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Optimization of engine noise reduction measurement procedure

Master's thesis in Sound and Vibration

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Department of Architecture and Civil Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2019

Master's thesis ACEX30-19-93

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Cover: Volume source, prototype microphones and car in the semi anechoic room.

Typeset in LaTeX
Gothenburg, Sweden 2019

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Abstract

A comfortable and quiet environment in the car cabin is a key component for the driving experience and safety. The noise generated in the cabin, from the engine compartment, can be transmitted both via air-borne or structure-borne paths. The engine noise reduction measurement technique (ENR), takes into consideration only the airborne sound.

The measurement technique is used before and after placing absorbers in the engine compartment to compare the different transmitted levels. Therefore, it is fundamental to understand if the difference in the two results is due to the actual absorbers or because of the uncertainties in the measurement procedure.

This Master thesis focuses on the robustness and precision of the method within the frequency range for internal combustion engines and Electric battery vehicles. The available equipment and a new prototype of rugged pressure microphones from G.R.A.S Sound and Vibration have been used.

The smallest possible error within the method has been found to be equal to 1 dB and therefore also the precision of the method. The robustness of the method for Combustion engine vehicle and Electric vehicle has been investigated and a safe frequency range has been found to be from 400 Hz to 8 kHz. In addition, an optimized number of microphones and their optimal location has been recommended.

According to the data and the analysis, the method can be considered robust within the safe frequency range. The procedure has also been improved, weighting less the positions of the volume source, close to the windows, in the car compartment.

Keywords: Reciprocical measurement, rugged pressure microphones, measurement optimization, robustness, deviation, Error

Acknowledgements

Thanks to the people at the Applied Acoustics department at Chalmers, to my supervisors Patrik Höstmad, Christian Fransson, Fredrik Bartholdsson, Thomas Englund and the NVH department at Volvo Cars. Thanks to all my classmates for these wonderful 2 years.

Federico Nicastro, Gothenburg, 2019

Contents

List of Figures

List of Tables

1

Introduction

1.1 Background

The noise generated in the cabin, from the engine compartment, can be transmitted both via airborne or structure-borne paths. The engine noise reduction measurement (ENR) procedure, deals only with the airborne sound. The measurement technique is used before and after placing absorbers in the engine compartment in order to study how the absorbers affect the sound levels. Therefore, it is fundamental to understand if the difference in the two results is due to the absorber or because of the uncertainties in the measurement procedure. The previous ENR measurement technique uses 24 microphones standard cylindrical shaped microphones evenly spread in the engine bay and a volume sound source in the cabin. The Shape of those microphones does not facilitate the repeatability of the measurements, due to different positioning all the time. In fact, the microphones were attached using tape, and therefore difficult to always place them in the same position. In addition, an optimal number of microphones and their location in the engine bay is necessary to have a more robust method. Therefore new easy to mount microphones have been used to tackle this problem. The method has to be robust and accurate regardless of the type of engine, internal combustion engine or electric motor, and the engineer who is performing the measurements. Due to the nature of the reciprocal measurement, also the positioning of the volume sound source in the cabin is important for the precision and robustness of the method.

1.2 Investigation

1.2.1 Aims

This master thesis project aims to answer the following questions:

- May the accuracy and robustness of the method be improved? If affirmative, How?
- What is the expected precision in the results? Is the measurement method considered robust with this precision?
- How can the measurement chain be improved? What is a good choice of sensors/microphones/sound source? What is an optimized number of those and their optimal location?

1.2.2 Limitations

The main limitation has been the available equipment. During the measurements only seven prototype microphones were available, and additionally, the car and the semi-anechoic room were available for a limited amount of time.

1.2.3 Collaboration

This master thesis has been carried out in collaboration with Volvo Car Corporation.

1.3 Motivation of this work

It is fundamental to trust the results when using the ENR measurement technique. The method has to be clear, easy to repeat and well defined in order to have robust results. Therefore in this master thesis, an analysis of the robustness of the method has been done. In addition, a global understanding of the acoustics inside the engine bay can be gained.

1.4 Thesis Outline

This is a guide to understand the structure of the following text.

In the **Theory** section, the necessary knowledge to understand the further results is reported. Basic knowledge in acoustics and details about the third octave bands calculation are given. In addition, the acoustics in the engine bay and the different sound sources in the engine are analyzed.

In the **Implementation** section, the measurement procedure and the three sets of measurements are explained. The first set of measurements was about the investigation of the volume source and the second about positioning microphones in different areas in the engine bay. In the third set of measurements, different types of microphones have been tested inside the engine bay.

In the **Results and Discussion** all results are shown with the related discussion and thoughts of the author attached. The author prefers to give a combined section results and discussion in order to avoid the tiring process of reading the comments and going back to the pictures in the results section.

In the **Conclusion** the knowledge gained from the work is given and consequently conclusions and recommendations.

2

Theory

This chapter is an overview of the theoretical background and the basic principles necessary for an understanding of the approached problem in this master thesis.

2.1 Acoustics

2.1.1 Sound pressure Level

[1] Sound $p(t)$ is a pressure fluctuations around the static pressure p_0 :

$$P_{tot}(t) = p_0 + p(t) \tag{2.1}$$

where $p_0 \approx 101.3$ kPa is the mean sea-level atmospheric pressure on Earth. From the pressure values in time, the Root mean square $\tilde{p}$ value of the time signal can be calculated according to the following:

$$\tilde{p} = \sqrt{\frac{1}{T}\int_0^T p^2(t)dt} \tag{2.2}$$

where T is the length of the signal in time. The pressure is more favorable to express in Sound pressure levels using the decibel, dB:

$$L_p = 10\log\left(\frac{\tilde{p}^2}{p_{ref}^2}\right) = 20\log\left(\frac{\tilde{p}}{p_{ref}}\right) \tag{2.3}$$

where $p_{ref} = 2 \times 10^{-5}$ Pa is the treshold of human hearing.

2.1.2 Third octave bands

Suitable standards are required for spectrum analysis systems so that satisfactorily uniform results can be obtained from any analyzer that meets the standard for its Type [2].

The energy of the frequency components of a spectrum is summed up in frequency bands. Octave and third octave bands are widely used. Third octave bands have proportional bandwidth and the relation between the upper bandwidth f_u and the lower bandwidt f_l are constant:

$$\frac{f_u}{f_l} = 2^{\frac{1}{3}} \tag{2.4}$$

In addition the center frequency f_m and the relative bandwidth B/f_m can be calculated by:

$$f_m = f_l \cdot 2^{\frac{1}{6}} \tag{2.5}$$

$$\frac{B}{f_m} = \frac{f_u - f_l}{f_m} = 0.23 \tag{2.6}$$

Therefore 1/3-octave filters do not have a constant absolute bandwidth, but a constant relative bandwidth.

2.1.3 Normalized random error

[9] While measuring a random process, there is always an uncertainty in the estimation. The random error estimation is given by:

$$\epsilon_r = \frac{1}{\sqrt{(BT)}} \tag{2.7}$$

where B is the bandwidth at that particular frequency and T is the measurement time. Therefore, the error can only be reduced either by increasing the bandwidth or the measurement time. For smaller bandwidth B, longer measurement time is needed. In this case, using third octave bands, the bandwidth at lower frequencies are smaller compared to higher frequencies, therefore a longer measurement time is needed as shown in figure 2.1:

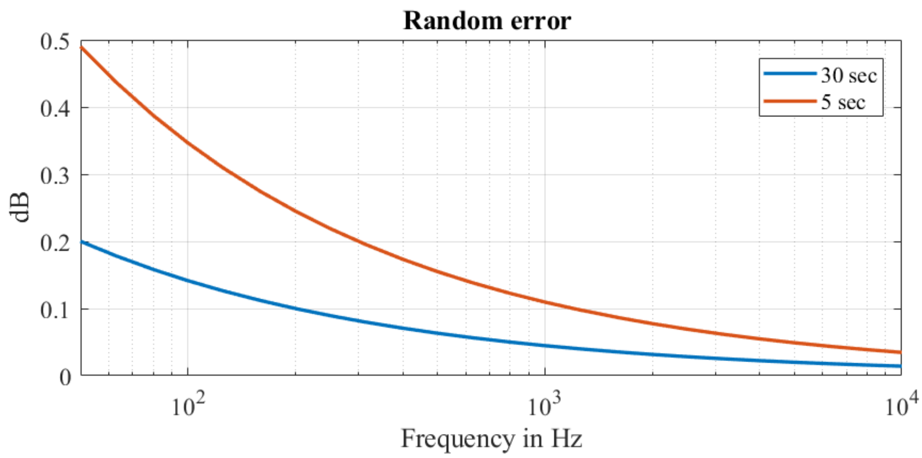

Figure 2.1: Random error dB estimation

Therefore, measuring for 30 sec at 100 Hz a random error of plus or minus 0.15 dB is present.

2.2 Microphones

A microphone, sometimes abbreviated mic, is a transducer that converts sound pressure fluctuations into an electrical signal. Therefore fluctuation of air particle.

2.2.1 Pressure microphones

A pressure microphone works using a diaphragm between a fixed internal volume of air and the external environment. It has a response that is uniform to pressure from all directions, so it has an omnidirectional behavior, therefore the orientation of the microphone is not important. This type of microphone measures the actual sound pressure on the surface of the microphone's diaphragm. It can be used in a cavity or an enclosure that is small when compared to the wavelength. The microphones can be used on a surface of a wall, inside structures like housings, tubes or cavities in general.

2.3 Measurement Technique

2.3.1 Reciprocal measurements

A reciprocal measurement is a particular measurement where the excitation source is interchangeable with the receiver. As explained in Figure 2.2, it is equivalent to measure the sound pressure in the left and right scenario.

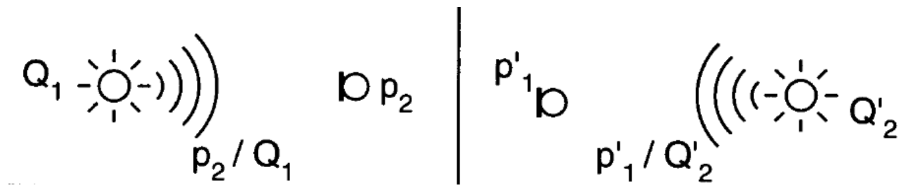

Figure 2.2: Reciprocity scheme[7]

The governing equation, according to the notation of Figure 2.2, that defines the acoustic reciprocity is the following one:

$$\left.\frac{p_2}{Q_1}\right|_{\vec{Q'_2}=0} = \left.\frac{p'_1}{Q'_2}\right|_{\vec{Q_1}=0} \tag{2.8}$$

The application of reciprocity is usually possible in all stable, lumped linear, passive, dynamical systems which only contain bilateral elements (for example masses, stiffnesses). Linearity intend that the system follow additivity and homogeneity, this is therefore fulfilled in a vehicle since the sound propagation is linear up 134 dB A fundamental cause of non-reciprocity is flow due to wind and turbulence which makes the system non-reciprocal [8]. According to Andreas Schuhmacher [13], the procedure of interchanging the microphone with the volume source is possible when both of them have the same directivity. In addition, the volume velocity has to meet specific requirements:

- Source should produce a sufficiently high sound level
- Omnidirectionality
- Frequency range covered should be appropriate
- Source should behave as a monopole in the frequency range of interest
- Output volume velocity should be measurable even when the acoustic environment changes

2.3.2 Engine noise reduction

The engine noise reduction (ENR) is a measurement technique, used by Volvo Cars in order to quickly assess the noise reduction of the dash between the engine bay and the cabin compartment. It is used when new absorbers are placed inside the engine bay to verify the new noise reduction of the dividing structure.

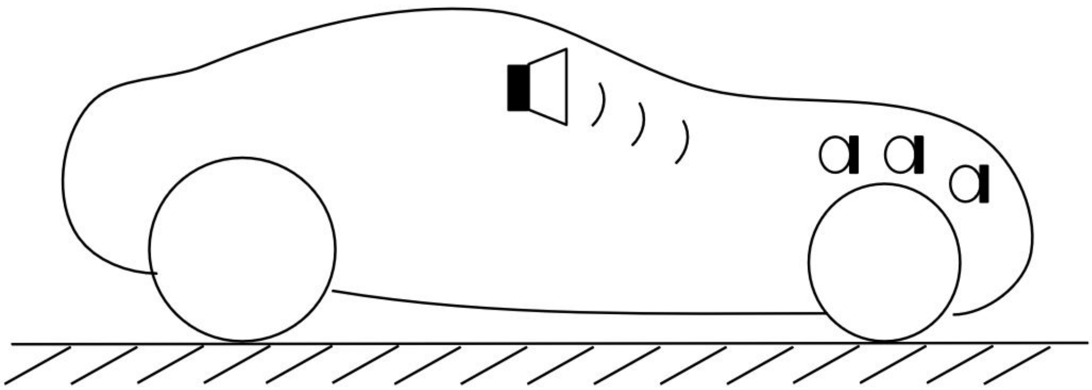

Figure 2.3: Engine noise reduction measurement Scheme

The actual final values are calculated according to the following:

$$ENR = SPL_{Source} - SPL_{Receiver} \tag{2.9}$$

Where SPL_{Source} is the calibrated sound pressure level of the sound source, While $SPL_{Receiver}$ is the averaged value between the microphones channels and as well for each sound source position calculated according to the following formula:

$$SPL = 10 \log \left(\frac{1}{N} \sum_{n=1}^{N} 10^{\frac{Lp,n}{10}} \right) \tag{2.10}$$

where N is the number of channels or the source position.

Therefore, the engine noise reduction values do not represent absolute values but are a good tool for comparing relative differences. Additionally, for this method, the influence of the space where the sound source is placed is affecting the results but it is not a problem to have it embedded in the results. For example, different materials in the inside of the car can affect the measurements but the engine noise reduction value is going to be related for that specific car with those specifications.

2.4 Acoustics in the Engine bay

In this section, a brief explanation of the acoustics of the engine bay is illustrated. Then all the main kind of noise sources present in the engine bay are considered as shown in figure 2.4

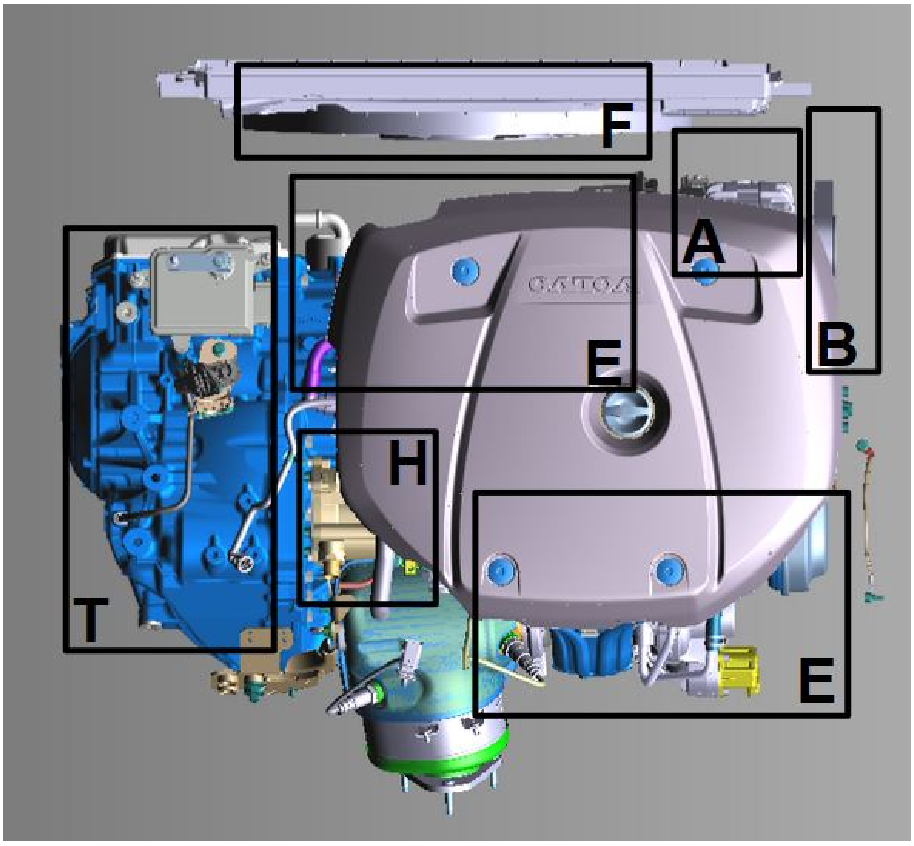

Figure 2.4: Main Sound sources : A-Alternator, B-Belt, F-Fan, H-High pressure fuel pump, T-Transmission box, E-Engine

2.4.0.1 Structure

The engine bay can be approximated as a partially open enclosure densely filled with different components made of different materials. It is partially opened in the bottom part covered close to the undertray. In the engine compartment there are several noise sources that radiates sound in the surrounding spaces with different frequency contents [3]. Prager and Petersson suggested that the engine in the compartment may be modeled as a distribution of spheres in an enclosure, where the spheres are used to model the scattering effects of the engine.[5]. It is an important parameter the ratio between the wavelength of the acoustic phenomena and the physical dimension of the structure into consideration. The acoustical behavior of the system changes when increasing the frequency. According to Prager J. [6] the acoustical behavior of the engine bay can be described identifying different frequency regions:

- Low frequencies - Quasi static behavior
- Middle frequencies - Modal behavior
- High frequencies - Statistical behavior

At low frequencies, one octave below the first eigenmode, when the system is closed it behaves quasi-statically like a spring while when the system is open it behaves like a mass. Therefore in this frequency region there are no modal patterns. The main parameters are the stiffness of the free volumes in the engine bay and the masses formed at the openings. In the middle frequencies range the acoustical behavior is strongly dependent on the largest sub-volume eigenfrequencies. This range is recognized when the modal overlap factor is less than unity. In the high-frequency range the sound field becomes more diffuse. The latter is mostly influenced by the absorption inside the bay and the coupling with the environment.

2.4.0.2 Internal combustion engine - Diesel Engine

[10] The noise produced by a diesel engine can be identified by different noise sources:

- engine surface (surface noise) and vibrations (structure-borne noise)
- pulsations (aerodynamic noise) generated by intake, exhaust and cooling system
- Transmission of vibrations by the engine mount to the chassis or foundation

In most cases, the engine surface plays the biggest role.

2.4.0.3 Battery Electric vehicle

[12] This type of vehicles emits less noise at a lower speed. At low speed, under 50km/h, the wind and tyre/road interaction noises are not high enough to signify the presence of electric vehicles to road users. Another type of noise is emitted at higher frequencies, the component called inverter, emits tonal components at higher frequencies around 10 kHz.

2.4.0.4 Cooling Fan

In addition to the engine inside the engine compartment, the cooling fan is an additional source of noise. Most of the fan types are subject to the blade passing frequency (BPF) noise generation. [14]. This parameter indicates the approximate frequency at which the main noise is generated and it can be calculated according to 2.11:

$$BPF = \frac{N_{blades} * RPM}{60} \tag{2.11}$$

where N_{blades} is the number of blades and RPM is the revolution per minute of the fan. According to [15], the main noise contribution comes from the blade. From lower to higher frequencies, the noise changes from distributed on the blades to concentrate on the end of the blades. Moving along the circumference of the casing, local maxima of noise can be associated with the individual blade passages. These can be attributed to tip leakage flow.

2.4.0.5 Alternator

There are different causes of noise emission due to the alternator: The magnetic noise, rotor eccentricity, Aerodynamic noise, Mechanical noise sources.[16], [17]
The *Magnetic noise* is mainly produced by two phenomena: the first one is the magnetostriction, which is an infinitesimal contraction of the materials related to the frequency of excitation of the magnetic field; the second one is due to the magnetic

forces that are created in the air gap. There are consequently deformation and therefore vibration and noise. The *Mechanical noise sources* are mainly due to the noise coming from bearings. The latter produce noise due to sliding contacts and rotor unbalance. In general, the alternator produces a noise at start up when there is a high energy demand, typically at around 1000 Hz. This noise can be detectable in the passenger compartment in vehicles. [18]

2.4.0.6 Transmission Box

The transmission box, due to the rotating components present inside, is a source of vibration and therefore noise. Noise-generating mechanisms in gearboxes include gear rattle from unloaded gears, gear whine from gears under load, vibrations in bearings. [19] The term gear rattle is referred to the sound generated by the impacts between the unloaded gear mesh pairs in the transmission. It can be noticed on manual transmission vehicles and especially on diesel vehicles. The gear whine,which originates from vibrations excited mainly by transmission error, is not the loudest source but since it generates a pure tone , is easily distinguished from other noise sources and easily associated with poor quality of the product. [20]

2.4.0.7 Timing Belt

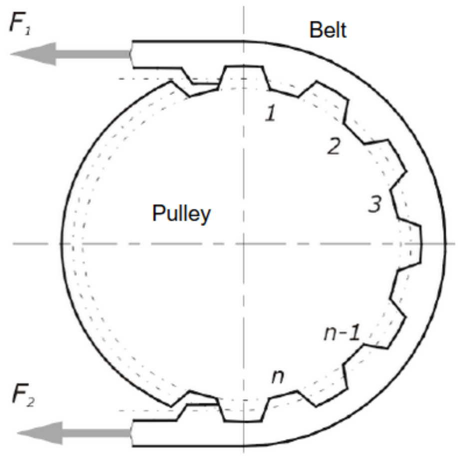

Figure 2.5: Pulley and Belt schema [11]

Timing belts are present as a component in the engine. The produced noise is low in level but it is an unpleasant noise. The noise is composed by the low frequency component occurring during the meshing and the high-frequency component. The latter occurs mainly from the friction at the beginning and end of meshing between the belt and pulley, figure 2.5 and from the flow of the air at the meshing position between them. [21]

2.5 Statistics

2.5.1 Mean and Standard Deviation

In this master thesis the mean value and standard deviation have been used according to the formulas 2.12:

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}|A_i - \mu|} \tag{2.12}$$

$$\mu = \frac{1}{N}\sum_{i=1}^{N}A_i \tag{2.13}$$

The standard deviation is useful to quantify the amount of variation of a certain set of values. A low standard deviation, means that the data values tend to be close to the mean value. A high standard deviation indicates that values are more spread over a wider range of data [23]. In addition, the standard deviation can be expressed with the same units as the data of interest.

2.6 Limitations and source of error

It is necessary to report the quality of the results in order to ease the readability of the document, without it, measurements cannot be compared and fully understood. It is well known that after all the suspected components of the error have been taken into consideration, there are still uncertainties about the correctness of the results. In many industrial and commercial applications, it is necessary to provide an interval providing a level of confidence that assure the quality of the results. [22]

3

Implementation

3.1 Measurement procedure

3.1.1 Volume sound source investigation

In this section, the Volume sound source itself and its position have been investigated. Several measurements have been performed to see the influence of the position of the volume sound source in the cabin. White noise has been delivered from the Volume sound source. The sound source has been positioned using the hose on the right and left side of the headrest in order to be in the ear position as shown in figure 3.1

Figure 3.1: Position of the volume sound source relative to the head rest

The distance of the seats from the dash and the angle of the headrest compared to the horizontal plane, have been changed and results therefore analyzed. The configurations are shown in the figures 3.2,3.3. The seats have been moved close to the dash, and far from it. The difference in space between the close and the far configuration is about 12 cm. The angle of the volume source has been changed approximately from 90 degrees (perpendicular to the ground) to 15 degrees inclined compared to the ground.

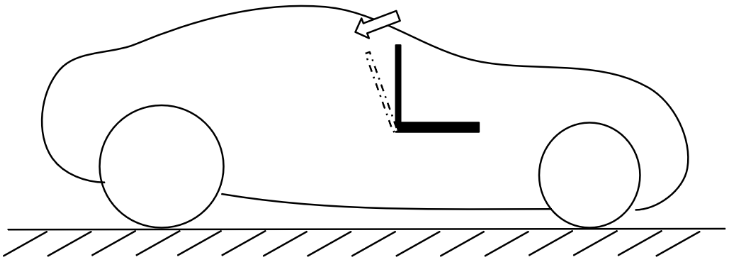

Figure 3.2: Angles 90 and 105 degrees of the seats.

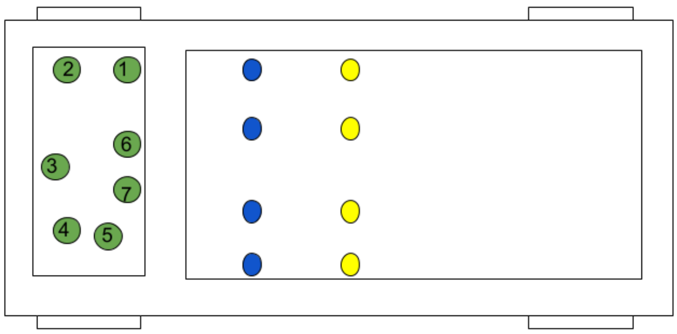

Figure 3.3: Measurements schema: left and right position compared to the head-rest, blue is the close configuration and yellow the far one. The green dots represent the microphones in the engine bay approximately with the same spatial location

Therefore a total of 16 measurements have been performed plus background noise. The measurements have been done on the right and left ear of the driver and the same for the passenger seat. The six microphones have been placed in the proximity of the engine sound sources and in the different areas of the engine bay, figure 3.4, to have an overview of the general levels in the engine bay. In addition, a reference microphone has been placed in the same position for the entire master thesis to check and compare data.

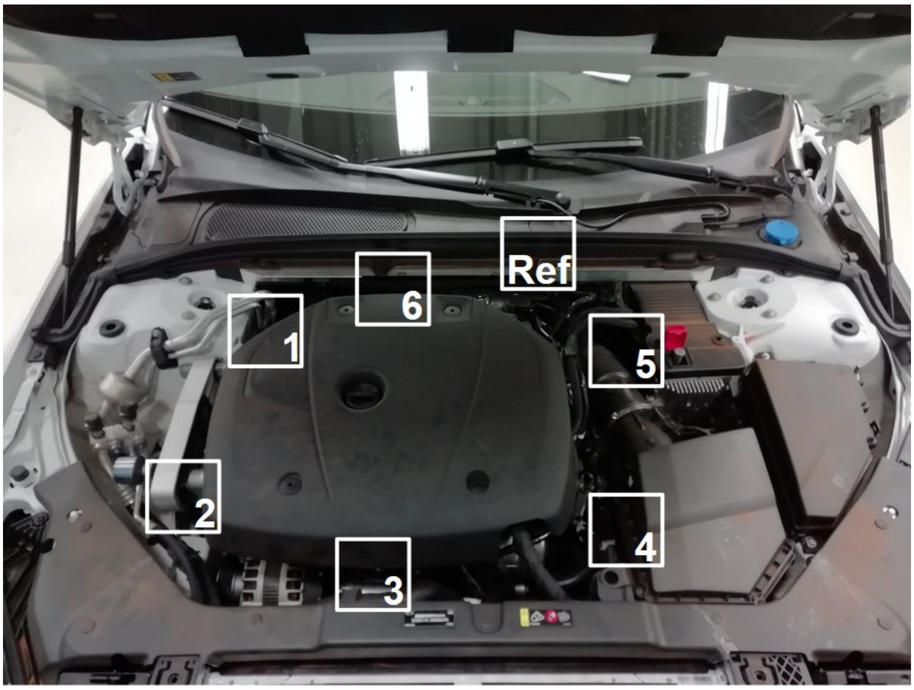

Figure 3.4: Approximately microphone positions, during the volume sound source investigation measurement

Due to the densely packed environment in the engine bay, all the sound sources are mainly contaminated by early reflections from other parts components. In the second investigation, a more thorough positioning has been done. The cooling fan has been fixed with tape in order to have a solid place for the microphone. The ideal scenario was to create a fine mesh with equally spaced microphones all over the engine bay structure but the lack of space has been definitely a limiting factor.

3.1.2 Microphones Subareas investigation

In this subsection, the engine bay has been ideally divided in 20 subareas. The name *Area* in the engine bay is referred to the right, left, back, bottom and front areas. Instead, smaller parts in the engine bay are called *Subareas*. Areas include smaller subareas. Only seven prototype microphones were available therefore six microphones have been placed for each subarea all the time. The reference microphone is in the same position as the previous investigation. The coordinate reference system has been taken from the driver prospective, therefore the left area in the engine bay is the driver's left. In the figures 3.5,3.6 the Areas are defined graphically. In the appendix, the exact picture of each subareas and each microphone's position have been reported. The engine bay has been divided in five main areas: Right,Left,Front,Back and Bottom.

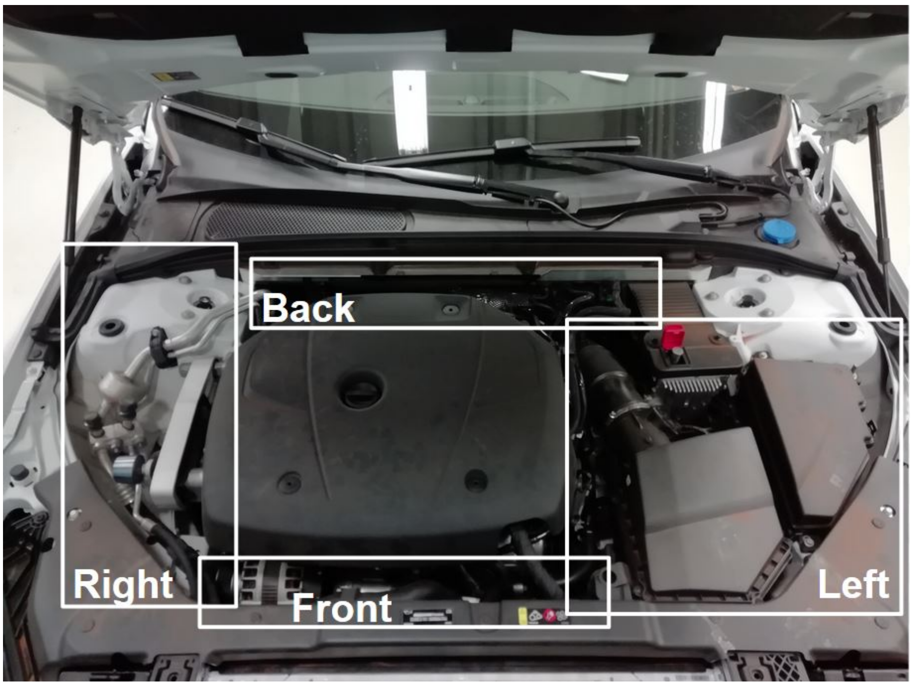

Figure 3.5: Areas visible from from the upper part of the car

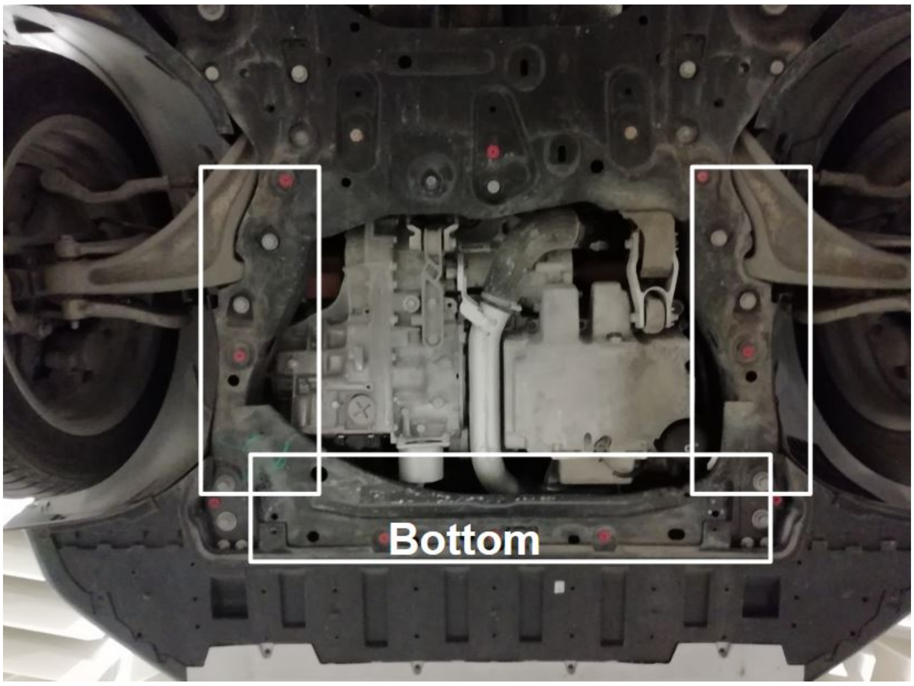

Figure 3.6: Bottom area,the undertray has been removed to take the picture and mounted again

The following figure 3.7 is an example of one subarea. In this case the microphones are placed on the body of the car next to the alternator and the timing belt.

Figure 3.7: Subarea example

During this investigation, the seats have been positioned in a central configuration and the volume sound source has been moved along the 3x4 positions according to figure 3.8 for all the subareas for a total of 12x20x7 acquired signals. More details are in the appendix.

Figure 3.8: Seat and Volume sound source positions

The following schema 3.9 shows the number associated to the volume sound source position.

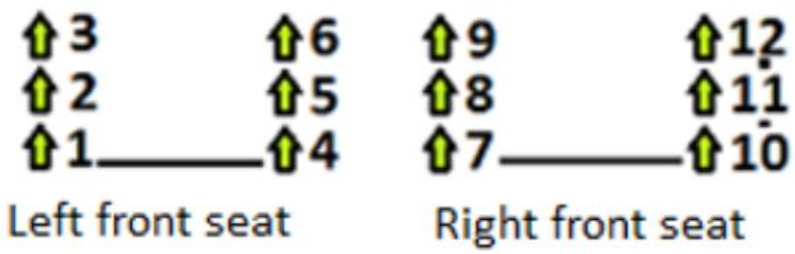

Figure 3.9: Volume sound source positions

In the Results and Discussion chapter section, six different paths have been investigated in the engine bay according to the figures 3.10,3.11,3.12. The paths from the front towards the back have been reported in red, while the paths from the left towards the right area in green.

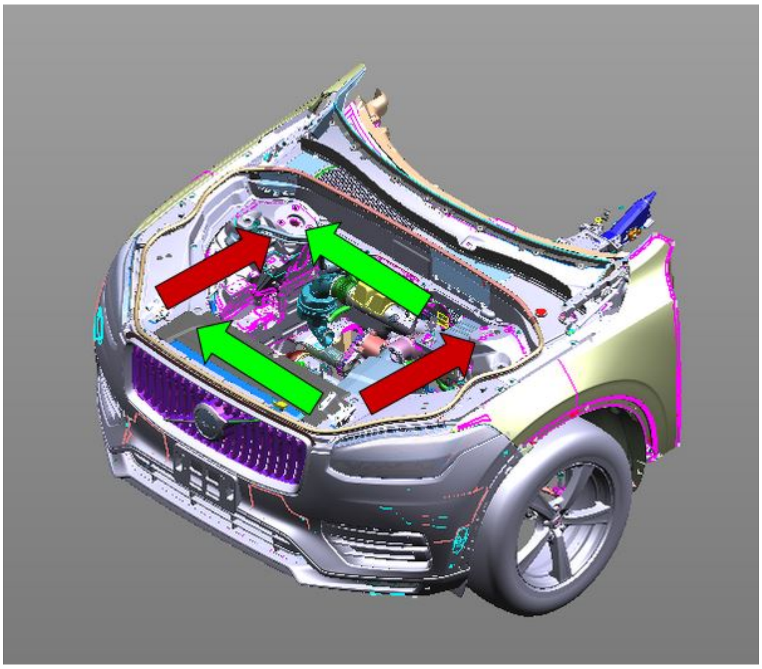

Figure 3.10: Paths : Along right side, Along left side, Along front side, Along back side

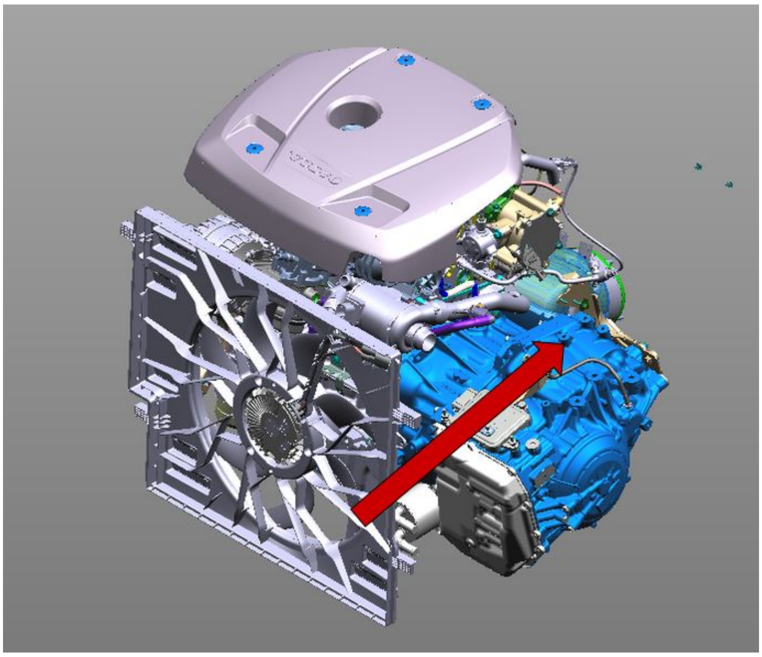

Figure 3.11: Path: Along bottom side

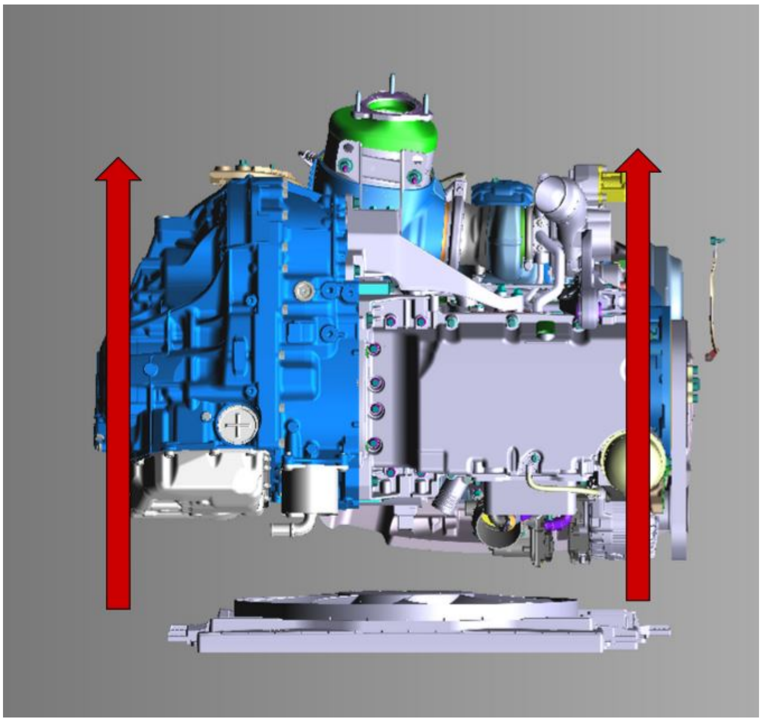

Figure 3.12: Path: Along bottom driver side, Along bottom passenger side

In this way, the levels inside different areas of the engine bay have been investigated. The bottom side paths go from the lower part of the fan then above the transmission box. To reach this point the air filter has been unmounted, the microphones placed, and the filter mounted again.

3.1.3 Different microphones investigation

In this subsection, three different types of microphones in the engine bay have been tested. One high sensitivity microphone, one low sensitivy microphone and the flat rugged mounted pressure microphone. The two configurations are the following in the figure 3.13. Only volume sound source position one has been used in this investigation.

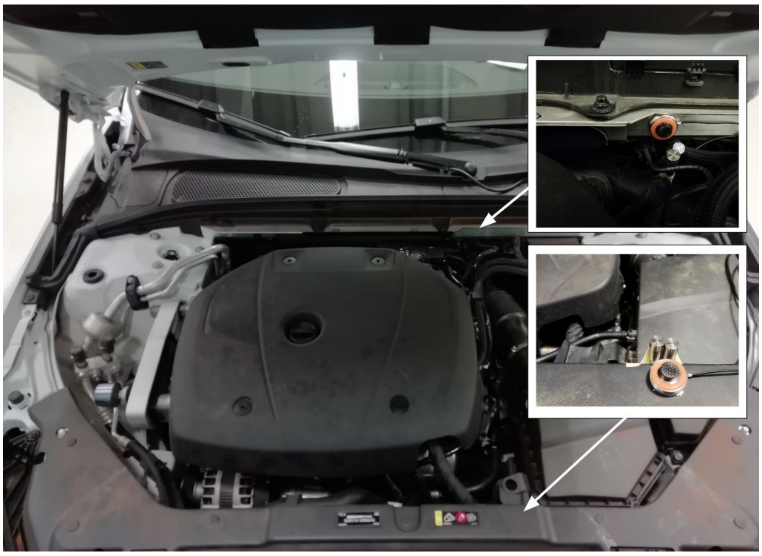

Figure 3.13: Microphone with different sensitivity in the front and back of the engine bay

3.2 Softwares, Scripts and details

The softwares Head recorder and Artemis Suite, from Head Acoustics, have been used to acquire data in time domain and export it into Matlab where they have been analyzed.
All the third octave bands plots have been calculated in MATLAB, using ANSI S1.6-1984 specifications. The functions *oct3bank3*,*oct3bank*, *oct3dsgn* from Christophe Couvreur, Faculte Polytechnique de Mons (Belgium) have been used. The filter is designed according to the Order-N specification of the ANSI S1.1-1986 standard where N has been chosen equal to 3.

In addition, the software Team center has been used to check all the different components inside the engine bay and to decide the precise location of the microphones before going to in the semi anechoic room.

Approximately 35 Gigabytes of measurements in time have been analyzed. The data have been sampled with a sampling frequency of 44.1 kHz, using a fixed time for each measurement of 30 seconds.

3.3 Equipment

3.3.1 Microphones

In this master thesis, a new rugged mounted pressure microphones from GRAS Sound Vibration, as shown in figure 3.14 have been used.

Figure 3.14: GRAS 147AX CCP Rugged Pressure Microphone (Prototype)

The sensor is composed of the actual pressure microphone which is coupled magnetically with the mounting system. The latter can be attached directly to the car body or other components in order to take track of the exact position. The main advantages of using this kind of microphone in this thesis is the increased repeatability of the measurements and the fast mounting and unmounting. In fact, when using the mounting system, it is possible to alway position the microphones in the same position in the engine bay. In addition, the microphone has a light that is turned on when it is connected. The light has been useful to immediately detect the microphone and the number of the channel in the acquisition system. The Table 3.1 illustrates the technical specifications.

Parameter	**Specification**
Frequency range	3.15 Hz to 20 kHz
Dynamic range	19 dB(A) to 133 dB
Sensitivity	35 mV/Pa
Temperature operation	-40 to +125°C

Table 3.1: GRAS 147AX CCP Rugged Pressure Microphone PROTOTYPE technical details

During the thesis, a prototype kind of microphone has been used, which has a sensitivity of 35 mV/Pa while the one on the market has a sensitivity of 45 mV/Pa. In addition, the Pressure Frequency Response function is shown in figure 3.15

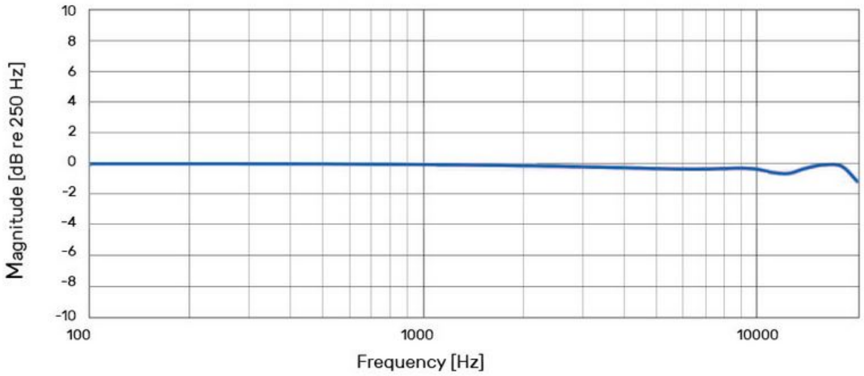

Figure 3.15: Pressure Frequency Response
http://www.gras.dk/147ax

Therefore this kind of microphone is easily mounted on the car body or other components in the engine bay and the exact position can be tracked using the mounting discs.

3.3.2 Volume sound source

A high-frequency volume sound source has been used. In particular the MKIII High-Frequency Omni-Directional Sound Source from ISVR Consulting, shown in figure 3.16

Figure 3.16: MKIII High Frequency Omni-Directional Sound Source from ISVR Consulting
https://www.isvr.co.uk/automotive/sound-sources.htm

The high-frequency sound source is made up of a horn driver unit, that is connected to an orifice via a 34 mm diameter, 3 meter long flexible hose.

Parameter	Specification
Noise Level	54 dB at 300 Hz ; >81 dB 2000-10000 Hz
Omnidirectionality	± 1 dB: < 2 000 Hz; ± 2 dB: 2 000 Hz - 6 300 Hz

In addition, the figure 3.17 shows the Directivity of the high-frequency volume sound source in one third octave bands, one meter free field sound pressure level. The sound source shows different directivity above 2.5 kHz.

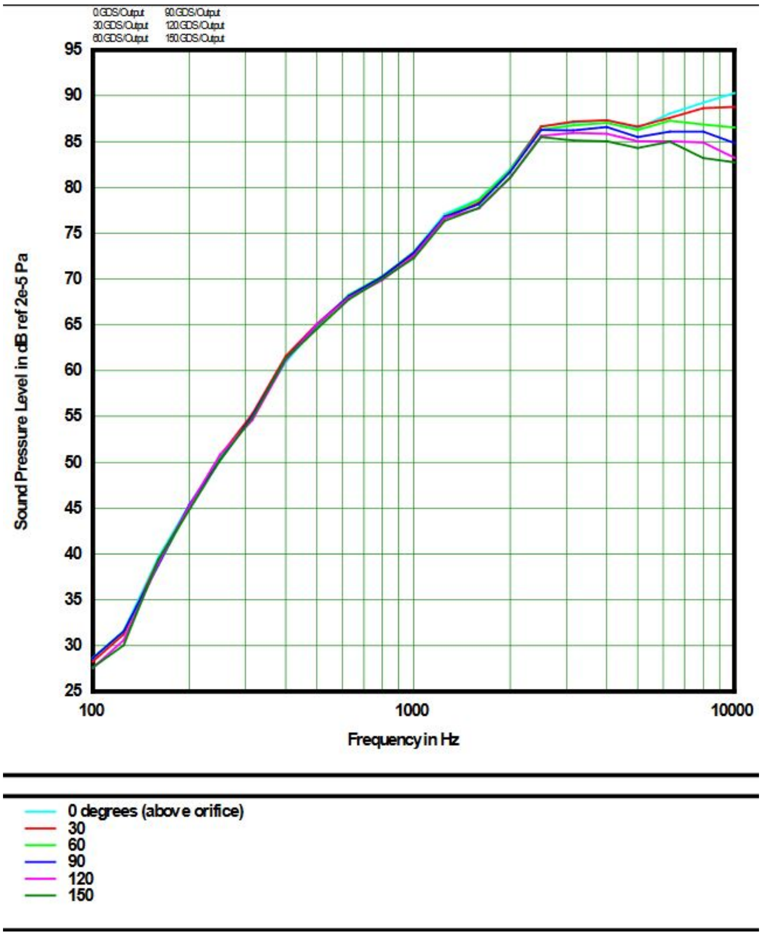

Figure 3.17: Directivity
https://www.isvr.co.uk/automotive/HFSS-Spec-June-2017-with-spectra.pdf

Unfortunately, it wasn't possible to monitor the volume sound source because the inside microphone was broken.

3.3.3 Car model and semi-anechoic room

A Volvo XC90 and the semi-anechoic room with concrete floor shown in figure 3.18 has been used during all the measurements.

Figure 3.18: Volvo XC90 and Semi anechoic room

3.3.4 Front end

In figure 3.19 the front end from Head acoustics that has been used during the measurements is shown.

Figure 3.19: Front end

3.3.5 Noise source power unit

In figure 3.20 the Noise source power unit that has been used, is shown.

Figure 3.20: Noise source power unit

3.3.6 Source of error from the Equipment

During the measurements, a series of details related to the equipment have been taken care of in order to control and minimize as much as possible the errors.

3.3.6.1 Volume sound Source

- It has been warmed up for about 3 minutes before starting measurements, according to previous experience at VCC.
- The signal sent to the volume sound source has been paused in between measurements in order to not overheat it
- The bending of the hose has been taken care in order to have similar bending during all the measurements
- Its position has been the same, inside the trunk of the car, for all the measurements

3.3.6.2 Car

- The hood, undertray, and doors have been closed
- The ventilation system between the engine bay and the cabin has been closed
- Unnecessary items from the car have been removed
- The car has been placed in the same position on the floor according to the lifting machine
- The car emits a tonal component around 495 Hz in the engine bay when opening and closing the doors, so none of the measurements have been performed at the same time

3.3.6.3 Semi-Anechoic room

- All the doors of the semi-anechoic room have been closed and the rolling wall has been placed in front of the secondary door
- All electronic devices or ventilation pump in the room have been turned off
- It has been paid attention about the 301 Hz tonal component present in the room coming from adjacent room

3.3.6.4 Acquiring module

- None of the measurements have been performed while the fan of the acquiring system turned on to cool down the module.

4

Results and Discussion

4.1 Volume sound source investigation

4.1.1 Goal

In this section, the Volume sound source itself and its influence regarding the accuracy and the robustness of the method have been investigated. The following points show the main investigations:

- Delivered Power of the Sound source, covered frequency range relative to the background noise
- Position of the seats
- Position of the hoose relative to the headrest
- Necessary number of positions in the averaging process
- Amount of contamination in the signals

In addition, a small investigation about the modes inside the cabin has been made. The accuracy and robustness of results using the particular sound source are considered, with particular attention to the main differences when analyzing internal combustion engine (ICE) or battery electric vehicles (BEV).

4.1.2 Results

In figure 4.1 an overview of the all measured third octave spectra and the corresponding background noise are shown. Each color correspond to the specific microphone position as shown in the Implementation chapter. A total of seven microphone channels times 16 Source positions have been plotted at once. In this way it is possible to see for each channel the upper and lower limit regardless of the sound source position. This is useful to have a general SPL overview of subareas of the Engine bay while moving the Sound source in the cabin. For example, one colour represents 1 microphone position for all the 16 sound source position.

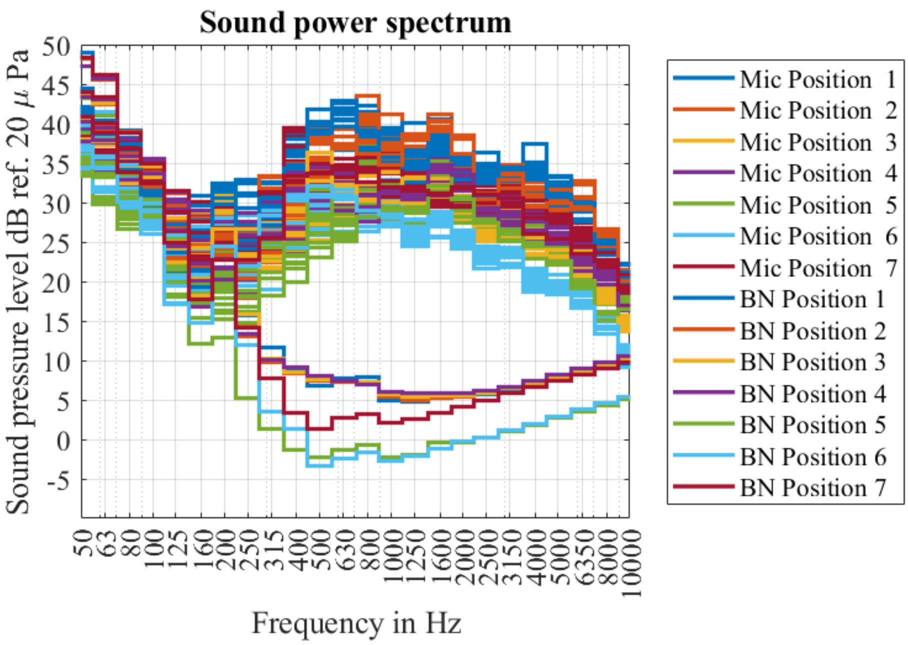

Figure 4.1: Sound power spectra overview and background noise

The light blue corresponding to the Microphone in position six shows the lowest values, while the microphone in position one and two more or less the highest values. The microphone in position six is surrounded by absorbers, therefore, shows low values at higher frequencies. The microphones in position four and seven show an average behavior. In addition it is possible to compare levels related to the background noise. Considering the lowest curves for the microphone positions and the highest curve for the background noise, a difference of at least 10 dB from the background noise is reached from approximately 400 Hz to 5000 Hz. Therefore this frequency has to be taken into account in order to be on the safe side. From now on only a slightly bigger frequency range will be used from 400 Hz to 6350 Hz in order to have a slightly larger frequency range but with still proper results compare to the background noise. According to previous measurements done at Volvo, a general internal combustion engine, substantially cover a frequency range from 300 Hz until 5000 Hz. Therefore, the considered frequency range can be considered acceptable except for lower frequencies, where the lack of power due to the mid-high frequency sound source might be a limiting factor. On the other hand, when taking into consideration electric vehicles, sound sources with higher frequency component are present in the engine bay. According to previous measurements done at VCC, especially a higher frequency, around 10 kHz, the inverter produces a precise tonal component. Therefore, according to figure 4.1 is clear that more power is necessary at those frequencies. In fact, at higher frequencies, e.g 10 kHz, the corresponding wavelength is about 3,4 cm and therefore strongly affected by the dimension of the objects inside the engine bay.

In figure 4.2, four third octave band spectra are shown for different setups. Four volume sound source positions have been used for each configuration, approximately 11 cm perpendicularly from the orifice of the hose to the headrest.

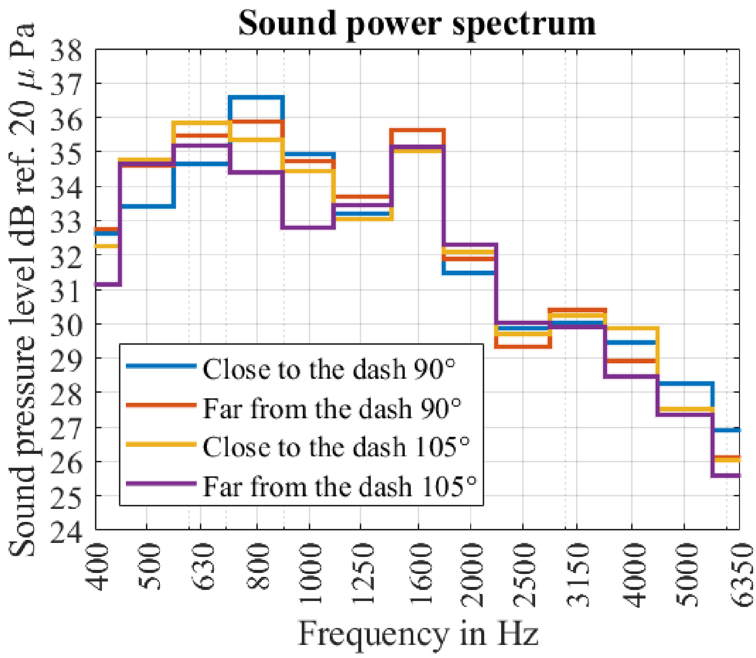

Figure 4.2: Third octave band spectra analysis far and close to the dash at 2 different angles

In general, the lowest values are shown for the setup far from the dash and at 120 degree which should be avoided in order to not lose additional information, especially at higher frequencies, due to the background noise. There are three predominant peaks around 630 Hz, 800 Hz and 1600 Hz and the corresponding wavelength are approximately 54 cm, 42 cm and 21 cm. The distance from the left ear for the driver and right ear for passenger and the corresponding closest window is around 20 cm. Half the wavelength at 830 Hz fit that space. The author thinks the relative position of the seat must be taken into account carefully when repeating measurements and also the position of the hoose considering the influence of the window at this particular frequency. According to picture 4.2, can be seen that the configuration close to the dash at 90 shows a higher peak at 800 Hz compared to the far from the dash due to the less influence of the driver window. The levels differ more in the frequency range from 400 Hz to 1000 Hz, compared to 1250 Hz to 6350 Hz. In fact, the volume source has been moved with a distance that is comparable to the wavelength in the first frequency range.

In the following figure 4.3, the seats have been placed in three configurations: close, centered and far from the dash. The volume source has been placed in four positions: all of them 11 cm far from the headrest. Only one microphone in the same position has been used during the investigation, according to the appendix microphone number 1. Approximately a maximum spread of 2 dB has been found in this investigation between the maximum and minimum of each configuration at different frequencies. Therefore moving the seats between the far and close position relative to the dash can lead to 2 dB difference at different frequencies when averaging only for four sound source positions.

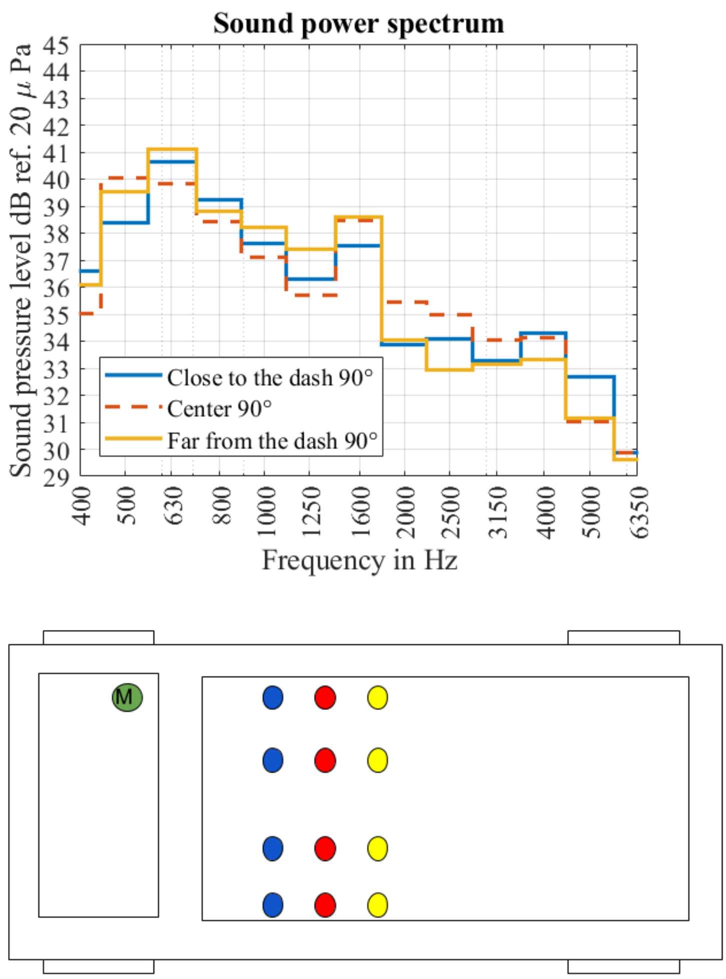

Figure 4.3: Third octave bands using 1 microphone in position 1 and the average of 4 position of the volume source for each setup, close (blue), centered (red) and far (yellow).The seats are 90 degrees. The schema represents a car so the engine bay on the left, where the microphone is placed and the cabin on the right.

In addition, the time signals have been investigated to see if the actual measurements have been contaminated with accidental sound pulses. A maximum threshold of 0.3 Pa has been chosen and everything above 0.3 and below -0.3 amplitude have been considered pulses.

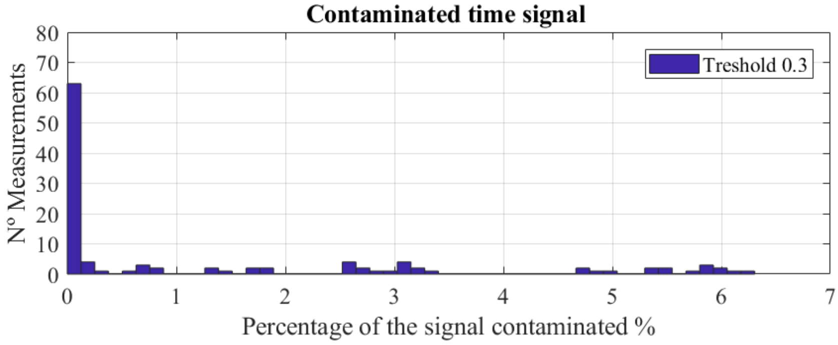

Figure 4.4: Time signal contamination analysis

According to figure 4.4 the majority of the data haven't been contaminated with pulses. Most of the measurements are within the bin of approximately 0 % where 100 % would be the total length of the signal.

In addition, using the measurements from the second investigation, it has been possible to investigate the influence of averaging over different sound source positions. 140 channels in the engine bay have been used, over 12 sound source positions for a centered seat location.

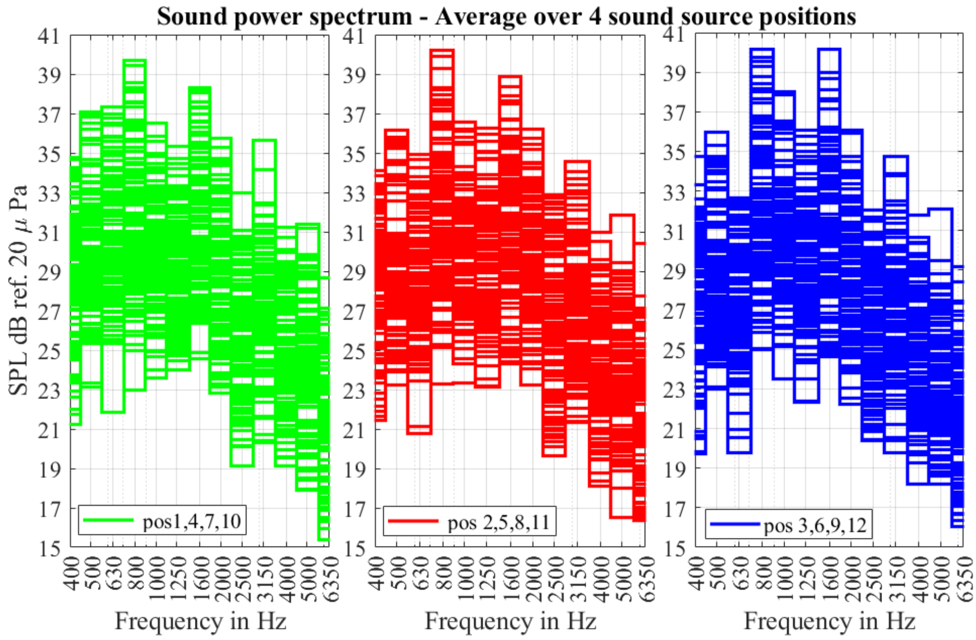

Figure 4.5: Sound power spectrum , averaged over four source positions , three combinations

When comparing the three different sets of sound source positions from the left to the right the overall SPL show similar level except at 630 Hz. It can be seen that the levels at 630 Hz decrease gradually from 37 to 35 to 33 dB. At low frequencies in the cabin, the author expects, a low number of modes with a simple shape all over the cabin, therefore moving the sound source around 10 cm is not going to affect the results drammatically. At higher frequencies the sound field is more diffuse. However, the main frequency range of interest here is from above 400 Hz. In the middle range more difficult modes shapes appears. In the following pictures 4.6. a really rough approximation of the modes inside the cabin around 630 are shown.

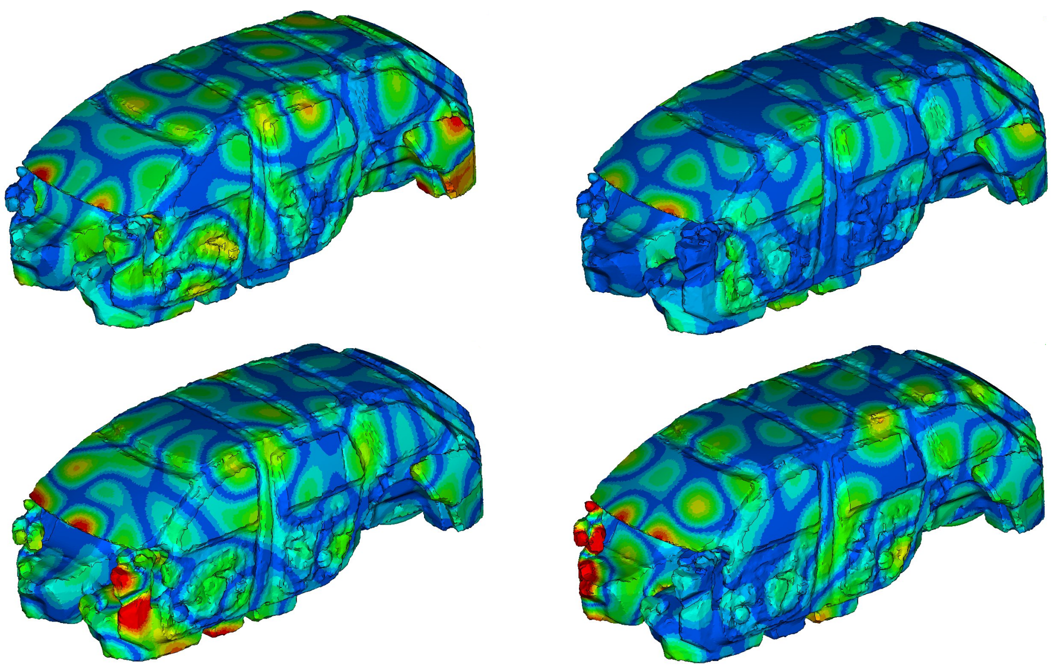

Figure 4.6: Different Mode shapes around 630 Hz

When moving the sound source, the hose can be position on a node or antinode of the mode shape inside the cabin, therefore excite more or less the cabin. It is difficult to predict which modes are going to be excited by the volume sound source, particularly in the middle frequency range.

4.2 Microphones number and position investigation

4.2.1 Goal

In this section different subareas of the engine bay have been investigated. The main goal of the investigation is to find out the positions of the microphones in the engine bay with the following features:

- Good signal to noise ratio in the frequency range of interest for ICE and BEV
- Close enough to the sound sources in the engine bay
- Easy to reach position for further analysis

A good position has been considered as a trade-off between having a good signal to noise ratio and be as close as possible to the sound source. The easy to reach position has been considered as a secondary goal. While for ICE the frequency range is limited from approximately 300 Hz to 5000 Hz, for the BEV the frequency range goes up to 10 kHz. In addition, an overview of the acoustic field in the engine bay is given.

4.2.2 Results

At first, the overall characterization of the engine bay and the validity of the results compared to the background noise have been investigated. In figure 4.7 the third octave bands spectra from all the different subareas are shown with the respective background noise levels. All the spectra are shown on a grey scale, additionally, the upper and lower values for spectra and background noise are shown.

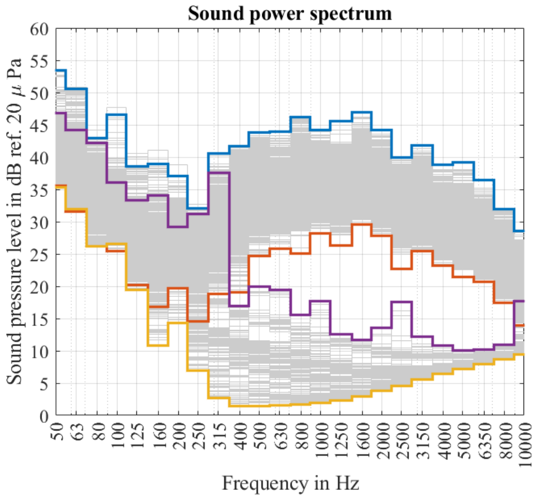

Figure 4.7: 20 Subareas in the engine bay using six microphones and one reference microphones for all the measurements

If considering the upper and lower limit, the safe frequency range is rather limited. Therefore, there would be good results from 800 Hz to 6.35 kHz. On the other hand, considering the mean values as shown in figure 4.8, the safe frequency range is wider, from 250 Hz until 8 kHz. The peak at 315 Hz is due to the constant tonal component coming from a wheel balancing machine in the adjacent room.

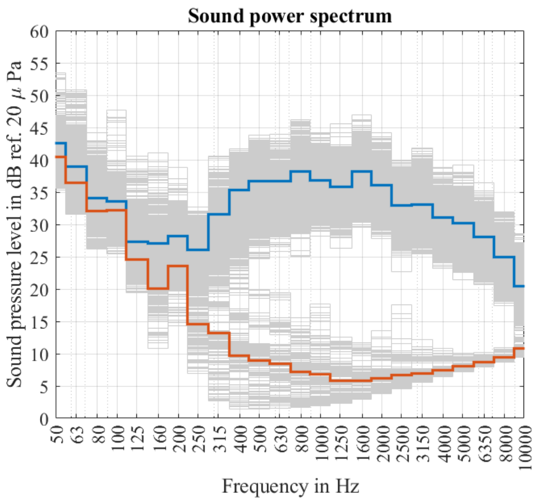

Figure 4.8: 20 Subareas in the engine bay using six microphones and one reference microphones for all the measurements (average)

Therefore averaging the results would lead to a wider frequency range available to use. At 10 kHz, there is a difference of 10 dB between the mean of the background noise and the mean of the levels.
In the following figure 4.9 the different sound power spectrum contributions from each area of the engine bay have been shown. The third octave bands, from each microphone have been averaged over the 12 sound source positions and plotted separately.

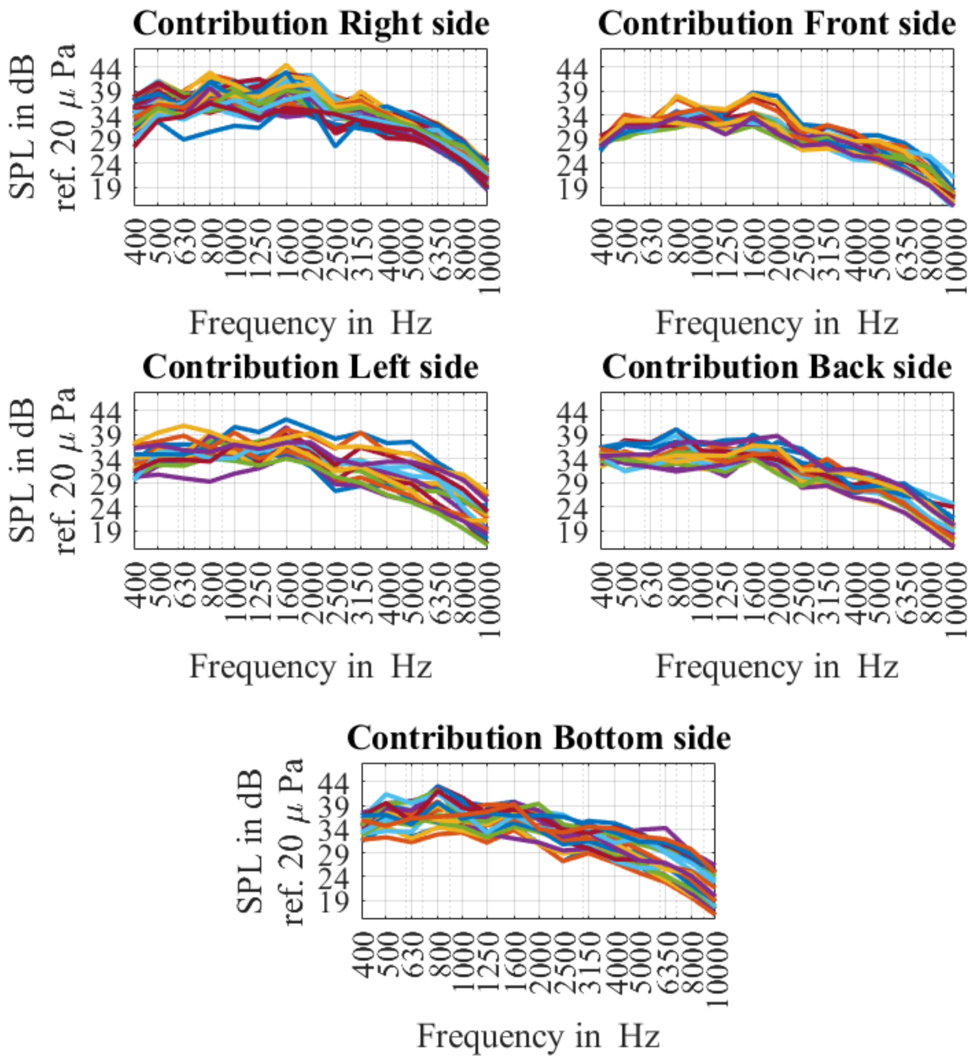

Figure 4.9: Contributions from each areas of the engine bay

According to figure 4.9, it is visible, that the highest contributions in levels, comes from the right and bottom side of the engine bay. The front part of the engine bay shows lower levels compared to all the other sides. In figure 4.9 third octave bands are plotted, without using the stairs lines, because in this way some peaks are more visible. In fact, in the right side, there are visible peaks at 500 Hz, 800 Hz and 1600 Hz. In the bottom side there is a prominent peak at 800 Hz. Both in the right

and the bottom parts, there are cavities with rigid metal walls, which could be the reason for the prominent peaks. The front side, left side and back side show less prominent peaks. In these areas there are more components made of plastic. In the back side, a visible higher drop at higher frequency is present compared to other sides due to the present of absorbers. The front part shows lower levels as explained before. Also from the thickness of the sets of sound pressure levels is possible to see the overall deviation when placing microphones in that particular area. The front side shows a lower range in dB, compared to the right side or left side.
All the reference microphones have been analyzed for each source position. In figure 4.10 the standard deviation of the measurements captured by the reference microphones is plotted for each of the 12 volume source position. Therefore the standard deviation has been performed among 20 measurements captured by the reference microphones.

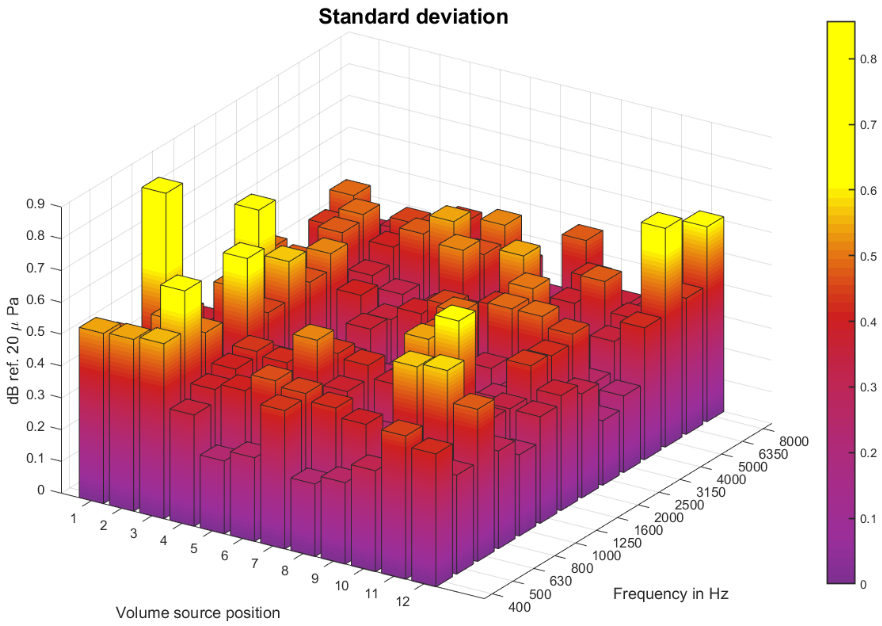

Figure 4.10: Standard deviation captured by the reference microphone during the 20 subareas measurements, for each volume source position

Using the reference microphone and the same volume source position, an overall standard deviation of around 0.5 dB in the frequency range from 400 Hz until 8000 Hz appeared in the data. Hence, double the standard deviation, is the lowest error that is possible to reach. Since the microphone position has always been the same, only the minimal error in the positioning of the volume source might have contributed to this deviation. In figure 4.10 the darkest colors show lower values of standard deviation while brighter colors show highest values. According to the data the highest values occur in the volume source position 1,2,3 and 10,11,12 which correspond to the ones closer to the cabin windows. In addition, from 400 Hz to 1.6 kHz in the central position (volume source position 4,5,6,7,8,9), a general lower deviation trend appears.

In addition, in the section limitation and source of error, a list of possible error difficult to control might have contributed to the deviation in the data.

The physical influence of the microphones on other microphones in the subcavities has been investigated. Subarea number one has been taken into consideration. Therefore, results from one microphone alone in the subarea compared to the same microphone surrounded by other microphones have been analyzed. The microphone was left in the same position without touching it while removing the other microphones.
According to figure 4.11 when averaging over the 12 sound source position the physical influence of the microphones is neglectable, therefore is not considered as strongly influential and therefore ignored in this study.

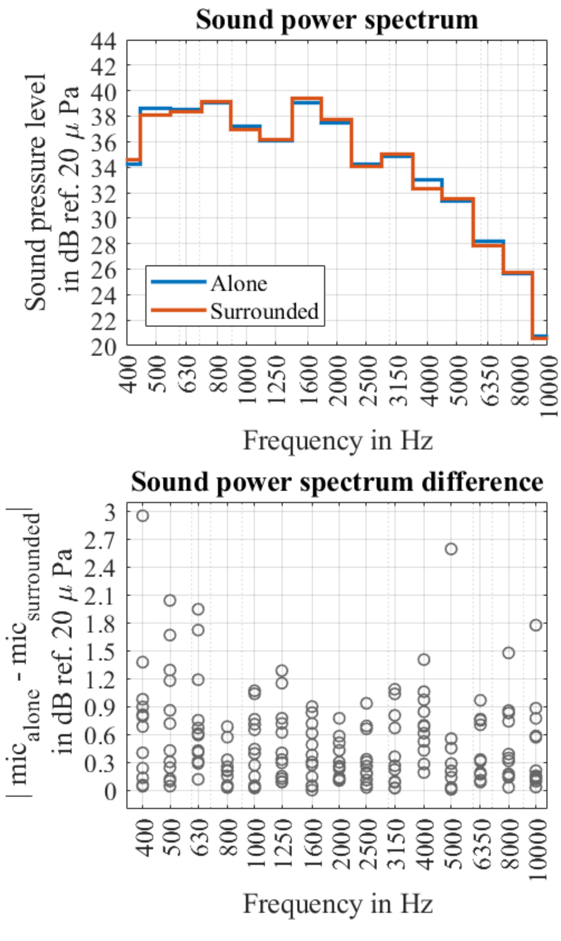

Figure 4.11: Upper: averaged third octave spectrum over the 12 positions
Lower: Absolute value of the arithmetic difference of the microphones alone minus the microphone surrounded for each volume source position

In the following part of the thesis, an overall picture of the captured frequency contents in the engine bay is shown. Six plots are shown to describe how the sound pressure levels change in the different areas in the engine bay. The understanding of the levels in the engine bay, and how they can change, is crucial for determining the areas where there might be higher deviations when placing microphones slightly in other positions. The figures 4.12a, 4.12b, 4.12e and 4.12f shows different paths going from the front area of the engine bay towards the back area of he engine bay. The figures 4.12c, 4.12d, show paths going from the left area towards the right area.

From all the following plots, the acoustics behavior, as described in the theory section 2.4 in the engine bay is visible. In fact, at lower frequencies, there is a modal behaviour, dominated by the biggest cavities in the engine bay. At higher frequencies the sound field is more diffuse and there are fewer prominent peaks. The color scale goes from lower values in blue to higher values in yellow. However the levels are shown on the Z-axis.

The right side and the bottom side clearly show peaks at different frequencies. In those areas, metal walls and bigger cavities are present with fewer absorbers. In the back side, the presence of damping material (absorbers) is clear according to the smoother shape of the peaks. Therefore, when placing microphones in the right and bottom areas, they can capture lower or higher values of the peaks according to where they are placed. This areas must be taken carefully into consideration and can be a reason of higher deviation in the measurements.

In the figures 4.12a, 4.12b, 4.12e and 4.12f, the decrease in levels is more pronounced at higher frequencies where the wavelength is way smaller compared to the objects inside the engine bay. On the other hand in the figures 4.12c, 4.12d, the levels fluctuate from higher levels at the borders (left and right) and lower levels in the middle.
The high frequency components, especially around 10 kHz, show lower levels in the entire engine bay. Only next to the back of the engine is slightly higher, therefore this would be a good position in the case for a BEV vehicle, although a more powerful source at higher frequencies would be more helpful.

In the figures 4.13a, 4.13b, 4.13c, 4.13d, 4.13e, 4.13f, the sections of the spectra are shown to understand at what frequencies the peaks are higher. The higher peaks are present in the right, back and bottom side. Along the right side, there are peaks at 500 Hz, 800 Hz and 1600 Hz. In the back side only at 800 Hz, while in the bottom side the same frequencies as in the right side show higher magnitude.
The bottom side driver and bottom side passengers, showed similar results therefore the latter has been omitted.

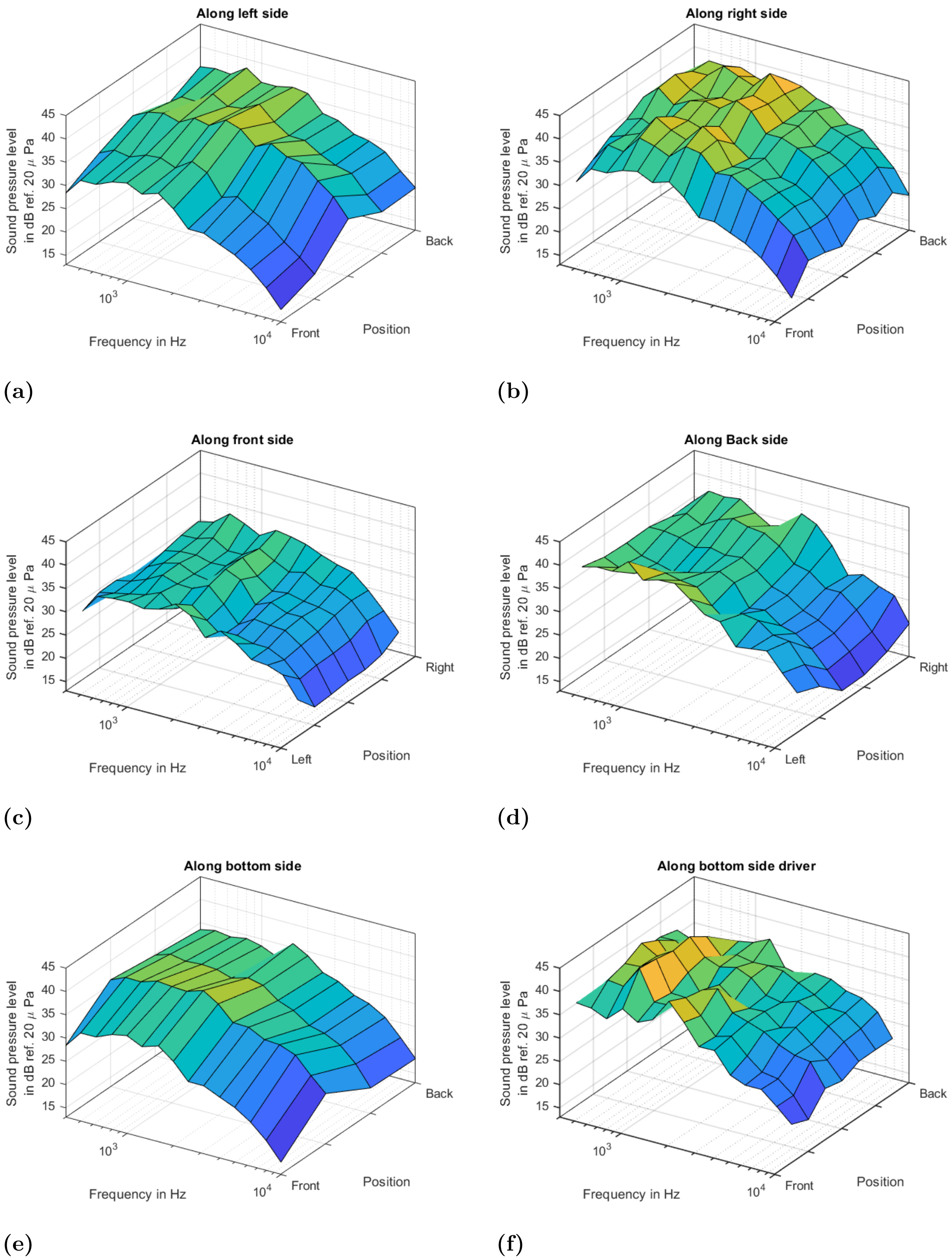

Figure 4.12: Spectra along different paths in the engine bay

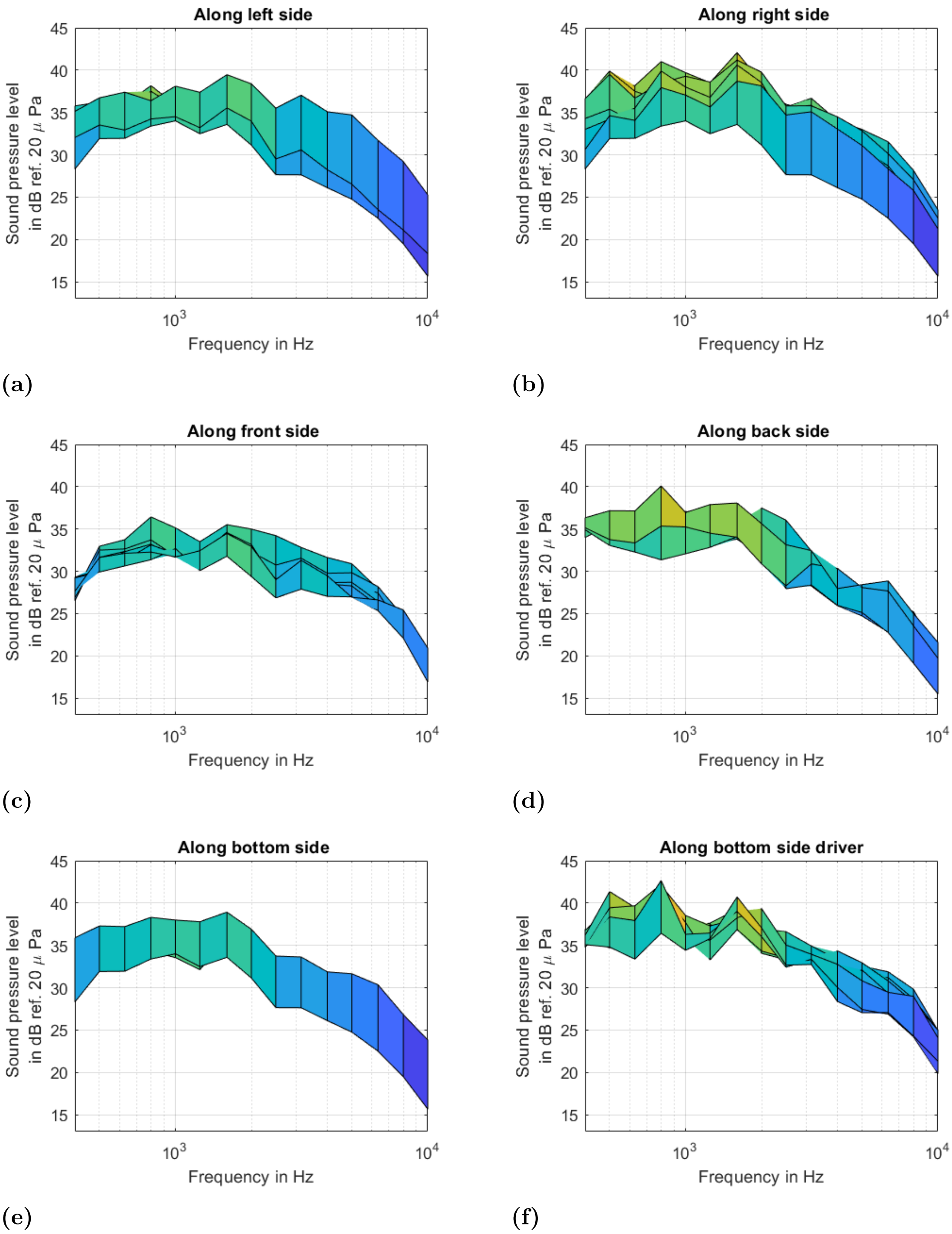

Figure 4.13: Section of the Spectra along different paths in the engine bay

In the following part of the thesis, the effect of decreasing the number of microphones in the engine bay has been investigated. The investigation has been divided into two sets:

- 90/80/70/60 Microphones
- 30/25/20/15/10 Microphones

The figure 4.14 shows the effect of decreasing the number of microphones from 90 to 60 ignoring 10 microphones each step. For all configuration, an equal amount of mics has been used in each areas. For example for the 90 case, 18 microphones have been placed in each area: Right, Front, Left, Bottom, Back. The levels are averaged over 12 sound sources positions and the number of microphones.

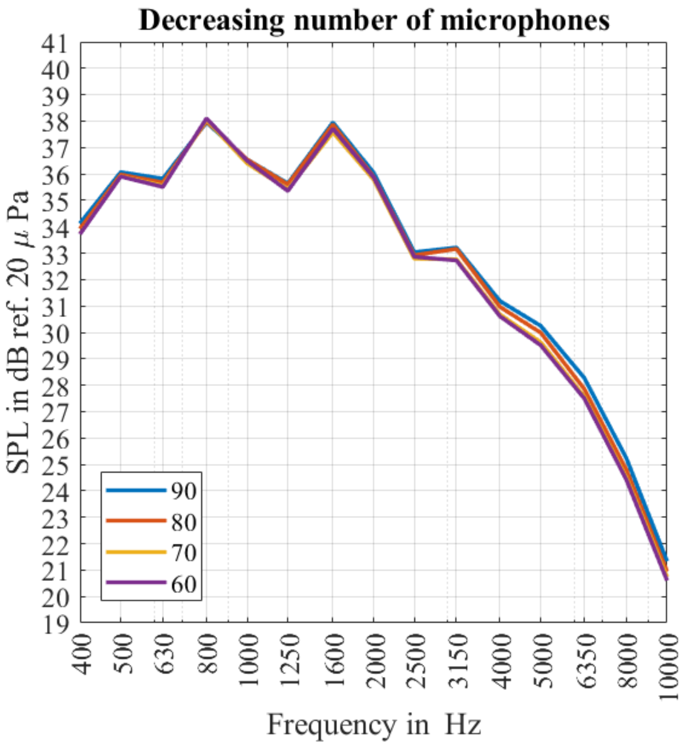

Figure 4.14: Effect of decreasing a high number of microphones

According to figure 4.14, decreasing the number of microphones from 90 to 60 does not affect he results from 400 Hz until 2.5 kHz where the difference starts to grow. At higher frequencies there are deviations higher than 1 dB between using 90 and 60 microphones.

When lowering the number of microphones to a limited number the results vary within a bigger range. Therefore in the following parts, the combinations of different positions of the microphones have been investigated. All the combinations have been taken into consideration, always equally distributed. For example two microphones from the RIGHT subarea combined with two microphones from LEFT subareas and so on.

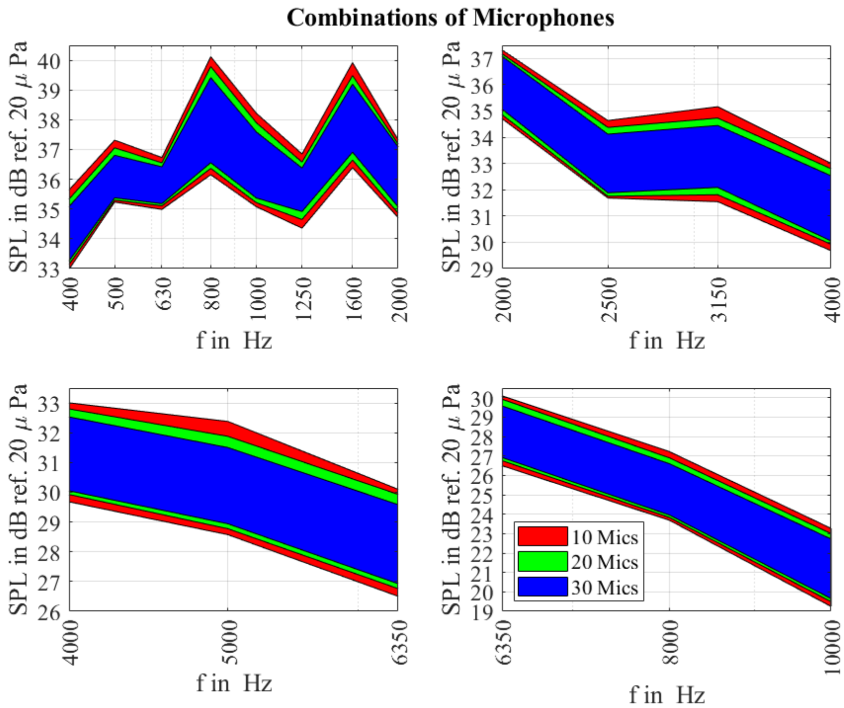

Figure 4.15: Effect of decreasing a low number of microphones

According to figure 4.15 when choosing a lower number of microphones the decision of which one to choose can lead to a wider spread in the results.

In addition, the distribution of those results has been investigated for 10,20 and 30 Microphones. The main interest was to check if all the combinations results were focused close to the mean. To test the normality of the data, three tests have been used: Anderson-Darling test, Jarque-Bera test and the Kolmogorov-Smirnov. The 10 microphones combination has been the only case with a normal distribution of data according to the Anderson-Darling and Jarque-Bera tests. Therefore, most of the combinations were more focused around the mean rather than on the tales of the distribution. In the figure 4.16 the normal distribution at different frequencies for 10 mics combinations is shown.

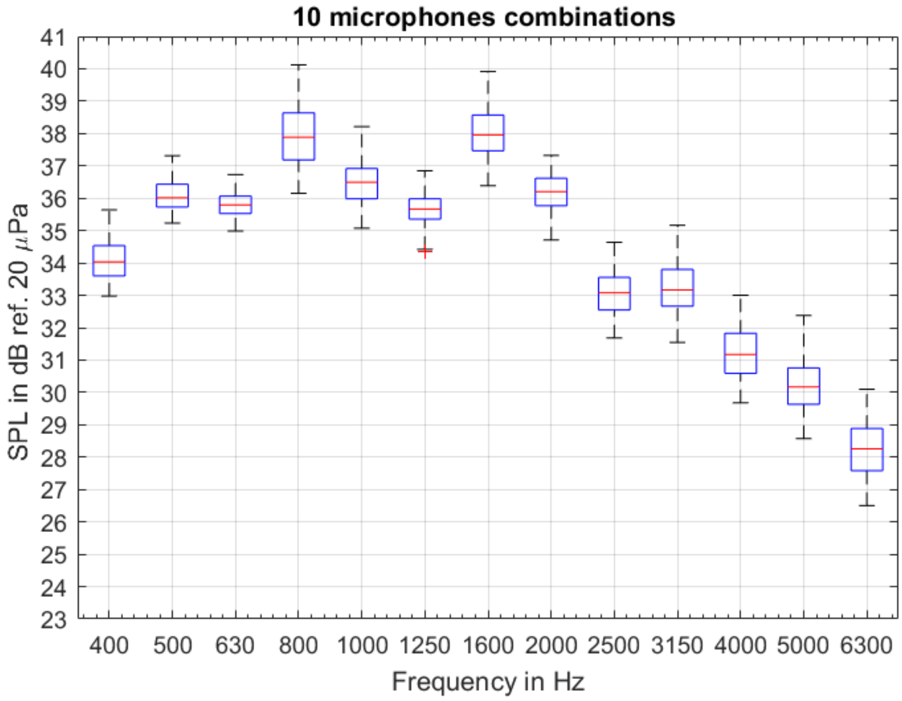

Figure 4.16: 10 microphones combinations, median in red, 25 percentile, 75 percentile and extremes

According to figure 4.16 frequencies like 400 Hz, 500 Hz, 630 Hz show less spread results rather than others. Therefore when measuring in the engine bay with 10 microphones, results from those frequencies can be trusted more than others. This is helpful because in case of measuring and placing the microphones slightly in different positions compared to others position, in this case for these frequencies it is more likely to have similar results at those frequencies.

In the figures 4.17,4.18,4.19,4.20,4.21 the spectra of each of the areas of the engine bay are shown, taking into consideration an equal number of microphones for each subareas. On the right side, for example, there were 6 microphones for 3 subareas therefore 18 microphones in total. Then 1 microphone for each subarea has been removed and the average has been calculated for 15 microphones and so on. Same thing has been done for the other areas of the engine bay.

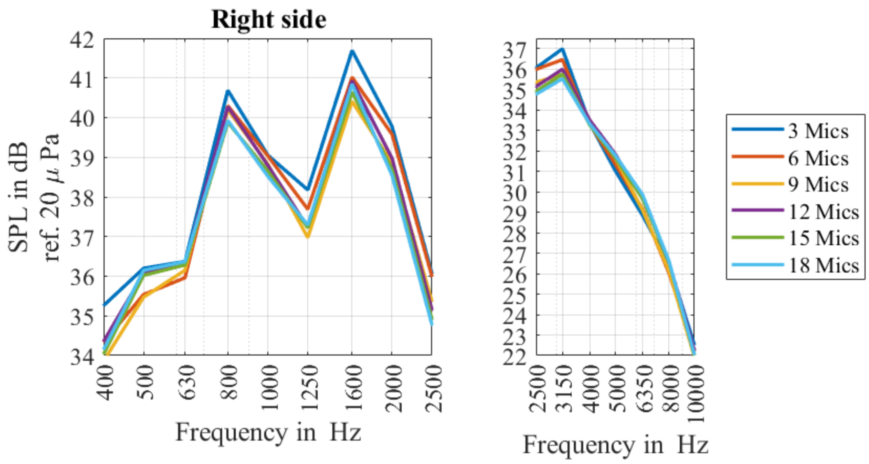

Figure 4.17: Removing microphones from the right side

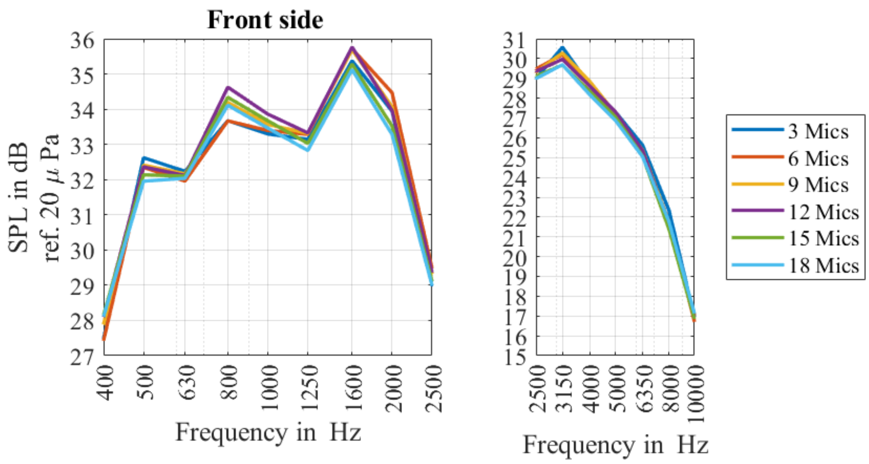

Figure 4.18: Removing microphones from the front side

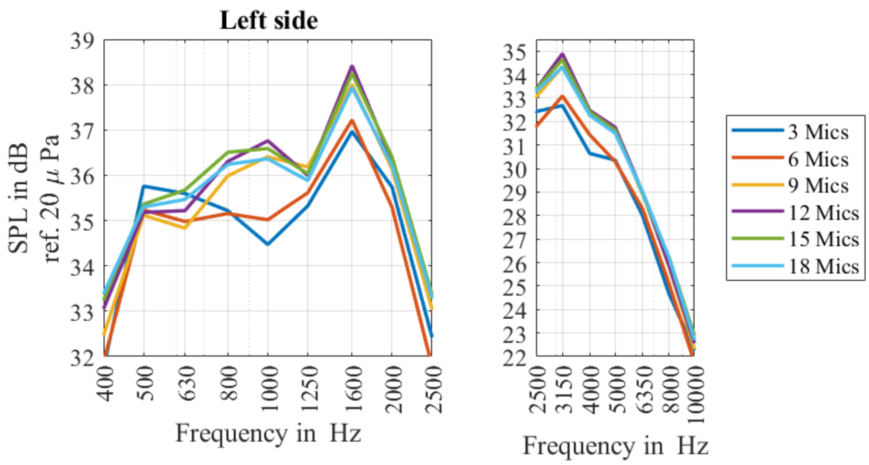

Figure 4.19: Removing microphones from the left side

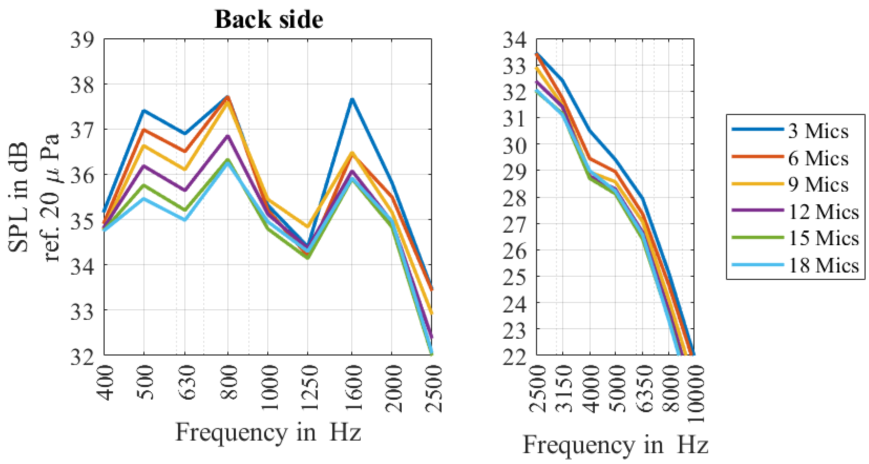

Figure 4.20: Removing microphones from the back side

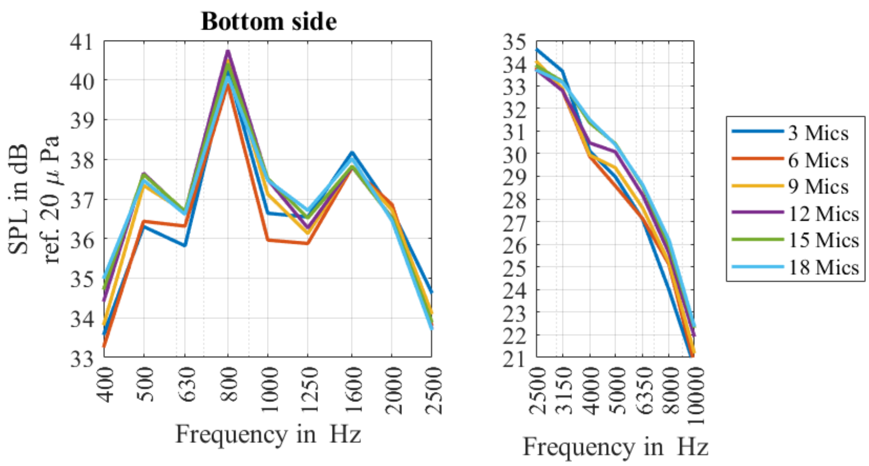

Figure 4.21: Removing microphones from the bottom side

It is visible that the biggest deviation appears on the left side and on the back side. In the right area, six microphones are considered the lowest number of microphones in order to have a deviation around 1 dB. In the front area, nine microphones would be a good number of microphones to have a deviation of no more than 1.5 dB. On the left side, also nine microphones can be considered a good compromise. On the back side, where a large number of absorbers have been placed, the difference at deviation is quite big, when decreasing and increasing the number of microphones. On the bottom side, except for three and six microphones, the deviation from 400 to 2.5 kHz is within 1 dB, while at higher frequencies is higher than 1 dB.

In addition, measurements have been done in the same car with three different microphones in two positions: one in the front and one in the back. In figure 4.22, the spectra are shown, exciting the cabin with volume source in position one.

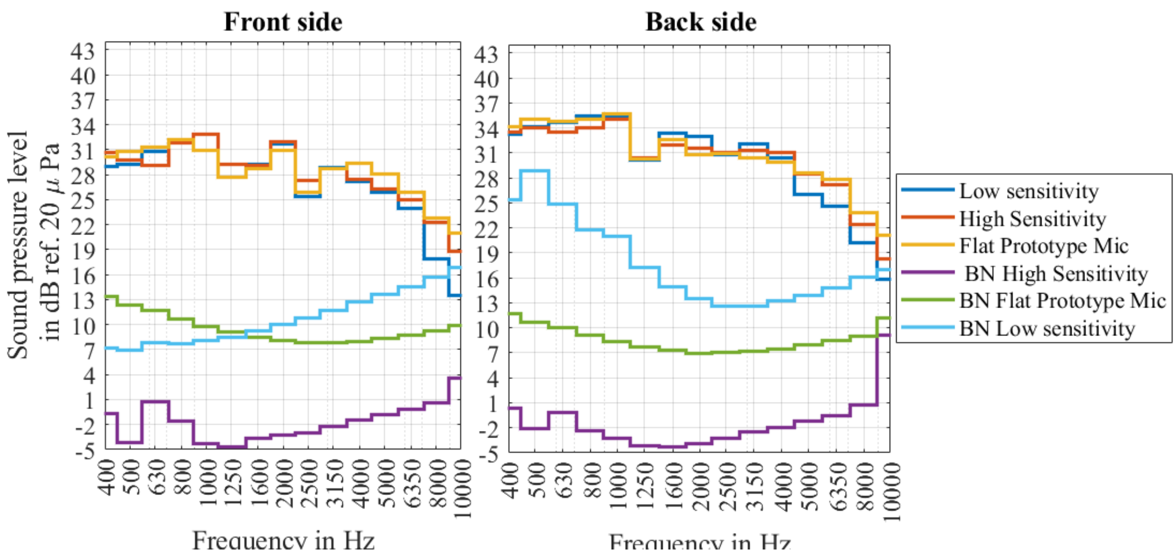

Figure 4.22: Spectra using different type of microphones

The high sensitivity microphone in the front side position, shows higher delta at higher frequency compared to the background noise, while on the back side it is affected by some tonal components. In addition, the cylidrical shape of the high sensitivity microphone affect the repeatability of the measurements. This is due to the fact, that the shape and the dimension of the microphone do not allow to precisely allocate it. In addition, the microphone has to be tape and therefore extra space to tape it is necessary. The flat prototype microphone is preferred to the other microphone, due to the repeatability and good levels also at higher frequency in a particular position in the engine bay.

5
Conclusion

The method has been tested and its robustness investigated using the available equipment and the facilities at Volvo Cars Corporation. According to the existing method and the available equipment, it has been found a lower limit, given by the lowest possible deviation around 1 dB using third octave bands according to the standard ANSI Standard S1.6-1984. Therefore, when adding absorption material inside the engine bay, a result can be trusted taking into consideration, that the modification should be higher than 1 dB in order to not be misunderstood with possible errors. The method can be considered robust only considering that 1 dB deviation can be found in the results. The safe frequency range compared to the background noise in the facility and according to the power of the volume source, is from 400 Hz to 8 kHz which is suitable for Combustion engine but not for Electric Vehicles.

The theory has been confirmed by the data, that the acoustics in the engine bay is divided in the modal frequency range and in the more diffuse frequency range. The modal frequency range is determined by the cavities in the engine bay, and levels increase when placing microphones in those areas. Different areas of the engine bay give different contributions to the total sound pressure level. The right area, show the highest level at 800 Hz and 1.6 kHz, while the front area shows the lowest levels. The levels decrease going from the back area to the front area in the engine bay. Where there are cavities with metallic walls, the levels increase at 500 Hz, 800 Hz and 1.6 kHz. When the microphones are surrounded by plastic surfaces, tubes and absorbers, the levels decrease and show lower and smoother peaks.

The measurement chain and the semi-anechoic room are suitable from 400 Hz until 6.3 kHz. This range can be extended in the higher range due to averaging and choosing locations with higher levels in the engine bay. It can be extended in the lower range due to the high background noise levels present in the room. Therefore the method is considered robust for a combustion engine. When using 60,70,80,90 microphones equally distributed in the different areas, the averaged levels over the channels and volume source positions differs less than 0.5 dB between each other from 400 Hz until 2.5 kHz. However, from 2.5 kHz until 10 kHz they differ more (from 0.8 dB to 1.2 dB) with each other with a maximum of 1.2 dB at 8 kHz. When decreasing the number of microphones the uncertainties grow, depending on the positions of the microphones. However, the rugged mounted microphones are a good choice since the mounting rig can be left in the engine bay and the microphones mounted exactly in the same positions. From 400 Hz until 2.5 kHz using 60 or 90 microphones does not add significant precision to the method. On the other hand at higher frequencies, a lower number of microphones can lead to lower levels. Since the method is going to be used to add absorbing materials in the engine bay, it is difficult to know *a priori*, which locations will have more absorbers and which fewer absorbers, therefore the author thinks that lowering too much the number of microphones might lead to higher deviation in the results at higher frequencies. Therefore 60 microphones equally distributed among the areas, might be a good compromise to capture the entire picture of the engine bay. In addition, the microphones are equally distributed in the areas of the engine, close to the main sound sources in the engine bay in order to comply with the reciprocal measurement. Most of the microphones have been placed mainly on the car body to facilitate the positioning process and to make the method flexible also on other car models with a different engine. Regarding the available volume source, it is suitable for combustion engine application but not for an electric vehicle. Volume sources with higher power at higher frequencies should be taken into consideration for electric vehicle applications where the range from 9 kHz to 11 kHz is of interest due to high frequency components from the Alternator. In this case, the lack of omnidirectionality of the source should be tested in the cabin, defining the deviation according to the positioning of the source.

The author thinks that the method can be improved acting on the volume sound source, since its position in the car can be less precise than the positioning of the microphones with the new mounting rig system. In fact, weighting less the volume source position close to the windows, therefore positions 1,2,3 and 10,11,12 could lead to a lower deviation. This is confirmed by the data since the higher deviation appears in those positions from 400 Hz to 8000 Hz. In addition, when having deviations at 500 Hz, 800 Hz, and 1600 Hz, the responsible areas are the right and the bottom part, therefore microphones placed in those areas.

5.1 Outlook

In order to test Battery electric vehicles (BEV), a higher suitable frequency range is necessary. A more powerful small loudspeker, could be tested for this purpose. It must be taken into consideration that, for definition a high frequency, the loudspeaker is not omnidirectional, and therefore the reciprocal measurement loses one of the prerequisites. This could be investigated by looking at the deviation of the loudspeaker when mounted in the car with different angles. In addition, 10 to 20 microphones could be used and the position of those maintained in order to compare results with future measurements.

Bibliography

[1] H. Kuttruff: *Acoustics -An Introduction*,CRC Press, 2006

[2] ANSI Sl.ll-1986 (ASA 65-l 986) [Revision of ANSI Sl.ll-1966(R1976)], Standards Secretariat Acoustical Society of America , 335 East 45th Street, New York, New York 10017-3483

[3] Eskil Lindberg, Patrik Andersson: *Literature Review on Models for Sound Propagation in Engine Compartments*, Department of Applied Acoustics, Chalmers University of Technology

[4] Eskil Lindberg; Patrik Andersson : *Experimental investigation of sound power radiation form partly open enclosure with numerous interior objects* Department of Applied Acoustics, Chalmers University of Technology, Göteborg, 2005 , 19th Inernational congress on acoustics, Madrid , 2-7 Sepember 2007

[5] Prager, J. and Petersson. B. A. T: *A probabilistic approach for the description of the acoustics inside small densely packed enclosures*,Berlin

[6] Prager, J.: *On the acoustics of small partially open enclosures densely packed with active and passive installations*, PhD thesis, Technische Universit at Berlin,February 2008

[7] Jan W Verheij: *lInverse and Reciprocity Methods for Machinery Noise Source Characterization and Sound Path Quantification Part 2: Transmission Paths*,1997

[8] T. ten Wolde *Reciprocity measurements in acoustical and mechano-acoustical systems. Review of theory and applications* , Leidschendam, The Netherlands

[9] Anders Brandt: *Noise and Vibration Analysis – Signal Analysis and Experimental Procedures* , 2011

[10] Bruno M. Spessert and Hans A. Kochanowski: *Diesel Engine Noise Emission*

[11] Blaza Stojanovic , Ivan Milanović, Saša Milojević, Radomir Janjić: *The impact of the pre-tensioning on the load distribution of timing belt drives*

[12] Petiot, Jean-François ; Kristensen, Bjørn G.; Maier, Anja: *How should an electric vehicle sound? User and expert perception*

[13] Andreas Schuhmacher: *Techniques for Measuring the Vibro-Acoustic Transfer Function* , Bruel Kjaer Sound Vibration Measurement A/S, Naerum, Denmark

[14] Charles Burgess; Rhys Thompson: *Practical Consideration of Noise from Fans* , Australia

[15] Tamás Kalmár-Nagy, Bendegúz Dezső Bak, Tamás Benedek, János Vad: *Vibration and Noiseof an Axial Flow Fan*,Periodica Polytechnica Mechanical Engineering

[16] J. S. Campbell, W. A. Andersen, V. B. Hansinger: *Analysis of Induction Motor Noise and Vibration*, Defense Documentation Center for Scientific and Tech-

nical Information, Cameron Station Alexandria, Virginia; section 3 “Magnetic Noise”, section 4 “Bearing Noise”, section 5 “Fan Noise”, section 6 “Unbalance Noise”, section 7 “Effect of Load”;

[17] Carlo Marazza: *Noise and Vibrations Measurements and Analysis in High Power Diesel Generating Sets*, Politecnico di Milano

[18] W. Eversmana, S.Burnsa, S.Pekarekb , Hua Baib , J. Tichenorb: Generation mechanisms in claw pole alternators, Department of Mechanical and Aerospace Engineering and Engineering Mechanics, University of Missouri-Rolla and Electrical and Computer Engineering, University of Missouri-Rolla

[19] U. Sellgren and M. Åkerblom : *A model-based design study of gearbox induced noise*, International design conference - design 2004 Dubrovnik, May 18 - 21, 2004

[20] Hugo Heidy Miyasato, Vinicius Gabriel Segala Simionatto, Milton Dias Junior : *Study of the gear rattle phenomena in automotive powertrain systems*,Department of Mechanical Engineering, Faculty of Mechanical Engineering, State University of Campinas

[21] Hiroharu Tokoro, Mayu Nakamura, Noboru Sugiura, Hirofumi Tani, Ken-ichi Yamamoto, Tatsuo Shuku: *Analysis of high frequency noise in engine timing belt* , Mechanical Engineering Div. 1I, Toyota Central RD Labs., Inc., Nagakute-cho, Aichi-gun, Aichi, 480-11 Japan b Engine Engineering Div. I, Component System Development Center, Toyota Motor Corporation, Toyota-cho 1, Toyota-shi, Aichi, 471 Japan

[22] *Guide to the expression of uncertainty in measurement*, CGM 100:2008 GUM 1995

[23] Bland, J.M.; Altman, D.G.: *Statistics notes: measurement error* 1996

A

Appendix 1

A.1 Subareas

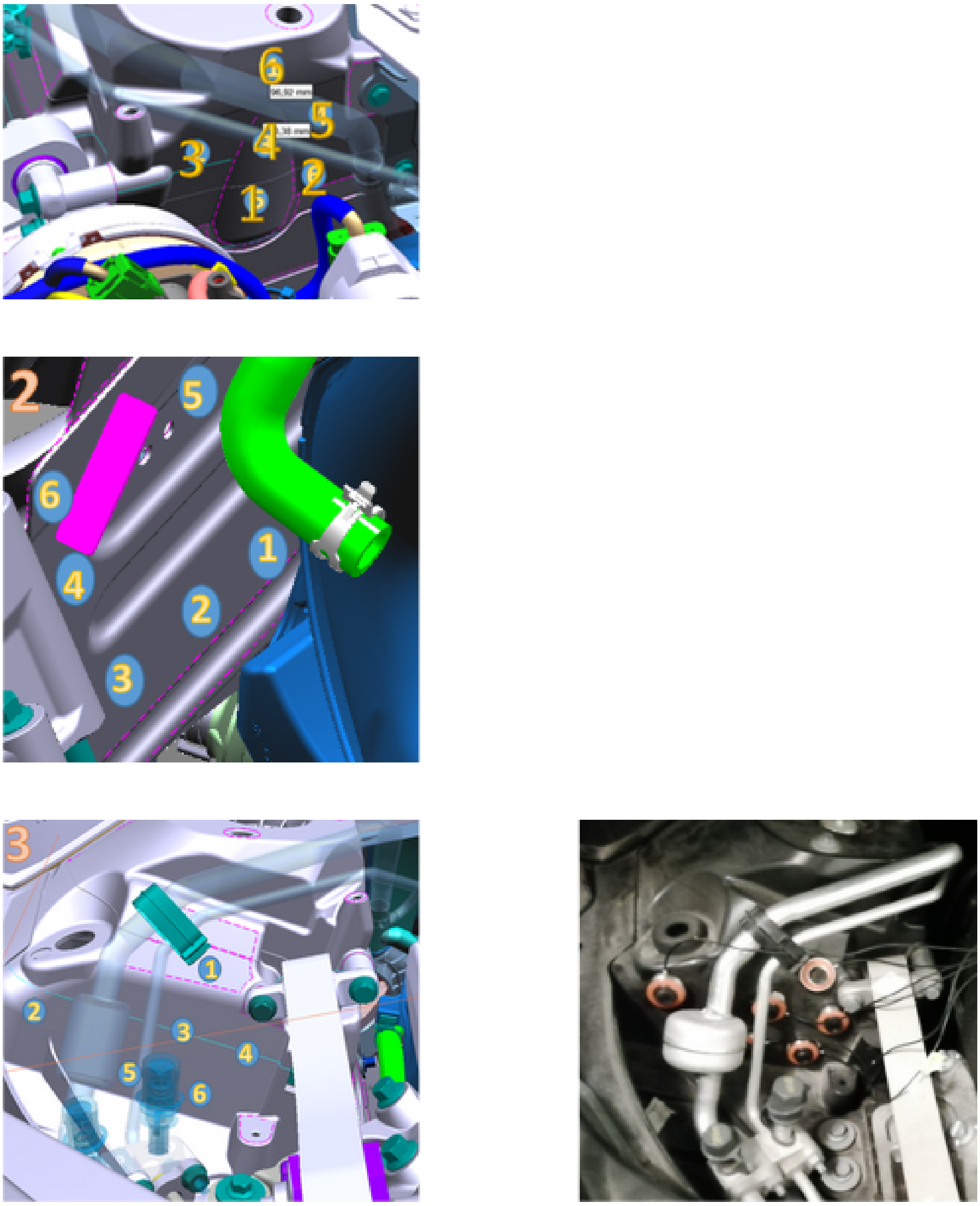

Figure A.1: Subareas 1 to 3

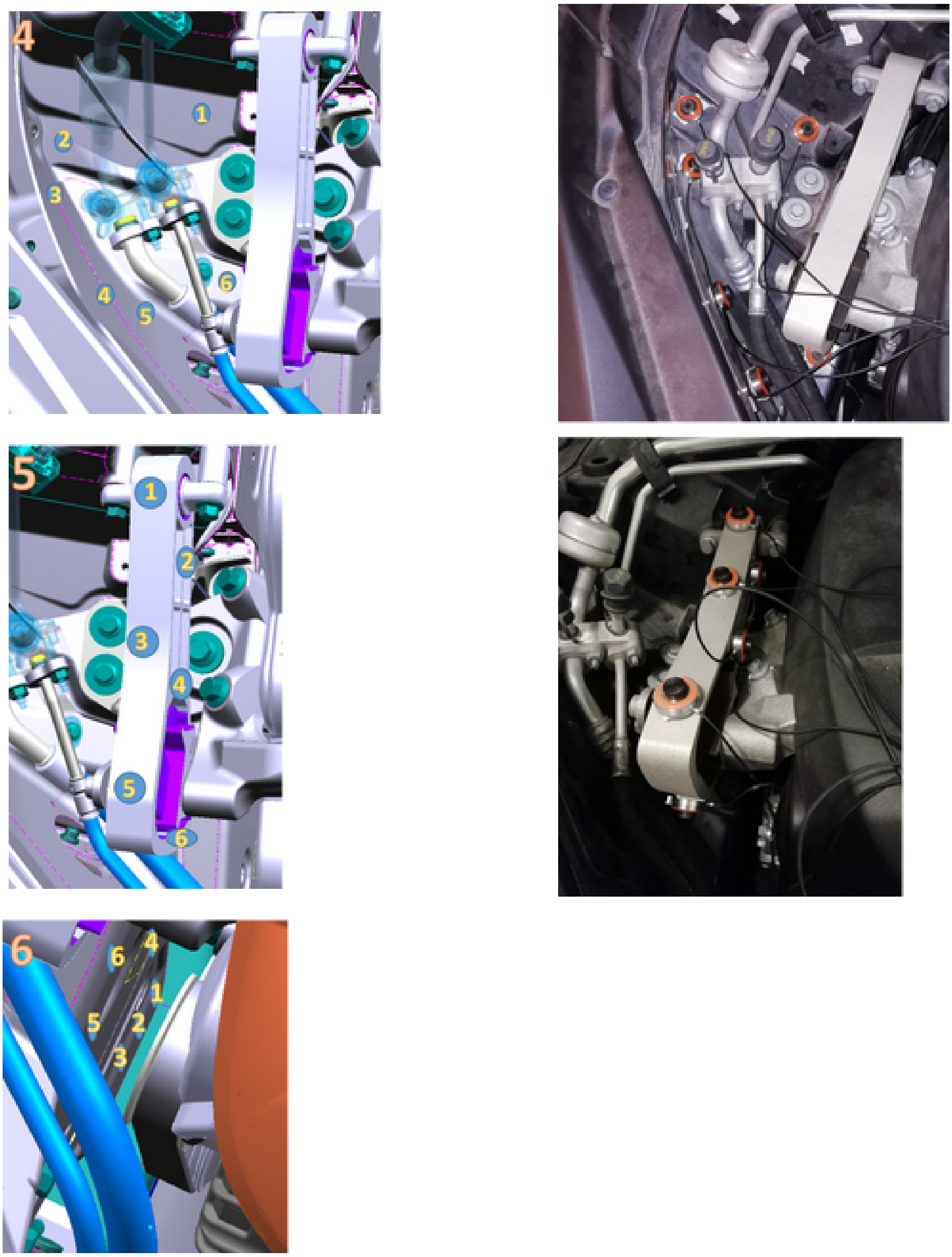

Figure A.2: Subareas 4 to 6

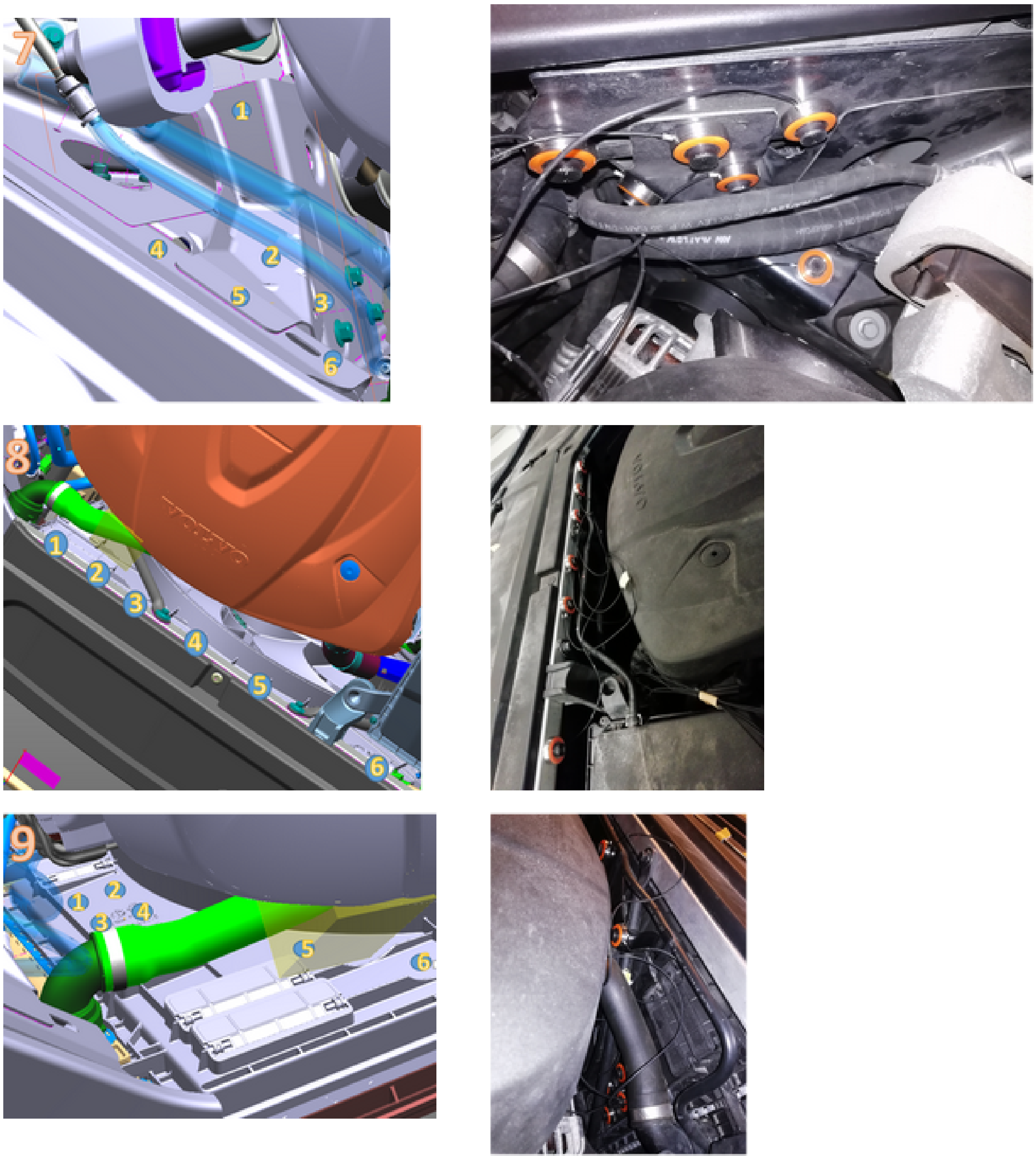

Figure A.3: Subareas 7 to 9

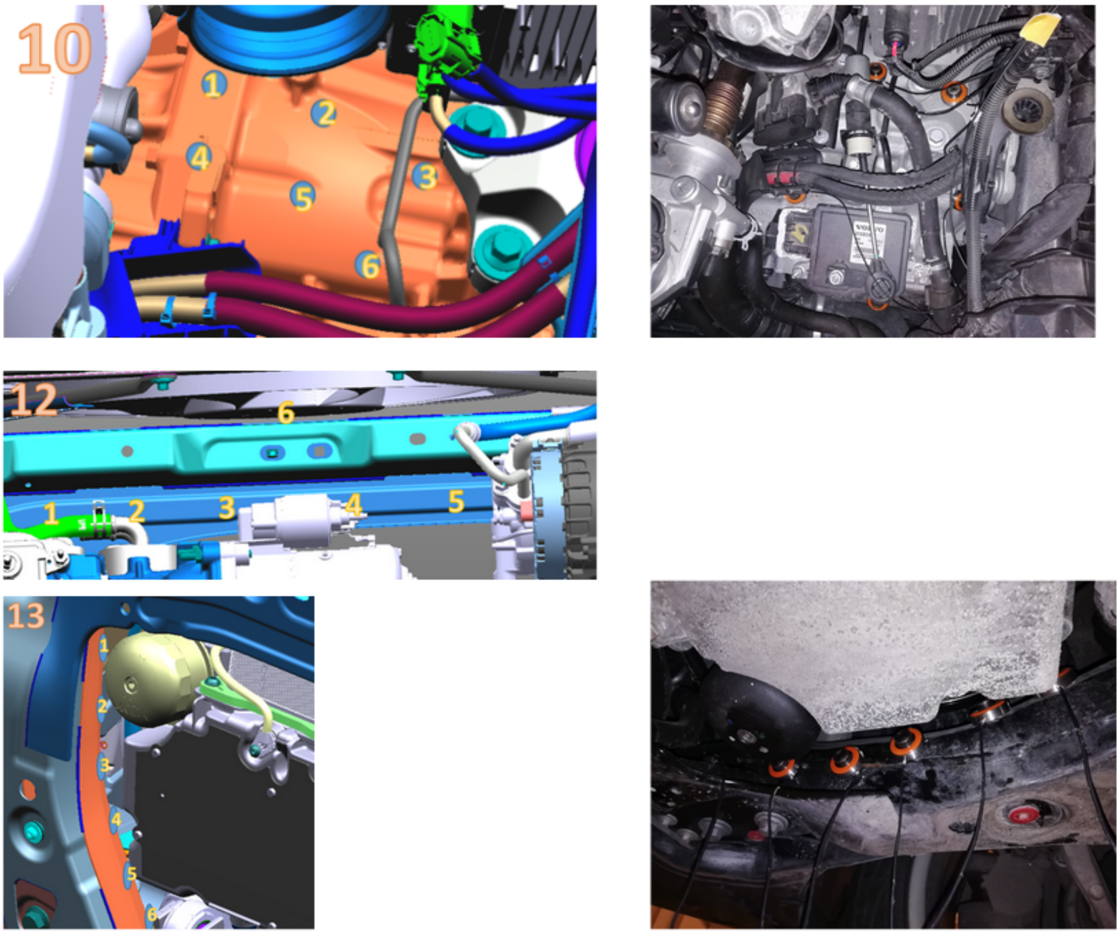

Figure A.4: Subareas 10 to 13, the subarea 11 has been skipped

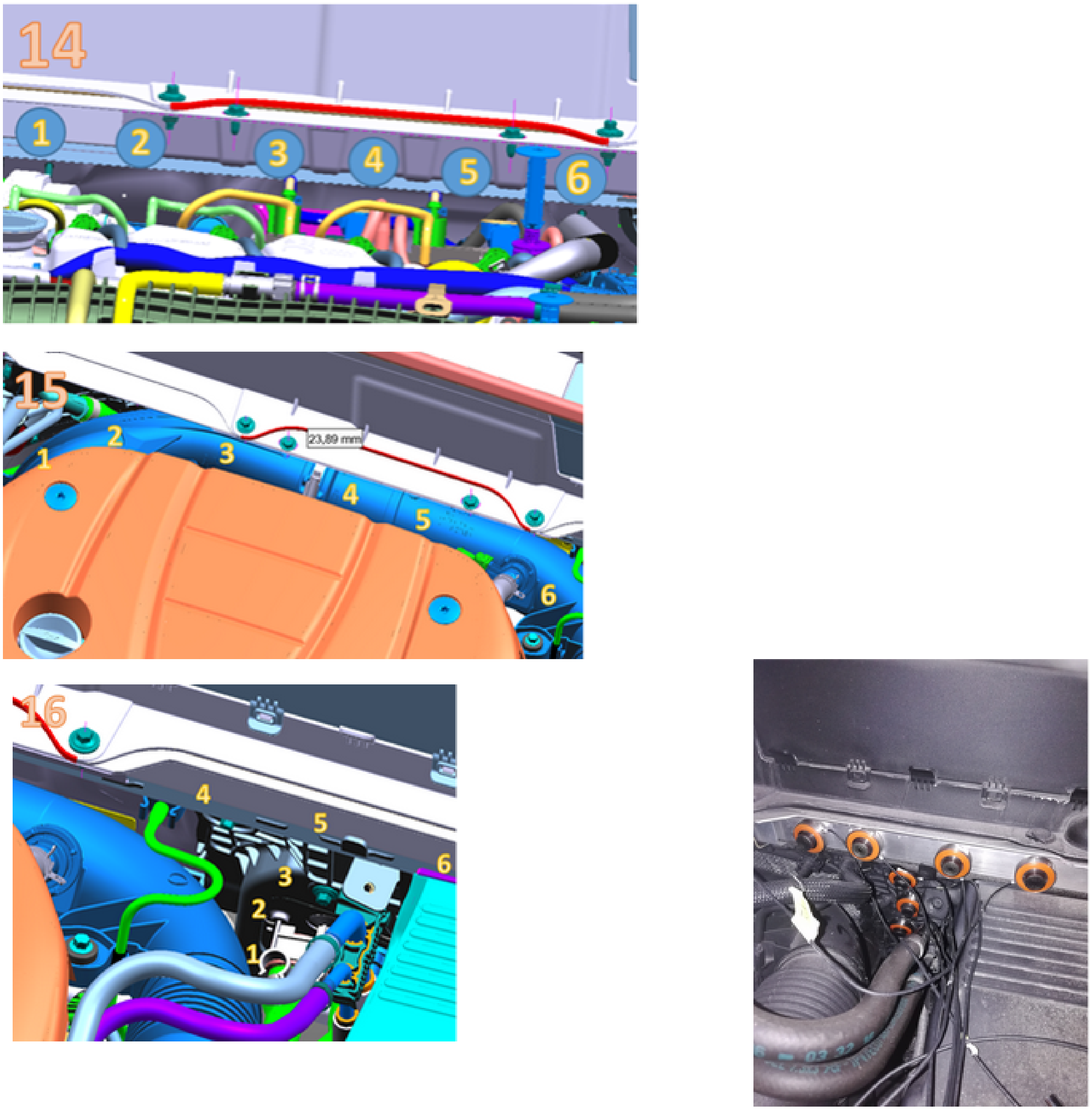

Figure A.5: Subareas 14 to 16

Figure A.6: Subareas 17 to 19 . The subarea 20 has been skipped.

Additionally: in the subarea 20 there have been 6 microphones in the center part of the cooling fan. The subarea 21 is the same as subarea 13 but on the driver side.