A WHEELFLAT DETECTION DEVICE BASED ON CEPSTRUM ANALYSIS OF RAIL ACCELERATION MEASUREMENTS

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Summary

Damages and costs due to wheelflats are particularly heavy both from economical and environmental points of view. That's why, among the devices of automatical detection of vehicles imperfection, an instrumentation capable to find and, if possible, quantify the presence and the effects of wheelflats is certainly useful.

In this work a new device that uses a rugged transducer particularly suitable for the very demanding railway environment is presented. In order to detect and quantify the presence of wheelflats at the passage of different trains at different velocities, a signal processing procedure based on cepstrum and energy analyses is used. With some precautions, this method detects localized defects which are hidden in a very high global signal while other methods, based only on threshold comparison, can fail to find out these defects. This device can detect defects of locomotives and passenger/freight vehicles, and gives good results at a very low cost and with little calculation requirements.

Some significant results obtained with a prototype of the device are presented in this work. Hypotheses for the serial production of the device are depicted with particular reference to a possible low cost automation and integration in already installed devices (hot bearings detectors, for example).

Key words Wheelflat, tread defects, cepstrum analysis, piezoelectric cable, diagnostics, detection device.

Introduction

A railway wheelflat is a flat spot on the rolling surface of a wheel caused by its unintentional sliding on the rail. The reason for the sliding may be frozen or defective brakes, malfunctioning anti-skid devices or too high braking forces in relation to wheel/rail adhesion. Contaminations on the rails such as leaves, ice and snow aggravate the problem (Jergéus, 1995).

Many railway administrations analysed the problem from an economical point of view. The damages induced both in the rolling stock and permanent way are such that an early detection and retire from the service of defective wheels is strongly advisable. Some authors found that commonly used criteria for wheel tread removal and replacing are not very economical and that substantial money savings could be obtained by the detection of the maximum impact load given by wheelflats (Kalay, 1995).

Most of existing wheelflat detection devices contain a data transmission apparatus to a remote office, and their analysis pointed out that even the more recent systems (see for example Ohtani, 1995) are based on commercial transducers, typically strain gauge or industrial accelerometers, and that the signal processing is limited to a threshold comparison of peaks due to wheelflat impacts.

A cooperation between the Dipartimento di Meccanica e Tecnologie Industriali (University of Florence) and SIL-E-I SpA has led to the new wheelflat detection device presented in this work, whose heart is a non-conventional vibration transducer, i.e. a piezoelectric cable, a cheap and rugged transducer capable to detect and sum up vibrations in all directions. A relatively unusual processing tool, i.e. a cepstrum analysis, is used to enhance the contribution of the wheelflats to the overall vibration due to the wheel-rail contact, as the cepstrum function is able to find out wheelflat impacts thanks to its echo detection capabilities.

A prototype of the device and of the acquisition HW/SW was tested during spring 1997 with good success. This work describes the principles of application of the system; the reader is referred to Bracciali (1997) for further details on the signal processing algorithm.

The application of the piezoelectric cable, the signal processing algorithm and the whole device are currently patent pending.

Loads and stresses induced by the wheelflats

During rolling, the wheel and the rail undergo mutual forces that induce vibrations and noise. The amount of these vibrations is strictly related to the roughness of contact surfaces and to the vertical load, while lateral loads, except for very low curvature radii, do not sensibly influence vibration and noise levels.

Even in the hypothesis of perfectly smooth rail, the roughness of the wheel tread is responsible for the mentioned phenomena. Tread defects are commonly divided in two classes:

- global defects, i.e. lack of roundness of the wheel tread, due to not completely understood phenomena, such that the profile is no more perfectly circular but is characterized by an "ondulation" (this defect is also called "polygonization");

- local defects, i.e. the local absence of material (or, better, the redistribution of the material due to thermoplastic phenomena) generated by sudden sliding of the wheel under even temporarily unfavourable adhesion conditions (excessive braking, wet rails, etc.) during the train movement.

Despite their small depth, that is often limited to only several μm, the effects of all these defects are particularly dangerous, because the very high stiffness of both the wheel and the rail generates high periodic or impact forces.

Only wheelflats detection is dealt in this work, even if both kind of defects can be present at the same time on a railway wheel. As it is discussed later, this can introduce an ambiguity for the detection of localized defects as they can be "hidden" in a globally defected wheel tread, thereby vanishing simple threshold or energy detection criteria.

Impact forces can arrive up to several hundred kN, while rail accelerations arrive up to more than 900 m/s^2 (Williams, 1987) and have a good frequency content up to about 1 kHz. The definition of an acceptability threshold for wheel removal mainly depends on economical considerations: a too early removal and turning implies a reduced wheel life, while a too late removal implies excessive loads on the track and on the wheel with the possibility of severe consequences (fracture of the railhead and of the wheel tread and web). Recent works (Kalay, 1995) identify this limit in 85 kip (about 387 kN), i.e. 3 to 4 times the static load on the wheel. Another important wheelflats effect is impact noise, to which the passengers are continuously subjected and that is very annoying even for people that live aside railway lines. The increased SPL values are even more disturbing as they are strongly impulsive. All these effects increase with the depth of the flat and with the speed up to about 100 km/h; at higher speeds loads are lower, as the flat tends to "fly" above the rail. Conversely, polygonization (radial runout) effects, not analyzed here, always increase with the speed.

Common methods to automatically detect wheelflats in fixed locations use strain gauges (to measure rail and/or sleepers deflection), accelerometers (to measure rail vibrations) and microphones, even if the latter are considered not to be sufficiently rugged for the railway environment.

Description of the sensor

The detection element used in this work is the piezoelectric cable (AMP, 1993). It has interesting properties for the application in a wheelflat detection device:

1. it is particularly cheap and rugged (good linearity in the temperature range -40÷+125°C);
2. it is electrically insulated from the rail, thereby preventing EMI from traction return or signalling currents;
3. the power supply/conditioning device (charge amplifier) is particularly simple;

4. as verified during preliminary measurements made with triaxial accelerometers, the effect of wheelflats on rail vibration is mainly in vertical and longitudinal directions and also in lateral direction; hence the good cable sensibility in all directions makes more robust the wheelflat detection;
5. sensibility is not affected by aging.

The application of the piezocables to a wheelflat detection device is anyway not trivial, as the response of the sensor to high acceleration levels must be carefully investigated. Laboratory tests were performed on specimens of several piezocables, comparing their properties to standard measurement accelerometers under the following conditions (fig. 1):

a) check of linearity and dynamics mounting the cable and an accelerometer on an electrodynamic shaker;
b) likelihood of the response applying the cable and several accelerometers on a 3.6 m span of a suspended UIC 60 rail;
c) verification of the response on a railway track under impulse forces.

The cables passed satisfactorily all three phases; it is worth to remind that the dynamics of the autospectrum of the rail acceleration is normally lower than 20 dB, while the manufacturer grantes that piezocables have a dynamic range greater than 200 dB.

The application of the piezoelectric cables on a railway line during normal operations allowed the definition of some optimal test conditions:

- the velocity of each train should be constant (no acceleration or deceleration) and in the range 30÷100 km/h to maximize wheelflats effects (Kalay, 1995) and then to obtain the best performances from the detection algorithm;
- the sensing element should be only some cm long, as longer cables behave as low-pass filters, cutting portion of the autospectrum that are important in the detection algorithm; the sensibility is anyway sufficient, as a cable is equivalent to several sensors connected in parallel;
- no particular provisions needed to be taken to prevent EMI problems, both for traditional and electronic locomotives.

Description of the detection algorithm

Usually only one wheelflat is present on the tread of a railway wheel, and local conditions of hardness/adherence can lead to a wheelflat on only one wheel of a wheelset, while the other one can slip without consistent damage.

Under these conditions, only one hit happens per revolution, i.e. about 3 m, and the detection of the flat can be prevented by high acceleration levels due, for example, to adjacent highly polygonized wheels. The common practice is then to use two or

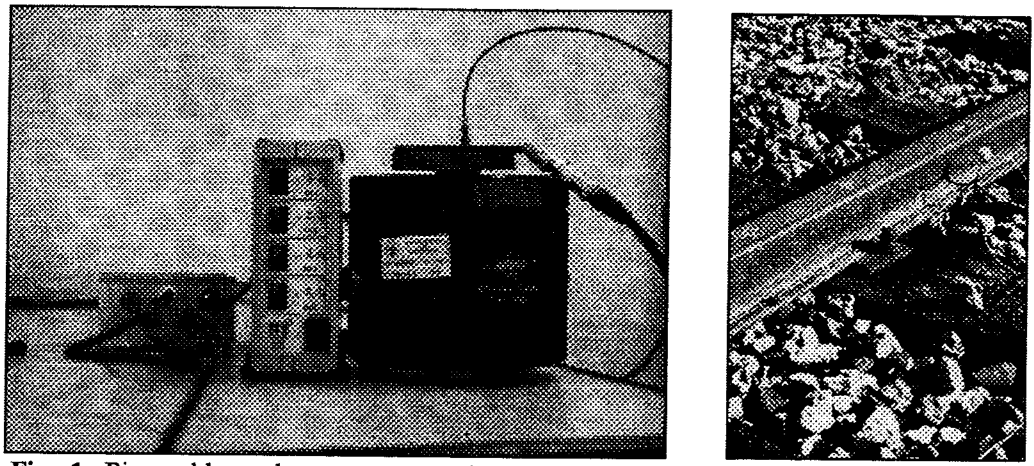

Fig. 1. Piezocable under test on an electrodynamic shaker (left) and mounted on a ballasted track on wooden sleepers (right).

more sensors usually equispaced along the rail (see for example Ohtani, 1995), such that at least one of the sensors falls under the passing wheelflat. This necessity arises from the intrinsically damped nature of rail vibrations: the rail behaves as a waveguide, does not undergo to eigenmodes, and can be considered as a beam supported on an elastic-damping foundation, such that a very high attenuation (ranging from 1 to more than 5 dB/m depending on the frequency) of vibrations is normally observed.

The use of many transducers descends from the signal processing method. Apart for the signal conditioning, that clearly depends on the type of the trasducers, signal processing is usually limited to a threshold comparison. If the mechanical property (acceleration, strain, load) exceeds a predetermined level a flag is usually send, through more or less sophisticated data trasmission protocols, to a remote operation control where an operator takes a decision based on defined criteria.

This detection method has several disadvantages:

1. it requires more than one sensor to be sure to get an impact above one of them;
2. the definition of the threshold is critical to avoid unintentional detections;
3. no discrimination can be made between long wavelength and short wavelength defects;
4. the detection of polygonized wheels is normally not possible, as they give too low contact forces w.r.t. wheelflat impacts;
5. the early detection of small wheelflats is prevented by the high threshold fixed.

To overcome some of these problems, a non-conventional processing was performed on digital acquired piezocable data. It is well known that an even not trained person can easily recognize the presence of *even a single small wheelflat* on a complete train. What the human brain does is the acoustical detection of *repetitions* inside the background train rolling noise, even if it is very high.

A mathematical function that proved to be useful when echo detection and/or removal properties are required is the *cepstrum* function, defined by Bogert (1963) as the *power spectrum of the logarithm of the power spectrum* of a signal defined in a certain interval. The reader is referred to Randall (1987) for a comprehensive description of the properties of the cepstrum function and for application details; originally introduced for seismic echo detection, it is also used for diagnostics of repetitive phenomena, such as gear toothmesh, milling tools conditions, turbine blade malfunctioning, and so on.

The application of the cepstrum function to recorded data proved to be valid once that the length of the segments and their appropriate *overlap* are defined. A too short length makes the cepstrum analysis useless (too few "echos" detected) while an excessive length only introduces unwanted noise (the amplitude of the detected impacts rapidly decreases and the wheelflat goes away). The best compromise is a length equivalent to 3.5 revolutions of the wheel with a 75% overlap. The number of samples will not be in general a power of two; the use of DFT instead of FFT for cepstrum computation does not appear to be a major problem, as calculations can be made *off-line* on collected data, and no more that 2 minutes are required to process an Intercity train running at 50 km/h using a common PC.

In parallel to cepstrum analysis an energetical analysis is performed. The well-known *covariance* function that averages the sum of all the squared samples in a signal segment is used.

The combination of covariance and cepstrum analyses allows to:

1. discriminate between wheels that are only either locally or globally strongly defective (respectively high cepstrum/low energy and low cepstrum/high energy);
2. identify even small local defects in globally defective wheels (medium to high cepstrum/high energy);
3. avoid the unintentional detection of wheelflats for polygonized wheels (low cepstrum/high energy);
4. filter out spurious peaks always present in acceleration signals due to local roughness profiles (only the *repetition* of the peaks has a meaning for the cepstrum function, and local peaks do not significatively affect signal energy) that can deceive threshold comparators.

Detection device prototype and a wheelflat detection example

During a preliminary test campaign several piezocables were glued in semicircular vanes milled in small aluminium blocks (fig. 2); this setup allowed the comparison of cables of different length. The blocks are separated by a 5 mm airgap, sufficient to dynamically uncouple the different parts of the cable without introducing an excessive flexibility (and thus free vibrations) of the unfixed cable. A comprehensive analysis of data collected at passage of more than one hundred trains obviously lies outside the scope of this paper. A significant example is given by the analysis of data relative to a freight train running at around 45 km/h.

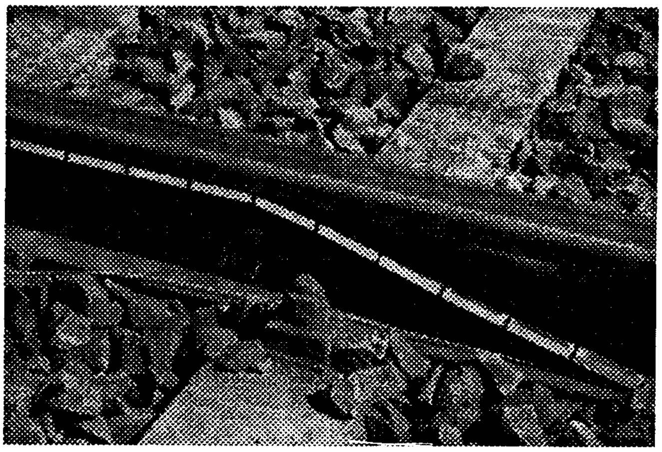

Fig. 2. Piezoelectric cables during mounting under the head of a UIC 60 rail. Aluminium blocks are 70 mm long with an airgap of around 5 mm. Cables 2.5 m, 1 m, 0.1 m and 0.05 m long were tested.

Figure 3 shows, for a portion of the train, the pulses generated by an electronic pedal and the vertical acceleration detected by a monoaxial piezoelectric measurement accelerometer. The maximum of the cepstrum function computed on overlapped segments of the signals of the accelerometer and of some of the piezoelectric cables is also shown; it is important to remark that while the energy content of recorded data (not shown) is high for many wheels, only the central portion of cepstrum maxima diagram has pronounced peaks. The detection of defective wheels can be easily done on the basis of a set of defined cepstrum thresholds that take into account train type and velocity.

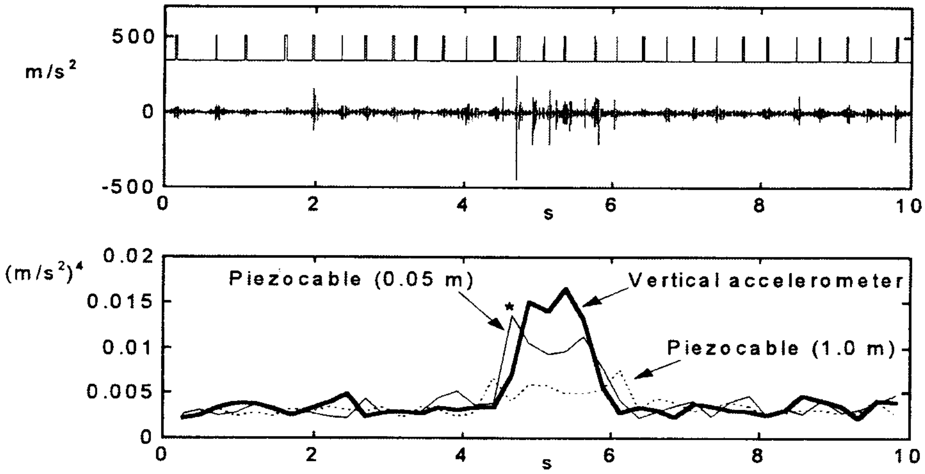

Fig. 3. Electronic pedal signal and vertical acceleration measured by a monoaxial accelerometer (top) at the passage of a section of a freight train running at 45 km/h; cepstrum maxima for overlapped segments for several transducers (bottom). * Indicates the signal section for which the cepstrum function is shown in fig. 4.

Comparing results obtained with the vertical accelerometer and with short cables, it looks clear that the former gives better performances; however it should be mentioned that the signal processing procedure has been developed and tested on accelerometer signals, and it is therefore improvable taking into account peculiar properties of piezoelectric cables.

The cepstrum function for the segment of the signal measured by 5 cm long piezoelectric cable where the cepstrum maximum is higher is shown in fig. 4. The distances indicated on the peaks are related to wheelflat impacts repetition time and to train velocity.

In the industrial solution, that nowdays undergoes final tests, the piezocable is fitted inside a hole bored in the V-shaped clamp of an electronic pedal built by SIL-E-I SpA and used by Italian State Railways FS. The final position of the transducer is still under study, even if the indicated configuration appears to be valid for the protection of the cable from mechanical and electromagnetical interferences. A test campaign to verify the final solution is planned at the beginning of September 1997 near Florence Santa Maria Novella main station.

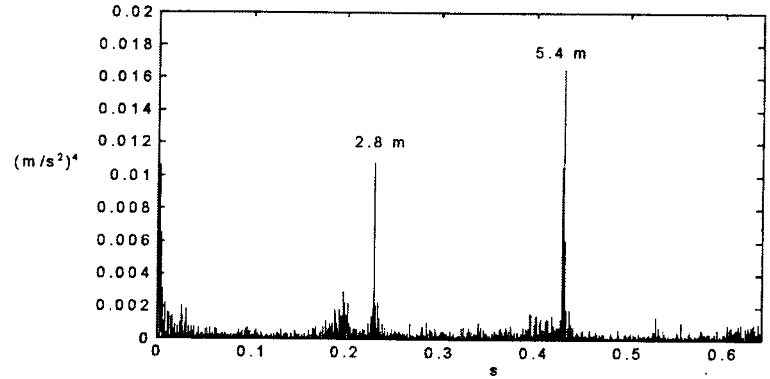

Fig. 4. Cepstrum function for the signal segment detected by a 5 cm long piezoelectric cable indicated with * in fig. 3. Distances are obtained by considering train speed and repetition time of wheelflat impacts.

Conclusions

The aim of this research was the development of an innovative device for wheelflats detection. Use of non-conventional transducers and signal processing led to particularly promising results, so that an industrial version of the described prototype is now under construction.

Clearly some work has to be done prior the release of the final version of the detector; for example the SW/HW platforms and the remote data transmission protocols are now under definition, but certainly the monitoring of wheel tread conditions will be greatly improved by an extensive use of such a device, leading to substantial cost reduction in the old and still partially unsolved problem of wheel wear detection and removal.

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