Application of the sound substructure modification method
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Application of the sound substructure modification method

- using an Audi A4 Avant -

DCT 2001.52

A.A.A. Peeters

External traineeship (4W708)

AUDI AG, Ingolstadt

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Introduction

Reduction of interior vehicle road-noise, specifically the low-frequency „booming noise“, is an important comfort target in the development of a new car model. Structural vibrations of the car-body are often responsible for the low frequency noise, but the relationship between the interior sound level and the car body vibrations is not straightforward.

In the past an analytical-experimental method that permits the prediction of interior sound level variations due to the local coupling of defined subsystems has been developed at AUDI AG. The method has been derived from the substructure analysis used in structural dynamics. It has been extended to a hybrid acoustical / structural formulation, applied on a system constituted of the interior passenger car cabin and the car-structure. This method is known as the „Sound Substructure Modification Method“ or the „Impedance-method“.

During my traineeship at AUDI AG in Ingolstadt this method has been applied on an Audi A4 Avant. Booming noise, road-excited, is typically seen in combi/stationcar like cars. Goal of this traineeship is to make the „Impedance-method“ a workable tool for AUDI AG, so that it can be used more easily for future, new car-models. Secondly, an optimisation routine has to be implemented. In this way it becomes possible to calculate the optimal modifications of the car, with respect to the minimisation of the „booming noise“.
1. Booming noise

Reduction of interior vehicle road-noise, specifically the low-frequency booming-noise, is an important comfort target in the development of a new car model. But what is in fact this so called booming-noise? The booming-noise inside a passenger car mostly occurs when the car is driving at low speeds of about 25 to 50 km/h. When the car hits an irregularity at this speed (e.g. rough asphalt, a small bump etc.) the booming noise can increase to an unacceptable level. Structural vibrations of the car-body are often responsible for this low-frequency noise. The frequency range in which this noise occurs, is about 30 to 50 Hz. As can be seen in figure 1.1 the booming noise is not the same inside the entire car. For the A4 Avant, which was the topic in this traineeship, the booming noise mostly occurred at the front seats of the car. This is typically for so called stationwagon cars, like, for example, the A4 Avant. In these cars the booming noise is more a problem than in other cars, because the internal cavity space is much larger. Therefore, low frequency noise is able to resonate inside the car, and so amplifying the booming noise.

![Figure 1.1 Sound Pressure Level inside A4 Avant](image.png)

Figure 1.1
Sound Pressure Level inside A4 Avant
(Rolling road measurement, rough asphalt, 30 km/h)
2. Description of the sound substructure modification method

Vehicle interior noise generally results from structural vibration (radiation and transmission) and airborne sound. In the low-frequency range there is further the interaction with the first acoustic cavity modes. In order to obtain a quantitative relationship between the interior sound pressure and the vibration of the surrounding body-structure, the sound substructure modification method has been developed. The basic approach of the sound substructure modification method is to identify and predict the structural contribution of a sound resonance by only using the measured sound and acceleration data.

Consider the testing of an entire car as seen in figure 2.1, where one excitation $F_A$ is applied at location $A$. The frequency response function (FRF) $G_{k,A}$ of the interior sound pressure at the passenger ear positions $k$ to the global excitation $F_A$, and the FRF of the acceleration of the surrounding structure at point $B$, $G_{B,A}$, are measured, using hammer- or shaker excitation. It is assumed that the system is linear so that the superposition principle may be applied:

$$ p_{k,A} = G_{k,A} F_A $$  

and

$$ \ddot{x}_{B,A} = G_{B,A} F_A $$

The subscript $k$ denotes the position where the sound pressure is measured, $B$ the position of the accelerometer and $A$ the location where the excitation force is applied. The coupled system of structure and internal cavity is described by the equations (1) and (2), where the sound pressure and the structural vibration acceleration are uncoupled. $G_{k,A}$ contains the contribution of the whole structure. How the structural vibration at point $B$ contributes to the global sound transfer relation $G_{k,A}$ is unknown.

Let us consider a local excitation, $F_B$ as seen in figure 2.2. The sound and the local structural FRFs, $G_{k,B}$ and $G_{B,B}$ can be measured, and a set of equations, similar to (1) and (2) is obtained.

$$ p_{k,B} = G_{k,B} F_B $$  

and

$$ \ddot{x}_{B,B} = G_{B,B} F_B $$

Theoretically $G_{k,B}$ contains the contributions of all radiating surfaces although only one panel was locally excited at point $B$. If the excitation is small enough, it is reasonable to assume that a local vibration around point $B$ will only be generated by the excitation at point $B$, and the vibrations from all other structural parts will be negligible small. Then $G_{k,B}$ mainly contains the contribution of the structure around point $B$. 

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Application of the sound substructure modification method

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When both forces $F_A$ and $F_B$ act simultaneously on the vehicle, then the result for this linear assumed system is the sum of equations (1), (2) and (3), (4):

\[ (p_k)_{\text{new}} = p_{k,A} + p_{k,B} = G_{k,A}F_A + G_{k,B}F_B \]  \hspace{1cm} (5)

\[ (\ddot{X}_B)_{\text{new}} = \ddot{X}_{B,A} + \ddot{X}_{B,B} = G_{B,A}F_A + G_{B,B}F_B \]  \hspace{1cm} (6)

Although equation (5) is only a simple sum of equations (1) and (3), it plays an important role in the newly developed sound substructure modification method. This equation makes it possible to analyse the sensitivity of the sound pressure at a point in the interior space to a point on the surrounding structure.

Now consider a structural modification at position $B$, which can be seen as the coupling of an additional system $C$, at position $B$ (figure 2.3). The transfer function of the additional system is given by equation (7):

\[ \ddot{X}_C = G_{C,C}F_C \]  \hspace{1cm} (7)

It is assumed that the system $C$ is rigidly joined at point $B$ on the vehicle body and that further no external forces act at point $B$, then the continuity and equilibrium equations are given by equations (8) and (9):

\[ \ddot{X}_C = \ddot{X}_B = \ddot{X}_{B,C} \]  \hspace{1cm} (8)

\[ F_B + F_C = 0 \]  \hspace{1cm} (9)

By combining equations (5) to (9), under the assumption that $F_A$ is known, a system of five equations with five unknown quantities ($p_k$, $\ddot{X}_B$, $\ddot{X}_C$, $F_B$ and $F_C$) is obtained. Equations (6) and (7) can be combined and rewritten in equation (11), with use of the definition of $H_{C,C}$, as given in equation (10):

\[ F_C = (G_{C,C})^{-1}\ddot{X}_C = H_{C,C}\ddot{X}_C \]  \hspace{1cm} (10)

\[ F_B = (G_{B,B})^{-1}(\ddot{X}_B - G_{B,A}F_A) = H_{B,B}(\ddot{X}_B - G_{B,A}F_A) \]  \hspace{1cm} (11)

Substitution of equations (10) and (11) in equation (9) and implementing equation (8) results in equation (12):

\[ X_{B,C} = (H_{B,B} + H_{C,C})^{-1}H_{B,B}G_{B,A}F_A \]  \hspace{1cm} (12)

The substitution of this last equation into equation (6) delivers a new formula for the force $F_B$:

\[ F_B = \left[H_{B,B}(H_{B,B} + H_{C,C})^{-1}H_{B,B} - H_{B,B}\right]G_{B,A}F_A \]  \hspace{1cm} (13)
Substituting equation (13) into equation (5) results finally into equation (14):

\[ p_k = \left[ G_{k,A} + G_{k,B} \left( H_{B,B} (H_{B,B} + H_{C,C})^{-1} H_{B,B} - H_{B,B} \right) \right] G_{B,A} F_A \]  

(14)

Or, written as a transfer function:

\[ \frac{p_k}{F_A} = G_{k,A} + G_{k,B} \left( H_{B,B} (H_{B,B} + H_{C,C})^{-1} H_{B,B} - H_{B,B} \right) G_{B,A} \]  

(15)

It is evident that in case of no modification \((H_{C,C} = 0)\), equation (15) reduces to:

\[ \frac{p_k}{F_A} = G_{k,A} \]  

(16)

In the case of road operation, the system of the cars structure and the acoustical cavity won’t be described with frequency response functions. Its accelerations and sound pressure levels due to a particular load case are directly measured. The system can still be considered as linear. Equations (5) and (6) become:

(17)

(18)

Here \( p_{k,\text{road}} \) and \( \ddot{X}_{B,\text{road}} \) represent the sound pressure level and the structural acceleration measured during road operation. By combining the equations (17) an (18) and rewriting them in the same way as has been done with equations (5) and (6), as shown above, we obtain:

\[ (p_{k,\text{road}})_\text{new} = p_{k,\text{road}} + p_{k,B} = p_{k,\text{road}} + G_{k,B} F_B \]  

(19)

In equations (14) and (19) the sound pressure in an interior space point is mathematically connected with the local structural vibration and its modification.

The quantities in equation (19) are all obtained by physical measurements. \( G_{k,B} \) and \( G_{B,B} \) are obtained by laboratory measurements, using hammer excitation. \( p_{k,\text{road}} \) and \( \ddot{X}_{B,\text{road}} \) are obtained under road conditions, or by laboratory measurements, using a rolling road or shaker excitation. The unique quantity needed to be determined is the characteristic of the additional system \( H_{C,C} \). The form of this matrix depends on the additional system \([2]\). Equation (20) determines this matrix for adding a mass or multiple masses:

\[ H_{C,C} = m = \text{diag}(m_1, m_2, \ldots, m_n) \]  

(20)
3. Measurements
As described in the previous chapter, the quantities from equation (19) are all obtained by physical measurements. Two kinds of measurements are required. $G_{k,B}$ and $G_{B,B}$ are obtained by laboratory measurements, using hammer excitation. $p_{k,\text{road}}$ and $\bar{X}_{B,\text{road}}$ are obtained under road conditions, or by laboratory measurements, using a rolling road. In this case these quantities are obtained by using a rolling road, because measurements in real-life, road conditions, are too complicated and cost too much time to be performed during this traineeship. Also is assumed that for the matrix $H_{C,C}$ only additional masses are applied.

During this traineeship an AUDI A4 Avant has been used for all experiments. For technical specifications of this car, see appendix I. Before the measurements are being performed, one has to compose a list of points on the car, on which one eventually wants to apply a additional mass. It seems obviously, but only for points of which all the data is measured, the effect of an additional mass on the interior sound pressure level can be calculated. In this case, 28 measurement points have been defined. The choice of those points has been made, after some initial measurement in which the sensitivity of particular points has been evaluated. Knowledge at AUDI AG about parts of the car that are important to the booming noise has also been used. The list of points is specified in appendix II.

Measurements at AUDI AG in Ingolstadt are performed using LMS CADA-X Software. The data retrieved in the experiments can be exported into Universal-files, which can be imported into MATLAB (MATLAB 6.1, rel. 12.1). Therefore, the program project_admin.m can be used, which has been developed in the past at AUDI AG. The exact procedure is described in the Instruction Manual: Using the sound substructure modification method in MATLAB [7].

3.1. Obtaining $G_{k,B}$ and $G_{B,B}$

The quantities $G_{k,B}$ and $G_{B,B}$ are obtained by laboratory measurements, using hammer excitation.

$G_{k,B}$ is the frequency response function of the interior sound pressure at the passenger ear position $k$ to the force excitation by the impulse hammer at point $B$. The interior sound pressure level is being measured by microphones inside the car at the position of the passengers ear $k$.

$G_{B,B}$ is the frequency response function of the structural acceleration at point $B$ to the force excitation by the impulse hammer at the same point $B$ (So called inertance). The accelerations are being measured by accelerometers at the measured points on the car. The direction of these accelerations are normal to the surface on which the accelerometer is attached. The hammer excites these surfaces also in normal direction.

If one is interested in the calculation of a new sound pressure level after applying more than one additional masses at the same time, the FRF $G_{B,B}$ becomes a matrix $G_{B,B}$. This matrix is of the form:

$$
G_{B,B} = \begin{bmatrix}
G_{1,1} & G_{1,2} & \cdots & G_{1,n} \\
G_{2,1} & G_{2,2} & \vdots & \vdots \\
\vdots & \vdots & \ddots & \vdots \\
G_{n,1} & \cdots & \cdots & G_{n,n}
\end{bmatrix}
$$

(21)

$G_{i,j}$ to $G_{n,n}$ are the inertances of the excitation points, as described above. $G_{i,j} (i \neq j)$ are the frequency responses of a point $i$ to the excitation at point $j$. All these so called cross-FRFs have to be measured, in order to calculate the effect on the interior sound pressure level after addition of multiple masses. When these cross-FRFs are not being measured, only the effect of single masses can be calculated.
3.1.1 Laboratory measurements using hammer excitation

For the measurement of the FRFs in $G_{k,B}$, microphones have to be installed inside the car. In this case, two microphones are used. One installed at the driver's ear position (Microphone Left Front Seat) and the second at the passenger's position in the back at the right side of the car (Microphone Right Back Seat). All the FRFs from the point of excitation $B$ to these microphones are being measured. An example of such FRFs is shown in figure 3.1.

![Figure 3.1](image)

FRFs of excitation point $B$ to microphones inside the car

To fill the matrix $G_{B,B}$, all the FRFs from the acceleration at a particular point $B$ at the car to the hammer excitation have to be measured. If the excitation and measurement point are the same, the FRF is the so called inertance of that particular point. Example of such inertances and FRFs are shown in figure 3.2a and 3.2b.

![Figure 3.2a](image)

Inertances of DACH:0005 and DACH:0006

![Figure 3.2b](image)

FRFs of DACH:0005 and DACH:0007 to DACH:0006

The hammer used in the experiments is a so called impulse-hammer. This hammer is so designed that it is possible to produce similar input signals. Although, for every measurement, 3 measurements are being performed and these results are being averaged.

The frequency range being used in the experiments is from 0 to 256 Hz, using a frequency resolution of 1.0 Hz. On the input channel, which is the force input of the impulse hammer, a force window has been applied of 90%. On the response channels, which are the accelerations of the accelerometers normal to the planes on which they are attached, a uniform window has been applied. LMS CADA-X applies a filter on the data, to prevent signal leakage and aliasing. This filter has a cut-off of 78%.

The measurements of the FRFs with hammer excitation are being performed under triggered conditions. The channel on which is triggered, is the input channel on which the force signal of the impulse hammer is. The trigger level is 6% on the negative slope of the force signal and measurement starts at minus 10% of the total measurement time. To calculate the FRF an $H_v$-estimator has been used. This estimator gives the best estimation for the FRF.

In Appendix III some screenshots from LMS CADA-x are given, in which the actual set-up used in the measurements during my traineeship is displayed.
3.2. Obtaining $p_{k,\text{road}}$ and $\ddot{x}_{B,\text{road}}$

Before the measuring of $p_{k,\text{road}}$ and $\ddot{x}_{B,\text{road}}$ is being described, we take a closer look at equation (19). All quantities in equation (19) have to be complex quantities. During the measurement of $G_{k,B}$ and $G_{B,B}$, these quantities become naturally complex. But, $p_{k,\text{road}}$ and $\ddot{x}_{B,\text{road}}$ which are defined as complex frequency spectra, are not naturally complex. Theoretically, it may be possible to measure $p_{k,\text{road}}$ and $\ddot{x}_{B,\text{road}}$ directly as complex frequency spectra, but in practice this is not possible because of technical problems. To measure $p_{k,\text{road}}$ and $\ddot{x}_{B,\text{road}}$ directly as complex frequency spectra, one has to measure the exact input forces, in order to have the phase references. Under road conditions the exact input forces are not exactly known, and therefore difficult to measure. Therefore another method to obtain $p_{k,\text{road}}$ and $\ddot{x}_{B,\text{road}}$ as complex frequency spectra is applied. During the measurements on the rollbench autopower spectra (APS) and frequency responses (FRF) are being measured. This results in the following quantities:

$$\text{APS}\{p_{k,\text{Road}}(\omega)\} \quad \text{and} \quad \text{APS}\{\ddot{x}_{B,\text{Road}}(\omega)\} \quad (22 \ a \ & b)$$

and Frequency Responses to a particular reference, e.g. channel 1:

$$\text{FRF}_1\{p_{k,\text{Road}}(j\omega)\} \quad \text{and} \quad \text{FRF}_1\{\ddot{x}_{B,\text{Road}}(j\omega)\} \quad (23 \ a \ & b)$$

The measured APS aren't complex, the measured FRFs are. Now it is possible to calculate the complex frequency spectra out of these measured quantities:

$$\text{Amp} = \sqrt{2 \cdot \text{APS}} \quad (24)$$

$$p_{k,\text{Road}}(j\omega) = \text{Amp}\{p_{k,\text{Road}}(\omega)\} \times e^{j\text{Phase}[\text{FRF}_1(p_{k,\text{Road}}(j\omega))]} \quad (25)$$

$$\ddot{x}_{B,\text{Road}}(j\omega) = \text{Amp}\{\ddot{x}_{B,\text{Road}}(\omega)\} \times e^{j\text{Phase}[\text{FRF}_1(\ddot{x}_{B,\text{Road}}(j\omega))]} \quad (26)$$
3.2.1 Laboratory measurements using rolling road

When \( P_{k,\text{road}} \) and \( \vec{X}_{B,\text{road}} \) are measured using the rolling road, the car is placed with its rear wheels on the rolls with rough asphalt (Appendix X). The rolls rotate at a speed of 30 km/h, because at this speed the booming noise is clearly present. By doing so, one obtains an input signal on the car, which can be considered to be equivalent to a random noise input. Although only the rear axis of the car is being driven, this is a good representation of real life, road conditions.

To calculate the complex values of \( P_{k,\text{road}} \) and \( \vec{X}_{B,\text{road}} \), one has to measure both Auto Power Spectra and FRFs, as shown in chapter 3.2. The Auto Power Spectra are measured as rms power spectra. If this isn’t the case, formula (27) isn’t correct, and must be adjusted.

The interior sound level is measured at two positions inside the car, at the front seat left (Microphone Left Front Seat) and at the back seat on the right side (Microphone Right Back Seat).

The references used during my traineeship are the 2 microphones (they are used as microphone, as well as a reference!) and the wheel hub rear axle right and left. Accelerations on the wheel hubs are measured in \(+Z\) direction. All together 4 references. After calculating the new, complex values of \( P_{k,\text{road}} \) and \( \vec{X}_{B,\text{road}} \), one can consider the influence of the choice of the reference on these new, complex quantities. This will be discussed in the next chapter, Calculating modified interior sound levels.

The Auto Power Spectra of all the defined points (microphones, references and 'ordinary' points) have to be measured. In figure 3.3 the APS of two of the references, both wheel hubs of the rear axle, are displayed. The frequency response functions of all the 'ordinary' points with respect to all the references and the FRFs of all the references to each other have to be measured. It has to be noted that the FRFs can’t be measured as MIMO FRFs. This is only possible if the chosen references are clearly not correlated. As shown in figure 3.3 the APS from these two references are, especially in the low frequency range, quite similar. The assumption that the signals are not correlated is false. An \( H_\gamma \)-estimator is used to calculate the FRFs. Because the FRFs have to be measured to all the references, one has to make sure that no measurements are forgotten. If the data set isn’t complete, one won’t be able to calculate all the desired interior sound levels. Also one must not forget to measure the FRFs from one reference to the other chosen references.
The frequency range used during the experiments on the rolling road, is the same as used before during the experiments with hammer excitation. So, it is from 0 to 256 Hertz, with a sample frequency of 1 Hertz. Measuring with a smaller frequency interval results in FRFs that become noisy. Greater frequency intervals aren't used, in order to prevent loosing crucial information. Because the car is on the rolling road, and its rolls are not exactly round, measurements are executed 30 times and averaged over these 30 measurements. The measurements have not been triggered. Although, it is possible to start the measurement on the same position of the rolling road every time. Uniform windows are applied on all channels. The acceleration data is measured in the direction normal to the surface on which the accelerometers are attached. Hanning windows are applied to both the references as well as the responses.

In Appendix IV & V some screenshots from LMS CADA-x are given, in which the actual set-up used in the measurements is displayed.
4. Calculating modified interior sound pressure levels

After all the data has been obtained in the measurements, it is possible to calculate the modified interior sound pressure levels, according to formula (19):

\[
(p_{k,\text{road}})_{\text{new}} = p_{k,\text{road}} + G_{k,B} \left( H_{B,B} ( H_{B,B} + H_{C,C} )^{-1} H_{B,B} - H_{B,B} \right) X_{B,\text{road}}
\]  \hspace{1cm} (19)

Before the new sound pressure level \((p_{k,\text{road}})_{\text{new}}\) is calculated one has to evaluate the directions in which the measurements have been performed \([3]\). During the experiments using hammer excitation the direction of the applied force is opposite to the direction of the measured accelerations. Therefore the matrices \(G_{k,B}, G_{B,B} \) and \(H_{C,C}\) have to be multiplied by \(-1\). Formula (19) changes into formula (27). The difference between those two formulae may be minor, but it is a crucial difference!

\[
(p_{k,\text{road}})_{\text{new}} = p_{k,\text{road}} + G_{k,B} \left( H_{B,B} ( H_{B,B} - H_{C,C} )^{-1} H_{B,B} - H_{B,B} \right) X_{B,\text{road}}
\]  \hspace{1cm} (27)

The calculation of the new interior sound pressure level \((p_{k,\text{road}})_{\text{new}}\) has been programmed in MATLAB. For the exact description of this program an Instruction Manual has been written. For further details of the program, refer to this manual \([7]\).

Now modified interior sound pressure levels can be calculated and considerations about the influence of the choice of the reference can be made. In Appendix VI two mass modifications have been applied and the influence thereof on the interior sound level for both used microphones is calculated. Each calculation has been executed three times, and every time a different reference has been used, in order to calculate the complex values of \(p_{k,\text{road}}\) and \(X_{B,\text{road}}\). It becomes clear, that the choice of the reference has little influence of the calculated, new interior sound level. Therefore, for next calculations, the choice of the reference will be the other microphone. E.g. when calculating a modified sound pressure level on the left front seat, the reference will be the microphone on the right back seat. For calculating a modified sound pressure level on the right back seat, the reference will be the microphone on the left front seat.
5. Calculating optimised interior sound pressure levels

The calculation of modified interior sound pressure levels is now possible. But, which modification of the car has the greatest influence on the sound pressure level? And which points are sensitive for changes on the sound pressure level, when a mass is applied onto it? And what size should that mass be? Those questions can be answered if an optimisation tool is implemented, so a optimised mass application can be calculated, in order to achieve a optimised interior sound pressure level.

Implementing an optimisation tool requires a goal function. What is it exactly you want to optimise? In this case, one is interested in minimising the "booming noise". But in which way? Reducing only the peak value of the interior sound pressure level, or reducing the entire sound pressure level in a wider frequency range? During this traineeship a goal function has been developed that combines those two. This goal function is defined as follows (in dB):

\[
goal = t \cdot \text{peak}(p_{k,\text{road}}) + (1-t) \cdot \text{average}(p_{k,\text{road}})
\]  

(28)

The value for \( t \) can be chosen by the user and must be between 0 and 1.

For \( t = 1 \) the goal function becomes:

\[
goal = \text{peak}(p_{k,\text{road}})
\]

(29)

For \( t = 0 \) the goal function becomes:

\[
goal = \text{average}(p_{k,\text{road}})
\]

(30)

The goal function is evaluated in a frequency domain defined by the user, so it becomes possible to focus on the frequency range of the "booming noise", from ca. 30 to 50 Hz. In order to illustrate the resulting values of this goal function, the unmodified interior sound pressure level on the left front seat is observed. In figure 5.1 the goal function is evaluated for 4 different values of \( t \). It can be seen that for the value \( t = 1 \), the goal function represents the peak value of the sound pressure level. The value \( t = 0 \) represents the average of the sound pressure level in the frequency range, as mentioned before.

![Figure 5.1](image_url)
With the goal function now known, an optimisation routine can be implemented. Because the calculation of the modified interior sound pressure levels is already in MATLAB, the use of the optimisation toolbox in MATLAB is obvious. Before using the optimisation toolbox from MATLAB, one has to consider what kind of problem this is.

The problem of calculating the modified interior sound pressure level is of the following form:

$$\min_x f(x)$$

In this case, $x$ is the input for the calculation of the interior sound pressure level, the applied mass(es). $f(x)$ is the calculated goal function, as described before. The only constraints that are active for this problem is the minimal and maximal mass(es) that can be applied. The minimal mass is always 0 kg, which corresponds (of course) with no mass application at that particular point. The maximal mass can be defined by the user:

$$0 \leq x \leq m_{\text{max}}$$

In the MATLAB optimisation toolbox a routine is available for this kind of problems: `fmincon.m`. This routine makes use of so-called constrained non-linear optimisation or non-linear programming. It is appropriate to find the minimum of a constrained non-linear multivariable function by starting at an initial estimate, and therefore suitable for this problem. In this case, a medium-scale algorithm is used, which uses so called Sequential Quadratic Programming (SQP) to find an optimised solution to the problem. For exact information on this routine or the algorithm it uses refer to the MATLAB HELP Documentation [5] or Papalambros [6].

This optimisation has been programmed in MATLAB. For the exact description of this program an Instruction Manual [7] has been written. For further details of the use of the optimisation routine with respect to the calculation of optimised interior sound pressure levels, refer to this manual.

In order to determine which points are important in order to change the interior sound pressure level, for every point the mass has been calculated that results in the greatest change of the goal function ($t = 1$). Both the greatest positive as well as the greatest negative change in the goal function has been calculated. The results hereof are listed in Appendix VII'. Combinations of the most sensitive points are made, and the optimised mass combinations for those points are calculated. The results thereof are listed in Appendix VIIb. From these results it becomes clear that the use of different references has little influence on the calculated optimal masses. This is another argument for only using the reference of the ‘other’ microphone, as previously mentioned in chapter 4.

After calculation of the optimised masses for single mass applications (Appendix VII'), it becomes clear that some points have great influence on the change of the interior sound pressure level. Although, some other points have no influence on the change of the interior sound pressure level at all. Noticeable is that of the points that have great influence on the interior sound pressure level on the left front seat, 4 of them are on the tail door (HECK:0010, HECK:0011, HECK:0013 and HECK:0014). The points on the left side windows have also great influence (SSML:0020 and SSHL:0021). The point on the right rear side window (SSHR:0027) is very sensitive to change the interior sound pressure level on the back seat right.
After this optimisation for single mass applications has been performed, also an optimisation has been performed in order to maximise the interior sound pressure level. It is typical that the points that result in an improvement of the interior sound pressure level at one of the seats, results now in a aggravation of the interior sound pressure level on the other seat. E.g. application of a mass of ca. 2.5 [kg] on SSML:0020 results in a decreased sound pressure level on the front seat left of about 5.3 dB and an increased sound pressure level of about 2.4 dB on the right back seat (figure 5.2 and 5.3). This phenomenon is typical in these type of cars, and was already known at AUDI AG. Improvement of the interior sound pressure level at one position in the car often results in worsening the interior sound pressure level at another position.

After the calculation of optimised single masses in order to minimise or maximise the interior sound pressure level, optimised mass combinations are being calculated. Combinations of points, sensitive for changing the interior sound pressure level, are being made and the optimised mass combinations are calculated (Appendix VII). In figure 5.4 the optimised interior sound pressure level (goal function: \( \tau = 1 \)) on the front seat left is shown, after calculating an optimised mass combination of 5 masses. The points on which these masses are applied must be defined by the user, the optimal size of the masses is then being calculated. In figure 5.5 the development of the goal function during the optimisation is shown.

It has to be noted, that the choice of the initial estimate of the optimal solution, can have effect on the found optimum. The assumption has been made that the initial estimate equals no mass applications, so all mass(es) are, at the start of the optimisation, equal to zero.
6. Validation of calculated modified interior sound pressure levels

Now it is possible to calculate modified and optimised interior sound pressure levels, it has to be considered if those calculations are correct. In the past the sound substructure modification method has been used at AUDI AG, and it was proved that the method delivers correct results. However, in the past the measurements where performed using shaker excitation ([1] & [2]) or real life road conditions [3]. Using shaker excitation, it is possible to perform measurements that can be easily repeated and reproduced. For measurements under real life conditions it is very hard to get reproducible measurements. During this traineeship the measurements under road conditions where performed using a rolling road.

It now has to be considered how the reproducibility of those measurements is. Because the validation measurements are executed about 3 weeks later, on the same car, it is of great importance that the reproducibility of the measurements is quite good. In figure 6.1 and 6.2 (Appendix IX) the interior sound pressure levels of the two used microphones are displayed, when no mass modifications on the car are applied. It becomes evident that between two measurements, performed on the same physical set-up, a certain difference in the sound pressure levels is present, which is normal. But there are greater differences between the initial measurements and the 'new' measurements. On the left front seat, the difference manifests mostly above 80 Hz, on the back seat right the difference is much greater. This may be caused by several reasons. In the time between the car has been used for other analyses, and some changes have been made to the car. The gear box has been replaced. The new gear box has the same mass as the old one. Also some changes have been made to the compressor of the climate control. The influence thereof on the interior sound pressure level is not known. Another reason could be the way the car stands on the rolling road. A little difference in the way it stands on the rolls, can cause a difference in the measured sound pressure level. The air pressure in the tires during both measurements was 2,4 bar. Another possible explanation for the difference between the sound pressure levels could be the contents of the fuel tank.
Because the differences between the 'old' and 'new' interior sound pressure levels with no mass applications can't be explicitly cleared, it is assumed that the 'new' interior sound pressure level is the correct one. For further calculations and validations those new sound pressure levels will be used. In this way, the comparison of the calculated and measured sound pressure levels is the most fairest. If the validation is compared with the initial calculation (Figure 6.3) the comparison between validation and calculation seems very poor. This is due to the difference between the 'old' initial sound pressure level and the 'new' initial sound pressure level. In figure 6.4 the calculated sound pressure level is calculated using the 'new' interior sound pressure level, and the comparison is now better.

With use of the optimisation tool the sensitivity of all points has been evaluated. Also some combinations of sensitive points are optimised. The results hereof are used to validate the calculated interior sound pressure levels. Twenty different masses or mass combinations are being put on the car, and the interior sound pressure level at the two used microphones is being measured. The car is on the rolling road, under the same conditions as described in chapter 3. In Appendix VIII the different masses or mass combinations used in the validation measurements are listed. In Appendix IX all the measured and calculated interior sound pressure levels are presented in graphics.

As can be seen in the results, the method is able to predict the modified interior sound pressure levels. E.g. in figure 6.5 and 6.6 (Appendix IX and IX') both calculated as well as the measured modified interior sound pressure levels on the front seat left are presented. For the combined mass application of 5,0 kg at HECK:0010, 2,0 kg at SSML:0020 and 2,0 kg at SSHL:0021 the calculated sound pressure level reduces in peak value with 7,0 dB. Measured is a reduction of about 5,6 dB (Figure 6.5, App. IX'). For the combined mass application of 3,05 kg at SSML:0020 and 4,5 kg at SSHL:0021 a reduction of 4,1 dB is calculated and a reduction of 5,3 dB is measured (Figure 6.6, App. IX').
However, in some cases, the method is not able to predict the modifications to the sound pressure levels. After a closer look at the results, it becomes clear that in all the cases for which the prediction is incorrect, mass application on two particular points (HECK:0013 and HECK:0014) is involved. Examples of those false predictions are given in figure 6.7 and 6.8. (Appendix IX and IX). After applying 2.0 [kg] at HECK:0013 a worsening of the peak level of the interior sound level with 24.5 dB is calculated, although a decreased peak of 1.3 dB is measured (Figure 6.7, App. IX). After applying a mass combination of 2.0 [kg] at HECK:0011 and 2.25 [kg] at HECK:0014 an increased peak of the interior sound pressure level at the right back seat of 17.1 dB is calculated, although an increased peak value of 2.4 dB is being measured (Figure 6.8, App. IX). After calculating the modified interior sound pressure level of a lot of other masses and mass combinations, it became clear that only for those two points such extreme changes in the sound pressure level could be achieved, and that only for those two points the predictions do not match the validations.

There are two ways to interpret this observation. The first is that during the measurements on those points, something has gone wrong. The quality of the measurements for those points, or a FRF to one of these points may be unclear. E.g. the coherence of the measurements using hammer excitation can be of a lower level, due to a ‘false’ hit with the hammer. It may also be possible that the direction in which the accelerations on those points has been measured was false. A second possibility is that the interior sound pressure level is very sensitive to modifications at those points. It is known that the tail door is a very complicated and sensitive system with respect to the acoustical behaviour of a car.

After studying and verifying the measurement data, it was not possible to find irregularities in the measurement data. So, the second explanation seems more likely. When looking at the measured modified interior sound pressure level, it becomes evident that the interior sound pressure level is indeed very sensitive to mass applications at those points. For example, the peak value of the booming noise of the interior sound pressure level on the front seat left with 4.5 kg on HECK:0014, drops with 11 dB (measured)! (Figure 6.9, Appendix IX).
7. Conclusions

After finishing the measurements, calculating modified interior sound pressure levels and validating them, it became clear that the sound substructure modification method is able to predict the modifications in the interior sound pressure level due to mass applications on the car. This was already proved in the past, but not in combination with the use of the rolling road.

The whole procedure, from the measurements until the validation of the calculated sound pressure levels, has passed and is described in this report and an Instruction Manual [7]. So, the sound substructure modification method is now a applicable tool at AUDI AG, and can be used more easily in the future.

An optimisation tool has been implemented in MATLAB, so it is now possible to calculate optimised mass or mass combinations in order to minimise the booming noise. The optimisation tool is also very useful for checking which points of the car are sensitive for changing the interior sound pressure level.
References


Appendix I  Technical Specifications of Audi A4 Avant (711-307, IN-W-4613)

Car: Audi A4 Avant

Car #: 711-307
Number Plate: IN-W-4613
Engine: 3,0 L V6 (162 kW)
Drive: Front Wheel Drive
Changing Gears: Manual B80 5-speed
Steering Wheel: Left
Tires: Michelin 215/55 Radial R16 XSE (2,4 bar)

Configuration: Sliding Roof
Cloth Panelling
Appendix II  Definition measurement points on Audi A4 Avant

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Appendix IIb  Definition measurement points on Audi A4 Avant (IN-W-4613)
Appendix III  LMS set-up FRF measurements with hammer excitation
>> Channels >> Identification:

The reference channel for the estimation of the FRF (in this case the hammer), must always be on top of the list of available channels!

>> Points >> Geometry Format:

The input of the Node Names (Comp), the Node Numbers (Node) and their Directions (Dir) must exactly match the names, numbers and codes you defined in the list. (Appendix II)! This in order to prevent problems with the calculation in MATLAB later.
Appendix IV  LMS set-up APS measurements with rolling road

For the set-up in >> Channels >> Identification and >> Points >> Geometry Format the same remarks as made in Appendix III have to be observed!
Appendix V    LMS set-up FRF measurements with rolling road

For the set-up in >> Channels >> Identification and >> Points >> Geometry Format the same remarks as made in Appendix III have to be observed!
Appendix VI Influence of the reference on \( (p_{k,road})_{new} \)

Mikrofonpegel Vorne Links -- 2,0 kg auf HECK:0012 & 1,8 kg auf HECK:0014 -- VAL121

- Ausgang
- Berechnet (Ref: MIKR:HiRe)
- Gemessen

Mikrofonpegel Vorne Links -- Ausgang

- Berechnet (Ref: HART:0003)
- Gemessen

Mikrofonpegel Vorne Links -- Ausgang

- Berechnet (Ref: HART:0004)
- Gemessen
Appendix VIb  Influence of the reference on $(P_{k,\text{road}})_{\text{new}}$

Mikrofonpegel Hinten Rechts -- 2,0 kg auf HECK:0012 & 1,8 kg auf HECK:0014 -- VAL122

![Graph 1: Ausgang, Berechnet (Ref: MIKR:VoLi), Gemessen vs dB vs Hz]

![Graph 2: Ausgang, Berechnet (Ref: HART:0003), Gemessen vs dB vs Hz]

![Graph 3: Ausgang, Berechnet (Ref: HART:0004), Gemessen vs dB vs Hz]
Appendix VIc  Influence of the reference on $(P_{k,road})_{new}$

Mikrofonpegel Vorne Links -- 2,0 kg auf HECK:0012 -- VAL131

- Ausgang
- Berechnet (Ref: MIKR:HiRe)
- Gemessen

Mikrofonpegel Vorne Links -- 2,0 kg auf HECK:0003

- Ausgang
- Berechnet (Ref: HART:0003)
- Gemessen

Mikrofonpegel Vorne Links -- 2,0 kg auf HECK:0004

- Ausgang
- Berechnet (Ref: HART:0004)
- Gemessen
Appendix VI$^d$ Influence of the reference on $(p_{r,\text{road}})_{\text{new}}$

Mikrofonpegel Hinten Rechts -- 2,0 kg auf HECK:0012 -- VAL132

- Ausgang
- Berechnet (Ref: MIKR:VoLi)
- Gemessen

Mikrofonpegel Hinten Rechts -- 2,0 kg auf HECK:0012 -- VAL132

- Ausgang
- Berechnet (Ref: HART:0003)
- Gemessen

Mikrofonpegel Hinten Rechts -- 2,0 kg auf HECK:0012 -- VAL132

- Ausgang
- Berechnet (Ref: HART:0004)
- Gemessen
### Appendix VII  Optimised masses for single mass applications

#### tU/e technische universiteit eindhoven

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#### Appendix VII  Optimised masses for single mass applications

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#### Appendix VII  Optimised masses for single mass applications

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### Appendix VIIb  Optimised mass combinations

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## Appendix VIII  List of validation measurements

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<th>Appendix IX</th>
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Appendix IX - Comparing measured and calculated sound pressure levels

Microphone Left Front Seat

![Graph showing interior sound pressure level for left front seat](image)

Microphone Right Back Seat

![Graph showing interior sound pressure level for right back seat](image)
Appendix IXb  Comparing measured and calculated sound pressure levels

Microphone Left Front Seat

![Graph of measured and calculated sound pressure levels for the left front microphone.]

Microphone Right Back Seat

![Graph of measured and calculated sound pressure levels for the right back microphone.]

Appendix IXc  Comparing measured and calculated sound pressure levels

Microphone Left Front Seat

Microphone Right Back Seat
Appendix IXd  Comparing measured and calculated sound pressure levels

Microphone Left Front Seat

Microphone Right Back Seat
Appendix IX – Comparing measured and calculated sound pressure levels

Microphone Left Front Seat

Microphone Right Back Seat
Appendix IXf  Comparing measured and calculated sound pressure levels

Microphone Left Front Seat

![Graph showing measured and calculated sound pressure levels for the left front seat.](image)

Microphone Right Back Seat

![Graph showing measured and calculated sound pressure levels for the right back seat.](image)
Appendix IX² Comparing measured and calculated sound pressure levels

**Microphone Left Front Seat**

![Graph showing measured and calculated sound pressure levels for Left Front Seat.](image)

**Microphone Right Back Seat**

![Graph showing measured and calculated sound pressure levels for Right Back Seat.](image)
Appendix IX\textsuperscript{b} Comparing measured and calculated sound pressure levels

Microphone Left Front Seat

![Graph showing sound pressure levels for the left front seat microphone.]

Microphone Right Back Seat

![Graph showing sound pressure levels for the right back seat microphone.]

\textit{Berechnete Mikrofonpegel} [Goal (30 - 50 Hz): 82.5405 dB $\rightarrow$ 77.8817 dB]
Appendix IX  Comparing measured and calculated sound pressure levels

Microphone Left Front Seat

Microphone Right Back Seat
Appendix IX: Comparing measured and calculated sound pressure levels

Microphone Left Front Seat

Microphone Right Back Seat
Appendix IX\textsuperscript{k} Comparing measured and calculated sound pressure levels

**Microphone Left Front Seat**

Berechnete Mikrofonpegel [Goal (30 - 50 Hz): 82.5485 dB \(\rightarrow\) 76.1989 dB]

**Microphone Right Back Seat**

Berechnete Mikrofonpegel [Goal (30 - 50 Hz): 66.7506 dB \(\rightarrow\) 74.4119 dB]
Appendix IX  Comparing measured and calculated sound pressure levels

Microphone Left Front Seat

Microphone Right Back Seat
Appendix IX Comparing measured and calculated sound pressure levels

Microphone Left Front Seat

Microphone Right Back Seat
Appendix IX° Comparing measured and calculated sound pressure levels

Microphone Left Front Seat

![Graph showing measured and calculated sound pressure levels for the left front seat microphone.]

Microphone Right Back Seat

![Graph showing measured and calculated sound pressure levels for the right back seat microphone.]

---

**TU/e technische universiteit eindhoven**

---
Appendix IX° Comparing measured and calculated sound pressure levels

Microphone Left Front Seat

Microphone Right Back Seat
Appendix IX* Comparing measured and calculated sound pressure levels

Microphone Left Front Seat

Microphone Right Back Seat
Appendix IX Comparing measured and calculated sound pressure levels

Microphone Left Front Seat

![Graph of measured and calculated sound pressure levels for Microphone Left Front Seat]

Microphone Right Back Seat

![Graph of measured and calculated sound pressure levels for Microphone Right Back Seat]
Appendix IX'  Comparing measured and calculated sound pressure levels

Microphone Left Front Seat

Microphone Right Back Seat
Appendix IX' Comparing measured and calculated sound pressure levels

Microphone Left Front Seat

Microphone Right Back Seat
Appendix IX: Comparing measured and calculated sound pressure levels

Microphone Left Front Seat

Microphone Right Back Seat
Appendix IX° Comparing measured and calculated sound pressure levels

Microphone Left Front Seat

![Graph showing measured and calculated sound pressure levels for the left front seat microphone.]

Microphone Right Back Seat

![Graph showing measured and calculated sound pressure levels for the right back seat microphone.]

---

1° The Appendix IX° section discusses the comparison between measured and calculated sound pressure levels. The graphs illustrate the level changes over frequency for microphone placement comparisons.

2° The microphones are identified as Left Front Seat and Right Back Seat, indicating the locations from which the sound pressures were measured.

3° The graphs display the calculated microfonpegeil (Berechnete Mikrofonpegel) for both microphone positions, along with measurements (Gemessen) and masses (Massenbelegung: HECK:0009 = 4.5 [kg]).
Appendix X  Pictures of measurements on rolling road

The test car on the rolling road

Rear wheels on rough asphalt

Microphone

Accelerometer

Accelerometer on reference right rear wheel hub

4 accelerometers on the car
Appendix XI   Used projects, Universal files, .mat-files and .m-files

This appendix contains a list of files which were used during my traineeship at AUDI AG. A short description of each file is also given.

LMS-CADA-x Projects:

Each project consists of 5 files:

- **b6avrm**: The project *b6avrm* contains the data obtained during the experiments using the rolling road.
  - *b6avrm.dat*
  - *b6avrm.ix0*
  - *b6avrm.ix1*
  - *B6AVRM.dat*
  - *B6AVRM.idx*

- **b6avemph**: The project *b6avemph* contains the data obtained during the experiments using hammer excitation.
  - *b6avemph.dat*
  - *b6avemph.ix0*
  - *b6avemph.ix1*
  - *B6AVEMPHI.dat*
  - *B6AVRM.idx*

In each project some tests are present:

- **b6avrm**:
  - *RolB6Av1Time*: Time data of all channels (useless due to averaging the time data)
  - *RolB6AvAPS*: APS data of all channels
  - *RolB6Av1FRF*: FRF data of all points with respect to MIKR:0001
  - *RolB6Av2FRF*: FRF data of all points with respect to MIKR:0002
  - *RolB6Av3FRF*: FRF data of all points with respect to HART:0003
  - *RolB6Av4FRF*: FRF data of all points with respect to HART:0004
  - *RolB6Av4FRFxx*: So-called cross FRFs of the references to each other.
  - *RolB6AvVal1 - 50*: Validation Experiments. (20 and 30 are the new initial measurements, 31 -50 are the validation experiments as listed in Appendix VIII)
  - *RolB6AvVal120-150*: Same validation experiments as in 20/30-50, but now on Audi A4 Avant, 1.8T Quattro (721-253)
  - *test01-31*: Measurements used in order to find the correct setup.
  - *standsetup*: backup test, with the standard setup used during the measurements

- **b6avemph**:

  - *EmpB6Av1*: All data of experiments using hammer excitation

Universal Files:

- **ImpB6AvEmp.uff**: Measurement data of experiments using hammer excitation (*b6avemph ==> EmpB6Av1*)
- **ImpB6AvEmp2.uff**: FRF data of experiments using hammer excitation (*b6avemph ==> EmpB6Av1*)
- **ImpB6AvRolAPS.uff**: APS data of experiments using rolling road (*b6avrm ==> RolB6AvAPS*)
- **ImpB6AvRolFRF.uff**: FRF data of experiments using rolling road (*b6avrm ==> RolB6Av1FRF, RolB6Av2FRF, RolB6Av3FRF, RolB6Av4FRF and RolB6Av4FRFxx*)
- **AusgangVal.uff**: 'new' initial measurements (*b6avrm ==> RolB6AvVal20 and RolB6AvVal30*)
- **ValDef.uff**: Validation measurements (*b6avrm ==> RolB6AvVal20 - 50*)
- **ValB6AvQuattro.uff**: Validation measurements A4 Avant, 1.8T Quattro (*b6avrm ==> RolB6AvVal120 - 150*)
### .mat-Files

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<th>File</th>
<th>Description</th>
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<td>Measurement data of experiments using hammer excitation (imported in MATLAB from ImpB6AvEmp.uff)</td>
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<td>FRF data of experiments using hammer excitation (imported in MATLAB from ImpB6AvEmp2.uff)</td>
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<tr>
<td>ImpB6AvRolAPS.mat</td>
<td>APS data of experiments using rolling road (imported in MATLAB from ImpB6AvRolAPS.uff)</td>
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<td>ImpB6AvRolFRF.mat</td>
<td>FRF data of experiments using rolling road (imported in MATLAB from ImpB6AvRolFRF.uff)</td>
</tr>
<tr>
<td>AusgangVal.mat</td>
<td>'new' initial measurements (imported in MATLAB from AusgangVal.uff)</td>
</tr>
<tr>
<td>ValDef.mat</td>
<td>Validation measurements (imported in MATLAB from ValDef.uff)</td>
</tr>
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<td>VHVal.mat</td>
<td>Same data as ValDef.mat, but now in dB. (Variables: V20-50 (Microphone left front seat) and H20-50 (Microphone right back seat))</td>
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<tr>
<td>ValB6AvQuattro.mat</td>
<td>Validation measurements (imported in MATLAB from ValB6AvQuattro.uff)</td>
</tr>
<tr>
<td>ValQuattro.mat</td>
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<tr>
<td>f.mat</td>
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<td>INW4613.mat</td>
<td>Used microphones, references and points (names, codes, numbers and directions)</td>
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### Matrices GkB, GBB, pkF and XBF:

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<tr>
<td>MatrVL3.mat</td>
<td>Microphone left front seat, Reference right wheel hub rear axle</td>
</tr>
<tr>
<td>MatrVL4.mat</td>
<td>Microphone left front seat, Reference left wheel hub rear axle</td>
</tr>
<tr>
<td>MatrVLVal.mat</td>
<td>Microphone left front seat, Reference microphone right back seat, 'new' initial measurement</td>
</tr>
<tr>
<td>MatrHR1.mat</td>
<td>Microphone right back seat, Reference microphone left front seat</td>
</tr>
<tr>
<td>MatrHR3.mat</td>
<td>Microphone right back seat, Reference right wheel hub rear axle</td>
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<tr>
<td>MatrHR4.mat</td>
<td>Microphone right back seat, Reference left wheel hub rear axle</td>
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<tr>
<td>MatrHRVal.mat</td>
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### .m-Files

The following .m-files are being used:

- Impedanz.m
- berechnung.m
- beropt.m
- datenladen.m
- feingabe.m
- fladen.m
- frequenzbereich.m
- HCCmanual.m
- HCCopt.m
- HCCmanual.m
- loadGkB.m
- loadGkB.m
- loadXBF.m
- manplot.m
- Matrausfull.m
- matrixladen.m
- MikrRef.m
- opptplot.m
- punkteingabe.m
- punktladen.m
- TestRecords.m

(For more information see the Instruction Manual: Using the sound substructure modification method in MATLAB)
Appendix XII  Validation Measurements using an Audi A4 Avant 1.8T Quattro

The validation measurements as described in Appendix VIII are also performed on an AUDI A4 Avant 1.8T Quattro.

Technical Specifications:

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<th>721-253</th>
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<tbody>
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<td>Number plate:</td>
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</tr>
<tr>
<td>Engine:</td>
<td>1.8T (110 kW)</td>
</tr>
<tr>
<td>Drive:</td>
<td>Quattro</td>
</tr>
<tr>
<td>Changing Gears:</td>
<td>Manual B80 5-speed</td>
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<td>Steering Wheel:</td>
<td>Left</td>
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<td>Dunlop 215/55 Winter Sport M2 (2,2 bar)</td>
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<tr>
<td>Configuration:</td>
<td>No Sliding Roof</td>
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<tr>
<td></td>
<td>Cloth Panelling</td>
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In Appendix XII are the APS of the two microphones displayed and compared with the APS of the two microphones from the measurements with the Audi A4 Avant 3.0L V6 (711-307). From those APS it becomes clear that the booming noise is less present in this car under the same conditions. When sitting in the car, during the measurements, it can also be heard that the booming noise is less present.

In Appendix XII the APS of the two microphones after mass applications are compared with the APS of the two microphones when no masses are applied.
Appendix XII  
Comparison of Interior Sound Pressure Level 3.0L V6 and 1.8T Quattro

Vergleich Ausgangsmessungen B6 Avant (3.0L V6 Front vs. 1.8T Quattro)

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<thead>
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<th>dB</th>
<th>Audi B6 Avant</th>
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<th>1.8T Quattro</th>
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<tbody>
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<tr>
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<td>250</td>
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Microphone Left Front Seat

Microphone Right Back Seat
Appendix XIIb  Validation Experiments on Audi A4 Avant 1.8T Quattro

Mikrofonpegel Vorne Links

Mikrofonpegel Hinten Rechts

Mikrofonpegel Vorne Links

Mikrofonpegel Hinten Rechts
Validation Experiments on Audi A4 Avant 1.8T Quattro

Mikrofonpegel Vorne Links

Mikrofonpegel Hinten Rechts

[Graphs showing microphone levels for front left and rear right with various loads and measurements]
Appendix XII

Validation Experiments on Audi A4 Avant 1.8T Quattro

Mikrofonpegel Vorne Links

Mikrofonpegel Hinten Rechts

Mikrofonpegel Vorne Links

Mikrofonpegel Hinten Rechts
Validation Experiments on Audi A4 Avant 1.8T Quattro

Mikrofonpegel Vorne Links

Mikrofonpegel Hinten Rechts
Appendix XII

Validation Experiments on Audi A4 Avant 1.8T Quattro

Mikrofonpegel Vorne Links

- Ausgang
- 2.0 kg auf HECK 0011

Mikrofonpegel Hinten Rechts

- Ausgang
- 2.0 kg auf HECK 0011

Mikrofonpegel Vorne Links

- Ausgang
- 1.2 kg auf HECK 0013

Mikrofonpegel Hinten Rechts

- Ausgang
- 1.2 kg auf HECK 0013
Validation Experiments on Audi A4 Avant 1.8T Quattro

Mikrofonpegel Vorne Links

- Ausgang
- 2.25 kg auf HECK:0013

Mikrofonpegel Hinten Rechts

- Ausgang
- 2.25 kg auf HECK:0013
- 2.0 kg auf HECK:0010
Appendix XIIb  Validation Experiments on Audi A4 Avant 1.8T Quattro

Mikrofonpegel Vorne Links

- Ausgang
- 5.0 kg auf HECK:0013

Mikrofonpegel Hinten Rechts

- Ausgang
- 5.0 kg auf HECK:0013

Mikrofonpegel Vorne Links

- Ausgang
- 4.5 kg auf HECK:0014

Mikrofonpegel Hinten Rechts

- Ausgang
- 4.5 kg auf HECK:0014
Appendix XII\textsuperscript{i} --- Validation Experiments on Audi A4 Avant 1.8T Quattro

Mikrofonpegel Vorne Links

\begin{tabular}{|c|c|}
\hline
\textbf{Ausgang} & \textbf{3.05 kg auf SSML:0020} \\
\hline
\end{tabular}

\begin{itemize}
\item [\textbf{Ausgang}] \textbf{3.05 kg auf SSML:0020} \\
\item [\textbf{Ausgang}] \textbf{4.5 kg auf SSML:0020} \\
\end{itemize}

Mikrofonpegel Hinten Rechts

\begin{tabular}{|c|c|}
\hline
\textbf{Ausgang} & \textbf{3.05 kg auf SSML:0020} \\
\hline
\end{tabular}

\begin{itemize}
\item [\textbf{Ausgang}] \textbf{3.05 kg auf SSML:0020} \\
\item [\textbf{Ausgang}] \textbf{4.5 kg auf SSML:0021} \\
\end{itemize}
Validation Experiments on Audi A4 Avant 1.8T Quattro

Mikrofonpegel Vorne Links

- Ausgang
- 5.0 kg auf SSHR:0027

Mikrofonpegel Hinten Rechts

- Ausgang
- 5.0 kg auf SSHR:0027

Mikrofonpegel Vorne Links

- Ausgang
- 5.0 kg auf FSCH:0032

Mikrofonpegel Hinten Rechts

- Ausgang
- 5.0 kg auf FSCH:0032
Validation Experiments on Audi A4 Avant 1.8T Quattro

Mikrofonpegel Vorne Links

Mikrofonpegel Hinten Rechts

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Appendix XIIb

TU/e