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A Two-Stage Direct Integration Approach to Find The Railway Track Profile Using In-Service Trains

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ABSTRACT: The railway track is an important element in transportation networks. In recent years, drive-by monitoring of railways has become more popular. Using data measured from in-service trains, the railway profile can be found. In previous research, a complex optimiziton method is used to calculate the railway profile. This paper introduces a new two-stage direct integration approach to find the same track profile much more efficiently. The calculated track profile is similar to a 'true' profile and can be used to monitor the condition of the track.

KEY WORDS: Direct Integration, Railway Track, Monitoring, Drive-by.

1 INTRODUCTION

Railway track stiffness and permanent settlement are important track properties which influence vehicle-ride comfort, ground-borne vibrations, and track geometry [1]. A railway track can be considered in two parts, the superstructure (rails, rail pads, sleepers) and the substructure (ballast, sub-ballast, sub-grade, drainage systems) [2]. The performance of the substructure is heavily dependent on the subgrade performance, and regular track maintenance such as ballast cleaning or tamping cannot correct for poor subgrade [3]. Track geometry defects associated with a poor subgrade tend to reappear relatively quickly, meaning these regular track maintenance techniques are both costly and largely ineffective. Therefore it is important to have measurements of track stiffness in order to assess the subgrade performance so that more suitable maintenance measures (e.g. mini-piles, subgrade replacement) can be chosen as appropriate [1].

Railway track stiffness can currently be measured using stationary equipment or specialised low-speed vehicles. Bowness et al. use geophones and digital image correlation (DIC) of video to determine track movements [4]. Also, Murray et al. use track side mounted cameras and digital image correlation (DIC) to measure track deflection. The results show that foundation parameters can vary significantly over a short length of track [5]. Traditionally, a track recording vehicle (TRV) is used by railway infrastructure managers to assess the condition of their network. European Standard EN13848 defines the method of measurement for railway tracks using TRVs in Europe [6]. The standard also defines the approach for evaluating track condition by means of various safety-related limits associated with each of the parameters measured so that maintenance interventions can be planned. TRVs are the current preferred method of measurement for these parameters. However, these vehicles are expensive to run and may disrupt regular services during their operation. Using in-service vehicles to determine these parameters represents a potential saving for railway infrastructure managers [7] and can provide information in real time.

The concept of using trains in regular service to measure track stiffness has the potential to provide inexpensive daily 'drive-by' track monitoring to complement data collected by the less frequent (but more accurate) monitoring of TRVs. In this method, sensors mounted on in-service vehicles are used to collect acceleration and other dynamic properties for monitoring the condition of railway tracks. Improvements in the band-width of wireless communications, sensor robustness and electronics have allowed the development of unattended track geometry inspection systems that are compact and robust enough to be mounted on in-service vehicles [8].

Using bogie acceleration readings, Le Pen et al. detect changes in track stiffness after track renewal. These results are corroborated by measurements of individual sleeper deflections using geophones and DIC [9]. Odashima et al. use inverse dynamics to estimate track irregularity from car-body accelerations with a Kalman filter. This research estimates the track irregularity in the longitudinal plane (track geometry and 10m-chord versine) [10]. Bocciolone et al. use vertical and lateral sensing accelerometers on a metro train in Milan to detect corrugation and side wear in curved sections [11]. Using data from accelerometers mounted on both the bogie and the axle box of an in-service train, Lee et al. calculate the vertical and lateral track profile through a mixed filtering approach [12]. Paixão et al. use sensing capabilities of smartphones or other current low-cost inertial systems to get acceleration measurements to complement the assessment of the structural performance and geometrical degradation of the tracks [13].

Railway track longitudinal profile is an important indicator of serviceability condition. A longitudinal profile of rail is comprised of a combination of macro changes in track elevation in the longitudinal direction and local rail irregularities. A perfect level track profile can increase passenger comfort, reduce wear on vehicle components and reduce power consumption [7]. A reduction in vehicle dynamics also reduces the vehicle load on the track. Therefore, keeping a good vertical longitudinal profile helps maintain overall track condition through a reduction in vehicle dynamic effects [14].

There are two dimensions to calculating the track profile, forward problem, and the inverse problem. For the forward problem, the responses of the vehicle are calculated using a given track profile. In the inverse problem, the response of vehicle is used to back-calculate the track profile. The inverse problem is solved by Obrien et al. using a Cross Entropy optimisation technique. They determine the railway track profile elevations that generate a vehicle response which best fits the measured dynamic response of a railway carriage bogie [7].

This paper will introduce a new two-stage direct integration approach to calculate the railway track longitudinal profile which is more efficient than previous work in this area.

2 VEHICLE AND TRACK MODEL

For the forward problem, a train-track model is used to generate vehicle accelerations. This model is developed from the train-track-bridge model described by Cantero et al [15]. For the vehicle, a two-dimensional vehicle model which has ten degrees of freedoms (DOF) is used. As shown in Figure 1, it includes four wheelsets (allowing vertical translation only), two bogies (allowing vertical translation and rotation about each centre of gravity) and the main body (allowing for vertical translation and rotation). For the track, a three-layer track model is used. The track is modelled using beam elements and is supported by masses and springs. The masses represent sleepers and ballast and the springs represent the pad, ballast and sub-ballast.

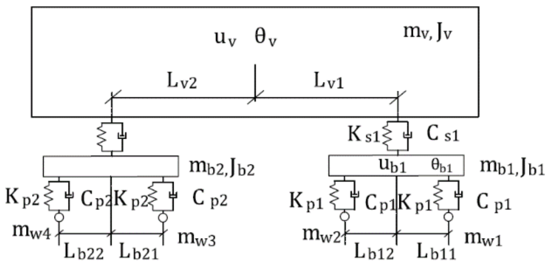

Figure 1. Ten DOF train model.

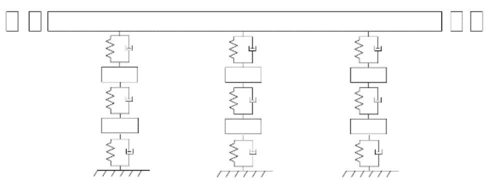

Figure 2. Three-layer track model.

For the inverse problem, a half-car model is used, which is shown in Figure 3. There are four independent degrees of freedom in this model. These degrees of freedom correspond to sprung mass bounce displacement, u_s, sprung mass pitch rotation, θ_s, and axle hop displacements of the unsprung masses at axle 1 and axle 2, u_{u1} and u_{u2}, respectively.

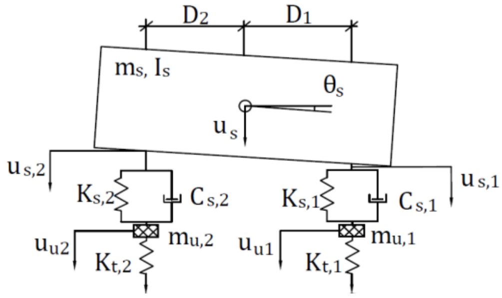

Figure 3. Half-car vehicle model.

3 TWO-STAGE DIRECT INTEGRATION APPROACH

In this section, a new two-stage direct integration approach is introduced to solve the inverse problem. For the forward problem, the train-track model is used to generate vehicle accelerations and rotation accelerations of the main body and one bogie which are regarded as the 'measured' data. The properties of the train are given in Table 1. Using this 'measured' data, the half-car model is used twice (in two stages as described below) to calculate the track profile under the vehicle. The properties of the half-car model are given in Table 2.

Stage 1: Firstly, the whole train model is represented by the half-car model. Then, the direct integration method introduced by Keenahan et al. [16] is used to solve this half-car model. Here, 'measured' accelerations and rotation accelerations of main body are used as inputs. The force between the sprung mass and the unsprung mass for the half-car model (between the main mass and the bogie in train model) can be calculated, using the equation of force for the 1st axle as follows:

$$F = K_{s,1} \times \left(u_{u1} - u_{s,1}\right) + C_{s,1} \times \left(\dot{u}_{u1} - \dot{u}_{s,1}\right) \quad (1)$$

Stage 2: Then, the half-car model represents the bogie of the train model and the track profiles under the first bogie are calculated using the direct integration method. Here, the 'measured' accelerations and rotations of the bogie are used. Also, the force calculated from Stage 1 is transferred and added to the bogie mass.

Table 1. Train properties in the forward problem.

Property	Unit	Symbol	Value
Wheelset mass	kg	m_{w1}, m_{w2}, m_{w3}, m_{w4}	1 813
Bogie mass	kg	m_{b1}, m_{b2}	2 615
Car body mass	kg	m_v	28 979
Moment of inertia of bogie	kg.m^2	J_{b1}, J_{b2}	1 476
Moment of inertia of main body	kg.m^2	J_v	1.97×10^6
Primary suspension stiffness	N/m	K_{p1}, K_{p2}, K_{p3}, K_{p4}	2.4×10^6
Secondary suspension stiffness	N/m	K_{s1}, K_{s2}	8.6×10^5
Primary suspension damping	Ns/m	C_{p1}, C_{p2}, C_{p3}, C_{p4}	7×10^3
Secondary suspension damping	Ns/m	C_{s1}, C_{s2}	1.6×10^3

Distance between car body centre of mass and bogie pivot	m	L_{v1}, L_{v2}	9.5
Distance between bogie centre of mass axles	m	L_{b11}, L_{b12}, L_{b21}, L_{b22}	1.28

Table 2. Half-car properties in Stage 1 and Stage 2.

Property	**Symbol Value and Unit**	**Stage 1**	**Stage 2**
Pitch Moment	I_s (kg m^2)	1.97×10^6	1 476
Body mass	m_s (kg)	28 979	2 615
Axle mass	$m_{u,1}$, $m_{u,2}$ (kg)	6 241	1 813
Suspension Stiffness	$K_{s,1}$, $K_{s,2}$ (N/m)	8.6×10^5	2.4×10^6
Tyre Stiffness	$K_{t,1}$, $K_{t,2}$ (N/m)	4.8×10^6	1×10^9
Suspension Damping	$C_{s,1}$, $C_{s,2}$ (N s/m)	1.6×10^3	7×10^3
Distance of axle to centre of gravity	D_1, D_2 (m)	9.5	1.28

4 RESULTS

In this two-stage method, the track profiles are calculated using the Newmark-Beta integration method on a step by step basis. The calculated results are introduced in this section. Figure 4 shows the calculated track from Stage 1 and the track profile used in the forward problem to generate accelerations (i.e. the 'true' profile). The calculated profile have the same shape as the 'true' profile but it is not accurate. However, the calculated track from Stage 2, which shown in Figure 5, is close to the 'true' profile. The demonstrates the merit of the two-stage approach to finding the track profile, and represents a significant improvement in efficiency compared with previous work in this area.

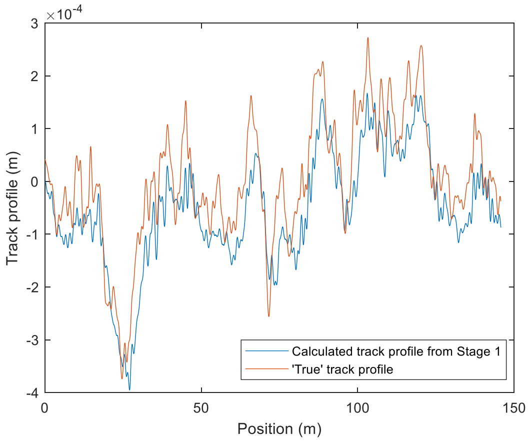

Figure 4. The calculated track of Stage 1 and 'true' profile.

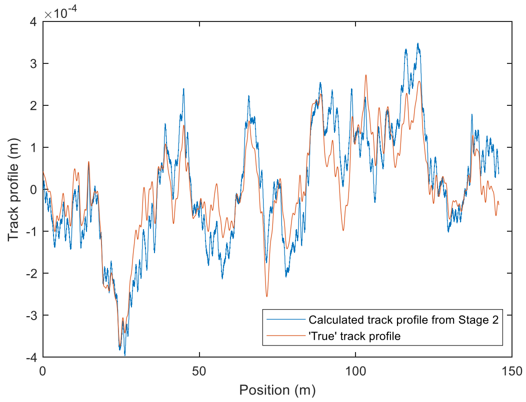

Figure 4. The calculated track of Stage 2 and 'true' profile.

5 CONCLUSION

Previous research has shown that railway track profile is a good indicator for monitoring the conditions of railways and can be determined using a complex optimization method. This involves finding the profile that gives a best fit to the measured data which is computationally expensive and time consuming. In this paper, the railway track is calculated using a two-stage direct integration approach. The railway car model is represented using the half-car model twice. The calculated profile is calculated in a fraction of the computing time and the results are very close to the 'true' ones.

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