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Numerical study for a new methodology of flaws detection in train axles

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ABSTRACT

Train loads and travel speeds have increased over time, requiring more efficient non-destructive inspection methods. Railway axles are critical elements; despite being designed to last more than 20 years several cases of premature failure have been recorded. Train axles are inspected regularly, but the limits associated to the traditional inspection technologies create a growing interest towards new solutions. Here a novel non-destructive inspection method of in-service axles based on non-contact data collection is presented. The propagation of surface waves, generated by a thermo-elastic laser source, is investigated using a finite element method based on dynamic explicit integration. Coupled thermo-mechanical simulations allow visualization of the ultrasonic field guiding the definition of the optimal NDT setup. The geometry of the axle and of the elements mounted on it is accurately reproduced; moreover the press fit effect caused by the wheel and the bearing rings is implemented. The current NDT techniques for railway axles require removing wheels and other components from the axle. The presented scheme uses non-contact ultrasonic generation and detection allowing non-contact in-service inspection of railway axles at trackside station. The numerical results are promising and encourage us to test the new approach experimentally.

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1. Introduction

The defects affecting the railway components can be caused by various mechanisms such as fatigue, stress corrosion cracking, high temperature creep, or combinations of these mechanisms [1]. The common mechanism for railway axles is fatigue. Fatigue cracks, usually originate from a sub-critical bulk or surface imperfection and grow along the transversal section of the axle. Fractures in the body of the axles (Fig. 1) are reported [2], however fatigue cracks frequently initiate in the press fitted parts (Figs. 1 and 3) of the axles by fretting fatigue. Typical sites for those cracks are the wheel seat (i.e. part of the axle where the wheel bore is mounted on) and the journal (i.e. part of the axle that rotates against two bearings). In addition to the press seat areas, fatigue initiation may occur at other locations such as the transition region between two diameters beside the wheel seat (Fig. 1), where the transition radius is of crucial importance to stress concentration considerations. Typically a crack starts as a semi-elliptical or semi-circular surface defect and grows along the transversal section inside the volume.

Railway axles are designed for infinite life. However, a small number of axle failures still occurs, often with tragic consequences. The main non-destructive techniques (NDT) applied over the years to inspect railway axles are liquid penetrant testing, eddy current, magnetic particle inspection and ultrasonic testing [1,3].

During regular inspections, axles remain mounted on the bogie (i.e. the chassis or framework attached to the railway wagon, serving as a modular subassembly of axles and wheels). During bogie check-ups and general inspections, axles are dismounted and the wheels are removed from the wheel seats. Exceptions are the gear seats of the driving axles and the break disk seats of the trailing axles, which are kept fixed and inspected by the near end-low angle beam ultrasonic technique.

Since these inspections are performed in workshops, they are time consuming. Moreover the dismantling required for axle inspections can produce scratching damage and facilitate fatigue initiation [1]. Developments in fatigue fracture mechanics [2] permitted the progress of many statistical techniques that reduce the maintenance costs through the calculation of reliable inspection frequencies [4,5].

In the case of railway axles, fatigue cracks usually grow to a considerable size before fracture; the consequence is that it is more important to find relatively large cracks with sufficient reliability than very small defects less reliably [6]. Despite of the existence of regular inspections the unexpected failure of railway axles still occurs. New NDT approaches are deemed necessary to overcome the limits of current techniques.

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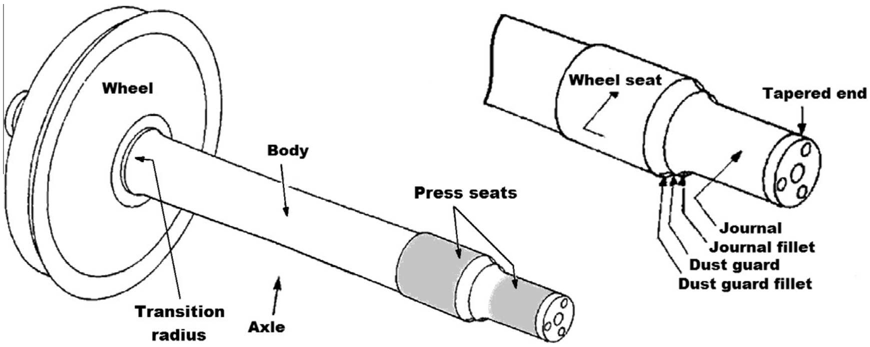

Fig. 1. Train axle geometry [15].

Proof of concept demonstrations using a laser-air ultrasonic technique for remote detection of railroad cracks is described in [7–9]. The current paper uses a numerical method based on explicit integration, already used in previous works [10–12], to investigate a new approach that could be developed for a non-contact in-service inspection of railway axles at trackside. The attention is focused on the axle terminal part, the region between the wheel seat and the axle journal, where it is more difficult to detect flaws through traditional methods.

2. Inspection configuration and numerical method

Axle design guides have begun to converge worldwide during the last 20 years. Europe has adopted common standards, EN 13103:2001 [13] and EN 13104:2001 [14], for trailing and powered axles respectively. The new design, named "raised-wheel seat" because the diameter of the wheel seat is greater than the diameter of the axle body, is shown in Fig. 1 [15]. The geometry of a European axle [13] was considered for the model of this work. The physical parameters of the steel are presented in Table 1.

A fatigue crack is generally initiated from surface defects or internal inclusions [16] that become larger and propagate along a transversal section of the axle, as shown in Fig. 2a and b. During the growth of a crack, its geometry changes; its depth to surface length ratio a/c changes with increasing aspect ratio a/D. Its basic shape stays semi-elliptical as showed in a number of papers [16–19].

Table 1
Physical parameters of steel used for the model.

ρ	Mass density	7900 (kg/m$^{3)}$
E	Young's modulus	210 (GPa)
v	Poisson's ratio	0.291
α	Expansion coefficient	1.07 (10^{-5} °C^{-1})
C	Specific heat	480 (J/kg °C)
T_f	Melting temperature	1810 (K)
K	Thermal conductivity	50 (W m^{-1}K^{-1})
$k = K/\rho C$	Thermal diffusivity	3.95×10^{-6} (m^{2}s^{-1})

Because most fatigue cracks are generated by superficial flaws, surface waves are deemed to be a promising new NDT technique for inspecting railroad axles. For a reliable simulation of the surface wave propagation, wheel and inner bearing rings (Fig. 3) were considered in the geometry, mounted on the axle with proper contact pressures.

Previous works [10–12] demonstrate that an explicit dynamic analysis together with the use of diagonal element mass matrices is computationally more efficient than the implicit integration rule. This is true for the analysis of large models with relatively short dynamic response times, as it is the case for ultrasound wave propagation problems with frequencies in the MHz range travelling in relatively large bodies. The same approach was adopted in this work; the main steps of the numerical technique are recalled in the following lines. Simulations of laser generated ultrasound waves require a coupled thermal-stress analysis. Here we used a fully coupled thermal-stress analysis where the mechanical solution response is obtained using an explicit central-difference integration rule, and the heat transfer equations are integrated using an explicit forward-difference time integration rule. The mechanical solution response is based upon the implementation of an explicit integration rule together with the use of diagonal element mass matrices. The equation of motion at a specific instant of time is:

$$[M]\{\ddot{d}\}_n + [C]\{\dot{d}\}_n + [K]\{d\}_n = \{F\}_n \tag{1}$$

where the subscript n marks the time increment number, $[M]$ is the mass matrix, $[C]$ is the damping matrix, $[K]$ is the stiffness matrix, $\{F\}$ is the external load vector, and $\{d\}$ is the displacements vector. In the explicit method:

$$\{d\}_{n+1} = f\left(\{d\}_n, \{\dot{d}\}_n, \{\ddot{d}\}_n, \{d\}_{n-1}, \dots\right) \tag{2}$$

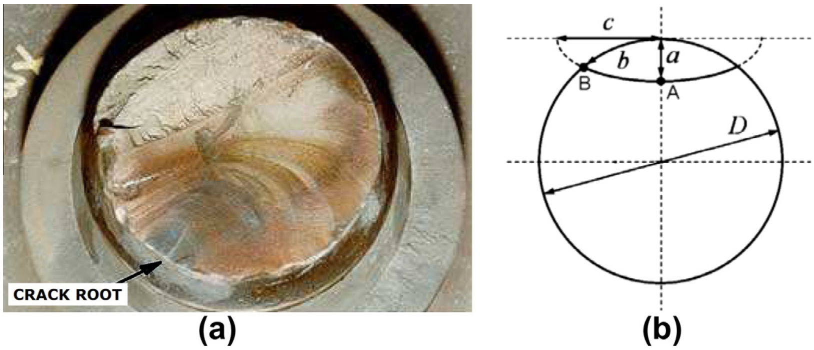

Fig. 2. Example of fatigue crack and failure in the area between the journal and the wheel seat (a); crack model (b) [16].

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