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Condition monitoring of railway axles based on low frequency vibrations

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ABSTRACT

Railway axles are safety–critical components and their structural integrity needs to be properly monitored against potentially catastrophic failures. This paper proposes a method for the continuous condition monitoring of railway axles by measuring the axle in-service bending vibration and diagnosing the presence of a fatigue crack based on the examination of harmonic components with periodicity corresponding to an integer sub-multiple of the axle revolution period (*n*xRev).

To analyse the feasibility of the proposed method, full-scale measurements were performed on cracked and non-cracked railway axles undergoing fatigue tests and a mathematical Finite Element (FE) model of a cracked railway axle was defined and used to reproduce the laboratory experiments and also to analyse the case of a railway wheelset with cracked axle rolling on a railway track.

The results of both experimental and numerical investigations show that the 1xRev, 2xRev and 3xRev components of axle bending vibration can be used to detect the presence of cracks in axles, provided the crack area is in the range of 16% of axle cross section or larger. Hence, the proposed method cannot replace periodical non-destructive inspections, but may serve as an additional safety measure detecting cracked axles in an advanced stage of the damage process but still on time to avoid in-service failures.

1. Introduction

In railway vehicles, wheels are often used in pairs connected by an axle, this assembly being called the "wheelset". Wheelsets are a very important subsystem in the vehicle, as they provide the interface with the track, support static and dynamic loads, provide traction, braking and guidance, the latter being the ability of the vehicle to follow the track [1]. Due to their very long service life (30 years or even more on European lines), railway wheelsets, and especially their axle, are prone to fatigue damage, which can be triggered by initial material defects or by service-related damage such as corrosion [2,3] or impacts with ballast stones [4]. The consequences of a fatigue failure occurring in a railway axle may be catastrophic, as the failure of one axle is likely to produce the derailment of the entire vehicle, which may in turn cause serious damage to the rolling stock and the infrastructure, injury of passengers and, in the worst case, even lead to fatalities.

To prevent fatigue failures in railway axles, the traditional design [5,6] based on the fatigue limit is complemented by a damage tolerant approach [7–9], where non-destructive testing (NDT) inspections are periodically performed on railway axles, typically using ultrasonic testing (UT) and magnetic particles testing (MT) techniques in combination [9]. However, despite the high standards of present engineering practice in NDT inspection, fatigue-induced axle failures still occasionally occur, representing a serious threat to the safe operation of railway systems [2]. A way to further reduce and possibly eliminate in-service failure is to implement continuous on-board structural health monitoring (SHM) of railway axles. In the technical literature, few initial investigations of possible strategies for continuous SHM of railway axles can be traced. One proposed solution is to extend the standard ultrasonic inspection methods so that they can be applied to a railway axle moving at service speed [10], but this requires the use of a very complicated wayside measuring equipment and the actual reliability of the SHM system has not been proved yet. Alternatively, the suitability of acoustic emission to detect cracked axles has been investigated [11–13], but a number of practical issues remain to be addressed before the feasibility of this method for practical use can be demonstrated.

In this paper, a method for the continuous structural health monitoring of railway axles is proposed based on measuring the axle in-service bending vibration. Indeed, the presence of a crack perturbs the axi-symmetric bending stiffness of the axle, affecting the bending vibration at frequencies that are multiple integers of the frequency of revolution, referred to as *n*xRev in this paper. This SHM strategy entails the measure of harmonic components of axle bending vibration occurring in the low frequency region

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(below 200–300 Hz), therefore allows the use of a relatively simple, robust and inexpensive measuring set-up. It should be made clear however that, in order to produce a significant alteration of the *n*xRev axle enabling fault detection, the size of the crack must be relatively large (as will be shown later, the crack area should be in the range of 16% of axle cross section or larger). Therefore, the SHM application proposed here is not meant to replace NDT inspection, but to serve as an additional safety measure that aims at detecting cracked axles in an advanced stage of the damage process, but still on time to avoid a catastrophic failure. The research reported in this paper was partly performed in the framework of the SUSTRAIL project [14], funded by the European Commission under FP7.

The method investigated in this paper takes inspiration from previous research performed in the field of rotordynamics and condition monitoring of rotating shafts. For these systems, the so-called "crack breathing" mechanism is known to produce typical signatures in the spectrum of bending vibration that can be used to detect the presence of a crack, locate the crack along the shaft and provide an estimate of the crack size [15–18]. When these methods are applied to a railway axle however, significant additional issues need to be addressed, mainly because railway axles are rotating at speeds well below their first critical speed, whereas shafts in turbomachinery and other industrial machinery are often working above at least the first critical speed. Furthermore, heavy disturbance caused by wheel–rail contact in presence of track irregularity and wheel out-of-roundness needs to be faced.

To analyse the feasibility of the crack detection method proposed in this paper, full-scale fatigue (durability) experiments were performed on railway axles in the lab and a Finite Element (FE) model of a cracked railway axle was defined and used to reproduce them and to analyse the case of a railway wheelset with cracked axle rolling on a railway track.

The paper is organised as follows: in Section 2, the mechanism of crack-induced vibration in a rotating axle is introduced. In Section 3, full-scale laboratory experiments are described, providing experimental evidence of the relationship between the existence of a propagating crack in the axle and the occurrence of additional *n*xRev vibration. In Section 4, a non-linear FE model of a cracked axle reproducing the crack breathing mechanism is introduced and numerical results are presented for two different scenarios: first, the laboratory test scenario is considered and numerical results are compared to laboratory measurement. Then, the scenario of a wheelset running on a railway track is considered, including disturbance arising from geometrical imperfections in the track and in the wheels, in order to perform a preliminary analysis of the suitability of the proposed SHM methodology in view of its real application.

2. Crack-induced vibrations in a rotating axle

The presence of a crack in a rotating axle affects its bending vibration under several aspects. Firstly, it causes a local change in the bending stiffness affecting the amplitude of forced vibration as well as the system's natural frequencies and modes of vibration. If the axle is statically loaded, the presence of a crack increases the axle's static bow and results in the amplification of the 1xRev vibration component, i.e. synchronous with the revolution of the axle. Secondly, the crack perturbs the axi-symmetric behaviour in bending of the axle (Fig. 1a). When the rotating axle is subjected to bending along a fixed direction, as caused e.g. by gravitational loads, its static deflection changes with the angle of rotation, giving rise to bending vibration at *n*xRev frequencies [15].

Finally, the crack breathing mechanism may occur. This consists of the cyclically opening and closing crack surfaces caused by the application of rotating bending. This phenomenon is illustrated in Fig. 1b: assuming the cracked rotor is rotating under the effect of a force that bends the axle downwards, compressive stresses are generated in the upper part of the axle section, whereas tensile stresses are generated in the lower part. Hence, when the crack is in the upper position, its surfaces are compressed so that the bending stiffness is the same or similar to that of a non-cracked section. When the crack moves to the lower position, the crack surfaces are separated resulting in a reduced bending stiffness. The breathing mechanism is therefore the result of the action of static loads (weight, reaction forces, etc.) and dynamical loads (i.e. unbalance, external excitation) combined with the axle rotation. Experimental results reported in [15] show that as long as static loads are predominant over the dynamic ones, the crack breathing is governed by the angular position of the shaft with respect to the stationary load direction. In this configuration, the crack opens and closes completely once per revolution.

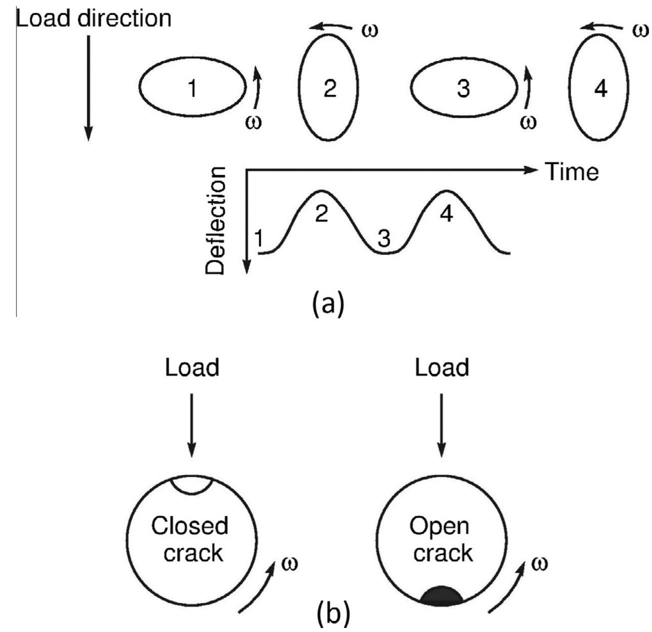

Fig. 1. *n*xRev vibration induced by: (a) a non-axisymmetric bending stiffness of the axle; (b) the crack breathing mechanism.

Taking into consideration the above-mentioned phenomena, the analysis of the different harmonic components in the cracked axle vibration signal provides opportunities for the detection of the crack itself. According to [15], when deflections are measured along the shaft loaded by its weight during a complete revolution of the shaft, the Fourier expansion allows the definition of 1xRev, 2xRev and 3xRev deflection shapes. Therefore, some typical symptoms of crack influence on shaft dynamic behaviour can be observed, namely a change in 1xRev, 2xRev and 3xRev vibration signal harmonics [16–19].

It should be noted that the above-mentioned results were obtained for industrial machinery and turbo-generators, for which the speed of revolution is often close or above the first critical, and the effect of external disturbances on the rotor is relatively limited, leading to a favourable signal-to-noise ratio in the analysis of *n*xRev vibration components. The aim of this paper is otherwise to investigate the feasibility of crack detection for a railway axle, considering the effect of disturbances arising from the interaction of the wheels with the rails and, particularly, the effect of wheel out-of-roundness, which represents an excitation phenomenon synchronous to the revolution of the axle.