Experimental investigation by Laser Ultrasonics for train wheelset flaw detection

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Abstract. The transport safety is a key factor in the rail field and to ensure it the monitoring of train components structural integrity must be performed regularly and following strict regulations. Consequently, the development of Non-Destructive Testing (NDT) procedures is a topic of great interest and impact, aiming at the early identification of cracks and inhomogeneities on train axle and wheels which propagation can cause faults and accidents undermining the passenger and crew safety. Ultrasound based nondestructive testing is currently applied in ordinary maintenance procedures, although they are applied to axle and wheels dismounted from the train wheelset. In fact, the technique requires ultrasonic probes to be in contact with the object under test and therefore the fretting surface between wheel and axle, where fatigue phenomenon induces cracks nucleation and propagation, cannot be monitored. The possibility of applying NDT systems to the whole wheelset, without dismounting it in its components, will allow drastically reducing the inspection time and increasing the inspection frequency. The present paper proposes a feasibility study for the development of a Laser-Ultrasonic Testing (LUT) procedure to improve performances of train wheelset ultrasonic inspection. The method exploits one or an array of air-coupled ultrasonic probes, which detects ultrasonic waves generated by a high-energy pulsed laser. Thanks to the non-contact nature of both the response measurement sensor and the excitation system, the experimental set-up is extremely flexible and it allows extremely speeding up the inspection time.

Keywords: Train wheelset diagnostics, NDT, air-coupled ultrasound, Laser Ultrasonics.

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1. Introduction
In the last few years, the demand for new non-contact systems for remote control of the structural integrity of the main train components related to the safety of the exercise, such as axles, wheels and tracks, is growing. The procedures based on NDT methods are constantly evolving to meet the European standards
EN 15313 \cite{1} and the directives of the National Agency for Safety of Railways (ANSF) dictating the regulation for the safety of railway traffic.

The axles and wheels are often the main responsible for breakdowns and accidents, being the most stressed in both static and dynamic conditions. In particular, the wheels are subjected to high loads caused by wheel-rail contact \cite{2}, leading to the generation and propagation of different types of defects, Figure 1 \cite{1}.

At the state of the art, manual ultrasound techniques are used for the detection of radial defects, through the use of eight double angled probes (settled in the so-called “Tandem” arrangement) and distributed along a circumference, \cite{3}. Being those techniques manual, the occurrence of human error is extremely likely. Automated systems equipped with phased arrays \cite{4} are currently unattractive, given the high costs associated with the acquisition of instrumentation and the adaptation of test benches to these systems. The main disadvantages of phased arrays are:

- difficult adaptation to different wheel profiles (Velaro, TGV, Shinkansen, Bombardier etc.),
- encumbrance that limits their integration into the system for the monitoring of the wheelset while the train is moving,
- complexity of the measurement set-up and in particular of the system for the accumulation, injection and recovery of the coupling means, necessary in the application of contact probes.

![Figure 1. Typical morphology of railway wheel defects.](image)

To overcome these problems, LUT systems have been developed which, by applying high power laser sources and air receiving probes, represent completely non-contact techniques, flexible in installation and configuration. Air-coupled ultrasound inspection has already been successfully used in many industrial
applications e.g. NDT on curved composites elements [5], NDT on light thin historical vaults [6], density measurement of ceramic tiles [7], NDT on thin metallic laminated [8, 9], etc.. In [10] and [11] a LUT procedure has been defined for the inspection of railway components, axles and wheels respectively. A FE model has been also developed to compute the ultrasound wave propagation in thermoelastic regime and allowing to guide the design of the experimental set-up and the analysis of the results. It has been shown that it is possible to work with low energy waves in the thermoelastic-ablative limit maintaining a satisfactory contrast level for the detection of the defect. However, at present LUT methods have been only applied to dismounted wheelset, i.e. for the monitoring of axles and wheels separately. This is due to the fact that the energy of the ultrasound waves travelling into the axle is strongly attenuated when passing through discontinuities such as the fretting region between axle and wheel. Since that region is the one in which there is the greatest probability of presence of defects, in order to ensure an accurate inspection the wheel dismounting from the axle is required.

In this paper, following the indication of a previous work [12], demonstrating by a numerical model that a high power laser is able to generate ultrasound wave sufficiently energetic to propagate across the fretting region, LUT has been applied to a whole wheelset and its suitability has been confirmed by the experimental results.

2. The wheelset and experimental set-up

2.1 The tested wheelset
Trenitalia provided a train wheelset (Figure 2) in whose axle two typical fatigue cracks were simulated, see Figure 3:
- Defect A located on the axle surface at XX mm from the fretting region,
- Defect B located on the fitting region between the axle and the wheel.
2.2 Experimental set-up

The train wheelset was mounted on a support that made it possible to control its rotation, in order to be able to scan the axle surface along a circumference. The probes were installed on a frame where they could move along the axial direction. Therefore, the complete lateral surface of the axle could be inspected by the laser ultrasonic system, see Figure 4.

The laser ultrasonic system was made up of a pulsed laser source, a Nd-Yag IR laser (1064 nm), pulses of 12 ns duration and 82 mJ energy, from Continuum, and a 500 kHz air-coupled ultrasound piezoelectric probe from Ultran Group (model NCT210, with 20 mm diameter of active area). The probe was inclined with respect the normal to the axle surface of 33 deg, as shown in Figure 5 and Figure 6. This angle has been determined from a numerical analysis of the ultrasonic wave propagation from the generation point, where the laser impinges the axle, through the material and the air gap between the axle surface and the receiving probe [10]. The ultrasound probe conditioning system was a DPR 300 Pulser/Receiver from JSR Ultrasonics. The ultrasound signals were amplified with a gain level of 69 dB and acquired with a high speed Digitizer board NI PXI-5122 (100 MHz bandwidth). The laser beam was guided towards the axle under test by means of an arm connected to the pulsed laser cavity as shown in Figure 4.

Data were collected by sampling at 100 MSamples/s and performing 4 averages on each measurement point in order to improve the Signal to Noise Ratio (SNR).
The laser ultrasonic system was installed with the laser source and receiving probe far apart, on opposite sides with respect to the wheel, as shown in Figure 4. A collimated laser beam with a diameter of about 8.5 mm was used to keep the ultrasonic waves generation within a thermo-elastic regime [13].

The axle was made to rotate by an electric motor and the rotation angle was measured by an integrated encoder. A circumferential scan was performed along an angle of 63 deg with an angular resolution of 1.5 deg.

3. Results

For each configuration, a series of ultrasound time histories with a duration of 180 μs was acquired at every scanning position along the arc considered. The experimental set-up (i.e. laser and probe positions), the axle section tested and the defect location are shown in the subplot (a) of Figure 5 and Figure 6 for defect A and B respectively. The subplot (b) of each figure reports a close-up around the excitation position and the damaged area. In the draw it is also sketched the path of the ultrasound waves travelling into the material once generated by the laser pulse impinging onto the axle surface. The time history acquired in the first angular scanning position is plotted in the subplot (c). Subplot (e) illustrates the time histories at two angular positions located within and outside the damaged region. As far as it concerns the defect A, it is evident that the presence of the defect acts as a filter for the bulk wave Figure 5 (b). This is confirmed also by the B-scan reported in Figure 5 (d) where the extension of the cracks is clearly visible. Observing the time history close-up around the bulk waves and the B-scan recorded for defect B, Figure 6 (e) and (d) respectively, it can be noticed that part of the bulk waves are transmitted even in presence of the defect and specifically the fastest one. This can be explained by the fact that the defect located in the fitting region between wheel and axle does not hinder the passage to all the ultrasound waves. As it is sketched in the scheme of Figure 6 (b), the direct bulk wave (solid blue arrow in the sketch), the fastest
one, passes undisturbed by the defect, while the scattered waves (dashed blue arrow in the sketch) are reflected backwards.

Figure 5. Experimental set-up scheme (a), time history (b), B-scan (c) and time history close-up on the bulk waves (d) - Defect A.
Figure 6. Experimental set-up scheme (a), time history (b), B-scan (c) and time history close-up on the bulk waves (d) - Defect B.

The RMS plots over the time axis (abscissa) of the B-scans has been calculated for defect A on a time window between 90 and 120 μs and for defect B on a time window between 102 and 115 μs in order to cut the signal related to the direct wave which is insensitive to the presence of the defect. Table 1 shows the RMS plots and the contrast between the RMS in the damaged and in the undamaged areas, which can be
seen as a damage index. That index was calculated considering the minimum values of the RMS (in the damaged area) and the floor values RMS (in the undamaged area). Both the defects exhibit a high contrast.

4. Conclusions
The paper demonstrates the applicability of the LUT based on ultrasonic waves generation by pulsed laser and air coupled ultrasound probes for damage identification on train wheelset. The technique has been applied to a wheelset provided by Trenitalia where typical fatigue defects have been created in region where those defects frequently occur. Several works have demonstrated the power of such technique for the diagnostic of train axle and wheel. The standard practice for the defect identification in rail industry is based on ultrasound methods. However both the ultrasound based NDT technique and the LUT requires dismounting the wheel from the axle when performing the test. This is due to the fact that the ultrasonic wave is strongly attenuated when passing through the fretting area between axle and wheel. By optimizing the laser energy of the impinging pulse generating the ultrasonic wave and the position of the detecting probe collecting the wave transmitted through the material and the air, it has been demonstrated that the LUT can be applied also to the whole wheelset and that the resulting signal exhibits a very good contrast (a RMS contrast of 11.3 dB for defect A and 12.1 dB for defect B) allowing to clearly identify the defect position.

The good results achieved with the experimental procedure proposed in this paper incentivize the authors to develop a dedicated FE numerical model to optimize the measurement procedure with the aim to prove its suitability for the remote inspection of railway axles in service.

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