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UTILIZATION OF SPECTRAL VELOCITY OF FLEXURAL WAVES TO DETECT LOOSE SLEEPERS

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Abstract

The identification of a loose sleeper is important for the operation and safety of a railway system because the excessive movement of a loose railway sleeper can cause derailment and passenger discomfort. There are available methods on how to detect a loose sleeper, such as: 1) a method using a conventional approach based on human judgement and experience, which is not advisable if the researcher is a beginner; 2) Fixed Post method, wherein a fixed post with displacement sensor is installed in a ballast, which is not reliable because vibration of a sleeper during train passage might affect the results from this test; and 3) Non-Destructive Testing (NDT) methods, which include the use of Light Falling Weight Deflectometer (LFWD) and line scan camera, both of which are, however, expensive to use for a routine testing technique. In this paper, Finite Element Analysis (FEA) was performed to set the criteria for the loose sleepers. Impulse Response (IR) Method was used on an actual site. The spectral velocity of flexural waves and mobility function from the impulse response test were proposed to investigate the quality of a railway sleeper.

Keywords: Ballast, FEM, Flexural velocity, Loose sleepers, Mobility function, NDT.

1. Introduction

A loose sleeper is attributed to a void space between a concrete sleeper and a ballast track bed. A loose railroad sleeper, if there are any, should be replaced for a safe railway operation. Rail distortion and derailment caused by a loose sleeper can adversely affect safety and passenger discomfort.

The most common way of detecting a loose sleeper is human judgement and experience using an acoustic sound generated by impact rod to the sleeper [1].

However, this method is not preferred if the person conducting this test has not accumulated experience. Another way to detect a loose sleeper is the Fixed Post Method. This method requires a fixed post with displacement sensor penetrated in the ground. This method is affordable and practical. However, it is not reliable because the vibrations caused by a moving train load can affect the results of this method [2].

There are also non-destructive testing (NDT) methods available to detect loose sleepers, which included the use of Light Falling Weight Deflectometer (LFWD) and line scan camera. The LFWD is a device typically used to measure the degree of compaction of soil. This is a fast and simple method [3]. Another NDT method is by using line scan cameras to shoot the vertical displacement when a train passes, which makes it possible to measure the displacement [2]. Both techniques are useful but not practical because they are expensive to be used as a routine testing technique.

The objective of this paper is to use Impulse Response (IR) Method to detect a loose sleeper. From this method, the spectral velocity of flexural waves is determined to detect a loose sleeper. The use of velocity to determine the quality of concrete material has been done before. Mirmiran and Wei [4] conducted a study about damage assessment of fibre reinforced polymer (FRP) encased concrete using ultrasonic pulse velocity (UPV). Their study found that concrete with FRP has higher sensitivity at lower stress ratios as compared to plain concrete. Another study using UPV was conducted by Hong et al. [5]. Their study uses UPV to estimate compressive strength of concrete structures, then compare its results with the velocities analyzed using Spectral Analysis of Surface Wave (SASW) method. Their study showed a good correlation between compressive strength and velocities. Kaewunruen and Remennikov [6] investigated prestressed concrete sleepers using low-velocity impact analysis and the result of this study provided a very good correlation with their numerical simulations.

This paper will also include the use of mobility function from IR method to investigate a loose sleeper. Mobility has been used as early as 1947 based on a study by Ottosen et al. [7]. Ottosen et al. [7] investigated the theoretical interpretation of impulse response tests of embedded concrete structures. Their research used three conditions: (1) both slab and soil should be in good condition; (2) a void should exist in the soil immediately below a portion of the slab; and (3) part of the concrete slab should be poorly consolidated. Their study found that a specimen with void in the bed would increase the mobility for small frequencies, however, the mobility curve at higher frequencies is unchanged. They also found that honeycomb in the concrete will increase the mobility at high frequencies, however, it causes insignificant changes at low frequency.

Additionally, this paper will also perform finite element analysis for several cases, which includes materials with best to worst conditions. For this paper, a material with the highest stiffness is considered as best condition, while a material with the lowest stiffness is considered as the worst condition. Results from the simulation using finite element analysis will be the basis of the criteria in categorizing the condition of the railroad concrete sleeper.

2. Finite Element Analysis for Dynamic Response of Railway Sleepers

Finite element analyses were conducted to analyze the response of a concrete sleeper when an impact load is applied. The result from the finite element analysis will be the basis of the criteria to categorize the quality of a tested concrete sleeper. The model for the finite element analysis is shown in Fig. 1. The whole system was modelled using a three-dimensional solid element. The modelled railway sleeper is 80% embedded. A hinge boundary condition was placed on top of elastic concrete tracks, while the ballast is modelled with an infinite boundary condition. For this study, two ballast sections were modelled, namely, Ballast 1 and Ballast 2, to represent the end support and the central support of a sleeper, respectively. A half sine loading with a maximum load of 1 Newton and period of 0.0025 seconds was used to simulate impact source.

To simulate the degraded properties of ballast, density (ρ) and velocity of the hear wave (v_s) were reduced. The reduced parameters were used to simulate a weakened ballast. Shear modulus (G) for a normal Ballast 1 was 94 MPa and the poor Ballast were 3, 12, 30 and 56 MPa, respectively. Although a loose sleeper is attributed to a void space between a concrete sleeper and a ballast, modelling with void space was not conducted during the finite element analysis because there are a lot of possible location of void space in the ballast. Instead of modelling with void space, ballast with the lowest stiffness (or ballast with the worst condition) is assumed as void.

A numerical model for a ballasted track was simulated as shown in Fig. 1. It is conducted by deploying two sensors at the surface of a concrete sleeper to determine particle velocity response at both centre and end of the sleeper in the vertical direction. From this simulation, h_C and h_R are achieved as the responses of the first sensor (centre of the sleeper), and the second sensor (edge of the sleeper), respectively. Figure 2(a) shows the particle velocity history, while Fig. 2(b) shows spectral velocities of H_C and H_R corresponding to time histories, h_C and h_R, respectively.

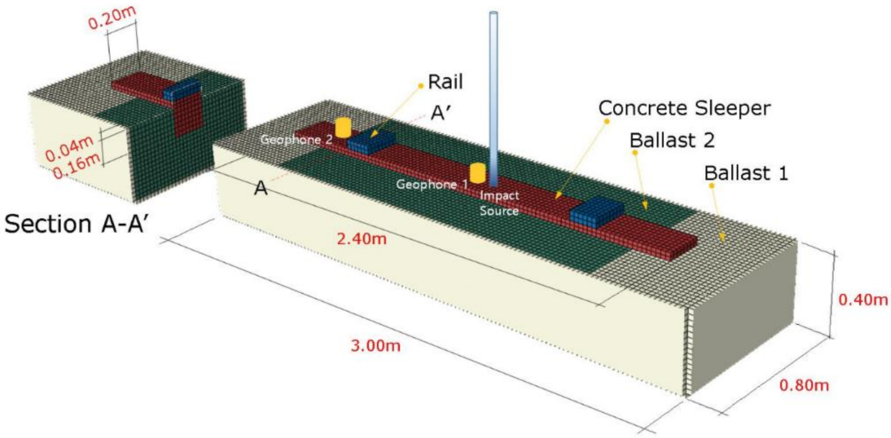


Fig. 1. Finite element model.

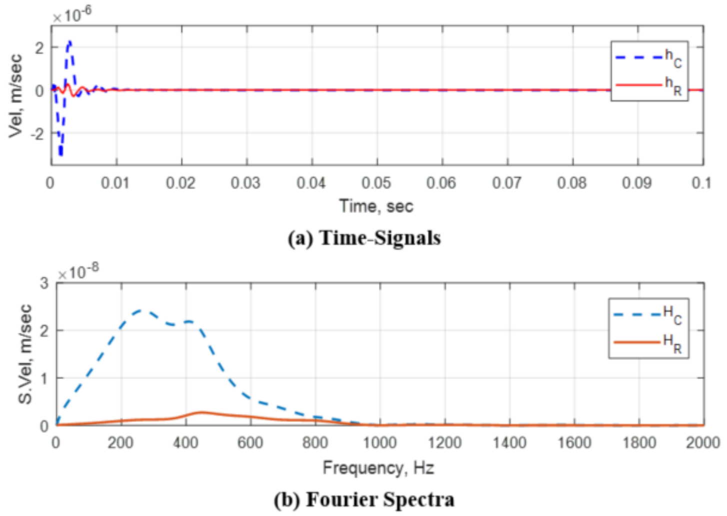


Fig. 2. Typical dynamic response of a good ballast based on finite element analysis.

The second sensor, located at the edge of the sleeper, is considered as a reference because it is far from the impact source. Transfer functions H_{CR} and H_{CS}, as shown in Figs. 3(a) and 3(b), are computed using Eqs. (1) and (2). In Eq. 2, H_S refers to the Fourier transform of the source function used in the finite element analysis.

$$H_{(CR)} = \frac{H_C}{H_R} \tag{1}$$

$$H_{(CS)} = \frac{H_C}{H_S} \tag{2}$$

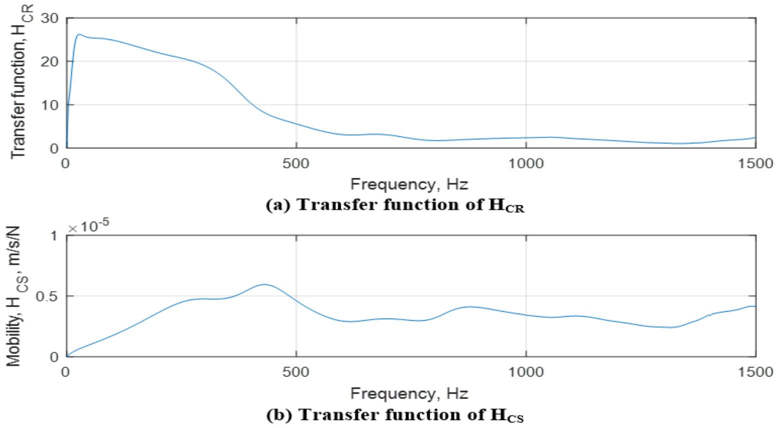


Fig. 3. Transfer function of a good ballast based on finite element analysis.

During the finite element analysis, five different conditions of a central ballast were investigated for the establishment of the criteria for a loose sleeper. The shear moduli used for the different conditions of centre ballast were 3, 12, 30, 56 and 94MPa, respectively. In addition, the shear-wave velocities corresponding to the shear moduli of the ballast conditions are 50, 100, 150, 200 and 250 m/s, respectively.

3. Detection of Loose Concrete Sleepers

Using the results from the finite element analysis, several possible methods were proposed to detect a loose concrete sleeper. The first method is to obtain the ratio of the peak spectral velocities of H_C and H_R. The second method is to utilize the peak amplitude of transfer function between the centre receiver and the reference receiver (H_{CR}) . The third method uses peak spectral velocity of centre receiver(H_{Cpeak}) for each of the conditions. The last proposed method utilizes the slope of mobility function (H_{CS}). For this method, mobility is defined as the ratio of spectral velocity and spectral impulse, as shown in Eq. 2. The reciprocal of the slope of mobility function is the dynamic stiffness of the structure. Therefore, the slope of the mobility function is an indicator of the system stiffness.

Figure 4 shows the results of finite element analysis for the moduli of different ballasts normalized by the maximum result in all the analyses. From the comparison in Fig. 4, methods 3 and 4 clearly reflect the distinction between the different conditions. These show that both these methods are used to investigate the quality of concrete sleeper.

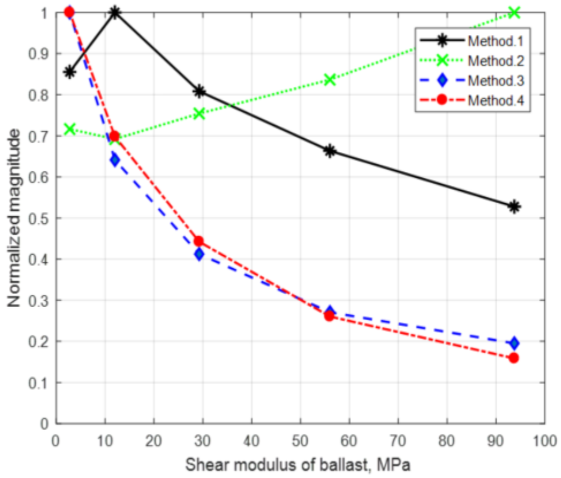


Fig. 4. Comparison of the four methods from finite element analysis.

Figure 5 shows the comparison of all peak spectral velocities at the centre receiver, determined by method 3. Softer ballasts give higher peaks in spectral velocities. Thus, an increase of peaks in spectral velocities implies a degradation of ballast quality.

The comparison of different conditions for method 4 is shown in Figs. 6(a) and 6(b). Method 4 utilizes the slope of the mobility function. Softer ballasts have steeper slopes, thus, having lower dynamic stiffness.

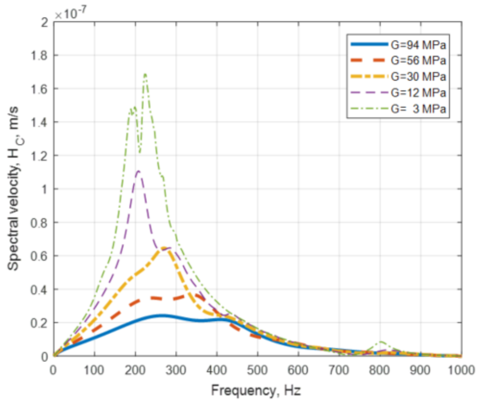
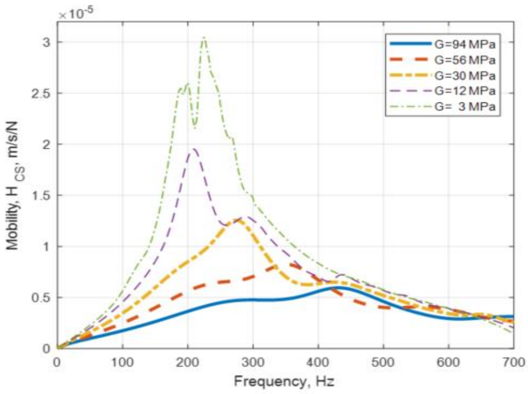
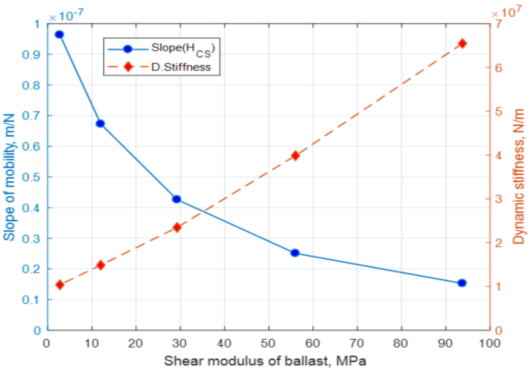


Fig. 5. Result of method 3 for all conditions.



(a) Mobility function for all conditions.



(b) Comparison between slope of mobility function and dynamic stiffness.

Fig. 6. Result of method 4 for all conditions.

4. Field Application

In this paper, the impulse response method is proposed to detect a loose railroad sleeper. In this section, an application of impulse response method was made to actual railway sleepers.

A section of concrete sleepers on a ballasted track was investigated. Sixteen sleepers were selected (Sleepers no. 48 to 64). Impulse response tests were performed to determine peak spectral velocities and dynamic stiffness. To measure particle velocities of a concrete sleeper due to an impact, a geophone was used as a sensor. Also for the measurement of dynamic stiffness of a concrete sleeper, both an accelerometer and a geophone were used. The geophone was placed at the centre of the sleeper and the shock accelerometer was attached to the hammer. The measured velocities and acceleration were converted to spectral velocities and spectral accelerations by Fast Fourier Transform.

NI-USB 4431, a dynamic signal analyzer, was used for data acquisition, as shown in Fig. 7. This device was used to measure particle velocities of a geophone and accelerations of a shock accelerometer for an impact loading.

(a) NI USB-4431 (b) Shock Accelerometer and Geophone

Fig. 7. Data acquisition device and sensors used during the field test.

Velocity and acceleration histories of two concrete sleepers (Sleeper 52 and Sleeper 57) were measured using NI USB-4431 are shown in Figs. 8(a) and 8(b), respectively. Figures 8(c) and 8(d) show spectral velocities and spectral accelerations at corresponding concrete sleepers. Lastly, Figs. 8(e) and (f) show the transfer functions of a concrete sleeper for an impact loading. Evidently, Sleeper 57 has a higher peak spectral velocity than Sleeper 52. Referring to the results of the finite element analysis, Sleeper 52, apparently, is in a better (denser) condition, as compared with Sleeper 57.

Figure 9(a) shows the resulting peak spectral velocities for the all the tested concrete sleepers. The comparison of peak spectral velocities indicates that sleepers 55, 56, 57 and 58 are in the worst condition, compared with other concrete sleepers. Similarly, the result from dynamic stiffness also shows that the sleepers with the worst condition are sleeper 55, 56, 57 and 58. These results agree with the field engineer's judgement based on uncomfortable vibrations while conducting impulse response test.

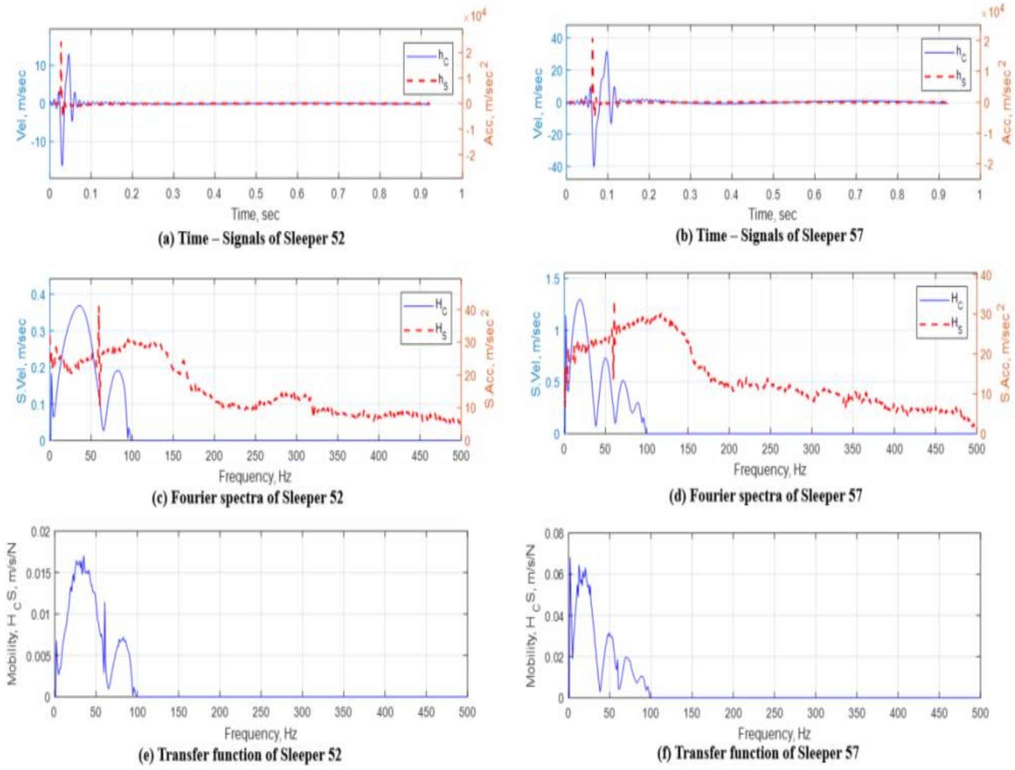


Fig. 8 Velocities of sleeper 52 and sleeper 57.

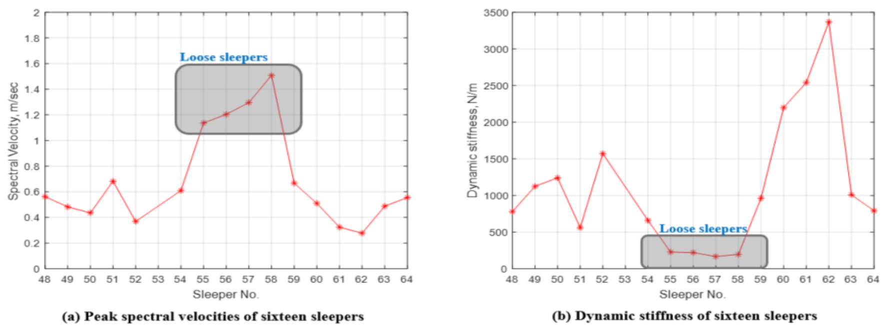


Fig. 9. Summary of peak spectral velocities and dynamic stiffness of sixteen sleepers.

5. Summary and Conclusions

Impulse response test was conducted to detect a loose railway sleeper. Simultaneously, finite element analysis provided the basis for the criteria of sleeper quality. The findings from the research are summarized as follows:

- The process of the impulse response method is simulated using finite element analysis.
- From the results of the finite element analysis, four different methods were investigated to find the most effective way to figure out loose railroad sleepers.
  - Method 1: The first method utilizes the ratio of the peak spectral velocities of H_C and H_R.
  - Method 2: The second method is to use peak amplitude of transfer function between the centre receiver and the reference receiver (H_{CR}).
  - Method 3: The third method is to use the peak spectral velocity of the centre receiver (H_{Cpeak}) for each of the conditions.
  - Method 4: The last proposed method utilizes the slope of the mobility function.
- From the comparison of all the methods, method 3 and method 4 proved to be useful indicators of the quality of the railway sleepers.
- Impulse response test was conducted at an actual site. The spectral velocities from the chosen sleepers proved that method 3 would be reasonable to categorize quality of a concrete sleeper.
- Further research about this topic should be conducted in the future to finalize the quantitative criteria in determining the quality of concrete sleepers.

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