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Structure borne sound from a lightrail in a fishnet stocking

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Abstract A new line for lightrail is developed in the centre of the Hague. This line is planned at a height of approx. 7 m above ground level. The design is a transparent steel construction like a fishnet stocking.
Important concern was the sound radiation of such a steel structure that can be quite high. The SPL should be acceptable for the people near and under the railway.
To assess the sound radiation an impedance model was made to calculate the vibration in the steel structure from a given source strength. The source strength was obtained form several measurements with different light rail trains and different tracks.
It was found that for a sufficient reduction of sound radiation it was necessary to apply concrete beams as supports in combination with resiliently mounted rails. The expected equivalent sound pressure levels at ground level around the elevated rail are approx. 75 dB(A) during passage, which is expected to be sufficiently low to be acceptable for the shopping public.

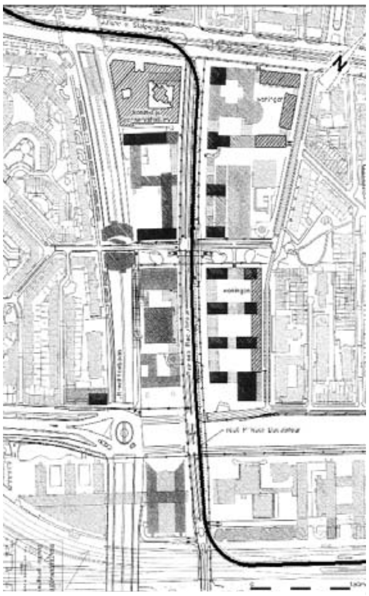

Figure 1: overview of the new lightrail section in The Hague were the steel fishnet construction is applied.

1. INTRODUCTION

A railway carriage produces noise. This is inevitable but does not have to be a problem.

Part of the plans to improve transport in and between the nearby cities in the western part of the Netherlands ("Randstad") a new railway (lightrail) is planned between Rotterdam, Zoetermeer and The Hague. The line is called Randstadrail. This line will partly use existing railway, existing tramway and parts of it will be built. This paper deals with the new section at the Beatrixlaan in The Hague, see figure 1. This section is between Dutch railways at "laan van Noord-Oostindië" (in the bottom of the figure) and then bends into the Beatrixlaan. At the tram stop Ternoot in the "Juliana van Stolberglaan" it connects to the existing tram way with a curve (upper part of the figure).. The curves are made in traditional concrete bridge constructions. The straight parts have the steel fishnet construction.

The area of the Beatrixlaan is newly developed, with new buildings and larger pavement area and shopping facilities. To be able to connect to the existing, raised railway and tramway lines and to enable these shopping areas with high quality outer space, this section of the railway line is planned at an height of approximately 7 m above street level.
To realise a light and open character with a maximum of light transmission, to prevent the street will be dark and gloomy, and a minimum of columns at street level an open steel construction was designed with diagonal steel beams, called a fishnet stocking.
An impression of the original design by the architect, Zwarts & Jansma is given in figure 2.

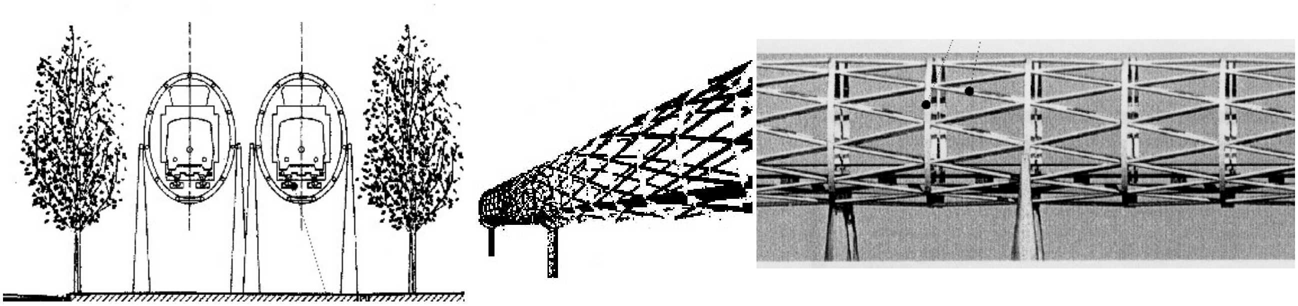

Figure 2: the original design by the architect, Zwarts en Jansma, completely steel construction and a fishnet stocking for each track

Important concern was the sound radiation of such a steel structure, that can be quite high, as we know e.g. from the well-known Chicago Elevated Train.
This sound radiation is partly a jurisdictional aspect, and has to be considered together with the influence of the road noise, mainly because the road structure is also to be changed. Another part however is the perception of the noise in the pavement area. High sound pressure levels in this area can cause disturbing or even frighten the walking public. This would interfere with the intended high quality standard for the outer space in this area.

It is known that light constructions can easily be exited to high vibration levels, and thereby causing high sound radiation. Steel railway bridges are sound examples for this phenomenon.
The task for the acoustical consultant was to reduce the sound levels from the railway to acceptable levels in the walking area's near and under the railway.

To assess the sound radiation an calculation model was made to calculate the vibration in the steel structure from a given source strength. The source strength was obtained form several measurements with different light rail trains and different tracks.
Based on the results of this study concrete beams are added to the steel construction (see figure 3).

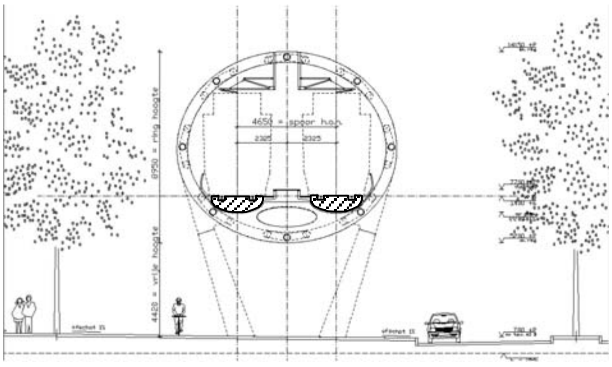

Figure 3 Final design with concrete beams (shaded) added to the steel fishnet stocking and both tracks joined in a single construction.

2. NOISE LIMITS

In the Netherlands there is a legal system with limiting levels for railway noise and road noise.

The noise is considered railway noise if the train (or tram, it is actually sort of in between a train and a tram) is running over a railway line that is indicated as such in a decree (on railway noise nuisance, part of the noise act). Normally roads with tramway tracks are not being considered as railways, since usually the road vehicles dominate the sound immission.

The noise is considered as road noise if road vehicles produce it. In this case it’s not a road vehicle, so it’s not road noise either. In practical use however it is considered as a part of the road noise. Noise levels are applicable for dwellings and other sound sensitive buildings. Most of the buildings in the Beatrixlaan however are office buildings. Only in the upper curve towards the Juliana van Stolberglaan there are some dwellings and a music school for which the legal system is applied. These dwellings however are at sufficient distance from the steel fishnet stocking (the curves are in traditional concrete). Since it is a reconstruction of a road (including the new rail/tramway) the increase of sound immission has to be considered. In case the increase is more than 2 dB sound reducing measures have to be considered. This increase is calculated, including the contribution of air borne and structure borne noise from the railway.

More important are the limiting sound pressure levels due to the railway. The calculated equivalent sound pressure level due to the road in the pavement area is 65 to 70 dB(A). Maximum sound pressure levels due to busses and truck will be 80 dB(A) or more. Based on these data it is expected that there a sound pressure level of 75 dB(A) during pass by of a train will be acceptable. The airborne sound form a train at approximately 50 km/h will be within that limit. Objective was that the structure borne sound might increase this level with not more than a few dB’s.

3. CALCULATION MODEL

The train for the randstadrail is different from the tram carriages already in use, the lightrail is something in between a tram and a train, see the picture of figure 4.

Figure 4: Picture of a lightrail

Both the carriages as the railway construction differ from the normal situation. The vibration excitation depends on many factors such as weight and spring characteristics of the carriage, roughness of the surface, speed and construction of the rail bed. The best prognosis can be made by comparing measurements from similar trains on a comparable railway bed, combined with (small) corrections for the differences. Since these situations were not available measurements with similar trains on a different railway track are performed. The vibrations in the projected situation are calculated for this specific railway construction, making use of the measurements performed.

Starting point of the model is that there is certain internal source strength based on the speed and rail and wheel roughness. The vibration level of the coupled wheel and rail system depends on the impedance's of the rail system and the wheel system. For these systems a relatively straightforward one-dimensional impedance model is made. Track and cariage are modelled with masses, springs and dampers. The model is summarised in figure 5.

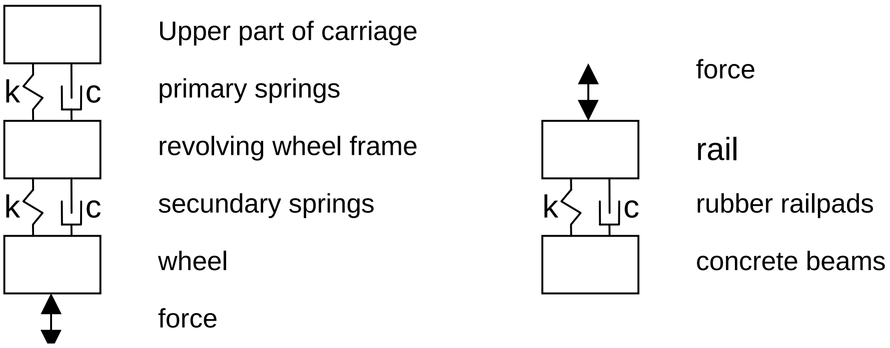

Figure 5: mass-spring model of the carriage (left) and the track (right) where m=mass, k=spring stiffness, c=viscous damping

The relation between total impedance, internal force of the source and rail velocity is described by:

$$Z_{tot} = F_{source} / v_{rail} \tag{1}$$

Where:: Z_{tot} = total impedance of the trach and the carriage [Ns/m]
F_{source} =effective (vertical) source strength [N]
v_{rail} =(vertical) vibration velocity of the rail (and the wheel) [m/s]

These are complex quantities, with an amplitude and phase. The Z_{tot} can be calculated from:

$$Z_{tot} = Z_{rail} + Z_{wheel} \tag{2}$$

The impedance of the wheel is to be calculated from the (mass impedance of the wheel itself and the impedance of the carriage (see right part left part of figure 5). From top down the impedance of the upper part of the carriage (first approximation) can be described by:

$$Z_{m,b} = j\omega m_{,u} \tag{3}$$

Where: $m_{,u}$ = mass of the upper part of the carriage

The impedance of the combination of this upper part and the primary spring/damper can be calculated from a summation of the inverse impedance's (admittance):

$$Z_u = \frac{1}{\left(\frac{1}{Z_s + Z_d} + \frac{1}{Z_m} \right)} \tag{4}$$

Where: Zs = impedance of the spring = k/jω
Zd = impedance of the damper = c

This procedure can be repeated to add the mass impedance of the revolving wheel frame, the secondary spring/damper and the impedance of the wheel. This stepwise addition of impedance's in a chain of masses, springs and dampers is an powerful and easy to use modelling system [lit. 1]. Condition is that the chain starts with a known impedance (in this case the free moving mass of the carriage). When, for a given source strength, the vertical velocity at the end of the chain (the wheel) is known, the velocity at all other points can easily be calculated [lit. 1].
Because of the resilient mounting of the wheels the impedance of the carriage is for a great deal determined by the mass impedance of the wheel.
The impedance of the rail track is calculated in a similar way.

Of course in this calculation model a number of assumption and simplifications are made:

- The model is primarily made for vertical translation, other translations and rotations are considered less important;
- The characteristics of continuous structures (the rail) are translated to characteristics in a single point;
- For the characteristics of springs the contribution of the material within half a wavelength in the rail is considered;
- The wheels of one revolving wheel frame are considered to be within this half wavelength and therefore they both give a dynamic load on the rail.

The necessary data is given by the suppliers.


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Figure 6: Example of a rail mounted on a rubber rail pad

4. MEASUREMENTS

The most important factor to be obtained is the source strength. This source strength is calculated from several measurements. This source strength can be calculated from formula (1) when the impedance's of the carriage and the track are known (te be calculated) the vibrations are measured. The measurements are performed in two types of situations: a number of bridge-like situations with the old trams as source and number of situations with a lightrail (Saarbrücken) and a conventional track. For these different situations different calculation models for the track were made. For the bridge-like construction impedance's of endless beams are applied, for the conventional railway-soil construction impedance models from the literature are applied [lit. 2]. Two of these models are shown in figure 7.

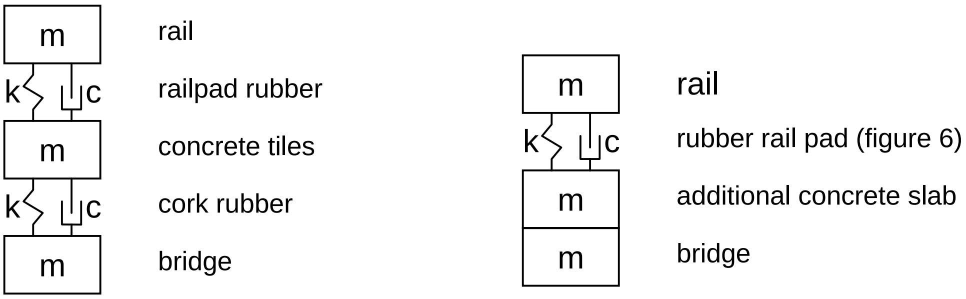

Figure 7: Examples of models of the track applied for calculation of the source strength (left: bridge CS-Ternoot, right: Josephbrücke Saarbrücken)

The calculated effective source strength from these measurements are presented as force level, $L_F = 20\log(F/F_0)$ in figure 8.

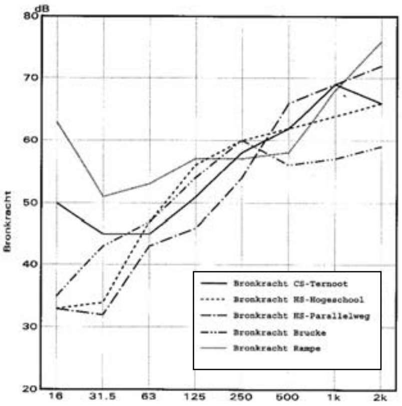

Figure 8: measurement results source strength at different measuring locations

The measured force strength differs in the measured situations, but apart from the very low frequencies the differences are limited. The air born sound emission of the light rail is much lower than from the conventional trams, but the structure born source strength is in the same order of magnitude as the conventional trams.

Based on these measurements an average effective source strength is used for further calculations. With this source strength the vibrations in the fishnet stocking construction were calculated.

5. PREDICTION OF VIBRATIONS

When the source strength is known and the impedance of the receiving structure can be calculated, the vibration level of the concrete beams of the fishnet stocking can be calculated, using formula (1).

The receiving construction is presented in figure 5 (right side), in this stage the influence of different sizes of concrete beams is considered. In this construction the rails are mounted on rail pads. As a first approximation it is assumed that the impedance of the steel structure can be neglected.

Table 1 presents the calculation results of the vibrations of the rail and the concrete beam for the different sizes of the beam. The velocity level greatly depends on the vertical size of the beam, as can be expected. The half-elliptical beam is applied in the final design (see figure 3).

Table 1: Calculated vertical velocity level in rail and concrete beam

source	L_v in dB (re $1\text{x}10^{-9}$ m/s)				
	Half-elliptical beam (wxh)	Width x height of concrete beams(m) under each rail			Concrete slab (wxh)
	2,4 x 1,4	0,45 x 0,60	0,45 x 0,3	0,9 x 0,6	2,5 x 0,15
Rail	126	128	131	126	128
concrete beam	108	122	129	116	124

6. PREDICTION OF RADIATED SOUND POWER

As for the radiation of sound caused by a train passing the contribution of five sources has to be taken into account.

- Airborne sound radiation (including sound radiated by the wheels and the track when firmly mounted)
- Structure borne sound excitation and radiated by:
- the (resiliently mounted and therefor much more radiating) rails;
- the concrete beams;

- the egg-form vertical rings of the steel construction;
- the diagonal steel beams that form the fishnet.

For each of these contributing sources the vibration level, the radiating surface and the radiation efficiency is determined. The radiation efficiency describes the relation between vibration level and radiated sound power and is dependent on dimensions of the object and for lager objects (plates) also on the material properties, the thickness and the way of excitation.
Because of the small dimensions compared to wavelength the steel beams will have a low radiation efficiency for low frequencies. A typical radiation efficiency of such a beam is given in figure 9. Only the high frequencies will properly radiate. At these higher frequencies the rubber mounting of the rails is an effective measure to reduce vibration excitation.

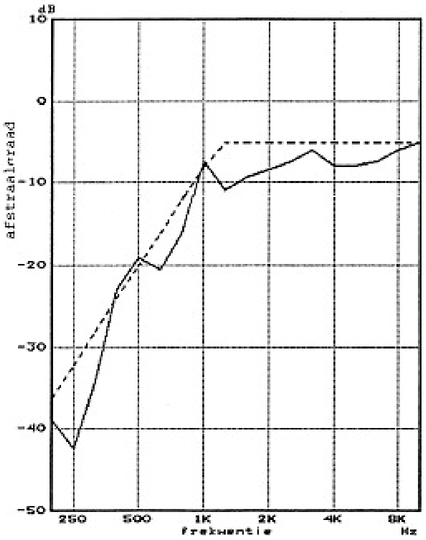

Figure 9: example of calculated (dashed line) and measured (solid line) radiation efficiency of a steel beam (size 80 mm), lit [4].

At the start of the investigation it was clear that an increased impedance of the receiving structure would be necessary. Firstly some different concrete beams were calculated (see table 1). In a next design a half elliptical concrete beam is introduced, with both rails mounted on this concrete beam (see figure 3).
table 2 shows for the different sizes of the concrete beams the radiated sound power per m1 of the different sources, taking into account the radiation efficiency of these sources, and the total sound power per m1.

Table 2: Sound power of the sources en total sound power per m1

Sound source	L_W per m in dB(A)				
	Half-elliptical beam (wxh)	Width x height of concrete beams(m) under each rail			Concrete slab (wxh)
	2,4 x 1,4	0,45 x 0,60	0,45 x 0,3	0,9 x 0,6	2,5 x 0,15
rails	84	84	84	84	84
concrete beams	71	79	84	75	85
egg-form steel rings	69	79	87	74	82
diagonal steel beams	71	83	90	78	86
total	85	88	93	86	91

The calculations show that the increase of the impedance has a significant effect on the radiated sound power. At a certain level adding more mass and/or stiffness doesn't help anymore because the radiation of the rails and of course the airborne sound radiation (not in this table) will be the dominant factor. The contribution of the radiation of the rail is relatively high because of the low coupling to the construction. A further decrease in radiated sound power is expected by applying embedded rail.

Based on these calculations the expected sound pressure level and ground level due to passing trains in the fishnet stocking will be approximately 73 to 76 dB(A). The radiation of structure born sound contributes 3 to 4 dB(A) to this level. By the use of embedded rail sound pressure levels below 73 dB(A) may be expected.

7. CONCLUSIONS

The section of the lightrail project “Randstadrail” in the Beatrixlaan in the Hague, Netherlands, is going to be constructed as a combined steel/concrete construction in the form of a fishnet stocking. Based on measurements and a an impedance calculation model the sound power of the construction is predicted. Based on these calculations it was decided to apply a concrete beam as part of the bearing construction.

The calculations show that application of concrete beams, combined with resilient mounting of the rails, give sufficient reduction of structure borne sound radiation. Using embedded rail can further reduce the sound radiation.

The expected equivalent sound pressure levels at ground level around the elevated rail are approx. 75 dB(A) during passage, which is expected to be sufficiently low to be acceptable for the shopping public.

8. LITERATURE

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