AN ALTERNATIVE APPROACH TO SOLVE THE RAILWAY MAINTENANCE PROBLEM

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Abstract

In Italy there are more than 16.000 kilometers of railway. The Italian companies for the railway maintenance need every year a lot of money to guarantee the service efficiency. Nowadays, the control is manually executed by qualified technicians. ENEA suggests an alternative approach to solve the maintenance problem, installing accelerometers in opportune locations. Data acquired by means of sensors have been analyzed through the singular value decomposition (SVD) method. By experimentally obtained data, using the variation of modal parameters, it is possible to determine the warning threshold. An electronic system will be required to send the warning signal preventing damages, increasing the users' safety and saving money.

1 Introduction

Maintenance of railways has always been a problem of large interest. In the last years, the development of high speed trains has focused moreover the attention on the railway maintenance problem. In a first description, a railway is made of long beams, bolted (or supported in different ways) to concrete (or sometimes wooden) sleepers at regular intervals; sleepers lay on a ballast layer and finally on the ground surface. Due to several reasons, many kinds of damage can be found on a railway track. Ballast properties could be altered, connections between rail and sleepers (bolts or pads) could be loss or damaged.

The actual damage estimation techniques are based on visual inspection of railways, new approaches based on instrumented trains have been proposed. In this paper a new technique for the damage detection on railway tracks will be described. The main objective is to establish an effective instrument set-up in particular areas such as in curve, or for tracks which lay on bridges, subjected to severe motion, or in areas close to stations. In order to improve this approach, finite element models (FEM) as well an experimental model will be tested.

It is not easy to find works which deal with the damage detection in railway tracks. Many efforts are focused on the reduction of noise due to the wheel-rail interaction. FEMs for both the train wheels and the rail are proposed in several papers. In [7] the track has been modelled as an Euler-Bernoulli or a Timoshenko beam lying on spaced sleepers. All the physical parameters are given in the paper and an estimation of the pinned-pinned frequency is also established. The pinned-pinned frequency is defined as the first mode of a simply supported beam of length equal to the sleepers spacing. The goal of this paper is the definition of the waves' propagation from the wheel area to the other components. Different properties for the pad, the sleeper and the ballast have been investigated in order to provide a prediction of the system's attenuation. In [5] and in [6] the cross – sectional deformation has been investigated. Using the given parameters for the rail geometry, it has been shown that the cross-section deforms significantly above about 1500 Hz. In [4] experimental tests have been performed on a full scale track to define a vibration model of railway ballast. The shear stiffness and the shear damping have been introduced in the definition of a numerical model. In [11] the definition of a FEM has been validated by means of several field tests on a real track. The proposed model accounts the interaction between the train, the track and the soil. In [8] multiple layers are considered to model the track. Several beams interconnected by viscous-elastic layers have been used to model the rail, pad and ballast behaviour. A simpler FEM is proposed in [9] in order to represent a track model. Sleepers and ballast behaviour are modelled using linear springs and viscous dampers. A similar model has been presented by [12]. The rail lays on linear springs and dampers representing the rail-pad characteristics, a further layer of springs and dampers has been introduced in order to represent the ballast properties; geometrical and physical parameters are also presented in the paper.

2 Finite Element Model

This work aims to define a damage definition technique for railway systems avoiding the traditional visual inspection. In order to improve the method, a full scale experiment on a small portion of a railway will be presented (Figure 1). A F.E. analysis has been considered through Nastran to evaluate the modal behaviour.

The geometry of the model accounts the common measures for the Italian railways. The sleepers are placed at 700 mm, the rails are at 1050 mm, the cross section respects the prescriptive dimensions (UNI 3141); the total length is 8.60 m (12 bays).

The definition of the FEM is similar to the one shown in [9]. An in plane model has been considered. An Euler-Bernoulli beam with a proper section is constrained to a layer of discrete spring-dampers represented the interaction between the rail, the pad and the ballast.

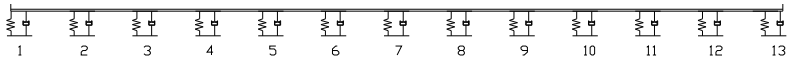


Figure 1 Finite Element Model

A simplified cross-section has been considered, using a double-tee section. Comparing the rail moment of inertia of the model with the one proposed in the prescriptions, a good agreement between the simplified and the real section is reached. In order to obtain the properties of the layer connecting the sleepers to the rail and to the ground, a table summarizing the properties found in

different works is shown (Table 1). Two different models are usually considered: a single layer (K, c) to model the connection track-pad-ballast, and a double layer to model with different properties the track-pad connection (K_p, c_p) and the pad-ballast connection (K_b, c_b).

	K_p [MN/m]	c_p [kNs/m]	K_b [MN/m]	c_b [kNs/m]
G.Lambert	153.4	13.5	920.7	16.6
L.Baeza	150	50	67.8	25.4
W.M. Zhai	65	75	78.4	80
Amy de Man	140	32	78.3	30

Table 1 Rail-ground connection, proposed properties

Considering the above shown values, a quite wide range has been proposed. In order to obtain a significantly representative FEM, different values will be taken into account and the main FEM modal characteristics will be compared with the experimental model. The values used in this paper are:

- K=70 MN/m
- c=20 KNs/m

It is easy to recognize a first order of modes, concerning the full model, which have frequencies under 150 Hz; and a second kind of vibration concerning single portions of the rail between two adjacent sleepers. The second kind of vibration is the so called pinned-pinned mode. In order to obtain an estimation of its value, a 70 cm long portion of the rail has been considered, giving a pinned-pinned frequency of 800Hz.

3 Experimental Set-up

A first application of the technique proposed in section 4 has been performed on a railway model. The model represents a 1:1 scaled railway of a total length of 8.60 m. All the model components respect the Italian prescriptions (Figure 2).



Figure 2 Experimental model: railway and sensors

In order to obtain the model modal properties, several impact tests using an instrumented hammer have been performed. It is not easy to simulate real damages. Changes in the connection between

track, pad and sleeper are frequent as well as changes in the ballast properties. In this experimentation, damaged scenarios, tightening bolts in several locations with a force lower than the prescriptions, have been considered. Four different scenarios have been considered:

- Scenario 1: undamaged structure
- Scenario 2: damage on sleeper n°7
- Scenario 3: damage on sleepers n° 3 and 11
- Scenario 4: damage on sleepers n° 3, 7 and 11.

Accelerations in six different locations have been measured (bay 3-4, 5-6, 8-9, 10-11, 12-13 and on sleeper n°7).

4 Damage Identification Technique

In order to identify possible damages on railway tracks, an appropriate number and location of sensors is here investigated. The problem which we are dealing with has to be considered an identification problem with unknown input. Frequency domain techniques are easily able to identify the system frequencies using peak-picking methods. It is possible to relate frequency changes to changes in the system configurations. However those changes are strongly dependent on several factors, as the temperature or the humidity in different moments.

Therefore a different approach is needed. Using a frequency domain approach, it is possible to identify the system's mode shapes. The procedure, aims to decompose the entire system in several single degree of freedom systems.

This technique [1, 2] is closely linked to Basic Frequency Domain techniques, such as peak picking techniques. In traditional techniques, it is easy to obtain good estimates of the system's frequencies. However with closely spaced modes, it may be difficult to accurately identify the power of each mode, and the mode shapes are hardly available.

The Frequency Domain Decomposition retains the classical frequency approach's advantages; the intermediate data presented to the user is generally intuitive. The user must manually select the dominant peaks, as in the classical peak picking techniques, ignoring anomalies from interference or input excitation leakage. Through a Singular Value Decomposition (SVD), the FDD effectively decomposes the *n*-DOF system into *n* SDOF systems

The Power Spectral Density (PSD) at discrete frequencies ω_i for the *m* measured responses *y(t)* due to the *r* inputs *x(t)* can be written as:

$$G_{yy}(\omega_i) = \overline{H}(\omega_i) G_{xx} H(\omega_i)^T \qquad (1)$$

where $H(m \times r)$ is the frequency response function and the overbar and superscript *T* indicate respectively the complex conjugate and the transpose. $G_{xx}(\omega_i)$ is the PSD of the *r* unknown inputs, constant with respect to frequency for white noise input. In that case, it can be shown that $G_{yy}(\omega_i)$ does not depend on the input but only on the frequency response.

The $G_{yy}(\omega_i)$ can be easily calculated through output-only data as Fast Fourier Transform (FFT) of the cross-correlation of the *m* measured responses *y(t)*. $G_{yy}(\omega_i)$ is then decomposed at discrete frequencies through SVD:

$$G_{yy}(\omega_i) = \overline{U} S U^T \qquad (2)$$

where $S_i = diag[s_{i1} \quad s_{i2} \quad ... \quad s_{im}]$ contains the singular values and $U_i = [u_{i1} \quad u_{i2} \quad ... \quad u_{im}]$ contains the respective singular vectors.

When the frequency ω_i is close to a structural mode, i.e. when there is a peak in the plot of the singular values, the first singular value s_{i1} becomes dominant and the respective singular vector ($u_{i1} = \phi$) is assumed to be an accurate estimate of the real mode shape.

This approximation of the real mode shape could be used in order to establish the presence of damage in the system, comparing the mode shapes (ϕ_a^T and ϕ_b^T) for different times (t_a and t_b). Using the Modal Assurance Criterion (MAC) it is possible to establish if a difference has occurred for different instants.

$$MAC = \frac{\left(\phi_a^T \cdot \phi_b^T\right)^2}{\left(\phi_a^T \cdot \phi_a\right)\left(\phi_b^T \cdot \phi_b\right)} \qquad (3)$$

In the experimentation, different values for the MAC coefficient will be calculated for different configurations. If its value considering the undamaged configuration and a further one is close to 1, it is possible to asses that no damage or a light damage occurred; if its value decreases, the railway is affected by damage. The smaller is the MAC value, the higher is the damage level.

5 Experimental Results

Using data from the six accelerometers on the track, it is possible to identify the structure's frequencies. Characteristics of the structures are approximately known from the FEM. Frequencies at about 50-100 Hz are connected with the bending modes of the whole track; while higher frequencies (800 Hz) are connected with the pinned-pinned modes. In Figure 3-6 the FFT of the six accelerations for the four different scenarios are presented. In each of them, modes at about 50-100 Hz appear clearly. In this section we aim to demonstrate that, even if there are no evident changes in the frequencies, it is possible to recognize changes in the mode shapes.

A mode at about 90 Hz appears has been identified for all the system FFTs for different scenarios. Using the technique described in section 4, it is possible to calculate an estimation of the mode shape. For each damage scenario the approximate mode shape has been obtained (Figure 7).

The MAC coefficient given in equation 3 is then calculated in order to estimate the damage level for each scenario. In Table 2 the three values are shown.

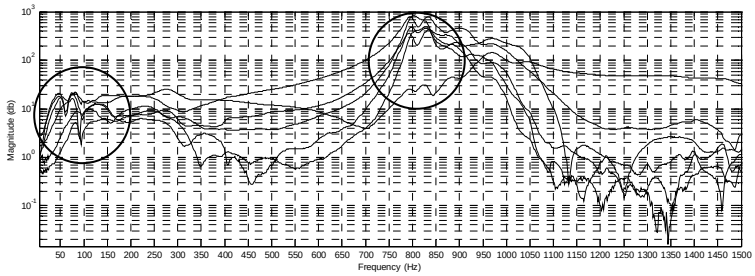


Figure 3. FFT of the 6 channels, for undamaged scenario (scenario 1).

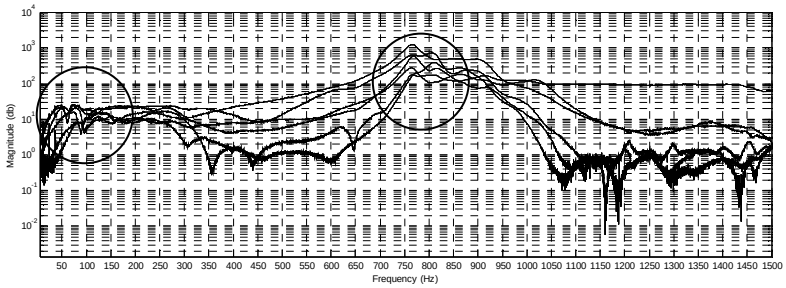


Figure 4 FFT of the 6 channels, for damaged scenario 2.

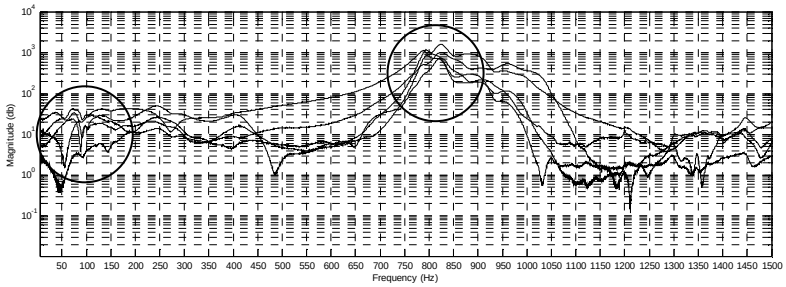


Figure 5. FFT of the 6 channels, for damaged scenario 3.

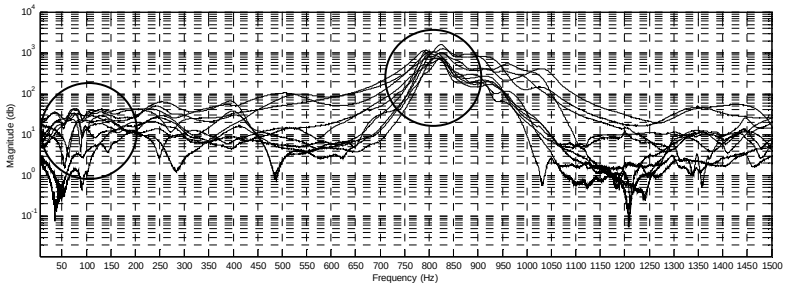


Figure 6 FFT of the 6 channels, for damaged scenario 4.

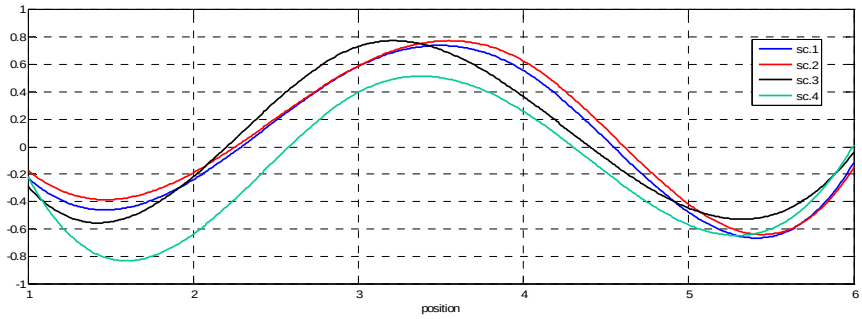


Figure 7 Mode shapes, scenarios 1-4.

Damaged scenarios	MAC values
Sc. 2	0,95
Sc. 3	0,92
Sc. 4	0,76

Table 2 MAC values for the damaged scenarios

6 Conclusions

In order to establish the presence of damage on railways, an approach based on SVD has been proposed. This approach has been tested on a 8.60 m. long model representing a real railway. To simulate a known damage level, bolts in several locations have been tightened at a lower level. Three different damaged scenarios have been simulated. Using the proposed approach, mode shapes have been identified. Calculating the MAC value for corresponding mode shapes in different scenarios, it is possible to relate its value with the damage level.

A complete experimentation on a real railway will be performed (Figure 8). In some initial tests, railway's responses to normal traffic have been measured. In further tests, a higher number of sensors will be used in order to identify mode shapes in different times. Damage due to usual exercise will be identified through visual inspection and compared with the proposed approach.

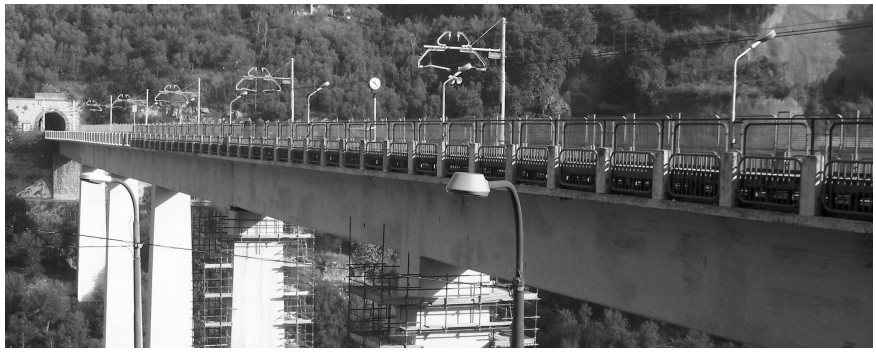


Figure 8 Railway on a bridge, Seiano (Naples).

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