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Optimization of a High-Speed Railway Track Using Multipoint Approximation Method

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1. ABSTRACT

A procedure for analysis and design of an embedded rail construction (ERC) is presented. The dynamic behavior of the ERC track is analyzed using a linear 2-D finite element model wherein the track and moving train have been incorporated. The numerical model implemented in a computer program DARTS-1 is then verified experimentally. Finally, an attempt is made to determine optimal dynamic parameters of the ERC track by applying a numerical optimization technique. Requirements for the optimal design of the track are related to the reduction of the wear of rails and wheels, as well as to the reduction of the level of the acoustic noise produced by the train moving on the track. To obtain the optimal design mechanical properties the ERC track, such as stiffness and damping parameters are varied. The optimization problem is solved using multipoint approximation method implemented in IMOPT software package. Results of the optimization are presented and discussed.

2. INTRODUCTION

A classical railway track structure consists of a flat framework built up of two rails and sleepers connected to each other by fasteners, and a ballast bed as shown in Figure 1. Recently some improvements of the design have been made, such as, for example, the introduction of concrete sleepers and new types of the fasteners but still the construction principle of the railway tracks has not been notably changed. One drawback of the classical railway structure is the high cost related to inspection and maintenance of the railway track. Because of strong availability requirements to modern railway tracks (i.e. they should always be available for trains), especially to these used for high-speed trains (HST), a reduction of the maintenance effort has become an important aspect in the design of new railway structures[2]. Other important requirements to the new track structures concern bearing capacity and durability of the track, passenger's comfort and level of the acoustic noise produced by a moving train.

During the last two decades, many theoretical and practical efforts have been made on the design of new railway structures, which satisfy the above mentioned requirements. One of such new non-conventional structures is a railway construction without ballast, a so-called Embedded Rail Construction (ERC). The ERC consists of a continuous reinforced concrete slab and rails embedded in a cork/polyurethane mixture (Corkelast®*) as shown in Figure 2. It should be noted that only few types of railway structures without ballast have specifically been designed for high-speed trains.

In the present paper a procedure for analysis and design of an ERC track for high-speed trains is described. The procedure consists of three main parts, namely numerical modeling

* Corkelast® is a trademark of Edilon BV

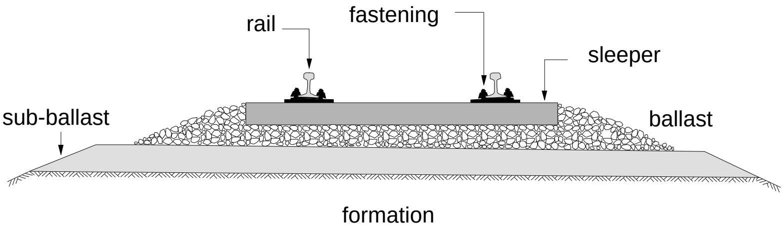

Figure 1 Construction principle of classical track structure

of dynamic behavior of the track, verification of the numerical model, and optimization. The dynamic behavior of the embedded rail construction is described using the finite element method. The track and moving train are analyzed simultaneously as one mechanical system. Steady state dynamic analysis is performed in time domain. The analysis procedure has been implemented in a computer program DARTS-1. To verify the numerical model, an instrumented hammer test with a small specimen of the embedded rail has been performed. The numerical modeling and analysis verification procedures are only briefly presented here, for details we refer to Reference[3].

As the numerical model of the ERC was verified, an attempt has been made to determine optimal parameters of the ERC track using a numerical optimization technique. Stiffness and damping parameters of the fill material has been chosen as design variables. The optimization problem has been formulated for a particular train moving with a prescribed velocity using the requirements to the railway tracks related to the rail-wheel wear and the level of the acoustic noise produced by the train.

To solve the optimization problem, a multipoint approximation method[6] has been applied. According to this method, the original optimization problem is replaced with a sequence of simpler approximation problems. The approximations used in this method belong to a mid-range class[1]. They are built upon the information about the original functions obtained at several points of the design variable space. The method, implemented in a computer program IMOPT, has been successively applied to various structural static and dynamic optimal design problems[4,5].

To perform the optimization of the ERC track, the IMOPT software package has been coupled to the dynamic analysis of railway tracks software DARTS-1. Results of the optimization are presented and discussed below.

3. DYNAMIC ANALYSIS OF ERC

An ERC track with the train moving on it represents a complex mechanical system. The dynamic behavior of such a system depends on the mechanical characteristics of the railway structures and the train as well as on the profile of the rails. In this paper only vertical displacements are considered. Because of small magnitude of the displacements, the dynamic behavior of such a system can quite adequately be described by a 2-D linear finite element model.

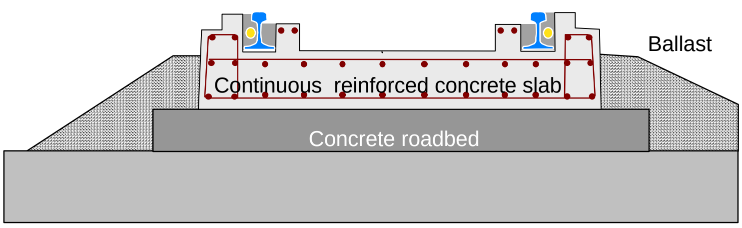

Figure 2 Embedded rail construction

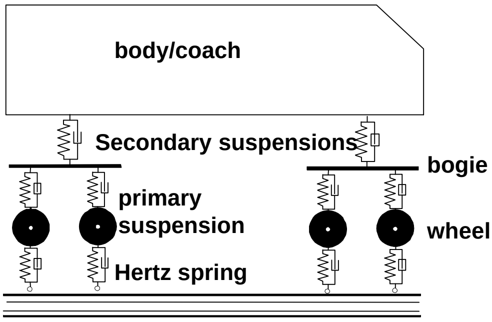

Figure 3 Train model

In a simple case the train can be modeled by moving loads applied to the rail but to obtain more realistic results a more complex representation should be considered. In the mechanical model used here, the train is represented by the 2-D mass-spring system shown in Figure 3. Contact forces between the rail and wheels of the train are modeled using a Hertz spring.

The dynamic behavior of the embedded rail construction is defined by mechanical properties of its components (Figure 4). The rail is modeled as a Timoshenko beam. To reduce the load transfer between the rail and rigid foundation, the fill material is used. Its dynamic behavior is described by the Winkler model. Stiffness and damping parameters of the fill material have been determined experimentally using an instrumented hammer test with a small specimen of the embedded rail (0.5 m) and a simple 2-DOF numerical model of the specimen. The numerical model shown in Figure 4 with the obtained stiffness and damping parameters has further been verified using a longer specimen (4 m) of the embedded rail. More information about this and other numerical models of the embedded rail constructions is given in Reference[3].

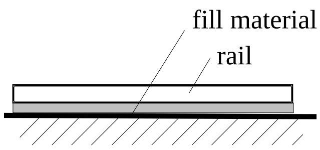

Figure 4 Model of embedded rail on rigid foundation

4. OPTIMIZATION OF ERC

4.1 Requirements to ERC

After the verification of the numerical model of the ERC, an attempt has been made to optimize it using a numerical optimization technique. To formulate an optimization problem the requirements concerning the rail-wheel wear and noise hinder have been used.

The wear of the wheel and rail can be estimated by analyzing the contact forces between the wheels and rail. To reduce the degree of the wear the contact force variation should be as small as possible.

The acoustic characteristics of the ERC are estimated by a specific response quantity, a so-called distance damping. The distance damping characterizes the ability of a mechanical system to reduce the acoustic noise. To evaluate the distance damping, an impulse load is applied to the rail of the ERC and the responses (displacements) of the structure are calculated at several points of the rail located on the different distances from the load application point. The response in each point is measured in decibels using the transformation

$$\hat{U}_i(w) = 10\log_{10}(U_i(w)). \qquad (1)$$

The noise reduction at each considered point can be estimated by an attenuation rate that reads

$$\Delta_i = (\hat{U}_i - \hat{U}_0)/l_i, \qquad (2)$$

where l_i is the distance between *i*-th point and the impulse load application point. The distance damping C_d is then defined as the mean attenuation rate that can be written as

$$C_d = E[\Delta_i], \qquad (3)$$

A graphical representation of the distance damping for a particular ERC is given in Figure 5. The negative values of the C_d mean that the noise in the corresponding frequency range can be reduced. Thus, for the rail structure with good acoustic characteristics the distance damping should have large negative values within a wide frequency range. The size of the negative distance damping range is defined by the lowest natural frequency w_0 of the system (denoted by a black spot in Figure 5). To enlarge this range, w_0 should be increased.

4.2 Formulation of optimization problem

Using the above mention requirements for the railway track, the determination of the optimal parameters of the ERC can be formulated as the following optimization problem. For a given train moving with a prescribed velocity on the ERC track with a given profile of the rail surface:

Minimize the inverse of the lowest natural frequency of the ERC or

$$F_0 = 1/w_0 \rightarrow \min \qquad (4)$$

subject to the constraints on the contact forces *P*

$$F_1(\mathbf{x}) = P/P_{al} \leq 1 \qquad (5)$$

and the constraint on the minimum value of the distance damping

$$F_2(\mathbf{x}) = 2 - \min_{w}(C_d(\mathbf{x}, w))/C_d^* \leq 1 . \qquad (6)$$

Here P_{al} is the maximum allowable value of the contact force variation between the rail and wheel. The distance damping should not be larger than C_d^*. The stiffness and damping of the fill material are chosen as the design variables ***x***.

4.3 Numerical results

The optimization problem formulated in the previous section has been solved for the train moving on the ERC track (150[*m*]) with the velocity *V*=30[*m/s*]. The parameters of the train and rail models used for the optimization are given in Table 1. The rail profile has been represented by a harmonic function. The maximum allowable contact force variation $P_{al} = 1.4\,kN$ and the maximum (desirable) distance damping $C_d^* = -15\,dB/m$ have been chosen.

Table 1 Properties of train model

	Wheel	Body	Bogie	Units
M	1032	27075	1400	Kg
K		150	1150	kN/m
C		2.0	2.5	kNs/m
r	0.42			m

To solve the optimization problem, a multipoint approximation method[6] has been used. The objective and constraint functions have been approximated by the multiplicative function

$$\tilde{F}(\mathbf{x}) = a_0 x_1^{a_1} x_2^{a_2} .$$

Table 2 Results of optimization

	Lower bound	Upper bound	Initial design	Optimal design	Units
x_1	5280	5280000	52800	608107	N/m
x_2	1	40	4.98	32.50	Ns/m
w_0			160	520	Hz
P			1.33	1.48	kN
C_d			-4.3	-9.7	dB/m

The optimal design has been obtain after 8 iterations. The results of the optimization are summarized in Table 2. The distance damping for the initial and optimal design is shown in Figure 5. From this figure it can be observed that the distance damping of the embedded rail construction have considerably been improved.

Figure 5 Distance damping for initial and optimal design of ERC

5. CONCLUSIONS

A procedure for design of an embedded rail, construction which includes numerical modeling and dynamic analysis, laboratory testing and optimization of the railway structure has been presented.

Determination of mechanical properties of the embedded rail construction for a high-speed train was formulated as an optimization problem which has been solved using a multipoint approximation method.

Results of the optimization have shown that the numerical optimization can effectively be used in the design of the railway structures.

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