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A Novel Method for Railway Crossing Monitoring Based on Ambient Vibration Caused by Train-Track Interaction

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Abstract. Railway crossings are critical components in the rail network. They usually degrade faster than the other components. It is therefore vital to monitor their conditions using appropriate methods. This paper proposes to use the ambient vibration caused by the train-track interaction from a distance to monitor the condition of railway crossings. Both impact tests and pass-by measurements were performed on an instrumented crossing. The eigenfrequencies and mode shapes in the frequency range of 10–2000 Hz are first identified by impact tests using three different devices, i.e. a falling weight device, a big hammer and a small hammer. For the pass-by measurement, the dynamic features of both the wheel-crossing impact and ambient vibration are analyzed using time-frequency representations. It is shown that the ambient vibration signals are stationary and contain several characteristic frequencies. Then a method based on the frequency domain decomposition is applied to the ambient vibration signals to further identify the frequency components. It is found that the frequencies identified from the pass-by measurement agree well with the eigenfrequencies identified from the impact test. The proposed method can be further developed to continuously monitor the condition of railway crossings without interrupting train operations.

Keywords: Railway crossing · Condition monitoring · Pass-by measurement · Ambient vibrations

1 Introduction

Railway crossings are subjected to large repetitive impact load, which would quickly deteriorate their conditions. Such deterioration should be monitored appropriately so that maintenance actions can be taken before it jeopardizes running safety and passenger comfort. Vibrational-based condition monitoring can be used for this purpose. There are two steps involved in this process. The first step is to identify the dynamic characteristics of the crossing, e.g. the eigenfrequencies. The second step is to correlate the dynamic characteristics to the condition of the crossing, e.g. the ballast/railpad stiffness and the crossing geometry. This paper focuses on the first step.

The dynamic behavior of the train-track interaction at railway crossings has been investigated using both numerical simulations [1–3] and field measurements [4–6]. Impact tests [3, 5] and pass-by (or trackside) measurements [2, 6] are two primary ways

to identify the dynamic characteristics of a railway crossing. The impact test method is broadly accepted as a standard method for the identification of railway track dynamics. The main advantage of the impact test is that the input excitation (usually with a hammer) can be measured so that the frequency response function (FRF) can be directly derived. However, previous studies [2–6] focus more on the dynamics of the crossing nose while ignoring its coupling with the substructures, e.g. the sleeper and ballast. Besides, as railway crossings have larger inertia than plain tracks, considerable input energy is needed to excite the low-frequency vibrations [7]. Another disadvantage of the impact test is that it requires direct access to the track, and thus an out-of-service period has to be arranged.

In contrast, the pass-by measurement does not interrupt train operations and once the sensors are installed, they can be used to monitor the crossing condition continuously. Operational modal analysis methods [8–10] can be used to identify the crossing dynamics in this case. The pass-by measurement usually focuses on the vibrations caused by wheel-crossing impact [4, 6]. However, as the impact process is highly transient, it is more difficult to characterize than a stationary process. Moreover, there is still a lack of understanding of the correlation between the pass-by measurement and the standard as well as more commonly used impact test method.

This paper reports a comprehensive field test campaign on a railway crossing using both the impact test and pass-by measurement. The impact test is used to identify the eigenfrequencies and mode shapes of the crossing in the frequency range of 10–2000 Hz. For the pass-by measurement, a new method is proposed based on the ambient vibration caused by the train-track interaction from a distance for the identification of the eigenfrequencies. The capability of the method is demonstrated by comparing the results to the impact test.

2 Method

2.1 Field Test Setup

The field test was conducted on a 1:9 cast crossing. We have installed nine three-dimensional accelerometers (labeled as R1–R9) on the crossing nose and eight one-dimensional (vertical) accelerometers (labeled as S1–S8) on the sleeper, see Fig. 1(a). These accelerometers were used for both the impact test and pass-by measurement. In this paper, only the vertical accelerations are analyzed.

2.2 Test Procedures

Impact Test. To properly excite the crossing vibrations in the frequency range of 10–2000 Hz, three impact methods were used, i.e., with a falling weight (FW) device, a big hammer (BH) and a small hammer (SH), respectively.

The impact location for all the FW tests was on the crossing nose above the instrumented sleeper. The test scheme combined different falling weights (40–80 kg) and heights (20–40 cm). Such combinations can provide enough impact energy to excite the vibrations of the crossing nose and the underneath sleepers at the same time.

Unlike the FW, the BH and SH may not be able to generate the amount of energy required to excite both the sleeper and crossing nose at the same time. Therefore, a multi-reference single-input-multiple-output (SIMO) test scheme was used. The scheme includes multiple impact locations on both the crossing nose and the sleeper (indicated with the green triangle in Fig. 1(a)). At each impact location, the hammer test was repeated five times.

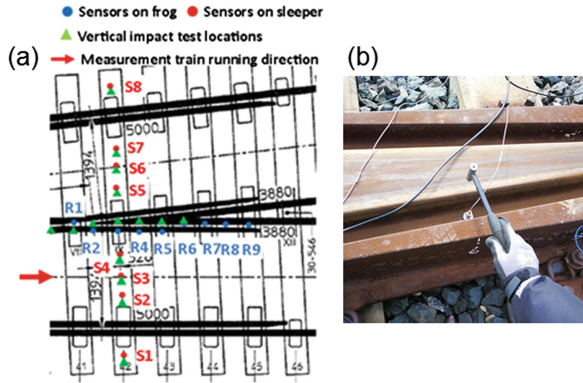


Fig. 1. Field test setup. (a) Sensor arrangement and impact locations. (b) Hammer test.

Pass-By Measurement. A measurement train ran over the instrumented crossing with multiple speeds, ranging from 20 km/h to 220 km/h (see Table 1). Except for the measurement from the ground, the axle box accelerations (ABA) were also measured, though the results are not presented in this paper.

Table 1. Recorded pass-by measurements in different velocities

Velocities(km/h)	20	30	40	50	60	100	120	140	160	180	200	220
Repetitions	1	1	5	1	5	5	3	2	5	4	4	2

2.3 Data Analysis

Data Preparation. For each impact test, the frequency response functions (FRF) were calculated with the impact force as the input and 17 acceleration signals as the outputs. There were in total 9 loading conditions for the FW test and 15 impact locations for the BH/SH test (Fig. 1(a)). Therefore, we formulated a three-dimensional FRF matrix of the size 9 by 17 by N for the FW test and two FRF matrices of the size 15 by 17 by N for the BH and SH test, where N is the number of frequency points in the FRF. Each entry (i, j, k) represents the FRF between the force at impact location i and the acceleration measured from accelerometer j at the frequency point k .

For each pass-by measurement, there were 17 output accelerations available. We formulated a cross power spectrum density (CPSD) matrix of the size 17 by 17 by N for each pass-by measurement. Each entry (i, j, k) stores the CPSD between accelerometer i and j at the frequency point k .

Post-Processing. First, we can subtract a sub-matrix from the FRF matrix with the size of p by q by N , where p is the number of impact locations or loading conditions and q is the number of output accelerometers. For example, we can take all 7 impact locations on the crossing nose as p and 9 outputs from R1–R9 as q . This submatrix can then be used to evaluate the dynamic behavior of the crossing nose while ignoring the responses from the sleeper. The same applies to the CPSD matrix.

At each frequency point k , the singular value decomposition (SVD) of each sub-FRF matrix is calculated. The singular values at different frequencies are called the Complex Mode Indicator Function (CMIF) [10] and can be used to identify the eigenfrequencies of the crossing.

For the CPSD matrix, an output-only identification method called the frequency domain decomposition (FDD) [8, 9] is adopted. The first singular values obtained by the SVD of the CPSD matrix are used to indicate the characteristic frequencies.

3 Characterizing the Dynamic Behavior of Railway Crossings

3.1 Impact Test

The three impact test methods, i.e. the SH, BH and FW, target different frequency ranges. A direct indication of the valid frequency range of each impact test is the coherence between the input (force) and outputs (accelerations). Figure 2 compares the coherence of the three methods. The valid frequency ranges are approximately 10–200 Hz, 30–800 Hz and 500–8000 Hz for the FW, BH and SH respectively.

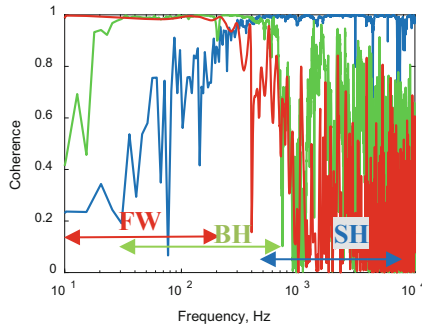


Fig. 2. The valid frequency range of different impact methods based on coherence.

Figure 3 shows the CMIFs for the crossing nose and sleeper separately. Eigenfrequencies are indicated with the arrows. Below 100 Hz, the CMIFs of both the crossing nose and sleeper show two modes and similar magnitudes. This indicates the two parts are equally excited by the FW tests. The two modes are the rigid and 1st order bending mode of the sleeper, see Fig. 4.

Between 100 Hz and 500 Hz, the sleeper vibrations dominate the response of the whole structures. Two pieces of evidence can support this: (1) the CMIF of the sleeper has a larger magnitude; and (2) Mode No. 3 and 4, which are the 2nd and 3rd order bending mode of the sleeper (Fig. 4), are also reflected in the crossing vibrations (see the two peaks in the blue curve at Mode 3 and 4 in Fig. 3(a)).

Between 500 Hz and 800 Hz, the CMIFs of the crossing nose and sleeper are at the same level of magnitude. In this frequency range, the sleeper and crossing nose are decoupled and vibrate separately: Mode 5 can only be found in the crossing nose while Mode 6 and 7 are only with the sleeper. The reason is that the modal displacements at the interface between the crossing nose and sleeper are almost zero for Mode 5, 6 and 7 (see the triangles in Fig. 4). Thus there is minimum energy transfer between the sleeper and the crossing nose.

Above 800 Hz, the vibration of the crossing nose becomes dominant. The sleeper vibration is much lower than the crossing nose. Because it is hard for the small hammer to excite the sleeper vibrations, the measurement becomes noisy (see the red curve in Fig. 3(b)). The modes become more closely spaced. In fact, as the crossing is infinitely extended, there could be waves at every wavelength (i.e. modes at every frequency). It is challenging to identify the shapes of these high-order modes because the current test setup only covers a part of the crossing nose. A more complicated setup, such as the one in [5], or a numerical model, would help to clarify these modes.

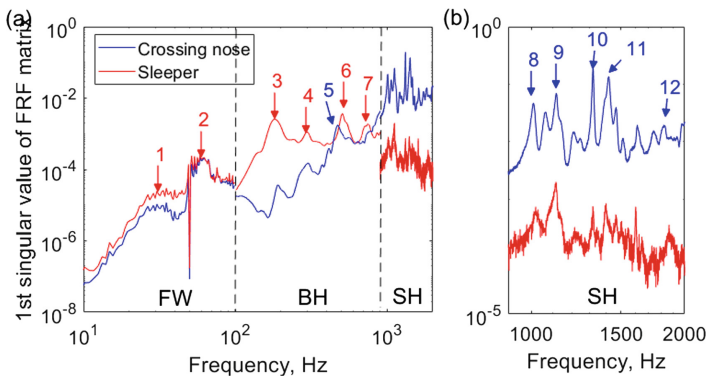


Fig. 3. Eigenfrequencies identified by impact tests based on CMIFs. The CMIF of the crossing nose is calculated using the 7 impact locations and 9 responses on the crossing nose. The CMIF of the sleeper is calculated using the 8 impact locations and 8 responses on the crossing nose.

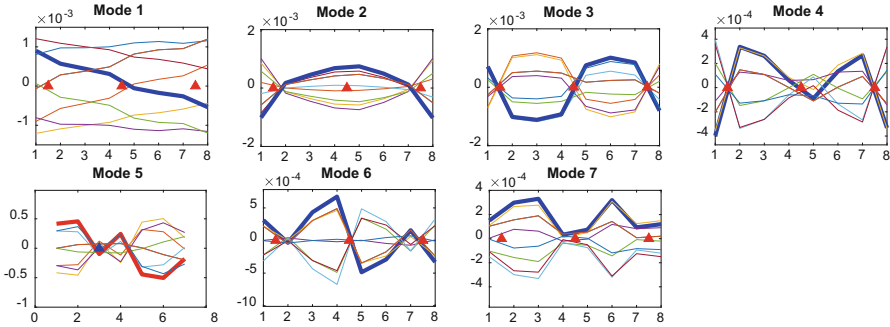


Fig. 4. Complex mode shapes at identified eigenfrequencies. A complete vibration period is divided into nine phases and each line represents a phase. Mode 5 shows the shape of the crossing nose. The blue triangle indicates the position of the instrumented sleeper. The other modes show the shapes of the sleeper. The red triangle in the middle indicates the position of the crossing nose and the other two at the sides indicate the two rails.

3.2 Pass-By Measurement

As mentioned earlier, the impact test requires an out-of-service period of the track, whereas the pass-by measurement directly uses the train-track interaction as the excitation source and therefore does not interrupt train operations. This section explores the possibility of reproducing the eigenfrequencies identified in Sect. 3.1 using the pass-by measurement.

Figure 5 shows a set of typical results from the pass-by measurement. The measurement train consists of one locomotive with three wheelsets in each bogie and a passenger wagon with two wheelsets in each bogie. The eight peaks in Fig. 5(a) correspond to the eight wheels impacting on the crossing nose.

The measured signals can be divided into two parts. When the measurement train was approaching the instrumented crossing, the accelerometers can already get signals due to the excitation of the train-track interaction from a distance. We refer these signals as the ambient signals, e.g. the part indicated by the rectangular in Fig. 5(a). Several distinct frequency bands are visible in the spectrogram of the ambient signal, as indicated by the arrows in Fig. 5(c). It is also noted that ambient signals are stationary as the distribution of the frequency components does not change over time. The ambient signals should reflect the eigen-characteristics of the crossing in its unloaded condition. This provides the opportunity to reproduce the eigenfrequencies based on the ambient signals, which will be elaborated later in this paper.

On the other hand, when the wheel ran over the crossing nose, a large wheel-rail impact occurred, inducing a distinct peak in the time domain signals (Fig. 5(c)). As this process is transient, we use the synchrosqueezed wavelet transform to obtain the time-frequency representation (Fig. 5(d)). It can be seen that the frequency bands are different from the ambient signals. This is because the impact signals reflect the dynamics of the train-crossing system instead of only the crossing. Moreover, the frequency components shown in Fig. 5(d) change over time, indicating the impact process may be non-linear or time-variant.

The wheel-crossing impact signals may carry valuable information about the crossing condition that cannot be traced by the ambient signals, e.g. the degradation in the crossing geometry and hanging sleepers. However, transient signals are in general more difficult to characterize and interpret than stationary signals. Besides, substantial effort is needed in postprocessing to isolate the influence of train dynamics, which is much more complicated at crossings than in plain tracks. These problems will be tackled in future studies.

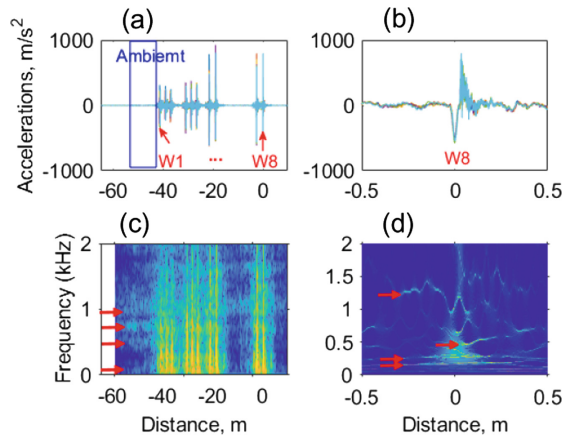


Fig. 5. Pass-by measurement results of accelerometer S3 with the vehicle speed of 100 km/h. (a) Accelerations from five repeated measurements mapped to the space domain. Wheel impacts are labeled as W1–W8. The horizontal axis indicates the distance between the last wheelset (i.e. W8) and the crossing nose. (b) Zoomed-in view at the wheel impact W8. (c) Spectrogram of the signal in (a) using the Short-time Fourier transform. (d) Wavelet power spectrum at W8 using the synchrosqueezed wavelet transform.

To get a clearer view of the frequency content shown in Fig. 5(c), we took the ambient signals between -52 m and -42 m indicated by the rectangular in Fig. 5(a). The FDD algorithm (see 2.3) was then applied to the ambient signals with a Hamming window of 1 m long and a 50% overlap between adjacent windows.

As with the CMIFs in Fig. 3, the first singular values were calculated separately for the crossing nose and sleeper, as shown in Fig. 6(a) and (b), respectively. Figure 6 also shows the results with different vehicle speeds. The magnitude of the singular values increases with vehicle speed, while the characteristic frequencies (indicated with the arrows) are not sensitive to vehicle speed. However, some of the modes are not excited when the vehicle speed is low, see for example Mode 11 in Fig. 6(a).

Figure 7 makes a direct comparison between the impact test and pass-by measurement. The characteristic frequencies identified by the ambient signals agree well with the eigenfrequencies identified by the hammer test. Only some of the closely spaced modes are not distinguishable, such as Mode 8–11. This is because more excitation energy is induced by the train-track interaction than the small hammer and therefore there is more damping caused by railpad and ballast.

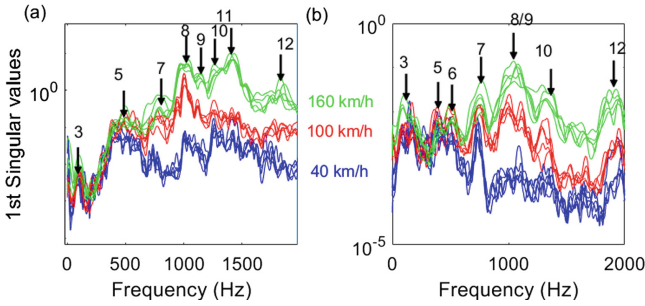


Fig. 6. Characteristic frequencies identified by pass-by measurements. (a) Crossing nose. (b) Sleeper. Each line represents a single measurement. The numbers above the arrows correspond to the mode number in Fig. 3.

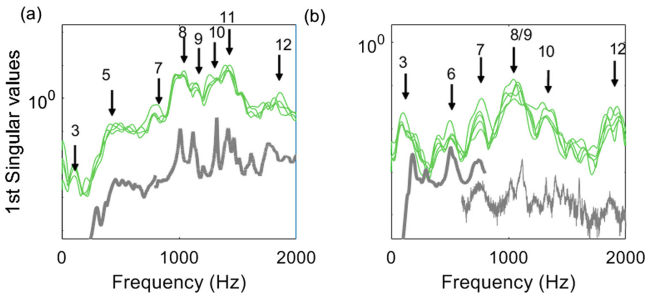


Fig. 7. Comparison between the impact test and pass-by measurement using ambient vibrations. (a) Crossing nose. (b) Sleeper. The green lines are the same as in Fig. 6. The grey lines are the CMIFs from the impact test as shown in Fig. 3.

4 Outlook

The next step is based on the characteristic frequencies (Fig. 6) to estimate the track parameters of the railway crossing (e.g. the stiffness and damping of ballast and railpads). For this purpose, a numerical model is required.

The dynamic features of the wheel-crossing impact shown in Fig. 5(d) need to be further investigated. They may be useful to monitor local defects on the crossing nose or the nonlinear behavior of railpads or ballast. For this purpose, the ambient signals can still be useful to establish a baseline state of the crossing.

Once the dynamic features of the pass-by measurement are fully understood, it can facilitate the understanding of the ABA measurement and a train-borne condition monitoring method can be further developed.

5 Conclusions

This paper identifies the eigenfrequencies and mode shapes of a railway crossing in the frequency range of 10–2000 Hz using the FW, BH and SH impact methods. The modes below 800 Hz are mostly the sleeper bending modes while those above 800 Hz are the modes/waves of the crossing nose.

The signals measured from the pass-by measurement are divided into the wheel-rail impact part and ambient vibration part. The ambient signals are shown to be stationary while the wheel-rail impact signals are transient and time-variant. They also show different frequency components.

A method is proposed by applying the FDD to the ambient vibration signals to identify the eigenfrequencies of the crossing. It is verified that the frequency identified by the proposed method agrees well with the impact test results.

References

1. Li, X., Torstensson, P.T., Nielsen, J.C.O.: Simulation of vertical dynamic vehicle–track interaction in a railway crossing using Green’s functions. *J. Sound Vib.* **410**, 318–329 (2017)
2. Alfi, S., Bruni, S.: Mathematical modelling of train–turnout interaction. *Veh. Syst. Dyn.* **47**(5), 551–574 (2009)
3. Kassa, E., Nielsen, J.C.O.: Dynamic interaction between train and railway turnout: full-scale field test and validation of simulation models. *Veh. Syst. Dyn.* **46**(sup1), 521–534 (2008)
4. Kaewunruen, S.: Monitoring structural deterioration of railway turnout systems via dynamic wheel/rail interaction. *Case Stud. Nondestruct. Test. Eval.* **1**, 19–24 (2014)
5. Wei, Z., Boogaard, A., Núñez, A., Li, Z., Dollevoet, R.: An integrated approach for characterizing the dynamic behavior of the wheel-rail interaction at crossings. *Trans. Instrum. Meas.* **67**(10), 2332–2344 (2018)
6. Boogaard, M.A., Li, Z., Dollevoet, R.P.B.J.: In situ measurements of the crossing vibrations of a railway turnout. *Measurement* **125**, 313–324 (2018)
7. Pålsson, B.A., Nielsen, J.C.O.: Dynamic vehicle–track interaction in switches and crossings and the influence of rail pad stiffness – field measurements and validation of a simulation model. *Veh. Syst. Dyn.* **53**(6), 734–755 (2015)
8. Brincker, R., et al.: Modal identification of output-only systems using frequency domain decomposition. *Smart Mater. Struct.* **10**(3), 441 (2001)
9. Tarinejad, R., Damadipour, M.: Modal identification of structures by a novel approach based on FDD-wavelet method. *J. Sound Vib.* **333**(3), 1024–1045 (2014)
10. Reynders, E.: System identification methods for (operational) modal analysis: review and comparison. *Arch. Comput. Meth. Eng.* **19**(1), 51–124 (2012)