Rail-strain-based identification of freight train loads

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ABSTRACT

Increased standards of safety in railway transport require control of train loads on behalf of railway administration, in view of programmed maintenance and monitoring of wear and fatigue of rails. This paper presents a procedure that applies interpretative mechanical models to the modelling of time-histories of rail strains, in view of the identification of travelling loads. On comparing the model output to experimental time-histories, we verify their ability to describe satisfactorily the real response. Then, given a time-history of rail strains, the travelling load is identified minimizing an objective function which measures the match between the experimental time-histories and the model response in terms of curvatures. The inverse problem is solved in two steps. First, the stiffness of the foundation is identified using a known load. Then, the unknown loads are determined by a least square procedure. An application to experimental data recorded on the foot of a rail is also presented. The identified train load is finally compared to the train loads as declared by the carrier, providing satisfactory results, with mean errors around 7%.

KEYWORDS: *load identification, rail monitoring, rail strains.*

INTRODUCTION

The development of methods for the identification of travelling loads is gaining more and more interest in the industrial environment for the increased standards of safety required in the railway transport. Awareness of the loads actually travelling on railway lines enables to timely schedule maintenance and wear, as well as to check unbalanced loads which can affect vehicle safety. A one-dimensional Euler-Bernoulli beam with constant geometric and mechanical properties, resting on a linear elastic soil with viscous damping, and subjected to a Dirac delta load travelling at constant speed was used in past research to describe the response of rocket test tracks (Kenney, 1954) and train tracks (Lei, 2011). This model has proved its ability to describe the real experimental response. More complex models involving 2D descriptions of the elastic foundation were also proposed (Shamalta and Metrikhine, 2002). Identification of the load involves the evaluation of the Dirac delta amplitude, which requires the solution of an inverse problem. An overview of the different approaches presented in the literature for the solution of load identification problems can be found in Ouyang (2011). It is worth citing the approach proposed by Trujillo and Busby (1997), based on dynamic programming, where not only the forcing term which provides the best match is sought, but also that which has a certain degree of smoothness according to Tikhonov's regularization. An application of dynamic programming to train load identification is presented by Zhu et al. (2013). Among other possible approaches, Ronasi et al. (2011) calculate the minimum of an objective function measuring the distance between experimental and analytical data. In the framework of an algebraic solution, Meli and Pugi (2014) made hypotheses to simplify the load time-histories and adopted a multibody model for the railway vehicle. In this paper, we present a procedure for the identification of travelling loads based on the measurement of the rail longitudinal strains at the foot of the rail.

DIRECT PROBLEM

The rail is represented as a plane beam with constant geometrical and mechanical properties resting on a linearly elastic foundation with viscous damping, and subjected to a Dirac delta load moving at constant speed v. On setting E the Young's modulus of the cross section, I its moment of inertia, w the transverse displacement, and P the amplitude of the Dirac delta, the solution takes the form

$$w(z,t) = \begin{cases} \frac{P}{EI}\left(\frac{e^{(z-vt)k_3}}{(k_3-k_4)(k_3-k_1)(k_3-k_2)} + \frac{e^{(z-vt)k_2}}{(k_2-k_4)(k_2-k_1)(k_2-k_3)}\right) & z \leq 0 \\ \frac{-P\left(\frac{e^{(z-vt)}k_4}{(k_4-k_3)(k_4-k_2)} + \frac{e^{(z-vt)k_1}}{(k_1-k_3)(k_1-k_2)}\right)}{EI(k_4-k_1)} & z > 0. \end{cases} \tag{1}$$

with k_1, k_2, k_3 and k_4 the wavenumbers. Figure 1 a shows the analytical time-history of the strains due to a series of ten Dirac loads with P=78400 N, which is approximately the load insisting on one wheel of an unalden ETR324, obtained using Equation 1 for a travelling speed of 28 km/h. Figure 1 b reports, for comparison, the experimental time-history of an ETR324, travelling at around 30 km/h. The pattern of the time-history obtained satisfactorily agrees with the time-history observed experimentally.

INVERSE PROBLEM AND EXPERIMENTAL RESULTS

The inverse problem consists in the identification of the amplitude of the train loads. The solution is obtained through minimization of the difference between the measured time-history of the strain $\boldsymbol{\epsilon}_e$ at the foot of the rail and the same quantity $\boldsymbol{\epsilon}_a$ a provided by the model. The analytical time-histories $\boldsymbol{\epsilon}_a$ a are modelled as a linear superposition of n

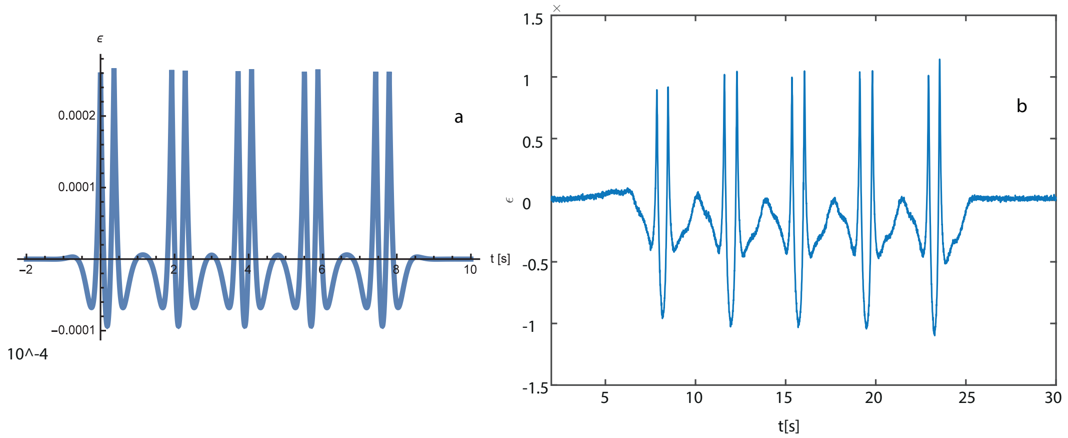

Figure 1: Analytical (a) and experimental (b) strain time-histories of an ETR324.

strains due to a unit load $\boldsymbol{\epsilon}_a^1$, expressed in N^{-1}, with coefficients P_i which are the object of identification. Since experimental time-histories are actually discrete, we will refer to them as m-length column vectors $\boldsymbol{\epsilon}_a$, whose component ϵ_j is the quantity measured at the j-th time step. The same can be done for the analytical time-histories, whose linear superposition can be written as:

$$\boldsymbol{\epsilon}_a(P_i) = \sum_{i=1}^{n} \boldsymbol{\epsilon}_a^1 P_i = \mathbf{E}_a^1 \mathbf{P} \tag{2}$$

where the vector $\mathbf{P}$ collects the unknown load amplitudes and $\mathbf{E}_a^1$ is a matrix collecting n $\boldsymbol{\epsilon}_a^1$ column vectors with m rows. The time at which the maximum of the load occurs is not considered a parameter to be identified, as it can easily be determined from the time-history. Among the system parameters which can influence the result of the load identification, the soil stiffness k_v is one of the most important. The load identification procedure is hence performed as a two-steps procedure. The first step consists in the identification of k_v: using a known load, an objective function which measure the difference between numerical and experimental data is minimized. The second step is the actual load identification. The difference between analytical and experimental data is minimized in a least-square sense, so that the vector of unknown loads is obtained as:

$$\mathbf{P} = (\boldsymbol{\epsilon}_a^{1T} \boldsymbol{\epsilon}_a^1)^{-1} \boldsymbol{\epsilon}_a^{1T} \boldsymbol{\epsilon}_e \tag{3}$$

Time-histories of strains were measured experimentally using fiber Bragg grating strain gauges, with a sampling frequency of 1000 Hz. Six sensors were installed at the foot of both rails near a station, where trains run at a speed of around 30 km/h. Freight trains only were analyzed, for some of which the loads were also declared by the carrier. Table 1 reports a sample of the results obtained for one train.

carriage #	l_d[tons]	l_i	% error	carriage #	l_d[tons]	l_i	% error
Locomotor	89	90	-1.12	14	69	69	0.00
2	31	30	3.23	15	70	71	-1.43
3	36	29	19.44	16	64	67	-4.69
4	37	35	5.41	17	63	67	-6.35
5	72	61	15.28	18	67	70	-4.48

Table 1: Sample of comparison of loads declared by the carrier (l_d) and identified (l_i) for a freight train

CONCLUSIONS

We presented an approach for the identification of travelling loads of freight trains based on the minimization of the difference between the experimental time-history of strains at the base of the rail and their analytical counterpart. The model describing the response is a one-dimensional Euler-Bernoulli beam resting on an elastic soil, whose stiffness is one of the unknowns of the problem. The load is modelled as a Dirac delta load travelling at constant speed, whose amplitude is unknown. The procedure of identification is performed in two steps, first identifying the soil stiffness, then the amplitude of travelling loads. The results obtained are compared with the loads of a train of known weights, providing satisfactory results, with mean errors of about 7%.

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