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Monitoring of non-ballasted railway tracks in tunnel: development of a robot for the automatic detection of damaged concrete blocks

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Abstract

The non-ballasted technology has yielded numerous new railway tracks, especially in tunnels. The “low vibration track” (LVT) is a system developed in 1980s, and it today covers more than 1100km of track around the world, including the Channel tunnel. This system contains a concrete block based on a micro-cellular pad all integrated in a rubber boot embedded in the slab of unreinforced concrete. It is difficult to determine the block degradation because it is hidden by the surrounding. This article presents a fast and efficient detection method for the block monitoring. Basically, the block damage occurs in two types: vertical and horizontal cracks. Based on the modal analysis, this study firstly presents the link between the eigenmodes and the block damages by measurements and modeling. The 3D modeling shows that the first mode (flexion) and the second one (torsion) are influenced by two types of damage. Then, we present the database of 284 damage blocks to analyze the relation between eigenmode and damage. Finally, the detection method has been developed to identify block damage level by using modal analysis of vibration response. A robot called COBRA has been developed for the Channel tunnel which automatizes the block monitoring at a high speed.

Keywords: non-ballasted railway, non-destructive monitoring, modal analysis, robot.

1. Introduction

Railways have been evolving since the onset of the first rail rolled iron (1789). Wooden sleepers now give way to concrete sleepers, while, in some countries and commonly in tunnels, ballast is replaced by continuous concrete slabs. This type of track, however, requires the integration of rail support systems to ensure passengers' comfort. The “low vibration track” (LVT) system developed by the company Sonnevile is a system that contains a concrete block based on a micro-cellular pad all integrated in a rubber boot embedded in the slab of unreinforced concrete (see Fig. 1). This system today covers more than 1100km of railway track around the world, including the Channel tunnel.

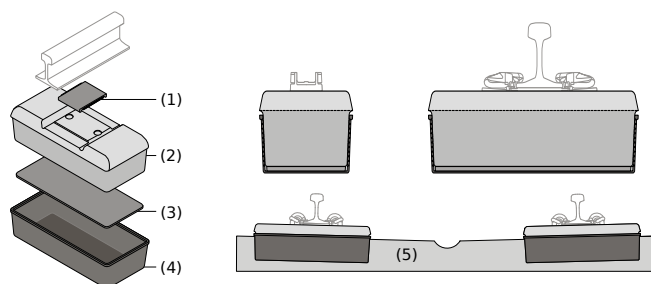


Fig. 1: LVT system: (1) rail pad, (2) block, (3) elastic pad, (4) rubber boot, (5) slab

The LVT system is very recent (compared to the ballasted track). There is very little research on the damage of this system. In addition, the damage is not easily observable because the block is inserted in the elastomer boot, which is embedded in the concrete slab. Thus, for the traditional monitoring during maintenance, the rail must be raised to be able to observe the block's upper surface. However, the observation result cannot identify all block damage because most cracks are inside and/ or at the lower

surface of the block. Therefore, it is necessary to have a method to detect block damages and this method must meet certain criteria:

- The method must be non-destructive. It must be applicable under normal track conditions so as not to disturb traffic after the measurement.
- The measuring time must be short enough because the total time for maintenance is limited.
- The result obtained with this method must make it possible to detect the state of general damage of the block in order to predict its remaining lifespan.

Among the non-destructive methods, the modal analysis appears best suited to the blocks. There are different methods of detecting damage based on the vibration response. The eigenfrequency method is the simplest one developed in the 1970s with research on frequency variation due to change in mass and stiffness of the structure. Salawu [1] summarized 65 articles on the damage detection from the frequency change. For example, Farrar [2,3] showed the existence of the change in natural frequencies of a reinforced concrete structure using numerical modeling and measurements. Plachý [4] used this method to detect bridge damage thanks to its excitation and mode measuring system. However, the measurement of the modal deformation requires to have several sensors placed in different positions of the structure. Wang et al. [5] proposed a new technique based on the FRF to identify structural damage with steel bars. Other techniques use the Hilbert-Huang transformation or wavelet transformation [6,7]. The advantage of these methods is that the data can be obtained directly from the vibratory responses in time independently of the modal domain.

The modal analysis has been applied for ballasted railway sleeper. Remennikov et al. [8] studied the coupling effect of the ballast on the eigenmodes of a sleeper using the finite element method and experimental measurements. They showed that the frequencies and damping of a sleeper increase significantly when the sleeper is placed on the ballast. Lam et al. [9] studied the feasibility of the modal analysis method to detect ballast damage. The authors showed how eigen modes change when ballast damage occurs. Matsuoka et al. [10] proposed a method of detection of damage using the measurement of eigenmodes in situ. These authors have shown that the 3rd mode is the most usable for detecting damage because it is not influenced by the ballast and the rail base. However, none of these methods has been developed for non-ballasted track. This is the aim of this article. We firstly present the measurement of block eigenmode and the relation between these modes and the block damage. This relation is then summarized and analyzed by modelling. Finally, we develop a database of damage level and eigenmodes, which is used for the block monitoring in situ.

2. Experimentation of railway mono-block

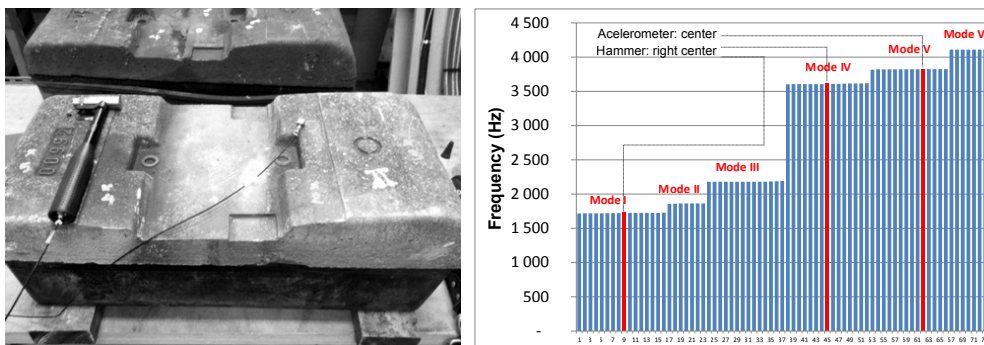


Fig. 2: Measurement devices (left) and eigenfrequencies of a block (right)

The measurement of block eigenmodes is shown in Fig. 2, where the accelerometer is glued on one end of the upper face of the block, and the block is excited by hammering by tapping with it on the other end. When the block is excited by the hammer, the vibration response from the accelerometer is converted to frequency response (FRF). Frequencies and damping coefficients are detected by FRF maxima. We ignore the peaks below 100Hz, which correspond to the noises and modes related to the

elastomeric components of the LVT system. Depending on the positions of the accelerometer and the hammer impact, the detected eigenfrequencies can correspond to different modes. We need to sort all detected frequencies to find the mode corresponding to each frequency (see Fig. 2 right).

We compare the frequencies and the damping coefficients of two blocks (a new one and a damaged one with cracks in the lower part). Tables 1 and 2 present these results with the variance and error of each mode. We see that the errors are small (<1% for the new block and <5 % for the damaged damaged). In addition, the frequencies of the damaged block are smaller than those of the new block.

Table 1: Eigen frequencies of a new block

<i>Parameter</i>	<i>Unit</i>	<i>Mode I</i>	<i>II</i>	<i>III</i>	<i>IV</i>	<i>V</i>	<i>VI</i>
Max	[Hz]	1728	1863	2191	3619	3825	4113
Min	[Hz]	1716	1856	2181	3603	3816	4109
Average	[Hz]	1723	1861	2182	3610	3823	4110
Variance	[Hz]	11.1	8.0	10.0	24.6	5.8	2.3
Error	%	0.6	0.5	0.4	0.4	0.2	0.1

Table 2: Eigen frequencies of a damaged block

<i>Parameter</i>	<i>Unit</i>	<i>Mode I</i>	<i>II</i>	<i>III</i>	<i>IV</i>	<i>V</i>	<i>VI</i>
Max	[Hz]	859	1222	1572	1866	2644	2919
Min	[Hz]	813	1163	1516	1803	2594	2906
Average	[Hz]	836	1187	1544	1839	2620	2914
Variance		193	180	423	317	317	31
Error	%	5.0	3.4	4.0	2.0	0.6	2.1

Then, we measure three categories of blocks: new or non-observed cracks (I), cracks in concrete (II) and broken blocks (III). We see that these categories have different frequencies. In particular, the more damaged the block is, the lower the frequencies are. However, the damping coefficients do not vary systematically in the same way. The blocks with small broken pieces have greater damping coefficients. On the other hand, the signals from damaged blocks are weaker and noisier than those of healthy blocks. This result therefore shows a relation between the eigenfrequencies and the block's damage. We note that the measurement of several modes is unnecessary because the big order modes of a damaged block can be confused with the first modes of a healthy block. This is why we will only study the first two modes of the block, which are sufficient to determine the types and levels of the block's damage.

3. Modelling of railway mono-block and validation

3.1 Calculation of the eigen frequencies of a new block

To calculate the frequencies and the eigen modes of the blocks, one uses the finite element method. From the geometrical data of the block, we created a 3D model using the ABAQUS. We use linear solid elements with reduced integration C3D8R with 130122 nodes and 124519 elements. Figure 3 presents the first three eigen modes of a new block.

- The first mode is a simple bending mode that has two nodes in $L/4$ and $3L/4$, where L is the length of the block.
- The second mode is a simple torsion mode in which the torsion axis is also the longitudinal axis passing through the geometric center of the cross section of the block.

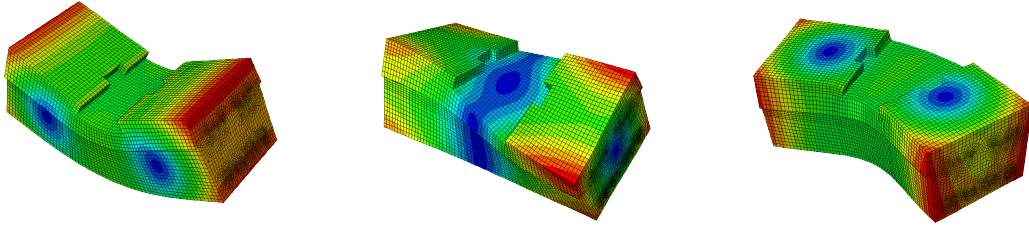


Fig. 3: First three eigen modes of a new block

Figure 4 presents the results obtained by modelling and measurement. We see that the results agreed well with the error less than 0.3% for the first mode and 5% for the sixth mode.

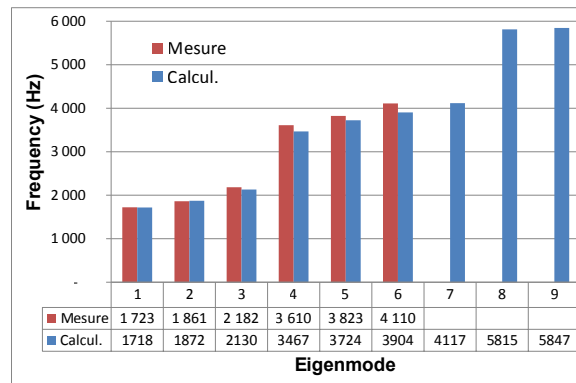


Fig. 4: Eigen frequencies by measurement and modelling

3.2 Calculation of the eigen frequencies of damaged blocks

The block works in bending, and the cracks appear in the middle plane or at the level of the bar in the case of the delamination. We can therefore define two types of crack: vertical and horizontal crack (see Fig. 5). We can define 7 types of damage, and we determine damage level depending on the size of the cracks for each type of damage. We have shown in this work that the frequencies of the first two eigenmodes depend on the type of crack (horizontal and vertical) and on the size of the crack in different ways. However, common features are observed:

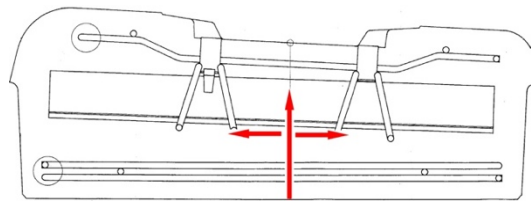


Fig. 5: Propagation of cracks in the block

- The first two frequencies always correspond respectively to the modes of bending and torsion.
- In general, cracking decreases in the first two frequencies systematically (when cracking increases, the frequency values decrease).
- Damaged blocks can cause new eigenmodes, and the order of the modes may change. But, the first two modes remain the same.
- The delaminating detachment of the lower part of the block is accompanied by a slight increase in the values of the frequencies. In this case, the ratio of second frequency on the first is larger.

4. Database and identification method

We have performed the measurement on 284 damaged blocks which are placed on the ground (free condition). For each block, the frequencies and damping coefficients of the first two eigen modes are measured. The vibration responses of the blocks are recorded by a laser vibrometer. To determine the damage level of the blocks, we observe the block surfaces (upper, lower and 2 lateral surfaces) and classify each surface according to 5 levels of cracking:

- Level 0: no crack or difficult to observe
- Level 1: initiation of cracks
- Level 2: cracks on the whole surface
- Level 3: crack opening
- Level 4: crack opening and broken

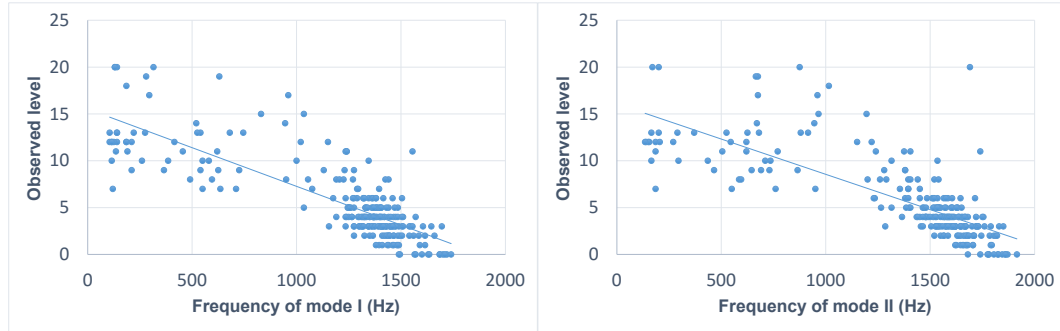


Fig. 6: Observed damages vs. the first (left) and second (right) eigen frequency

In addition, we also observe the delamination and rupture of each block, which are also classified according to 5 levels of delamination and rupture. In total, we have 5 observable criteria to determine the level of block damage. Photos of surfaces of the block are taken during the measurement. For each block, the level of damage obtained by the observation is defined by the sum of the levels on the 5 criteria. This level therefore globally represents the observable damage of the block, but it does not take into account the damage inside the block. Hence, the largest values are obtained for the most degraded blocks. The value zero corresponds to a block without crack. Figure 6 represents the variation of this level respectively according to the first and the second eigen frequencies of the block. We see that the lower the frequency, the greater the level of damage.

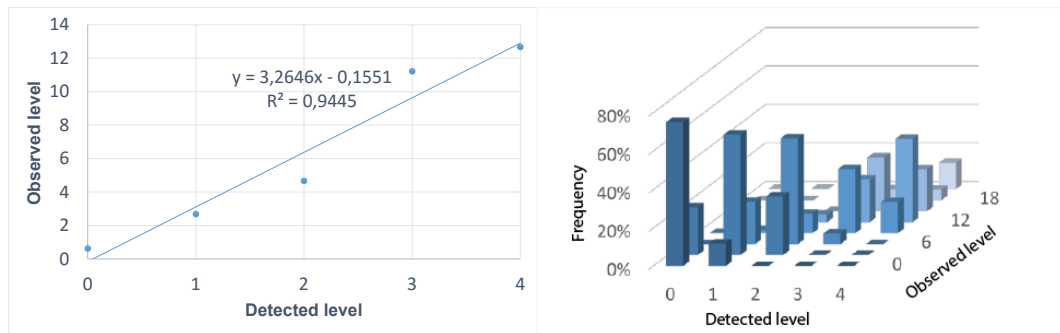


Fig. 7: Correlation between observed and identified level: average (left) and histogram (right)

Using the results of the modeling, the damage level of the block is determined from the frequencies of the first two eigen modes (detected level). We can then compare these levels with the level determined by the observation (observed level). Figure 7 shows that there is a good correlation between the detected and observed results. A database has been built from the measurement results. The identification of the level of block damage has been developed by calculating the standard deviation between the frequencies and the damping of the measured block and the database. This method is simple and effective when there is a sufficiently representative database. Moreover, this method is evolutive where the database can be enriched during monitoring campaigns. A robot called COBRA

(see Fig. 8) has been developed for automatic monitoring in the Chanel tunnel. This robot can automatically travel on the track, make an excitation, record response and analyze block's damage.

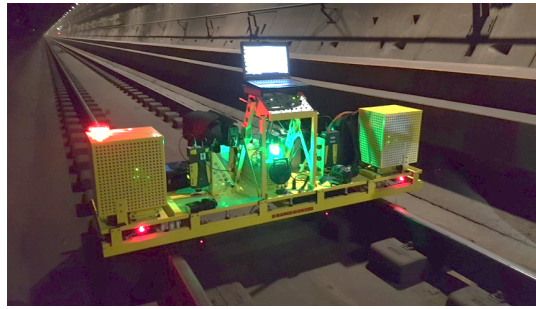


Fig. 8: Automatic monitoring of block damages: robot COBRA

5. Conclusions

We have developed a method of detection of damage of the block on the track by using vibration responses. It is shown that the eigenfrequencies and the damping of the blocks depend on the block's damage. This relation was studied by modeling using the finite element method and validated by measurements of 284 blocks. Then, the identification method has been developed from this relation and the measurement database. Finally, the robot COBRA has been developed for the automatic monitoring of the blocks which can analyze the vibration responses of the blocks to determine the level and types of damage to the blocks in situ.

Acknowledgment

This research is in collaboration with Eurotunnel Group, the owner and operator of the Channel tunnel (connection between France and England). A patent of the monitoring method has been submitted internationally.

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