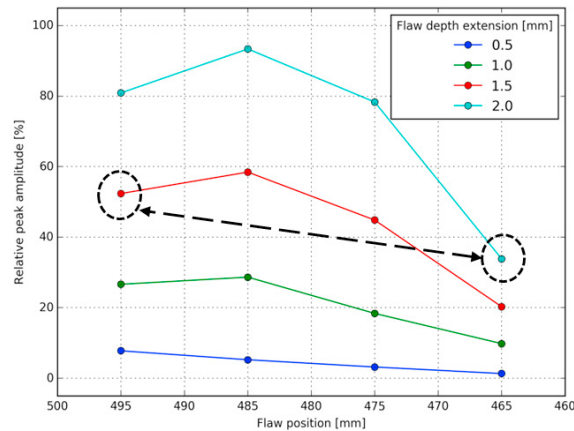


Fig. 6. Maximum response amplitude for different crack depth extension.

### 3.4. Crack shape

According to the standard for the non-destructive inspection of railway axles, the capability of the NDT system to detect cracks is determined on the saw-cut type of reflectors [4]. However, the cracks that can occur in the axles are semi-elliptical with an aspect ratio of minor and major axes of 0.8. Therefore, the influence of the shape of the crack on the response amplitude was also investigated. In Fig. 7 the amplitude for both types of reflectors is plotted against the crack depth extension. It can be seen that for the depth extensions smaller than 2 mm, the saw-cut reflector has a larger response amplitude than the semi-elliptical reflector. Hence, it is important to perform investigation with the appropriate reflector, when establishing the capability of the inspection system to detect cracks smaller than 2 mm.

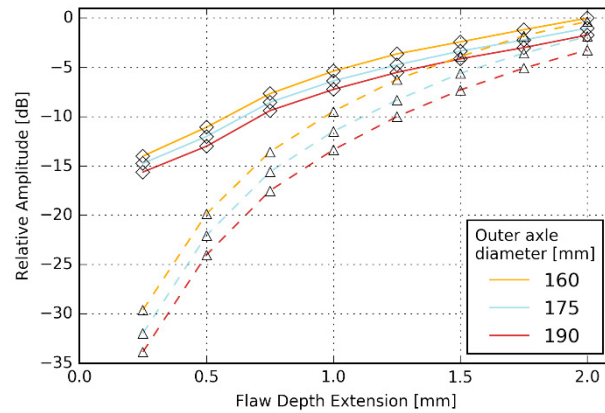


Fig. 7. Response amplitude for a saw-cut reflector (solid lines) and for a semi-elliptical notch with the aspect ratio 0.8 (dashed lines)

### 3.5. Geometry of the axle

The geometry of the axle also influences the response amplitude. In Fig. 8, two axles with different curvature in the transition region from the free shaft to the wheel seat are shown. In Fig. 8 a) the old design of the axle is shown. In Fig. 8 b) from the fracture mechanics point of view improved design is shown. To investigate the influence of the changed design on the response amplitude of the ultrasonic inspection system the crack with the same characteristic is placed on the same location in both axles and the ultrasonic response is calculated. For the  $35^\circ$  inspection angle, the response amplitude in the new axle was -10 dB smaller than in the old. The inspectability of the axle for a given example has been reduced through the new design.

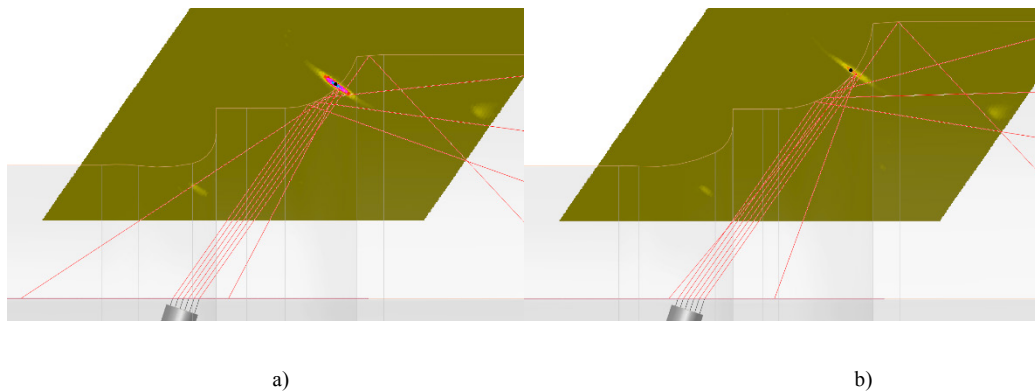


Fig. 8. (a) Ultrasonic B-scan for the old design of the axle; (b) Ultrasonic B-scan for the new design of the axle.

## 4. Influence of the amplitude drop on the probability of detection

The change in the response amplitude will have a direct influence on the probability of detection. It will be shown here how a drop of amplitude influences the probability of detection. In Fig. 9 a) the signal distribution (solid line), the noise distribution (dashed line) and a decision threshold (red line) are shown for the case of a good signal-to-noise (SNR) ratio.

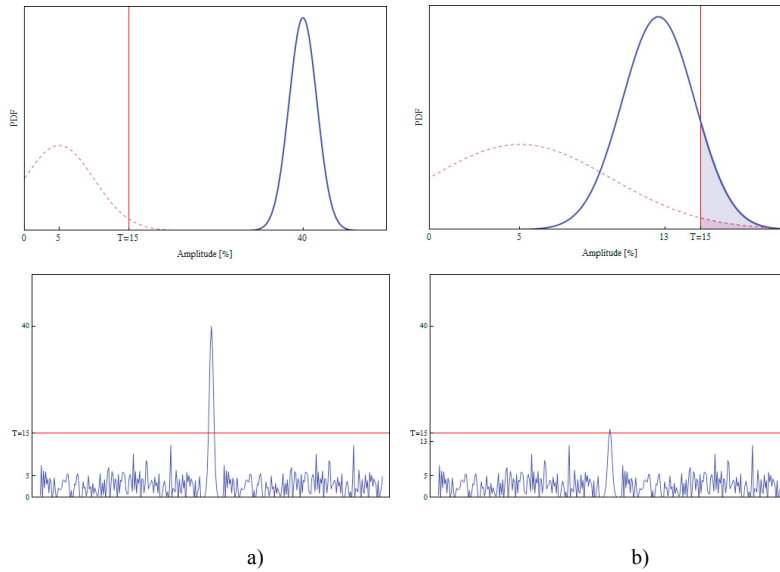


Fig. 9. (a) Signal and noise distribution with good signal-to-noise ratio; (b) Signal and noise distributions for bad signal-to-noise ratio.

The SNR is 8 and the decision threshold is set to 3 times noise level. Below the probability density distributions this is schematically shown as it would look like on the screen of the ultrasonic inspection device. For this case, the calculated POD is practically 100% and the probability of false calls is very small,  $PFC = 2\%$ . In Fig. 9 b) the case is illustrated when the amplitude of the signal drops -10 dB. Signal-to-noise ratio is only 2.5. The calculated POD is 12% and the PFC stays the same. Obviously, the drop of amplitude of -10 dB has also drastically reduced the POD.

To improve the POD the decision threshold can be decreased. This is illustrated in Fig. 10). The decision threshold is reduced to 2 times the noise level. The POD calculated for this case is 91%. However, due to the decrease of threshold, the probability of false call increases to 16%.

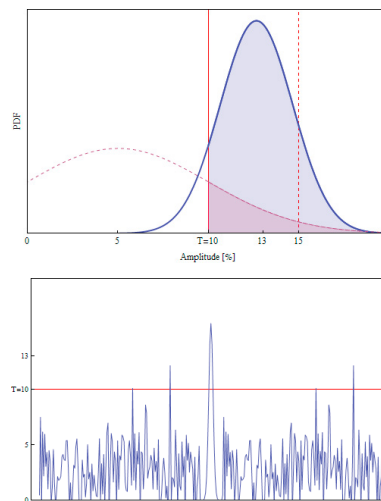


Fig. 10. Decreasing the decision threshold increases the POD but increases the PFC.

## 5. Conclusions and outlook

The investigation showed that several factors have an influence on the response amplitude of the ultrasonic inspection system. Furthermore, the change of amplitude will have a direct influence on the probability of detection of the crack. The analysis showed that crack position, crack orientation, crack depth extension, crack shape and geometry of the axle are all influencing factors. All these factors have to be included in the reliability analysis to properly estimate the capability of the inspection system to detect cracks.

After the initial investigation with the ultrasonic simulation software, a series of experiments on realistic and real cracks will be performed. Finally, by using both the experimental and the simulation results, applying the multi-parameter model, the POD as a function of all influencing parameters will be calculated. This should give a comprehensive view of the capability of the inspection system to detect cracks. The sensitivity of the inspection can be adjusted so that the false alarms are minimised without reduction of the probability of detection.

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