XIX INTERNATIONAL WHEELSET CONGRESS

JUNE 16-20, 2019
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Tuesday, June 18, 2019

11.20 - 13.15 **Main Oral Session 5 - Plenary** Sala degli Arazzi

Inspections: equipment, techniques and methods.
ERWA.

Session Chair: **Stefano Cantini,** *Italy, Lucchini RS*

- **Evaluation of Influence of Sound Beam Displacement on Axle Ultrasonic Flaw Detection**
  Kazunari Makino, *Railway Technical Research Institute*

- **Innovative ultrasonic testing technology guaranteed higher sensitivity for production testing of railway wheels**
  Andreas Knam, *Rosen Germany*

- **Application of induction thermography for wheel inspection**
  Andreas Ehlen, *Fraunhofer-Institute for Nondestructive Testing IZFP*

- **Ultrasonic inspection of solid railway axles by a phased array rotating probe applied by blind holes manufactured at their ends**
  Michele Carboni, *Politecnico di Milano*

- **ERWA Coating Guideline presentation**
  Marcel Ujfaluši, *Bonatrans Group*
  Steven Cervello, *Lucchini RS*
  Stefanos Gogos, *UNIFE*

- **Q&A**

13.05 - 14.10 **Lunch Time** Chiostro dei Cipressi

Ultrasonic inspection of solid railway axles by a phased array rotating probe applied to blind holes manufactured at their ends

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Abstract:

The traditional approach to ultrasonic inspection of solid railway axles, applied in Italy since the '70s of the last century, is based on the so called "rotating probe", a device composed by mono-crystal piezoelectric transducers generating longitudinal ultrasonic waves differently tilted in order to inspect all of the critical sections of the axle from its ends. Even if such approach has proven to be more effective with respect to the conventional one based on single ultrasonic probes applied at the sides of the axle, the known limits of this technique are mainly related to the geometry of axle ends. The present research proposes a novel technical solution able to improve furtherly the performance of the rotating probe, while mitigating, at the same time, its known limits. In particular, the phased array ultrasonic technique is implemented and the application of the rotating probe is no more at the ends of the axles, but at suitable blind holes manufactured on the same ends. The validation of the developed inspection technique is carried out by a dedicated experimental campaign and its reliability is, eventually, derived by a Model-Assisted Probability of Detection (MAPOD) approach, which required a generalization of the traditional statistical procedure, introduced by Berens, for determining the Probability of Detection curve from inspection data.

Keywords: solid railway axle; phased array ultrasonic testing; rotating probe; probability of detection; MAPOD

1. INTRODUCTION

The present scenario of European railway applications shows a tendency towards new maintenance procedures for in-service solid axles, with the aim to define higher safety levels and, at the same time, to optimize the total cycle life cost of the wheelset. Actually, in Europe, solid railway axles are typically employed for both freight and passenger applications, varying from urban and regional service to some High Speed Applications (i.e. TGV).

It is worth mentioning Non-Destructive Testing (NDT) inspections, whether performed in service or off vehicle, aims to detect possible damages, and consequent crack propagation to failure, due to typical in-service phenomena, such as corrosion-fatigue and ballast impacts, according to a "Damage Tolerant" [1]-[2] approach. Inspections must, then, be particularly effective for those axle sections where stresses and probability of damage are higher.

Today, in-service inspections of solid axles mainly involve the application of Visual Testing (VT), Magnetic Particle Testing (MT) and Ultrasonic Testing (UT), with some differences in the techniques employed for either freight or passenger applications. An important reference for maintenance of all kind of wheelsets is EN 15313 [3] where mandatory NDT inspections are defined, although the design and validation of suitable NDT procedures is assigned to NDT experts who, basing upon the wheelset design and service mission, may define the acceptable defects and the inspection intervals frequency.

When it comes to freight applications, a fairly widespread reference, in Europe, is provided by the VPI guidelines [4] developed by the association of private operators of freight wagons (VPI). Such guidelines require, for medium wheelset maintenance, UT inspections based on many tilted probes applied to the external surface of the axles. This methodology is characterized by two drawbacks: the need of partial removal of coatings and the need for disassembling of bearings and axle boxes.

Different is the case of the UT inspection of solid axles from their ends, having the advantage to avoid dismantling them from the train. This approach is preferred in UK and, especially, in Italy where, since the '70s of the last century and thanks to the work of the Italian Railways [5], the rotating probe (Fig. 1a) has been adopted for the inspection. The rotating probe technique has evolved along the years and following the technological development of UT. Nowadays, it is operated by motorized multiple probes as, for instance, the one adopted by Lucchini RS's inspecting procedure [6] where such a probe is equipped with different tilted transducers (Fig. 1b) emitting longitudinal ultrasonic waves able to inspect the critical regions of axles (geometrical transitions and press-fit seats).

The traditional limits of the rotating probe are mainly related to the geometry of axle ends: in particular, identification markings must not be so deep to influence sensitivity and the presence of the three/four threaded holes, needed for the application of the taps of the axle boxes, shadow the inspection of longitudinal portions of the axle. Furthermore, the adoption of single crystal transducers forces inspecting using fixed refraction angles, which could not be the optimized ones for each type of defect that may be present on axle surface.

Based on the described background, the present research proposes a novel technical solution (Fig. 2) able to improve furtherly the performance of the rotating probe, while mitigating, at the same time, its limits. In particular, the phased array ultrasonic technique is implemented in order to simplify the optimization of refraction angles. The application of the rotating probe, then, is no more to the ends of the axles, but to suitable blind holes drilled on the center of axle ends in order to overcome the limits given by threaded holes and deep marking.

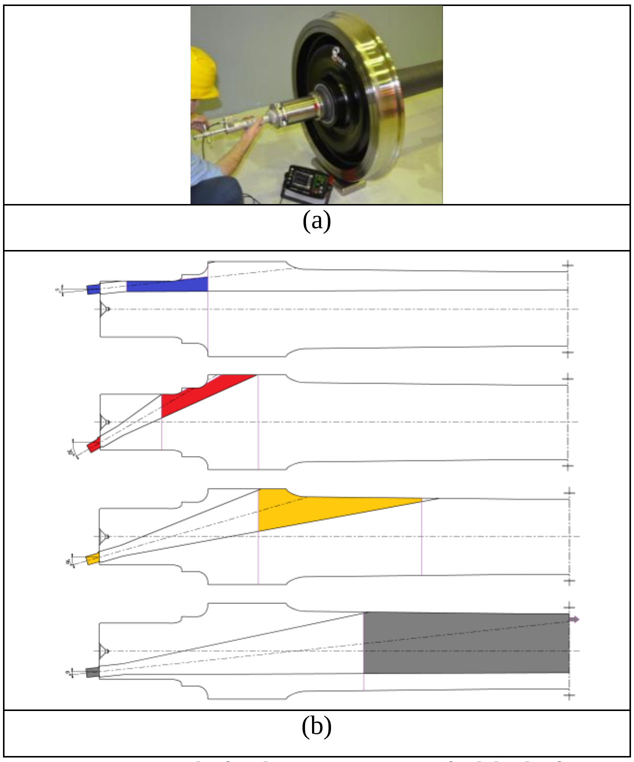

Fig. 1 Rotating probe for ultrasonic inspection of solid axles from their ends

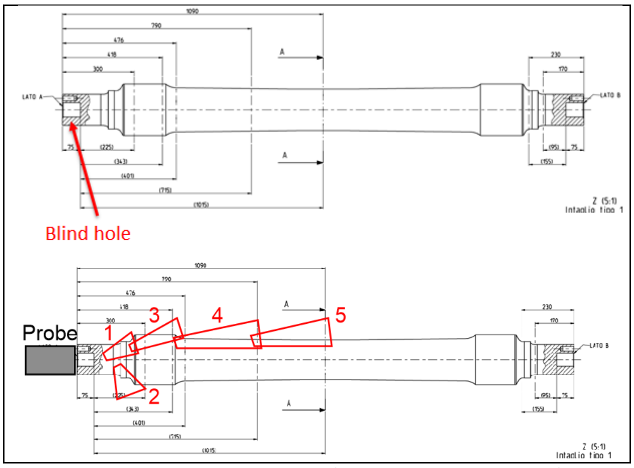

Fig. 2 Phased array rotating probe for ultrasonic inspection of solid axles from blind holes manufactured at their ends

The validation of the developed inspection technique is carried out by a dedicated experimental campaign and its reliability is, then, derived by a "Model-Assisted Probability of Detection" (MAPOD) [7]-[8] approach.

2. Experimental set-up and tests

2.1. The phased array rotating probe

The developed phased array rotating probe uses two ultrasonic phased array transducers. The first one, numbered as "1" in Fig. 3, has a 24 mm diameter circular geometry divided in 16 linear elements, 4 MHz central working frequency and applies S-Scan visualizations (±30°) based on longitudinal ultrasonic waves. This transducer inspects the far regions of the axle, as shown by points 3, 4 and 5 in Fig. 2.

The second transducer, numbered as "2" in Fig. 3, has a 14x14 mm^2 square geometry divided in 16 linear elements, 4 MHz central working frequency and applies S-Scan visualizations (between 30° and 70°) based on shear ultrasonic waves. The inclination of the transducer with respect to the inspecting plane is equal to 48°. Moreover, this transducer inspects the near regions of the axle, as shown by points 1 and 2 in Fig. 2.

Both phased array probes are operated by a suitable PA flaw detector (i.e. GE Vision+) and the coupling between the probes and the inspected axles is realized by axlebox grease.

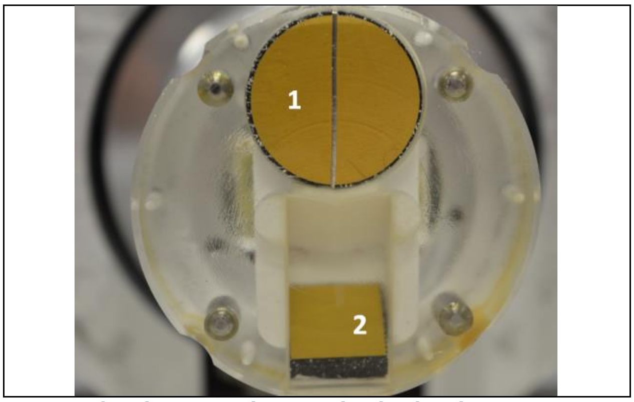

Fig. 3 Phased array transducers used in the phased array rotating probe

2.2. The adopted sample block

The sample block adopted for experimental measurements consists in a real axle made of EA1N steel, sampled from running production, characterized by blind holes at its ends and having different sections (highlighted by red dashed lines in Fig. 4) presenting artificial notches manufactured by EDM.

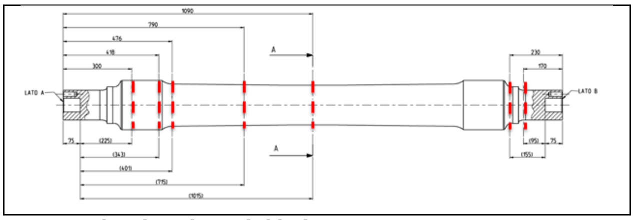

Fig. 4 The adopted sample block

In particular, each artificially defected section is characterized by multiple notches having different morphology (either convex or concave) and size. Fig. 5 shows some examples.

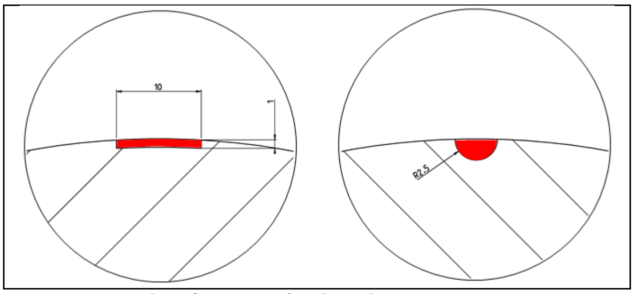

Fig. 5 Examples of EDM artificial notches

2.3. Experimental responses

Fig. 6 shows the experimental ultrasonic responses obtained from the sample block using the phased array rotating probe. In particular, Fig. 6a shows the responses obtained by probe #1, while Fig. 6b those obtained by probe #2. Data are presented in terms of percentage response amplitude taking, as 80% full screen height reference value, that of the convex notch having R=3.5 mm and located at the centerline of the sample block (1090 mm).

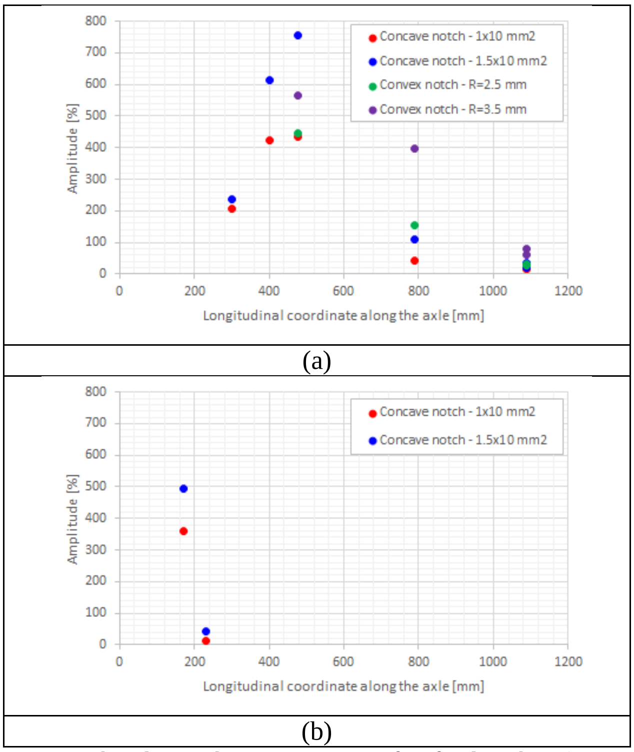

Fig. 6 Phased array ultrasonic responses of artificial notches: a) longitudinal probe; b) shear probe

As can been seen, and as expected, the longer is the time of flight from the axle end, the lower is the response amplitude. Likewise, the bigger is the notch at the same time of flight, the higher is the response amplitude.

3. Numerical Simulation of Phased Array Ultrasonic Responses

Numerical simulations of the inspections by the phased array rotating probe were carried out by means of CIVA^{nde} 2017 software package [9]. The first step consisted in simulating the experimental responses, got from the sample block, with the aim to validate the numerical model. From this point of view, a key parameter is the structural attenuation of the involved steel, which was experimentally derived and resulted to be equal to 12 dB/m at 4 MHz.

Fig. 7 shows the direct comparison between experimental outcomes and numerical simulations. A part from the inherent uncertainty and limited variability of measurements, the correspondence of numerical results can be considered good and the model validated.

3.1. A "Model-Assisted Probability of Detection" Approach

With the aim to define the performance and the reliability of the proposed inspection technique in an affordable way, the validated model was, then, applied for implementing a MAPOD approach.

Such a procedure consisted [7]-[8] in a statistical process based on Monte Carlo extractions: before each inspection simulation, a value for the location of the flaw along the axis of the axle was randomly extracted from a uniform distribution representing the fact it is not known in advance where a damage will initiate during service. For each inspected region (1 to 5 in Fig. 2), 10 increasing crack sizes were simulated and 30 extractions simulated for each crack size. Fig. 8 shows, as an example, the numerical results obtained for the case of probe #1 applied to region 5 in Fig. 2. The other regions provided similar results for both probe #1 and probe #2.

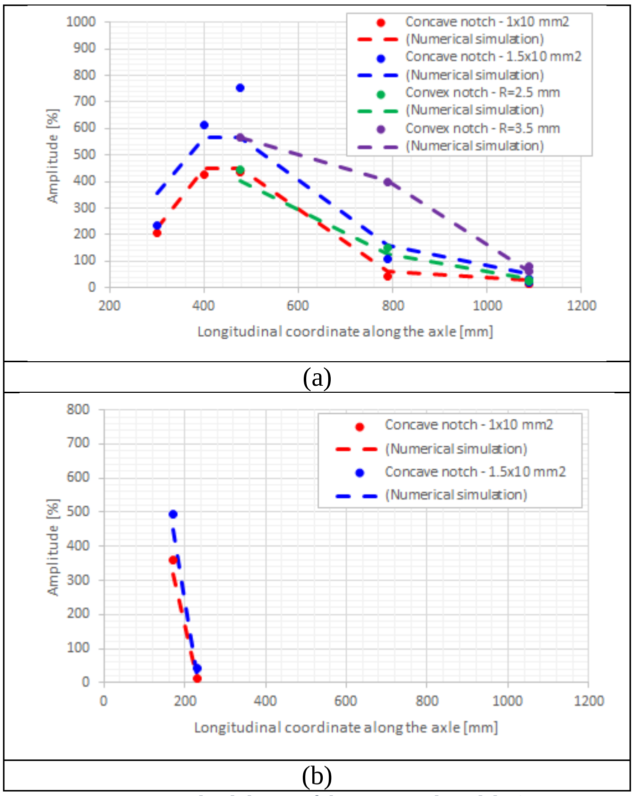

Fig. 7 Experimental validation of the numerical model: a) longitudinal probe; b) shear probe

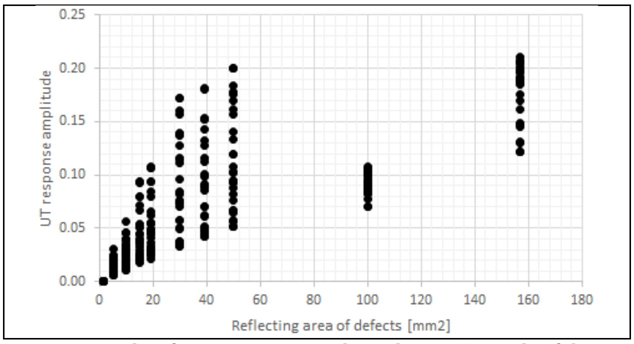

Fig. 8 Results of MAPOD numerical simulations (example of the case of probe #1 applied to region 5 in Fig. 2)

It is worth mentioning two main points: the first one is that the hypotheses of Berens method [10]-[12], to estimate "Probability of Detection" (POD) functions from inspection data, require a linear trend of responses with defect size, but this does not seem the case. The second one deals again with the hypotheses of Berens method, which require, also, a Gaussian distribution of residuals with respect to the linear regression of responses, but this hypothesis seems not to be respected, as well.

Actually, these two problems have been previously observed and studied [13] for the case of the traditional rotating probe. This topic requires in-depth analysis.

4. Rationale behind the Observed Unconventional Behavior Of Ultrasonic Responses

The non-linearity of responses with defect size can be ascribed to the misaligned interaction (Fig. 9) between the sound beam, generated at the axle end, and the defect, which typically lies on a plane perpendicular to the axis of the axle. This problem has already been studied and understood in [13], to which the reader is referred for all the details. The same phenomenon seems to take place in the case of the application of the phased array rotating probe.

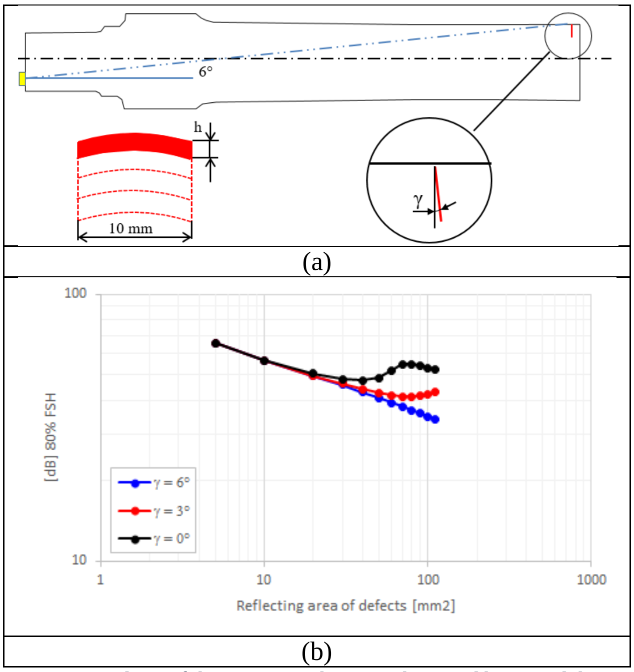

Fig. 9 Analysis of the interaction between the sound beam and the defect for the case of UT inspection from the axle ends

Considering the problem about non-Gaussian residuals, it should be remarked that an effective UT inspection practice requires the maximization of echo responses reflected by indications because this allows obtaining an always-repeatable reference condition before carrying out the evaluation of indications in terms of amplitude and size. From a practical point of view, the maximization of echo responses reflected by indications is obtained regulating the acoustic axis of the sound beam so to point at the location of maximum reflection of the indication itself. However, in some operative cases, maximization is not achievable, mainly due to geometrical constraints not allowing the inspection of the whole region of interest with uniform sensitivity. The UT inspection of solid axles from their ends is one of these cases [13], because no longitudinal movement of the rotating probe is permitted along the axle (Fig. 10). In particular, the ultrasonic response amplitude is going to be maximum for a defect located at the impact point of the acoustic axis on the external surface of the axle, while it is necessarily lower for all the other points of the inspection region because the energy of the sound beam gradually decreases moving away from the acoustic axis. This means that ultrasonic responses tend to accumulate data in the region close to the maximum one and that their distribution cannot be symmetrical with respect to the mean one, i.e. residuals cannot be distributed according to a Gaussian distribution.

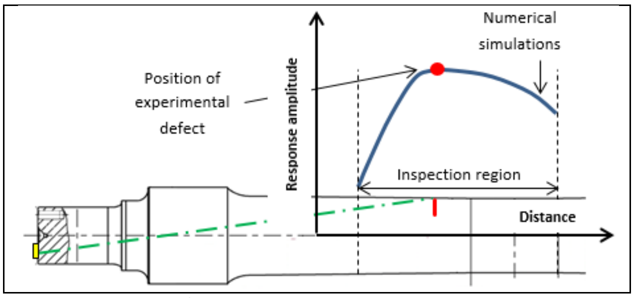

Fig. 10 Behavior of non-maximizable ultrasonic responses along the inspection region

As an exemplifying proof of the above-described point, Fig. 11 shows the histogram of all the ultrasonic responses reported in Fig. 8. It is worth remarking all the shown data sets of Fig. 8, before defining the histogram, have been translated in order to have the same maximum value and, consequently, to become directly comparable. As can be seen, and as expected, data tend to accumulate at the maximum response and their statistical distribution is not symmetrical with respect to the median value, confirming the rationale about non-Gaussian residuals for the phased array rotating probe. The other inspected regions provided similar results for both probe #1 and probe #2.

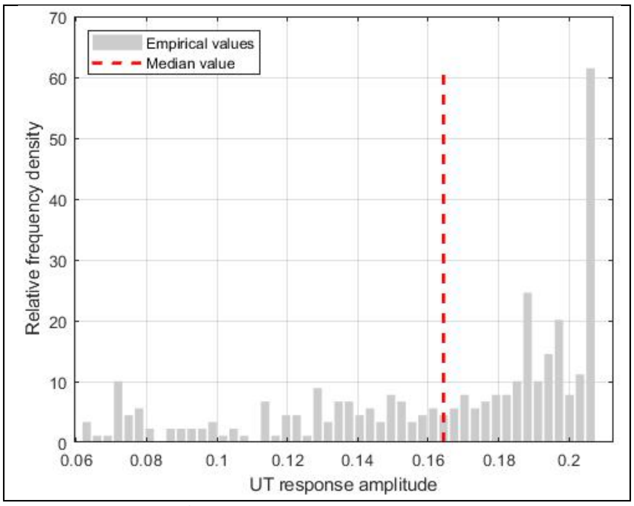

Fig. 11 Behavior of non-maximizable ultrasonic responses along the inspection region

5. A Generalized Procedure for Determining the "Probability of Detection" of Defects

In order to supersede the issues described in Sections 3 and 4, a generalization of the traditional Berens method for POD calculation was developed (Fig. 12) and is here proposed. Such a generalization was based on two different actions: the introduction of a non-linear regression of maxima and the adoption of a specific and optimized statistical distribution for describing residuals.

5.1. *Non-linear regression of maxima*

The traditional approach [10]-[12] applies a linear regression to the linear trend of the mean values of ultrasonic response data sets descript by a Gaussian distribution.

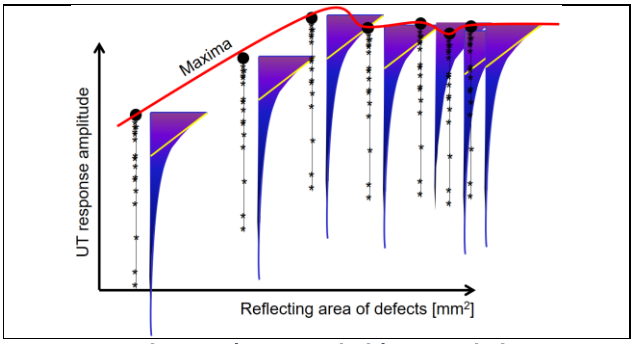

Fig. 12 Generalization of Berens method for POD calculation

In the present case, the most characteristic value of the data sets is not the mean one, but the maximum one (see Fig. 11) whose trend (Fig. 8) is not linear. To supersede these differences with respect to the traditional approach, the present trend of maximum data was interpolated by means of Piecewise Cubic Hermite Interpolating Polynomial curves [14]. With respect to traditional polynomial or spline interpolations, Piecewise Cubic Hermite Interpolating Polynomial curves have the advantages to present less overshoots and oscillations, if the data are not smooth, and are less expensive to set up. Fig. 13 shows the resulting interpolation for the case of the data shown in Fig. 8. The same figure reports the 95% unilateral confidence limit of the regression curve, as well.

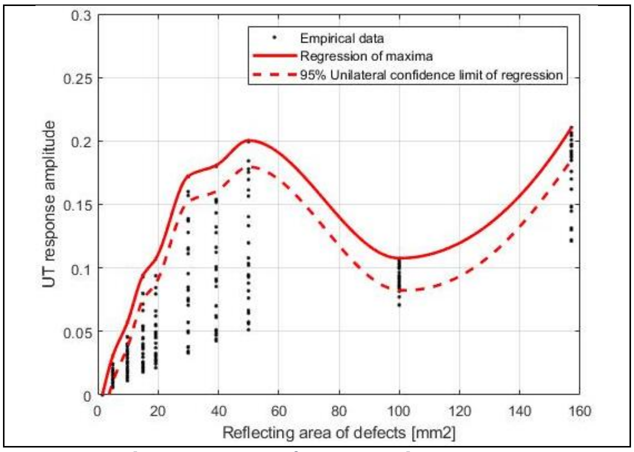

Fig. 13 Non-linear regression of maximum ultrasonic responses

5.2. *Statistical analysis of ultrasonic responses*

In order to introduce a suitable statistical distribution able to represent the trend of residuals and to supersede the hypothesis of Gaussian residuals, it is worth observing the morphology of ultrasonic responses shown in Fig. 11 is characterized by a significant negative skew. This seems to suggest the need to treat such responses by means of a statistical distribution of the Gamma family. In particular, the following distributions were considered in the analysis: Negative Exponential, Weibull, Gamma, Nakagami and Generalized Pareto. Fig. 14 shows the probability density functions and the cumulative density functions of all the considered distributions compared to the empirical data of Fig. 11. It is worth noting the data were suitably translated and reflected, with respect to the zero value of the axis of responses, in order to simplify the analysis. Fig. 14 shows the cases of the Normal and Log-Normal distributions, as well, as a comparative reference.

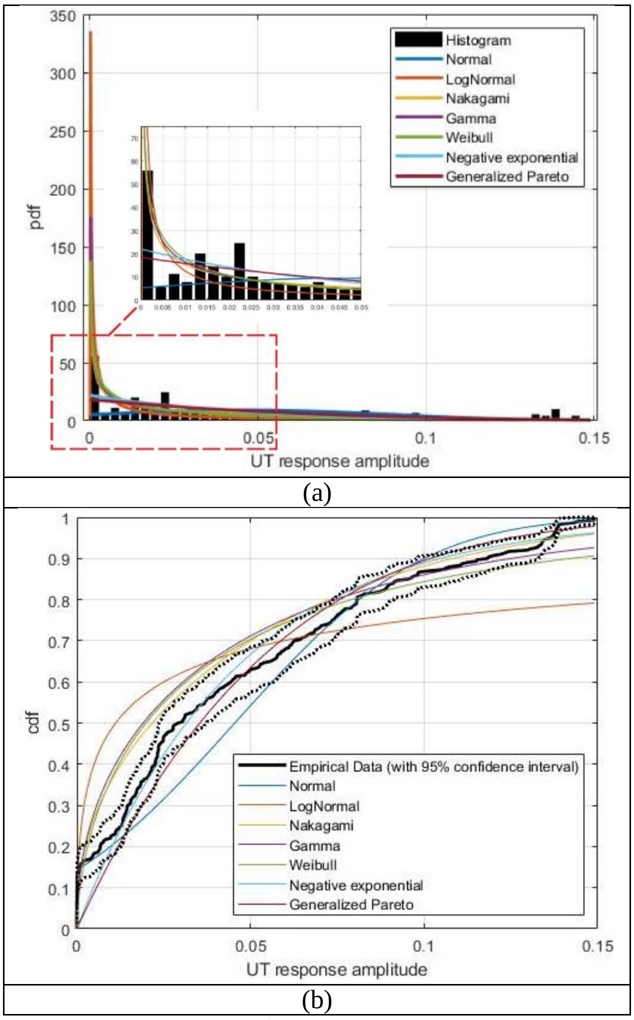

Fig. 14 Statistical analysis of ultrasonic responses

The choice of the best fitting distribution from the considered set was carried out estimating the specific parameters of each of them by the Maximum Likelihood method [15]. Based on the maximum values of the Log-Likelihood, the best fit, for the inspection regions of Fig. 2, was always achieved by means of the Nakagami distribution [16]. This distribution is a particular case of the Gamma distribution and has the following probability density function:

$$f(x;\ \mu, \omega) = \frac{2\mu^{\mu}}{\Gamma(\mu)\omega^{\mu}} x^{2\mu-1} e^{-\frac{\mu}{\omega}x^2} \tag{1}$$

where μ is the shape parameter and ω is the scale parameter (both estimated by the Maximum Likelihood method for the present case).

6. "Model-Assisted Probability of Detection" curve for the Phased Array Rotating Probe

Once solved the issues related to the nature of ultrasonic data generated by the inspections of axles from their ends, the proposed method was applied, as an example, to the data shown in Fig. 8 and the resulting MAPOD curve is presented in Fig. 15, without confidence bounds for the sake of clarity.

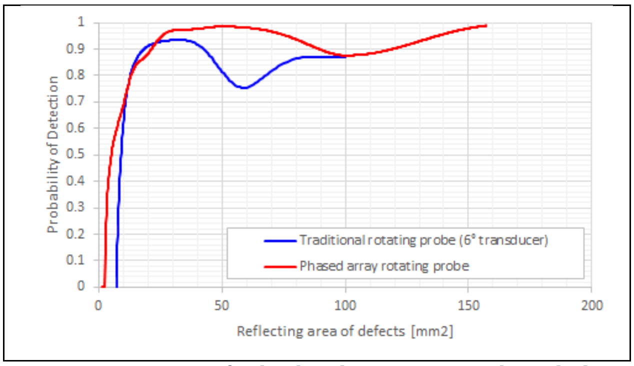

Fig. 15 MAPOD curve for the phased array rotating probe applied to region 5 shown in Fig. 2

The obtained MAPOD curve is directly compared to the MAPOD curve [13] of the traditional rotating probe, which applies a 6° longitudinal wave transducer to inspect region 5 in Fig. 2. Both MAPOD curves were derived assuming, as decision threshold [10]-[12], the ultrasonic response of the concave defect with size 10x1 mm^2.

As can be seen, the performance of the phased array rotating probe is systematically either equal or better than that of the traditional rotating probe, especially considering the region of the small defects, which is the most important for the inspection of railway axles.

Based on what is stated in Section 1, it is worth remembering the phased array rotating probe presents other advantages with respect to the traditional one. These advantages consist in superseding, by the adoption of the blind hole, of the problems related to the surface conditions of axle ends (markings and threaded holes): these effects are not reflected in the MAPOD curve shown in Fig. 15, but they would tend to lower the MAPOD curve of the traditional rotating probe down to zero in some circumstances.

7. Concluding Remarks

A novel technical solution, able to improve the inspecting performance of the traditional rotating probe for solid railway axles, has been proposed. Such a novel technique, from the point of view of the experimental set-up, is based on two key points:

1. the adoption of the ultrasonic phased array technology in order to simplify the optimization of refraction angles
2. the application of the probe to suitable blind holes drilled at axle ends in order to mitigate the traditional problems of the technique, mainly consisting in the presence of markings and threaded holes at the ends themselves

The technique was validated by a dedicated experimental campaign and its reliability was, then, derived by a “Model-Assisted Probability of Detection” approach. The latter step required to develop a novel statistical procedure, based on the Nakagami distribution and on the Piecewise Cubic Hermite Interpolating Polynomial interpolation of data, to analyze experimental ultrasonic in-service inspections and to generalize Berens’ method for the definition of POD curves.

The final comparison between the MAPOD curves obtained by the traditional rotating probe and the novel one clearly showed a better performance of the latter, suggesting the adoption of this technique to increase safety level of the inspection plan, both of newly designed and of existing wheelsets, thus further reducing the probability of non-detection.

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