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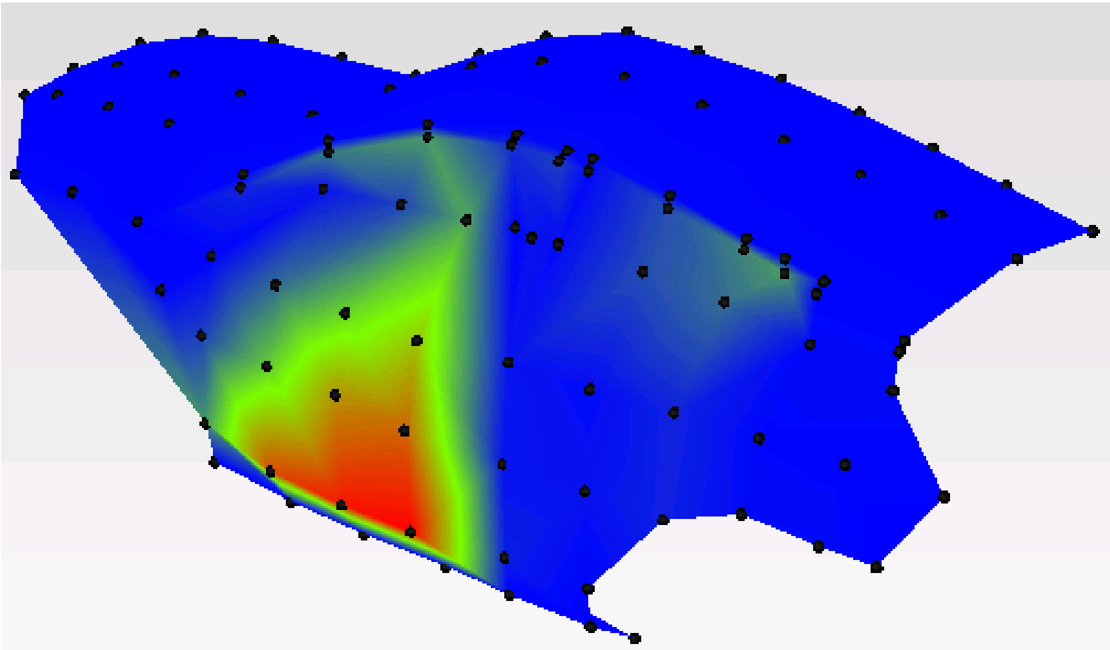

Experimental investigation of mechanisms affecting the door closing sound of passenger cars

Master of Science Thesis in the Master Degree Programme, Sound and Vibration

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Cover:
Operational deflection shape (ODS) of a Volvo V60 at 28 Hz.

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Abstract

The work presented in this report deals with studying parameters that affect the generation of the door closing sound for passenger cars. Previous studies have concluded that there are certain sound characteristics that correlates with good door closing sound quality. Beyond the absence of double impacts and rattles, the main characteristics are frequency content and it's time decay, which should be dominated by low frequencies. The question is how to realize a door closing sound with these characteristics. The classic approach may be to increase the mass of the door. However, by the means of lightweight material and the production standards of today, this is not possible. The objective of this Master's Thesis is therefore to investigate whether there are parts of the car that affects the sound radiation more than others and find out how to change them to achieve a better door closing sound.

This project was made on the behalf of Volvo Cars and the measuring object was a Volvo V60. An Audi A4 was used as reference object due to its previous proven quality in door closing sound. Measurements were done on the reference object and on the Volvo V60 with and without modifications. The modifications applied on the Volvo includes changing the stiffness in the B-pillar and adding damping material in the door rim sealing to see how that changed the radiated sound.

Vibration measurements were performed on the cars using uni- and triaxial accelerometers attached to the surface of the car. An acoustical dummy head with both internal microphones and extra mounted 1/2-inch measurement microphones recorded the radiated sound from the door closing. The measurements were used to create ODS (Operating Deflection Shape) visualizations, sound frequency spectra, sound figures and transfer functions. The ODS were visualized for both car models and the modified Volvo to see which surfaces of the cars that were vibrating at certain frequencies. This was later compared with the sound recordings to make a correlation between vibrations and radiation. Transfer functions for the two car models and for the modified Volvo were compared to see if there was any correlation between mobility and/or stiffness and the radiated sound. The force interaction between striker and latch was also investigated with a transfer function method.

Sound figure plots revealed what might be causing the perceived less quality of the Volvo's door closing sound; the decay of the lowest frequency was faster than some other decays at higher frequencies. This was not the case for the Audi to any greater extent. The ODS Analysis showed a lot of motion in the doors but not so much in the rest of the car body. The main parameters of importance for the generation of the door closing sound was found to be the modal behavior of the car doors and the design of the latch and striker, which determines an important portion of the force input. Modifying the seal on the door rim proved to have the ability to modify the modal behavior and somewhat increase the low frequency content of the door closing sound. By comparing the Volvo and Audi it could be seen that the force led into the striker had the best correlation to the radiated sound of the parameters studied. Future work will hopefully evoke a latch and striker design that together with an improved door rim sealing will create a better door closing sound.

Keywords: Door closing sound quality, Radiation, Vibration, ODS analysis, Transfer functions, Digital signal processing

Contents

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Chapter 1

Introduction

1.1 Background and Purpose

The door closing sound is usually one of the first impressions a customer gets of a car in a show-room, except for the visual impression. Studies have shown that the door closing sound has a strong link to the perceived quality of a vehicle and is of great importance for a good first impression of the car (Cerrato Jay, 2007).

Having a high quality sound is getting more and more important from the customers point of view and if he/she finds the door closing sound highly qualitative, the car will probably be perceived as secure and robust. The perception of a car with low quality sound might instead be that it is a cheap car without any further qualities (Pröpper & Schönherr, 2010).

The operational and functional sounds are very quiet in a modern vehicle but there are still sounds that have to be present. In surveys made it shows that sound such as the opening and closing of car doors is perceived as meaningful and therefore not annoying because they are sounds with a known origin. On the other hand, unknown sounds like ventilation seems to be more annoying (Beitz, Wagner & Enigk, 2010).

For sounds in cars one talk about character, quality and comfort which refer to engine, accessories (like doors) and road- and wind noise. The level of quality in a sound is not always determined by whether the sound is of known character or not. Even if sounds as opening and closing of the doors is not perceived as annoying, the quality of these sounds is still important. A high quality sound is of course a subjective issue and therefore several studies have been made in this area to obtain objective knowledge. Such studies show that the door closing sound should have low frequency content with only one single impulse in the time domain to avoid multiple sounds which would be perceived as rattle (Heppelter & Petniunas, 2008).

In order to design a door closing sound with high quality it is important to understand which surfaces that contribute to the sound radiation and which material parameters that might change the character of the sound, both regarding frequency content and level. To achieve a reasonable good amount of low frequency content, the classic approach may be to increase the mass of the door. By the means of lightweight material and the production standards of today this is not possible. Instead it is important to find what areas of the vehicle that is actually radiating and which ones that easily can be improved by parametrical changes.

1.2 Objective

The objective of this project is to find the vibration pattern of a car and find what parameters that affect the sound radiation. There are large differences between different but similar car models why it would be valuable to find what parts of the car or what material parameters that could be changed to achieve a door closing sound with higher quality. Today new models are designed, produced and then unsatisfactory parts are are modified. If one could find a correlation between the sound and vibrations and find the origin of the sound it would save both cost and time in process redesigning and evaluating. The ultimate goal is therefore to be able to make a model that can simulate the door closing sound in the design phase and this project is a milestone on the way to get there.

1.3 Previous Work

Similar work done at Volvo, before this project, is mainly radiation measurements done both for Volvo and competitor cars. It has been concluded the competitor car models that are highly ranked in door closing sound quality studies have a lot of low frequency content.

1.3.1 Results from the Initial Study

Much literature found about sound and car doors are focusing on how to measure the different mechanisms that is affecting the door closing sound (Zhang & Young, 2005). A discussed topic is also how to design different parts as the sealing which should not be too hard nor too soft. A too soft sealing would result in a hard, metallic noise when the car door hits the car body with too much force. With a too damped material, the door would be hard to close properly because of the higher pressure in the sealing. That could also result in a bad control of the door when being opened which in turn could cause damage of the door itself and surrounding objects.

Another commonly observed area in reference literature is the spectral content of the sound when closing (Hamilton, 1999). It is mainly psychoacoustic studies where it is investigated what frequencies the customers prefer for a higher quality sound (Musser & Young, 2005). This project will not put any emphasis on this subject. What is used from the initial study is the knowledge of what frequencies that should be generated to be perceived as high quality sound. The function of the lock device; the latch and the striker, knowledge of how to measure force, sound and vibration in a door and the function of the seal are background facts that was also handled in the initial study. This can all be read in the theory chapter.

1.4 Scope

This project includes first an initial study just to get familiar with the assignment. Measurements will then be performed on a Volvo V60 and also for a competitor car, Audi A4. Furthermore, modifications of the Volvo V60 is done to see how parameters can be changed to achieve a door closing sound that is more similar to the Audi car, which according to customer research has a higher quality sound (Heppelter & Petniunas, 2008). The vibrations should be visualized through an ODS-analysis (Operational Deflection Shapes), the stiffness on latch and door striker should be measured and calculated, a modal analysis on door and B-pillar should be done and correlation between the door closing sounds level and frequency content should be investigated. Conclusions and report writing is the last part of the project and input to further research is presented here.

1.5 Limitations

As mentioned before, the psychoacoustical approach about the perception of high qualitatively door closing sound is not treated more than in the initial study.

In the Volvo V60, it is accepted to make irreversible modification changes since it is to be scrapped. Modifications will not include things that can not be easily built and implemented on the car as it is. The Audi is rented and irreversible modifications can not be done on it.

The frequency range investigated is mainly 20 - 130 Hz. The reasons are that these are the most interesting frequencies for door closing sound and including higher frequencies would set high demands on the sound recording environment. The method used to record sound only had two measurement positions located on each side of the dummy head. For higher frequencies, the difference between the signals increased because the influence of position and directivity increases with frequency. Since the dummy head had to be moved between different measurement and might not end up in exactly the same position, it is not possible to make comparisons for higher frequencies. The fact that the cars could be parked at slightly different positions in the room further increased this effect. In reality, people have different lengths so the high frequency content they hear will differ somewhat anyway.

Another limitation is that the work should be done in 20 weeks why unfortunately all side tracks can not be followed up.

Chapter 2

Theory

2.1 Door closing sound quality

What is the sound of high quality? This type of subjective questions can not be measured using a microphone and without knowing the specific properties of high quality sound. Fortunately, several studies have been made regarding the characteristics of a good door closing sound. These generally consists of letting an evaluation group listen to door closing sound in which some parameters has been changed. The parameters are frequency content, loudness, existence of rattles and the decay of different frequencies over time. The result from most such tests says that the frequency content should be dominated by low frequencies, it should have a medium loudness (there are graphs correlating loudness to perceived good quality), there should be no rattles and the decay should be longer for low frequencies. (Hamilton, 1999)

The frequency content's change over time is usually shown in a "sound figure", see example in figure 2.1. These are obtained by taking the frequency spectra from sub time intervals of the whole time interval and placing them in time order. The 3D-version of this is also known as a waterfall-plot. All parameters of importance can be illustrated in this figure.

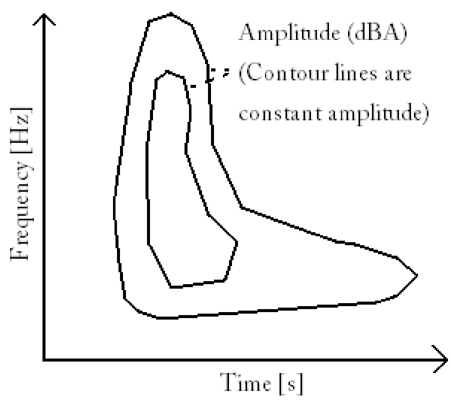


Fig. 2.1: Example of a "sound figure" (Hamilton, 1999)

2.2 Measure sound and vibration of the car body and door when closing

When measuring the sound from the closing sequence, an acoustical dummyhead can be used. The dummyhead has microphones installed inside the ear canals to achieve results that correlate to how the sound is percieved by the human ear. The vibrations can be measured using accelerometers attached to the surface of the car body. To measure the level of the vibrations and understand how the energy transfers through the door and into the car body one have to have knowledge both about the closing force and where this force is applied. When the door closes the latch hits the striker and the sides around the door hits the sealing. The difficult part of the analysis is to divide these two sources to find the force interaction for each, since the force between the sealing and door can not be measured easily. (Hamilton, 1999) Some approximation has to be done but they should of course be as accurate as possible and for that special measurement methods are needed. The latch is the locking mechanism which locks around the striker attached at the B-pillar on the car body and the sealing is the damping that runs around the whole door which has the function to both damp the door when closing and keep away dirt, wet and noise when driving. For the car body there are three important pillars on each side to add stability. The A-pillar is situated on each side of the windshield, the B-pillar is the one between the front and rear door where the belt is attached and the C-pillar is behind the rear door.

The latch is closing around the striker as can be seen in figure 2.2. Inside the latch there is a rubber which damps the force when it closes around the striker to avoid metal hitting metal, stop the motion of the door and keep the door from bouncing back out again. Unless the sealing is very thick, this is where the major part of the force interaction between door and car body takes place.

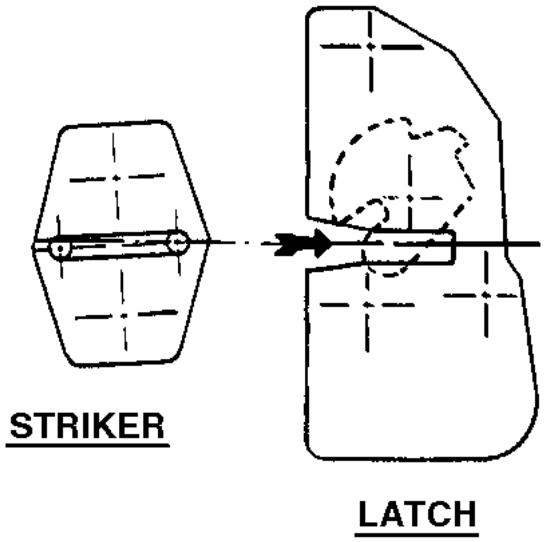


Fig. 2.2: Drawing of the lock device; the latch and the striker

(a) Picture of the striker

(b) Picture of the latch

Fig. 2.3: Picture of the lock device; the latch and the striker

The sealing is also made of rubber and as for the latch, it is important that the rubber has the right stiffness as read in the introduction. If the rubber in the sealing is too soft it would result in a hard, metallic noise when the car door hits the car body with too much force. With a too damped material, the door would be hard to close properly because of the high pressure in the sealing and it might also result in both a bad noise and a bad control of the door when open.

To get valuable results when measuring it is essential to know the size of the excitation force compared to the response in the surrounding surfaces. The force from the door closing is obviously exciting in several areas when closing the car door why it is impossible to achieve the exact force excitation in every point. It is impossible to excite the car body with an impact hammer so that it correlates with the real closing excitation. To get as close as possible to the closing force an impact hammer is first used to excite the outermost rod of the striker while an accelerometer is attached to the innermost rod of the striker. Assuming that for low frequencies, the geometric distance between front and rear rod of the striker is small compared to the wavelength, the measurement is good enough and the relationship between impact force and resultant vibration in the location around the striker is obtained. Using the accelerometer in the same position also when closing the door and assuming the same relationship between force and response as before, it is possible to estimate the force from the door.

For the sealing it is even harder to find the size of the force since it is the area around the whole door that receives the force. In references found it is possible by using a membrane pressure sensor that is working good for measuring static and low frequency pressure (Zhang & Young, 2005). These sensors can measure the pressure of that area that it is covering and by this way it is possible to get a measure of the force at the whole sealing. Volvo has not access to this kind of equipment so the membrane pressure sensor will not be used in this project.

If there is no possibility of using the above mentioned methods to estimate the force it is still possible to measure the vibrations when exciting with the real force, the closing of the door. In those measurements the value of the force can not be obtained but it is still possible to investigate whether the changes gave positive or negative effects. A photocell or a speed meter that measures the speed of the door during the closing sequence can be used to give repeatability to the measurements.

By measuring vibrations over half the car, it is possible to make a visualization of the vibration patterns of it. The vibrations can be analyzed in either a time- or frequency spectra and the areas moving the most at a certain frequency are also the areas where large improvements can be made if the sound radiation has much content at that frequency.

2.3 Digital signal processing

This is a short explanation of the digital signal processing tools used in the data analysis.

2.3.1 Sampling

A continuous signal can not be stored in a digital format without some loss of information. Ultimately, one would have measured values at any continous time with exactly the correct amplitude. In reality, the continous time signal is only measured at discrete times, limited by the samplerate and the accuracy of the amplitudes are limited by the bitrate, dynamic range settings and noise in the system. The sample rate and bitrate is limited by the measurement system hardware. In order to be able to properly reproduce the real time signal, the samplerate must in theory be at least twice that of the highest frequency in the signal. This is called the Nyquist criterion. To avoid having higher frequencies in the signal that is sampled, a low pass filter (anti-aliasing filter) is used on the signal before it is sampled. Since it is not possible to achieve infinitely steep decay of low pass filters, oversampling is required to compensate for the low pass filter decay. (Mulgrew, Grant & Thompson, 2003)

2.3.2 Fourier transform

The Fourier transform is used to convert a signal in time domain to frequency domain. The result of taking the Fourier transform on a time signal is a double sided amplitude spectra and phase information. Only half of the values in a double sided spectra carries real information. The right side is a mirror and complex conjugate of the left side and those sides are split by the sampling frequency. When creating a single-sided spectra, the left side values are summed with their corresponding mirror values to get the correct amplitude. In order to get the result proportional to energy they are also multiplicated by their complex conjugate, this is called the auto-spectrum. Average amplitude spectras, AS_{xx} can be obtained by simply taking the average of a number N spectra in the frequency domain X_n. The averaged autospectrum is given by:

$$AS_{xx} = \sum_{n=1}^{N} \overline{X}_n X_n$$

The single-sided auto-spectrum, AG_{xx} of Na aliasing free frequency components is given by:

$$AG_{xx}(1) = AS_{xx}(1)$$

$$AG_{xx}(2,3,4...Na) = 2AS_{xx}(2,3,4...Na)$$

The Fourier transform assumes the signal to be periodic. In order to avoid adverse effects known as leakage, the ending and start amplitudes have to be the same, i.e. the repeated signal should be smooth. This is usually not the case for real measurements so a time window has to be choosen properly if one wants to limit this effect. The signal is multiplied by a time window to lower it's amplitude in the start and end parts. For impulse measurements, a time window can also reduce the noise influence by limiting the part in a data block that is taken into account. Preferably, only the impulse and not the noise in the end should be covered by the window if the blocksize is a bit too long.

The frequency resolution of the frequency spectra is given by:

$$df = \frac{f_s}{N}$$

where df is the frequency resolution, f_s is the sampling frequency and N is the number of samples in the block. Consequently, in order to have a good frequency resolution, the measurement time must be long enough. This can be a problem when measuring short impulses. Plotting a spectra with low frequency resolution will not appear as smooth. By filling out the time signal with zeros in the end, the plotted frequency resolution can be increased to create a more smooth curve. This method is called zero-padding. However, zero-padding can not help to reveal information that could not be seen in the non zero-padded frequency spectra, i.e. in order to detect two close frequency peaks without having them blend together, the original frequency resolution must be sufficient. (Kropp, 2008)

2.3.3 Transfer functions

The frequency domain representation of two signals obtained by Fourier transform can be combined to create a transfer function which is one signal divided by the other. In order to create transfer functions, single-sided, averaged cross-spectras, are used. These are similar to the autospectras but multiplicates the spectra of two different signals. The single-sided averaged cross spectra AS_{xy} of Na frequency components is created from the averaged double-sided cross-spectra of N frequency spectra of a signal X and another signal Y.

$$AS_{xy} = \sum_{n=1}^{N} \overline{X}_n Y_n$$

$$AG_{xy}(1) = AS_{xy}(1)$$

$$AG_{xy}(2,3,4...Na) = 2AS_{xy}(2,3,4...Na)$$

Some transfer functions of interest for structure dynamics are mobility (velocity over force) and stiffness (force over displacement). These can be measured by using an accelerometer and impulse hammer. The accelerometer gives a measured signal in the unit acceleration, which needs to be integrated if velocity and displacement are sought. Time integration can conveniently be done on a frequency domain representation of a signal by the $j\omega$-method. Integration of time is division by $j\omega$ and a derivative is multiplication by $j\omega$ to the fourier transform of a signal. The following equations are used to calculate mobility and stiffness from acceleration and force.

$$\text{Mobility} = \frac{AG_{aa}}{AG_{fa}} \frac{1}{j\omega}$$

$$\text{Stiffness} = \frac{AG_{fa}}{AG_{aa}} (j\omega)^2$$

where AG_{aa} is the averaged single-sided autospectrum of the accelerometer signals of the acceleration signal, AG_{fa} is the averaged single-sided signal cross-spectrum between the force and acceleration signals and ω is the angular frequency.

When evaluating transfer functions it is important to investigate their coherence. If the coherence is low for a certain frequency (it should be or be very close to one), there is a lot of noise in the measurement or too low excitation for that frequency and the result is likely invalid. If the coherence is equal to one this means that the signals have a perfect linear relation, which is expected from linear systems. The coherence between two signals x and y is calculated as:

$$\text{Coherence} = \frac{|AGxy|^2}{AG_{xx} AG_{yy}}$$

(Kropp, 2008)

2.4 Radiation

Dealing with vibrations in structures and the sound in the surrounding medium one talk about radiation from structures. Radiation is sound transferred from one medium to another. There are both bending and longitudinal waves in structures but it is mainly the bending waves that generate sound to surrounding mediums. In air and liquids there is very low shear stiffness why mainly longitudinal waves occur in these mediums.

The wavelength in a material is depending on the speed in the material, how far the wave can travel in the material at a certain time. Changing the stiffness of the material one will also change the velocity and in turn the wave length and frequency. The bending wave velocity is frequency dependent which means that it travels faster for higher frequencies. (Kropp, 2007)

Looking at the car door for the interesting frequency span, up to 130 Hz, the door is small compared to the wavelength why the theory for infinite plates can not be used. The door will radiate as a finite plate where most of the radiation comes from the edges. Because of the complex geometry of the door, it can not be fully treated as a plate. In order to estimate in which order of magnitude the door's resonance frequency is, a simplified model can be made assuming a steel plate in the size of the door. The radiation of a finite plate is correlated to the modal behaviour and the frequence of the excitation. Depending on the power of the excitation the radiated sound has a frequency that is influenced by both the excitation and resonance frequency.

2.5 A-weighting

A-weighting is the most common weight function that relates to human perception of loudness for different frequencies. It is applied on raw sound pressure level spectras. Equation 2.1 where f is frequency is a function to realize the A-weighting curve that is shown in figure 2.4. (Wikipedia, 2011)

$$R_A(f) = \frac{12200^2 \cdot f^4}{(f^2 + 20.6^2)\sqrt{(f^2 + 737.9^2)}(f^2 + 12200^2)}$$

$$A(f) = 2.0 + 20\log_{10}(R_A(f)) \tag{2.1}$$

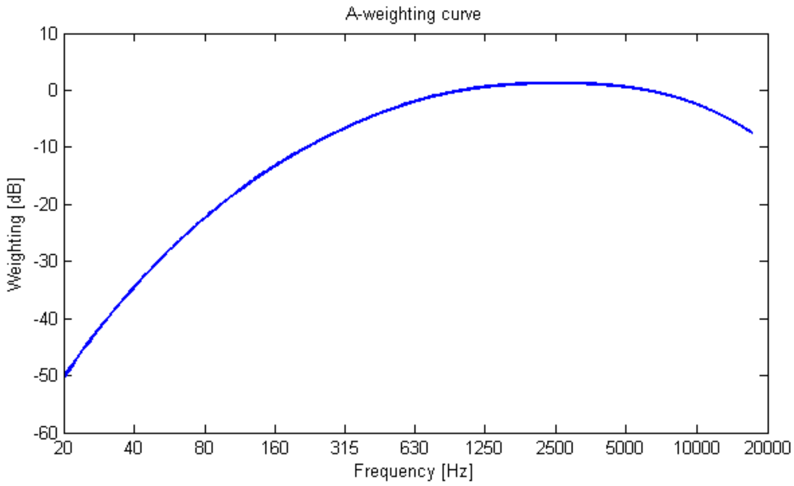


Fig. 2.4: A-weighting curve

Chapter 3

Equipment

This chapter will mainly describe the equipment used for all measurements but also scripts and programs used for the analysis of these measurements.

3.1 Measurement equipment

The following equipment was used for all measurements in this project:

- 62 x uniaxial accelerometers
- Accelerometer calibrator
- 2 x 1/2 inch microphones
- Microphone calibrator
- 13 x triaxial accelerometers
- PULSE Frontend 65 channels
- Head Acoustics dummy head with internal microphones
- Impact hammer
- Attachment for the latch to make stiffness measurements possible
- Laptop with PULSE software
- Laptop with Head Acoustics software
- Dynamometer
- Force meter
- Volvo V60 car
- Audi A4 car
- Cables etc
- Semi-echoic room (PV16) at Volvo Cars, Torslanda

See appendix B for equipment serial numbers

(a) A Tri-axial accelerometer

(b) The PULSE Frontend and a microphone in a microphone calibrator device

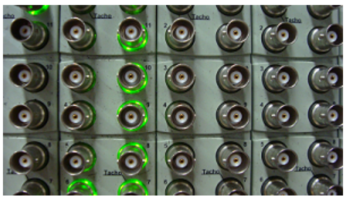
(c) The attachment in the lock

(d) Medium tip on hammer

(e) An uniaxial accelerometer attached to the accelerometer calibrator

(f) Accelerometer covers and cables used in measurements

(g) Soft tip on hammer



(h) Close-up of the 65-channel PULSE Frontend

(i) Acoustical dummy head with extra microphones attached

Fig. 3.1: Examples of equipment that was used in the measurements

3.2 Data acquisition

The PULSE frontend was connected to the computer by a network cable which set the upper limit for possible sample rate. When using all channels it was possible to have a sample rate of 16384 Hz and bit rate 24. For most measurements when only half the channels were used (triaxial measurements), the sample rate was 32768 Hz. The 1/2 inch microphones placed on the dummy head were connected to the PULSE frontend and therefore has too low sample rate for high fidelity listening purposes but are sufficient for low frequency analysis. The dummy heads internal microphones were recorded separately on another computer with sample rate 44100 Hz and are more suited for listening.

3.3 Data analysis

Raw data from the measurements comes in the form of time signals. The data for all measurements was exported into MATLAB and treated with scripts. The first script is used to extract impulses with the correct door closing speed. This script uses an amplitude detection algorithm to detect impulses, i.e. if amplitude is larger than threshold then save a block around this as an impulse. Parameters such as blocksize, threshold and pretrigger samples (see figure 3.2) are set to suitable values for each type of measurement. One channel is chosen as "detection channel", i.e. the channel that the amplitude detection algorithm works on. This channel was taken as one of the reference channels in the ODS analysis measurements and impact hammer channel in transfer function measurements. The reference channels in the ODS analysis measurements are measurements points that were used in both the side and roof accelerometer placing. Choosing such a channel as detection channel made the impulses chosen at similar times. For each impulse a note was manually made of door closing velocity and whether the measurement was ok or not (door might fail to lock and impact hammering might hit wrong). This information is considered in the script as it only picks out impulses that are marked as ok and within the set range of acceptable velocities. Finally, the blocks of impulses are ordered in a matrix suitable for further analysis and the data is saved.

The analysis is done with scripts that uses Fast Fourier transform to create frequency spectra, sound figures and transfer functions (see section 2.3). Another tool is used to merge data from side and roof measurements that is to be used for ODS visualization. It orders the channel data so that it ends up in the right visualization position and compensates for time differences in the impulses, i.e. if side impulses on the chosen reference point for example come earlier in time than roof impulses, they are shifted backwards to ensure correct phase relation.

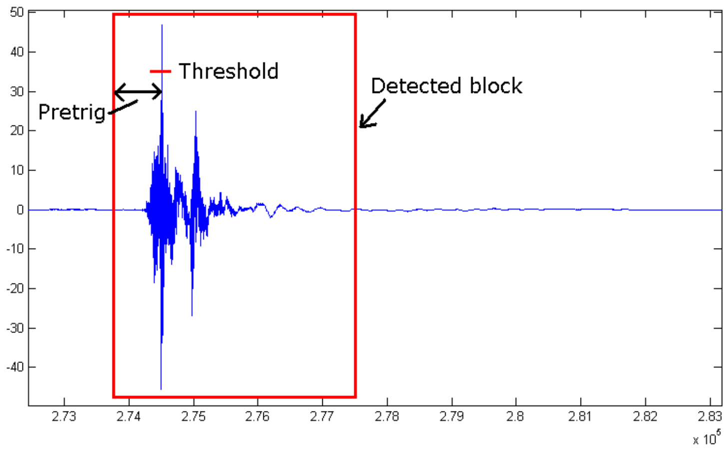


Fig. 3.2: Impulse detection

3.4 ODS Visualization

The visualization of the signals is made in a program called ME'scopeVES which is a series of post-test analysis software tools with which one can observe, analyze and document the dynamic behavior of machines and mechanical structures (Vibrant Technology, Inc., 2003). The program displays Operating Deflection Shapes (ODS), mode shapes, acoustic shapes or Engineering Data Shapes. Operating Deflection Shapes analysis is used for determination of the vibration pattern of a structure under given operating conditions. Vibration measurements are performed at different points and directions on the structure and the vibration pattern can be shown as an animated geometry model of the structure. The ODS Analysis can be done in either the time- or frequency domain.

The measurements at the V60 are done using uniaxial accelerometers why the response is in the normal direction from the surface of the car. ME'scope makes it possible to rotate each measurement point to get the direction of the movement right in the 3D animation.

Chapter 4

Radiation and ODS analysis

This chapter presents the measurements that includes sound and half-body vibration recording for door closing. The presentation is divided into different parameter studies but the set-up is common for all.

4.1 Set-up and general method

The vibrations were measured with accelerometers attached all over the car side and roof in the positions as can be seen in the figures below.

In order to be able to keep track of all the accelerometers, they were marked with the numbers. This was also done for the cables (at both ends) to ensure that the same cables were used with the same accelerometer in the measurement as in the calibration.

The sensitivities of the accelerometers and microphones were put into the PULSE software and the calibration were performed on the accelerometers and microphones one by one.

Measurement points on the car was marked with numbers on the side and the accelerometer with the respective number was glued at each measurement position. The accelerometers were glued right on the body of the Volvo but a piece of tape was put in between the glue and the body of the rented Audi to avoid damage. This type of mounting is still expected to give a relatively stiff connection for the low frequencies that are of interest. The measurement had to be split into two parts since there were not enough accelerometers to measure all positions at once. Some points were used as reference and measured both in the side and roof setting in order to be able to check that the timing is right when they are combined. So when the car roof, windscreen and engine hood was measured, the accelerometers at the sides were moved. There were nine additional positions that can not be seen in the figures. Those were placed on the undercarriage of the car and on the B-pillar. The measurement positions on the Volvo and Audi are shown in pictures 4.1 and 4.2, respectively.

There were some issues with the dummy head's sound recording, therefore sound graphs are made from the data of the 1/2-inch microphones attached to the head. The issues consisted of having different sensitivities normalizing the data in the head recorder which gave different amplitudes for different measurements when they were analyzed in MATLAB. This unables comparison between different measurements using these signals. There were also some unexplainable noise issues with the dummy head's internal microphones in some measurements.

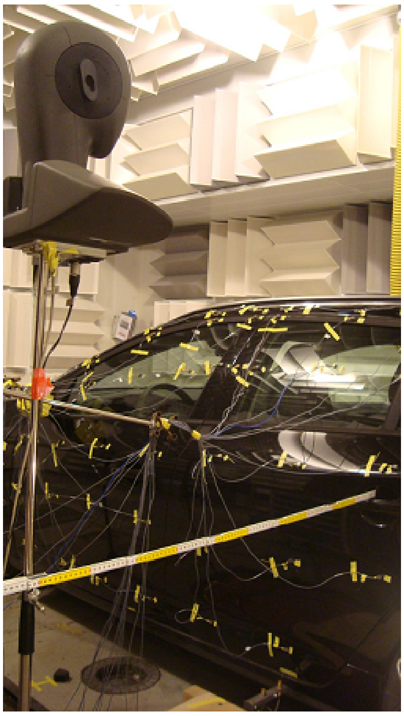
(a) Positions on side (b) Positions on top

Fig. 4.1: Accelerometer positions for Volvo

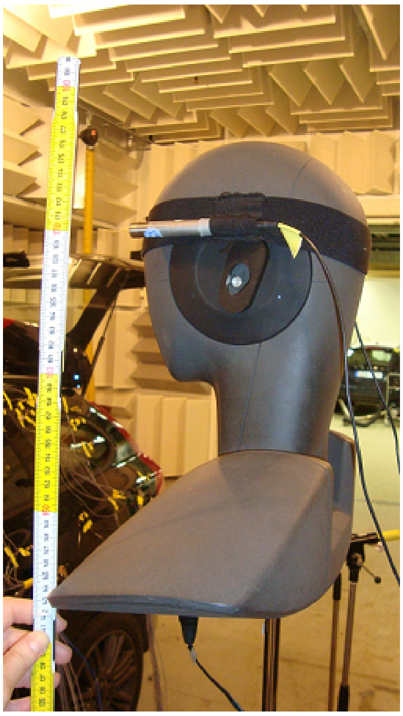
(a) Positions for side (b) Positions on top

Fig. 4.2: Accelerometer positions for Audi

The dummy head was placed right in front of the handle of the door that was measured (front or rear) in the current measurement, at one meters distance and at a height of 1.70 meters as seen in figure 4.3.



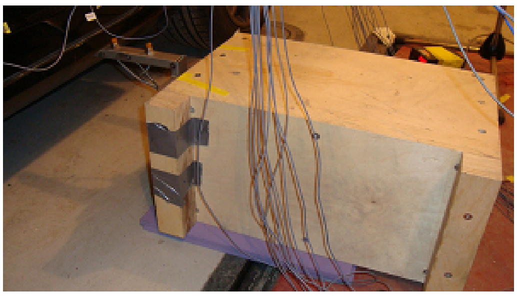
(a) The dummy head placed in front of the back door at one meters distance



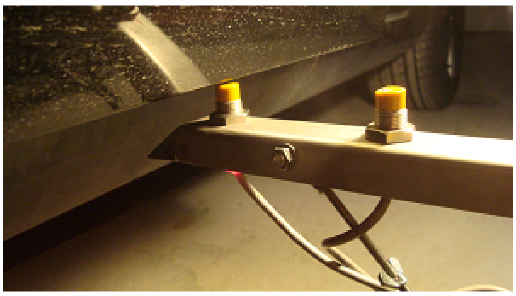
(b) The dummy head at a height of 1.70 meters

Fig. 4.3: Dummy head set-up

The door were closed in the regular way by a hand push. Another way could be to use a rubber band but that is not how a car door is closed in reality and such an attachment could possibly change the properties of the structure. The door closing speeds were measured with the speed meter seen in figure 4.4. It had to be really close to the passing door to react so it was taped to a wooden case of a size that matched the height of the door. When the door was close enough the red lights of the speed meter were lit to show that the door had been detected and the speed could be read. The speed meter was placed at the same distance from the hinge for all measurements so the angular velocity should be the same. The door closing speeds were noted manually for each measurement in order to enable selection of impulses that had velocities within a certain interval when they were analyzed.



(a) Speed meter attached to box



(b) The red light of one of the sensors in the speed meter lit when door passing

Fig. 4.4: Speed meter set-up

The coordinate system used when dealing with cars is shown in figure 4.5.

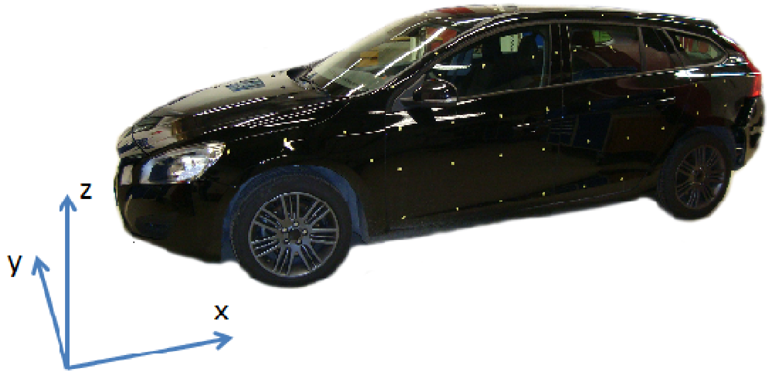


Fig. 4.5: Car coordinate system

The coordinates were measured with a Farao arm, which is an arm that can measure coordinates of points by touching them, see figure 4.6.

(a) Farao arm

(b) During measurement with Farao arm

Fig. 4.6: Measuring the coordinates of measurement points

4.2 Door closing speed

4.2.1 Method

Three different door closing speeds were measured to study it's influence. The slowest speed that still closed the Volvo V60 door properly was between 0.55 and 0.60 m/s why this was decided to be the "slow speed". "Regular speed" was a speed that felt natural and was set to 0.95-1.05 m/s. "Fast speed" was when closing the door hard, 1.45-1.55 m/s. It could not be chosen higher since that would cause overload to the accelerometers. "Regular speed", was decided to be the reference velocity that all other measurements would have. This spectra is included in all other radiated sound spectra for comparison convenience. Measurements were done both for front and rear door but this report will focus on the results for the front door, see appendix A for rear door graphs.

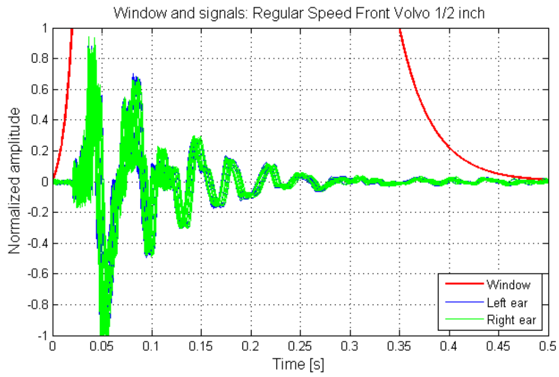
4.2.2 Results and discussion

Results presented as A-weighted are weighted as described in section 2.5.

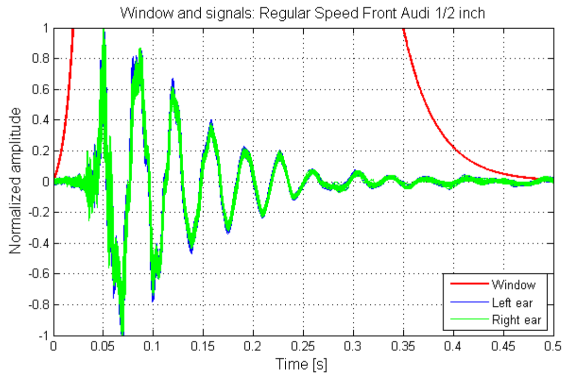
Figures 4.7, 4.8 and 4.9 shows the measured sound time signals recorded by the 1/2 inch microphones and the time windows used. Only one impulse for each channel is shown in the time window, but the other impulses are very similar. These were used to make the averaged A-weighted spectra. The parameter that can cause any large difference in the impulses are if there are a big difference in door closing speed. Since this speed was measured and only impulses with the chosen door closing speed (0.55-0.60, 0.95-1.05 and 1.45-1.55 m/s) is used in creating the averaged spectra, these averages are assumed to be valid representations of each case and hence can be compared with each other. Figure 4.10 shows the result of another measurement with regular door closing speed on the Volvo. From this it can be seen that the difference is less than one dB at most frequencies of interest. Consequently, it should be reasonable to assume that the measurement error is in the range of a few dB at most. The slow speed was only done for the Volvo because the Audi required higher speed to close properly (higher "closing resistance"). The first peak around 28 Hz have almost equal amplitude for Volvo and Audi. However, looking at the ODS around this frequency (see figure 4.11), it can be seen that the Volvo is mainly vibrating at the lower side of the front door while the vibrations for the Audi is smeared out over the whole front door. It should be noted that the whole transient process is visualized, which results in an average representation of the whole process that in reality changes dramatically over time. Although it can not be seen in this still picture, the Audi has more vibration in the rear door that moves in phase with the front door. For the Volvo they are rather moving out of phase.

The main difference between Volvo and Audi at low frequencies is that the Volvo has a large peak around 50 Hz while the Audi instead has a dip here. Figure 4.12 shows the ODS around 50 Hz. There are almost no vibrations at all on the Audi while the Volvo has vibrations almost over the whole side (mainly doors) but they show no clear, "regular" mode shapes. This indicates forced motion, i.e. high excitation but no large resonance. For slow closing speed, the peak around 50 Hz gets relatively lower. One possible explanation for this is that most of the force is taken by the sealing and not the striker for slow closing speed. This would in turn speak for a hypothesis that the peak around 50 Hz is caused by the striker excitation. The Audi has a peak at 35 Hz which can not be seen for the Volvo. There seems to be smaller amplitudes in the high frequency components in the Audi's sound, although these measurements are not made for further analyzing high frequencies.

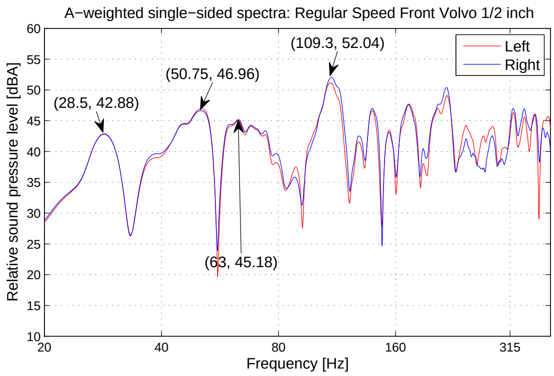
Sound figures from regular door closing speed for Volvo and Audi together with their windows are shown in figure 4.13. Both the Volvo and Audi has longer decay times at low frequencies. However, the Volvo have a longer decay time for the 50 Hz peak than for the lowest 28 Hz peak. According to section 2.1 studies have shown that people prefer sounds with longer reverberation at lower frequencies. The fact that the lowest frequency of the Volvo is not the most dominant might be a reason to why Volvo is not ranked as high as Audi when it comes to door closing sound quality.



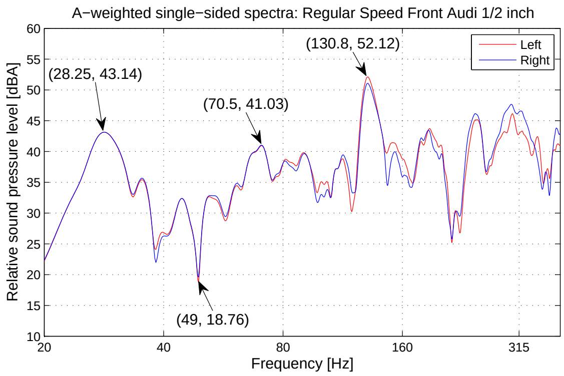
(a) Window and time signals Volvo



(b) Window and time signals Audi

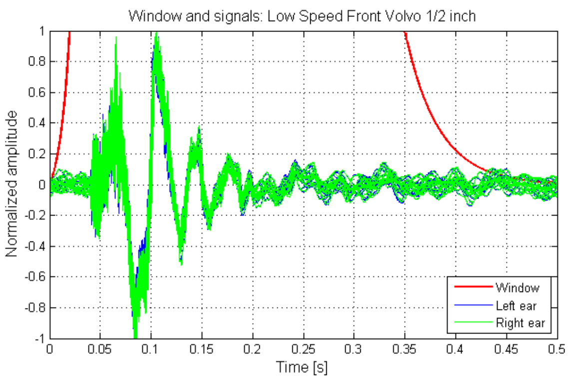


(c) Averaged A-weighted spectra Volvo

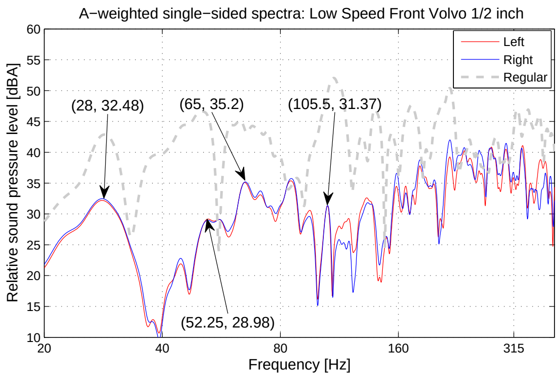


(d) Averaged A-weighted spectra Audi

Fig. 4.7: Sound radiation, regular door closing speed (0.95-1.05 m/s)

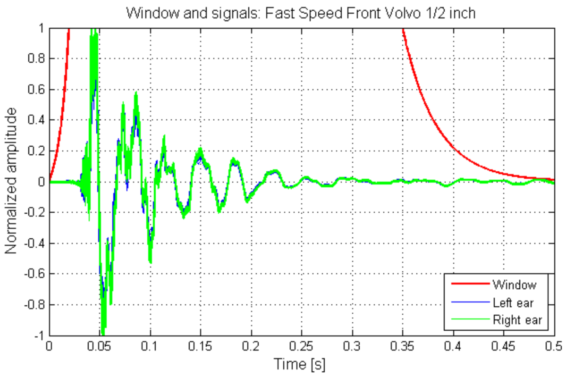


(a) Window and time signals Volvo

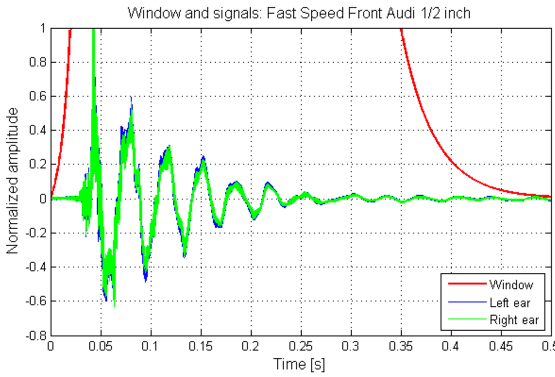


(b) Averaged A-weighted spectra Volvo

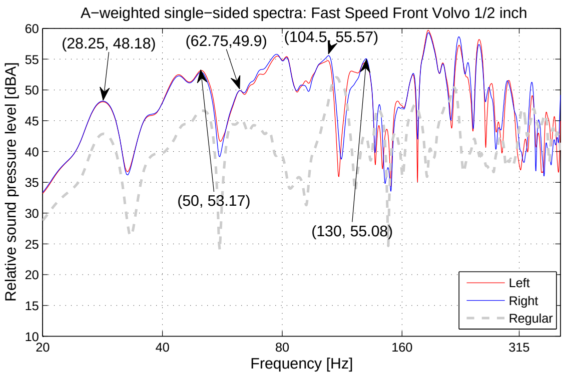
Fig. 4.8: Sound radiation slow door closing speed (0.55-0.60 m/s)



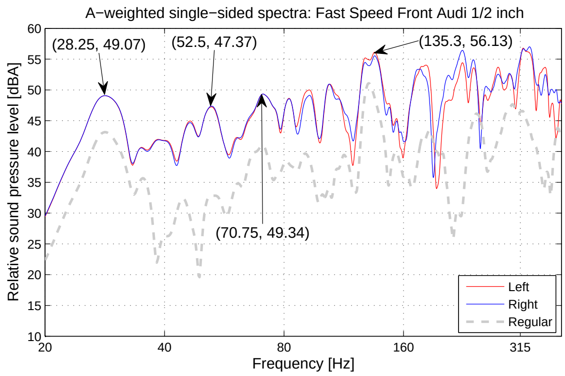
(a) Window and time signals Volvo



(b) Window and time signals Audi



(c) Averaged A-weighted spectra Volvo



(d) Averaged A-weighted spectra Audi

Fig. 4.9: Sound radiation fast door closing speed (1.45-1.55 m/s)

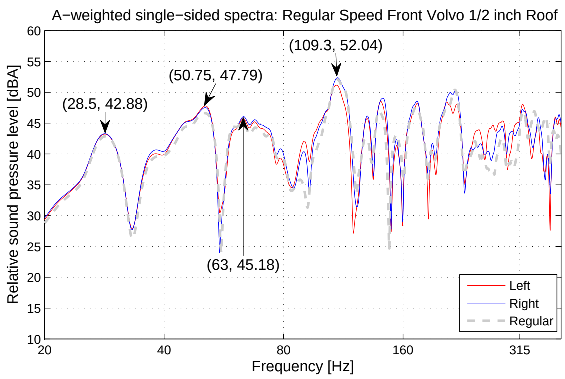


Fig. 4.10: Another averaged A-weighted spectrum of the Volvo for regular door closing speed

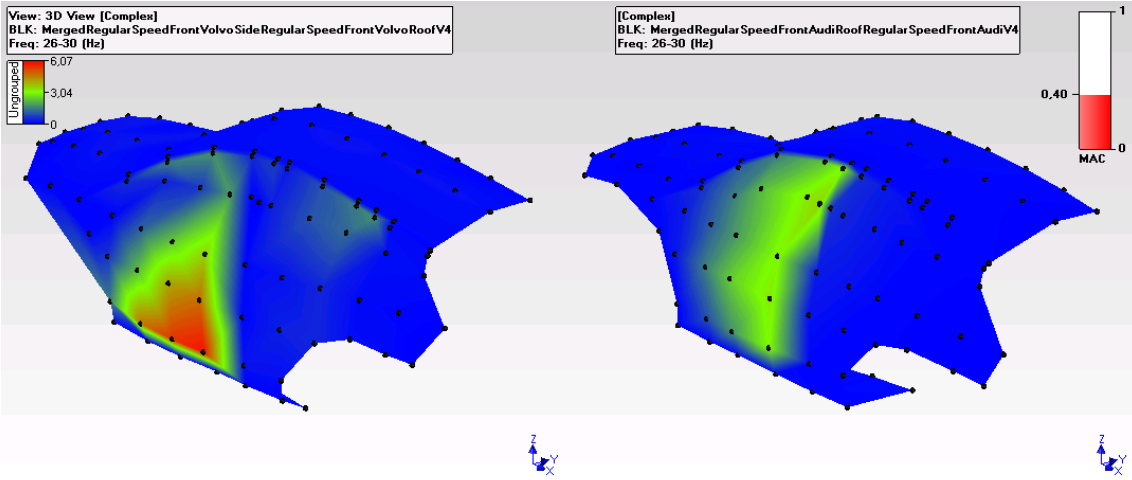


Fig. 4.11: ODS at 26-30 Hz for regular door closing speed of Volvo (left) and Audi (right).

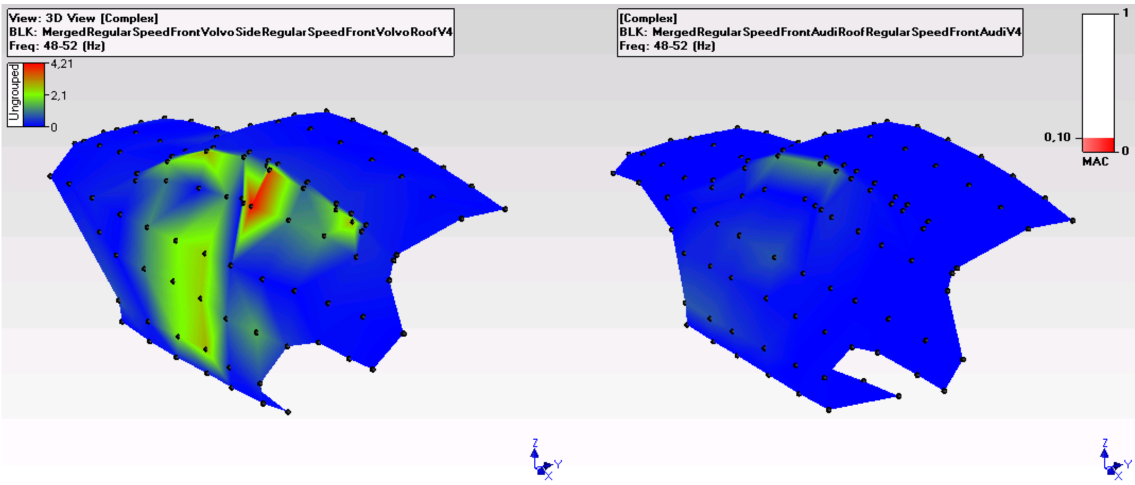
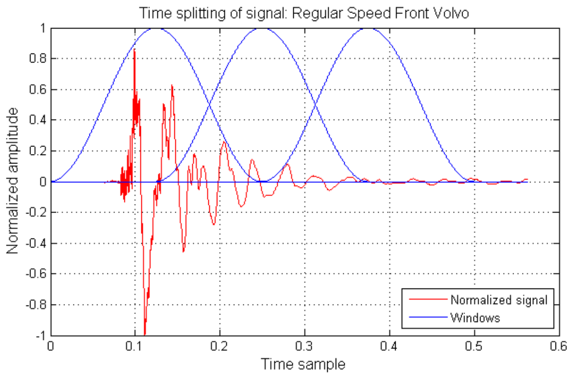
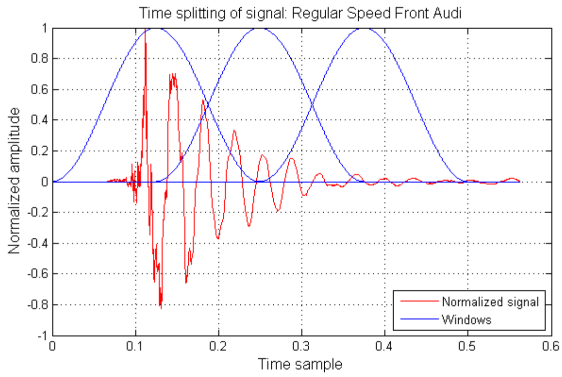


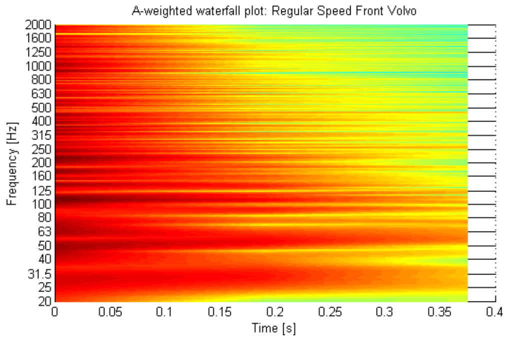
Fig. 4.12: ODS at 48-52 Hz for regular door closing speed of Volvo (left) and Audi (right).



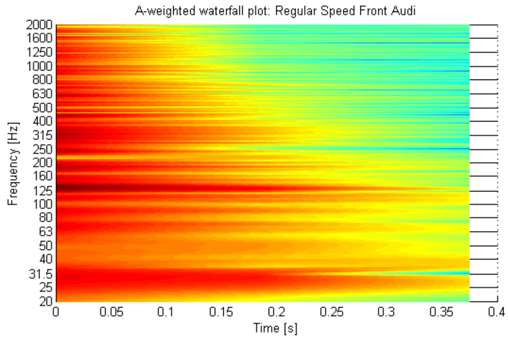
(a) Volvo time signal split



(b) Audi time signal split



(c) Sound figure Volvo



(d) Sound figure Audi

Fig. 4.13: Sound figures of regular door closing speed

4.3 Influence of the topside

4.3.1 Method

Measurements were made with sandbags over the roof, the wind shield, the engine hood and full top side cover to completely exclude the radiation from the top side, see figure 4.14. This measurement was only done on the Volvo since the sandbags caused scratches that would be unacceptable on the Audi.

(a) Sandbags on roof

(b) Sandbags on windshield

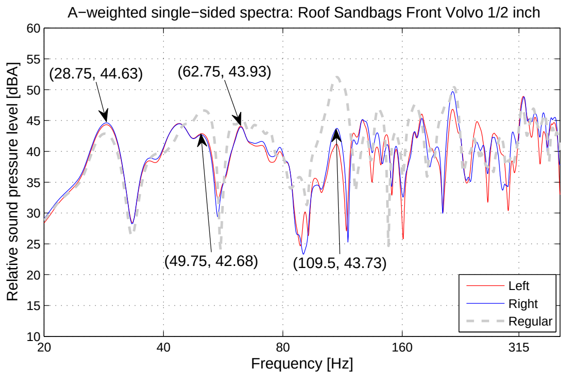
(c) Sandbags on engine hood

(d) Full top covered

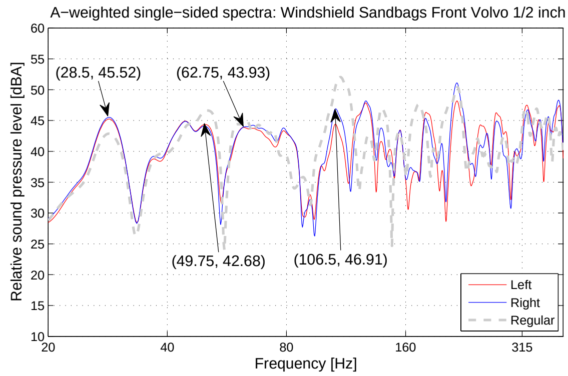
Fig. 4.14: Sandbag settings

4.3.2 Results and discussion

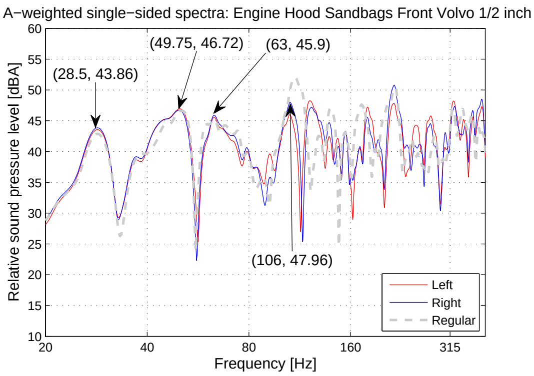
The windows applied to the time signals are very similar to the previous chapter, hence only the spectra are shown from now on. Figure 4.15 shows the measured radiated sound when covering different parts of the topside with sandbags. Comparing the full top covered graph in figure 4.15d with figure 4.7c it is clear that the peak at 108-109 Hz is decreased almost 10 dB with the sandbag modification. This prove that this frequency was mainly influenced by the roof.



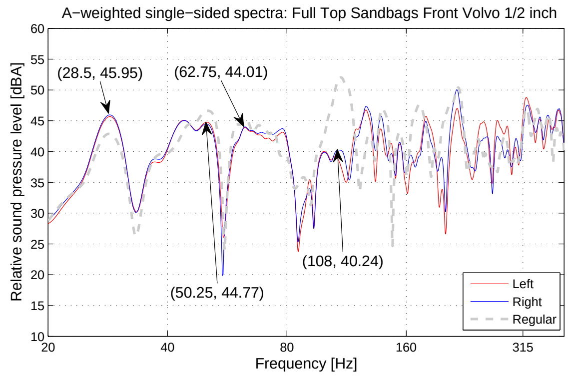
(a) Sandbags covering roof



(b) Sandbags covering windshield



(c) Sandbags covering engine hood



(d) Full top covered

Fig. 4.15: Sound radiation with sandbag settings

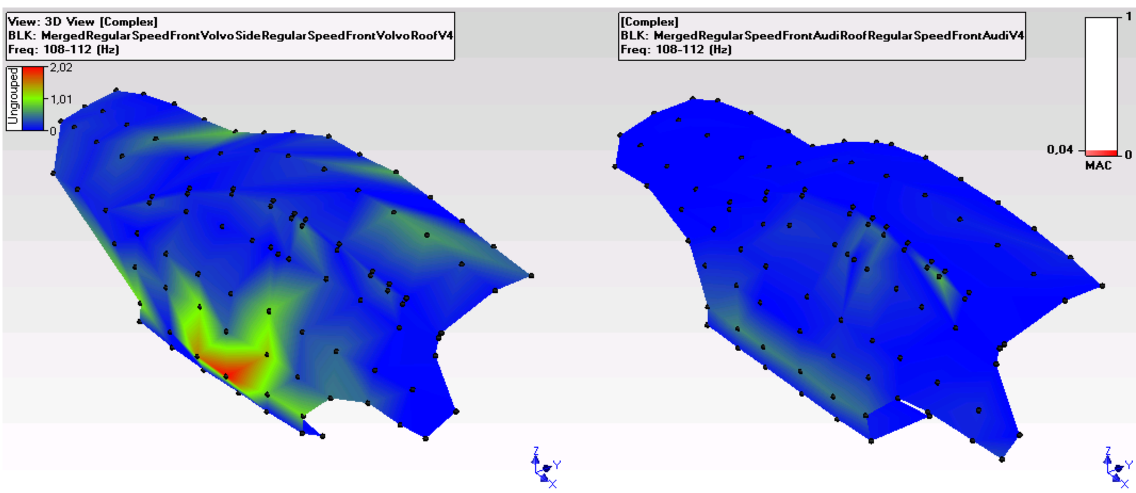


Fig. 4.16: ODS at 108-112 Hz for regular door closing speed of Volvo (left) and Audi (right).

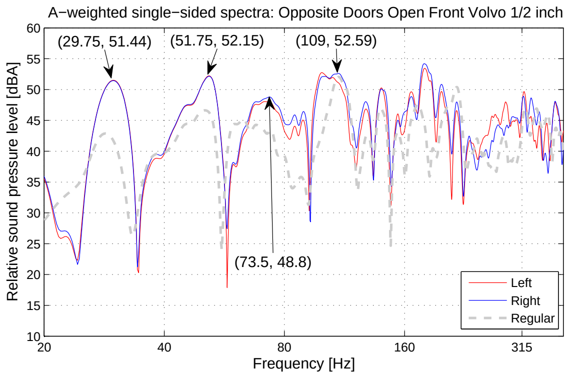
4.4 Other Doors and Windows open

4.4.1 Method

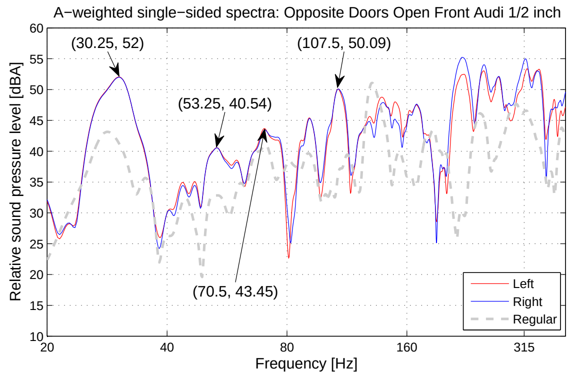
In order to see the influence of the air evacuation and coupling between the doors, door closing measurements were done with doors open on the opposite side (passenger's side), the rear door open on the driver's side and both door windows down on driver's side. All door closing and measurements are done on the driver's side.

4.4.2 Results and discussion

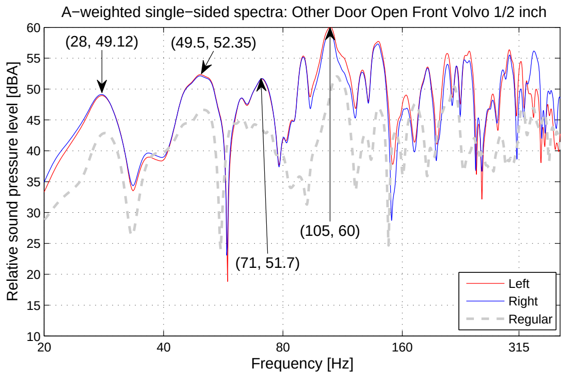
Figure 4.17 shows the radiated sound for the different settings. With doors on other side open, the overall amplitudes increase. This can be explained by the fact that the resistance from the air in the coupé decreases. With the windows opened, the amplitude of the peak around 28 Hz decreases, even if the air resistance should be reduced in the same way as with opposite side doors open. Other peaks in the open window setting increases as for the opposite side doors setting. This speaks for the fact that the windows are important radiators at 28 Hz even though the ODS analysis indicated that it is mostly he lower part of the door that vibrates at this frequency.



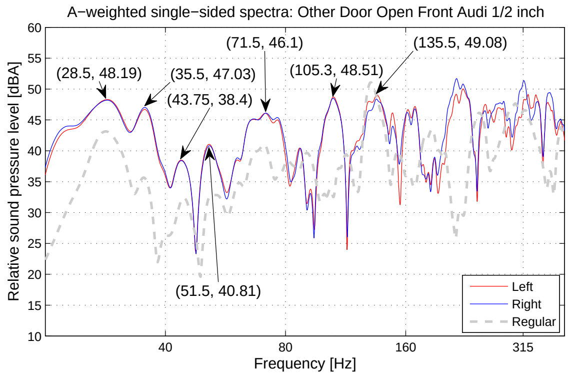
(a) Opposite doors open Volvo



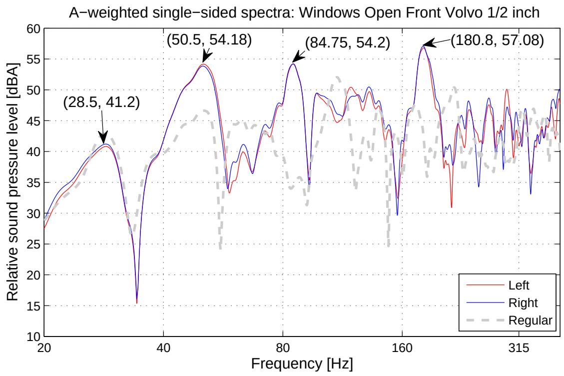
(b) Opposite doors open Audi



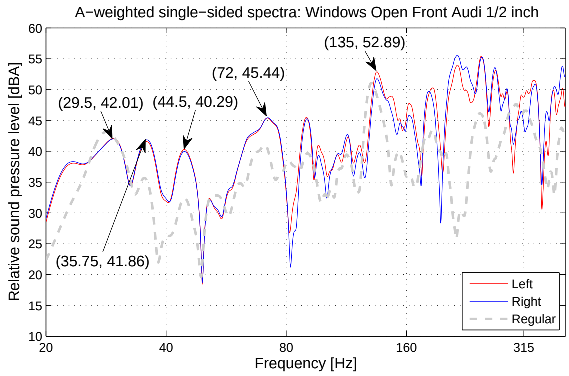
(c) Other door open Volvo



(d) Other door open Audi



(e) Windows open Volvo



(f) Windows open Audi

Fig. 4.17: Sound radiation with other doors and windows open

4.5 Striker position

4.5.1 Method

The position of the striker (see figure 4.18) could be moved approximately two mm outwards by moving it inside it's screw hole width. Changing the striker's position that little changed the static force required to close the door and have it lock properly. A measurement was done when the striker was moved into it's outermost position to see how this affects the sound. This measurement was only performed on the Volvo to avoid damage on the Audi.

The static force required to lock the door properly was measured with a dynamometer being pressed with very slow force increase on the door at the locks position, see figure 4.19. Several force measurements were done and the measurement giving the lowest value was considered to be the valid one. The larger values were caused by pressing a bit too hard in the end, just as the door locked.

Fig. 4.18: Striker

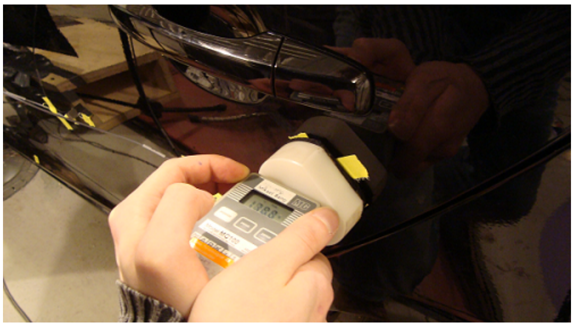
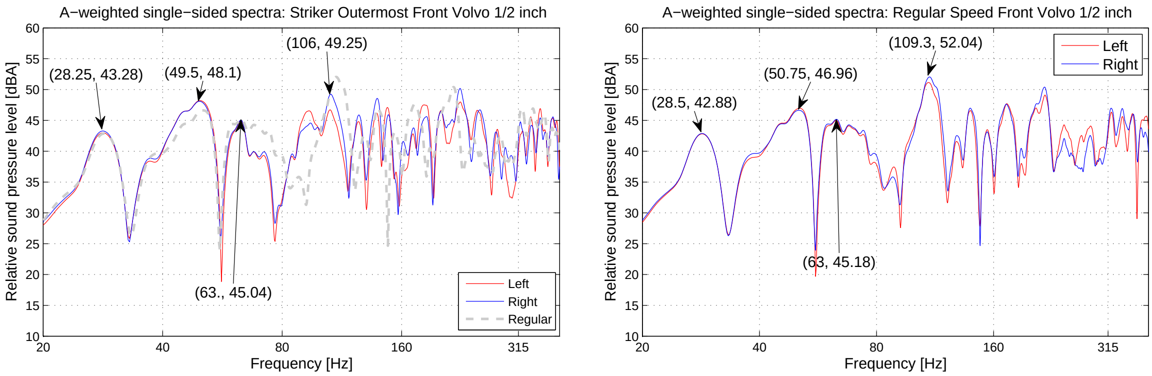


Fig. 4.19: Dynamometer measurement

4.5.2 Results and discussion

Figure 4.20 shows the measured sound with striker in outermost position and the original setting repeated here for comparison convenience. The static door closing force required to lock the front door properly was 232 N for regular striker position and 203 N for outermost position. It was also examined what the required force was at innermost striker position which was 245 N. Measurements was not made for this case because of the little difference to the original striker position. The spectra does not show any great differences. A hypothesis could be that if the striker is responsible for the peak around 50 Hz, this would increase with the striker in the outermost position since it should receive a greater part of the energy. Maybe the difference in position was to small to be able to cause any greater such effect.



(a) Striker outermost position

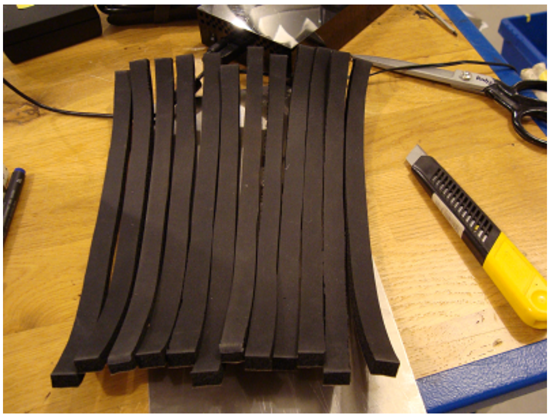
(b) Striker in regular setting

Fig. 4.20: Sound radiation for different striker settings

4.6 Modified door sealing and bump stops

4.6.1 Method

The sealing of the car door frame was modified by adding a soft closed cell foam in it's air-gap. Material was added gradually starting at the lower edge of the door opening, then adding to the upper edge, the rear edge by the striker and at last at the the front edge to get an idea of the influence of the added sealing force, see figure 4.21.



(a) Soft closed cell foam cut to fit under sealing

(b) Damping material added to the lower sealing

(c) How damping material is positioned under sealing

(d) Damping material added to the upper sealing

(e) Damping material added to rear sealing by the striker

(f) Damping material added to front sealing

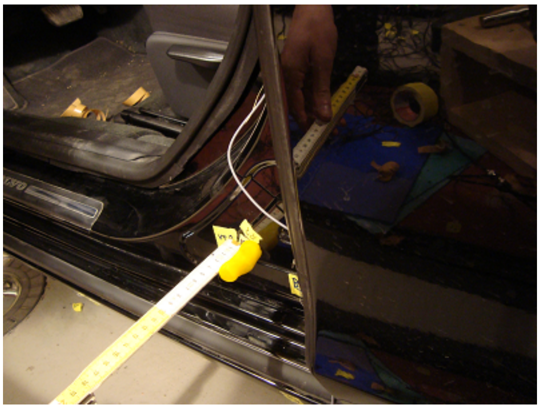
(g) How damping material is positioned under sealing

Fig. 4.21: Soft closed cell foam was gradually added to see how it changed the radiation and also in what position it gave most effect.

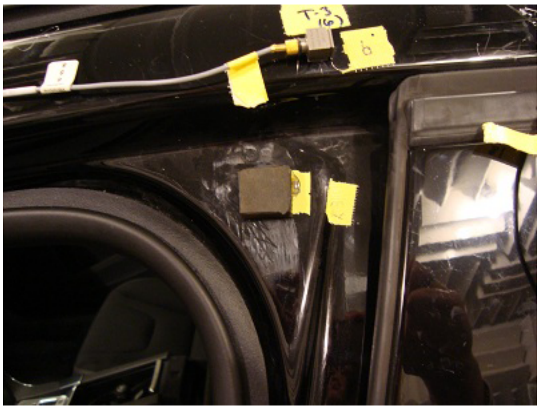
When the whole sealing was filled with soft closed cell foam, bump stops in the form of small pads of harder damping material were attached. The size of these bump stops were decided using a piece of clay between the car body and the door while closing to see how large the distance between them is. The clay revealed that a bump stop could not be fitted in the lower rear corner (see figure 4.22a) since there was a gap of 4 cm. The lower bump stop was instead positioned in the door rim, close to the sealing, see figure 4.22d. The upper bump stop was attached first and measurements were done with only this before the lower bump stop was also attached. This was done in order to see which position that gave the best result. The positions of the bump stops can be seen in figure 4.22. These measurements were only performed for the front door (driver's side).

The static door closing force needed to close and properly lock the door for each setting was measured with a dynamometer as described in section 4.5.1.

(a) Clay attached to car while closing to find the thickness of the bump stop needed



(b) Clay measured



(c) Bump stop added to in upper corner

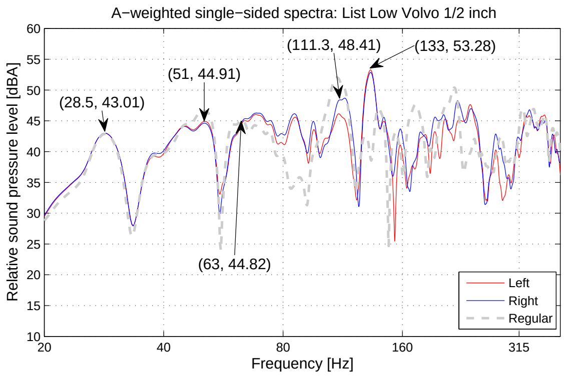
(d) Bump stop in lower corner to increase the damping and facilitate the energy transfer into the car body

Fig. 4.22: Bump stop settings

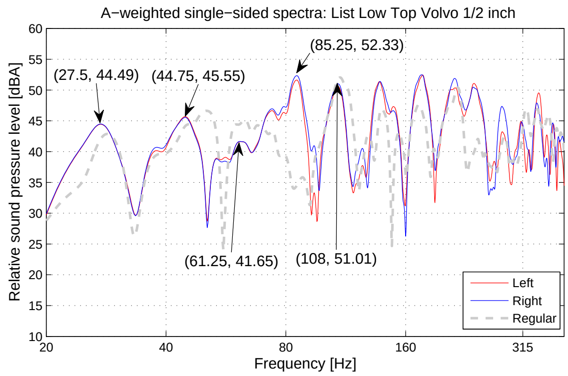
4.6.2 Results and discussion

Figure 4.23 shows the measured sound with damping layers attached to the door frame sealing at different locations. The static door closing force to properly close the door was for material added in order of low, top, rear and all sides: 268, 353, 458 and 468 N, respectively. Additionally adding bump stops (together with all damping material) in the top rear corner and both top and low rear positions gave 500 and 697 N, respectively. The overall low frequency level is increased with more damping material. A possible explanation is that a softer impact leads to a force insertion with more low frequency content. Some of the sealing settings introduce a new frequency peak around 85 Hz.

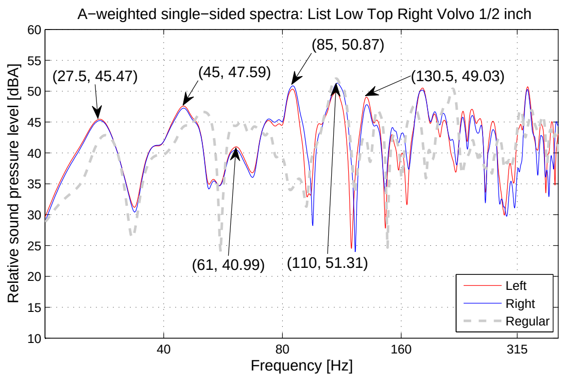
Figure 4.24 shows the measured sound with bump stops added together with damping layers. The top bump stop increases the 28 Hz peak and does not affect the other peaks to any greater extent. The lower bump stop decreases the amplitude at 28 Hz and increases the amplitudes 45 and 63,5 Hz, which is the opposite to the goal of increasing the amplitude at the lowest frequency. It should be noted that the lower bump stop is not placed at a very good position and dramatically increased the static force required to lock the door.



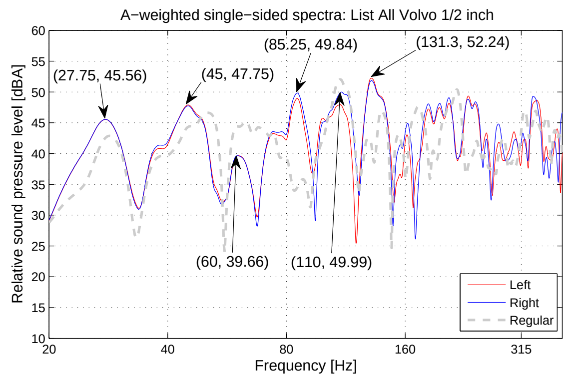
(a) Damping material added to lower sealing



(b) Damping material added to lower and top sealing

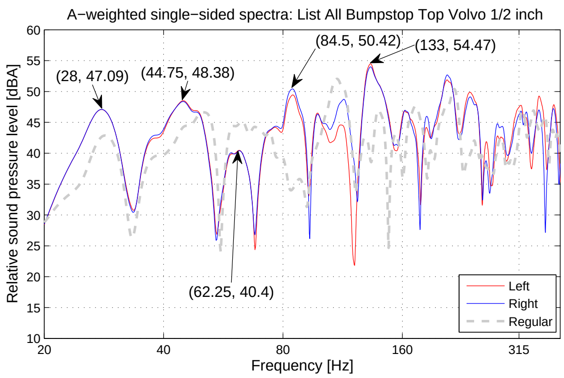


(c) Damping material added to lower, top and rear sealing

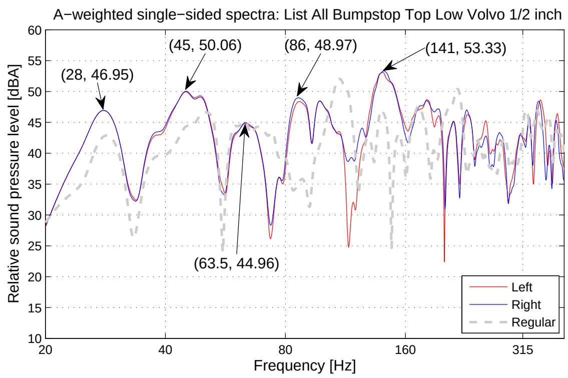


(d) Damping material added to lower, top, rear and front sealing

Fig. 4.23: Sound radiation at different sealing settings



(a) Damping material added for whole sealing and bump stop added on upper corner of door



(b) Damping material added for whole sealing and bump stop added on both upper and lower corner

Fig. 4.24: Damping material and bump stops added

4.7 Increased striker stiffness

4.7.1 Method

One hypothesis was that the stiffness of the striker would influence the door closing sound. Stiffness measurements (see section 5.2.2) showed that the stiffness at the striker was higher for the Audi. To investigate this effect further, a rod was put in between the B-pillars to actualize increased stiffness. Holes were drilled to make it possible to mount the rod right on the metal car body, see figure 4.25. The rod had screws at both ends so it could be properly fitted with tight connection to both pillars at a height close to the striker. Measurements were also done with both rod and sealing plus bump stop modifications from the previous chapter to see if these together would make the Volvo sound more like an Audi.

(a) Rod attached to driver's side B-pillar

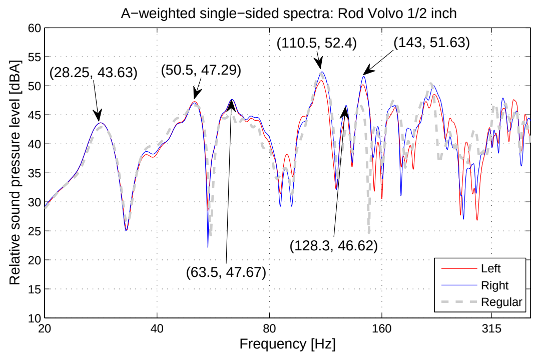
(b) Rod attached to passenger's side B-pillar

(c) Rod clamped between both B-pillars

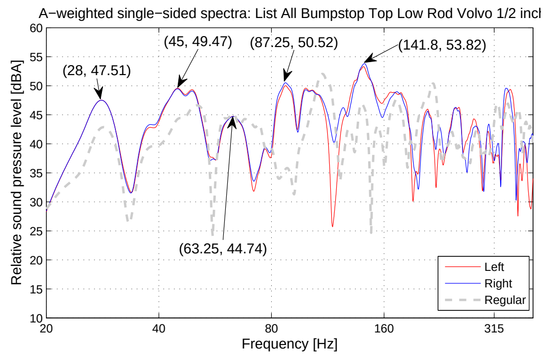
Fig. 4.25: Rod clamped between the B-pillars to increase the stiffness

4.7.2 Results and discussion

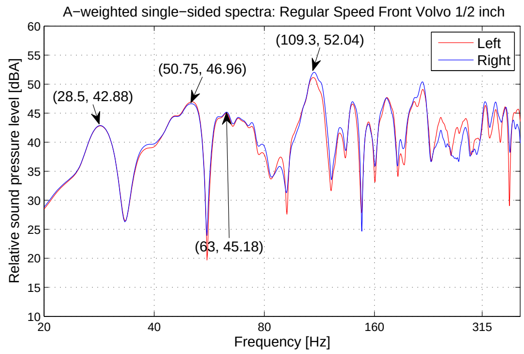
Figure 4.26 shows the measured sound spectra with rod attached between B-pillars with and without damping layers and bump stops. The results from the regular setting measurements are included again for comparison convenience. It can be seen that the rod had almost no influence at all to the radiated sound. This would mean that the stiffness of the B-pillar in the y-direction are of no importance for the sound radiation for this specific car at low frequencies. The rod itself also has modes so this way of stiffening the B-pillar is not ideal. A test at another car manufacturer has previously shown a more low frequent door closing sound using increased striker stiffness. One reason for the lack of impact in this measurement could be that the rod modification did not increase the stiffness enough to make a change.



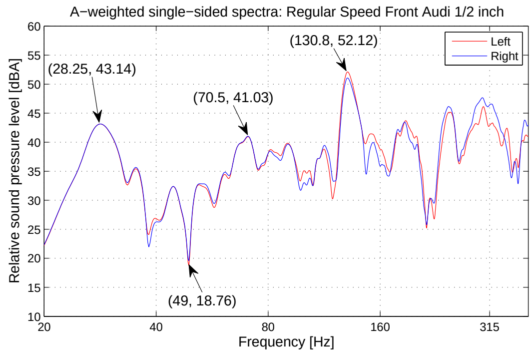
(a) Rod attached between B-pillars



(b) Rod attached between B-pillars, added damping material and bump stop



(c) Regular setting and speed for Volvo



(d) Regular setting and speed for Audi

Fig. 4.26: Rod settings compared to regular settings for Volvo and Audi

Chapter 5

Transfer functions

This chapter includes the transfer function measurements. The set-up are not exactly the same for all but the fundamental way to make transfer function measurements are so they will be presented together. Measurements were done for the Volvo, the Audi and the modified Volvo.

5.1 Set-up

Common for all transfer function measurements in this project are that an accelerometer is used in one position of the structure while a hammer excites with a measured force in the same or an other point of the structure. From the measured force and acceleration response, transfer functions such as mobility and stiffness can be calculated, see section 2.3.3.

The measurements with the impulse hammer were done with two different hammer tips, one soft and one medium hard (see figure 3.1g,d) in order to get optimal coherence for different frequency ranges. The results showed that the medium hard tip gave overall the best coherence for the investigated frequency range and is therefore chosen to be presented.

The Volvo has the same modifications as before and the set-ups are explained in the ODS Analysis part.

5.2 Striker

5.2.1 Method

The measurements in the striker were done in three different directions to decide the stiffness of the striker in all directions but only the y-direction was considered to be of greatest importance. The stiffness of both car models and the modified Volvo was later compared to see if there is any correlation between stiffness and radiation at certain frequencies. The modification used for these striker measurements were the rod modification explained closer in section 4.7. The stiffness was obtained from the transfer function between the applied force and accelerometer response. An uniaxial accelerometer was attached to the striker and the impact hammer excited from the opposite side as can be seen in figure 5.1. In this case the interesting frequency span is low why it can be assumed that the accelerometer and the hammer are working in the same position.

(a) An accelerometer attached in x-direction (b) An accelerometer attached in y-direction (c) An accelerometer attached in z-direction

Fig. 5.1: An accelerometer attached to the Volvo striker

5.2.2 Results and discussion

The results in figure 5.2 show that there is only a notable difference in stiffness at the striker for the different cars. It can be seen that the Audi has a slighter stiffer striker than the Volvo in original setting. When the rod is attached between the Volvo's B-pillars, the stiffness is increased and matches the Audi for most frequencies between 30 and 80 Hz. Looking at Volvo before and after the rod modification the spectra is uniform but the stiffness is slightly larger when the rod is used.

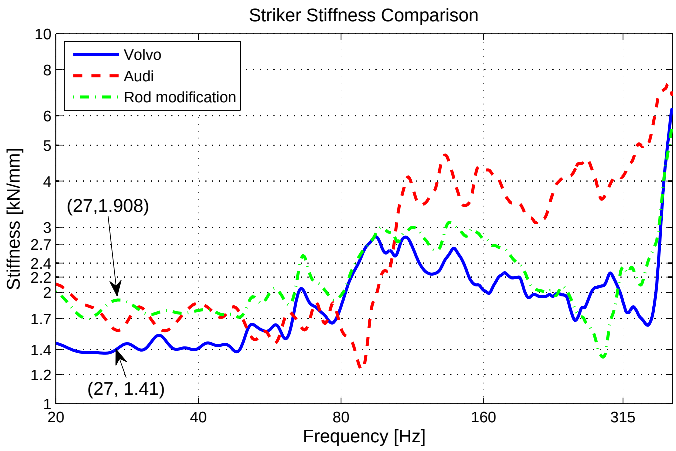
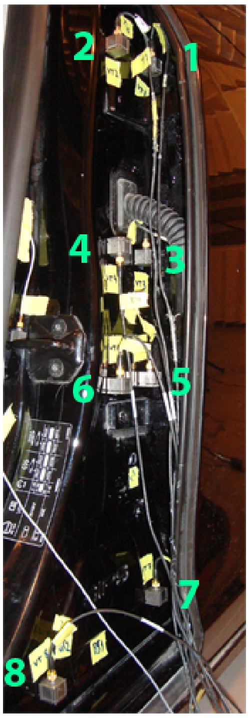


Fig. 5.2: With a good coherence between 20 Hz and 300 Hz, these graphs show the stiffness in the y-direction for the Volvo V60, the Audi A4 and the rod modification of the Volvo

5.3 Mobility from striker to B-pillar

5.3.1 Method

To obtain information about how the properties of the B-pillar, transfer function measurements are done between the striker and the B-pillar. The force is applied by hammer excitement in the striker while triaxial accelerometers were attached in eight positions at the B-pillar, figure 5.3. In the end it was decided to focus on the results in y-direction so this measurement could have been done with uniaxial accelerometers.The mobilities obtained from these measurements should give an idea of the modal behavior of the B-pillar. These measurements were, as for the striker measurements, done for the Volvo, Audi and the rod modification of the Volvo.



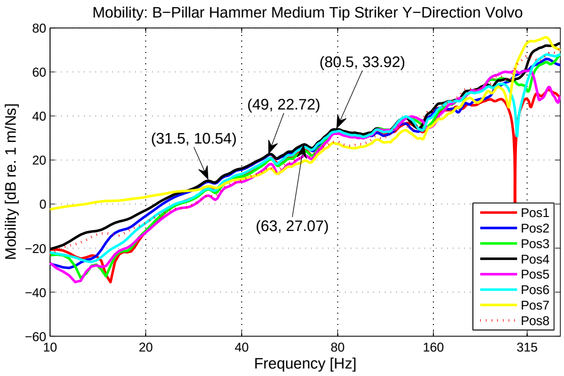
(a) Accelerometers and numbers on Volvo B-pillar

(b) Accelerometers on Audi B-pillar (same numbers as for Volvo)

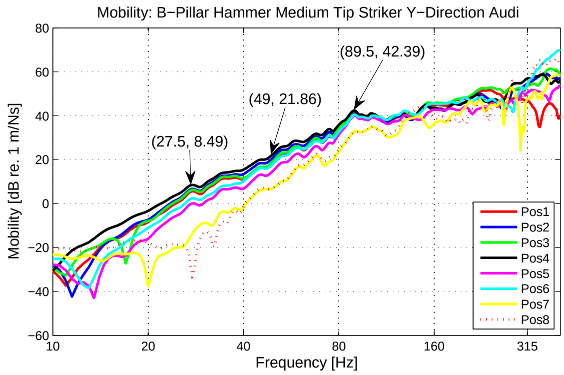
Fig. 5.3: Triaxial accelerometers on the B-pillar while exciting the striker

5.3.2 Results and discussion

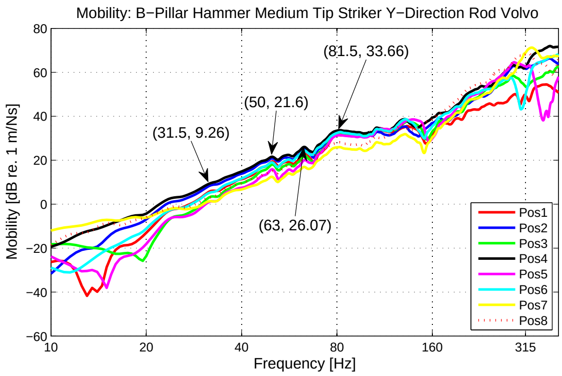
The mobility plots seen in figure 5.4 below show that the mobility peaks at the marked frequencies are more apparent for Volvo both with and without rod modification. A higher mobility means a lower stiffness and consequently less effort needed to move. The radiation results showed that a peak around 50 Hz only occurred for the Volvo. One possible explanation could have been modal behaviors, as these results indicates. The results shows a little bit more peaky behavior at 50 Hz for the Volvo than for the Audi but not matching the huge difference seen in the radiation. The mobility is a bit lower with the rod attached, which concludes that this modification increased the overall stiffness in the whole B-pillar.



(a) Mobility for Volvo



(b) Mobility for Audi



(c) Mobility for Volvo with rod modification

Fig. 5.4: The mobility of B-pillar when exciting in the y-direction on the striker

5.4 Resonance frequencies of the door

5.4.1 Method

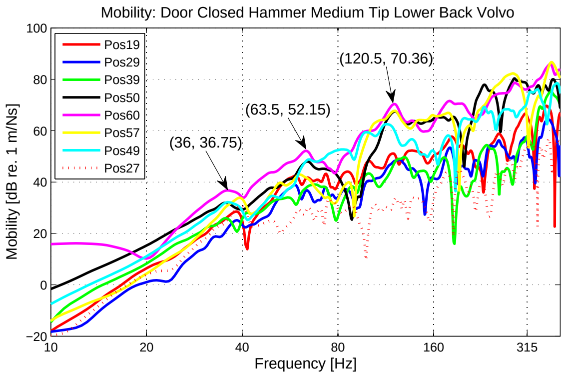
The ODS analysis showed that the vibrations were mainly located in the doors. In order to find out whether the vibrations originates from modes in the door, transfer functions were measured in the door, exciting the door in three of the four corners with an impact hammer, to find the resonance frequencies of the door. The corners were excited since the modes always have a maximum value there. The triaxial accelerometers were attached to eight positions at the door as can be seen in figure 5.5. Measurements for Volvo and Audi were done with the car door both opened and closed. Damping, bump stop and rod modifications were only used for the closed door position since these does not affect the door in open state.

(a) Excitation points (b) Accelerometer positions

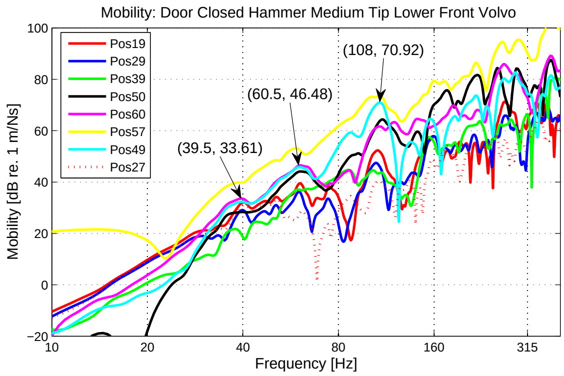
Fig. 5.5: Mobility measurements of the car door of the Audi to find the resonance frequencies.

5.4.2 Results and discussion

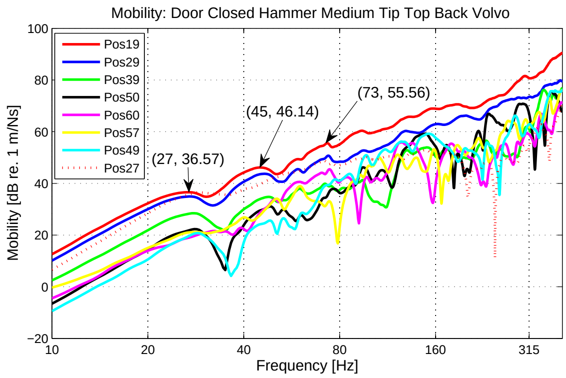
Graphs seen below in figure are the results from measurements done in three different excitement positions in the door, having the door closed. The first three graphs in figure 5.6 are for Volvo, figure 5.7 is for Audi and the last three in figure 5.8 are for the Volvo modified with both damping layers added to the sealing and bump stops. The reason for showing graphs for three different positions is just to see which frequencies are actually present in the whole door and which are just local. Comparing the open door graphs in figures 5.9 and 5.10 with closed door results, one can see that the modes have been shifted up in frequency. Most noticeable the first mode at 20 Hz for open door is shifted and damped when the door is closed. The first resonance in closed position is not as clear as for the open but it seems to appear slightly above 35 Hz where also the first sound radiation peak is. A possible explanation for this is that the actual state that radiates most when closing the door is somewhere between the open and closed states. The fact that the frequency of the door modes in closed state are a bit different than the radiated sound can also be caused by the excitation forces and the fact that the modal resonance is quite broad in frequency. This means that an exciting force with much frequency content close to (not necessarily exactly at) 35 Hz can cause considerable vibration levels and consequently radiate much sound. Both the Volvo and the Audi seems the have a mode around 50-60 Hz but only the Volvo can be seen to radiate at these frequencies. An explanation for this can be found in section 5.6. Generally, the Audi mobility and the Volvo mobility are rather similar.



(a) Door closed, excited in lower rear corner of Volvo door

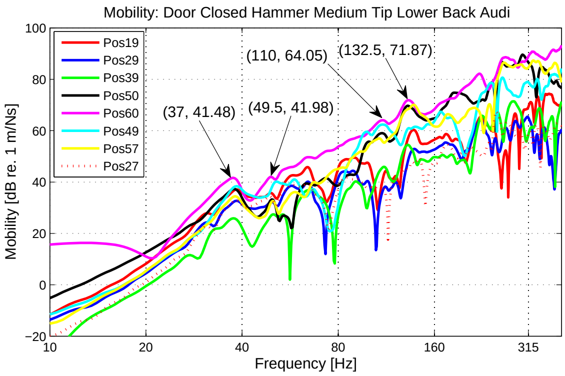


(b) Door closed, excited in lower front corner of Volvo door

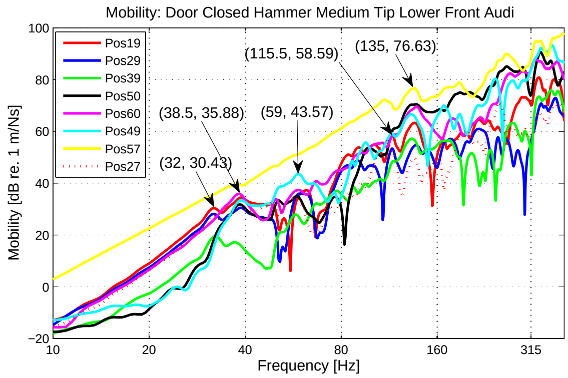


(c) Door closed, excited in upper rear corner of Volvo door

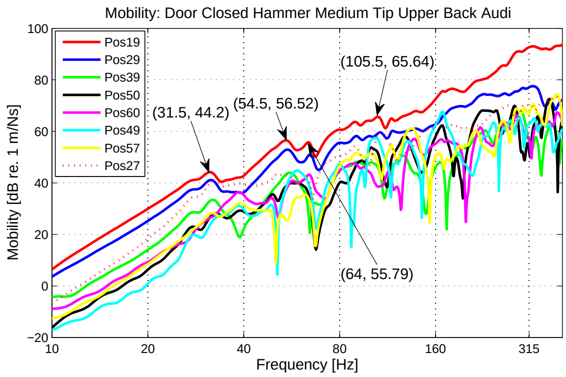
Fig. 5.6: Mobilities of closed Volvo door



(a) Door closed, excited in lower rear corner of Audi door

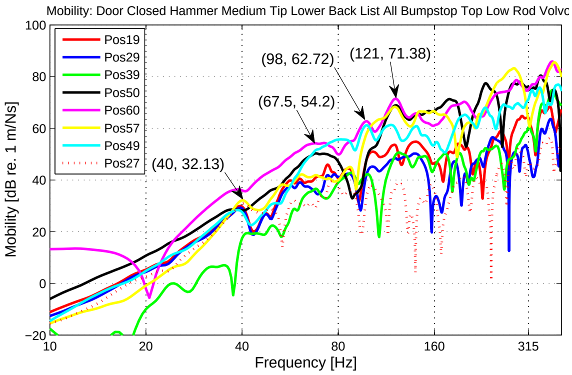


(b) Door closed, excited in lower front corner of Audi door

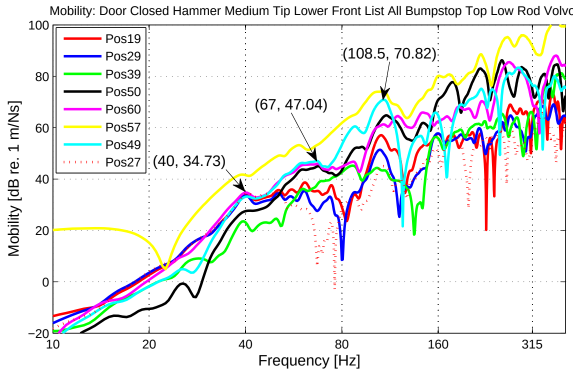


(c) Door closed, excited in upper rear corner of Audi door

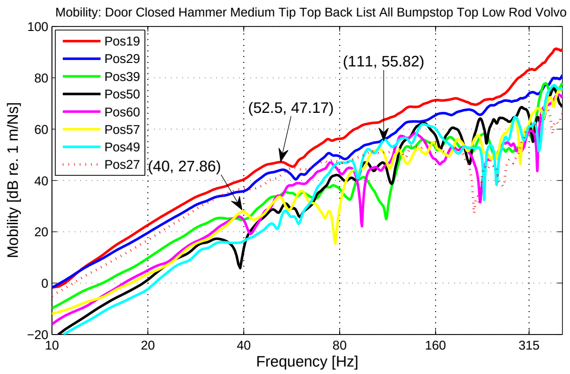
Fig. 5.7: Mobilities of closed Audi door



(a) Door closed, excited in lower rear corner of the sealing and bump stop modified Volvo door



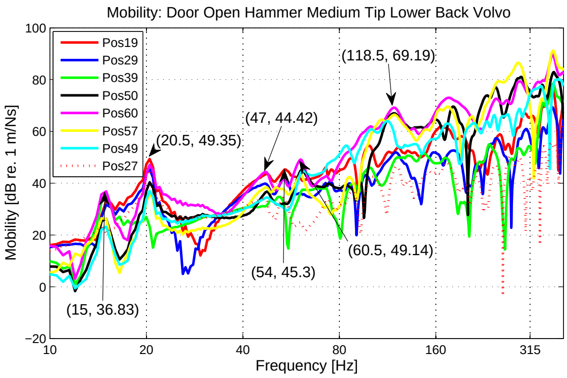
(b) Door closed, excited in lower front corner of the sealing and bump stop modified Volvo door



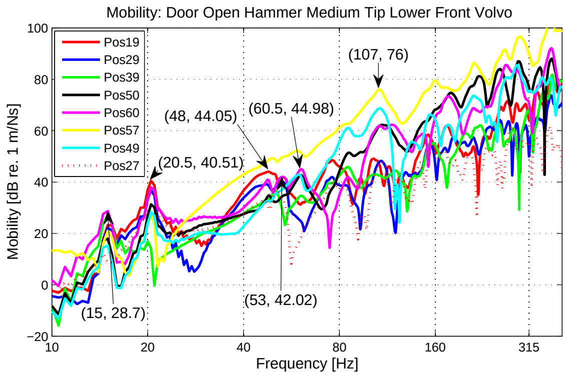
(c) Door closed, excited in upper rear corner of the sealing and bump stop modified Volvo door

Fig. 5.8: Mobilities of closed Volvo door with rod and bump stops attached

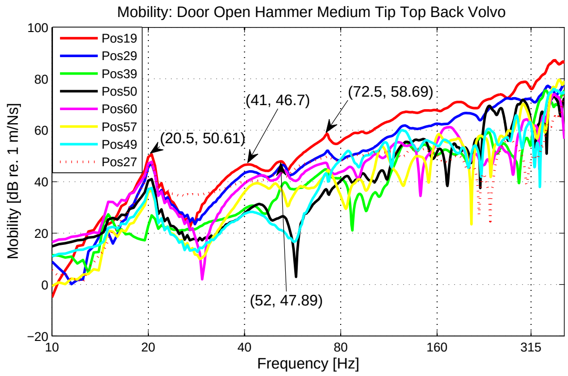
The mobility for the door in opened position is shown in figures 5.9 and 5.10. The first resonance increases in frequency for both cars when closing which might influence and result in the shift in frequency that occurs during the closing sequence.



(a) Door open, excited in lower rear corner of Volvo door

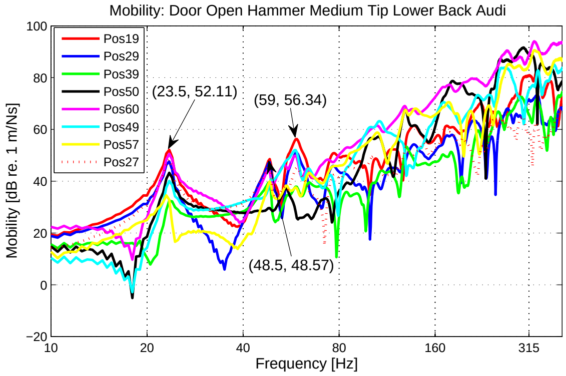


(b) Door open, excited in lower front corner of Volvo door

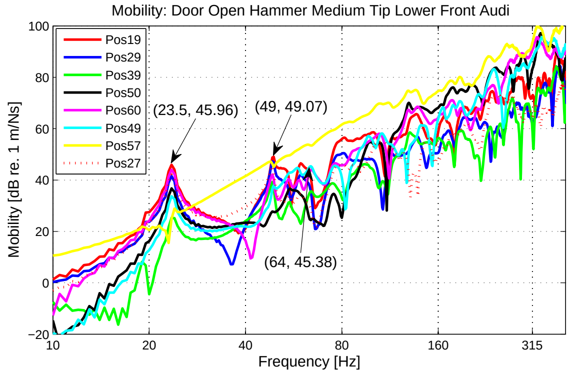


(c) Door open, excited in upper rear corner of Volvo door

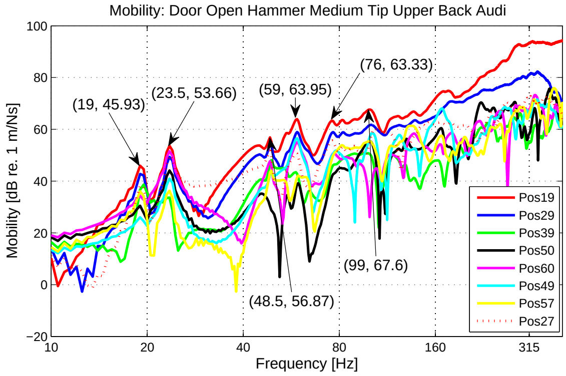
Fig. 5.9: Mobilities of open Volvo door



(a) Door open, excited in lower rear corner of Audi door



(b) Door open, excited in lower front corner of Audi door



(c) Door open, excited in upper rear corner of Audi door

Fig. 5.10: Mobilities of open Audi door

5.5 Latch stiffness

5.5.1 Method

Because of the unavailability of a method to excite inside the latch, an attachment was used to measure the stiffness of the material surrounding the lock device. This attachment is shown in figure 5.11 and consists of a metal piece to which an accelerometer can be mounted and force can be applied with an impact hammer. These measurements were done for Volvo and Audi to compare the stiffness between them. Unfortunately, no modifications could be done to change the character inside the latch.

Fig. 5.11: Attachment in the latch at the Audi car

5.5.2 Results and discussion

The graphs in figure 5.12 show the results from the latch measurements. Although it might be hard to draw any solid conclusions from these results it seems like higher stiffness in this measurement correlates to radiated sound at some frequencies. The Audi has a little peak around 35 Hz in radiated sound and a big peak in this stiffness. The Volvo lacks a peak in sound at this frequency and also a peak in the stiffness. Similarly, the Volvo has a peak around 50 Hz here and in the radiated sound which the Audi lacks. The measurement method was not optimal since it was not possible to excite inside the latch. The fact that the door has to be open gives a bit misleading results if the door is somewhere between open and closed state when it is actually radiating sound in the event of a door closing. As an evaluation of this method it can be concluded that some peaks seen from this measurement can be correlated with radiated sound but there will also be an influence of the modal behavior from the door in open state. The coherence was not very good at some frequencies so these results should not be taken too seriously.

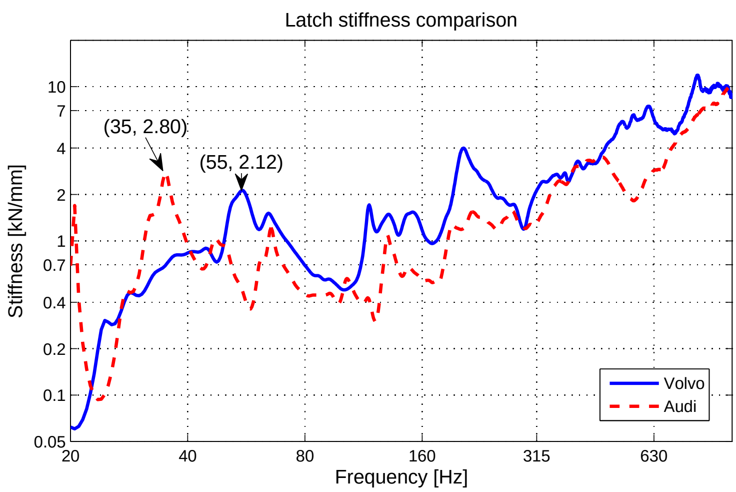


Fig. 5.12: The stiffness in the y-direction measured in the latch of the Volvo V60 and Audi A4

5.6 Force interaction between striker and latch

5.6.1 Method

An uniaxial accelerometer could be mounted near the striker and have it remain there undamaged while closing the door, see figure 5.13. On the Audi, the accelerometer could be placed on the innermost rod of the striker. This was not possible on the Volvo so it was placed on the body right behind the striker. This gives the opportunity to measure acceleration at the striker when the door is closed. It is also possible to measure a transfer function from impact hammer on the outermost rod of the striker where the latch attaches to this accelerometer. By combining these two measurements it is possible to calculate the force interaction between striker and latch in a door closing event. The transfer function can be calculated either in frequency domain or time domain using different methods. The frequency domain approach gives the average spectra for the whole time event while a time approach would be able to give a force signal in time domain as if it was measured by a force meter. The time domain approach is more complex and for the purpose of just comparing the Volvo and Audi, the frequency domain approach should be sufficient and is therefore used.
Unfortunately, no modifications could be done to change the character inside the latch to see how this would change the force and radiated sound.

(a) Accelerometer near the striker at Volvo (b) Accelerometer near the striker at Audi

Fig. 5.13: Accelerometer attached near the striker at door closing and hammer excitation

5.6.2 Results and discussion

Figure 5.14 shows the force insertion on the striker when the front door is closed at regular speed (0.95-1.05 m/s). It can be seen that the excitation force is around 28 dB higher on the Volvo at the peak around 50 Hz. This supports the idea that the striker and latch interaction is responsible for the peaks around 50 and 63 Hz in the radiated sound from the Volvo which is not present for the Audi. Both the Volvo and Audi has excitation peaks around 30 Hz but the Volvo has more amplitude.

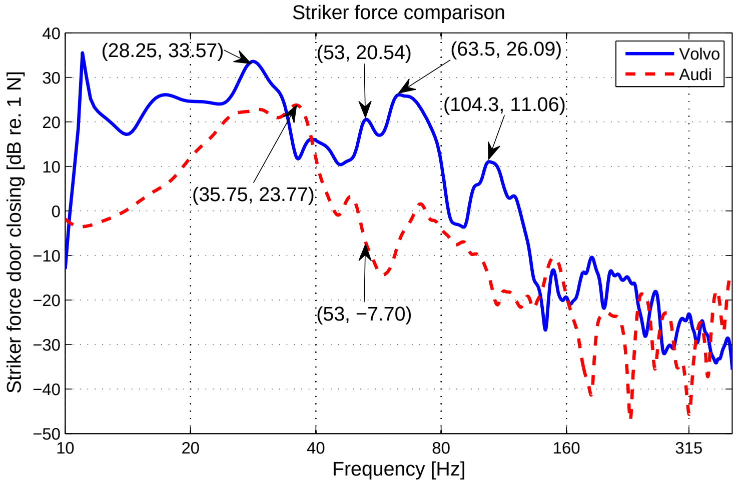


Fig. 5.14: A-weighted comparison of force insertion on the striker when door is closed

Chapter 6

Discussion summary

The results are summarized by focusing on each important peak i.e. the peaks at 28, 50, 63 and 109 Hz.

6.1 28 Hz

The first large frequency peak for the Volvo was present at around 26-30 Hz. This is also the case for the Audi car. The ODS in figure 4.11 for this frequency showed that the significant part of the vibrations are located in the doors for both cars. The main difference between the Volvo and Audi is that the Audi has a more uniform vibration pattern over the whole front door and a big part of the rear door while the Volvo has the vibrations focused in the lower, rear corner of the front door and the rear door moves out of phase with the front door. The radiation efficiency is likely higher on the Audi because of this fact. This is also indicated by the fact that the force interaction between striker and latch is higher for the Volvo than the Audi (see figure 5.14) but the radiation is about the same, which means that the Volvo needs more excitation to have the same sound levels.

Measurements done with the doors on the other side open decreased the air spring that usually damps the force transmitted to the car during closing. This setting therefore let a larger part of the excitation energy in the moving door actually reach the car body without being damped and consequently the amplitude of the peaks increased. Similar results would be expected also when having the other door on the same side open and the windows open. However, measurements done with the windows open showed a clear reduction in the 28 Hz peak (figure 4.17) but no change in the others. This indicates that this peak is strongly correlated to the door's modal behavior. It would therefore be interesting to see if there was a resonance in the door at this frequency that could explain the strong peak. Transfer function measurements were done in the door in both open and closed position, chapter 5.4. It showed a peak in mobility at around 20 Hz in an open position and at 36 Hz for the closed. This does not coincide with the major sound radiation peak at 28 Hz. One explanation is that the radiation takes place in a state somewhere between closed and open states. Another explanation is that the state is probably very similar to closed state but since the peak is quite broad, a strong excitation at 28 Hz could still lead to a peak in the radiated sound. The Audi speaks for the first explanation and the Volvo for the second. The Audi has quite an even striker/latch force interaction between 26 and 36 Hz but still a big peak around 28 Hz. The Volvo on the other hand has an extra high peak in the striker/latch force interaction.

6.2 50 Hz

The 50 Hz peak in the sound radiation from the Volvo was much lower for the Audi. Measurements in different speeds made for the Volvo showed a large difference in the relation between the 30 Hz peak and the 50 Hz peak at closing with low speed and regular speed (figure 4.8 and 4.7). For the regular speed the 50 Hz peak was 4 dB higher than the 30 Hz peak while for the low speed it was the other way around. When closing with low speed the energy is just enough to close the door and the sealing around the door is probably able to damp the door completely, which gives less excitation between striker and latch. Modifications were done to the striker where this was moved between its inner and outer positions. It was not possible to move the striker much why no large difference was seen. The notable difference was that the amplitude of the 50 Hz peak was slightly increased for the outer position of the striker which indicates that more force was inserted on the striker here, giving a stronger excitation at this frequency (figure 4.20). A reason to the lack of radiation for the Audi could be a better damping inside the latch so that the exciting force has it's frequency content more focused on the lowest frequencies. This was also confirmed by the striker and latch force interaction. This force is much lower for the Audi than for the Volvo, see figure 5.14.

6.3 63 Hz

The 63 Hz peak can be explained by the same figure as just mentioned, much force were acting between the striker and latch at this frequency. It can also be seen in the measurements done to find the resonance frequencies in section 5.4, that there is a peak in mobility for 63 Hz. The modifications done with more damping around the sealing change the boundary conditions for a mode shape. The modification increased the amplitude of the lower frequency peaks except for the 63 Hz peak as can be seen in figure 4.24. This was instead strongly decreased which should mean that the 63 Hz peak also is correlated to the modal behavior of the door.

6.4 109 Hz

The last peak that has been investigated is the 109 Hz peak. Looking at the ODS for this frequency (figure 4.16) one can see a strong movement in the top side. The top side was covered by sandbags to greatly reduce this motion. As can be seen in in figure 4.15d, the amplitude is reduced by about 12 dB when the whole top side is covered by sandbags.

Chapter 7

Conclusion

Combining the discussion in sections 4.2, 4.4, 4.6, 5.4 and 5.6 regarding ODS analysis, difference between open and closed windows and doors, sealing modifications, resonance frequencies in the door and force interaction between striker and latch the following conclusions can be drawn. The first peak in the radiated sound spectra at 28 Hz is mostly dependent on the modal behavior of the doors and secondly the force excitation between the striker and latch. Furthermore, the modal properties at 50 and 63 Hz are similar for both cars and seems to come mostly from the doors but the excitation force coming from the striker/latch interaction is much higher for the Volvo. This concludes that the striker/latch force interaction is mainly responsible for the high amplitudes of these peaks in the Volvo's door closing sound. This could be further verified if it is possible to mount a striker and latch from an Audi on a Volvo and see if the sound changes consequently. From the results regarding door resonance frequencies and sealing modifications, it can be concluded that the 63 Hz peak is affected by the modal properties in the door to a greater extent than the 50 Hz peak.

Conclusions about the final major peak at 109 Hz in the sound radiation that differed from the Audi in the frequency range of interest can be drawn from sections 4.3 and 5.6 about placing sandbags on the roof and striker excitation. It can be concluded that the Volvo has a modal behavior at this frequency in the roof, which could not be seen in the Audi. The striker excitation at this frequency also shows a much higher excitation for the Volvo than the Audi.

The results in section 4.6 and 5.4 shows that changing the parameters of the door rim sealings and adding bump stops can change the resonances of the door in closed state which also introduces new peaks in the radiated sound. Furthermore, changing the sealings can be used to tune the amplitude as adding more damping material to the sealings increases the radiation at low frequencies and although it could not be verified here, it also should lower the excitation of higher frequencies. Future investigations could reveal the influence of material properties of the material added to the sealing and the effect when both doors have a modified sealing since this was only done for the front door.

Increasing the B-pillar and striker stiffness by placing a rod between the B-pillars presented in section 4.7 gave very small differences in the radiated sound for this car. This might just as well be attributed to the error range of the measurements.

Based on the conclusions above, the suggestion for future work on the quest for a better door closing sound quality is to focus on the door rim seal and the interaction between striker and latch. It is believed that with a better door rim seal, there will be more wanted excitation at low frequencies and more damping for higher frequencies. A bump stop may be included in the striker and latch design to further move excitation from high to low frequencies. One should also strive for making the doors move more uniformly at 28 Hz to increase the radiation efficiency.

Chapter 8

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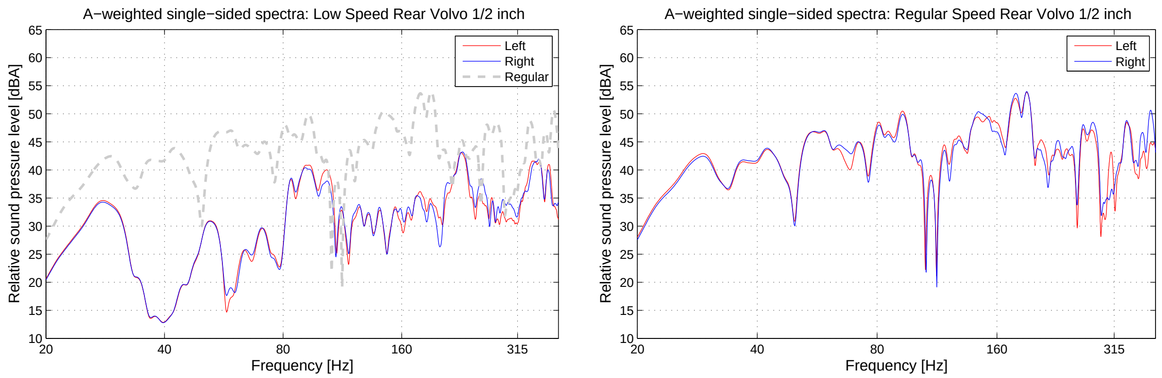
Appendix A

Results for rear doors

A.1 Different closing speeds

Radiation for closing at different speeds, low and regular with the rear door of the Volvo. Fast speed was not done for Volvo because of a too hard closing, resulting in accelerometer overload.

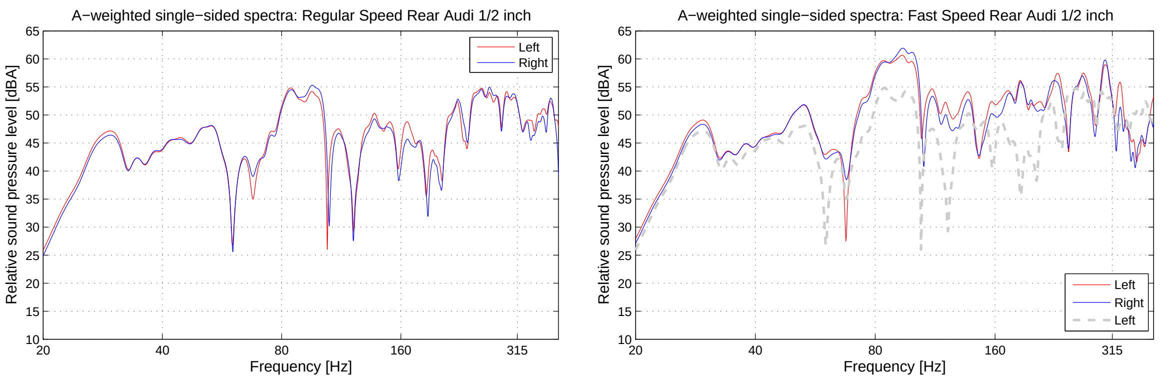


(a) Closing the door with a low speed (0.55-0.60 m/s)

(b) Closing the door with a regular speed (0.95-1.05 m/s)

Fig. A.1: Volvo car closing for low and regular speed

Because of the Audi door's large closing resistance the low speed could not be used.



(a) Audi car closing the door with regular speed (0.95-1-05 m/s)

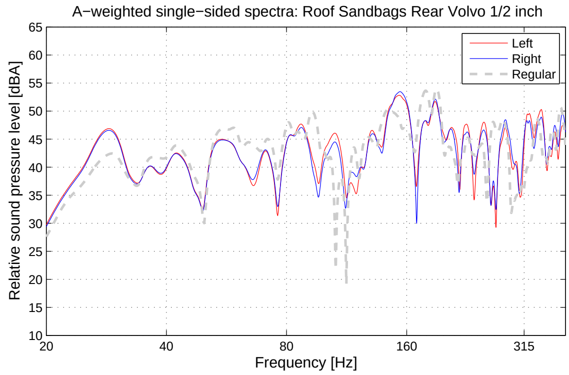
(b) Audi car closing the door with a fast speed (1.45-1.55 m/s)

Fig. A.2: Audi car closing for low and regular speed

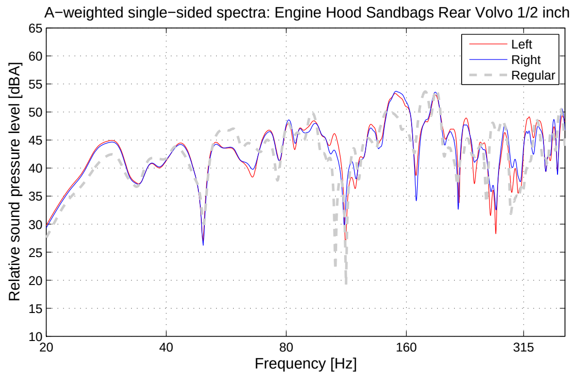
A.2 Influence of the top side

In figure A.3the rear door results from the modification done with sandbags on the top side of the Volvo are presented.

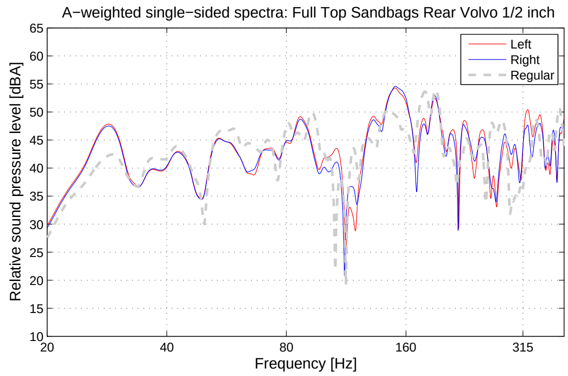
(a) Volvo car having sandbags on the windshield



(b) Volvo car having sandbags on the roof



(c) Volvo car having sandbags on the engine hood

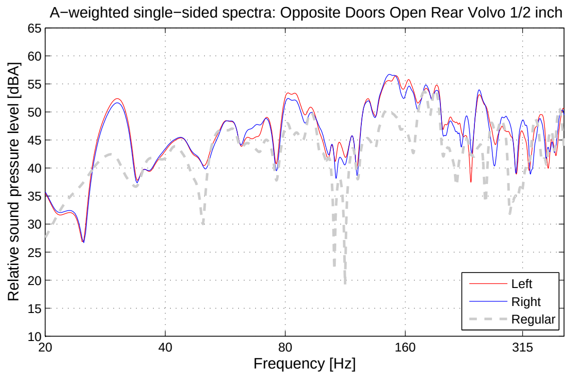


(d) Volvo car having full top covered with sandbags

Fig. A.3: Different sandbag settings at the top side of the Volvo car

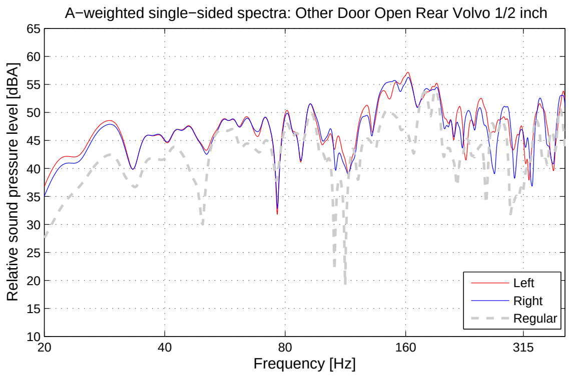
A.3 Other doors and windows open

Results seen in figure A.4are from the closing of the rear door when having the doors on the passenger's side open, the front door on the driver's side open and the windows on both windows at the driver's side.



(a) Measurements done while having the opposite doors open for Volvo

(b) Measurements done while having the opposite doors open for Audi



(c) The front door on the same side open for Volvo

(d) The front door on the same side open for Audi

(e) Measurements done having the windows on the same side open for Volvo

(f) Measurements done having the windows on the same side open for Audi

Fig. A.4: Measurements done having other doors and windows open while closing

A.4 Striker position

As the front striker, the rear door striker was moved between its inner and outer positions to see the change in sound radiation. Because of small differences between innermost and regular position, the regular position was measured and the results can be seen in figure A.3below.

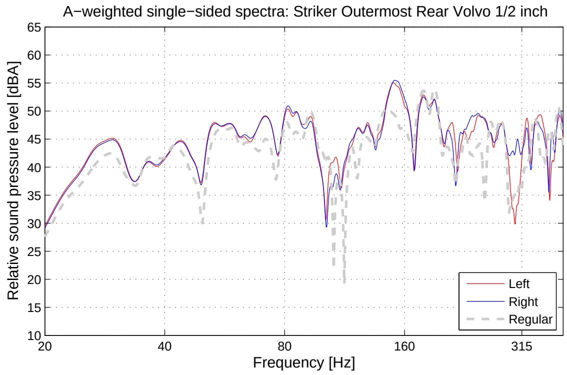


Fig. A.5: Striker in outermost positions

Appendix B

Equipment serial numbers

Accelerometers

The one-axial accelerometers are of model: B&K Type 4507B. The serial numbers of the one axial accelerometers used in the measurements are shown in the table B.1 below.

10002	10875	30394	30618	30627	2195936	2307505	2307538
10003	10899	30395	30619	30628	2195937	2307506	2307539
10004	10901	30550	30620	30629	2203551	2307507	2307547
10005	10903	30553	30621	30847	2203552	2307510	2307548
10864	10904	30614	30622	30848	2203558	2307511	2307553
10867	30273	30615	30623	30849	2203721	2307512	2307554
10868	30276	30616	30625	30855	2203722	2307513	2318782
10873	30278	30617	30626	30857	2203723	2307514	

Tab. B.1: Serial numbers for one-axial accelerometers.

The tri-axial accelerometers are of model: B&K Type 4506B. Their serial numbers are shown in table B.2 below.

10824	10830	10924	30160	30192	30411	30552
10828	10832	30061	30162	30359	30551	

Tab. B.2: Serial numbers for tri-axial accelerometers.

The accelerometer calibrator is of model: B&K Type 4294 with serial number 2571058.

Microphones

The 1/2 inch microphones are of model: B&K Type 4189-A-021 with serial numbers: 2468177 and 20439943. The microphone calibrator is of model: B&K Type 4231 with serial number 2466067.