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Dynamic behaviour of the ballasted track on railway bridges

A. Stollwitzer[1] and J. Fink[1]

[1]Institute of Structural Engineering – Research Centre of Steel Structures, TU Wien, Austria

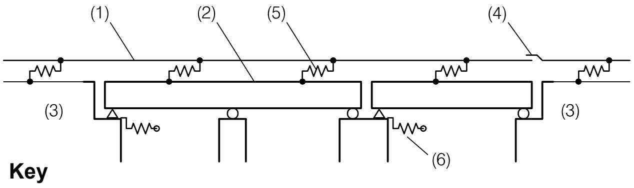
Abstract

The calculated dynamic behaviour of railway bridges under high-speed traffic often differs from the actual behaviour of its bearing structure. Dynamic calculations, especially of bridges with small and middle spans, generally overestimate the actual vibration responses and lead to conservative and therefore uneconomical results. The ballasted track significantly influences this complex gap between measurement and calculation. However, the consideration of its damping and stiffness properties still entails uncertainties. For accurate consideration of ballasted track in a dynamic calculation, there is a wide range of different models of a track-structure model. Still, these models and related characteristic values vary very widely. In their effort to develop track-structure models that take into account the dynamic properties of the ballasted track in a realistic as possible yet easy to handle way and to close the gap between measurement and calculation, researchers at TU Wien have developed a unique, large-scale test facility to investigate the dynamic behaviour of the ballasted track. The test facility allows for specific research of the ballasted track independent of the bridge structure. This contribution describes the operating principle of the test facility and the dynamic effects observed in it. The focus is on determining the damping properties and their dependencies (frequency, acceleration) and clearly identifying different energy dissipation mechanisms in the ballasted track. Furthermore, the test facility allows for determination of the longitudinal displacement resistance of the track, whereat deviations from the normative specifications appear.

Keywords: railway bridges, dynamics, ballasted track, experiments, damping characteristics, energy dissipation.

1 Introduction

Dynamic calculations of railway bridges under high-speed traffic require a realistic model of the track-structure system. Specifically, for railway bridges with small and middle spans, the ballasted track exerts essential influence on their dynamic behaviour. However, the consideration of its damping and stiffness characteristics in a dynamic calculation still entails uncertainties. Compared to measurements, calculations often lead to conservative and therefore uneconomical results. This gap between measurement and calculation is a complex research issue. But generally speaking, more detailed models for both the bridge and the crossing train reflect reality more closely. The simplest bridge model is the Euler-Bernoulli beam. In this case, the bridge structure and the ballasted track are combined in one single beam with five major characteristics: span, bending stiffness, mass per unit length, resonance frequency and damping. Following this approach, the damping properties of the ballasted track and the bridge structure are summarised in one value. The EN 1991-2 [1] provides an example for a more detailed model of a track-structure system that uses, inter alia, non-linear spring elements (with initial elastic shear resistance followed by a plastic shear resistance) to describe the longitudinal displacement behaviour of the track (see Figure 1). Stiffness properties in vertical direction or damping elements are not taken into account.



Key

(1) Track
(2) Superstructure (a single deck comprising two spans and a single deck with one span shown)
(3) Embankment
(4) Rail expansion device (if present)
(5) Longitudinal non-linear springs reproducing the longitudinal load/ displacement behaviour of the track
(6) Longitudinal springs reproducing the longitudinal stiffness *K* of a fixed support to the deck taking into account the stiffness of the foundation, piers and bearings etc.

Figure 1: Example illustrating a model of a track-structure system
(*Source: EN 1991-2 [1], Figure 6.19, S. 103, edited*)

Furthermore, there is a wide range of different models of a track-structure system, found for example in [2-5]. However, these models and the related characteristic values vary very widely.

In their effort to develop track-structure systems that take into account the dynamic properties of the ballasted track in a realistic yet easy to handle way and to close the gap between measurement and calculation, researchers at TU Wien/Institute for Structural Engineering – Research Centre of Steel Structures have developed a unique, large-scale test facility to investigate the dynamic behaviour of the ballasted track. The test facility allows for specific research of the dynamic properties of the ballasted track independent of those of the bridge structure. The dynamic effects observed in the test facility, in particular its vibrations and damping behaviour, are described below.

2 Methods

2.1 Operating principle of the test facility

The central element of the test facility (see Figure 2) is an 8 m long and 4.5 m wide steel trough with a very high bending stiffness acting itself as a rigid body. The trough consists of two main girders with a deck plate and eleven cross girders in between and is supported in two axes: one twistable, fixed bearing on a concrete base, and one movable spring bearing. An unbalance exciter at the free end of the trough generates a vertical harmonic force excitation; this causes a steady-state of vibration of the test facility. By varying the unbalance mass in the unbalance exciter, the test facility undergoes displacements and accelerations of different intensities, whereby accelerations below and above gravitational acceleration are achievable. Apart from that, varying the location and stiffness of the spring bearing changes the resonance frequency of the test facility. The achievable frequency range lies between 4 and 9 Hz.

Figure 2: Test facility (*Source: A. Stollwitzer*)

A six-metre long section of ballasted track (two rails, nine sleepers and ballast bed) is integrated in the trough (see Figure 3). Therefore, the cross section of the test facility correlates with the cross section of a typical single-track railway bridge. The track is connected with a concrete wall behind the trough through a steel construction; this ensures that the track is held in its horizontal position in case of vertical displacements of the trough - causing a longitudinal displacement between track and ballast. An integrated load cell in the connecting construction (Figure 3 – marked in red) allows for the measurement of the longitudinal shear resistance.

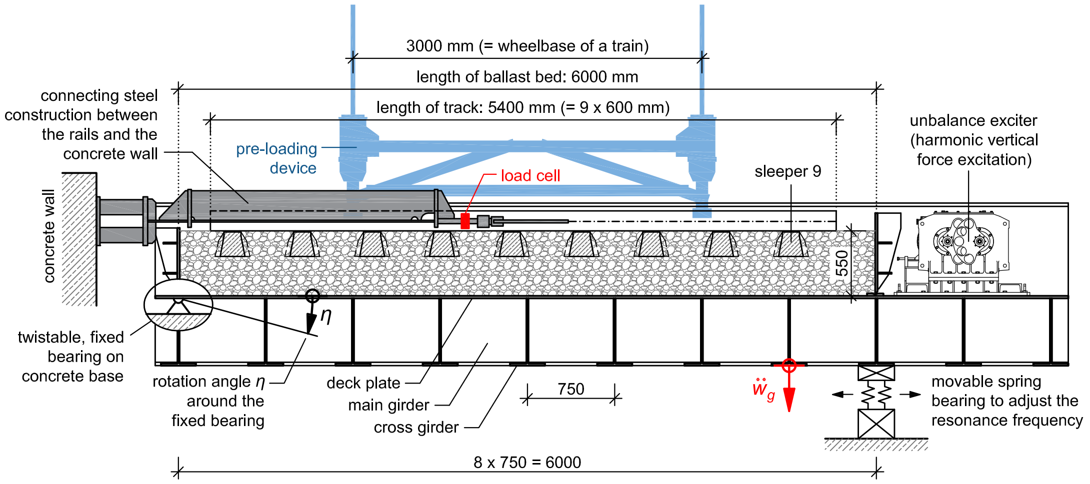


Figure 3: Longitudinal section of the test facility (*Source: A. Stollwitzer*)

A pre-loading device (see Figure 2 and 3 – blue construction) that can be forced down on the track in four points simulates two sets of wheels of a train. This allows for the investigation of both a loaded track and an unloaded track.

2.2 Discussed topics

Comprehensive analyses and further research on the facility are described in [6-11]. This contribution addresses the following topics, which primarily cover the situation of the unloaded track:

- Damping properties of the ballasted track as a whole (ζ_{bt}), separated from the damping properties of the steel trough structure (ζ_{trough})
- Different damping and energy dissipation mechanisms that occur in the ballasted track
- Measurement of the longitudinal displacement resistance of the track

3 Results

3.1 Damping characteristics

Operation of the facility runs at resonance, whereas the resonance frequency depends on the location of the spring bearing and the adjusted stiffness (number of springs in the bearing). Damping properties (expressed in Lehr's damping factor ζ_{bt}) are determined based on amplitude frequency responses and decay processes. Tests without integrated ballasted track in [6] have shown that the trough's damping is at a negligibly low level ($\zeta_{trough} \approx 0$). This means that the measured damping factor of the facility as a whole can be attributed to the ballasted track. Figure 4 illustrates the damping factor depending on the resonance frequency. The damping behaviour follows both a frequency and a displacement dependency, whereby the frequency dependency predominates.

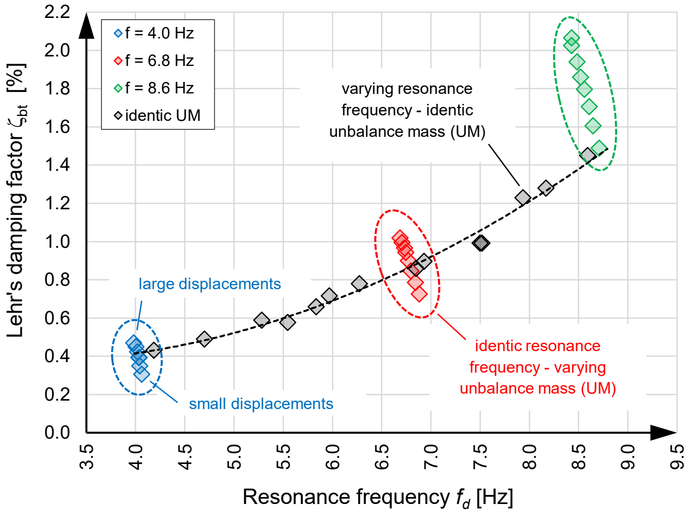


Figure 4: Damping scenario depending on the resonance frequency
(*Source: A. Stollwitzer*)

In addition to the frequency dependency, Figure 5 illustrates the displacement, more specifically, the acceleration dependency of the damping ζ_{bt}. At constant resonance frequency (coloured markings and regression lines), the damping increases linearly with increasing vertical accelerations (resulting from larger unbalance masses). This linearity also applies to acceleration levels above gravitational acceleration.

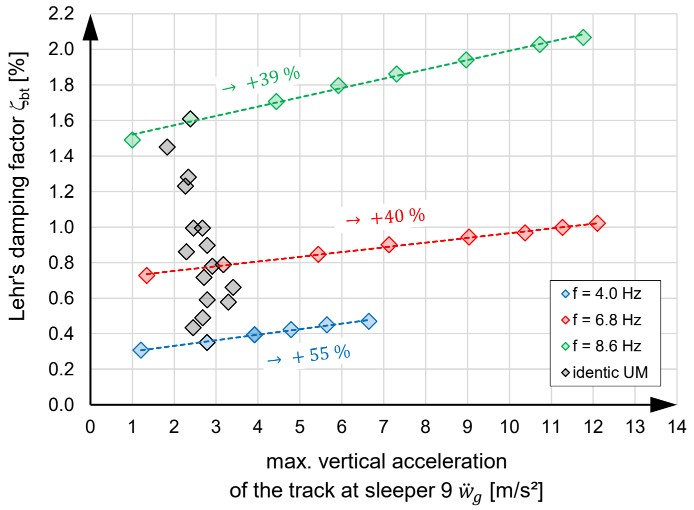


Figure 5: Damping scenario depending on the vertical acceleration
(*Source: A. Stollwitzer*)

The measured damping factors result from three major energy dissipation mechanisms (illustrated in Figure 6), which occur in the ballasted track:

- One horizontally orientated mechanism, based on a longitudinal displacement between the track and the ballast: vertical vibrations induce longitudinal displacements of the track relative to the trough structure.

- One vertically orientated mechanism, based on a relative vertical displacement between the track and the structure
- A vertically orientated mechanism related to the absolute movement of the ballasted track. This mechanism is based on inertia forces in the ballast, leading to friction in between the ballast grains.

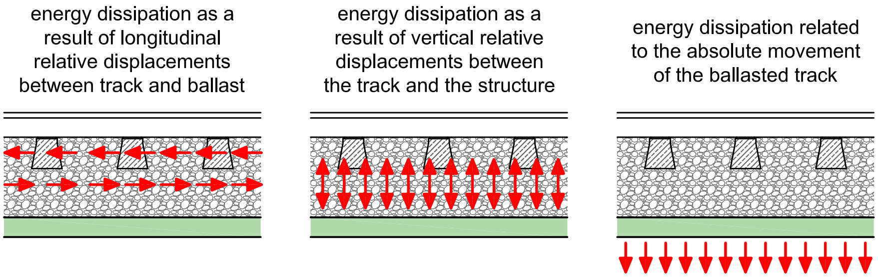


Figure 6: Energy dissipation mechanisms (*Source: A. Stollwitzer*)

The different energy dissipation mechanisms are subjected to various dependencies: in case of large displacements and at a low frequency level, a combination of the horizontally and the vertically orientated mechanisms occur. At higher frequency levels in combination with small displacements, the vertically orientated mechanisms dominate (see [7, 9]).

3.2 Longitudinal displacement behaviour

The longitudinal displacement resistance of the track (resulting from the measured force in the connecting construction – Figure 3: load cell – and the displacement between track and trough) shows significant deviation from the normative specifications of the Eurocode (Figure 7). The assumed linear elastic displacement behaviour in the range of 0-2 mm longitudinal displacement does not reflect reality.

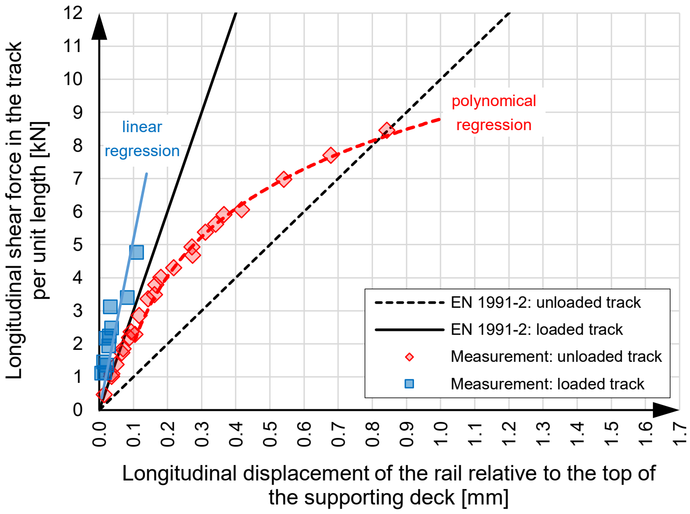


Figure 7: Longitudinal displacement resistance (*Source: A. Stollwitzer*)

4 Conclusions and Contributions

Comprehensive test series on the facility under different framework conditions have yielded new insights into the dynamic effects which occur in the ballasted track, including the damping behaviour resulting from different energy dissipation mechanisms or the longitudinal displacement behaviour. Furthermore, several mechanical models for consideration of dynamic effects of the ballasted track have been developed (see [7-9]). These models consist of one or more vertically or horizontally orientated spring-damper elements which represent the different energy dissipation mechanisms and consider the damping and stiffness properties of the ballasted track. For example, the horizontally oriented dissipation mechanism based on longitudinal relative displacements between track and ballast can be described using a longitudinal spring-damper element (similar to EN 1991-2 – see Figure 1), while the vertically orientated mechanism based on the emerging inertia forces in the ballast that lead to friction in between the ballast grains can be described by a damper element linked to the absolute movements of the bridge. The measured data of the test series form the basis for determining dynamic characteristic values of the mechanical models (see [8]). Subsequently, taking into account the newly designed models leads to a track-structure model for dynamic calculations of railway bridges which enhances the simple Euler-Bernoulli beam. A new track-structure model (Figure 8 shows an example of an enhanced model) reflects reality more closely than so far.

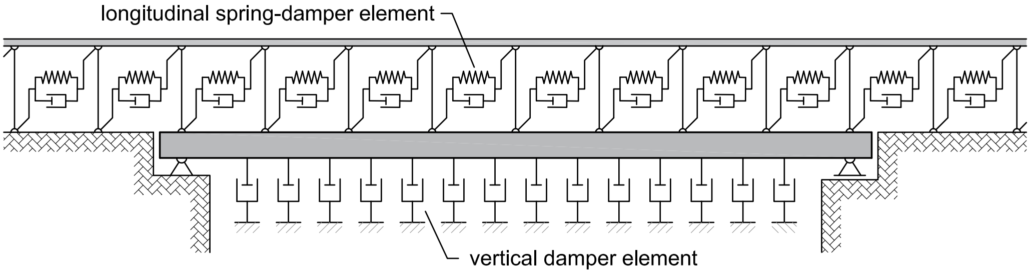


Figure 8: Enhanced track-structure model for dynamic calculations of railway bridges (*Source: A. Stollwitzer*)

The current and future research on the test facility involves the determination of characteristic values related to the newly designed mechanical models (see [8], [10] and [11]), the investigation of the dynamic behaviour of the loaded track, and a more comprehensive study of the longitudinal displacement resistance, including the loaded track situation and displacements between track and ballast up to 5 mm (initial results: see [9]).

Furthermore, the research concerning the dynamic properties of the ballasted track form the basis for the derivation of an approach for the mathematical calculation of the damping factor of railway bridges (see [12]). With regard to the damping factor, the EN 1991-2 [1] stipulates conservatively low values, which have to be used in dynamic calculations. This new calculation approach offers an alternative to the strict normative specifications and opens up potentials to minimise the discrepancy between measurement and calculation.

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