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New stopping criteria for crack detection during fatigue tests of railway axles

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ABSTRACT

There are several EN standards that regulate railway axles' design, manufacturing, and maintenance since axles are one of the most important elements in a railway vehicle in terms of safety [1]. Fatigue tests are included in the standards, and they are widely used in this area to verify whether fatigue limits surpass certain specified values. Fatigue tests can be performed using test machines in which the axle rotates or more frequently, using Sincotec resonance test machines. For both types of test machines, fatigue tests aim to check if a crack appears in an axle within 10^7 loading cycles, thus it is necessary to establish stopping criteria in case a crack appears during the test. In the case of resonance test machines, the axle is determined to have been cracked when the testing frequency drops more than 0.5 Hz. For rotating axle tests, there are alarm levels for the displacement of the center of the axle, axle temperature, and variation of the load applied. However, in both cases, stopping criteria have shown low sensitivity to cracks: when the machine stops, defects are very large. Thus, testing can involve a waste of energy and time, and risk of catastrophic failure of the axle, which raises safety concerns and could lead to serious damage of the machine and its environment. This paper addresses a new methodology based on vibration measurements to establish more precise stopping criteria for crack detection during fatigue testing of railway axles. The use of one of the latest developments of the wavelet transform, the Wavelet Packets Transform, allows a crack to be detected many cycles before the conventional methods. The methodology has been successfully applied to a machine where the axle rotates, with very promising results.

1. Introduction

Fatigue tests are a very important topic because they are widely used to validate fracture mechanics theory, i.e., to compare theoretical failure predictions with the practical happenings of real life. However, railway axles' design, manufacturing, and maintenance (including inspection intervals) are based solely on experience, with results obtained from the fracture mechanics field not taken into account. This leads to sub-optimal design and maintenance parameters. Results obtained from analytical analysis could help to make a damage-tolerant design, and to optimize the safety and planning of maintenance [2].

Railway axles' design and manufacturing are defined in the European standards, EN. However, standards are continuously modified to improve safety in service. Design is defined in [3] for non-powered axles and in [4] for powered axles. Maximum

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permissible stresses are calculated using fatigue limits and a safety parameter S, which depends on the steel quality and on the application.

The steel quality is defined by the notch sensitivity coefficient q, which can be calculated according to Eq. (1).

$$q = \frac{R_{fL}}{R_{fE}} \quad (1)$$

where R_{fL} and R_{fE} are the fatigue limits obtained from smooth surface small test pieces and notched small test pieces, respectively.

Fatigue limits and their verification are established in manufacturing and qualification standards, e.g., [5] for axles [6], for wheels and [7] for wheelsets. Two types of fatigue limits must be verified for axles:

- For the material: through tests on small test pieces (diameter of approximately 10 mm) that are used to calculate R_{fL} and R_{fE}. To verify fatigue limits a minimum of 15 test pieces must be used to guarantee a non-fracture probability of 50% in 10^7 cycles.
- For the product: through testing full-size pieces with dimensions and manufacture similar to the final product and its associated permissible fabrication defects. Three test pieces are necessary to verify that there is no crack after 10^7 cycles. Fatigue limits apply to different axle areas; however, only fatigue limits that refer to the axle body are considered in EN standards. These fatigue limits are:
  - F1: on the body surface.
  - F2: on the bore surface in the case of a hollow axle.

The fatigue limit values required for railway axles are shown in Table 1.

Tests are performed with machines that induce rotating bending stresses in the area where it is required to initiate a fatigue crack. The stress values are calculated by the application of classical beam theory and checked by strain gauges in the areas where the fatigue cracks initiate.

Fatigue tests can be performed using test machines in which the axle rotates or more frequently on Sincotec resonance test machines [8]. Resonance testing induces rotating bending stresses on an axle that is fixed at one end, while at the other a rotating eccentric mass applies a load. Here, fatigue tests are controlled by strain gauges in the testing area.

For both machines, fatigue tests aim to check if a crack appears in an axle within 10^7 loading cycles because they are designed to operate with infinite life [9]. Thus, one stopping criteria for the fatigue tests is reaching the predefined limiting value of cycles. However, it is necessary to establish other stopping criteria in case the axle breaks before the limiting value of cycles to reduce risks in operator safety and to avoid surplus energy requirements. In resonance test machines, the axle is considered to be cracked when the testing frequency drops more than 0.5 Hz. For machines with rotating axle, the temperature of the axle and variations on the center of the axle position and on the applied load are continuously monitored using sensors. When these values exceed certain alarm levels, previously defined, the test is stopped.

However, on the basis of the results from subsequent ultrasound testing (UT) and magnetic particles testing (MT), stopping criteria have shown low sensitivity to cracks: when the machine stops, defects are very large. Thus, conventional stopping criteria allow the test to be performed for a high number of cycles after cracks have initiated, involving a waste of energy and time and a risk of catastrophic failure for the axle, which raises safety concerns and could lead to serious damage of the machine and its environment.

This paper addresses a new methodology based on vibration measurements to establish more precise stopping criteria for crack detection during fatigue testing for railway axles. Most of the researches related to rotating machinery diagnosis agrees with the use of vibration signals, because they contain valuable information about the failures [10–12]. The use of one of the latest developments of the wavelet transform (WT), the wavelet packets transform (WPT), allows detecting a crack to be detected a many cycles before the conventional methods. The methodology has been successfully applied to a machine in which the axle rotates with very promising results.

2. Fatigue test development

Fatigue test were held at the Department of Mechanical Engineering of Politecnico di Milano, in the framework of EURAXLES project. The specimens tested were three hollow railway axles made from EA4T steel (25CrMo4), property of Lucchini RS.

Table 1
Fatigue limits for railway axles established in the European Standards [5].

Limit	F_1	F_2	R_{fL}	R_{fE}	$q = R_{fL}/R_{fE}$
Value	$\geqslant 200\ \mathrm{N/mm^2}$	$\geqslant 80\ \mathrm{N/mm^2}$	$\geqslant 250\ \mathrm{N/mm^2}$	$\geqslant 170\ \mathrm{N/mm^2}$	$\geqslant 1.47$