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Physics of railroad degradation: The role of a varying dynamic stiffness and transition radiation processes

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ABSTRACT

Variations in dynamic stiffness along railway tracks are at the basis of long-term degradation problems under train operation. For a spatially invariant and straight track, the dynamic response to constant axle loading at a constant velocity is stationary in a convective reference system. This is no longer true if geometrical and/or constitutive track properties are non-uniform over the length. Such discontinuities appear on many scales; the sleeper bay is an example with a periodical character, whereas examples with an incidental character are level crossings, bridges, tunnels, abutments, culverts but also switch panels and ballast and foundation stiffness variations. Also track irregularities may be considered as a non-uniformity. Any longitudinal variation in system properties causes a transient disturbance in the convective, stationary response field. A local and often strong amplification of the stress and strain field in the structure is the result. In terms of mechanical energy: the energy state varies continuously in a convective reference system due to transition radiation. Depending on its intensity it is accompanied by dissipation of mechanical energy. For repeating axle and train loading, such process is cyclic and a long-term degradation mechanism is established. For the running train, the inherent time- and position-dependent energy loss function could be described as 'dynamic drag', in analogy to the well-known 'viscous drag'. The present paper exposes in more detail the physical backgrounds of track degradation, with a focus on soft soils, where transition problems concentrate. Some propositions are made, on a conceptual level, for modelling and an improved design of track transitions with a reduced maintenance need.

1. Introduction and scope

Long-term performance of railway tracks becomes increasingly important in view of the demand on continuous availability of lines, with the inherent need to both reduce maintenance and shift its character from corrective to predictive. It is especially true in view of the worldwide expansion of the high-speed rail network, with its increased demand on punctuality. An important driver of this development is the European privatisation of the railway infrastructure, executed during the past two decades, giving rise to a separated administration from the rolling stock operation. The latter was accompanied with the introduction of life cycle costing/management and asset management in the railway sector.

On the other hand, it may be stated that 'long-term performance' has never been an explicit design goal since the introduction of the railways in the 19th century; the design of the classical railway track is based on load-bearing considerations and maintainability. An explanation can be found in the fact that tracks are traditionally designed by civil engineers, who concentrate on a purely 'static' design that performs well under instantaneous loading. When considering the long term, not only spatial dimensions but also the temporal one enters the picture: one needs to consider dynamic responses, cyclic loading and their interaction. This is typically the viewpoint of a mechanical engineer. Rarely however, tracks are being designed by mechanical engineers, not even our modern high-speed lines.

In order to achieve a better long-term performance of railway tracks, a fundamental understanding of the long-term behaviour of tracks under repeated train loading as well as the mechanisms governing this behaviour are of paramount importance and should get due attention. This understanding then can be reflected in an adapted design on issues that are critical regarding the long-term performance. In the scientific literature, the deterioration of railway tracks has received not particularly much but still some attention; a review has been given by Dahlberg [1]. This research and modelling is largely based on trend analysis of geometrical measurement data, leading to empirical and often very site-specific, non-generic black box-like models. This represents the state-of-the-art. An inherent but significant danger when optimising maintenance processes on the basis of such models (see e.g. Westgeest et al. [2]) is the fact that they are 'blind' for physical sources of deterioration. These are 'included' in and persist in the

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model, as it is based on data acquired from existing track conditions. In order to develop maintenance optimisation models which are ‘open’ for an identification and elimination of sources of deterioration they must include a physical basis.

The main aim of the present study is to arrive at and propose a general understanding of those physical processes that govern track degradation. In this approach, both the short and the long term system behaviour and their interaction are considered, and key elements in this interaction that govern deterioration processes are identified. A secondary aim of the study is to provide counter-balance to the growing amount of purely empirical prediction models, based on trend-analysis, and to point out the dangers of their application (for life-cycle management) in practice.

The novel contribution of the paper consists in that it presents a scientific, physical basis to explain and to model the phenomenon of long-term degradation of a railway track under train operation. No essentially new ‘laws’ or mechanisms are established, but existing knowledge is applied to the field of long-term system responses. The mentioned basis is generic; it covers ‘degradation’ in its widest meaning and its many scale levels: from large-scale track settlements to the growth of metallurgical defects into the microstructure of a rail. Later or other work, starting from this basis, may consist in the development of more specific models on this basis, or making a coupling to the earlier mentioned empirical models. The latter is important as ever more condition monitoring trains are active on the railway networks worldwide, gathering measurement data.

A fundamental consideration on the nature of a railway track and its mechanical response to the moving train loading may contribute to the understanding of the subject. Complicating factor in the process of long-term track behaviour is the occurrence of two time scales of the mechanical response: short and long-term, as well as the fact that they are interrelated.

A static axle load moving at a constant (and subcritical) speed along a longitudinally invariant and straight rail track yields a constant, stationary response field. In reality, such an ideally perfect track does not exist; along each track variations in system properties occur. These variations appear on many spatial scales; may have a periodical character or be occasional, and may be either smooth or discrete, forming a real discontinuity. Examples of such variations are, on a small scale and with a periodical character, the discrete sleeper bays. On a larger scale, examples with an occasional and discrete character are: level crossings, abutments, bridges, tunnels, culverts and switch panels. The presence and form of many of these types of structural discontinuities is often related to the geographical position of the railway network: in flat countries, mostly situated in coastal delta areas, tunnels and viaducts are represented with a different frequency as compared to mountainous areas. An example of an occasional and smooth variation is the non-uniformity in ballast compaction and support under the sleepers, or a local change in soil properties such as the Young’s modulus. Variations in this category occur frequently on lines in flat coastal areas with soft soils. Finally, not only changes in constitutive properties or in system configuration of the structure, but also each deviation of the rail geometry from a straight line can be considered as a system variation.

For a running train, each track property variation, in either material (composition) or geometry (form and layout), represents a *transition*: the system mechanical response moves, in a convective reference frame, to a different ‘regime’, and has to comply with different external conditions. Therefore, in reality the dynamic track response to a moving axle load is never stationary, but continuously changing, both in an absolute and a convective reference system.

The larger the spatial scale of the transition and the more discrete its character, the larger the effect is on this change in the local response: it may be evident that the presence of an abutment in the track has more significant consequences, in a quantitative sense, than that of a discrete sleeper support. However, the basic mechanism behind both transition types is of the same physical nature, and therefore also the induced long-term effects on the system are the same, be it that they emerge with different orders of magnitude and on entirely different time scales.

Theoretical and complex modelling work on transitions in mechanical structures with moving loads, often with a high level of mathematical abstractness but basically applicable to railways and related phenomena, has been published by Vesnitskii and Metrikine [3], Metrikine et al. [4], Verichev and Metrikine [5], van Dalen [6], Dimitrovová and Varandas [7] and Dimitrovová [8]. These studies were conducted in the linear-elastic regime and considered the instantaneous or short-term dynamic response. Although conclusions are useful to understand certain aspects of degradation mechanisms, these results are not immediately applicable to understand or model the fundamental process of degradation in time.

The present study is structured as follows. Section 2 introduces and discusses the dynamic stiffness concept, which is a key concept to understand dynamic train–track interaction at transitions. It also discusses, in the same context, the different forms of damping that may occur in mechanical systems and their role. Section 3 provides a short discussion on vibration hindrance due to train operation, in connection to Section 2. In Section 4 the link is made between the results of Section 2 and long-term performance: the role of transitions and transition radiation in degradation processes is explained. Section 5 then exposes the conditions for an optimum long-term behaviour of railway tracks and proposes, for reasons of illustration and on a conceptual level, some track and transition design measures to improve this behaviour. Section 6 finishes with conclusions.

2. The dynamic stiffness concept and damping types

A railway track can, like any mechanical load-bearing system, be characterised by its stiffness, which is the ratio of the load magnitude and the resulting displacement (deflection) at the loading position. Because the load exerted by the axles of a moving train on the railway track has a time-dependent nature, it is essential to make a difference between the static and the dynamic stiffness. The time-dependency of the loading can adopt different forms. The load exerted by a single moving axle may be either static or dynamic. In the first case, the load is constant in a convective reference system but time-dependent in an absolute system, whereas in the second case the load is time-dependent in both reference systems.

The dynamic stiffness is a key concept for an easy understanding of the interaction between the moving train and the track at variations of system properties. For illustration purposes, the well-known difference between the static and the dynamic stiffness for an undamped oscillator with one degree of freedom is shown in Fig. 1. The dynamic stiffness $K(\omega)(= \psi \cdot K_{\text{stat}})$ accounts for inertial effects as a function of frequency. For the undamped case, this stiffness is real-valued and has no imaginary part, but in the presence of viscous damping the dynamic stiffness of a lumped system is complex-valued in the frequency domain.

Continuous systems have a dynamic stiffness in the form of complex-valued functions in the frequency – wavenumber space. For predominantly one-dimensionally oriented systems there is only one wavenumber and the space is three-dimensional. In this context, it has become customary, since the introduction of this concept by Dieterman and Metrikine [9] for a railway track, modelled as a Euler–Bernoulli beam resting on a halfspace, to model