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Maintenance of bogie components through vibration inspection with intelligent wireless sensors: A case study on axle-boxes and wheel-sets using the empirical mode decomposition technique

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Abstract

The maintenance of bogie components, a critical aspect of railway maintenance, is difficult due to the confined underframe space. This makes it difficult to install traditional monitoring equipment, resulting in a labour-intensive process. Thus, a lot of time has to be expended to conduct these tests, which makes the process both tedious and expensive. Moreover, this approach is somewhat inadequate, since the tests can only be conducted at the depot and thus only when the trains are out of service. We have developed and deployed a non-intrusive solution based on a small wireless sensor network that can be easily installed on the different parts of the bogie and along the whole train. We have worked out a technique to discriminate between the various sources of vibration and can thus monitor the state of several components using only a few sensors. In this paper, we present a case study on how to maintain an axle-box and a wheel-set by attaching a single intelligent sensor to the bogie frame or the bearing cover and using the empirical mode decomposition technique to analyse the generated data. In light of the promising results obtained in this study, we suggest that the proposed approach can lead to a value-added predictive maintenance strategy as long as the test conditions are kept under control. However, we do highlight that the generalization of the approach relies on the flexibility of the system to adapt to new environments and operational scenarios.

Keywords

Vibration analysis, empirical mode decomposition, wireless sensor network

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Introduction

The requirement for rolling-stock maintenance activities, and in particular ones that are applicable in the current complex and competitive market, has spurred the adoption of new and innovative techniques that are considerably different from traditional approaches. By focusing on failure-specific problems, the use of predictive techniques allows the condition of train components to be diagnosed. They also allow the evolution of their degradation to be forecast based on salient indicative variables. As a result, the analysed components have experienced a reduction in maintenance costs and an increase in reliability, which has led to returns on investment in shorter timespans.[1,2]

Among all the physical variables that can be easily obtained from a component under analysis, the monitoring of vibration signatures yields the most comprehensive indication of possible problems. Vibration inspection is a technique that enables maintenance staff to conduct tests on a wide range of elements, including rolling-stock and railway infrastructure.[1,3,4] In addition, the analysis of vibrations can be used to analyse component faults under a wide range of test conditions such as a varying speed of a train.[5] These features make the acquisition of vibration information using accelerometers one of

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the most powerful and convenient approaches to guide predictive maintenance actions.

The traditional technology to perform a vibration inspection process is based on expensive equipment and relies on cabled settings, which usually creates several implementation problems: there is little underframe space in which to install the cables, it takes a lot of time for staff to install and manage the cables and data acquisition machines on the train, the cables disconnect and become unreliable, etc. Overall, this results in an increase in the maintenance service cost, which raises many challenging problems in the present competitive marketplace. As a solution, we propose using a small network of intelligent wireless sensors that we have developed from scratch and customized for the railway environment and for the problems at hand.[6] This system has many advantages with respect to the classic vibration inspection approach, including the wireless technology avoiding the problem of having to deal with unreliable cables and speeding up the overall test operations, which results in an overall increase in quality and a saving in cost (a time cost reduction of one-third has been obtained with this approach). Moreover, certain maintenance operations are complex to schedule (possible only when the trains are out of service during off-peak hours) and require a fast inspection test.

Regarding the electromagnetic compatibility (EMC) requirements that on-board railway electronic equipment must display, it should be noted that the radio parts of the sensors consist of commercial Digi XBee boards that comply with the European and American EMC standards. Moreover, the largest length of a printed circuit board is 47 mm and considering that the operating clock frequency is 4 MHz, the corresponding wavelength is 18 m. Therefore, the boards are far from behaving like transmission lines (less than 0.003l), so there is very little risk of generating spurious signals. Additionally, intelligent wireless sensors were designed (and are currently being validated) to pass the applicable EMC standards UNE-EN 50155, UNE-EN 50121-3-2 and ETSI EN 301489-17.

One last issue to take into account is that a large number of sensors increases both the economic cost (more hardware is being used) and the time cost (more time required to install them on the train) of the test. For the purpose at hand, it is convenient to magnetically attach the accelerometers onto the axle-bearing cover or the surrounding bogie-frame.[3] The magnets are made of neodymium (magnet diameter 25 mm) and exert a force of 18 kg (area 491 mm^2). This sensor attachment method is targeted at depot-based deployments with dedicated test tracks, where restrictions on train operation service do not apply. The trains under test are required to maintain a uniform speed of 5 mile/h (depot speed limit) during the whole of the data acquisition process. We have so far observed a successful operation of this attachment method for these test conditions, i.e. the sensors remain attached to the component during the whole test without any displacement (there is no interference with other components).

In these depot-based tests conditions, the magnitude of the vibration is quite low and the signal frequency characteristics are located at the lower end of the spectrum. Additionally, the vibration sources are additive and need to be discriminated in order to conduct a component-based analysis. To this end, the empirical mode decomposition technique has been applied given its recent promising results in application to railway environments.[3]

The purpose of this case study is to investigate the nature of bogie component degradation interactions along with their representation, and work out a viable and inexpensive solution with a small network of intelligent wireless sensors (where one objective is to monitor both the condition of an axle-box and a wheel-set). To that end, this paper is organised as follows: first the empirical observations that motivated this study are described and the practical basis of the empirical mode decomposition technique are presented. The application of this technique to the problem at hand is presented and various aspects of the obtained results are discussed. Finally, conclusions are drawn.

Method

This section first describes the working scenario and the train components under test. The empirical observations and the facts that motivated this study are discussed. Then, the empirical mode decomposition technique is presented as a means to extract useful information from the measured data and its use in his study is justified.

Empirical observations and facts

The type of train under test is a metro train. The train-set consists of three 17-m cars each with two bogies, weighting from 22 to 30 tonnes based on their traction function (from trailer to driver). The maintenance plan of the target components is:

- axle-boxes follow a 4-year greasing schedule;
- wheel-sets follow a 510-day tyre-rotation schedule

Based on these operating maintenance periods, it can be seen that wheel-sets undergo a maintenance action almost three-times more often than axle-boxes. Therefore, the wheel-sets must display a degradation function that is more abrupt than that of the axle-boxes (thus justifying a more frequent maintenance action plan). It is also expected that a larger change in condition will be seen on wheel-sets than on axle-boxes. The observable fact that supports this hypothesis was seen in the vibration signatures between two maintenance tests (July and December) taking into account that a rotation of the tyres occurred in that period (August); this test will be presented later in this section. Therefore, a control sample was obtained before rotation of the tyres and an experimental sample was obtained after rotation of the tyres. It should be noted that just before rotation of the tyres the condition of the wheel-set is at its worst, whereas immediately after the rotation it is at its best. Thus, the acquired signatures display the two extremes. This experiment should be taken as a proof of concept.

The vibration acquisition point was set on the axle-box cover, acquiring both the noise signal from the bearing and from the wheel-set (i.e. the wheel/rail contact), see Figure 1. It should be noted that there is no elastic component in any of these paths that could absorb or mitigate the transmission of the vibration.

The sensors contain an accelerometer with a dynamic range of 9 g, which is more than enough for the nature of the vibration that we have acquired under the test conditions at hand. In addition, the rules that trigger an alarm were set for the maximum of this range. Taking into account that the average wheel diameter is 750 mm, at 5 mile/h, the fundamental rotational frequency is 0.95 Hz. Thus, a 1-s vibration creates just under the minimum amount of information needed to extract useful information. It must also be considered that there is a trade-off between the amount of data that is to be downloaded and the time needed to perform that task given the low-throughput of the low-power wireless sensors (they must be powered with external batteries that do not interfere with the train's power source). Please refer to Trilla and Gratacos[6] for more detailed information about these sensors.

Having presented the test setting, Figure 2 shows a comparison between the waveform signatures obtained in July and December, and Figure 3 shows a similar comparison with respect to their vibration spectrum signatures.

Figure 3 shows the discrete Fourier transform obtained using the fast Fourier transform (FFT) algorithm of the signals represented in Figure 2. Note that the test conditions did not change during the time required to acquire the signals: the train is required to maintain a uniform and stable speed of 5 mile/h. Therefore, the signals are stationary and the computation of the FFT is valid and compliant with this requirement.

The vibration signature differences before and after rotation of the tyres validate that this maintenance action has an observable impact on the monitored components (particularly on the wheel-set). However, it remains difficult to analyse the conditions of individual components. Plots of the waveform and spectrum signatures are rather indistinguishable with respect to the sources of the vibration that generated them. The overall vibration noise is significantly reduced, especially in the 200–300 Hz frequency range. The exception is for a narrow range around 400 Hz. This could be indicative of the fast effect of wheel-set degradation and of the slower degradation function of the axle-box. The latter shows no large difference between July and December, i.e. the

Figure 1. Intelligent wireless sensor attached to the axle-box cover, it can capture vibration signals from both the axle-box and from the wheel-set.

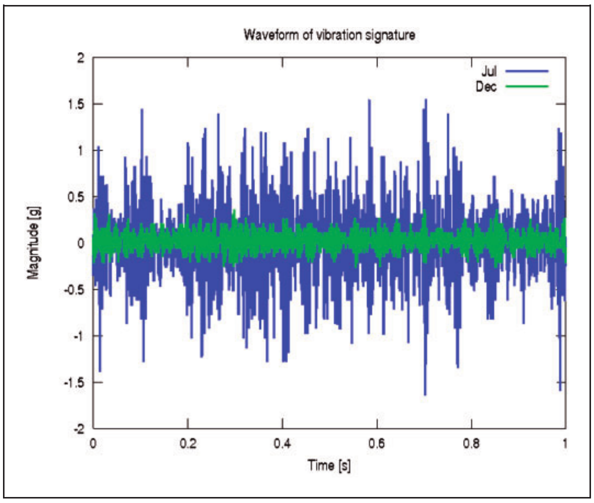

Figure 2. A comparison of the waveform signatures obtained before (July) and after (December) the tyre- rotation maintenance action.

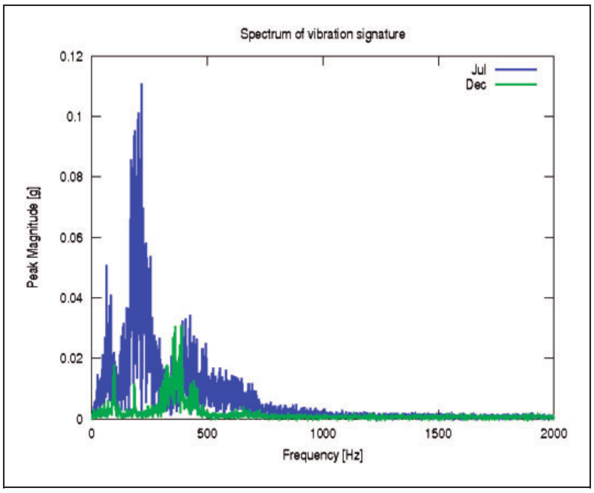

Figure 3. A comparison of the spectrum signatures obtained before (July) and after (December) the tyre-rotation maintenance action.

condition the axle-box essentially remains the same during this short period of time, whereas the condition of the wheel-set condition is restored due to the tyre-rotation operation, thus showing a radically different vibration signature. This issue calls for more experimentation in order to improve the reliability of the diagnostic. The following sections give more details on this problem.

The empirical mode decomposition technique

The empirical mode decomposition (EMD) technique is based on an iterative procedure that is used to decompose a given dynamic signal into a set of subsignals of decreasing frequency, which are known as intrinsic mode functions (IMFs).[7] Compared with traditional theoretical analysis methods based on Fourier transforms, an IMF represents a simple oscillatory mode as a counterpart to a simple harmonic function. Thus, instead of constant amplitude and frequency components, the IMFs can have a variable amplitude and frequency along the time axis. Therefore, the EMD technique can be directly applied to nonlinear and non-stationary signals that are typically acquired on a bogie frame.

The decomposed IMFs of an EMD must satisfy the following conditions.

1. In the given signal acquisition, the number of extrema and zero crossings must be either be equal or differ by a maximum of one.
2. At any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero.

The processed signal is thus modelled as narrow-band Gaussian noise. The sifting process for extracting the IMFs from the input signal $x(t)$ is described as follows.

1. Create an upper envelope $e_u(t)$ and a lower envelope $e_l(t)$ by connecting local maxima and minima with cubic splines. Then, compute their mean and subtract it from the input signal

$$h_1(t) = x(t) - \frac{e_u(t) + e_l(t)}{2} \tag{1}$$

2. If $h_1(t)$ does not meet the IMF requirements, take $h_1(t)$ for $x(t)$ and repeat step 1 until the new $h_1(t)$ satisfies them. Then, assign the first component

$$c_1(t) = h_1(t) \tag{2}$$

3. Compute the residue

$$r_1(t) = x(t) - c_1(t) \tag{3}$$

4. If more components are required, i.e. the residue still contains useful information of longer period components, the residue is taken for the new input signal and the sifting process is repeated until the residue becomes a monotonic function.

In the end, the input signal $x(t)$ is decomposed into an additive set of N components plus the residue

$$x(t) = \sum_{i=1}^{N} c_i(t) + r_N(t) \tag{4}$$

The application of the EMD to discriminate noise sources generated by rolling-stock has been recently reported in the literature.[3] Other techniques were considered in that publication, including various statistical methods, power spectral density, and wavelet analysis, but none seemed to rival the features of the EMD. Inspired by that work, we became interested in using this new robust approach (free from input signal constraints) to separate the signals from different noise sources so as to provide a more reliable and bespoke condition analysis of bogie components. Thus, we conducted a manual/heuristic IMF selection process based on their railway maintenance experience[3] (i.e. a fully empirical approach) as a first step towards validating the EMD technique in our scenario. We note that in the future the stationary signal characteristics may no longer hold as we extend the application of the sensors to other trains and to other test environments; however, we leave resolving these possible issues as future work if they ever appear.

Given that the modes of the vibration signal are directly related to the sources of the noise that generated them, that is, the faulty or degraded rolling-stock components (namely axle-boxes and wheel-sets in this work), our hypothesis is that by means of the EMD technique, we will be able to relate the IMFs to these modes and thus better identify the location of the degradation problems.

Results

This section reports on the experiments conducted on the application of the EMD technique to help identify bogie components and conduct more accurate component-based analyses.

Control vibration sample (before rotation of the tyres)

Figure 4 displays the independent contribution of the first five IMFs for the signature of the control vibration obtained on July, just before the tyre-rotation maintenance action. In order to facilitate reading the figure, each IMF has been plotted in a different colour.

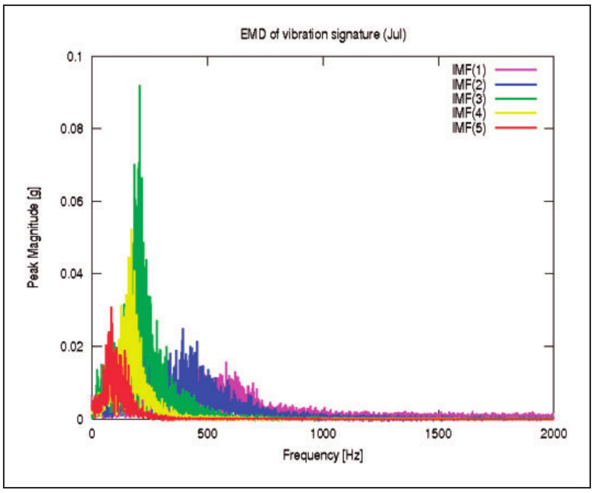

Figure 4. The EMD of the control vibration signature (July).

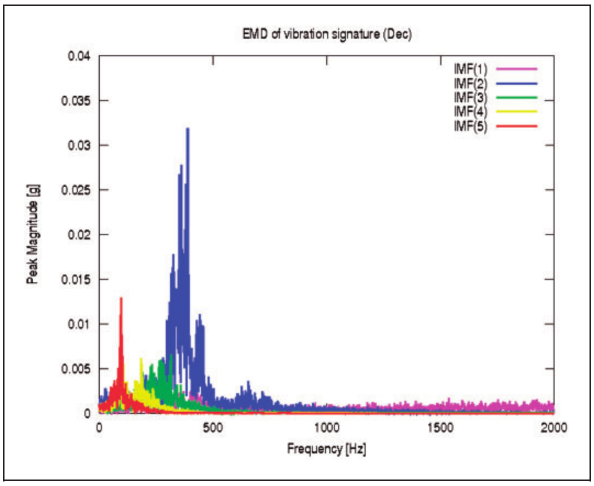

Figure 5. The EMD of experimental vibration signature (December).

It can be observed that the principal contribution to this signature (200–300 Hz frequency range) is made by the third and fourth IMFs, and the 400 Hz range mainly corresponds to the second IMF. Note that with respect to the direct frequency analysis shown in Figure 3, which is basically a smear of energy distribution along the spectrum, the IMF decomposition shown in Figure 4 provides a more detailed analysis of the natural resonances of the signal. It can now be seen that there is a relation between the oscillatory modes of the signal (denoted by the peaks) and the IMFs that are extracted. For each IMF there is one single dominant frequency that indicates the vibration mode produced by a degraded component. The challenge now becomes to identify the sources of the noise that generated these peaks, and the means to accomplish this is by having a close look at the signal decomposition after the tyre-rotation maintenance action, in other words only affect the condition of the wheel-set.

Experimental vibration sample (after rotation of the tyres)

Figure 5 displays the independent contribution of the first five IMFs to the experimental vibration signature obtained in December, a few months after the tyre-rotation maintenance action.

It can now be observed that the principal contribution to this signature (400 Hz frequency range) is made by the second IMF. The third and fourth IMFs have been drastically reduced by the tyre-rotation maintenance operation. In fact, this action has had an observable impact on the rest of the spectrum: the overall noise reduction ratio is at least one-third. As noted in the previous section, rotating the tyres only affects the condition of the wheel-set; in fact, it restores the good condition of the wheels. With this new condition, it is expected that the wheel-set produces less noise than in the old condition, and this is in accordance with what is observed in Figure 5. Therefore, what remains must correspond to the noise produced by the degradation of the axle-box and this is essentially identified by the second IMF.

Rationale of the component-based analysis

Given the presented results about the identification of the dominant IMFs and their relation with the two sources of vibration captured by the accelerometer, it can be tentatively concluded that the second IMF is a reliable indicator of the condition of the axle-box, and the third and fourth IMFs are reliable indicators of the condition of the wheel-set.

Based on this preliminary outcome, the IMF signals (or their addition, in the case where this applies), can be examined using classic component analysis methods. Regarding the axle-box vibration signature identified by the second IMF, we have applied a fundamental bearing frequency matching with the acquired vibration signature,[6,8,9] which is also known as order analysis,[10] taking into account the angular speed of the axle (order 1) and its harmonics (orders greater than one). For this, we have evaluated the envelope or demodulation technique,[8–10] see Figure 6, which has traditionally been more successful than the direct frequency analysis approach in analysing the test scenario at hand. The envelope technique separates the high-frequency components that are modulated on top of the overall signal. We created this demodulation process by first squaring the signal and then filtering the result with a low-pass filter. The obtained results were sensible with respect to the possible causes of bearing failure. There was a clear match between the expected location of the fundamental bearing frequencies and the peaks observed on the diagram.

Regarding the analysis of the wheel-set condition, the root-mean-square (RMS) and peak values of the sum of the third and fourth IMFs were computed as a

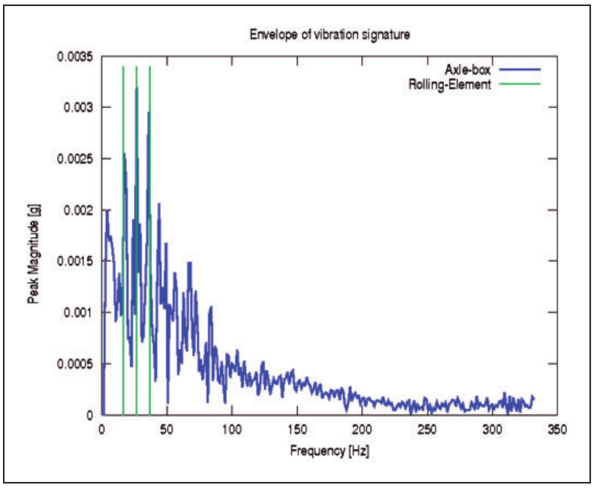

Figure 6. The envelope of the axle-box vibration signature showing an incipient rolling-element failure on orders 5, 8 and 11.

Table 1. Analysis indicators for the sum of the third and fourth IMFs that are related with the wheel-set condition.

Indicator	July	December
Peak (g)	1.13	0.21
RMS (g)	0.32	0.03

means to quantify the amount of vibration noise, see Table 1. The overall figures were greatly reduced after the tyre-rotation maintenance action.

When we tried to extrapolate this behaviour to the rest of the fleet (given the rapid wear function of the wheels), we did find that the overall trends were the same, but that the reliability of the degradation evolution model was only valid for the extreme values of the dynamic range (only when the indicators were clearly close to the upper or lower bounds). We must admit that we are uncertain about the condition of the test track, and that different tracks might have been used to conduct the experiments. However, we had no control over this environmental variable. Therefore, we cannot yet validate the generality of this approach to conduct a diagnostic and extract the condition of the wheel-set. Further research on this topic is indeed necessary, but we are confident that it may yield more promising results in the light of this preliminary study.

Discussion

The experiments conducted on the application of a small network of intelligent wireless sensors to the bogie of rolling-stock in order to assess the condition of axle-boxes and wheel-sets has provided rather promising results. The application of the EMD technique seems to be an effective solution to the problem of the overlap of vibration signals. We have obtained some evidence for this conclusion in the considered deployment. The vibration signatures of the axle-box and wheel-set were clearly identified in terms of specific IMFs, which were then used to conduct further analyses using classic vibration analysis approaches.

However, there are two main drawbacks that could limit the applicability of this approach. On the one hand, the high variability of the vibration signature with respect to an external variable sometimes makes it difficult to establish a concrete and steady analysis. The space of uncertainties is very high, and the vibration variable is rather sensitive to these changes. It is thus recommended to tackle the component analysis by considering an averaged statistical approach.

On the other hand, we have not explicitly taken into account the possible effect of inter-modulations. One of the main sources of vibration captured by the accelerometer can be considered to be a narrow-band noise (the wheel-set), and the other one can be accounted for as a mesh of at least one tone (the axle-box). Since the system is clearly nonlinear (the presence of harmonics is ubiquitous), the effect of inter-modulations might be expected. However, we cannot know the concise mathematical expression of the inherent nonlinearity, so we cannot assess it in any detail. Instead, we allow a certain degree of mismatch between the observed spectral signature and the theoretical location of the component faults in order to accommodate these shifted frequency modulations. Again, we recommend dealing with these issues by taking several tests and weighting the different analysis outcomes.

With respect to the heuristic selection of IMFs based on experience, it must be noted that further experimentation is necessary to reinforce the arguments given in this work as to what relation exists between the observed vibration mode, the corresponding IMF and the degradation of the component. This work was inspired by the application of EMD to rolling-stock[3] and follows the selection directives in that work that were based on experience. There are, though, other criteria based on more informed indicators that automatically weight the contribution of the selectors,[11] which will be worth considering in future work.

Conclusions

The application of a small network of intelligent wireless sensors to rolling-stock enables maintenance staff to monitor axle-boxes and wheel-sets with only a few sources of vibration data. Therefore, the testing and analysis time is reduced, and so is the cost of the maintenance actions. In the end, more reliable results can be delivered as the two components may be well-differentiated with the EMD technique as long as the test conditions are kept under control. However, more research is necessary to advance the general deployment of this predictive maintenance approach to railways.

Declaration of Conflicting Interests

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