Noise prediction of a steel-concrete railway bridge using a FEM

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Summary
In order to expand the Dutch motorway A1 the existing concrete railway bridge of the train line Amsterdam-Almere has to be replaced. In order to achieve the maximum amount of space for the layout of the motorway, a single span bridge is required. The bridge is situated near dwellings. According to the noise requirements set by the legislator the noise of the trains on the bridge has to be equal to or lower than the noise of the trains on a standard railway track. Due to the large span and strict noise requirements a steel-concrete bridge design was chosen, consisting of steel girders and arches and a concrete deck. The rails are fastened on concrete sleepers resting on track ballast. Between the concrete deck and the ballast layer a so called ballast mat is located in order to decouple the train induced vibrations from the concrete deck. To predict the noise of the trains on the bridge, vibration calculations were conducted with a finite element method (FEM). In order to calibrate the simulations, noise and vibrations measurements from a similar steel-concrete railway bridge were used to validate a FEM model of the reference bridge. To meet the noise requirements the new bridge design has been optimized, based on the measurements and calibrated calculations of the reference bridge.

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1. Introduction

The Dutch motorway A1 between Amsterdam and Hilversum has to be expanded because of traffic jams. In the vicinity of Muiderberg the motorway A1 crosses the train line Amsterdam-Almere. In the current situation the motorway consists of 10 lanes for normal traffic and one lane for buses. In the new situation 17 lanes are projected. The current concrete railway bridge has three intermediate supporting columns and a maximum span of about 50 m. In figure 1 the current bridge is shown.

In order to achieve a maximum flexibility in the layout of the motorway lanes and less traffic disruption during the build, the bridge design partners have chosen to build a single span bridge with a total span of about 250 m. The maximum span of a concrete bridge is about 60 m, therefore a concrete bridge design is not possible. The required span of about 250 m can be realized by building a steel bridge or a steel-concrete bridge.

Figure 1. Current railway bridge over the A1 at Muiderberg.

From experience it is known that the noise of trains passing steel bridges is generally much higher than the noise of trains on a standard railway track or concrete bridge. This is not acceptable in this case because of the vicinity of the dwellings. The distance between the dwellings and the bridge is about 75 m in southern direction and 120 m in northern direction. In figure 2 the situation of the bridge and the surrounding dwellings is given.

In the Netherlands the noise production of trains on a bridge is expressed as a noise increase with respect to the noise production of trains on a standard railway track. The standard railway track consists of rails fastened on sleepers resting on track ballast on soil. The first requirements for the project stated that the noise increase of the new bridge has to be +4 dB or less in every octave band from 63 Hz until 8000 Hz with respect to a standard railway track. For this reason a steel-concrete bridge was chosen. The bridge consist of steel girders and arches and a concrete deck. The rails are fastened on concrete sleepers resting on track ballast. Between the concrete deck and the ballast layer a so called ballast mat is located in order to decouple the train induced vibrations from the concrete deck. The construction of the bridge is optimized with respect to the form of the steel girders, the thickness of the concrete deck and the stiffness of the ballast mat. In figure 3 an artist impression of the designed bridge is shown.

During the design proces the authorities demanded a stricter requirement: the noise of the trains on the bridge has to be equal to or lower than the noise of the trains on a standard railway track. This means that the noise increase should be 0 dB(A) or less.

2. Calculation Method

Given the requirements as stated in chapter 1 the construction noise production in the low octave bands (63 Hz to 250 Hz) will be prevailing over the airborne noise. To calculate the noise production of the designed bridge a step-by-step method was formulated: Step 1: Make a finite element method (FEM) model for the new bridge and calculate the transfer of the vibrations of the railway track to the noise producing elements of the bridge; Step 2: Make a finite element method (FEM) model for an existing (reference) bridge with a similar structure as the new bridge. For this bridge also the transfer of the vibrations of the railway track to the noise producing elements of the bridge is calculated. In figure 4 the reference bridge is shown. This bridge has a similar construction as the new bridge: steel girders and arches and a concrete deck. The rails are fastened on concrete sleepers resting on track ballast. Between the concrete deck and the ballast layer a ballast mat is located. Step 3: Measurements of the vibrations and noise production on the reference bridge during the passage of trains the bridge. Step 4: Calculate the noise radiation of the reference bridge based on steps 2 and 3 and theoretical formulas and compare the calculated noise levels with the actually measured noise levels. Step 5: Calculate the noise radiation of the new bridge based on the measured vibrations of step 3, the differences in vibrations transfers between the two bridges of step 1 and 2 and the results of step 4. Step 6: Calculate the airborne noise production of trains on the new bridge, using a standard calculation method. Because of the noise shielding of the steel girders of the bridge the airborne noise will be reduced. This will lead to a noise increase of the bridge that is lower than 0 dB at high frequencies (above 500 Hz). Step 7: Calculate the overall noise increase based on steps 5 (construction noise) and step 6 (airborne noise). Step 8: Repeat steps 5 and 7 for design variants.

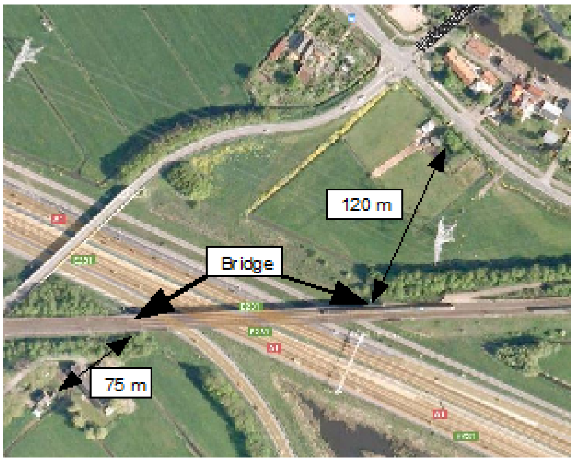

Figure 2. Location of dwellings near the bridge over the A1 at Muiderberg. Source: *Google Maps*

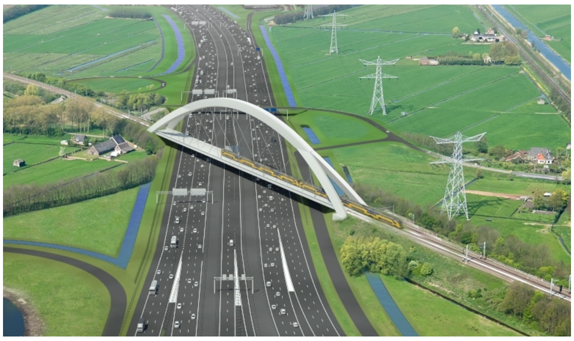

Figure 3. Artist impression of the new bridge.

Figure 4. Reference bridge.

3. Theory

3.1. Excitation of vibrations

During the passage of trains vibrations will occur in the construction parts of the bridge. These vibrations are caused by the both frequency and timedependent force. The force and the resulting vibrations also depend on the type of train, the speed of the train and the axle loads of the train. Furthermore the roughness of the track and the wheels of the train and the distance between the rail sleepers play a role in the excitation of vibrations. For the calculations this complex excitation is simplified. The forces and moments are based on the measured forces in vertical direction of the reference bridge.

The vibrations on the reference bridge are measured as acceleration levels. The velocity levels can be calculated by using equations 1 and 2 from [1],

$$L_v = L_a - 20 \cdot {}^{10}\log(f) + 20 \cdot {}^{10}\log\left(\frac{a_0}{v_0 \cdot 2\pi}\right); \tag{1}$$

$$L_v = L_a - 20 \cdot {}^{10}\log(f) + 44 \text{ dB}; \tag{2}$$

with:

$$L_a = 20 \cdot {}^{10}\log(a/a_0), a_0 = 1 \cdot 10^{-6} \text{ m/s\^{}2}; \tag{3}$$

and

$$L_v = 20 \cdot {}^{10}\log(v/v_0), v_0 = 1 \cdot 10^{-9} \text{ m/s}; \tag{4}$$

and a the vibration acceleration, v the vibration velocity and f the frequency of the vibration.

3.2. Noise radiation

The vibration of the construction parts of the bridge causes excitation of the surrounding air. The vibrations of the air is the noise that is radiated from the construction part. Not all the vibrations of the construction parts are transferred to noise. The amount of noise radiation of a construction part depends on several factors: the material, the dimensions, the mass etc. The amount of noise radiation with respect to the vibration levels is called the radiation ratio.

The theoretically radiated noise power of vibrating plates W_{rad} is given in equation 5 from [2]:

$$W_{rad} = \rho_0 c_0 \sigma S \langle \overline{v^2} \rangle \tag{5}$$

with ρ_0 the density of air, c_0 the speed of sound in air, σ the radiation ratio, S the surface area of the plate and $\langle \overline{v^2} \rangle$ the mean-square vibration velocity of the plate. This equation can also be expressed in logarithmic form: see equation 6 from [1],

$$L_w = L_v + L_\sigma + 10 \cdot {}^{10}\log(S) - 34 \text{ dB} \tag{6}$$

with:

$$L_\sigma = 10 \cdot {}^{10}\log(\sigma). \tag{7}$$

The frequency dependent radiation ratio of the different construction parts of the bridge can be calculated from the empirical equations from [1]. In practice a correction has to be made for the possible ways of acoustic short-circuiting that can take place.

For the steel beams the radiation ratio is calculated with the empirical equation for rectangular ducts:

$$L_\sigma = 10 \cdot {}^{10}\log\left(\frac{f}{f_{g1}}\right) \text{ for } f < f_{g1} \tag{8}$$

$$\text{and } L_\sigma = 0 \text{ for } f \geq f_{g1} \tag{9}$$

with:

$$f_{g1} = \frac{12.5}{h} \tag{10}$$

and h the thickness of the plate in m.

The radiation ratio of the concrete slab is calculated by using the empirical equation for plates:

$$L_\sigma = 10 \cdot {}^{10}\log\left(\frac{c_0}{\pi^2} \cdot \frac{O_1}{S} \cdot \sqrt{\frac{f}{f_{g2}^3}}\right) \text{ for } f < f_{g2} \tag{11}$$

$$\text{and } L_\sigma = 0 \text{ for } f > f_{g2} \tag{12}$$

with O_1 the circumference of the plate in m and

$$f_{g2} = \frac{17.3}{h}. \tag{13}$$

The radiation ratio of the cross beams is calculated by using the empirical equation for profiles:

$$L_\sigma = -5 - 40 \cdot {}^{10}\log\left(\frac{f_{g3}}{f}\right) \text{ for } f < f_{g3} \tag{14}$$

$$\text{and } L_\sigma = -5 \text{ for } f \geq f_{g3} \tag{15}$$

with:

$$f_{g3} = \frac{1.2 \cdot c_0}{O_2} \tag{16}$$

and O_2 the full circumference of the profile in m.

4. Measurements

4.1. Vibration measurements

The vibration measurements were conducted at eight specific locations on the reference bridge. In figure 5 the location of the vibration meters is given. A total of 79 train passages were measured, divided over nine types of trains. In figure 6 a typical result of the vibration levels at the eight locations during a train passage is given. In figure 7 the vibration levels on the web of the cross beam (location 2 in figure 5) is given for two types of trains.

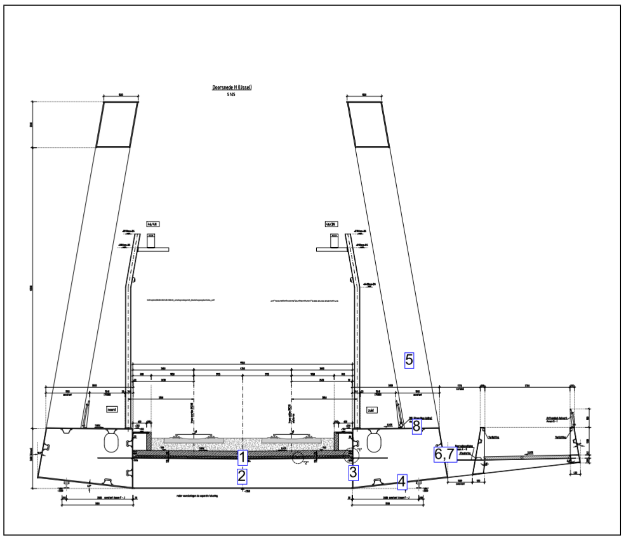

Figure 5. Location of the accelerometers on the reference bridge (cross-section).

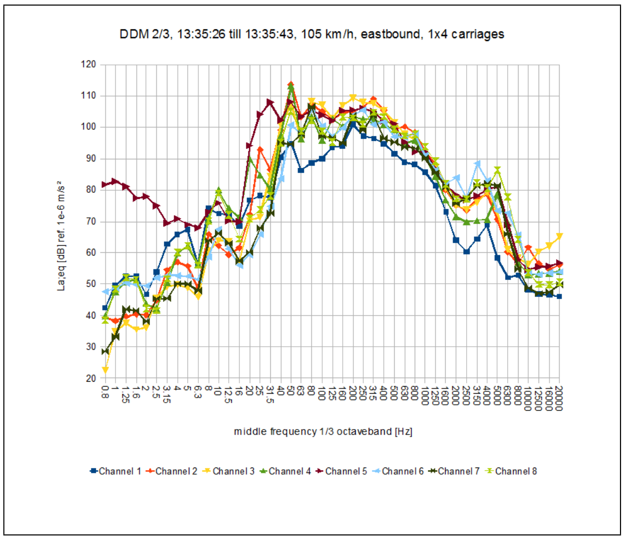

Figure 6. Spectral vibration acceleration of the passage of a train at eight locations on the reference bridge.

4.2. Noise measurements

The noise of the passage of trains was measured at three locations. Two locations were situated near the reference bridge. Location one was situated at 9.4 m distance from the heart of the nearest track and 3 m above the top of the rail. Location two was situated at 33 m distance from the heart of the nearest track and 10 m below the top of the rail. Location three was situated near the standard rail track at 25 m distance from the heart of the nearest track and 5 m above the top of the rail. In figure 8 the average values of the sound exposure levels (SEL) at location 1 of two types of trains is given.

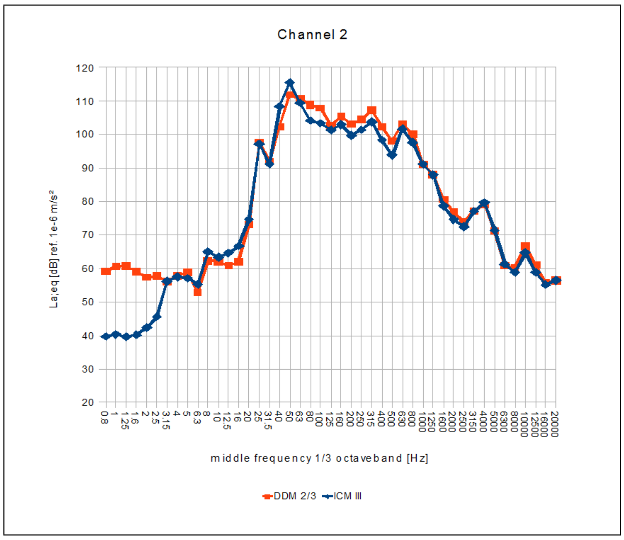

Figure 7. Spectral vibration acceleration at location 2 on the reference bridge for two types of trains.

5. Calculations

5.1. Finite element method

To calculate the vibration levels on the different construction parts of the bridge the finite element method (FEM) was used. The set of equations of motion are given in equation 17.

$$[M] \cdot \{a\} + [C] \cdot \{v\} + [K] \cdot \{u\} = \{F(t)\} \quad (17)$$

with $[M]$ the mass matrix, $[C]$ the attenuation matrix, $[K]$ the stiffness matrix, $\{F(t)\}$ the timedependent force vector, $\{a\}$ the vector with the accelerations in nodes, $\{v\}$ the vector with the velocities in nodes and $\{u\}$ the vector with the displacements in nodes.

The calculated models are 3D-elements of the bridges. In the models the symmetry of the bridges is used and the vibrations are evaluated on the middle part of the bridges, which reduces some of the boundary effects in the model. The calculations are made with the program Comsol Multiphysics version 4.3, using the models 'Structural mechanics' and 'Shell'.

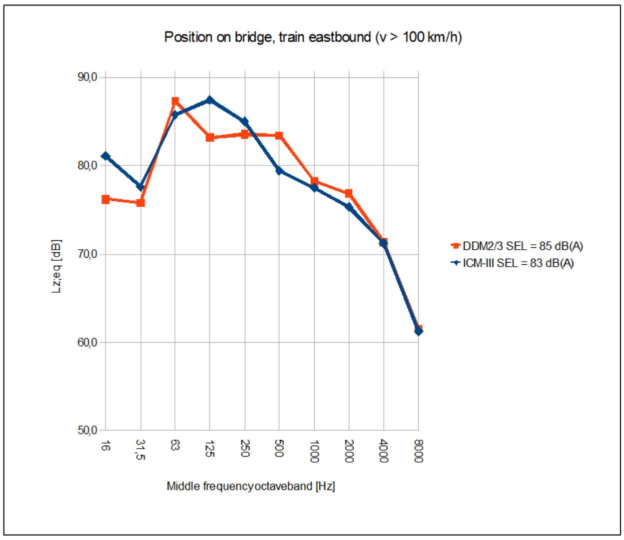

Figure 8. Spectral values of SEL at location 1 near the reference bridge for two types of trains

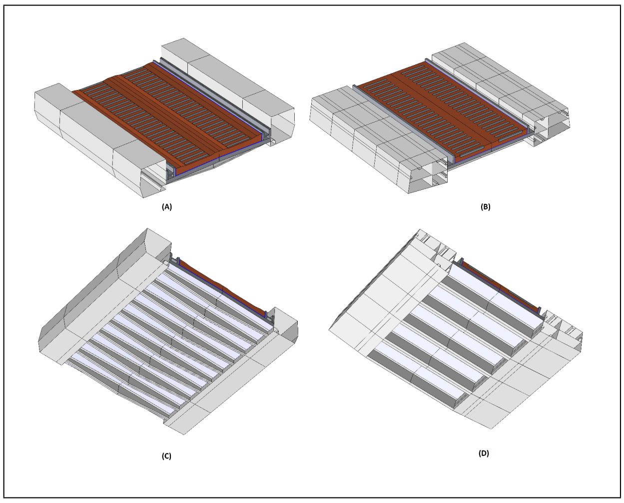

Figure 9. Top and bottom view of the 3D-models of the new bridge (A & C) and the reference bridge (B & D)

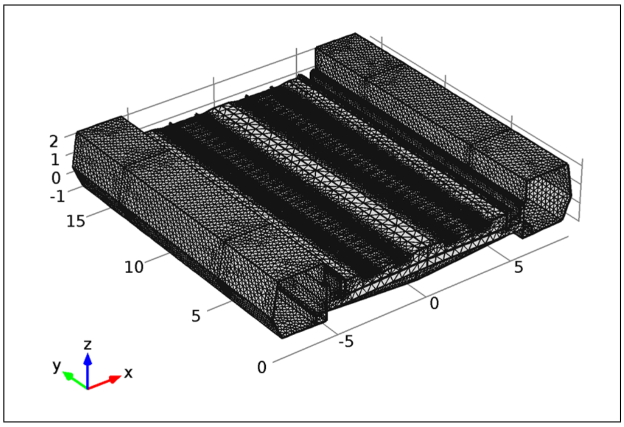

Figure 10. Mesh of the new bridge for a frequency of 100 Hz

In figure 9 the top and bottom views of the bridges are shown. In the models the concrete deck, ballast and the ballast mat are modelled as solid elements. The main beams and cross beams are modelled as shell elements. The mess used in the calculations consists of triangular and tetrahedral elements. For a sufficient accuracy the maximum dimensions of the mesh are well chosen: the wave length of the bending waves is modelled with at least six nodes. De wave length of the bending waves λ_{bend} is given in equation 18.

$$\lambda_{bend} = \frac{\sqrt[4]{\frac{4\pi^2 f^2 d^2 E}{12\rho(1-\nu^2)}}}{f} \tag{18}$$

with E Young's modulus in Pa, ρ the density of the material in $\mathrm{kg/m^3}$ and ν the Poisson factor. In figure 10 the mesh of the new bridge for a frequency of 100 Hz is shown.

The FEM-models are linear calculation models. This assumes that the occurring displacements are small compared to the dimensions of the bridge. Also the behaviour of the ballasted track is assumed linear. This modelling gives a simplification of the real situation, but because of the combination with the measurements on the reference bridge, systematic errors are filtered out to some extent and the method is sufficiently accurate.

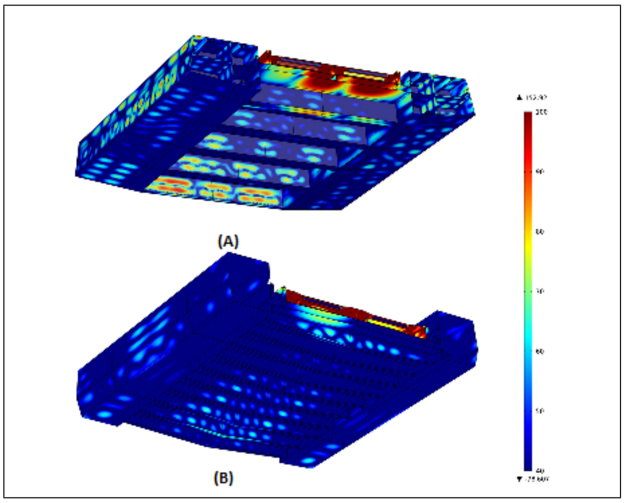

Figure 11. Vibration velocities (L_v) for an excitation of 1 N at a frequency of 141 Hz for the reference bridge (A) and the new bridge (B)

Table I. Calculated noise increase of the new bridge at frequencies between 31.5 Hz and 125 Hz.

Type of trains	31.5 Hz	63 Hz	125 Hz
Category 2	0 dB	+1 dB	0 dB
Category 8	0 dB	+2 dB	+2 dB

5.2. Results construction noise calculations

In figure 11 the results of the calculated vibration velocities are given for an excitation of 1 N at a frequency of 141 Hz for both the reference bridge and the new bridge.

From the calculated vibration levels the noise radiated by the bridge is calculated using the theoretical equations for the radiation ratio (equations 8 to 16).

In figure 12 the measured and calculated results of the construction noise levels for the reference bridge are given for a position at a distance of 35 m from the heart of the nearest track for two types of trains. From this comparison can be concluded that the calculated results are sufficiently accurate.

The radiated construction noise levels of the new bridge are calculated at 25 m distance of the bridge, based on the surface areas of the construction parts, the measured vibration levels, the calculated vibration reductions and the empirical radiation ratios. The radiated construction noise levels are added to the airborne noise of the standard track. From this the noise increase of the bridge is calculated for the octave bands 31.5 Hz up to 125 Hz. In table I the results are given for two categories of trains.

Table II. Calculated screen attenuation of the new bridge at frequencies between 250 Hz and 8000 Hz.

Position relative to top of rail track	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
-3.5 m	-9 dB	-11 dB	-13 dB	-15 dB	-18 dB	-21 dB
3.5 m	-4 dB	-3 dB	-2 dB	-2 dB	-1 dB	-1 dB

Table III. Resulting noise increase of the new bridge at frequencies between 63 Hz and 8000 Hz.

Type of train	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
category 2	+3 dB	+2 dB	-3 dB	0 dB	-1 dB	-1 dB	+1 dB	0 dB
category 8	+4 dB	+4 dB	-2 dB	0 dB	0 dB	0 dB	+1 dB	+1 dB

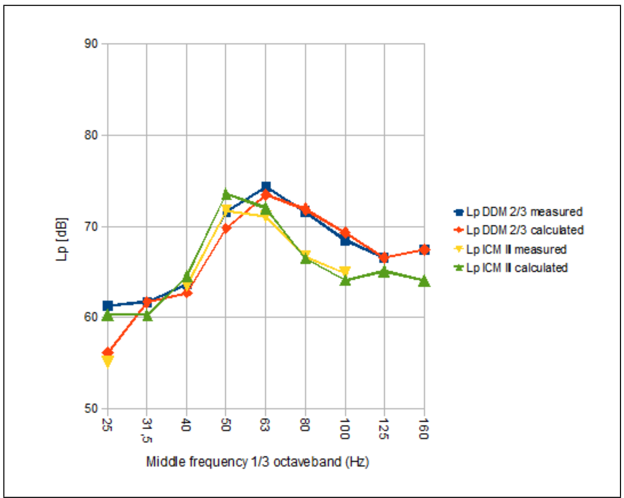

Figure 12. Comparison of calculated and measured bridge noise level at 35 m from the nearest track of the reference bridge

5.3. Results airborne noise calculations

The noise increase at higher frequencies will be mainly caused by the airborne noise as the ballast mat decouples the higher frequency vibrations induced by the trains. To calculate the airborne noise of the new bridge the standard calculation method [3] is used. According to this method the noise increase has to be calculated at 25 m distance of the heart of the tracks at a height of 3.5 m above and under the top of the rail track. At these positions the main beams cause an reduction of the noise levels. This screen attenuation causes a decrease of the noise compared to the noise levels at the standard railway track (negative increase). In table II the results of the calculated screen attenuation of the new bridge is presented.

6. Conclusion

From the calculated construction and airborne noise levels the total noise increase of the bridge is calculated. To account for the inaccuracies in the calculation method caused by te simplification of the real situation a value of 2 to 3 dB is added to the calculated noise increase. In table III the results of the estimated noise increase including a margin of the new bridge are given. The requirement of +4 dB or less in every octave band is met. Also the required noise increase of 0 dB(A) or less is met.

The bridge will be ready in 2016. The actual noise increase of the bridge will be measured as soon as the bridge is in service.

References

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[2] D. Thomson: Railway noise and vibrations: mechanisms, modelling and means of control, Elsevier 2009.

[3] Ministry of Infrastructure and Environment of the Netherlands: Standard Calculation Method 2 Rail Traffic, appendix IV of the Calculation and Measurement Requirements Noise 2012 (in Dutch).