NOISE ASSESSMENT STUDY ON THE COENBRUG/AMSTERDAM

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Abstract

Noise radiating from (traffic) bridges cause hinder in the vicinity of the bridge. With the development of quieter traffic and measures such as noise screens and silent joints, the emission of noise is most often dominated by the vibration of the steel structure. This vibration can significantly be suppressed by applying 'Constrained Layer Damping (CLD)' to the structure. In this study, the effect on noise reduction by applying CLD on the Coenbrug, a moveable bridge on the A8 motorway in the Netherlands, has been analyzed. Measurements using an acoustic camera have indeed shown that the noise emission of the Coenbrug is dominant in the lower frequency region and is stemming from the vibrating steel structure. As the bridge structure is of (older) age, the addition of (too much) mass is often problematic (as is the case with the Coenbrug), therefore a lightweight solution such as CLD could be a good solution. The resulting reduction in noise emission is dependent upon many different factors such as the actual position of the applied CLD-material on the bridge, with the stiffness and damping properties being frequency- and temperature-dependent. Using FEM, an eigenfrequency analysis was performed, resulting in mode shapes and accompanying natural frequencies. On this basis, we established the optimal location and material of the CLD-patches and an estimation of the achievable noise reduction. This prediction was based on an evaluation of the modal loss factor of the treated structure. This modeling approach is considered legitimate assuming both the radiation/emission characteristics of the bridge and the generalized force vector(the load) do not change by applying the CLD-material. This is advantageous as an acoustic model (which is numerically expensive) is not necessary. The modeling approach corresponds well with small-scale experiments of a steel profile treated with several CLD-patches.

1. INTRODUCTION

The Coenbrug is a moveable bridge on the A8 motorway in the Netherlands. This bridge is part of a busy connection from Koogaan de Zaan near Amsterdam, crossing the river Zaan. The Coenbrug causes significant noise pollution for residents in the vicinity of the bridge; a noise described as a thunder or rumble which occurs mainly when heavy traffic crosses the bridge. In an attempt to reduce this noise, the Dutch road authority Rijkswaterstaat has applied several measures, such as noise screens and silent asphalt. This seems to have little effect on the rumbling noise. In order to determine the dominant noise source, measurement have been performed using an acoustic camera (see Figure 1).

From the measurements it can be concluded that the noise emission is dominated by low frequent sound radiation from the bottom of the moveable part of the bridge. As can be seen in Figure 1, radiation of the bridge is still observable while the heavy truck has passed over the moveable part. Moreover, the tonality of this low frequent sound radiation is perceived to be high. Since the radiation of sound is dominant from the bottom part of the bridge, measures that do not focus on this part of the bridge are unlikely to have a significant effect. Also, the application of silent joints on this bridge to reduce excitation is not possible since the bridge deck needs to remain moveable to allow tall ships to pass.

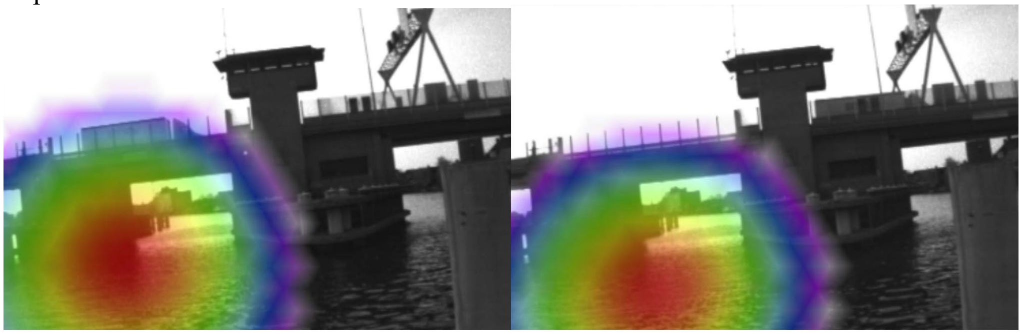

Figure 1: Sound Pressure Level measurement

After determining the source of the emission, several measures were evaluated in a study to estimate their expected effect. As the bridge is designed to comply with older design guidelines, there are restrictions to the mass that can be added. A light-weight measure was therefore compulsory. The first two proposed measures were covering either the bottom of the bridge deck or the abutments with low-weight sound-absorbing material. Since the emitted noise is low-frequent, large amounts of material would be necessary to achieve a desirable noise reduction. Moreover, these measures only absorb the emitted noise and do not reduce the vibrations in the steel structure. Constrained Layer Damping (CLD) was subsequently proposed as a viable solution.

CLD is a method of damping by constraining viscoelastic material between a base layer (the bridge) and a stiff constraining layer. For instance, CLD's can be composed of mild coated steel, stainless steel or composite fibre and carbon sheets. If the base layer is bending, shear movement of the viscoelastic layer is occurring, and the structure is highly damped (i.e. substantial higher damping values can be obtained compared to free layer damping).If applied properly, CLD can thus be an effective and light-weight solution. In fact, CLD is the only relevant solution for thick steel constructions; it requires little space for installation, the viscoelastic layer is highly protected and thus has a long lifetime (over 25 years), the CLD patches can be coated in any colour and require minimal inspection and maintenance.

This paper presents a novel engineering approach to estimate the noise reduction obtained by CLD. While it is possible to conduct a fully coupled mechanical/acoustical finite element analysis, the disadvantage of such an approach are the large model size, the resulting high computation times and complexity of the model (both the excitation and sound radiation should be modelled). We therefore opted for a simpler alternative based on a (complex) modal analysis of only the structure. As applying a CLD does not change the radiation characteristics of the structure, as well as the generalized force vector (unless you apply panels that significantly alter the mass, shape and stiffness of the structure), only the transfer of modal force to modal response changes. We can therefore obtain an estimation of the noise reduction by computing the modal loss factors, computing the modal reduction values and taking the average. This is explained in more detail in the next chapter. In addition, the method offers insight in the effectiveness of the applied CLD-panels, with respect to their specific positions on the bridge, allowing to optimally position the CLD panels for highest damping in a certain frequency range.

2. NOISE REDUCTION APPROXIMATION BY MODAL ANALYSIS

The moveable part of the bridge has been modelled in COMSOL Multiphysics, as shown in Figure 2. The untreated bridge deck was largely modelled as shells and no material damping was assumed. Based on an eigenfrequency analysis, we determined the mode shapes. From the location of the anti-nodes (the location of largest modal deformation), an estimation can be made about the relative contribution of the different parts of the bridge to the total sound emission.

The response of any structure to a dynamic load is a weighted sum of all mode shapes of which every mode shape has its own corresponding natural frequency (eigenfrequency). If a structure is excited at a specific frequency, the participation factors for modes close to this eigenfrequency will be large and the shape of the response will be similar to those mode shapes. Since the excitation as a result of passing traffic has a wide frequency range, the response of the bridge structure will consist of a large amount of mode shapes. The vibrating bridge structure will then radiate sound in the same frequency range. The extent to which different mode shapes contribute to the radiated noise is thus dependent on the excitation and radiation efficiency.

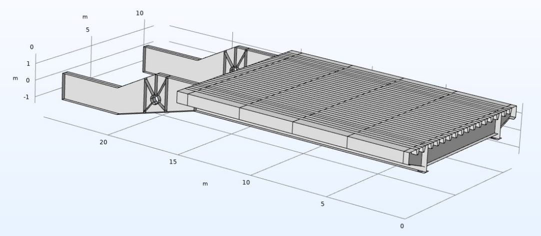

Figure 2: Geometry of the moveable part of the bridge.

If no material damping is assumed, the eigenfrequencies are real. If viscoelastic material is used, the eigenfrequencies become complex. For viscoelastic damping, the eigenfrequency can be written as:

$$\omega = \omega_r + i\omega_i = \omega_0\sqrt{1 + i\eta} \approx \omega_0\left(1 + i\frac{\eta}{2}\right), \tag{1}$$

where η is the loss factor and the approximation is true if η is small. Based on the calculated complex eigenfrequencies, the modal loss factor η_m, i.e. the loss factor for each mode, can thus be calculated as:

$$\eta_m = 2\frac{\omega_i}{\omega_r} \tag{2}$$

and the modal noise reduction is:

$$R_m = 10\log_{10}\frac{\eta_m}{\eta_0} \tag{3}$$

The material loss factor of the untreated steel structure, η_0, is assumed to be 10^{-3}, which follows from Figure 3 [1]. The modal reduction depends on the choice of the loss factor of the untreated structure and will be commented upon below. Where the reduction values are smaller than zero, the reduction value is set to zero. This is necessary, as no damping in the untreated structure was assumed during the simulation. The overall reduction value can then be calculated by averaging all M modal reductions:

$$R_s - \frac{1}{M}\sum_{m=1}^{M} R_m \tag{4}$$

Reduction values based on the loss factor of the untreated steel structure were confirmed by experiments (see below) and are thus realistic. Using a higher material loss factor of the untreated steel structure would lead to a large underestimation of the performance of CLD-patches, which is not in line with experimental observations. Note also that the average of all modal reduction values are considered (i.e. including also the reduction values which are zero); although a CLD-patch could highly damp a certain mode, it may not damp another mode and these effects are taken into account. Note also that in-plane and out-of-plane modes have been taken into account. Thus, we do not need to perform a complete mechanical/acoustical coupled analysis. Only a modal analysis is enough to calculate the system loss factor. Hence, if we apply CLD to the structure and have a high modal damping for a specific mode, we anticipate a large system loss factor and the CLD-patch has been applied in an effective location. If the CLD-patch is applied but the modal damping is small, the patch is ineffective and a different location would be preferred. Note that we would like damping in a larger frequency range. The number of modes which are highly damped within the given frequency range, is an indication of the effectiveness of the CLD patches applied. The proposed methodology is valid in two limitcases; no damping and fully damped. If no damping is applied, all modal damping values are zero, the average is zero and the resulting system loss factor is zero as well. If the complete bridge would be made out of a material with a given material loss factor, the modal loss factor is constant and equal to the material loss factor. Hence the system loss factor equals the material loss factor (as it should).

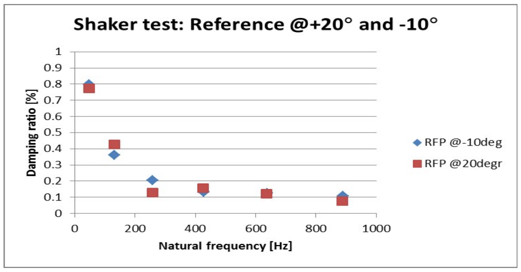

Figure 3: Measured damping ratios for an untreated steel base plate

The CLD-patches are added to the FEM model step by step and the resulting noise reduction was evaluated after each step. Based on the large modal displacements and low frequencies, first, we applied CLD-patches on the main beam (one-sided), in between the cross beams. This is shown on the left in Figure 4. Subsequently, CLD-patches were applied on the side plates (centre Figure 4) and finally applied to the cross beams (right Figure 4).

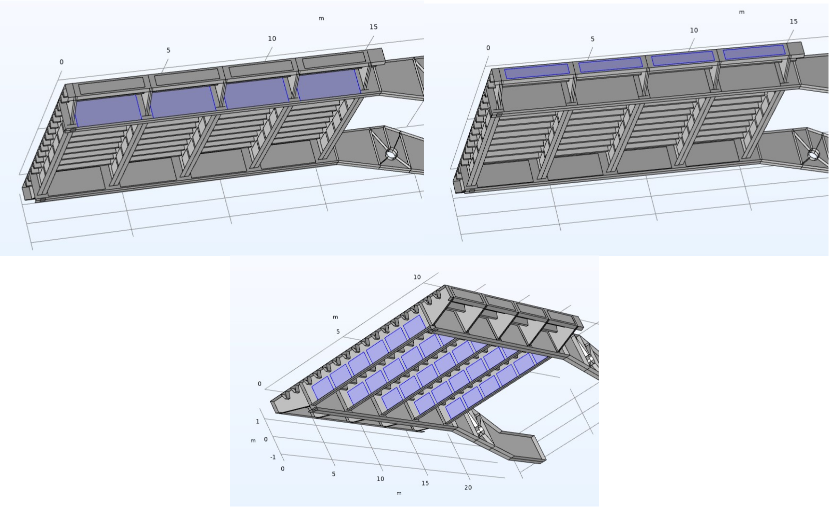

Figure 4: An overview of the positions and components to which the CLD patches were applied

As viscoelastic behaviour cannot be evaluated for the shell elements that were used, the viscoelastic material is modelled using volume elements. The constraining layer is then modelled as a shell element again. The viscoelastic behaviour of the CLD material is modelled by adding a complex term to the Young's modulus. As input for the viscoelastic material properties, the VT7044 viscoelastic material of Vibratec was used. This viscoelastic material is particularly suitable within a temperature range of 10 to 20 degrees. As can be seen from Figure 5, the material loss factor of the viscoelastic material varies with frequency and is also temperature dependent. For simplicity however, a constant material loss factor of 50% was applied. This is a conservative value corresponding to the temperature range around the Coenbrug.

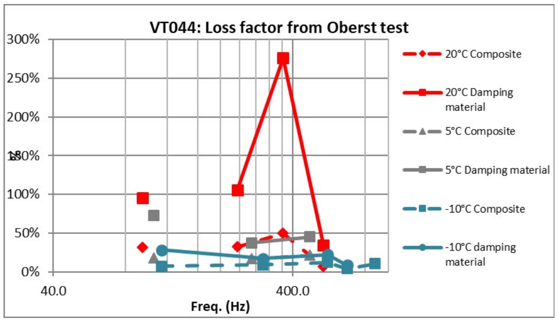

Figure 5: Loss factor of the viscoelastic damping material

3. NUMERICAL RESULTS

In Figure 6, as an example, an eigenmode of the non-treated model is shown; the large modal displacements are clearly visible on the main beam in between the cross beams. This explains why we have studied the application of CLD-material on the main beams. The applied patches consist of a 3 mm steel constraining layer on top of the viscoelastic layer. The modal reduction was evaluated for the first 300 eigenfrequencies, ranging up to 150 Hz.

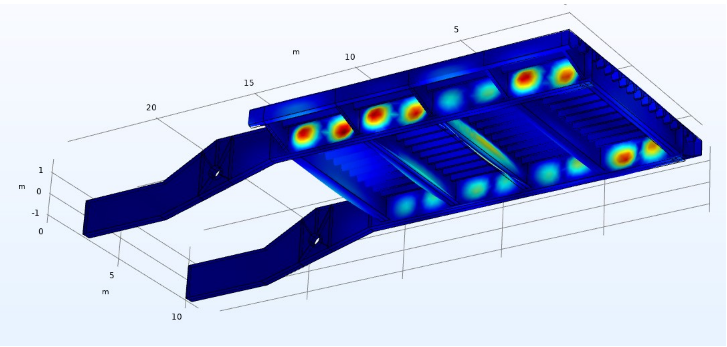

Figure 6: Mode shape of the Coenbrug at 51 Hz

In Figure 7, the modal reduction values for the different treatments are shown. One can clearly observe that high modal reduction is attained for only specific mode shapes. As verified, these are the modes which have a large modal displacement in the main beams. Within the same frequency range, it was noticed that the side panels were largely unaffected by the CLD patches on the main beam. Consequently, CLD-patches were added to the side panels of the bridge. The graphs in Figure 7 show that through adding more CLD-patches, more mode shapes are damped, resulting in a higher system loss factor. After treatment of the cross beams of the bridge structure, the graph shows only a small amount of mode shapes that are left undamped, resulting in high expected noise reduction within this frequency range. While the effect is only evaluated for the first 300 eigenfrequencies, higher order modes (outside the evaluated frequency range) will also be damped.

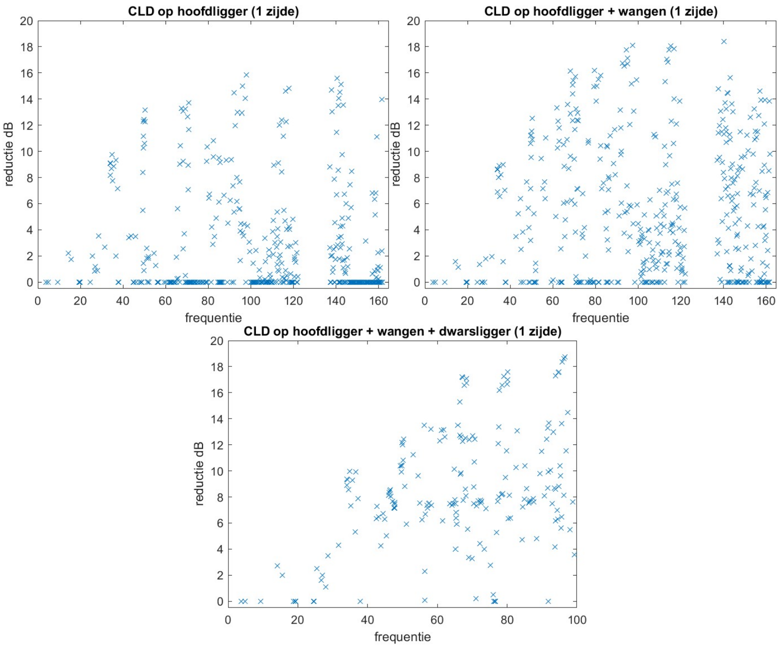

Figure 7: Consecutive treatment of the main beams, side plates and the cross beams

Table 1: Results from the modal analysis

Treated component	Estimated reduction	Surface area	Added mass
Main beams	~ 2.9 dB	33.6 m^2	892 kg
Main beams + side plates	~ 5.8 dB	55.6 m^2	1476 kg
Main beams + side plates + cross beams	~ 9.2 dB	68.1 m^2	1808 kg

In Table 1, the estimated noise reduction, the surface area covered by the CLD-patches and the added mass are given. Each additional step results in an increase in noise reduction of approximately 3 dB. The added mass is only 2.8% of the total weight of the bridge deck. Hence, the measure can be considered as 'light-weight'.

4. EXPERIMENTAL VALIDATION

A small-scale validation test was conducted in order to test the approach given in Section 2. A steelbeam was suspended from a forklift.It was then excited by slinging a heavy steel ball to the centre of the beam. The insertion loss was determined by comparing the noise levels (LA_{max}) for the untreated beam and treated beam.The configuration was treated with anumber of CLD-patches (see Figure 8).Thisconfiguration was then modelled in FEM, from which the noise reduction was estimated similar to the method described above.

Table 2: Results from the validation

Number of CLD-patches applied	Impact test	Modal analysis
1	-6.4 dB	-5.4 dB
2	-9.6 dB	-8.3 dB
3	-11.2 dB	-10.5 dB

Table 2 shows the results from the validation test, which shows that the given methodology provides a fair approximation of the noise reduction of the CLD-patches on the steel beam. In future research, validating the current method using a more complex structure would be preferable. Several viscoelastic materials and CLD configurations could then be tested.

Figure 8: Setup of the small-scale validation on the left and the modelledbeam on the right

5. CONCLUSIONS

In this paper, a novel engineering approach was presented to approximate the noise reduction of CLD-treatment of a steel bridge structure. This novel approach is based solely on the system loss factor (or 'composite modal loss factor'), based on the average of the modal loss factors. The advantage of this approach is that it can be conducted without knowing the excitation due to traffic. Also, a noise radiation analysis does not need to be performed, which makes the method quicker than conventional methods. In addition, a good indication for the effective and efficient placement of CLD-patches can be obtained. For the case of the Coenbrug, an estimated 3 to 9 dB of noise reduction can be achieved (depending on the amount of panels used), without an inadmissible addition of mass of the bridge deck structure (exceeding the mass budget).

References

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