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ScienceDirect
Physics Procedia 3 (2010) 811–817
Physics Procedia
www.elsevier.com/locate/procedia

International Congress on Ultrasonics, Universidad de Santiago de Chile, January 2009

Railway Wheels Flat Detector Using Doppler Effect

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Abstract

A new inspection system for railway wheels using the Doppler Effect is presented in this work. The proposed system analyses the rail-wheel contact by frequency and phase shifts. Cracks on the wheel tread are determined while the train moves at a low speed. A special rail is used to propagate monochromatic surface waves. When a wheel on the measuring rail moves at constant speed, the received signal will present a regular frequency shift related with the movement speed. The difference between the emitted and the received frequencies will change if any defect on the wheel tread is detected.

Keywords: Doppler Effect applications; NDT industrial applications; Railway wheels inspection; wheel profile.

1. Introduction

Nowadays, high speed trains represent a real technology challenge to cover long distances in the less time possible. Transport security and quality require a proper and effective maintenance system to avoid related risks and to prevent incidents and accidents. Wheels are a critical part of the train and must be watched very closely. A crack found just in time, can help to keep the passengers safe and the train free of damage. Therefore, a periodical wheel inspection improves the reliability, availability and the effective operations of the railway system. Moreover, it allows reducing the maintenance costs. A quick inspection procedure while the train is getting into the repair shop also is important to reduce time in maintenance scheduled tasks. Routine inspections allow to follow-up the wheel wear history by uploading the information into a database. Many NDT inspection systems by ultrasound techniques are used today, but most of them are offline methods. This work proposes a different approach, where the inspection process is dynamically applied to trains moving at low speed (10-15 Km/h typical). This way, all of the wheelsets mounted in a train can be inspected in a few seconds.

1.1. Wheel Flat Detector

In the proposed system, monochromatic surface waves are propagated on a measuring rail. The rail-wheel contact is considered as a mobile reflector point moving at constant speed υ over the measuring rail. The received frequency

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doi:10.1016/j.phpro.2010.01.104

will present a constant frequency shift fd. The frequency shift or Doppler frequency is proportional to the rail-wheel contact speed and can be expressed as:

$$f_d = \frac{2\upsilon}{c} f_S \qquad (1)$$

Where f_S means the emitted frequency and c is the ultrasonic propagation velocity. Moreover, considering a railway wheel with radius R moving at constant angular speed ω, (1) can be rewritten as:

$$f_d = \frac{2\omega R}{c} f_S \qquad (2)$$

The difference between the emitted and received frequencies can be recovered using a heterodyne demodulator. Then, a time-frequency analysis of the recovered frequencies provides information about the wheel tread state.

1.2. Damage Dimension

The height of the wheel center related to the rail is no longer constant if the tread is damaged. The rail-wheel contact area is affected by different types of damages on the tread making the rolling surface be out-of-round. For instance, a fresh or newly flat is formed as a result of a wheel-locking due to a braking action. After a time of service, successive impacts of the defect over the rail will round off its edges. Fig. 1(a) represents a fresh wheelflat, where X_c is height of the wheel center. The maximum depth of the defect d can be known using simplified models suggested by several authors [1, 2, 3]:

$$d = R - R_{\min} = R - R\cos\theta \qquad (3)$$

where θ is the rotation angle. Moreover, the wheelflat length can be known in function of the radius decrease by:

$$L = 2Rsen\theta = 2R\sqrt{(1-\cos^2\theta)} \approx \sqrt{8dR} \qquad (4)$$

Nominal Doppler frequency given by (2) for a radius R will present a deviation when the rail-wheel contact is irregular, $\Delta f_d = f_d(R) - f_d(R_{min})$. As a conclusion, the depth of irregularities is related with the Doppler shift frequency.

$$d = \frac{\Delta f_d}{f_d} R \qquad (5)$$

Hence, variations of the nominal radius can be known by measuring the Doppler frequency deviation. The length of damages can be estimated as well by using (4).

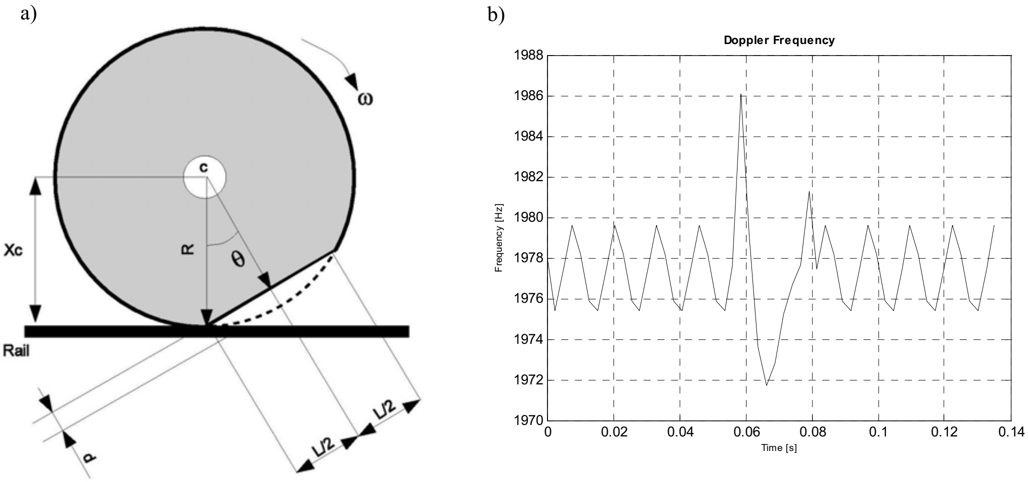

Fig.1. a) Wheelflat simplified model. b) Simulation results.

2. Simulation

A simulation has been carried out to verify the proposed model. The Doppler frequency deviation has been plotted in Fig. 1(b) for a simulated fresh wheelflat. The following parameters have been considered: υ= 3m/s, c= 3000m/s, f_S= 1MHz, R= 50cm and L= 7cm. By application of (1) the nominal Doppler frequency is 2 KHz. Then, the maximum wheel radius variation d = 1,2mm was estimated using (5).

The model takes measurements in a length equivalent to 12 flat lengths, with the simulated flaw centered in this range. It is assumed that the flat has been rounded off. A coherent Doppler demodulation is used: the received signal S_R, sampled at 3.6 MHz is multiplied by the emitted signal S_E and the result is filtered with a 64-coefficient FIR filter between 500 Hz and 2400 Hz. The spectrogram is computed by means a 256-point STFT and the mean frequency extracted. The result is shown in Fig 1 (b). Variations in the Doppler frequency shift can be seen during the irregularity modeled over the rail-wheel contact.

3. Prototype Testing

A simplified scheme employed in the laboratory used for testing is shown in Fig. 2.

3.1. Transducers and Amplifiers

Two 1MHz piezoelectric transducers were designed for emitting and receiving surface ultrasonic waves. The frequency was chosen considering attenuation along the material rail. The transducers were fixed to the rail in order to achieve a better acoustic coupling. The emitting transducer was located ahead of the receiver to avoid reflections.

Speed limits have been also taken into account in order to limit the Doppler signal spectra. The system has to be placed at the entrance of a maintenance workshop, where the inspection will be done. Therefore, trains are not allowed to move more than 10Km/h (≈ 3m/s) at repair shop areas. In this case, it is possible to consider a lower speed limit as 1m/s. The Doppler bandwidth is bounded between 700Hz and 2100Hz (using c= 2843m/s for austenite rails) by considering speed limits and solving (1).

A continuous 1MHz square wave TTL signal was adjusted by a power amplifier to drive the emitting transducer. The emitting transducer was excited by a signal with voltage levels from 0 to 12V. These levels guarantee the transducer to be driven without risks of damages. On the other hand, an ultralow noise amplifier was used in the reception stage. The low signal amplifier has a high bandwidth and adjustable gain (up to ≈ 50dB max).

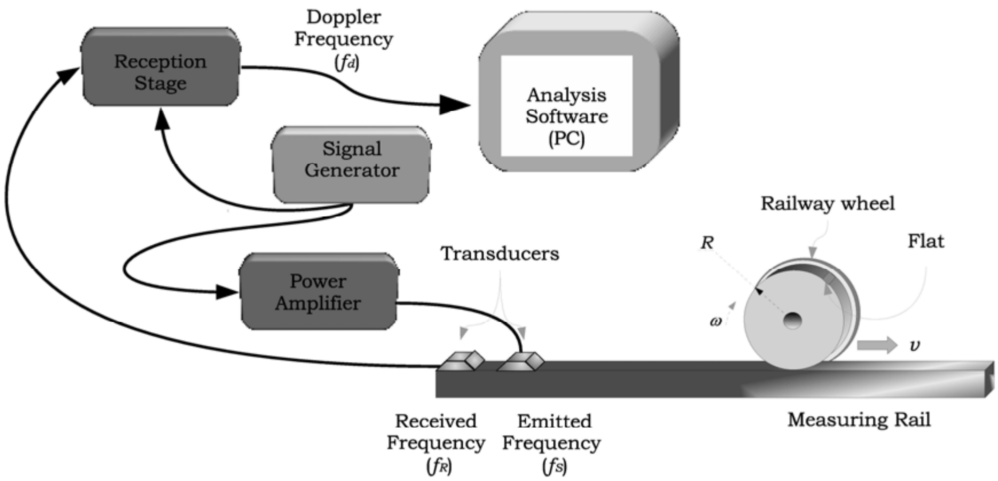

Fig 2. Wheelflat detector prototype.

3.2. Demodulation

Doppler signal spectra represent a 0.1% variation in terms of emitted signal. In order to get the frequency shifts the quadrature phase demodulation technique was used. The diagram of the reception stage used to get the Doppler spectra is shown in Fig. 3. Using the in-phase and quadrature components of the emitted signal as the reference in each coherent demodulator, the frequency shifts can be extracted from the received signal [4]. Then, an 8th order Butterworth low pass active filter was used in each channel to reduce frequencies higher than 3500Hz. The cutoff frequency f_C was chosen according to the design criteria established previously. The filter has 48dB attenuation at $2f_C$ (rejected band). This technique allows recovering the direction of movement by combining phase and quadrature channels. Only the phase channel was analyzed in the present work since the direction of movement is known.

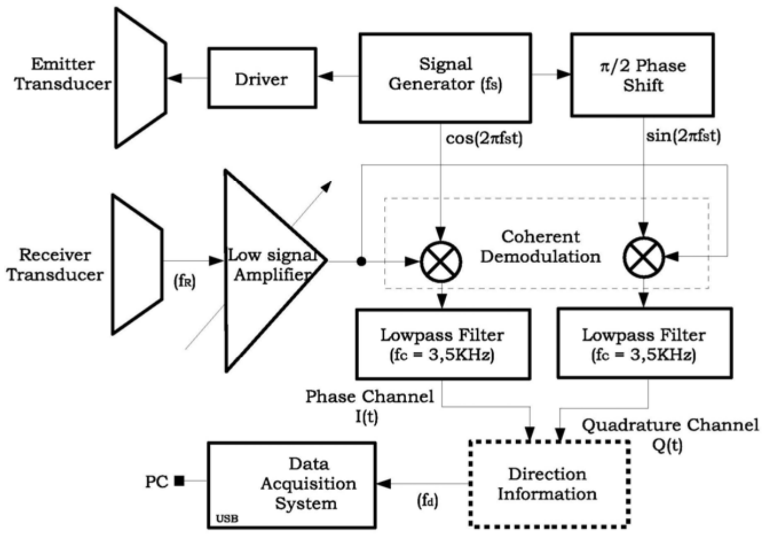

Fig 3. Reception Stage.

3.3. Data Acquisition System

A computer controlled measuring instrument was used to digitize the demodulated signals. The data acquisition system has selectable 14 bit or 16 bit resolution, 128Ksamples record length and programmable sampling frequency up to 100MHz. Finally, the digital signal processing was carried out with MatLab®.

3.4. Rail and Wheels

The rail-wheel contact echo in conventional rails was evaluated using ultrasound pulse-echo technique. A high noise level in the acquired signals was found. As a result, a special rail had to be designed to improve the signal to noise ratio. Some 6m long test rails were built for testing. The rail shape helps to propagate the ultrasonic waves over its surface. The mechanical support of the measuring rail allows matching the tread wheel angle (See Fig. 4(a)). A 10:1 wheelset scale was used for testing proposes. Such reduced wheelset allowed higher acceleration ramps in 6m long rails. Two flats (20 and 30mm long) and 1mm wide crack were machined on the wheelset as test defects (See Fig. 4(b)).

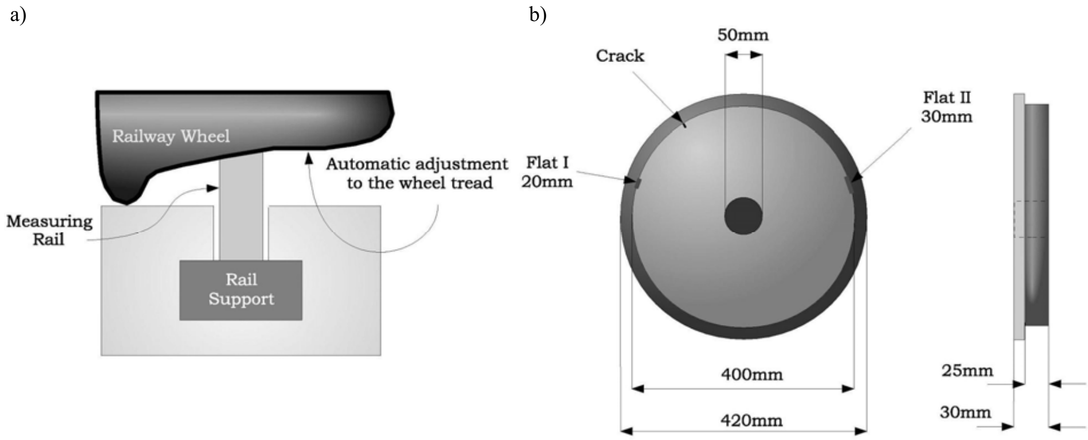

Fig. 4. a) Measuring rail construction. b) Wheel dimensions

4. Results

A 25000 points Doppler signal sampled at 10KHz was analyzed (See Fig. 5(a)). Wheelset was able to turn three times during the data acquisition process. The time-frequency spectrogram was made with a 127 points Hamming window taking into account a 126 points overlapping. The time-frequency spectrogram is shown in Fig. 5(b). A window of 127 points was chosen to avoid poor resolutions in frequency or time axes due to the uncertainty in time-frequency analysis [5].

The acquired signal has a low signal-to-noise ratio due to the small effective section of the wheel-rail contact point. The acceleration ramp can be seen in the first 5000 samples and the last 6000 points represent the braking ramp. Mechanized damages on the wheelset are able to be matched with discontinuities on the spectrogram. The presence of the artificial flats is clearly indicated by vertical lines in the spectrogram. However, a high level of noise makes difficult to distinguish the crack.

The low signal-to-noise ratio prevents estimating the wheel radius deviation by Doppler Effect. The low amplitude signal captured is easily hidden by noise.

Increasing the signal level would cause saturation of the system by the structural noise. Nevertheless, high frequency components appear in Doppler signal due to the irregularity edges, as was shown with the simulated model. Therefore, high pass filtering near to the mean Doppler frequency can be used to highlight the presence of wheelflats. Fig.5(c) shows the resulting filtered signal. The flats can be easily distinguished in the resulting signal. However, this time domain representation does not allow measuring their length.

Structural noise represents the principal constraint for the proposed method. The system developed so far only provides flats indications, which is very useful to give warning of failure. Other inspection techniques should be combined in order to sizing the defects.

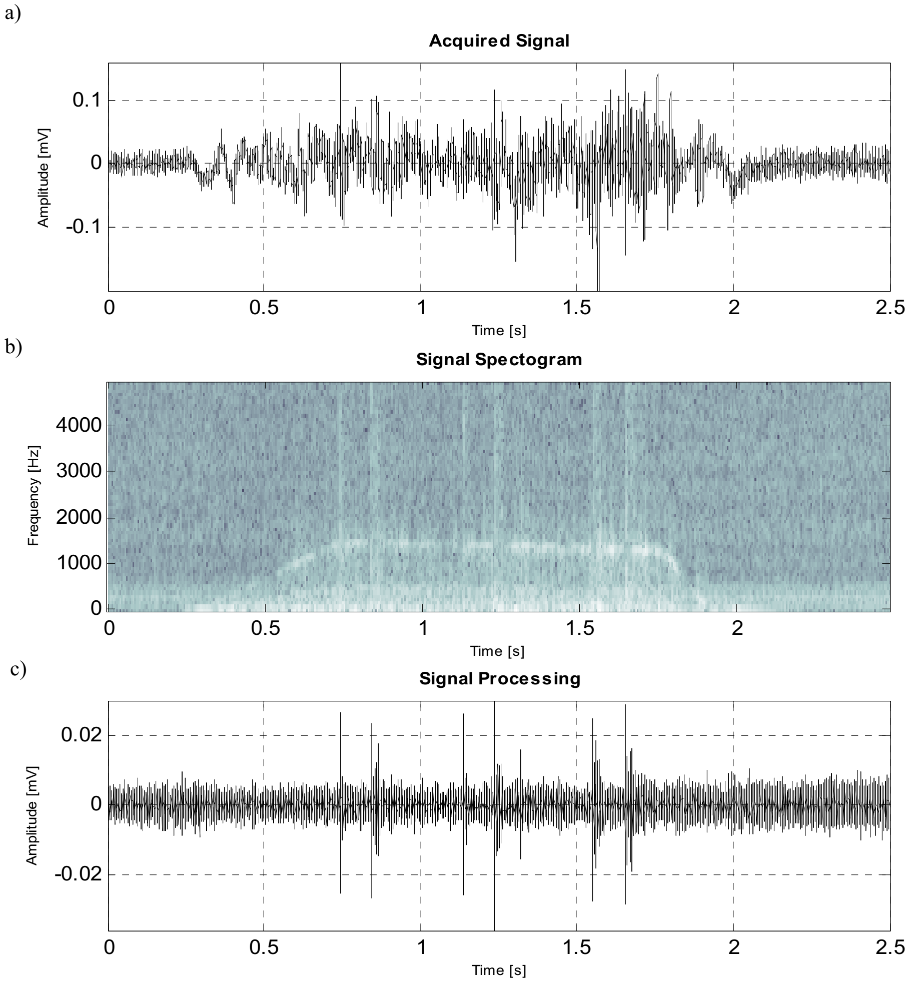

Fig. 5. a) Acquired signal. b) Time-frequency analysis. c) Signal processed.

5. Conclusions

A flat detector for railway wheels using Doppler Effect has been described. The system represents an innovation in the NDT ultrasound field, where defects are usually considered static reflectors. The proposed method is a dynamic technique that allows checking the railway wheels while the train is in movement within speed limits (1 to 3m/s).

The system can be placed at the entrance of the repair shops, performing routine inspections with a zero time cost, which helps to keep maintenance schedules. The proposed tread damage detector does not use wheel impact load measurements neither optical systems. Moreover, complex electronic systems or moving parts are not required. The transducers fixed to the measuring rail improve acoustic coupling leaving away variability problems. The flat steel bar measuring rail designed allows inspecting tread wheels by tracks. The train circulation direction can be determined by means the quadrature phase demodulation technique, although this information is known in advance.

The rail structural noise confines amplification levels to avoid saturation. Thus a low signal-to-noise ratio in acquired signals makes uncertain crack detection. Furthermore, flats longer than 20mm can be detected although sizing is difficult. Time-frequency analysis provides a quick reference about the wheel tread state. The use of high pass filtering reduces the low frequency noise and makes evident the flats presence. The resulting indications can be useful to turn alarms on by thresholds. Then, other techniques can be used to measure the damages found.

Acknowledgments

Work supported by DANO-RAIL of DANOBAT GROUP, Products & Services for the Railway Maintenance, Elgoibar – Guipuzcoa and Project TRA-2007-67711/AVT of the Spanish Ministry for Science and Innovation.

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