Automatic In-service Train Axle Inspection Systems

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Abstract.. A range of equipment has been developed for automatic inspection of rolling stock. This paper presents developments for the inspection of solid and hollow train axles. In both cases inspection is carried out in-service, that is, without the need of disassembly of wheelsets.

These systems have been developed at the request of, and in close cooperation with, the equipment & maintenance division of the Spanish national railway operator *Renfe Integria*. Together with a recently developed ultrasonic automatic in service wheel inspection equipment, these new systems represent the complete set of rolling stock inspection solutions based on INTERLAB IEC proprietary modular system ULTRASEN®. To date, a number of these axle and wheel automatic inspection systems are in service in RENFE workshops throughout Spain.

1. Introduction

High safety standards that apply in railway management call for periodic inspections of rolling stock to assert its ongoing capability to perform within the required safety margins. In the case of wheels and axles, a main objective of maintenance operations is the detection of cracks [1], that might lead to an in-service breakdown of the aforementioned wheel or axle, with potentially catastrophic consequences.

On the other hand, it is obvious that in order to maximise productivity, downtime of rolling stock due to maintenance operations should be kept minimum, which, in the case of inspection for cracks in wheels or axles, implies minimising both the inspection time itself and the inspection preparation time (i.e. the number of parts to be removed from the wheelset prior to inspection of the wheel or axle).

The apparent contradiction between frequent, thorough inspections of the rolling stock and minimum inspection associated downtime has been addressed by development of application specific ultrasonic systems to search for cracks both in wheels and in different axles (both solid and hollow types). In these systems, most of the inspection tasks are performed automatically, which yields an overall reduction in inspection time.

Furthermore, ultrasonic NDT examination of wheels and axles permits access to all critical crack formation areas from limited access points, so that only a minimum number of elements need to be dismantled from the bogie for inspection, thereby minimising inspection preparation time.

In what follows, we focus on the design, development and results of systems for the inspection of hollow and solid axles, since the wheel inspection systems have already been described elsewhere [2], [3].

Inspection of solid axles is performed using a set of probes at different incidence angles, performing the inspection from the axle head. A number of simple interchangeable adapter elements (ring adapters), allow the inspection of different types of locomotives employing a common inspection system, resulting in a convenient and optimised use the equipment. In the case of the hollow axle system, inspection is performed from within, scanning the axle bore with a motor-driven probe holder which follows a programmed set of trajectories.

Both systems mentioned above are based upon an advanced digital processing and control system employing ULTRASEN® technology, as well as on a comprehensive set of automatic assessment tools for determination of axle status, together with storage, retrieval and calibration software tools. A remarkable feature of these systems, which is in fact the origin of the development presented, is the possibility of storing full inspection results, providing complete traceability and enabling subsequent retrieval and reassessment of any given inspection. The auditability of the inspections is greatly advantageous for rolling stock operators and maintainers alike, providing full record of work performed, available for future use in trend analysis or auditing, and largely increasing confidence in inspection results.

2. Axle Inspection Strategies

In order to set up the requisites for an automatic inspection system, we must first define the inspection strategies that the system will be called to implement.

A first requisite is that axle inspection must be implemented within the scope of normal, or “light”, maintenance operations, and therefore not limited to major overhaul operations, which are far less frequent. This precludes any disassembly of bogies or wheelsets, so that the only feasible points of access for axle inspection are the left and right axle heads, which can be accessed by just taking off the head covers and then disassembling the speed measurement or the ground contact devices, depending on the axle. In hollow axles, it must be noted that, by accessing the heads, access is also gained to the axle bore.

A second requisite, also common to the inspection of both hollow and solid axles, is that inspection should focus on the detection of cracks originating on the outer axle surface, and propagating both along the axle circumference and inward toward the axle core. It must be noted that the ultrasonic echoes coming from these cracks cannot be told apart from those coming from axle-specific geometric features (such as corners, fillets and chamfers between different diameter zones), except for the latter occurring always at fixed locations along the axle. This fact must be taken into account in the design of the automatic assessment tools (see section 3.3), so that the expected axle-specific geometric features are not identified as cracks, thereby producing false alarms.

In what follows, we proceed to examine those features specific to the inspection of either solid or hollow axles.

2.1 Inspection of solid axles

For the inspection of solid axles, ultrasonic transducers are scanned following a circular trajectory around the axle head. The incidence angle and circular trajectory radius for each of the transducers is chosen to aim its beam to specific areas of interest in the axle outer surface, where it has been established both by RENFE and the axle manufacturer that the formation of cracks is likeliest.

Sensitivity calibration is done at the beginning of each shift, setting the gain so that the echo from a methacrylate reference block reaches a preset amplitude level.

Apart from the specific areas in each axle type, a general inspection is performed in all axles with a straight beam probe [1]. As an example, transducer deployment for the inspection of a sample axle (commuter train type UT S/447 motor car axle, requiring three different incidence angles, see [4]) is depicted in figures 1.a to 1.c. Beam profiles are drawn to scale, considering the standard 2.25 MHz ∅25mm transducers used in the inspection system.

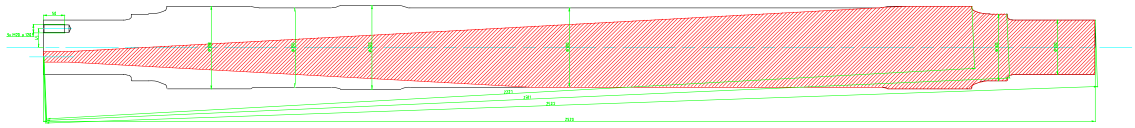

Figure 1.a: Overall axle inspection, 0º incidence angle.

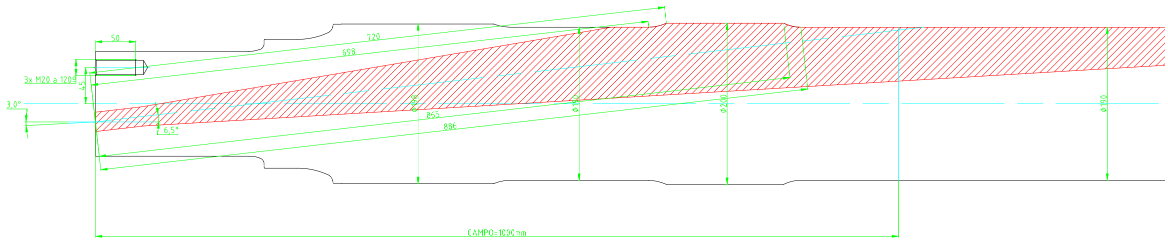

Figure 1.b: Specific inspection of reduction gear seat and fillet to body of axle, 6.6º incidence angle.

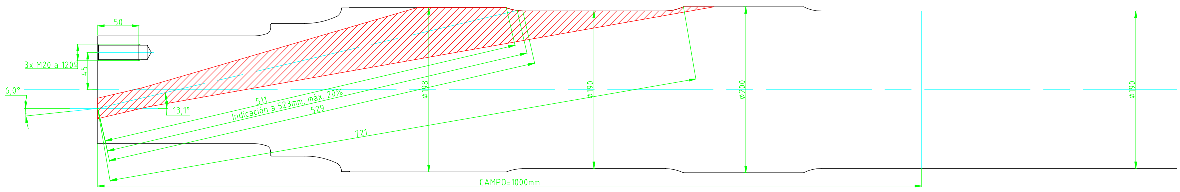

Figure 1.c: Specific inspection of wheel seat to body of axle fillet, 13,3º incidence angle.

A summary of all these inspection areas for different types of trains is presented in table 1.

Table 1. Summary of angles of incidence and inspected areas for different axle types.

Type of train/axle	Inspected Area	Wedge angle (º)	Incidence angle (º)	Range (mm)	Threshold (%)
U.T. S/447 [4] (motor car axle)	*Overall*	0º	0º	2500mm	40%
	Reduction gear seat and fillet to body of axle	3º	6,6º	1000mm	40%
	Fillet, wheel seat to body of axle	6º	13,3º	1000mm	40%
U.T. S/447 [4] (tow car axle)	*Overall*	0º	0º	2500mm	40%
	Fillet, Brake disk to body of axle	4º	8,8º	1000mm	40%
	Fillet, wheel seat to body of axle	7º	15,6º	500mm	40%
U.T. S/446 [5] (motor car axle)	*Overall*	0º	0º	2500mm	40%
	Fillet, wheel seat to body of axle	7º	15,6º	1000mm	40%
U.T. S/446 [5] (tow car axle)	*Overall*	0º	0º	2500mm	40%
	Fillet, wheel seat to body of axle	7º	15,6º	1000mm	40%
S/269.200 locomotive [6], [7]	*Overall*	0º	0º	2500mm	20%
	Axle-journal	3,5º	7,7º	500mm	20%
	Reduction gear seat	5º	11,1º	1000mm	20%
S/269.400 locomotive [8]	*Overall*	0º	0º	2500mm	20%
	Reduction gear seat	6º	13.3º	1000mm	20%

Study of the inspection experience summarised in table 1 yields some further requirements for the solid axle inspection system:

- Capability to manage simultaneously at least three ultrasonic transducers, with different wedges, since that is the maximum number of different incidence angles required for any axle. In this way, the inspection tool is configured by mounting the required wedges on the transducers and changes in this configuration are only necessary when switching to a different type of axle.

- Parameters such as gain, defect threshold level, angle of incidence, range of depths in which to process received echoes as cracks must be independently adjustable for each of the transducers. Furthermore, the system must be capable of storing different sets of configuration parameters so that it can be easily reconfigured for different axle types.
- To achieve consistent inspection results, triggering of the ultrasonic transducers must be synchronised to their position as they are scanned around the axle head.

2.2 Inspection of hollow axles

Inspection of hollow axles is performed form within the axle bore, using angle-beam transducers to detect cracks in the axle outer wall. Angles of incidence are specified by RENFE [9] to ±45º (2MHZ transducer) and ±70º (4MHz transducer), where the sign indicates which end of the axle the transducer is aimed to. An example of actual inspection from within the axle bore for these angles of incidence is depicted in figure 2, with beam profiles drawn to scale.

For hollow axle inspection, to achieve 100% coverage of axle outer surface, the transducers need to be scanned along the inner surface of the bore in a series of combined rotations and axial displacements.

In hollow axles, calibration is done for each specific axle [9], setting the gain for each transducer so that the echo from a geometric feature in the axle reaches a preset amplitude level. This calibrated gain is then increased by 12 or 24dB, depending on the area of the axle being inspected.

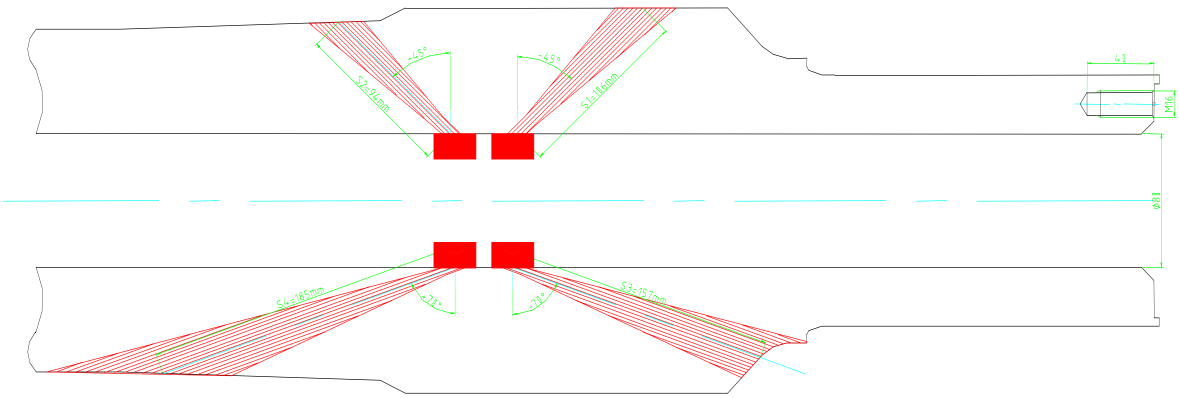

Figure 2: Inspection of hollow axles from the bore inner surface, using ±45º and ±70º angles of incidence.

Since only the echoes coming from the axle outer wall have to be considered, and the distance from the transducer to the outer wall (see S1 through S4 in figure 2) depends both on the incidence angle and the actual axle diameter at the point of measurement (which in turn varies as a function of transducer axial position and incidence angle), the position of the echo capture gate needs to be configured for each incidence angle, and dynamically modified as the transducers are scanned along the axle. In manual inspection, this requires of the operator to keep track of transducer axial position and calculate (or rather look up in a table) beam point of incidence on the outer wall of the axle, to look for the correct echoes.

Following the analysis of hollow axle inspection, we can set up some requirements for the solid axle inspection system:

- Capability to manage simultaneously four angle beam ultrasonic transducers, since there are four different incidence angles to be considered.
- The four transducers must be mounted on a common holder to scan them along the axle inner bore. Two scanning movements are required: rotation (360º) and axial displacement (0 to ½ axle length, since inspection is done from both axle ends).
- To achieve consistent inspection results, and repetitive 100% axle outer wall coverage, triggering of the ultrasonic transducers must be synchronised to their position as they are scanned around the axle head, and the scanning needs to be done automatically, following a sequence of programmed trajectories.
- Specifically, some means must be contrived to program axle geometry into the inspection system, so that gain and gate positions can be automatically set as required by transducer angle and axle diameter at the point of incidence of the beam. Furthermore, the system should be capable of storing different sets of axle geometry parameters so that it can be easily reconfigured for different axle types.
- Other parameters such as gain, defect threshold level and range of depths in which to process received echoes as cracks must be independently adjustable for each of the transducers. Again, different sets of parameters should be stored for different axle types.
- Since gain calibration is required for each axle, an automatic calibration routine that is executed by the system at the beginning of each inspection would be helpful in cutting down inspection time.

3. Axle inspection system design

Once the axle inspection strategies for solid and hollow axles have been analysed and the corresponding system requirements for both cases are set up, we can go on to system design.

Although the differences between hollow and solid axle inspection make it necessary to design an specific system for each case, the user interface and data processing features of each system are nearly identical, so that it is quite straightforward for a user to switch from solid to hollow axle inspection.

3.1. Solid axle inspection system

The solid axle inspection system (see figure 3) is made up of a transducer-holder tool which positions the transducers against the axle head and rotates them around the axle head during inspection, and a control module, which houses the ultrasound data processing unit and the computer-hosted GUI (Graphic User Interface).

It is a primary requirement for the solid axle inspection system to operate on the mounted axle, so that only the minimum number of parts required to gain access to the axle head need to be disassembled for inspection (namely, the axle-box cover, and the ground contact or speed measurement assemblies, depending on the axle). Precisely, the transducer-holder tool is fixed to the axle head for inspection using the axle-box cover mounting studs (or bolt holes).

Figure 3: Overview of solid axle inspection system, including control unit (foreground, right) and transducer-holder tool mounted on an axle during inspection (background, left).

Since axle-box cover bolt patterns vary for different axle types, the transducer-holder tool is split into a ***main body*** -which holds the ultrasonic transducers, the encoder used to synchronise triggering of the ultrasonic pulses to angular position and the crank and reduction required to rotate the three-transducer assembly around the axle head- and an axle-box ***adapter ring***. In this way, different axle-box bolt patterns corresponding to different axles can be accommodated by just selecting the appropriate adapter ring.

In order to adapt to the different wedge angles required (see table 1), the transducers are mounted on hinged cups (see figure 4), so that they can swivel as needed to guarantee the wedge seats properly on the axle head during inspection. Furthermore, in order to adapt to mechanical tolerances and possible surface irregularities on the axle head the transducer holding cups are mounted on spring loaded rods (see figure 4).

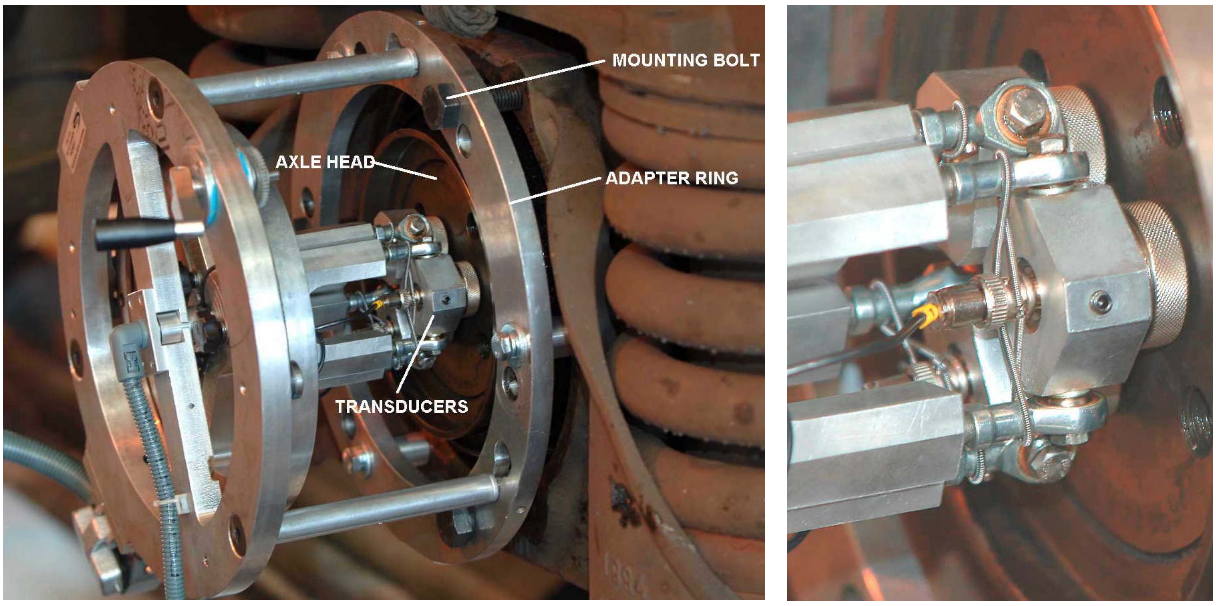

Figure 4: General view of transducer-holder tool mounted on an axle during inspection (left) and detail of articulated transducer holders (right).

The control module triggers the ultrasonic transducers, digitises and processes the returning echo signals, and sends the processed data to the computer hosted GUI, which presents final inspection results in a convenient C-Scan format with echo amplitude represented in false colour vs. axial position along the axle (horizontal axis) and angle of rotation around the axle head (vertical axis, see section 4.1 for samples of results).

Axial position along the axle, *z*, is calculated from measured sound-path, *S*, and transducer incidence angle, α (see table 1) as:

$$z = S \times \cos\alpha$$

Apart from the basic feature of axle inspection, the system software includes auxiliary modules for calibration and management of databases for both axle inspection results and configuration parameter sets for different axle types.

3.2. Hollow axle inspection system

Similarly to the case of solid axles, the hollow axle inspection system includes a mechanical subsystem, that positions the ultrasonic transducers against the axle bore inner surface and performs scanning along the axle bore, and a control module, which houses the ultrasound data processing unit, the electric motor drives and the computer-hosted GUI (Graphic User Interface).

As we mentioned in section 2, the solid axle inspection system is designed to operate on the mounted axle, from within the axle bore, so that only the minimum number of parts required to gain access to the axle bore need to be disassembled for preparation of inspection.

Therefore, the four transducers (see section 2.2) required for hollow axle inspection are mounted on a cylindrical holder attached to a motor driven pole, which performs the axial and angular scan movements of the transducer head. Connection to the axle head is done by a collar flange which bolts directly to the axle head. Transducers are mounted by pairs on spring-loaded shoes that guarantee correct transducer to axle surface contact (see design and photograph of actual transducer holder in figure 5).

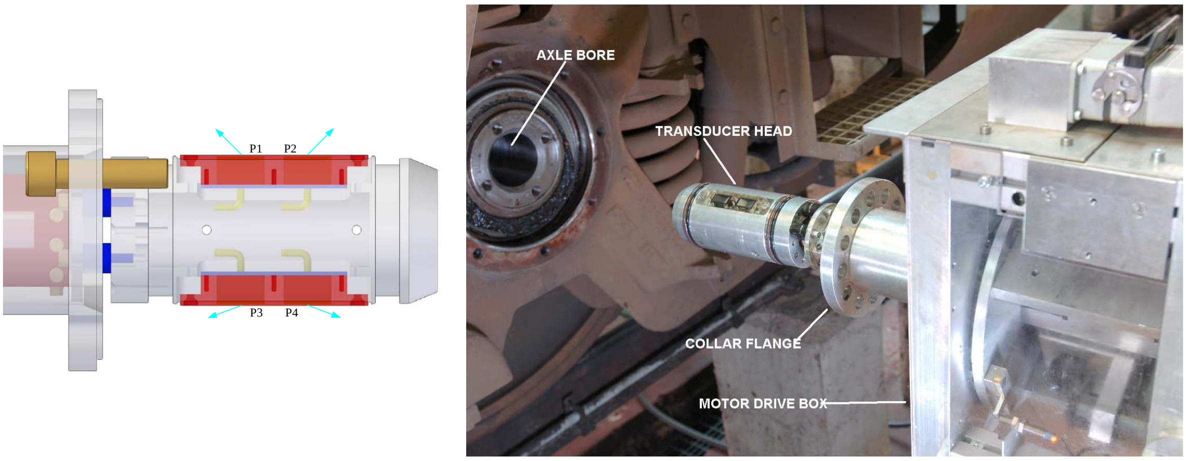

Figure 5: Design of four transducer head tool (left) and actual view of transducer head and collar flange for attachment to axle head (right).

Since axle height over the rails depends on wheel wear, and the system is specified to perform inspections both from the platform, more or less at rail height, and from an inspection pit situated more or less one metre below rail level, the pole-head assembly is mounted on vertical runners and driven by a crane, so that its height can be adjusted in a two metre range.

The complete mechanical subassembly is therefore much larger and heavier than the one used for solid axles. So, instead of being hand-mounted onto the axle head, it is installed on a three wheeled trolley (see figure 6) which includes all the elements described and the oil pump used to feed the SAE40 oil used as couplant to the transducer head.

The control unit is also larger than the one used for solid axle, since it must hold the same ultrasonic processing system and PC hosted GUI plus all the electric drives for the motor-driven pole.

Figure 6: General view of the hollow axle inspection system, with the mechanical subassembly (left) mounted to an axle under inspection. The control unit can be seen to the right.

During inspection, the control module automatically performs all necessary functions without operator intervention including:

- A prelubrication of the axle bore prior to inspection that guarantees good ultrasonic coupling.
- Automatic gain calibration, which is done by aiming the transducers toward the geometric feature specified for the axle, and setting the gain so that the echo amplitude reaches the specified level.
- Axle inspection, scanning the axle bore along parallel axial lines spaced at regular programmed angular intervals and triggering the ultrasonic transducers in synchronism with transducer position.
- Programming of gain and acquisition gates for each transducer as required by axle geometry (see section 2.2.). It must be noted that this is done each time the transducers are triggered.
- Acquisition and processing of the returned echo signals.
- Presentation of final inspection results.

Inspection results are presented in a convenient C-Scan format with echo amplitude represented in false colour vs. axial position along the axle (horizontal axis) and angle of rotation around the axle (vertical axis, see section 4.2 for samples of results).

Axial position along the axle, z, is calculated from measured sound-path, S, transducer incidence angle, α (±45º or ±70º), transducer head along the axle (z_H, measured by the axial motor encoder) as:

$$z = z_H + z_{HT} + S \times \text{sen}\,\alpha$$

where z_{HT} is the offset of the transducer emission point relative to centre of transducer head.

Apart from the basic feature of axle inspection, the system software includes auxiliary modules for calibration and management of databases for both axle inspection results and configuration parameter sets for different axle types.

3.3. Automatic assessment tools

As we mentioned in section 2, for both hollow and solid axles, inspection should focus on the detection of cracks originating on the outer axle surface, and propagating both along the axle circumference and inward toward the axle core. It must be noted that the ultrasonic echoes coming from these cracks cannot be told apart from those coming from axle-specific geometric features (such as corners, fillets and chamfers between different diameter zones), except for the latter occurring always at fixed locations along the axle.

So, simple application of a fixed threshold level to all received echoes would yield a number of false alarms for every axle inspected, with the operator having to verify if these echoes correspond to expected axle geometric features or actual cracks.

In both axle inspection systems, this problem has been addressed by adding to the inspection parameters for each axle type a set of user-defined no-process areas, so that above threshold echoes in these areas are not identified as cracks.

In this way, the expected axle-specific geometric features can be included within these no-process areas, so that they are not identified as cracks and false alarms are avoided.

These no-process areas can be defined by the user either numerically (by defining axial start and end coordinates) or graphically upon a C-Scan of a reference axle using the calibration tools.

4. Experimental results

Both inspection systems were tested against reference axles with machined artificial cracks, in order to test their crack detection abilities and set up inspection parameter sets for different axles, and then on actual mounted axles, to test system performance in real-life operation. Some sample results are presented in what follows.

4.1. Results for solid axle inspection

The reference axle used in the preliminary tests of the solid axle inspection system was a S/269.200 locomotive type with three artificial machined cracks in the reduction gear seat and the axle journal:

- Crack #1: crack in axle journal, 12x1mm.

- Crack #2: crack in reduction gear seat, 16x1mm.
- Crack #3: crack in reduction gear seat, 28x2mm.

The general inspection results for this reference axle are shown in figure 7, with each of the detected cracks marked on the C-Scan representation.

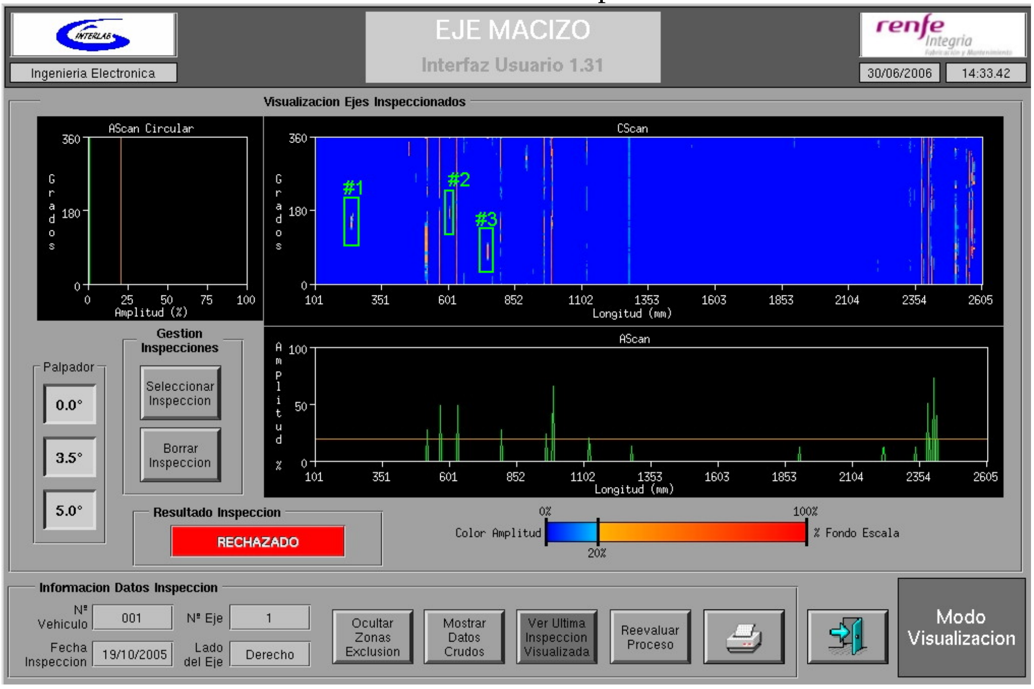

Figure 7: Inspection results for the solid axle inspection system with three artificial cracks

In figure 8 we show in detail inspection results restricted to reduction gear seat (thereby, only data for the transducer with the 5º wedge are shown, see table 1). Along with echoes from cracks #2 and #3, we can see the echoes from the five grooves in the reduction seat, and a strong echo from the end of the reduction area.

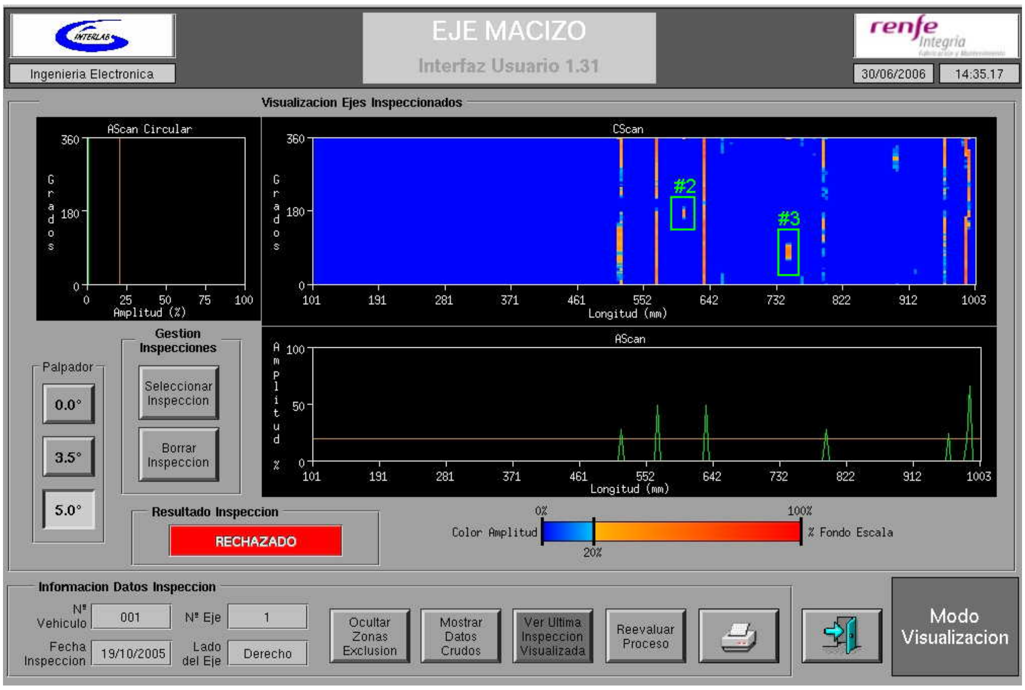

Figure 8: Detail of inspection results for the reduction gear seat in a 269.200 solid axle with a 5º wedge.

4.2. Results for hollow axle inspection

The reference axle used in the preliminary tests of the solid axle inspection system was a S/252 locomotive type with two artificial machined cracks in the axle body area:

- Crack #1: 30x2mm.
- Crack #2: 20x1mm.

In figure 9 we show the general results for the ±45º transducers (in [10] it is specified that inspection of hollow axles should rely basically on the 45º transducers, with the 70º ones used only in case of doubt).

Apart from the two crack echoes, three echoes coming from axle geometric features (see G1, G2 and G3 in figure 9) are present in the C-Scan.

It should also be noted that the echo from the edge of the axle, at the axial origin of the C-Scan, is interrupted at 90º regular intervals, due to the presence of the four M16 holes in the axle head (these can be seen in figure 5).

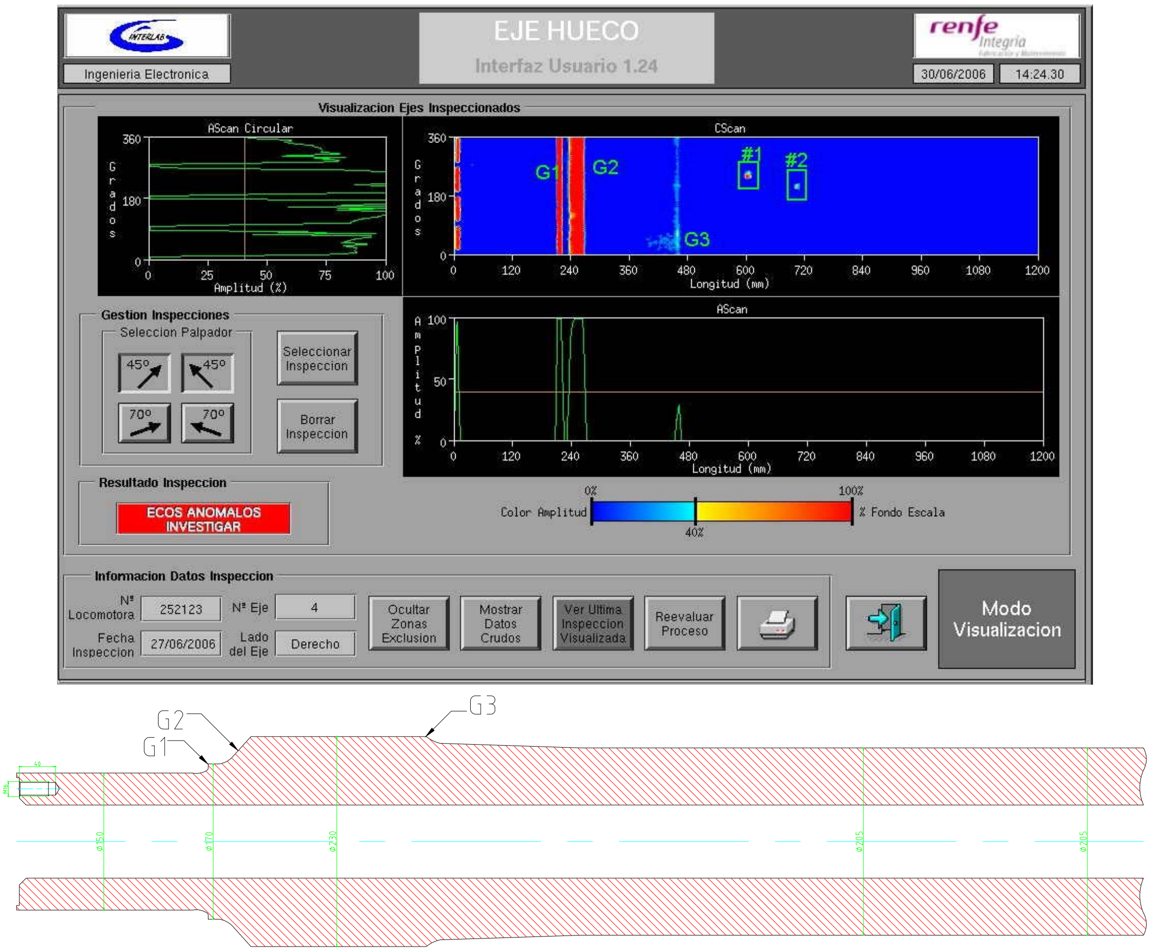

Figure 9: Inspection results for type 252 reference axle (above), and diagram of the same axle, showing the geometric features producing echoes (below).

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