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A Preliminary Analysis about the Application of Acoustic Emission and low Frequency Vibration Methods to the Structural Health Monitoring of Railway Axles

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Railway axles are safety-critical components whose failure could result in large additional costs for the infrastructure manager and the railway operator and, in most serious cases, even lead to unacceptable human losses. For this reason, they are periodically inspected by means of non-destructive techniques usually requiring expensive service interruptions. Considering the special case of solid axles for freight cars, this paper investigates the feasibility to apply two structural health monitoring (SHM) techniques to increase vehicle safety and reliability and, at the same time, to decrease the costs of damage inspection. In particular, the considered SHM techniques are Acoustic Emission and the measurement of low frequency vibrations. In the present paper, some preliminary results about the application of both these SHM techniques to freight railway axles are introduced and discussed.

1. Introduction

Railway axles are safety-critical components designed against fatigue limit, as defined in relevant standards like EN13261 (2011), EN13103 (2012) and EN13104 (2011). Actually, due to their very long service life, they are prone to service damages, like impacts due to the ballast or corrosive aggression. These events are able to initiate fatigue cracks leading to service failures, whose effects entail large additional costs for the infrastructure manager and the railway operator and, in the most serious cases, may be cause of serious accidents and even lead to unacceptable human losses. For this reason, in the framework of a damage tolerant approach for maintaining structural integrity, as generally defined by Grandt (2004) or specifically for axles by Carboni and Beretta (2007), railway axles are periodically inspected by means of well-established non-destructive techniques (typically ultrasonic and magnetic particle inspections) usually requiring expensive service interruptions. Considering the special case of solid axles made of A4T steel grade, this paper investigates the feasibility to apply structural health monitoring (SHM) techniques which, in the aeronautical field, have shown, according to Chang (1999) the possibility to decrease the costs of damage inspection up to 30 % without losing accuracy.
Among the several existing SHM techniques, the present study focuses on the application, to railway axles, of Acoustic Emission (AE) and on the measurement of low frequency vibrations (LFV). In particular, the chosen techniques were applied to a full-scale axle during a crack propagation test with the aim to analyse the influence of deep-rolling. It is worth noting that, due to the very high complexity of the activity, the complete crack propagation test is expected to take a very long time and, actually, it is still running while this manuscript is being prepared, so that only preliminary conclusions can be drawn on the applicability of the methods proposed hereafter, based on the available experimental results. The preliminary results of the research are then described in the following sections.

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2. Structural Health Monitoring techniques for railway axles

The number of SHM techniques available in the literature and likely applicable to the detection of cracks in railway axles is rather large. Among all of them, the present study focuses on acoustic emission and low frequency vibrations, as they are the ones whose equipment seems to be the less invasive and bulky, a very important and critical characteristic considering the configuration of real axles mounted on real trains. A short description of the basic ideas and concepts lying at the base of the chosen techniques is given in the following.

2.1 Acoustic emission (AE)

AE SHM is based on the observation that damage developing in a material releases energy in form of ultrasonic elastic waves which could be fruitfully detected (Grosse and Ohtsu, 2008). These waves (so-called "events") are typically short and transient with bandwidth in the 100-1000 kHz range, which makes AE quite robust against audible noise and structural vibrations. Traditionally, the so-called "parametric AE" is used, in which the transient waveforms are stored for the calculation of some well-established parameters (like peak amplitude, duration, energy). These parameters are then stored and used for further processing, while the full waveforms are generally deleted to avoid the need of undesirably large storage systems.

AE is traditionally used and standardized as a non-destructive technique to assess the structural integrity of metallic components (e.g. pressure vessels and pipelines) under static and fatigue loading (Huang et al.,1998), but with only few applications in the railway field, as by Jiang et al. (2005).

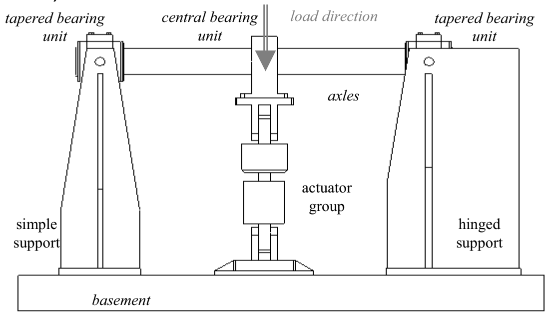
2.2 Low frequency vibration (LFV)

LFV is based on the measure of harmonic components in the axle bending vibration having periodicity which is an integer sub-multiple of the revolution period. These vibrations are induced by the "crack-breathing" mechanism and by asymmetry in the bending inertia of the axle, as produced by a propagating crack. The advantage of this second method consists in the possibility to use low-frequency vibration, hence using simple, robust and inexpensive transducers. This method was initially proposed for crack detection in the shaft of turbo-machinery (Pennacchi et al., 2006), and was demonstrated to provide reliable results for this kind of application based on experiments performed on a laboratory test rig. Crack detection and localisation is performed by representing the crack as an equivalent excitation, produced by a bending moment having nxRev periodicity applied on a short section of the shaft. Then, an inverse problem is solved in the frequency domain to derive the most probable location and amplitude of the equivalent excitation. The latter is then translated into a guess of the crack amplitude based on look-up tables defined using a finite element model of the cracked axle. Aim of this research is to assess the possibility to extend this method to crack detection in railway axles, considering some additional difficulties that are posed by this specific application, namely: i) effect of disturbance produced by wheel-rail contact (in particular, wheel out of roundness is also cause of nxRev vibration of the axle, so this effect needs to be depurated) ii) limited number of measuring sections available in the railway axle iii) in the railway application, the angular speed of the axle is changing according to a more complicate profile, whereas in a turbo-machine run-up and run-down measurements can be applied for identification purposes, iv) in turbo-machines, the method is typically applied to rotors running at high speed, above the first critical, whereas the railway axle is running at speeds much lower than the first critical.

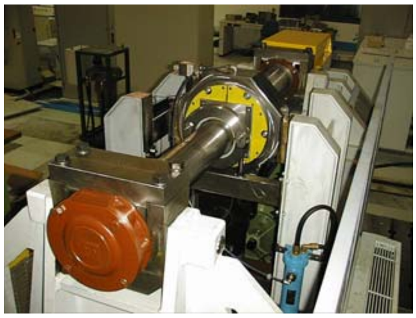
3. Experimental set-up

The experimental full-scale tests were carried out by means of the "Dynamic Test Bench for Railway Axles" (BDA) available at the labs of the Department of Mechanical Engineering at Politecnico di Milano. The BDA is fully compliant with the relevant standards on the qualification of axles - EN13261 (2011), EN13103 (2012) and EN13104 (2011) and the test procedure and results are Quality Certified ISO9001 since 2003. Figure 1 shows the static scheme and a view of the BDA. In particular, a three point rotating bending is applied to the full-scale specimen via an actuator group and an electric engine: in this way, both constant amplitude and block loading fatigue or crack propagation tests can be carried out as explained by Beretta et al. (2011).

The preliminary analysis of the feasibility of AE and LFV for SHM of axles was carried out considering the special case of cold-rolled solid axles made of A4T steel grade according to EN13261 (2011). The drawing of the full-scale specimen is shown in Figure 2. Two starting notches, located at 180° one from the other and useful for initiating two independent fatigue cracks in the section of interest of the axle, were introduced by electro-discharge machining (EDM) in the cold-rolled cylindrical part of the axle and have a semi-circular shape with radius R = 4 mm. The full-scale specimen was subjected to a block loading sequence experimentally derived from the typical service spectra of a tilting train on European lines. More details about the experimental set-up for the full-scale crack propagation test are reported by Regazzi et al. (2012).



(a)



(b)

Figure 1: Dynamic Test Bench for Railway Axles: a) static scheme; b) view of the test bench

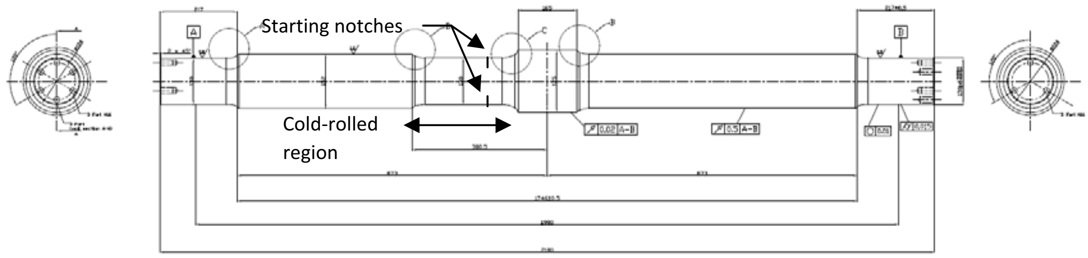


Figure 2: Drawing of the adopted full-scale specimen

AE and LFV were acquired to monitor damage development during the application of multiple repetitions of the block loading sequence. In particular, AE was applied at one free end of the axle (Figure 3) using a custom made carter (Figure 4) designed to hold in position the sensor and its pre-amplifier. The rotating group is then connected to a sliding contact to bring the signals to the AE acquisition system (Vallen AMSY-5). The custom carter allows the positioning of the sensor without removing the whole assembly, with the aid of a thin sheet metal part. The sensor is then coupled to the axle with grease, to avoid the formation of air bubbles (which will attenuate the signals). The assembly is then checked regularly to ensure that the grease has not deteriorated or moved away.

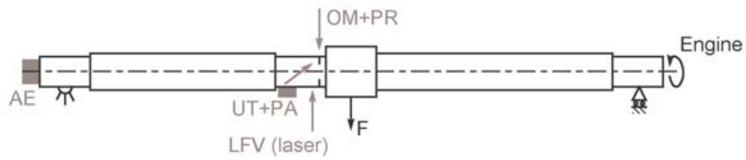
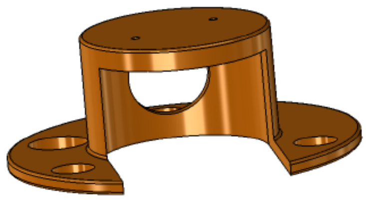


Figure 3: SHM and NDT techniques applied during the full-scale crack propagation test



(a)

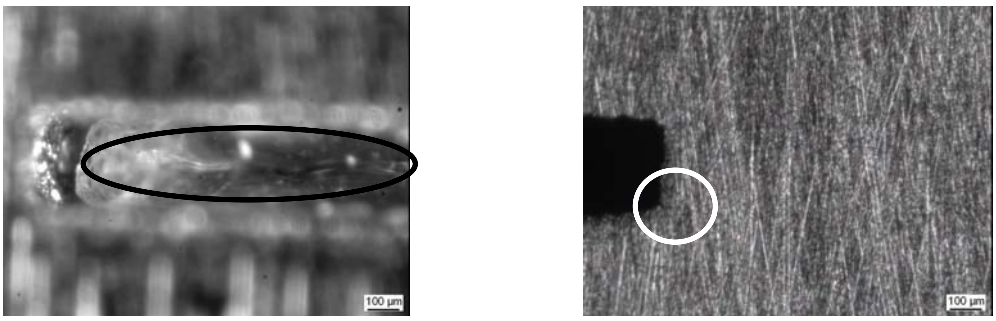
(b)

Figure 4: Custom made carter to hold the sensor and the preamplifier: a) CAD model; b) application at the axle end

The use of a single AE sensor does not allow the localization of signals, due to test bench issues. In a real world application, the use of two sensors (one at each axle end) would allow to localize the signals along the axle axis, by means of a “time of arrival” algorithm.
A calibration of the AE system was performed according to the standard pencil lead break test (ASTM E976): the signal attenuation along the axle found to be negligible. Acquisition was run throughout the entire test, setting the noise threshold at 55 dB after one minute of rotation without any load application, to filter noise.
LFV was, instead, applied via a laser pointing to the central region of the axle, close to the starting notches (Figure 3), so to get the highest displacements due to the applied loads.
Crack propagation in a cold-rolled axle is a quite complicate problem because the rolled surface is subjected to a compressive residual stress field, while underneath, mild tensile residual stresses should be expected. It is then reasonable to expect that, at least in the first stage of the test, the crack is going to initiate and propagate at the deepest point of the notches, while it is going to initiate later on at the surface due to the lower driving force. Moreover, the surface compressive stresses are also expected to make the surface detectability of growing cracks harder as they tend to close them.
Considering the just described difficulties and with the aim to have a feedback on crack propagation to evaluate the efficiency of the applied SHM techniques, other NDT methodologies were applied at test interruptions between the repetitions of the block loading sequence. In particular, the surface region around the starting notches was inspected (Figure 3) by an optical microscope (OM) and the application of plastic replicas (PR). The possible under-skin crack growing was, instead, monitored (Figure 3) by traditional ultrasonic testing (UT) and by ultrasonic phased array testing (PA).

4. Preliminary results

At the time the present manuscript is being prepared, 16 repetitions of the block loading sequence have been applied to the full-scale specimen, just allowing to draw the preliminary results. At first, the actual initiation of fatigue cracks was checked in order to be sure the fatigue cycles applied so far were enough to start it. Figure 5 shows two examples of OM pictures taken at a deep point of one of the starting notches after 14 repetitions of the block loadings (Figure 5a) and at the surface of one of the surface edges after 14 repetitions of the block loadings (Figure 5b). In the latter case, the observation was supported also by PR. As expected, the deep crack seems to be more evident than the surface one, and this situation could be observed for both the starting notches.
The estimation of the dimensions of the whole defects (starting notches plus fatigue initiations) was carried out by UT and PA. Both the techniques seemed to suggest that the fatigue part of the defects still is very small, as both the gain by UT and the estimation by PA show a nearly constant trend.
A typical result of the AE acquisition is shown in Figure 6. It can be clearly noticed that there is a correlation between the amplitude of events and the load. The cumulate AE activity (Figure 7) indicate that during the load cycles with low levels of load applied the AE activity is low and almost constant, whereas during the higher load cycles it increases significantly. It has to be noted also that the activity is globally very low during most of the time, with events of moderate amplitude.



(a) (b)

Figure 5: Optical microscopy of fatigue cracks: a) deep region; b) surface

By separating the AE data at different load levels (Figure 8), it can be seen that after the first eight repetitions the AE data show few activity at low load levels, while the higher levels show an increasing trend. It has to be noted that since the crack propagation is of low entity so far, the present activity can be considered as a baseline for the detection of AE activity related to more consistent crack propagation.

As far as the preliminary results of the LFV technique are concerned, due to space limitations it is only possible to mention that the bending vibration signal measured by the laser transducer (Figure 3) clearly shows the presence of dominant contributions at 1xRev, 2xRev, 3xRev and 7xRev frequencies. These are due to the combined effect of axle out-of roundness and the presence of the cracks. Comparing measurements taken in the starting phase of the fatigue test and after repetition of 8 and 16 block loading sequences, an increasing trend is observed for some NxRev components, especially the 2xRev and 3xRev ones. This could be related to an increase in the size of the cracks, but needs to be confirmed by further investigation. Finite element modelling of the axle is now on-going to relate these results with the amplitude of the cracks as detected by OM, PR, UT and PA.

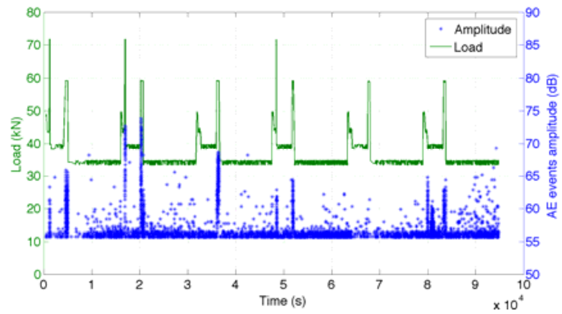


Figure 6: Acoustic Emission events during a test

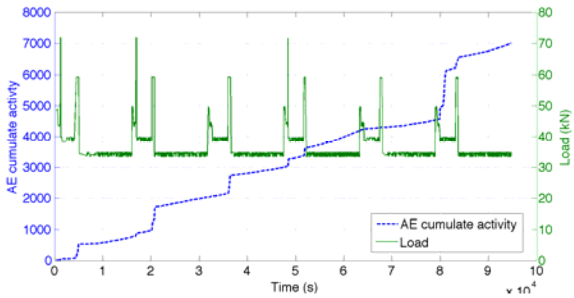


Figure 7: Acoustic Emission cumulate activity

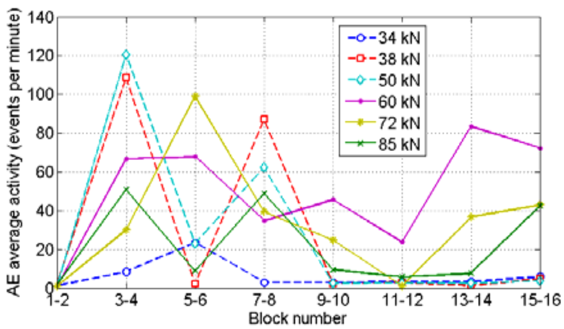


Figure 8: Acoustic Emission activity at different load levels

5. Concluding remarks

The paper proposed the possible application of two different SHM methods, acoustic emission AE and low frequency vibration LFV, to detect the presence of a crack in a freight railway axle, and possibly to locate the crack along the axle and to estimate the size of the crack.

A full scale fatigue tests performed on a railway axle was used to preliminarily assess the effectiveness of the two proposed SHM approaches. At the time when this paper is written, the test is still on-going;

nevertheless, preliminary results are encouraging and show the potential of both methods to represent viable approaches to crack monitoring in railway axles.

In more detail, the amplitude of Acoustic Emission events is well correlated with the load applied on the axle and the high AE activity observed in the initial phase of the fatigue test can be explained by crack initiation. Work is ongoing to further investigate how AE events correlate to crack propagation.

For the LFV technique, vibration measurements taken on the axle under test show the presence of dominant NxRev harmonic components. particularly important in this regard is the 2xRev component, whose amplitude is increasing with the accumulation of block loading sequences, and thus could be related to an increase in the size of the cracks.

Future developments of this work will be aimed firstly to derive a more comprehensive set of conclusions based on the completion of the on-going test and on repeating the test on other pre-cracked axles. In case the applicability of one or both methods to crack detection will be confirmed, the research will then aim at solving problems related with transferring the crack detection SHM system from the laboratory to the in-service application.

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