Dynamic behaviour of railway superstructures

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Railways have always been designed on the basis of experiences from previous designs. With the coming of new types of superstructures, i.e. ballastless track, combined with a new field of application, i.e. high speed lines, the empirical design method is no longer applicable. The use of computer models which predict the dynamic behaviour of the track and the vehicle have become necessary for designing this kind of track to ensure a save and trouble free exploitation.

In this paper a ballastless track with continuous support, the embedded rail structure or ERC, is modelled with the use of the computer program 'Rail', a program which has been developed at the Delft University of Technology. Laboratory tests are carried out for the validation of the computer model. The dynamic behaviour of the ERC is compared to that of a classic ballasted track. The frequency response functions and the distance damping as well as the accelerations of a simplified vehicle are determined and compared.

Furthermore a simulation of a complete Thalys high speed train running at high speed over the ERC is made giving information on the dynamic behaviour of the track and the comfort level for the passengers, the latter determined as acceleration levels in the vehicle.

Key words: **Dynamic track analysis, distance damping, vehicle track interaction**

1 Introduction

Railway tracks have been designed on empirical bases since the beginning of the railway epoch. Because of the very time consuming process, the empirical design method is less suited for the development of new types of track, such as ballastless track.

Insight in the dynamic behaviour of the track is of prime importance in a non-empirical design method. On basis of the dynamic behaviour of the track a choice can be made for a type of track.

In this paper the dynamic behaviour will be expressed by means of three items:

1. dynamic track response
2. distance damping
3. vehicle-track interaction

This will be illustrated with calculations on two types of track structures, i.e. classic ballasted track and the embedded rail structure.

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2 Description of the track structures

Ballasted track

The most common type of track structure world-wide is ballasted track, see Figure 1. With ballasted track, sleepers that are laid in a 300 to 400 mm thick ballast bed support the rails. These sleepers are spaced 0.60–0.70 m.

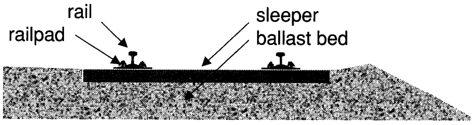

Fig. 1. Cross section of ballasted track.

Embedded rail structure

One of the ballastless track structures that were developed by the Dutch Railways is the embedded rail structure. Hereby the rail is placed in a groove that is spared in the concrete substructure.
A continuous railpad is glued on the bottom of the groove, ensuring a constant elasticity. The rail is then fixed by means of an elastic embedding compound, see Figure 2. The embedded rail structure offers a continuous support of the rail and has proven to be nearly maintenance free.

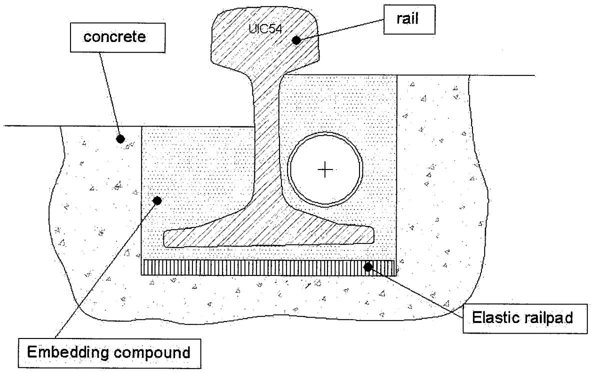

Fig. 2. Cross section of the embedded rail structure.

3 Description of the Rail program

The computer program used is called "Rail" and developed at Delft University of Technology.
The program "Rail" has been written for the one dimensional analysis of a railway track on an elastic foundation. The structural components are the rail, rail pad, sleepers, ballast bed and subgrade. These components can also be used to model various of ballastless tracks. Corrugation of the rail can be taken into account. The stiffness properties of the elastic foundation are modelled either by a Winkler or Pasternak foundation. The dynamic properties are characterised by damping and inertia properties.
Static loads such as dead weight and point loads can be applied and analysed. Possible dynamic loads are time dependent point loads, moving loads and moving vehicles.
The response to time dependent loads is calculated by a direct integration process, which evaluates the displacements at each time step. From these results stresses and forces are calculated following common procedures of the finite element method (f.e.m.) techniques.

In Figure 3 the schematisation is given for the considered track structures, ballasted track and the embedded rail structure.

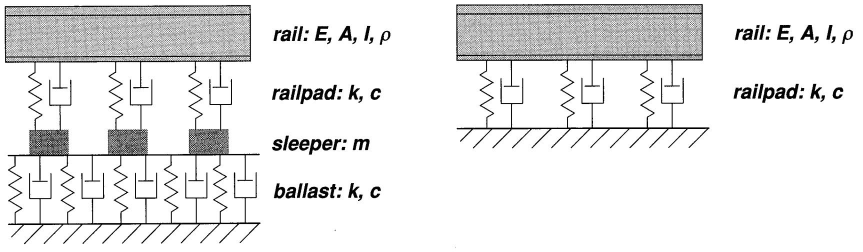

Fig. 3. Schematisation of respectively ballasted track and embedded rail structure.

The models used for the calculations of the dynamic track response, distance damping and vehicle-track interaction, have a length of 50 m in order to exclude reflections of the ends of the model.
The pulse used has duration of 0.2 ms and the integration time step is 0.1 s, giving a 10 Hz step in the frequency domain.
The adopted stiffness for both track structures is chosen in such a way that the static deflection under a 225 kN axle load approximates 1.5 mm.

4 Validation of the model

For the validation of the computer model, hammer excitation tests were performed on 0.50 m and 4 m long test species of the embedded rail structure.

The basis of the test is an excitation hammer to introduce a force in the track. The magnitude of the force is recorded in the hammer tip. The reaction of the rail is recorded with accelerometers.

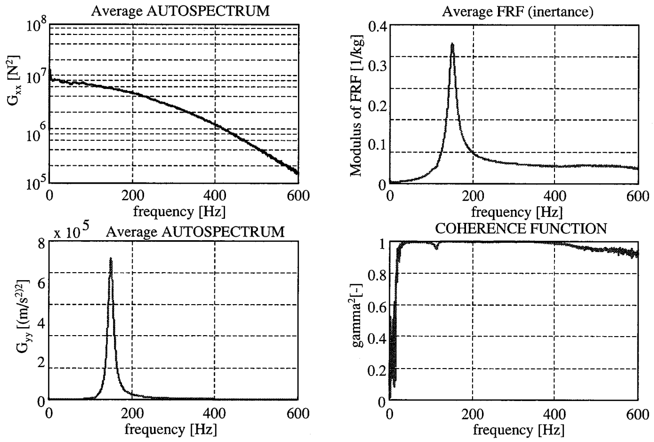

Fig. 4. Interpreted results from hammer excitation test.

In order to reduce the influence of less perfect hits with the hammer, five measurements are averaged into one result. Both the force and accelerations are recorded in the time domain. A Fast Fourier Transform (FFT) is used to transform the input and output signals into the frequency domain, see Figure 4, respectively top left and bottom left.

With the input and output signals the frequency response function (FRF) is calculated. The FRF gives the reaction of the track at a certain frequency and can therefore be considered as the fingerprint of the track. The FRF has different representations: as a function of accelerations (inertance), especially suited for small test objects and as a function of displacements (receptance), which is better suited for larger test objects.
In an FRF a peak corresponds to a resonance frequency or eigenfrequency. In Figure 4 top right the average FRF, inertance, of five measurements is shown. In Figure 4, bottom right, the coherence between the five measurements is shown. Coherence between 0,85 and 1 indicates that the results are reliable.

Because of the small length of the 0.50 m long test piece the movement of the rail can be interpreted as the movement of a SDOF system (Single Degree Of Freedom system). A SDOF system can be characterised by a mass m, a spring k and a damper c. The three parameters of a SDOF system are determined on the basis of the FRF by means of a curve-fit: in a given frequency domain the computer calculates a polynomial, with the three parameters as variables, that best fits the measured results.

Figure 5 shows the FRF of the 0.50 m long test piece and the results of the curve-fit as a dotted line with the determined parameters depicted at top right.

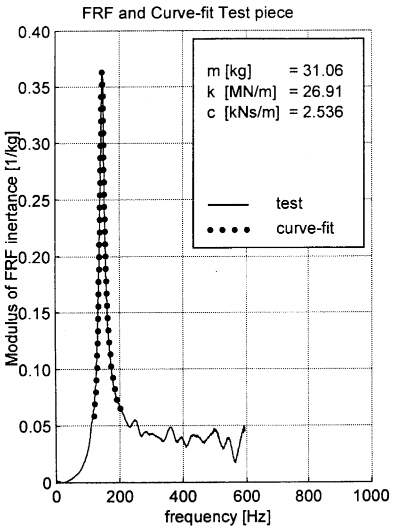

Fig. 5. *Curve-fitted test result.*

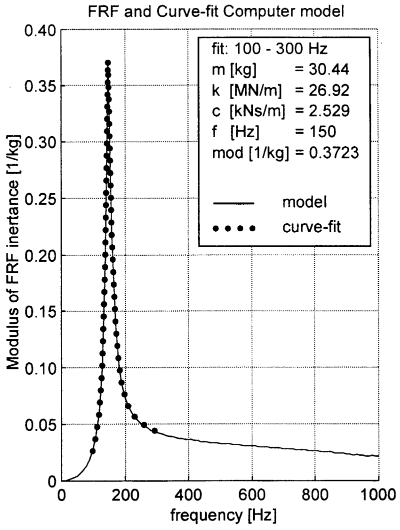

Fig. 6. *Curve-fit final iteration model.*

In the next step the test piece is modelled with the "Rail" programme, using estimated input parameters.

The computer model calculates the FRF and makes a curve-fit of it. The results are compared to the results of the test and the input parameters are adjusted until the values of the SDOF system match. Figure 6 shows the result of the iterative process, the SDOF system parameters of the test and the computer model being nearly the same.

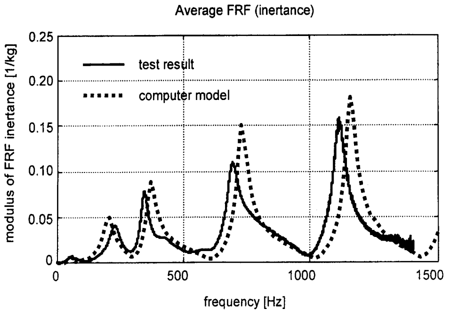

Fig. 7. *FRF of 4 metre long test piece and model.*

With the determined input parameters the 4 m long test piece was modelled. Figure 7 shows the good resemblance of the FRF of both test and computer model, proving that the determined input parameters are right.

5 Dynamic track response

The dynamic track response gives insight into the behaviour of the track all frequencies in the considered domain. It is used to predict the formation of short-pitch corrugation and to find out whether a track will be subjected to rapid deterioration. All information about dynamic track response is obtained from the frequency response function.

Results

The FRF of the ballasted track and the embedded rail structure calculated with "rail" are shown in Figure 8. For ballasted track, two lines are given, depending on the place of excitation. Excitation on the sleeper or between the sleepers causes a different response at the so-called pin-pin frequency (marked with 3). This is the frequency where the rail forms a sinusoid through the sleepers. In case the rail is excited between two sleepers, the rail vibrates easily corresponding to a resonance peak. In case of excitation on the sleeper the FRF shows an anti-resonance.

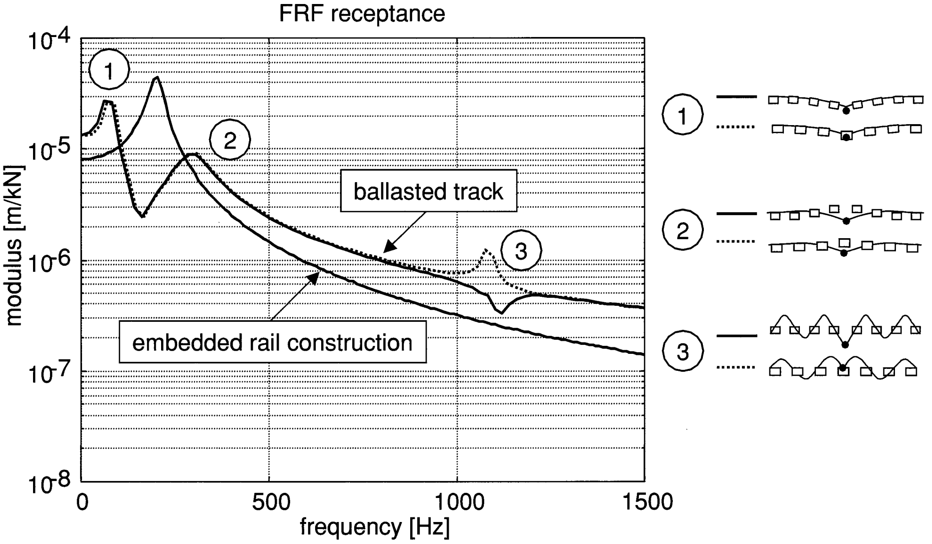

Fig. 8. Frequency response function ballasted track and embedded rail structure.

The FRF of ballasted track shows two other resonances, marked with 1 and 2. These correspond to respectively movement of rail and sleepers in phase and in anti-phase. Between these two resonances an anti-resonance occurs marking a frequency at which the track reacts stiff. The stiff behaviour of the track at certain frequencies increases the possibility to the formation of corrugation.

The first eigenfrequency of the ballasted track is relatively low. This can become a problem in case a highly elastic track structure is used in combination with high-speed trains as the excitation frequency increases with the speed according to formula (1).

$$f = \frac{v}{\lambda} \tag{1}$$

In (1) f is the frequency [Hz], v is the train speed [m/s] and λ is the wave length [m]. With a train speed of 300 km/hr, the excitation frequency caused by the spacing of the wheels in one wheelset of a Thalys high-speed train amounts to 28 Hz. The first eigenfrequency of the track must be sufficiently higher to prevent rapid track deterioration.
The embedded rail structure has a continuous support and has only one mass, the rail. Therefore the FRF of the embedded rail structure shows only one resonance peak. This resonance peak lays sufficiently high to prevent excitation by a train running with high speed.

Conclusions
The embedded rail structure with a continuously supported rail has only one resonance peak and no anti-resonance peaks. This will ensure a better dynamic behaviour than the ballasted track with two resonance peaks, an anti-resonance peak and a combined peak at the pin-pin frequency.
The formation of corrugation will therefore be less on the embedded rail structure.
The track stiffness of the ballasted track can not be chosen to low as to prevent excitation by a train running at high speed of the eigenfrequency.

6 Distance Damping

The noise emission of a train on a track depends on a number of factors. One of these factors is the capacity of the track to reduce the rail vibrations, which is expressed as the distance damping (DD). The DD shows the reduction of vibrations per unit length in longitudinal direction. The DD is determined as the averaged diminution of the vibration of the rail over 7 points up to 16 m from the driving point and is expressed in decibel.

Results
The results of the distance damping calculations for both track structures are shown in Figure 9. Again, for the ballasted track two lines are given because of the difference response at the pin-pin frequency in case of excitation at the sleeper or between the sleepers.

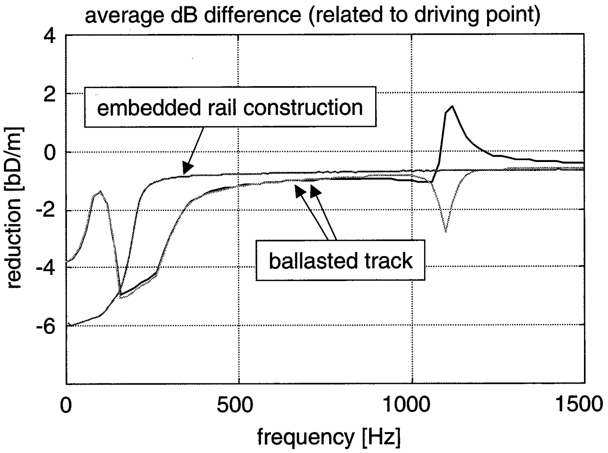

Fig. 9. Distance damping ballasted track and embedded rail structure.

It is seen that for the embedded rail structure at low frequencies the damping is high, higher than for the ballasted track. This is caused by the higher first eigenfrequency of the embedded rail structure.

From approximately 200 Hz to 1000 Hz the damping of the ballasted track is slightly higher than that of the embedded rail structure. This coincides for a large part with the frequencies important for noise production, which lay mainly between 500 and 1500 Hz. However, at the pin-pin frequency around 1100 Hz the vibrations of the ballasted track will be intensified.

Conclusions

The ERC has a high distance damping at low frequencies and an almost constant distance damping at the rest of the frequency domain. A stiffer structure will increase the highly damped low frequency domain.The ballasted track has a low distance damping at 150 Hz and will intensify vibrations at the pin-pin frequency. Overall the ERC has better distance damping capabilities then the ballasted track.

7 Vehicle-track interaction

One of the items that is contained by vehicle-track interaction is the acceleration of the vehicle. This is a measure for the passenger comfort. Calculations on vehicle accelerations are performed using a five-coach Thalys train as depicted in Figure 10.

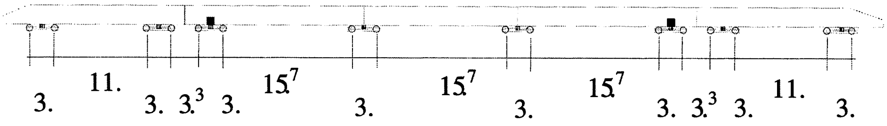

Fig. 10. Thalys high-speed train used to determine the vehicle-track interaction.

To excite the train, a corrugation pattern is applied to the rail head. This corrugation patterns is a sinusoids with a wavelength of 3 metres and an amplitude of 1.5 mm. The calculations are made for three speeds, i.e. 30, 60 and 90 m/s.

Results

Figure 11 shows the accelerations as calculated for three coaches, respectively the front coach body 1,second coach body 2 and middle coach body 3. At the left the accelerations running on ballasted track (BT) is shown, at the right the accelerations at the embedded rail structure (ERC) are shown.

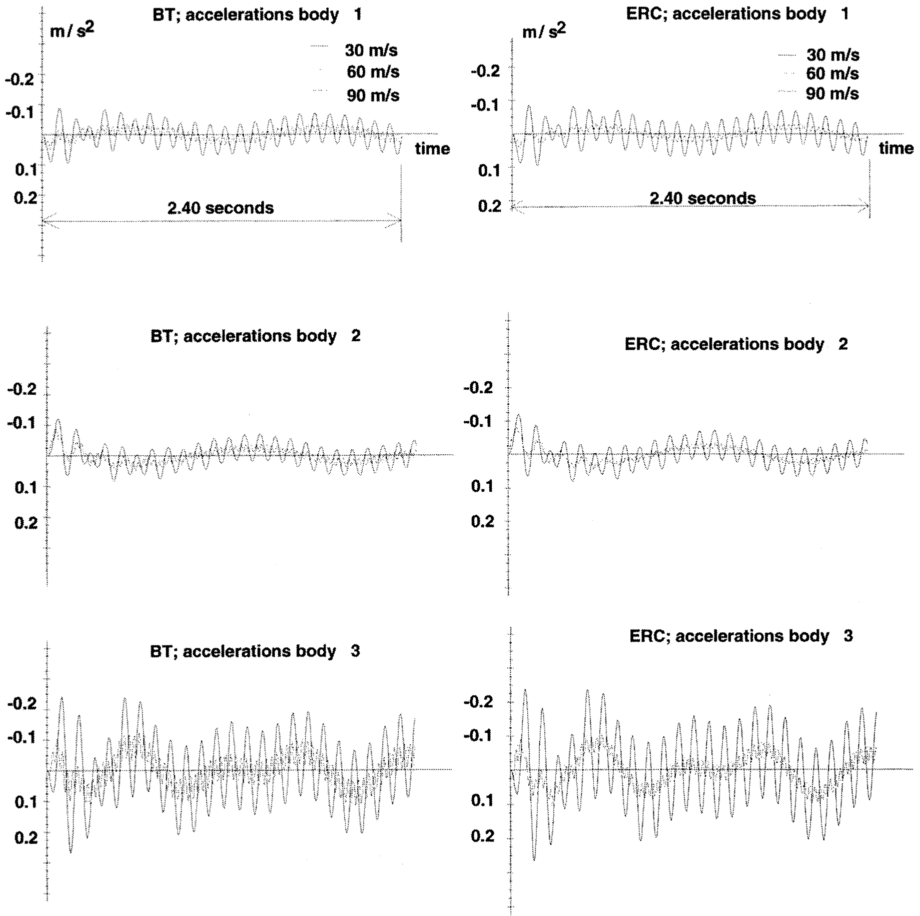

Fig. 11. Calculated acceleration in three different vehicles on both track structures.

The short waves that are seen in Figure 11 are caused by the corrugation pattern. The long wave is caused by movement of the body alone. The interference in this long wave at the middle vehicle is due to the shared bogies that support this body. The movements of the adjacent bodies influence the movement of the middle body.
It is seen the accelerations at a speed of 30 m/s are at a maximum level for both track structures. This is caused by the fact that at this particular speed in combination with the particular wavelength of the corrugation pattern, one of the eigenfrequencies of the vehicle is approached.
The accelerations at 60 and 90 m/s are slightly lower at the embedded rail structure.

Conclusions
The accelerations in the train are a little smaller when the train runs over the embedded rail structure instead of the ballasted track. This is caused by the better damping properties of the embedded rail structure. No influence is seen of the discrete support in the accelerations.
All accelerations remain well within the comfort levels.

8 Conclusions

With the help of the computer program "Rail" the dynamic behaviour of a railway track can be made clear.
It is shown that the embedded rail structure with its continuously supported rail has a better dynamic track response, better distance damping characteristics and gives a more favourable vehicle-track interaction than a classic ballasted track. This is expected to result in a lower wear of the track, a potentially lower noise emission and a higher passenger comfort.

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