A Novel Algorithm for Identifying Ballast Dynamic Properties from Impact Testing Method

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Abstract. In the past few years, the railway industry has been facing an unprecedented demand for the expansion of the railway network leading to the widespread use of ballasted tracks. Ballasted tracks are easy and quick to construct, making them a cost-effective solution for the railway industry. Ballast dynamic properties play a crucial role in the analyses for the performance and safety of the railway system, so accurate identification is necessary. Previous studies have taken a simplified approach by treating the sleeper-ballast system as a single-degree-of-freedom (SDOF) for ease of analysis. However, this overlooks the impact of sleeper stiffness and damping on the system's dynamic behavior. To account for this, a multi-degrees-of-freedom (MDOF) model can be used. The sleeper-ballast numerical model will be based on a beam resting on an elastic foundation, where the sleeper is modelled as a finite element beam and the ballast layer is represented as a spring-damper foundation. Traditional methods for testing of ballast dynamic properties are time-consuming and destructive, which can result in significant disruption to the railway network, therefore a non-destructive testing method that accurately characterizes the ballast dynamic properties is necessary. An instrumented impact hammering method, a non-destructive-testing approach, will be chosen. The impact force obtained from the testing will be used as an input parameter for the identification algorithm, the simulated and measured acceleration response will be curve-fitted by adjusting the ballast dynamic properties in the numerical model until the sum-square-residual of the two data sets reaches the acceptable range. This insight will provide a more accurate identification algorithm that can be further used for ballast dynamic properties.

Keywords: Ballasted track, Concrete Sleeper, Non-destructive-testing method, Impact Hammer test, Dynamic Simulations, Beam resting on an elastic foundation.

1 Introduction

Mainly, there are two types of railway tracks being used in a modern railway track structure namely ballasted tracks and slab tracks (ballastless tracks). Due to the demand for a rapid construction of low to medium speed tracks, often the ballasted tracks will be adopted. Ballast is a layer of granular material, typically sourced locally, that supports the sleepers and distributes the load to the underlying layers and allows water to flow through it. It is commonly made of rock and layered to create sufficient porosity for desired water flow [1].

Ballasted track structure which consists of rail, fastening system, sleepers, ballast, sub-ballast, and subgrade in that order. Ballast dynamic properties play a crucial role in the analyses for the performance and safety of the railway system, so accurate identification is necessary. Numerous studies have been done in attempts to accurately identify the ballast dynamics properties [1-4]. Traditional methods for testing of ballast dynamic properties are time-consuming and destructive, which can result in significant disruption to the railway network, therefore a non-destructive testing method that accurately characterizes the ballast dynamic properties shall poses beneficial for the railway industries.

This study will provide a more accurate representation of the sleeper-ballast interactions, by considering the impact of sleeper stiffness and damping on the system's dynamic behavior. By using a multi-degrees-of-freedom (MDOF) model of a full-scale track instead of a single-degrees-of-freedom (SDOF) model which has been used in [1, 4]. However, an instrumented impact hammering method, a non-destructive-testing approach will still be used in this study due to their advantages in the ease of usage and cost-effectiveness. The instrumented impact hammering method involves the use of an impact hammer to generate impulse on the sleeper and ballast layers, and the resulting vibrations are measured by sensors placed on the track. These measurements are then used in the idealization algorithm to identify the dynamic properties of the ballast layer, including its stiffness and damping coefficients.

The use of a MDOF model allows for a more detailed analysis of the sleeper-ballast interactions, considering the complexities of the system's behavior. This can lead to a more accurate representation of the ballast dynamic properties, which can ultimately improve the performance and safety of the railway system.

Overall, the non-destructive testing approach using the instrumented impact hammering method, combined with a more advanced MDOF model, provides a valuable tool for the railway industry to accurately identify the dynamic properties of ballast tracks in a timely and cost-effective manner.

2 Numerical Modelling of Sleeper-Ballast Layer

In order to accurately identify the ballast dynamics properties an accurate idealization of the structural system shall be made. Therefore, in this study the sleeper-ballast is modelled as a system of an Euler beam resting on a viscoelastic foundation with foundation stiffness and damping as k_b and c_b respectively. Fig 1 depicts the idealized sleeper-ballast systems with the sleeper elastic modulus, moment of inertia, cross sectional area and density as E_s, I_s, A_s and ρ_s respectively. For simplicity, the stiffness and damping value of the ballast are assumed to be the same in all regions.

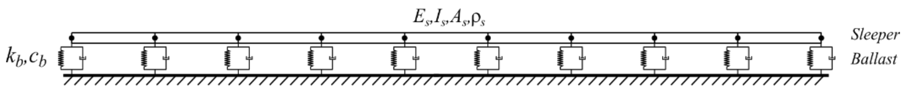

Fig. 1. Idealization of sleeper resting on ballast layer modelled as a viscoelastic foundation

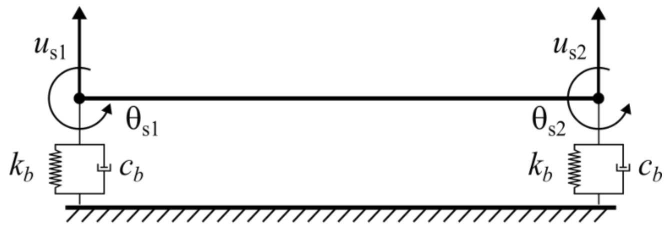

Fig. 2. Euler beam resting on viscoelastic foundation element

A formulation of an Euler beam element could be found in numerous literatures. The beam element formulation will be based on the derivation by Logan [5] in which a consistent mass matrix will be used. Fig. 2 shows the element used in modelling the sleeper-ballast system. The beam element will be discretized into four degrees of freedom (see Fig. 2), with the ballast foundation spring and dashpot connecting at each of the starting nodes of the beam element. The element mass and stiffness matrix could be expressed as follows [5]:

$$\mathbf{M}_e = \frac{\rho_s A_s L}{420}\begin{bmatrix} 156 & 22L & 54 & -13L \\ 22L & 4L^2 & 13L & -3L^2 \\ 54L & 13L & 156 & -22L \\ -13L & -3L^2 & -22L & 4L^2 \end{bmatrix} \tag{1}$$

$$\mathbf{K}_e = \frac{E_s I_s}{L^3}\begin{bmatrix} 12 & 6L & -12 & 6L \\ 6L & 4L^2 & -6L & 2L^2 \\ -12L & -6L & 12 & -6L \\ 6L & 2L^2 & -6L & 4L^2 \end{bmatrix} + 0.5Lk_b\left(\mathrm{diag}\begin{bmatrix}1 & 0 & 1 & 0\end{bmatrix}\right) \tag{2}$$

Rayleigh damping is assumed for the sleeper element, which will be computed from the assembled mass and stiffness matrix, due to the orientations of each element being similar and selected to be in the same direction as the global coordinates of the sleeper-ballast system. Therefore, no further transformation of the element matrices is needed. From Eq.(1) and Eq.(2). The formula for calculating the system damping matrix could be expressed as follows:

$$\frac{1}{2}\begin{bmatrix} 1/\omega_i & \omega_i \\ 1/\omega_j & \omega_j \end{bmatrix}\begin{bmatrix} a_0 \\ a_1 \end{bmatrix} = \begin{bmatrix} \zeta_i \\ \zeta_j \end{bmatrix} \tag{3}$$

$$\mathbf{C} = a_0\mathbf{M} + a_1\mathbf{K} + 0.5Lc_b\left(\mathrm{diag}\begin{bmatrix}1 & 0 & 1 & 0 & \cdots\end{bmatrix}\right) \quad (4)$$

The damping matrix of this system can be calculated by solving Eq.(3) for coefficient a_0 and a_1 with selected damping ratio ζ_i and ζ_j for given modal frequencies ω_i and ω_j respectively, then using the solved coefficient a_0 and a_1 with Eq.(4) to finally calculate for the damping matrix of the sleeper-ballast system.

With the system matrices calculated, the system equation of motion could be written as follows:

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{C}\dot{\mathbf{x}}(t) + \mathbf{K}\mathbf{x}(t) = \mathbf{F}(t) \quad (5)$$

Where $\mathbf{x}(t)$ and $\mathbf{F}(t)$ being the system displacement vector and system excitation force respectively.

3 Dynamic identification algorithm

The proposed testing methodology is an adaptation of the method employed by Kaewunruen and Tang [1].

From the discretization of the sleeper-ballast layer in Section 2, we can see that the degrees of freedom of the ballast layer will not be included in the system instead it will be idealized as a spring and dashpot only. As derived in Section 2, stiffness of the structure will be a combination of the sleeper and ballast, which in turns leading to natural frequency being dependent on both the sleeper and ballast stiffnesses. As a result, the natural frequency obtained from typical modal analysis by curve fitting the freqeuncy response function (FRF) from the measured response and analytical solution is not sufficient enough to determine the stiffness and damping of the ballast layer due to the dependency between the full stiffness of the discretized structure and the ballast stiffness. Therefore, a dynamic properties identification algorithm will be developed to address this issue.

The initial step in creating the algorithm for identifying dynamic properties is to create an algorithm to derive the desired output from the available input accurately. The output desired from the testing is the ballast dynamic properties (k_b and c_b). The inputs that can be measured from the impact hammering method are the impact forces and the acceleration response of the sleeper. Based on these input and output, a general process for identifying ballast dynamics can be summarized (see Fig. 3) .

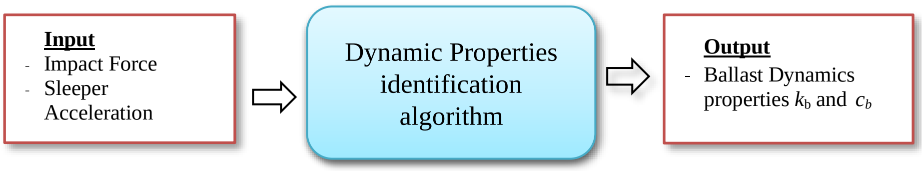

Fig. 3. Ballast dynamics properties identification process

In order to develop the identification algorithm, a numerical model of the structural system shall first be discretized. Let's consider a case of impact force acting on the sleeper resting on a ballast similar to the impact testing procedure. With the accelerometer, we can measure the acceleration at any point of the sleeper as shown in Fig. 4. The structural equation of motion and system matrices required for the numerical simulation has already been derived in Section 2.

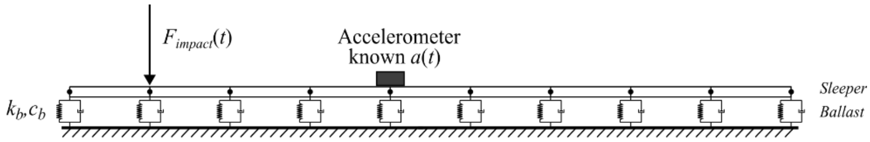

Fig. 4. Numerical simulation of impact hammer testing of sleeper-ballast system

In order to simulate for the structural response, the numerically modelled sleeper-ballast system will be solved using Newmark's method [6]. Since the ballast dynamics properties are unknown, a regression model will be applied to fit the simulated response to the measured structural response from the experiment, and the ballast stiffness and damping properties will need to be readjusted to minimize the objective function defined in Eq.(6) until the objective function reaches an acceptable tolerance value [7].

$$\mathbf{P}_i = \left\| \hat{\mathbf{r}}_i - \mathbf{r}_i \right\|_2 \leq \text{tolerance} \tag{6}$$

Where $\mathbf{P}_i$, $\hat{\mathbf{r}}_i$ and $\mathbf{r}_i$ being objective function to be minimized, simulated structural response, and measured response respectively at iteration i. With the operator $\|\cdot\|_2$ being the L^2 norm of the vector inside, which can be called as a square root of the sum squares (SRSS).

The process for the ballast dynamic properties identification is summarized in Table 1 and Fig. 5.

4 Numerical Example

In order to assess the efficiency of the identification algorithm, numerical case study will be carried out. Simulation of the impact testing will be carried out in MIDAS civil using 3D solid elements model (see Fig. 6.) with a ballast foundation modelled as a discrete nodal discrete spring as shown in Fig. 6. with the parameters extracted from studies by Lam and Wong [3] as shown in Table 2 except the impact forces and impact time. The impact force will be generated using parameters provided in Table 2 using the following MATLAB script.

```
%This script generate impulse
P0 = -10^3;
tspan = [0,0.18];
dt = 0.00001;
T_imp = 0.00625; %impact time
```

```
time = tspan(1):dt:tspan(2);
H1 = time>0;
H2 = time==0;
H3 = time-T_imp>0;
H4 = time-T_imp==0;
TOT = H1+H2-H3-H4;
func = @(t) P0*sin(pi()*t/T_imp);
P_imp = func(time).*TOT;
P_out = [time',P_imp'];
writematrix(P_imp,"Impulse.csv")
```

The impact force will be input at the middle as shown in Fig. 6. . The extracted acceleration responses at the leftmost, rightmost, and middle node of the sleeper will be used as an input for the objective function to be minimized due to the idealizing parameters being 2 parameters therefore 3 unique outputs should be used in the algorithm in order to obtain an accurate parameter.

Table 1. Ballast dynamic properties identification process

Testing process
1. Impact testing of sleeper (get acceleration response, impact load)
Simulation Process
2. Assume k_b and c_b
3. Simulate structural response under measured impact load with the assumed k_b and c_b using Newmark's method algorithm
4. Compare the simulated response to the measured response per objective function define as shown in Eq. (6).
5. If the sum of objective function exceeds the set tolerance, repeat steps 2 to 5 until the objective function reduced to the set tolerance, otherwise proceed.
Postprocessing steps
6. Store data from each testing process.

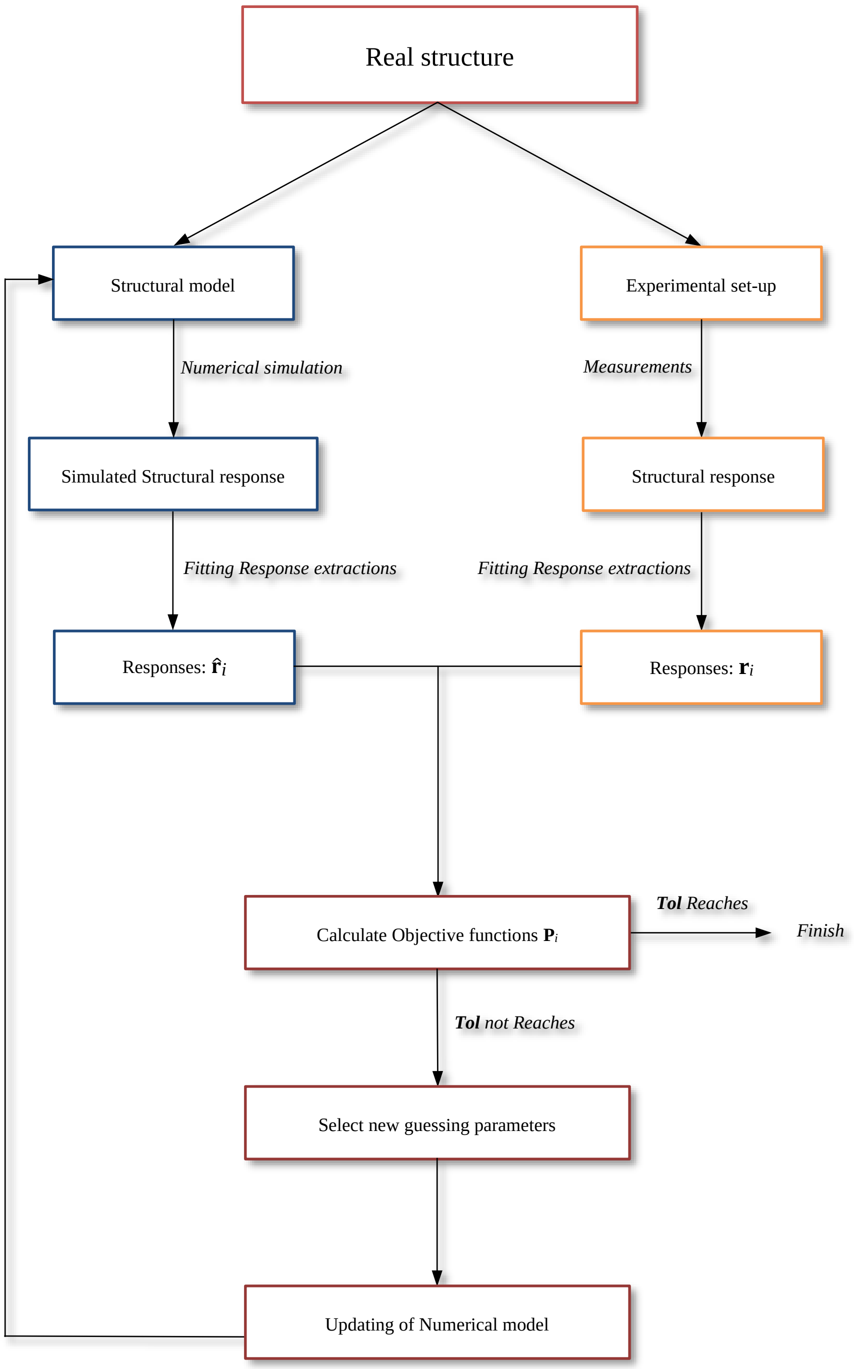

Fig. 5. Model updating sequence of structural model updating method [7]

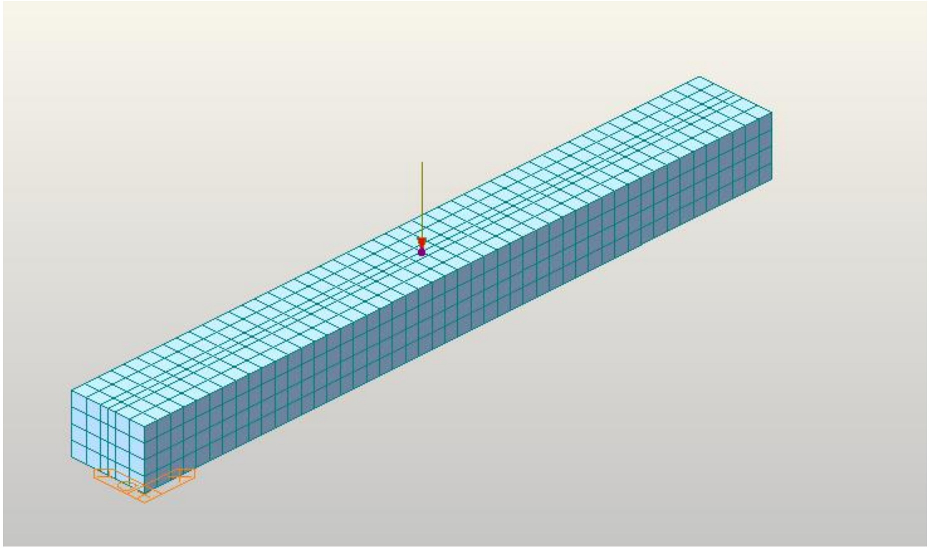

Fig. 6. 3D model of Sleeper in MIDAS Civil

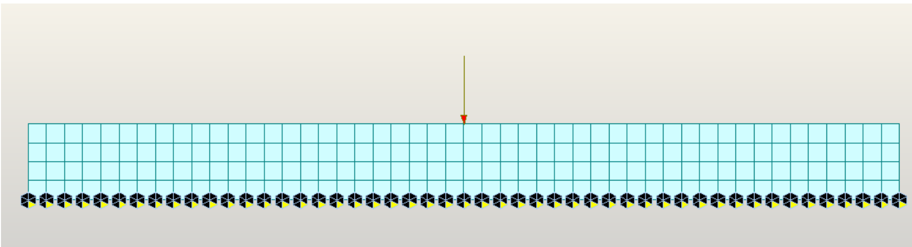

Fig. 7. Ballast spring boundary conditions of Sleeper in MIDAS Civil

Table 2. Model Parameters [3]

Parameters [unit]	Value
Sleeper length, L [m]	2.420
Sleeper height, h [m]	0.210
Sleeper Width, b [m]	0.280
Young's Modulus, E [N/m^2]	4.0 x 10^{10}
Density, ρ [N/m^3]	2750
Modulus of subgrade of Ballast layer, k_B [N/m^3]	2.8 x 10^8
Modulus of damping of Ballast layer , c_B [N/m^3]	10 x 10^6
Impact force, P_0 [N]	1000
Impact time, t_{imp} [s]	0.00625

Utilizing the “*lsqnonlin”* built-in function in MATLAB, the objective function will be minimized with the optimization function based on Eq. (6). Furthermore, MATLAB software will be utilized to simulate the structural response from the numerical model described in Section 2. This simulation will then be used as a curve fitting parameter to determine the dynamics properties of the ballast.

Fig. 8 and Fig. 9 show comparison between the simulated acceleration responses obtained from the MIDAS Civil software and the MATLAB identification algorithm. It is evident that the two acceleration responses are identical. The L_2 norm of the residual vector is approximately 0.0364%, which means that the identification algorithm can output an accurate value given a good enough input.

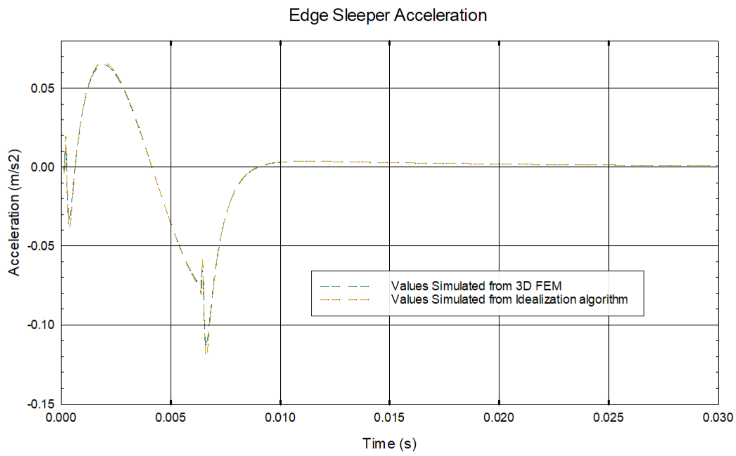

Fig. 8. Comparison of the simulated acceleration responses from MIDAS civil and identification algorithms at sleeper’s edges (x = 0 m and 2.420 m)

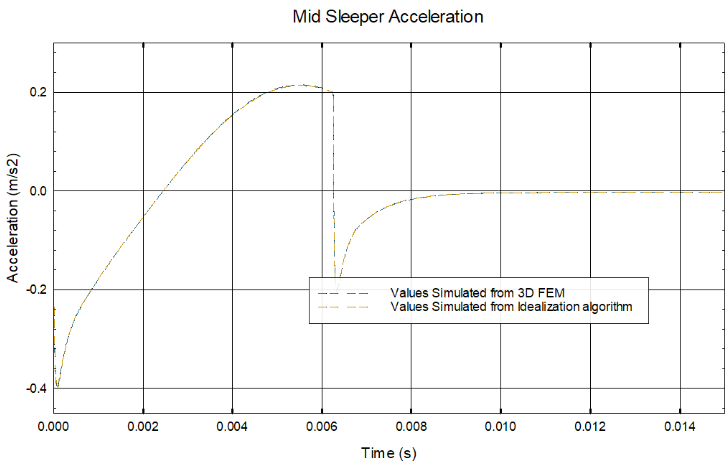

Fig. 9. Comparison of the simulated acceleration responses from MIDAS civil and identification algorithms at sleeper’s midpoint (x = 1.210 m)

The identified ballast dynamics properties are compared with the exact solution as seen in Table 3. The difference in the curve-fitted value is 0.18% and 0.734% for the ballast stiffness (Modulus of subgrade) and damping respectively.

Table 3. Comparison of identified dynamics properties with exact value

Parameters [unit]	Exact Value	Curve-fitted Value
Dynamic modulus of Ballast layer, k_B [N/m^3]	2.8 x 10^8	2.8052 x 10^8 (0.18%)
Dynamic damping of Ballast layer, c_B [N/m^3]	10 x 10^6	10.0734 x 10^6 (0.734%)

5 Conclusions

This study highlights the significant contributions that this research has made towards the identification of ballast dynamic properties. The study has developed a new algorithm that combines the use of an instrumented impact hammering test, a non-destructive method, with a MDOF beam on viscoelastic foundation model, which provides a more accurate and efficient approach to testing and analysis. The use of a MDOF model instead of a traditional SDOF model allows for a more detailed analysis of the sleeper-ballast interactions, considering the complexities of the system's behavior.

Furthermore, the instrumented impact hammering method has the advantages of being cost-effective, efficient, and minimizing disruptions to the railway network. This method can be used to identify the dynamic properties of ballast tracks in a timely manner and help reducing disruptions in the railway operations, which can lead to a major improvement in the design, maintenance, and safety of railway systems.

The proposed algorithm is found to be accurate in identifying the ballast dynamics properties in which the discrepancies are very small at 0.18% and 0.734% for ballast stiffness and damping respectively.

Nevertheless, it is essential to address the nonlinearity of the ballast layer, which results from its inherent nature. The foundation layer of the ballast should be viewed as a tensionless layer; however, due to the significant computational requirements, this factor has not been included in this study. Consequently, due to the creation of the numerical finite element model in this study, with minor adjustment this model could include the nonlinearity effect easily. However, additional research that focuses on reducing computational time would find to be advantageous, as solving the nonlinear problem is time consuming.

In conclusion, this study has developed a new algorithm that provides a valuable tool for the railway industry to accurately identify the dynamic properties of ballast tracks. The approach developed in this study has the potential to revolutionize the way that ballasted tracks are tested and analyzed, leading to more efficiency in this manner.

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