Acoustic characteristics and noise control measures for steel road bridges

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Summary

Moveable road bridges with large traffic flow and heavy vehicles are a potential source of noise disturbance for nearby dwellings. Low frequency noise caused by heavy vehicles can be disturbing, but also mid-frequency noise from joints and interaction between tyres and the bridge deck. The Netherlands has many such bridges, in particular bascule bridges, some of which are a cause of complaints due to annoyance or sleep disturbance. The Dutch Road Authority Rijkswaterstaat takes noise abatement into account when bridges are replaced, renovated or newly constructed. Different noise control solutions have been attempted with varying results. TNO and Rijkswaterstaat are working on improved solutions and prediction models for bridge noise.

In this paper some examples are given of motorway bridges, their acoustic characteristics and potential noise control measures and their effect. Prediction of the overall noise emission still contains uncertainties depending on the models and measurements available. The actual noise level depends on the excitation by the vehicle, the dynamics and sound radiation of the deck and girders, and the acoustics of the space between the bridge deck and the water below.

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1. Introduction

In The Netherlands, there are many road bridges made of steel, in particular bascule bridges, both on motorways and arterial roads. The steel structure tends in particular to radiate low frequency noise during pass-bys of heavy vehicles, often giving rise to complaints due to annoyance or sleep disturbance in nearby dwellings. In addition, joint passing and rolling excitation cause noise in the medium frequency range. The growth of road traffic and resulting need for replacement and new construction of such bridges means that noise must be taken into account as a design factor for the future. Low frequency noise is generally not well included in the statutory noise calculations, whereas it is known to be a source of annoyance, even more so if it is intermittent or pulsating in nature.

The Dutch Road Authority Rijkswaterstaat takes noise abatement into account, including low frequency noise, when bridges are replaced, renovated or newly constructed. In recent years a number of bridges have been investigated and remedial measures have been attempted with varying results. TNO and Rijkswaterstaat are working on improved solutions and prediction models for bridge noise.

In this article an overview is given of some examples of typical bridge design, the sound sources and radiation, potential noise control measures and their effect, measurements and modelling.

2. Typical bridge design

Current design of movable steel bridges for motorways and arterial roads consists of a welded structure of a steel deck stiffened with trough profiles, two main bearing girders on which the bridge rests, and a number of cross girders. The structure between de main bearing girders and the outer boundaries tapers off, resulting in a lower stiffness towards the edge. Examples of such bridges are shown in figures 1-2.

Figure 1: A10 motorway bascule bridge. Left: five lane bridge (foremost); right: deck with joint in foreground.

Figure 2: A44 double motorway bascule bridge. Left: whole bridge; right view of opened deck.

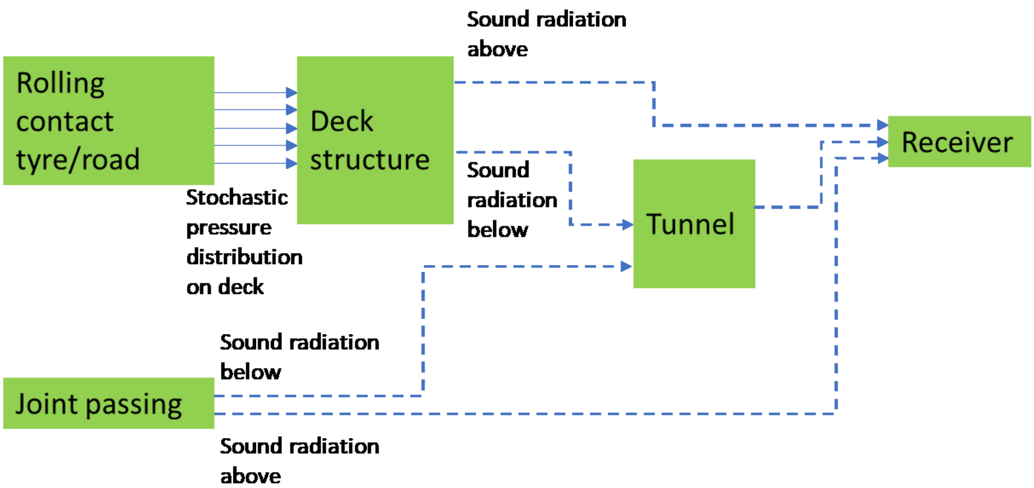

Figure 3: Schematic sound path model for steel road bridges.

The design evolved in this way mainly for reasons of weight, maintainability and fatigue.

3. Sound generation, transmission and radiation

Besides the usual vehicle noise radiation from road-tyre rolling noise and engine noise above the road surface, which is often shielded by a sound barrier, the bridge structure is excited by the tyre-deck interaction, both at the joints and on the deck surface. This excitation depends on surface profiles of wheels and deck, wheel diameter, speed, lane positioning and dynamic interaction between the vehicle and the bridge. In addition, the open gaps in the joints can radiate noise downwards underneath the bridge. In practice, cars with their smaller tyres tend to generate more mid-frequency joint and rolling noise, whereas the larger truck tyres tend to cause low frequency noise. A schematic sound path model of excitation and transmission of sound of steel road bridges is shown in figure 3.

If impacts occur at the bridge deck supports for heavy vehicle pass-bys, which can occur due to thermal expansion of the deck or extra supports for example, this can be an additional excitation mechanism for structure-borne noise.

Moveable bridges usually have supporting bulkheads or walls, forming a tunnel or semi-open tunnel. Such a tunnel tends to amplify the noise by 3-9 dB depending on the geometry and absorption for the simple reason that the energy is focused in one direction or towards one side. Consequently, the sound radiation from the tunnel is often larger than that from the top surface, especially for the observation points below the road surface. The plate-like deck structure in itself has a dipole-like radiation pattern although the tunnel increases the lower directivity lobe due to its amplification.

In general, the low frequency noise can be expected to propagate spherically, whereas mid-frequency noise has a stronger directivity due to the ratio between wavelength and tunnel opening dimensions.

The heavy welded structure of such bridges often results in a low structural damping, although the deck itself can be reasonably well damped due to the attached epoxy surface layer.

4. Measurements

An example of the sound level history for the C-weighted and the A-weighted sound level at 44 m from a bridge is illustrated in figure 4. The C-weighted level reflects the low frequency sound peaks from heavy vehicles, which can be upto 15 dB above the other traffic noise, and are a source of disturbance due to their fluctuating characteristics.

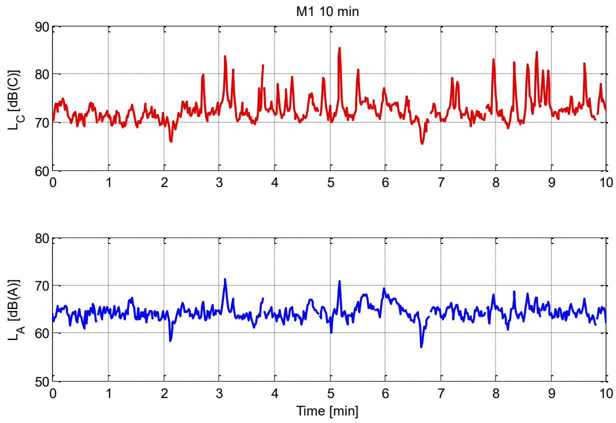

Figure 4: Sound level history of C- and A-weighted sound pressure near a dwelling due to bridge noise (A10), for 10 minutes, from [1].

Examples of sound pressure spectra near the bridge and near dwellings are shown in figure 5. Close to the road (M14) the medium frequency traffic noise is strong, whereas near the dwellings (M1-3), the low frequency contribution from the bridge is more predominant.

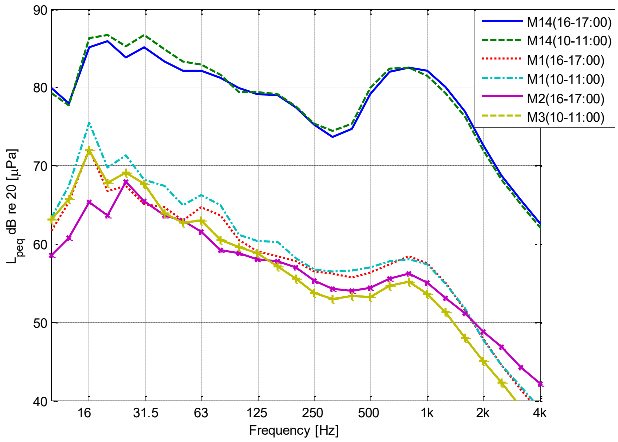

Figure 5: Equivalent sound pressure spectra in third octave bands (unweighted) for points directly next to the A10 bridge above road level (M14) and near dwellings (M1,M2,M3), from [1].

If vibration measurements on parts of the bridge structure can be taken, the radiated sound power level can be estimated for components such as the deck, the main girders, cross-girders and stiffener profiles. The sound power is estimated (see section 6) from the acceleration levels, radiating surface areas, and calculated radiation efficiencies, resulting in spectra such as shown in figure 6.

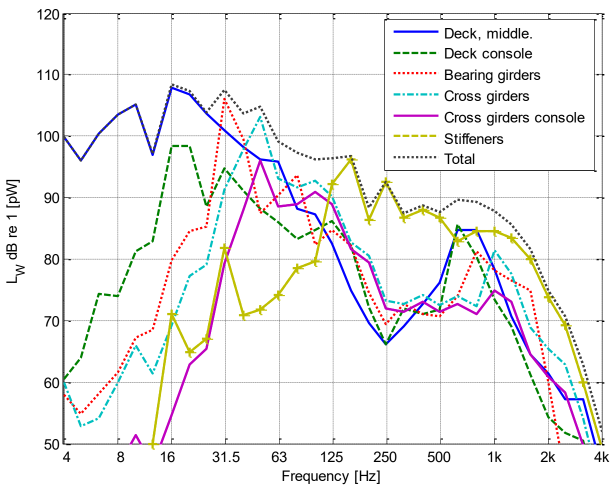

Figure 6: Sound power level estimate in third octave bands based on measured acceleration of bridge components (A10), from [1].

In this example the deck, main bearing girders and cross girders are the main sound radiators upto 100 Hz. Above 125 Hz, the deck stiffeners are a major sound radiator for the mid frequency range, although the other girders contribute again above 500 Hz due to the increased radiation efficiency.
If left undamped or unshielded, the deck stiffeners can be a significant medium frequency sound source.
This fairly straightforward procedure does provide a good indication of the main contributors, but contains some uncertainties in the radiation efficiency and assumed distribution of acceleration levels.

5. Noise control measures

A number of noise control measures can be proposed, based on general principles for low noise design, which can differ depending on whether the bridge in question is an existing structure or a new design. In table I, a number of these are listed together with their typical frequency range, potential design conflicts and primary applicability to existing or new bridges.

In practice, noise control measures need to be combined to achieve sufficient noise reduction. Relatively little testing of solutions has been done due to complexity and long turn-around time. Once applied, it is not always straightforward to attribute the contribution of each noise control measure to the total reduction.

An example of noise control measures is shown in figure 7 for a bridge which was renovated (see figure 2, A44), changing from a steel structure with a wooden deck to a fully welded steel structure with a steel deck with softer rubber block supports shown in figure 7.

Figure 7: New rubber block support under renovated A44 bridge.

The sound pressure spectrum in figure 8 shows a decrease in sound level below 125 Hz and an increase between 160 Hz and 1,25 kHz. The A-weighted sound level actually increases.

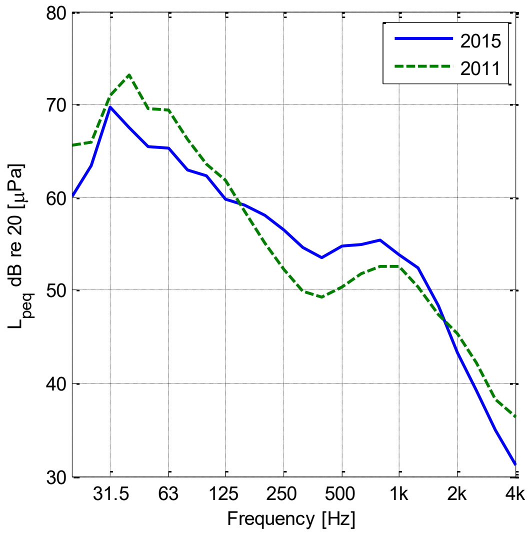

Figure 8: Sound pressure spectrum in third octave bands at receiver point at 66 m distance from the bridge (A44) before and after renovation, from [2].

Table I: Noise control measures for steel road bridges

	Low/ Medium freq.	*Potential design conflicts*	*Existing bridges, add-on or modification*	*New bridges, integral design*
Enclosure underneath	MF/LF	Weight and maintenance	x	
Sealing of joint underside	MF	-	x	x
Sound absorption on side walls	MF	Space and durability	x	x
Structural damping, surface	MF/LF	Weight and durability	x	(x)
Structural damping, discrete	MF/LF	Weight and durability	x	x
Structural stiffening - Cross girders at joints - Deck over length - At deck seams - Deck thickness	LF	Weight		x
Composite structure with integrated damping	LF/MF	Durability, fatigue predictability		x
Closed structure	LF/MF	Maintenance		x
Diagonal joints	LF/MF	Spatial constraints		x
Profile joints	LF/MF		x	x
Structural resonators	LF	Large number required	x	
Acoustic resonators	LF	Space and durability		
Rubber block support	LF/MF	Deck alignment	x	x
Hydraulic damping supports	LF/MF	Space and maintenance	x	x
Improved support of the joint bearing cross girders	LF/MF	Multiple contacts	x	x
Doors in front of tunnel	LF/MF	Access and maintenance	x	

The low frequency decrease is most probably due to the heavier and smoother deck structure of the new bridge, whereas the medium frequency increase is due to a lack of damping in the V-profile stiffening girders underneath the deck, compared with the previously wooden deck. Higher damping or shielding of the stiffener profiles would resolve this medium frequency noise.

6. Modelling

The main purpose of modelling is to compare new or modified bridge designs in terms of noise emission. Prediction of the overall noise emission still contains uncertainties depending on the models and measurements available. The actual noise level depends on the excitation by the vehicle, the dynamics and sound radiation of the deck and girders, and the acoustics of the space between the bridge deck and the water below.

The excitation of the bridge deck can be assumed to be evenly distributed over the deck surface of a traffic lane, if averaged over multiple pass-bys over time.

Numerical modelling is applied in the lower frequency range upto around 250 Hz for the prediction of a vibro-acoustic transfer function from deck excitation to sound pressure p close to the bridge. Such a transfer function H can be of the form

$$H = \frac{p}{F} \qquad (1)$$

with p= sound pressure at a receiver position near the bridge, averaged over a cylinder at 7.5 m from the first lane and 3 m below the deck, and F= excitation force at one or more points, or

$$H = \frac{p}{pin} \qquad (2)$$

where p_{in} is an average random excitation pressure over the part of the deck excited by the vehicles.

This requires a mechanical dynamic FEM model for the bridge structure and an acoustic model with infinite boundaries around the bridge. This type of transfer function can be used to understand the resonances most relevant for sound radiation and to derive potential structural modifications for improvement.
The corresponding eigenfrequencies and mode shapes are used for this. An example of vibrational eigenmodes of a bridge structure calculated with FEM at low frequency is shown in figure 9. The modes shown are sensitive to vertical excitation on the deck.

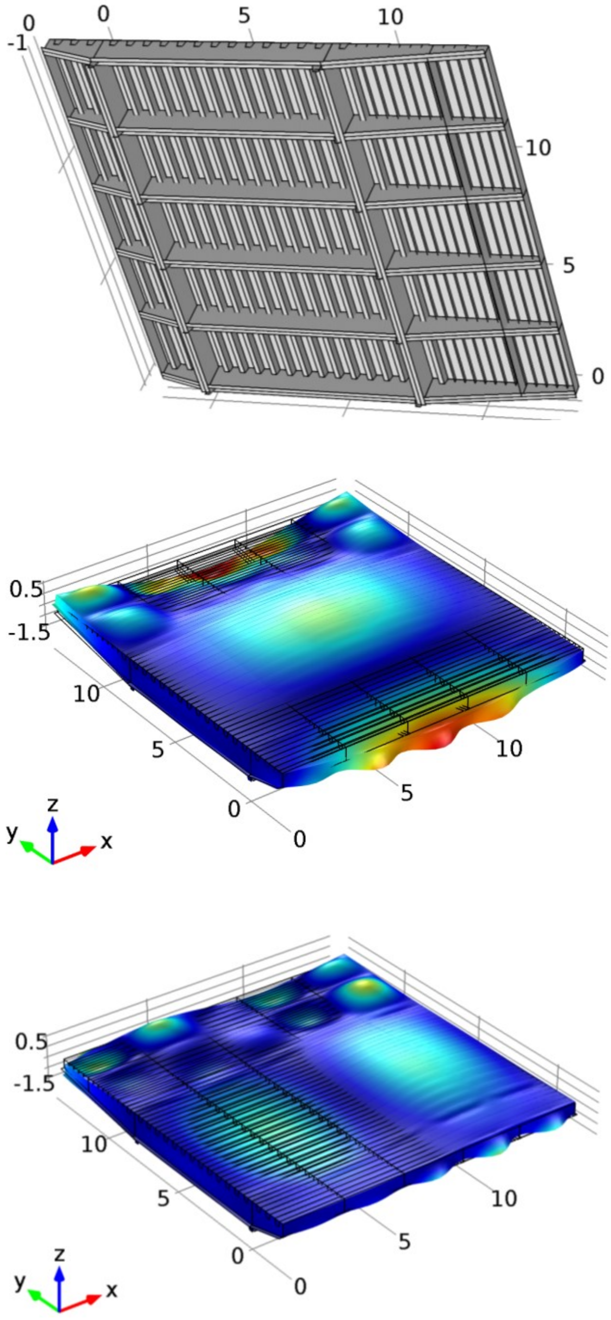

Figure 9: FEM model (top) and eigenmodes of a bridge structure (Wantij N3) calculated with dynamic FEM analysis, sensitive to vertical excitation of the deck, at 28 Hz (middle) and 31 Hz (bottom), from [4] (FEM Calculations A. Berkhoff, TNO).

The structural damping loss factor η is an input parameter usually based on measurement and experience, with a potentially significant effect on the sound emission.

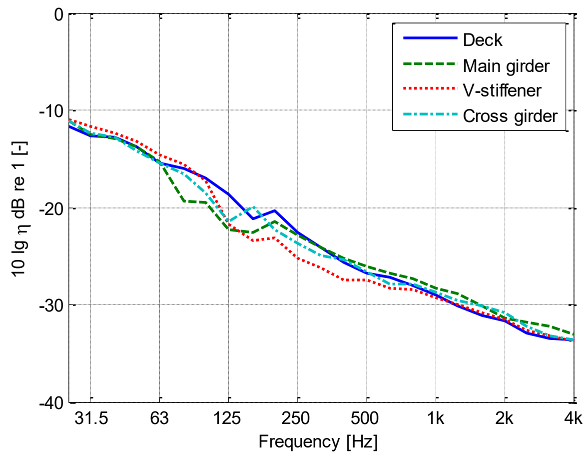

Figure 10: Measured structural damping loss factors on a large steel bridge (A10), from [1].

It tends to be high at low frequency at around η=0.1 dropping down at medium and high frequency to values between 0.0005-0.01. The damping loss factor generally affects the bridge vibration and thereby the radiated noise according to 10 lg η, so a doubling of the structural damping should reduce the bridge radiated noise by 3 dB.

Increasing the damping without too much weight increase is most difficult at lower frequencies.

Also other noise control measures such as stiffness changes are most demanding in the low frequency range as often substantial modifications to the structure are required to have a significant effect

For the medium frequency range, statistical models (SEA and third octave band estimates) are more practical due to the high modal density above 50 Hz. Due to the plate-like structure of steel road bridges, numbers of eigenmodes per octave band can easily run into the hundreds, quickly increasing with frequency. The same is the case for the acoustical transfer function of the tunnel under the bridge.

The sound pressure level L_p at a receiver point below road level at distance r can be calculated from the sound power radiated from the opening (tunnel) of the bridge, which typically would be half of the radiated sound power from the lower part of the bridge, taking monopole radiation and directivity D into account and other attenuation terms such as ground attenuation and reflections combined in term A:

$$L_p = 10\, lg\left(\frac{W_{tot,lower}}{2}\right) - 20\lg(r) - 11 - A + D \quad (3)$$

The directivity D in de horizontal plane can be spherical at low frequencies and more elongated at higher frequencies for wavelengths larger than the tunnel cross-section. In the vertical plane, the whole bridge can be more like an uneven dipole, due to the plate-like geometry of the deck and the amplified sound radiation from underneath the deck. This is shown indicatively in figure 11.

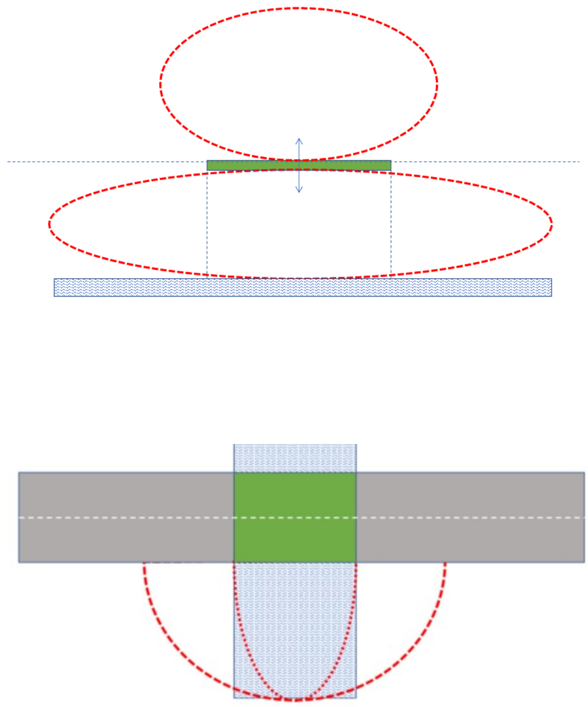

Figure 11: Indicative directivity patterns for bridge with tunnel: top: vertical plane on bridge cross-section; bottom: horizontal plane, with directivity for long and shorter wavelengths.

The sound power for each plate component W_i can be calculated from the radiation efficiency σ_i, the average plate vibration v_i^2, the surface area S_i and the acoustic impedance ρc:

$$W_i = \sigma_i \rho c S_i \overline{v_i^2} \quad (4)$$

and the total sound power level L_{Wtot} is calculated from the energy sum over all plates:

$$L_{Wtot} = 10\ lg \sum_{i=1}^{n} 10^{L_{W,i}/10} \qquad (5)$$

When considering the effects of structural stiffening in the case that the radiation efficiency is unchanged, then the noise reduction ΔL_W can be estimated from the change in injected structural power ΔPin

$$\Delta L_W = \Delta P_{in} = \Delta \mathrm{Re}(Y_{in}) \qquad (6)$$

where the injected power P_{in} is

$$P_{in} = \mathrm{F}^2 \mathrm{Re}(Y_{in}) \qquad (7)$$

with F= excitation force [N] and Y_{in}=input mobility [m/Ns].

All of the above formulas are applicable in third octave bands. Expressions for radiation efficiency and input impedance (reciprocal of input mobility) can be found in [6].

Although numerical and statistical models allow the studying of noise control measures on steel bridges, measurements are often still required to validate input data and transfer functions. Ideally, a parametric model would be preferable, covering the design range of such bridges. Work is underway to improve both numerical, statistical and parametric modelling of sound emission and noise control measures.

Besides numerical and statistical models and measurements, a global model may be required

- to take other sources such as joint noise, support noise and traffic noise into account ;
- if both the upper and lower parts of the bridge contribute to the receiver sound level;
- to assess effects of combined noise control measures;
- to include externally calculated and measured inputs.

Such a global model, which may be an extended form of the scheme in figure 3, consists mainly of energy summation of different sources, directivity terms, and correction terms for noise control measures.

7. Conclusions

Movable steel road bridges can be a major noise source for nearby dwellings, in particular the fluctuating low frequency noise caused by heavy vehicles. With existing bridges being renovated and new bridges being built there is need for clear design guidelines and efficient models for noise control. A series of noise control measures is available both for low and medium frequency ranges, but many of these have some practical limitations and need to be applied in combination to achieve sufficient noise reduction. Numerical and statistical models and measurements are required together with a global model to assemble and assess inputs and results. Some examples have been shown in this paper, but further work is required on modelling and validation of quieter bridge design and noise control measures.

Acknowledgement

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