Enhancement of Aeroacoustic Testing

Applied to closed-section wind tunnels

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TU Delft

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by

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	ir. N. Moonen (Peutz B.V.)

TU Delft

Acknowledgements

I have always looked for a way to combine theory and practice, so when the hunt for a thesis subject started I had a clear picture of projects I was not interested in. Thankfully, this quickly and smoothly changed into a project that had everything I was looking for, and how could I not? Thesis research that included working at a company, combining my track and elective courses, and focusing on the physical applicability of a system, to have a positive societal impact, who would say no? And so I went to work and became a thesis intern at Peutz B.V.

Across the organisation, I found colleagues eager to share ideas and help me figure out ways to improve my set-up, research question, literature study etc. Furthermore, during the building and testing days, everyone would lend me a hand, or a saw, and whenever I was stuck on some detail we would figure it out together. For all this, I'm grateful to all Peutz colleagues, with a special shout-out to Chris, Dennis and Victor for the experienced advice. Additionally, without the supervision of ir. Niels Moonen and enthusiastic insights by ir. Marcel van Uffelen, I am sure this thesis would not look the way it does today.

I would also like to thank all the other Peutz colleagues and interns for welcoming me with open arms and their willingness to hear me ramble on about my work and for the many lunch break walking tours around Mook.

This project has been the highlight of my Master of Science in Aerospace Engineering, even though it is not even in the track I chose to pursue. The choice to do my thesis in the Aircraft Noise and Climate Effects department has been a great one and it would not have been possible without the guidance and supervision of dr. Roberto Merino-Martinez. I have had a wonderful time working with you and could not thank you enough for the advice, tips and tricks, critical questions and care you put into the project. Also, prof. dr. Dick Simons, thank you for your teachings and great course which drew me to this project and gave me the necessary foundation in aeroacoustics, and your involvement in my project.

As I am writing this, hopefully not forgetting anyone, I am thinking of the past 6.5 years as a TU Delft student, and how much I enjoyed the highs and the lows. I will always remember the VSV activities, coffee breaks, lessons learned inside and outside lecture halls, and the road it took me to get here. But most importantly, I will never forget the people. I would like to thank everyone who has made an impact on my life in Delft, from friends that I made during the freshman weekend, to fellow committee members, mentors and mentees, and people who helped me finally understand the most difficult parts of maths, you know who you are. Lastly, a big thanks goes out to my parents and family who never stopped believing in me, encouraged me to get the best out of myself, and had my back throughout the years.

Yara M. Hinssen
February 22, 2024

Contents

Nomenclature

ANC	Active Noise Cancelling
B&K	Brüel & Kjær
CFD	Computational Fluid Dynamics
CLEAN-SC	Clean based on Source Coherence
CSM	Cross Spectral Matrix
DAMAS	Deconvolution Approach for the Mapping of Acoustic Sources
DAQ	Data Acquisition System
$L_{p,A}$	A-weighted Sound Pressure Level
MEMS	MicroElectroMechanical Systems
MSL	Maximum Side lobe Level
SEL or $L_{p,A,e}$	Sound Exposure Level
SNR	Signal-to-noise-ratio
SPL or L_p	Sound Pressure Level
TBL	Turbulent Boundary Layer

Introduction

Noise pollution is becoming a larger nuisance for society around the world with increasing noise sources ranging from aircraft and wind turbines to bridge fences and traffic noise. However, to limit or decrease this issue, the ability to design for noise reduction needs to be improved. For that reason, an ambition arose between Peutz B.V. and TU Delft to perform further research into the enhancement of aeroacoustic testing capabilities in wind tunnels. After all, if one can test designs during the conceptual design phase before mass production and installations, changes can be made to alter the noise produced by these designs. With that in mind, a research project was formed, and after performing preliminary literature research, the research problem was devised to be:

> *To what extent can the use of different measurement techniques, possibly combined with limited alterations to the wind tunnel, improve the aeroacoustic testing capabilities of a closed-section wind tunnel?*

To answer this question, research consisting of designing, building, and testing different measurement set-ups, altering analysis programs, and investigating advanced methods of analysis, was performed. To conduct this research, the wind tunnel facility of Peutz B.V. was used and focus was placed on cost-efficient and practical uses. Using an existing wind tunnel, which was never intended for aeroacoustic testing, with limited freedom in applying alterations naturally limits the maximum performance. However, if with small changes, considerable improvements could be achieved, it would be an even larger testament to the potential of the results. Additionally, an applicability study with a previously tested subject (a bridge fence) was performed to prove the goal of the research was met: improving aeroacoustic testing capabilities to combat noise pollution at an early design stage.

This thesis report is structured as follows: In Part I, the scientific paper, which will be presented at the Berlin Beamforming Conference 2024, is displayed. This is followed by Part II, which contains the relevant Literature Study that supports the research and the main decisions made during the process. Finally, Part III contains additional results and details on the program that was used, test matrices, and other relevant thesis work.

I

Scientific Paper

ENHANCEMENT OF AEROACOUSTIC TESTING IN CLOSED-SECTION WIND TUNNELS

Yara Hinssen*

Abstract

Aeroacoustic testing in wind tunnels is crucial for understanding and mitigating the noise generation mechanisms in several devices while maintaining satisfactory aerodynamic performance in the conceptual design stage. However, current measurements in closed-section wind tunnels face challenges in terms of installation, due to the effect of the boundary layer of the wind tunnel walls, and accuracy. To address these issues, the proposed methodology integrates advanced signal processing techniques and cost-effective and limited alterations in a closed-section wind tunnel. Different configurations, such as a perforated panel, a perforated panel with melamine foam rings, and the addition of melamine foam panels behind the array and inside the wind tunnel combined with the use of a microphone array consisting of 88 microphones, recessed behind an acoustically transparent stainless steel mesh, has led to significant improvements in signal-to-noise ratio and measurement accuracy compared to the baseline aeroacoustic testing. In general, this setup enables the identification of noise sources with a signal-to-noise ratio of at least -10 dB. Additionally, the utilisation of advanced beamforming techniques (CLEAN-SC and DAMAS) in post-processing yields clearer outcomes. Finally, the effectiveness of the set-up was evaluated, resulting in an approximate 15 dB improvement in peak prominence of the flow-induced noise source due to the higher number of microphones and beamforming.

1 INTRODUCTION

In recent years, there has been a growing emphasis on sustainability in various societal and environmental aspects, such as aerospace, industrial development, and mobility. As a result, interest in mitigating noise pollution and nuisance has also increased over time [1]. With the transition towards more sustainable energy sources, such as wind energy and its accompanying wind turbines, the increase in air traffic, and the rise in urban development there are now more aeroacoustic noise sources that produce flow-induced noise than ever [2]. These sources can have a detrimental impact on the environment and public health. According to the World

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Health Organisation (WHO), noise pollution is one of the biggest health risks in city life[1]. Aeroacoustics is the field of study concerned with flow-induced noise, and therefore aeroacoustic testing during the design stage is of utmost importance to minimise the noise annoyance of the resulting designs. Aeroacoustic tests can be performed in wind tunnels, which have been proven and validated for conducting experiments on smaller-scale models and in aerodynamically controlled environments. While computational analysis methods like CFD may provide accurate results, they are still modelled and not experimentally validated. Additionally, a high level of geometrical detail is required for aeroacoustic testing, especially because small details can be responsible for high-frequency noise, which is computationally expensive. On the other hand, full-scale and/or field tests can be very costly and may not yet be available during earlier design stages. Therefore, wind tunnel testing, with scaled models if necessary, can be a practical compromise solution for aeroacoustic testing. However, aeroacoustic testing in a wind tunnel is not straightforward, as most conventional wind tunnels are optimised for aerodynamic performance and the acoustic performance is not the main point of interest. As a result, wind tunnels are often noisy environments with many different noise sources coming from the flow, reflections, fans, etc. Therefore, research to improve aeroacoustic testing in a (closed-section) wind tunnel can lead to a better understanding of the phenomena that occur during testing and can lead to better results to modify designs for lower noise production [3].

Many advancements have been made over the years leading to a broad base of available steps and improvements to ensure good aeroacoustic testing results [4–6]. Therefore, it is crucial to identify a system that is suitable for the Peutz B.V. wind tunnel facility that was used in this research. Research was conducted on various types of hardware, such as different types of microphones, data acquisition systems, and structural components of the set-up, including microphone arrays. Given the vast amount of possibilities and proven ways of using a microphone array and its availability to the research, a readily available commercial microphone array was used to perform the measurements. Furthermore, the measurement set-up was based on previously found options to improve aeroacoustic testing in wind tunnels[7]. In these other research projects, multiple alterations were tested and led to promising results. These alterations included placing microphones recessed in cavities, behind an acoustically transparent metal mesh sheet as shown in VanDerCreek (2021) [7], wall treatments [8, 9], and using hybrid test sections [8, 10]. These alterations were further analysed and used to design the set-up for the experimental campaign of this research.

Lastly, different post-processing methods were researched and analysed to provide the best possible system for data analysis. Here, conventional frequency domain beamforming (CFDBF) was used as the baseline, and more advanced methods, such as CLEAN-SC and DAMAS [11, 12], were considered to further improve the obtained acoustic results.

In conclusion, this paper aims to present the research that was conducted to find a cost-effective, easy, and flexible way to enhance the aeroacoustic testing capabilities of a conventional closed-section wind tunnel in which the main focus is on the microphone array placement while applying minimal alterations to the wind tunnel.

[1] `https://ec.europa.eu/research-and-innovation/en/horizon-magazine/noise-pollution-one-biggest%2Dhealth-risks-city-life`

2 EXPERIMENTAL SET-UP

2.1 Wind tunnel facility

The location where this research was carried out is the wind tunnel facility at Peutz B.V., in Mook, The Netherlands. This closed-section, closed-return wind tunnel facility measures approximately 26.5 × 10 m (length × width), with a test section of 3.2×3.2×1.80 m (length × width × height). It is powered by four fans with flow velocity up to a maximum of approximately 25 m/s. The test section has a window that can be opened that is 2.75 m in length and 0.85 m in height, see Figure 1. This facility is mostly used for research regarding wind environment, wind pressures, dispersions of substances and aero- and hydrodynamic research for offshore projects[2] and can be altered using inserts leading to different atmospheric boundary layer properties. For acoustic testing, these inserts are removed and an empty wind tunnel is used.

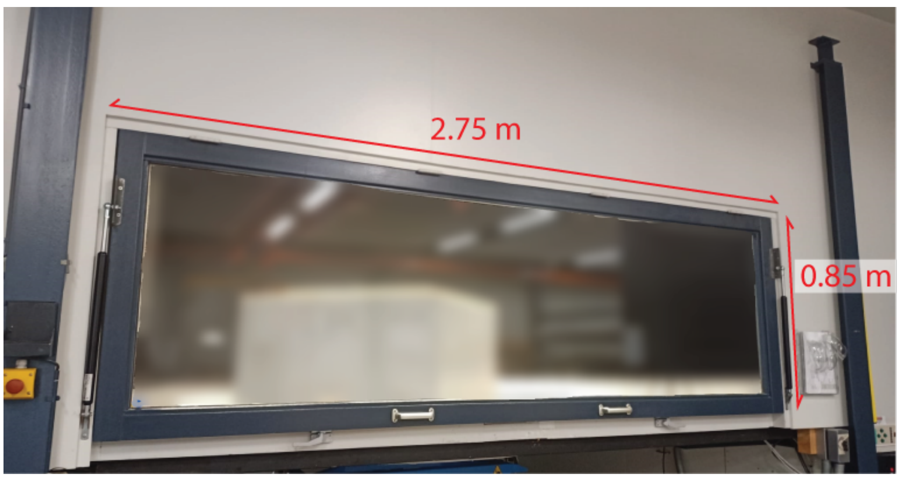


Figure 1: Peutz B.V. wind tunnel showing window location.

2.2 Measurement device

The tests were performed with the CAE Bionic M-112[3] microphone array and the measurements were recorded using the CAE Noise Inspector software. This array consists of 112 MEMS microphones and measures 1 m in diameter. Of these 112 microphones, only 88 had an unobstructed view of the test section throughout the set-ups and were, hence, employed in the analysis. The microphone array has a 24 bit resolution, sample rate of 48 kHz, and a frequency range between 10 Hz - 24 kHz.

[2] `https://www.peutzgroup.com/index.php/node/56`
[3] `https://www.cae-systems.de/en/products/acoustic-camera-sound-source-localization/bionic-m-112.html`

2.3 Microphone array placements

A test set-up was built consisting of three separate segments that cover the full window area of the wind tunnel. The main goal of this was to ensure that none of the parts would become structurally unstable or too heavy to handle. The two segments, or stands, on the outer sides, were purely designed to ensure a proper closed-section wind tunnel. They were constructed out of 2 MDF wooden panels, one measuring 870×840×18 mm (length×height×thickness) and one measuring 880×840×18 mm (length×height×thickness) respectively, held up by 2 beams that were placed on the floor next to the tunnel. The length of the load-bearing poles was adjusted to ensure the segments were clamped in place to then be taped off on the inside to prevent any air gaps or holes. The middle segment is the one that was altered to test multiple setups. For this segment, three different set-ups were devised. The full set-up, as seen from the outside of the tunnel is displayed in Figure 2.

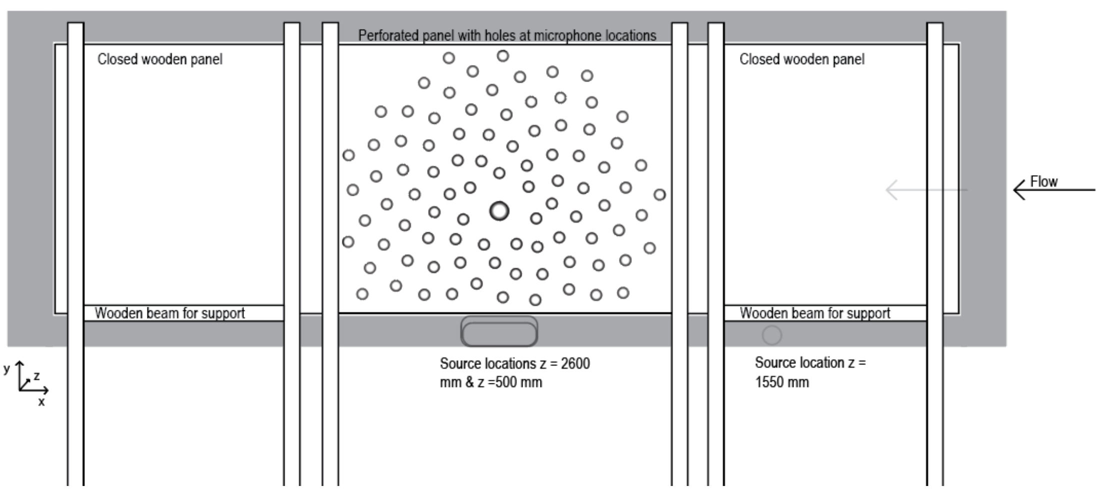
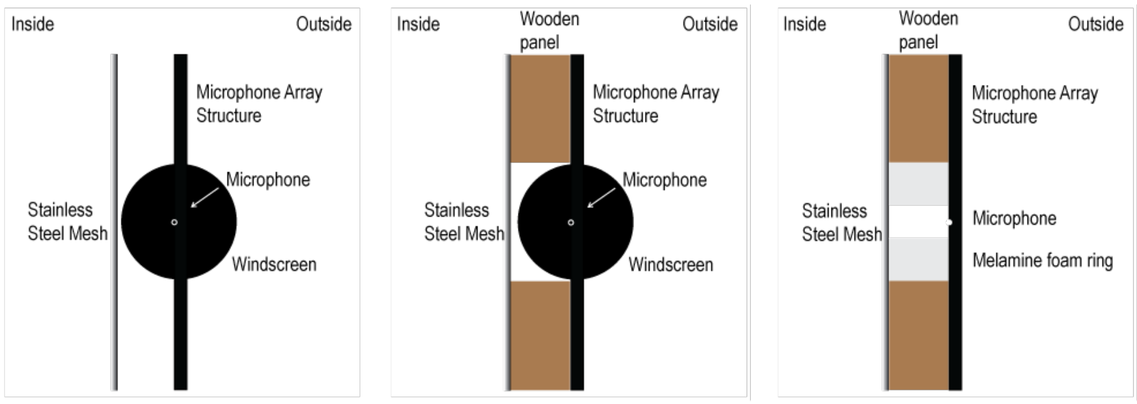


Figure 2: Structural set-up used during tests, side view seen from outside the wind tunnel. Note: Set-up 1 does not use the middle segment as displayed.

In Figure 3 the cross-sections of the three set-ups are displayed. In the first set-up, it was attempted to create an aerodynamically closed, yet acoustically open test section (i.e. a hybrid test section)[8] by using a 500 thread per square inch (#500) stainless steel cloth with a thread diameter of 0.026 mm and placing the measurement device directly behind it with the wind-screens touching the mesh. This mesh was adhered to the side panels and top and bottom edges of the wind tunnel and kept in place for all test set-ups. Then, for the second test set-up, an MDF panel with the same thickness as the side panels was clamped in between the side panels with circular holes of 36 mm at the exact locations of the microphones in the measurement device. The windscreens of the CAE Bionic M-112 microphone array were pushed into the cut-outs to further close the test section and ensure the microphones were aligned with the cut-outs. The last test set-up, set-up three (3), used the same perforated panel as set-up two (2), however, this time the original windscreens were removed from the microphone array. Instead, melamine rings with a diameter of 36 mm, an internal diameter of 9 mm, and a thickness of 20 mm were placed into the holes after which the microphone array was aligned and attached to the panel. These three set-ups were then tested using two experimental campaigns.

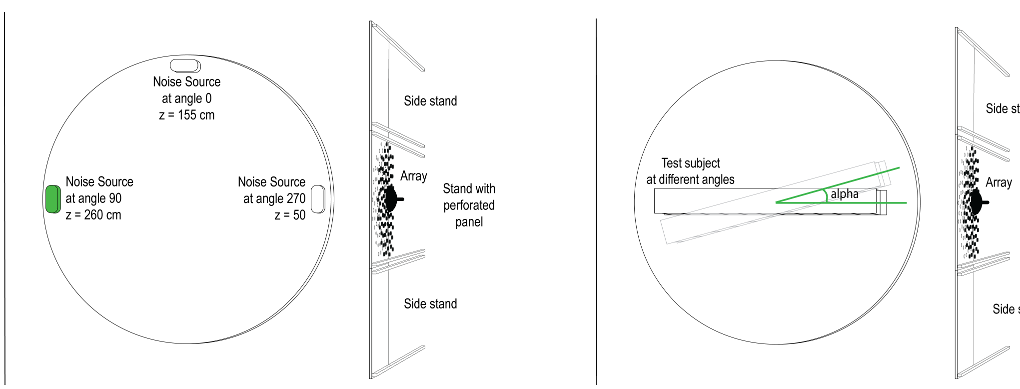


(a) Set-up 1 *(b) Set-up 2* *(c) Set-up 3*

Figure 3: Visual representation of the cross-section of the different set-ups.

2.4 Speaker Experiment

Measurements were performed with three different flow velocities, the speaker emitting tonal noise at six different frequencies and white noise, and three different source locations using a JBL Charge 5 speaker. This 40 Watt speaker measures 22×9.6×9.3 cm (length×width×height) and has a frequency range of 60 Hz - 20 kHz. It was placed on the turntable of the wind tunnel at 5 cm from the edge which by turning the turntable led to the different source locations. In addition, background measurements of the wind tunnel, and measurements without flow were performed to obtain the expected true signals. A visual representation of the test section and the different speaker locations can be seen in Figure 4a. The presented results all have use the source location furthest from the array as highlighted in Figure 4a.



(a) Experiment with a speaker source *(b) Experiment with a bridge fence*

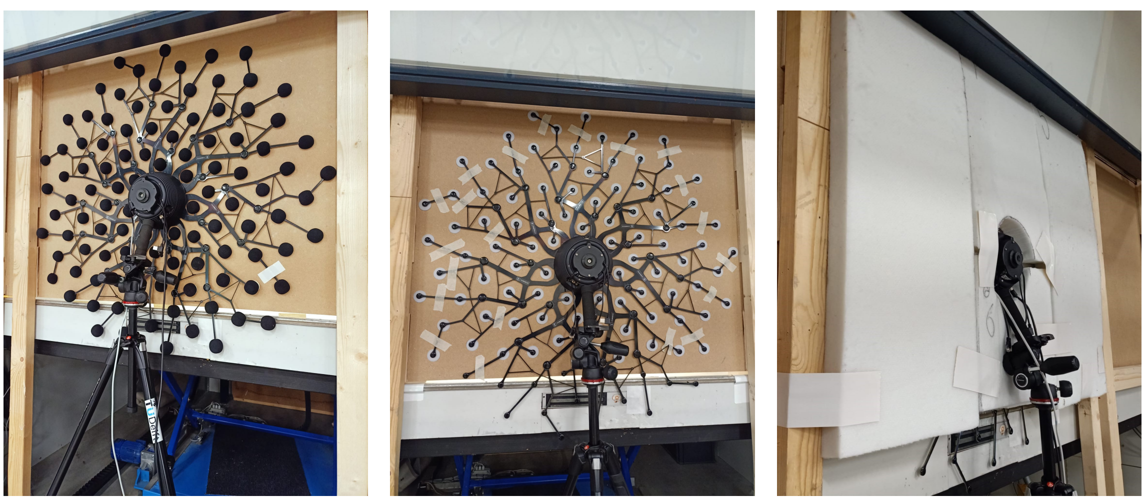
Figure 4: Visualisations of the two experimental campaigns in the wind tunnel seen from above.

2.5 Fence Experiment

Moreover, tests were performed to evaluate the applicability of the proposed test set-up. To accomplish that, two (2) previously analysed test subjects (two different bridge fences), were placed in the wind tunnel and the different array set-ups were used (see Figure 4b). Here the main focus was on the comparison to the previously reported results by Peutz B.V. using a single microphone flush-mounted into the floor of the same wind tunnel. This microphone was a Bruël & Kjaer 2250 single-channel class 1 sound level meter[4]. The results were primarily compared by focusing on the recorded frequency spectra of the wind tunnel and the test subject. During this study, the fences were tested for several flow velocities and sideslip angles between the fences and the flow to replicate the conditions of the original tests.

2.6 Melamine foam additions

In addition to the three different set-ups previously described, the implementation of a melamine foam back panel, attached to the back of the microphone array, was tested to see whether this would lead to further improvements by further attenuating the potential background noise outside of the wind tunnel. This panel was made to fit between the wooden beams and includes cut-outs for the hardware and measures approximately $1 \times 0.84 \times 0.08$ m (width×height×thickness). Lastly, a test was performed with melamine foam panels with a total dimension of $2.40 \times 1.40 \times 0.05$ m (width×height×thickness) placed on the wind tunnel wall opposite the microphone array to see whether this would decrease reflections without drastic alterations to the wind tunnel aerodynamic performance. Pictures of the set-ups and melamine foam additions on the back of the array can be found in Figure 5.



(a) Set-up 2 *(b) Set-up 3* *(c) Set-up 3 with foam backpanel*

Figure 5: Visual representation of the cross-section of the different set-ups.

[4] https://www.bksv.com/en/instruments/handheld/sound-level-meters/2250-series

3 METHODOLOGY

3.1 Conventional Beamforming (CFDBF)

Using the data acquired during the experimental campaigns, various methods of post-processing were applied to further improve the results. All the data was analysed using a MATLAB program with certain constant settings. These include an NFFT of 4096, zero padding, overlap of 0.5, and Hanning window type. Furthermore, for the white noise measurements, the third-octave band (T.O.B.) was analysed, whereas, for the tonal noise, analysis was performed on a 1000 Hz window around the given single frequency to limit computational time. The scan grid that was used for the measurements spans the entire wind tunnel with a grid spacing of 5 cm at a defined z distance. The speaker source results displayed in this paper all use a Z distance of 2.60 m. For the fence measurements, the chosen Z distance was 1.55 m. Additionally, an integration rectangle was defined for all measurements depending on the sound source location. In this rectangle, the Source Power Integration technique was applied [13].

Cross-Spectral Matrix (CSM) manipulation

In addition, diagonal removal (DR) of the cross-spectral matrix was used to decrease the effect of incoherent noise and therefore decrease the background noise. This DR was used for all the results except when explicitly stated otherwise to research the effect of this method and its alternatives. This method replaces all of the values in the diagonal of the CSM with zeroes which eliminates much of the incoherent noise. Furthermore, diagonal optimisation (DOpt) of the CSM was applied to assess its improvement compared to the original CSM without the potential nonphysical results that might be obtained by using DR [14]. For this, the method proposed by Hald [15] was used in which the diagonal is optimised to be as close to zero as possible while adhering to the positive-definite eigenvalues. This is performed by convex (CVX) optimisation in which a diagonal vector is added to the CSM. This is then minimised, which would lead to lower values of incoherent noise. Lastly, it was analysed whether it would improve the results if the CSM of a background measurement without a sound source was subtracted from the CSM of a measurement with the same wind tunnel and set-up properties including a sound source. This subtraction is performed for every frequency on every band that is analysed.

3.2 Advanced deconvolution methods (CLEAN-SC & DAMAS)

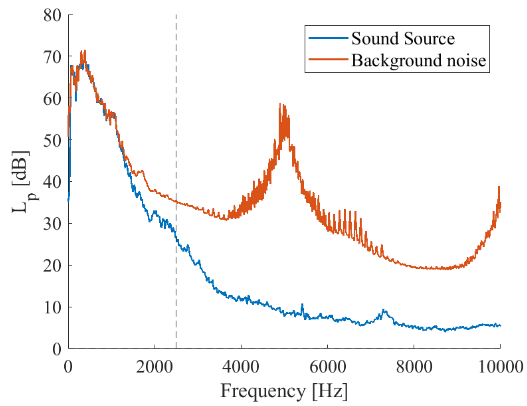
CLEAN-SC [12], was also used to further analyse the results from the experimental campaigns with a maximum iteration of 10, a gain of 0.99 and a beam width of 0.0125 cm. Lastly, the DAMAS [11] deconvolution method was applied with a maximum amount of iterations of 250-500 to further analyse the effect of this advanced beamforming method on the results. Both methods were applied to cases without CSM manipulation and DR.

4 RESULTS

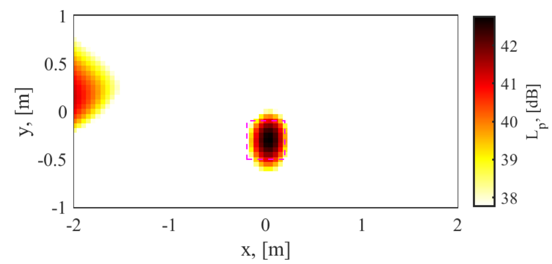
4.1 Speaker Experiment

From the original tests, it was found that set-up 1 already performs adequately from a localisation perspective. This is true for all tonal noise measurements and white noise measurements. The localisation of the source worsens at higher frequencies where the wind tunnel background noise is much louder than the noise source leading to a negative signal-to-noise ratio (SNR). In Figure 6a, the Sound Pressure level [dB] (SPL or L_p) is displayed for the white noise sound source, as well as the background at a flow velocity of 10 m/s. Here, it can be seen that at 2500 Hz (denoted with a vertical black dashed line), the SNR is approximately -10 dB. Using CFDBF, the source plot still clearly shows to noise source, as can be seen in Figure 6b.

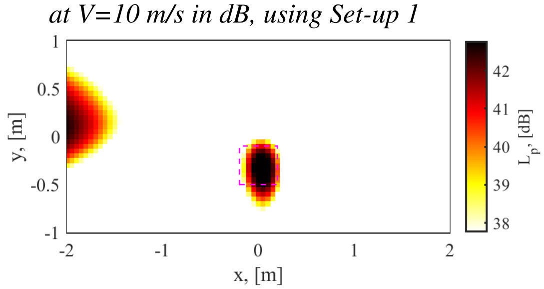
Set-ups 2 and 3 show similar source plots as can be seen in Figure 6c and 6d. Using these set-ups the recorded L_p was decreased, however, also the measured sound signals from the sound source were attenuated. Especially for white noise cases, in which the SNR at higher frequencies was negative, this would explain the lack of improvement in the source plots.



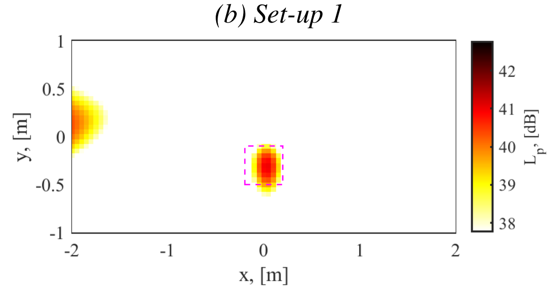
(a) L_p of white noise source and background noise at V=10 m/s in dB, using Set-up 1



(b) Set-up 1



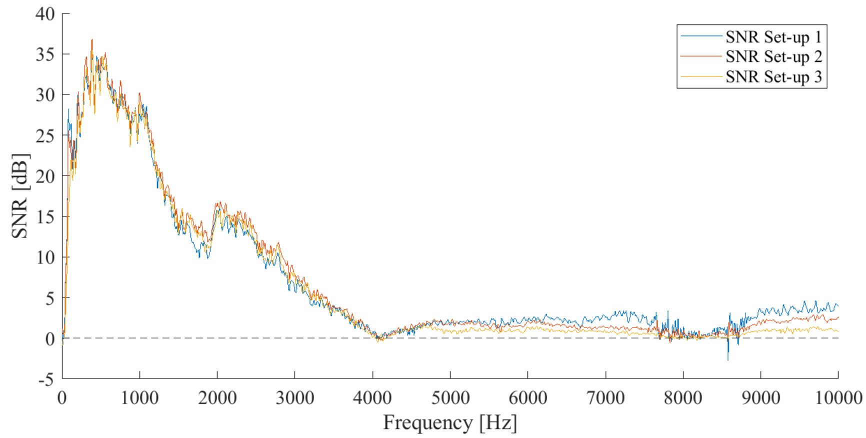
(c) Set-up 2



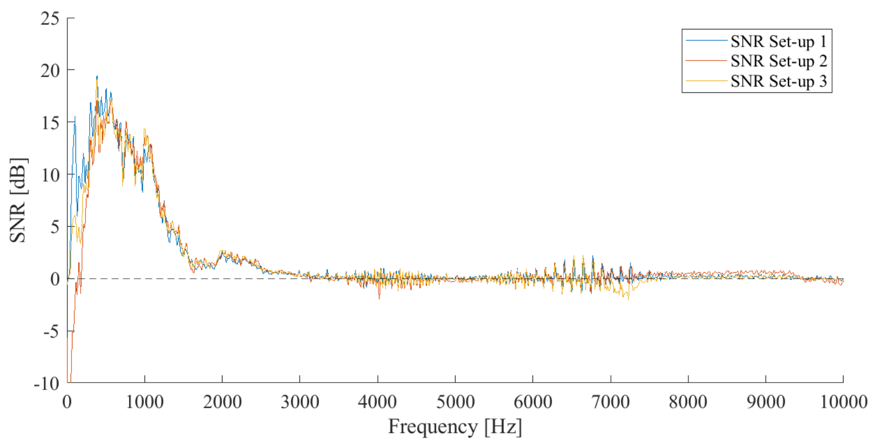
(d) Set-up 3

Figure 6: SPL of white noise sound source and background noise, and (b-d) resulting source plots of white noise source analysed on a T.O.B. centred at 2500 Hz using different set-ups, CFDBF, flow velocity V=10 m/s.

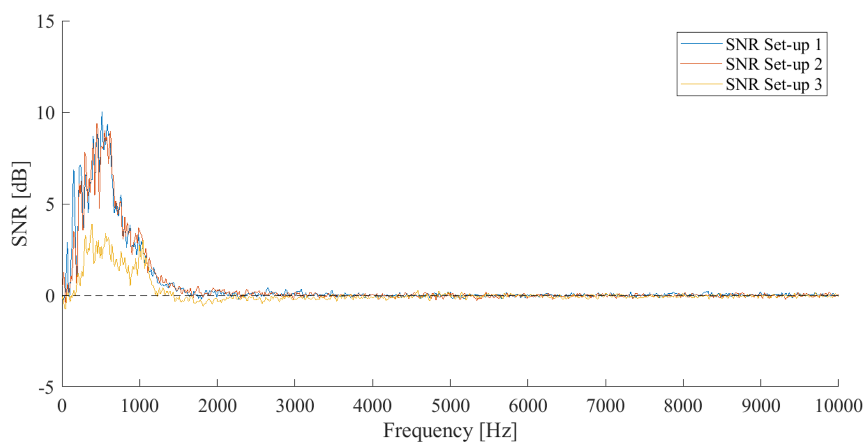
This attenuation of the signal and background can be seen in Figure 7.



(a) Flow velocity V = 5 m/s



(b) Flow velocity V = 10 m/s



(c) Flow velocity V = 15 m/s

Figure 7: Signal-to-noise ratios at 5, 10, and 15 m/s for the different set-ups.

In this figure, the SNRs are displayed for flow velocities of 5, 10, and 15 m/s for all three set-ups. From this, it is clear that there is no significant improvement in the SNR for the advanced set-ups, contrarily, the SNR obtained using set-up 3 at a flow velocity of 15 m/s is significantly lower in the frequency range under 2000 Hz. This phenomenon is most likely due to the different sound absorption characteristics of the melamine rings compared to the original CAE windscreens which are made from polyurethane foam. Additionally, the shape of the rings compared to the spherical windshields could explain this effect.

4.2 Fence Experiment

The applicability study, using the bridge fences, yielded additional results that provide evidence of the measurement set-up and strategy's proof of concept. The commercial real-time beamforming software from the CAE array successfully detected and located a source of noise during the live analysis, as shown in Figure 8. This same location was found during the post-processing of the measurement, see Figure 9.

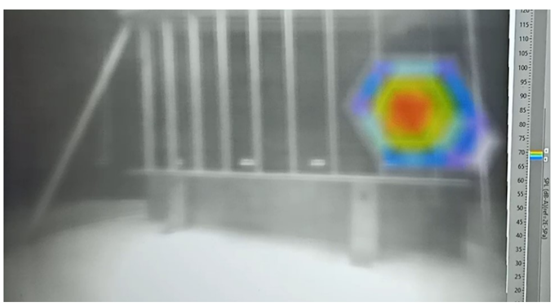


Figure 8: Real-time beamforming in CAE Noise Inspector Software at Z distance 1.5 m.

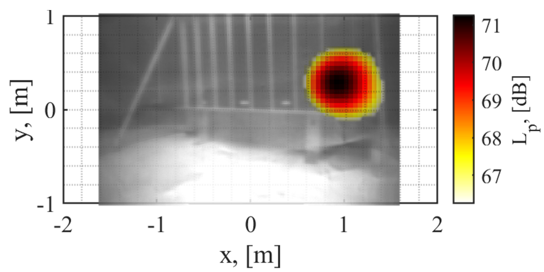


Figure 9: Source plot of the fence analysed on a T.O.B. centred at 1600 Hz, using CFDBF, flow velocity V = 8 m/s.

This noise localisation can not be performed with a single microphone and as such the proposed method broadens the aeroacoustic testing capabilities.

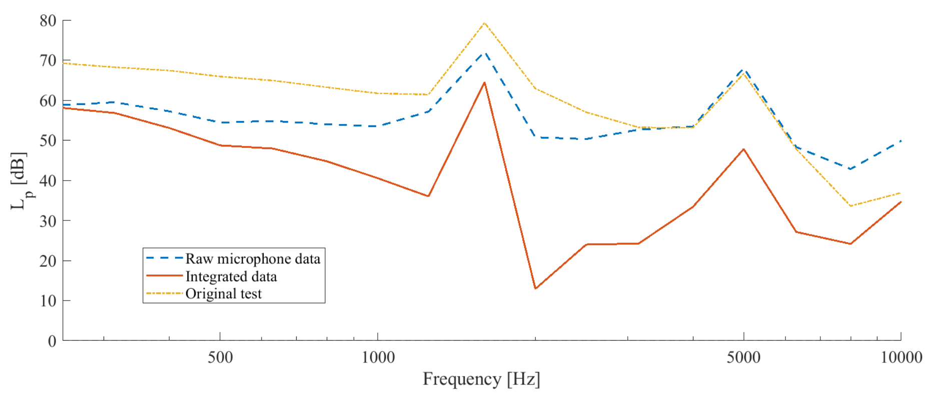
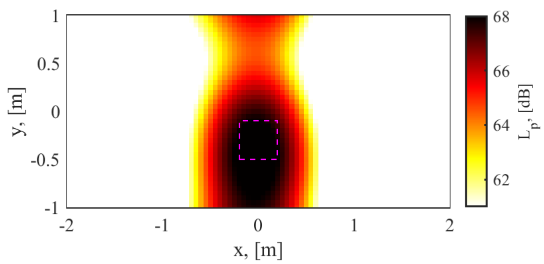


Figure 10: Integrated T.O.B. Spectra compared to results from original Peutz B.V. tests with one microphone.

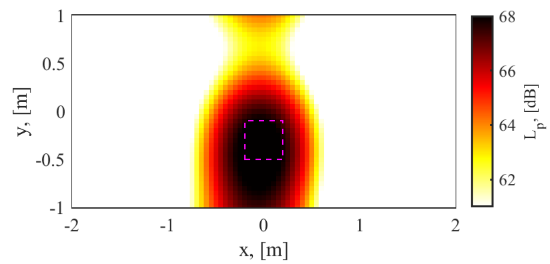
Furthermore, the prominence of the peak is increased which can be attributed to the improvement in SNR due to the increased number of microphones. In Figure 10 the T.O.B. spectra obtained using the current method and their integrated counterpart are visible, as well as the results from the original test reported by Peutz B.V. Here, a peak prominence of approximately 30 dB is found for the 1600 Hz source compared to its neighbouring frequency bands. This is approximately 12-15 dB larger than found during the original tests as reported by Peutz B.V.

4.3 Melamine foam additions

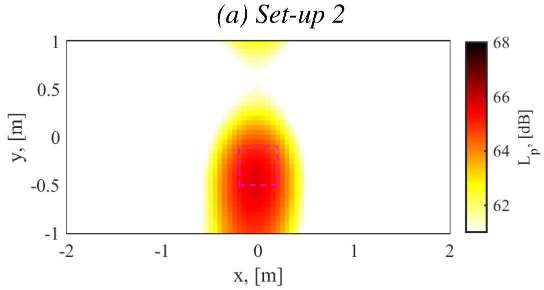
As explained before, two other additions using melamine foam were tested during the verification tests to evaluate whether they could further improve the results. The results of these two additions can be found below in Figure 11. These graphs show that the melamine foam has a positive impact in localising the noise source and identifying the reflections. It also shows that the melamine rings in set-up 3 absorb more sound than the windscreens in set-up 2 leading to a lower peak level of the speaker source.



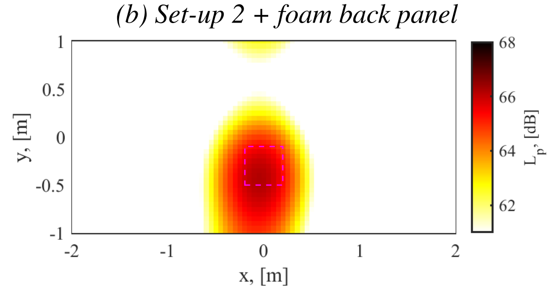
(a) Set-up 2



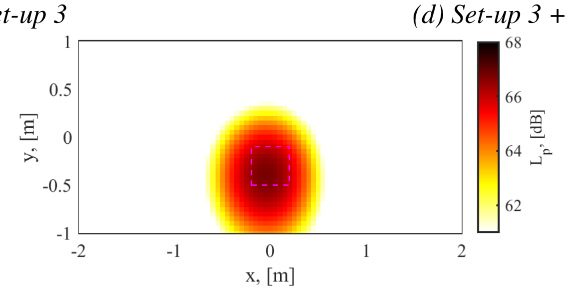
(b) Set-up 2 + foam back panel



(c) Set-up 3



(d) Set-up 3 + foam back panel



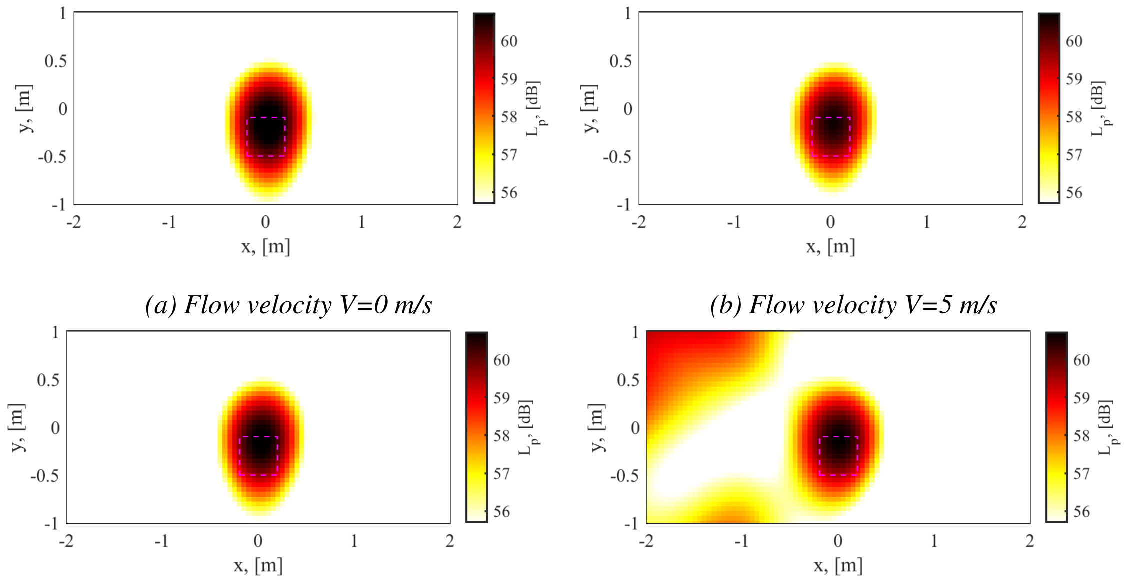
(e) Set-up 3 + foam back panel + foam opposite wall

Figure 11: Source plots analysed on a T.O.B. centred around 1000 Hz at a flow velocity V = 5 m/s using CFDBF and different set-ups.

Lastly, the addition of the melamine panel to the wall opposite the microphone array improves the localisation and reduces the reflection on the wind tunnel floor. Furthermore, a reason for the slight increase in peak level compared to set-up 3 in Figure 11c, and Figure 11d, could be that the absorption of the sound reflections prevents destructive interference at this particular frequency.

4.4 Advanced deconvolution methods

Applying different advanced deconvolution methods to the measurement results led to clearer results and can assist in clarifying the location of the noise sources. To understand the influence of the background noise, Figure 12 shows the same source at different velocities. The source in these graphs is a speaker emitting white noise.



(a) Flow velocity V=0 m/s

(b) Flow velocity V=5 m/s

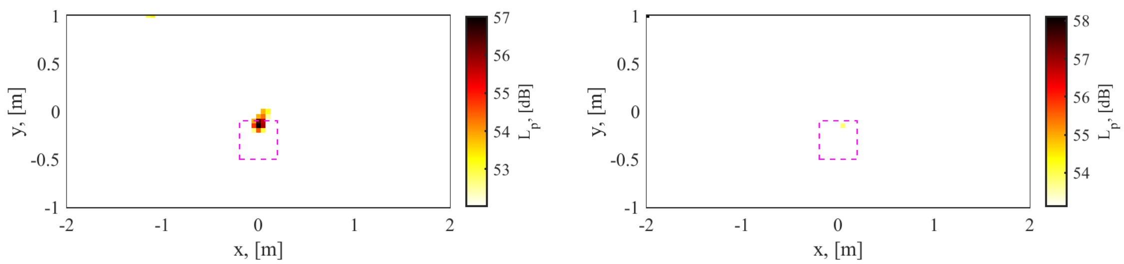
(c) Flow velocity V=10 m/s

(d) Flow velocity V=15 m/s

Figure 12: Source plots of white noise sound source analysed on a T.O.B. centred at 1250 Hz using Set-up 1, CFDBF, DR, and different velocities.

As can be seen in Figure 12d, at a flow velocity of 15 m/s, using CFDBF and DR, it is possible to identify the noise source but there is background noise contamination in the graph.

These results can be improved by using the advanced deconvolution methods CLEAN-SC and DAMAS.



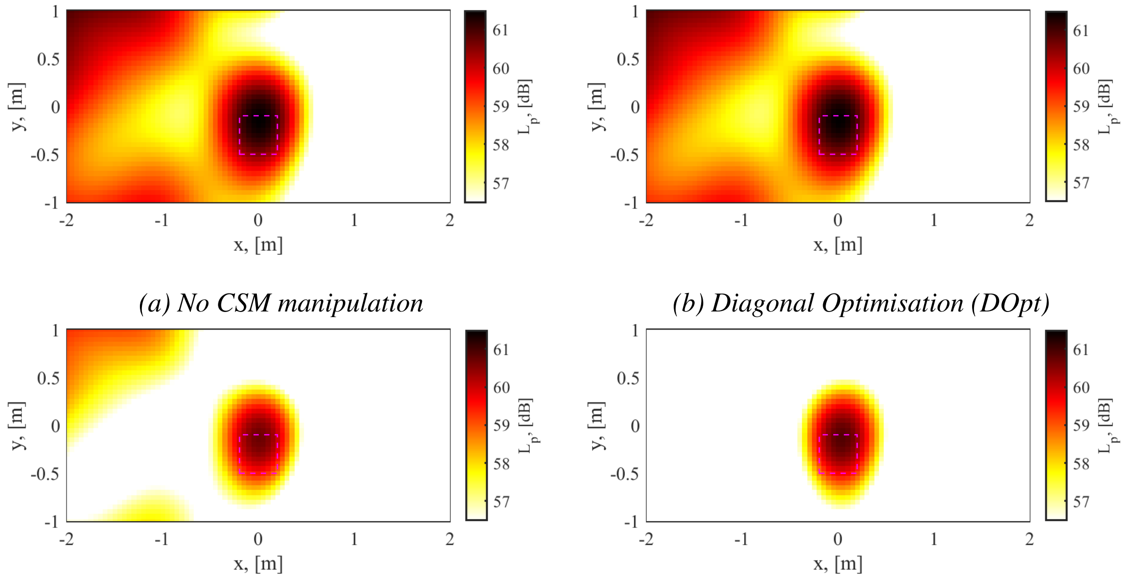
(a) CLEAN-SC with a 0.0125 m beamwidth *(b) DAMAS 250 iterations*

Figure 13: Source plots of white noise sound source analysed on a T.O.B. centred at 1250 Hz, flow velocity V=15 m/s, using Set-up 1, DR and different deconvolution methods.

In Figure 13 it can be seen that both methods clean up the results and eliminate most of the background noise. However, given the longer computational time and the coarser grid size required by the DAMAS method, CLEAN-SC appears to be the most efficient method. Furthermore, DAMAS shows a second sound source with a higher peak level at the top left of the grid, which is not shown by CLEAN-SC.

CSM manipulation

To prevent possible nonphysical results due to the use of DR, diagonal optimisation (DOpt) was also applied to the white noise sound source shown before. Using a convex (CVX) optimisation method [15], with the objective of minimising the diagonal of the CSM, this analysis was performed. As can be seen from Figure 14b, this effect is very limited for this specific case and frequency. Furthermore, a case was analysed in which the CSM of a background measurement without a sound source was subtracted from the CSM of measurement with the sound source. This improves the results significantly as can be seen in Figure 14d.



(a) No CSM manipulation

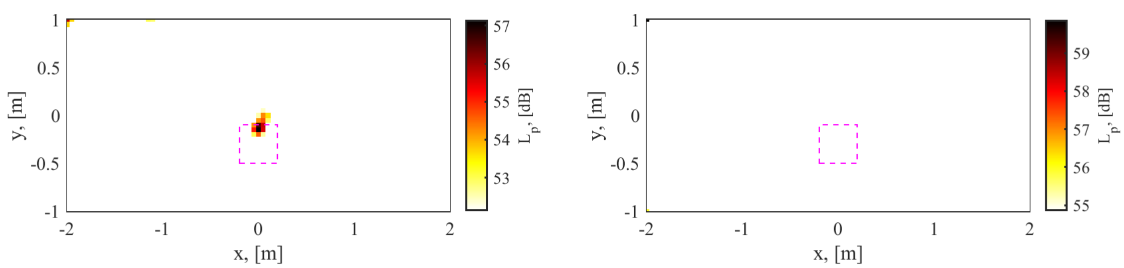
(b) Diagonal Optimisation (DOpt)

(c) Diagonal Removal (DR)

(d) CSM subtraction

Figure 14: Source plots of white noise sound source analysed on a T.O.B. centred at 1250 Hz, flow velocity V=15 m/s, using Set-up 1, CFDBF and different CSM diagonal manipulation methods.

Lastly, the advanced deconvolution methods were applied to a case in which no CSM manipulation was performed to assess their effect. In Figure 15, it can be seen that CLEAN-SC manages to locate the source but has a secondary source in the top left. DAMAS locates a primary source at this top left location but cannot locate the speaker source without the application of CSM manipulation.



(a) CLEAN-SC with a 0.0125 m beamwidth

(b) DAMAS 500 iterations

Figure 15: Source plots of white noise sound source analysed on a T.O.B centred at 1250 Hz, flow velocity V=15 m/s, using Set-up 1, no diagonal manipulation and different deconvolution methods.

5 CONCLUSIONS & RECOMMENDATIONS

To allow for the mitigation of noise pollution, aeroacoustic testing in the early design stage of products or structures could be a helpful tool. However, given the challenging application of aeroacoustic testing in closed-section wind tunnels, and the difficulties as a result of aerodynamic (and not acoustic) optimisation of wind tunnel facilities, a relatively simple and cost-effective way of aeroacoustic testing is necessary. Therefore, this research aimed to investigate to what extent simple set-ups combined with a microphone array and different data analysis methods could provide this improvement in aeroacoustic testing. From the results discussed before, it can be concluded that with relatively simple and cost-effective alterations to a closed-section wind tunnel, aeroacoustic testing with a microphone array can be performed involving sound source localisation provided that the SNR is at least -10 dB. These results can then be further improved using deconvolution methods to increase precision which is partly dictated by chosen parameters. Furthermore, alterations to the wind tunnel set-up can help to reduce the background noise, but for the sound signals tested, the decrease in the measured sound source was nearly the same leading to almost no improvement in signal-to-noise ratio. It would however be interesting to test more, especially higher-frequency, sound sources to evaluate whether, in that case, the SNR might be increased by the set-ups. Additionally, this research has proved valuable in the analysis of an application case with a realistic test subject (a fence) where this method of aeroacoustic testing correctly identified the frequencies of flow-induced noise and increased their peak prominence by up to 15 dB.

Using a different sound source, with a higher SNR, as well as more tonal noise measurements at higher frequencies, specifically with lower SNRs could complement the results and provide a more complete overview of the true applicability of the used method. Additionally, given the location of the noise source on the wind tunnel floor, the results were prone to many reflections, which might be reduced by placing the noise source at a different location in the wind tunnel, which is also more realistic for typical test subjects. Lastly, a quiet surrounding outside of the wind tunnel is of utmost importance to prevent corrupted measurements for which further improvements to the set-up by enclosing the array on the outside could provide better and cleaner results.

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II

Literature Study

previously graded under AE4020

1
Introduction

In recent years there has been an ever-increasing focus on sustainability in all societal and environmental aspects of the world including aerospace, industrial development, mobility, etc. Therefore, the interest in noise pollution and nuisance and ways to mitigate these issues has risen over the years [1]. Simultaneously, the transition towards more sustainable energy sources like wind energy and its accompanying wind turbines, combined with the increase in air traffic led to more noise sources than ever. Additionally, the changing urban environment leads to more noise sources with tall buildings and other structures that create wind-induced noise [2]. All these noise sources can have a detrimental impact on the environment and public health and have been deemed one of the biggest health risks in city life by the WHO.[1] Aeroacoustics is the field of study considered with flow-induced noise like the sources described above. Hence, the importance of aeroacoustic testing in the design stage is clearly proven. This can be done by performing aeroacoustic tests in wind tunnels since wind tunnels have been a proven and validated way of performing experiments on smaller scales and in controlled environments. Where analysis methods like CFD might give very accurate results, they are still modelled and not physically tested. Furthermore, the level of geometrical detail required for aeroacoustic testing is very high and computationally expensive. On the other hand, full-scale tests can be very costly and depending on the design stage of the subject not available at all times. Therefore wind tunnel testing can be very applicable to aeroacoustic testing.

However, aeroacoustic testing in a wind tunnel is, depending on a set of different conditions and parameters not straightforward. Since most wind tunnels are optimised for aerodynamic performance, acoustic performance is not the main point of interest and as a result, wind tunnels are often loud with many different noise sources coming from the flow, reflections, the fans, etc. Therefore, the research into the improvement of aeroacoustic testing in a (closed section) wind tunnel can lead to a better understanding of the phenomena that occur in testing and can lead to better results to alter designs for lower noise production [3].

In order to perform this research, a literature study was performed of which this is the final report. The structure of the report is as follows. First, the research problem and objectives are described including the research questions. Then, some basic theories and metrics that are used in aeroacoustic testing and wind tunnel testing are displayed and summarised. This is followed by three chapters on the main subjects of this research and the research objectives. First, the measurement setup and state-of-the-art practices concerning the hardware and its design are discussed. This includes microphones, microphone arrays, data acquisition systems, and associated items or hardware. Then, wind tunnel alterations are discussed and compared to see if simple, inexpensive, and non-structural alterations can cause a positive impact on the aeroacoustic testing capabilities of a closed-section wind tunnel. Ultimately, different ways of data processing, specifically beamforming methods, are researched and discussed. Finally, the results of the study are summarised and concluded in the final chapter.

[1] https://ec.europa.eu/research-and-innovation/en/horizon-magazine/noise-pollution-one-biggest%2Dhealth-risks-city-life

2
Research Problem

This chapter of the literature study explains and elaborates on the research problem that will be solved in the thesis including the main research question and sub-questions.

2.1. Research problem and objectives

As explained in the introduction of this report, issues occur when trying to perform aeroacoustic testing in a wind tunnel that is not optimised for that purpose. These might be mitigated using different practices. Hence, the research objective of the thesis is to enhance aeroacoustic testing in closed-section wind tunnels. In order to reach this objective, the following main research question needs to be answered:

> *To what extent can the use of different measurement techniques, possibly combined with limited alterations to the wind tunnel, improve the aeroacoustic testing capabilities of a closed-section wind tunnel?*

This question leads to further questions in different subjects. Many of those sub-questions can be found below. For ease of reading and overview, these questions were ordered according to their slightly more specific subject.

General:

- What are the current state-of-the-art measurement techniques in aeroacoustic testing?

Wind tunnel alterations:

- How can the wind tunnel be acoustically treated without decreasing the aerodynamic performance?
- Which other ways are there to decrease the background noise of the wind tunnel?
- To what extent could Active Noise Cancelling or Adaptive Noise Cancelling play a role in decreasing the background noise?

Measurement set-up:

- How can the use of microphone arrays improve the results of aeroacoustic testing?
- To what extent can cavities for placing microphones play a role in aeroacoustic testing, and are they a feasible solution in the wind tunnel?
- Which other ways are there to improve the collection of acoustic data in the wind tunnel?
- How would a microphone array need to be designed for optimum data acquisition?
- What would be the required quality of the subsystems of a microphone array?
- Would an off-the-shelf component be sufficient to adhere to the requirements? And which system would that be?

Data-processing:

- What role can improved post-processing of the data play in more accurate test results?
- Which advanced beamforming methods could be used to increase the quality of the results?

To answer these questions, this literature will delve into the current state-of-the-art microphones, measurement techniques, wind tunnel optimisations, and signal processing in the next chapters.

3
Aeroacoustics and wind tunnel testing

This chapter discusses the basic principles of wind tunnels and wind tunnel testing as well as the fundamentals of aeroacoustics that are required to solve the research problem.

3.1. Basic principles of a wind tunnel

As previously discussed, wind tunnel testing allows for an iterative approach in the early design stages of new products, vehicles, or parts due to its ability to test small-scale principles. To understand how certain tests are performed it is important to understand how a wind tunnel works. Additionally, if one would like to alter parts of the wind tunnel, understanding of its guiding principles is necessary.

In essence, a wind tunnel is a channel that uses a propulsion system to cause flow. This flow is then further altered using changes in the size of the cross-sectional area of the tunnel. This leads to a precisely determined/designed flow in the test section where a product model can be placed to obtain data on the aerodynamics, structural properties and more. A basic schematic of a regular closed-section wind tunnel is visible in Figure 3.1[4].

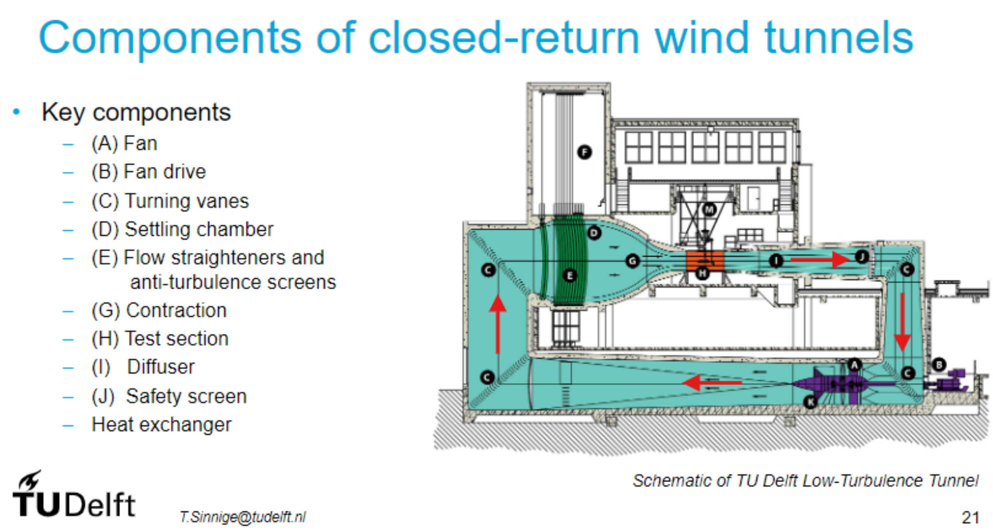


Figure 3.1: Schematic of the TU Delft Low-Turbulence Tunnel [4]

Now that the basic principle of a wind tunnel has been described, it is important to look at the difference between different types of wind tunnels. Since there are quite some differences between wind tunnels based on the test section configuration, tunnel configuration, flow regime, flow properties, and tunnel operation, many options are possible. However, in the context of aeroacoustics, the main division can be made based on the test section configuration. Namely, whether a wind tunnel has an open or closed section[4]. Both have their respective advantages and disadvantages and they need to be considered to gain a thorough understanding of limitations of the wind tunnels.

3.1.1. Open section wind tunnels

Open-section wind tunnels are closed-return wind tunnels where the test section is removed. In other words, the flow moves through an outlet to be then collected by a collector and forced back into the channel. A visual representation of such an open-section wind tunnel can be found in Figure 3.2. This type has certain advantages and disadvantages with respect to a closed-section wind tunnel. Due to the free shear layer from the tunnel outlet, some phenomena and issues can occur. For example: [4]

- Unsteady interactions can occur between the sheer layer and the collector
- The flow quality is generally lower and less predictable than in closed-section wind tunnels
- There are no reflections in the test section leading to better aeroacoustic properties

It is still important to note that even though the stream is free to move, there are still boundary conditions that need to be taken into account and accommodated in the analysis of results. Even though these corrections are most likely smaller than for a closed section, since the boundary is less precisely defined, the boundary corrections are harder to apply.

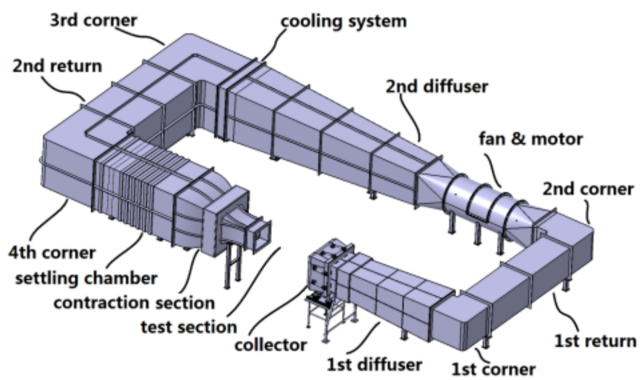


Figure 3.2: A representation of the open test section wind tunnel [5]

3.1.2. Closed section wind tunnels

Closed-section wind tunnels use the same guiding principles as open-section wind tunnels but instead of a free stream between the outlet and the collector, the section is enclosed and the walls impose a boundary condition on the flow. Due to the hard and impermeable walls, there can be no normal flow at the walls and the clear boundary condition of no normal flow at the walls can be imposed. This very precise condition leads to a more accurate correction and contributes to the precision and accuracy of the aerodynamic properties of the wind tunnel. Since it is a closed environment, the aerodynamic performance of the wind tunnel is optimised [4]. The wind tunnel that will be used for the thesis research is the wind tunnel at Peutz B.V. in Mook, The Netherlands.

Peutz B.V. wind tunnel

The wind tunnel at Peutz is a low speed closed section wind tunnel with maximum flow velocities up to approximately 25 m/s. The test section is approximately 3.20 m×3.20 m (l × w), and 1.60m high. This large test section allows for large test subjects and speaks to applicability of the tunnel for multiple different kinds of studies and research. One of the walls of the test section has a see-through glass hatch that can be opened like a window which can also be taken out completely.

3.1.3. Hybrid wind tunnels

In addition to the open and closed section wind tunnels, there are wind tunnels that use different forms of hybrid test section. Examples of these include ventilated test sections which explore the middle ground between open and closed sections, acoustically open test sections that are closed to aerodynamic pressure fluctuations but open to acoustic waves, and adaptive test sections that can be altered in shape to accommodate for different shapes of streamlines. Additionally, anechoic wind tunnels are becoming more and more popular. They are open-section wind tunnels where the open test section is situated in an anechoic room [6, 7]. Since they are open-section wind tunnels they have the positive features of this kind of wind tunnel. However, due to their still enclosed test section, they share some advantages with the closed-section type. An example of these wind tunnels can be found in Figure 3.3. These hybrids are considered out-of-scope except for the acoustically open test section which will be discussed later [4].

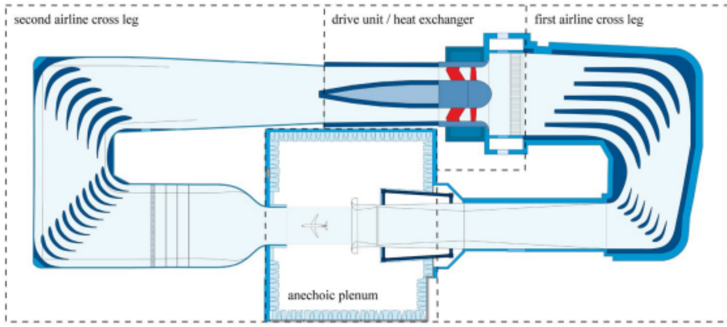


Figure 3.3: Anechoic wind tunnel [6]

3.2. Limitations and challenges in wind tunnel testing

In wind tunnel testing, not everything can occur as it would in real life. Especially at high wind velocities or high altitudes (mostly applicable to aerospace), the wind tunnel can not provide the exact same properties. This is due to the both the shape and size of the wind tunnel as well as the physical limitations with respect to a.o. Mach and Reynolds numbers. To ensure an accurate representation of the real-world problem, data processing needs to be performed, and corrections need to be applied. These corrections can include, based on the test subject, lift interference, solid blockage, wake blockage, buoyancy, slipstream blockage, scaling corrections, etc. [8]. However, due to the main purpose of the Peutz B.V. wind tunnel to assess non-aerospace models, and the main interest of aeroacoustic testing in the wind tunnel, the main limitations are those as a result of reflections, boundary layer flow noise, other noise sources from the tunnel, and possibly scaling. These limitations and challenges will be discussed below.

3.2.1. Noise generation mechanisms in closed section wind tunnels

In a closed section wind tunnel, several noise generation sources can affect the acoustic environment within the facility. These sources can be broadly categorised into aerodynamic noise and mechanical noise. Together they make up the background noise, or the noise that is present in an empty test section [9]. Understanding these noise sources is essential for optimising wind tunnel design and reducing noise levels to improve experimental accuracy and the working conditions for researchers.

Blumrich [10] explains that aerodynamic noise is generated by three different mechanisms. These are; pulsating volume flow through small openings; impact pressure variations on hard surfaces; and turbulent shear stresses. These generation mechanisms are what cause the test subject to generate noise, but they also lead to noise generation by the wind tunnel itself. Mechanical noise is the noise that is generated by for example the motor of the fan.

One of the biggest sources of aeroacoustic noise is the fan. For an axial fan, low-frequency discrete tones are generated as a result of the interaction between the rotating fan blades and stator blades. The wakes of the fan blades periodically go around the stator vanes causing pressure fluctuations that cause a tonal noise. This could be decreased or prevented by altering the cut-off frequency, periodicity, sound pattern rotation speed, axial flow speed and/or blade sweep. In addition to the tonal noise, broadband noise is generated by the fan as a result of the turbulent inflow, the movement of the blade tips through the wall boundary layer, and/or flow separation over the blades. This generation of noise can be limited by reducing the rotational speed of the fan [9].

Other large sources of noise in a closed section wind tunnel are the guiding vanes, cables, probes, and other hardware[11]. These sources lead to background noise due to flow separation, turbulent boundary layers and vortex shedding.

Additionally, the boundary is another source of background noise. According to Grissom [12], this is mainly due to the roughness of the wall. It is however important to note that the noise generated by the boundary layer only dominates the fan noise at certain velocities [11].

To decrease the background noise, some actions can be taken that will be discussed in further sections.

3.3. Fundamentals of Aeroacoustics

To be able to do the research and later the testing and processing of data, one must be familiar with the fundamentals of aeroacoustics. Therefore, some leading practices and theories are described in this section to ensure the correct background knowledge [13]. In its essence, sound is a propagating pressure disturbance of which noise is generally defined as unwanted sound. Noise levels at the observer are determined by the sound source characteristics, the propagation medium and the receiver of the noise. These factors play a role and are important to consider. The propagating pressure disturbance takes the shape of a wave, or a sound wave. This is a longitudinal wave, in other words, the displacement of the particles in the medium is in the direction of the wave propagation, in air this density equals the speed of sound. If the source is a point source radiating sound at a specific frequency, a harmonic wave is created. Of these waves, properties can be found to describe the sound. These metrics will be discussed below.

The audible frequency range of sound is between 20 to 20,000 Hz. Frequencies lower than 20 Hz are called infrasound, and frequencies higher than 20 kHz are called ultrasound. These frequency ranges are important since they are used in the metrics to place sounds in perspective.

Other aeroacoustic phenomena such as reflection, refraction, diffraction, constructive and destructive interference, phase shift, and properties need to be taken into account in the research for which the Reader of the Aircraft Noise and Emissions course of the TU Delft will and has been used [13].

3.3.1. Metrics for Aeroacoustics

The most important or most used metrics to quantify noise are the Sound Pressure Level (SPL or L_p), A-weighted Sound Pressure Level ($L_{p,A}$), and Sound Exposure Level (SEL or $L_{p,A,e}$). These metrics all describe noise in slightly different ways [14].

- SPL or L_p → This metric can be calculated using the reference pressure and the effective acoustic pressure defined as the root-mean-square value of an acoustic wave in a period of time. In other words, it gives a value between the hearing threshold and the pain threshold of human hearing. It can also be used to find an overall sound pressure level (OSPL or $L_{p,overall}$) from multiple sources.
- $L_{p,A}$ → The a-weighted sound pressure level is related to the SPL, however, due to the human ear perceiving different loudnesses for different frequencies of sound, weighting is applied to accommodate for this difference.
- SEL or $L_{p,A,e}$ → is a metric that incorporates the duration of the noise in the calculations. It integrates the acoustic energy and normalises it to a interval of one second. It can be used for measuring more than one noise event within a specified time to find averages.

In addition to these metrics that quantify noise, there are some metrics that describe noise in a qualitative way. They mostly describe how humans perceive noise for example by loudness or sharpness. However, due to the scope of the research to improve aeroacoustic testing in wind tunnels, these metrics are less relevant.

4
Measurement Set-up

To find the best method for performing aeroacoustic testing in wind tunnels, multiple measurement techniques and set-ups can be considered. Hence, this chapter delves into the current and state-of-the-art measurement techniques for aeroacoustic testing. It also describes how such measurement techniques can be optimised for different circumstances and takes into account the required interaction between systems.

4.1. State-of-the-art practices in aeroacoustic measurement techniques

Aeroacoustic testing is applied to many different fields in many different ways: From in-field testing with arrays of dimension 4×4 meters to find the main noise sources of an aircraft, to the small wall-mounted microphones in a wind tunnel for educative purposes. Many advancements have been made over the years leading to a broad base of available steps and improvements to ensure good aeroacoustic testing [15, 16, 17]. Since this chapter focuses on the measurement set-up specifically, and not the post-processing or other ways to influence or mutate the incoming signal, this chapter focuses mostly on hardware and physical objects. These include microphones and their properties, other relevant hardware to acquire the data, ways of combining these pieces of hardware, and other objects that can be used with a direct relation to the microphones to increase the quality of the incoming signal. In this section, an introduction will be given to these parts after which they will be further elaborated on in their respective sections.

Microphone development has come a long way from the first microphones designed in the late 1800s. Essentially, they are transducers that convert sound into an electrical signal which used to be analog but can now also be digital. They range in size from large singing microphones to MEMS microphones that are embedded in nearly every modern smartphone [18]. This leads to a wide catalogue of microphones to choose from with their own advantages and disadvantages. In aeroacoustic testing, the circumstances and possibilities of microphones play a large role in the selection of microphones. Additionally, their compatibility with data acquisition systems can lead to certain choices.

Figure 4.1: Bruel & Kjaer hand-held 2250 Sound Level Meter. [1]

In acoustic testing, small microphones, possibly combined with a preamplifier, are used in combination with sound level meters, or other data acquisition systems. An example of such a (hand-held) set-up can be seen in Figure 4.1

Such a set-up can be used for environmental, occupational and industrial measurement tasks, and has several analytic options included. These include sound and vibration FFT analysis, noise rating measurements and tone assessment[1].

If a problem asks for more than what a set-up like the one in Figure 4.1 can provide. Acoustic cameras

[1] https://www.bksv.com/en/instruments/handheld/sound-level-meters/2250-series/type-2250-s [Retrieved on 12-08-2023]

or acoustic arrays can come into play. Since they can be used to localise noise sources and obtain more detailed results due to the higher number of microphones, they can be used for multiple different applications. Examples include finding the most important noise source of a landing aircraft, determining the source of a whistling sound in a gate, or locating the source of a tonal sound in a factory. These arrays can be made specific to requirements or they can be bought off the shelf. Current off-the-shelf phased microphone arrays and acoustic cameras come in different shapes and sizes as can be seen in Figure 4.2

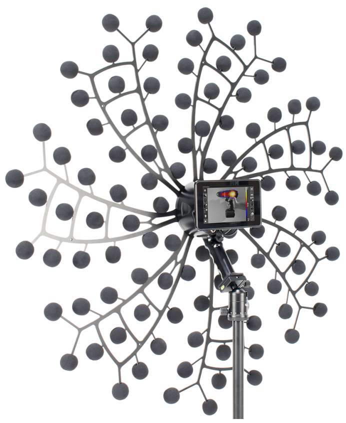


Figure 4.2: Left: CAE phased microphone array, Right: 3D acoustic camera [2]

In addition to using off-the-shelf components, it is possible and can lead to better results to design an optimised array for a specific wind tunnel or for a specific test. Given the broad range of possibilities with regards to microphones, data acquisition, layout and manufacturing, a new and personalised array can lead to the best results for the best price. Arrays and array design will be discussed in section 4.3.

The data acquisition systems are the next pieces of hardware that influence the capabilities of the measurement set-up. Not only are there differences in quality for data acquisition systems, but they also have different applications. In essence, the main function of a DAQ is to transform an analogue signal into a digital domain for displaying, storage, and analysis. A schematic representation for this can be found in Figure 4.3. Even though this representation is valid for all DAQs, the amount of sensors, the input parameters, and the specific software within the DAQ is different and very important for the trade-off. For example, for an array, it is important how many input channels the DAQ is equipped with since it directly influences the maximum amount of microphones an array can have. Additionally, when making an array, the DAQ is generally the most costly part due to its high complexity.

[2] https://www.cae-systems.de/en/products/acoustic-camera-sound-source-localization/bionic-m-112.html and https://acsoft.co.uk/product/acoustic-camera/ [retrieved on 16-08-2023]

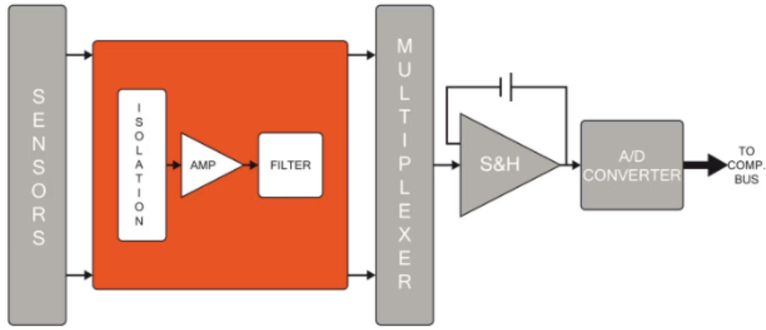


Figure 4.3: Schematic presentation of data acquisition system[3]

Other state-of-the-art measurement techniques in aeroacoustic testing are mostly concerned with protecting microphones to get a clear signal with less broadband noise, noise from reflection, boundary layer noise etc. This can be done in a number of ways using, for example, flush-mounted microphones, microphones embedded in cavities, screens that are impossible for the flow to penetrate but allow the noise to pass through, acoustically treated padding around the microphones etc. Further information and sources on these practices can be found in section 4.4

[3]https://dewesoft.com/blog/what-is-data-acquisition [Retrieved on 10/07/2023]

4.2. Microphones

Microphones play a crucial role in aeroacoustic testing, enabling the conversion of sound waves into electrical signals for analysis. Over the years, various types of microphones have been developed, each with its own advantages and disadvantages. This section explores different kinds of microphones commonly used in aeroacoustic testing and provides examples of their applications [18].

Condenser microphones, as displayed in Figure 4.4a, are widely used in aeroacoustic testing due to their excellent frequency response and sensitivity. They consist of a diaphragm placed close to a back plate, forming a capacitor. As sound waves hit the diaphragm, the distance between the diaphragm and the back plate changes, resulting in a variation in capacitance and generating an electrical signal.

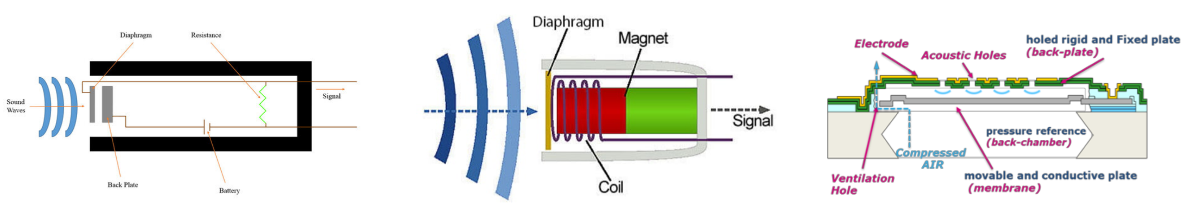
Advantages
- High sensitivity and accuracy in capturing sound details.
- Wide frequency response, allowing for precise measurements across a broad range.
- Low self-noise, enabling detection of low-level acoustic signals.

Disadvantages
- More delicate and prone to damage than other types of microphones.
- Higher cost compared to other microphone types.

Dynamic microphones are robust and versatile, making them suitable for aeroacoustic testing in various conditions. As can be seen in Figure 4.4b, they work based on electromagnetic induction, where sound waves cause a diaphragm attached to a coil to move within a magnetic field, generating an electrical signal.

Advantages
- Durability and resistance to rough handling and extreme environments.
- Relatively affordable compared to condenser microphones.
- Can handle high sound pressure levels without distortion.

Disadvantages
- Lower sensitivity compared to condenser microphones, limiting their ability to capture low-level sounds accurately.
- Limited high-frequency response, potentially affecting measurements in certain applications.
- Heavier weight compared to other microphone types.



(a) Condenser microphone (b) Dynamic microphone (c) MEMS microphone

Figure 4.4: Three different microphone types [4]

MEMS (Microelectromechanical Systems) Microphones, see Figure 4.4c, are miniaturised and widely used in various applications, including aeroacoustic testing and mobile phones. They are based on semiconductor technology and consist of a diaphragm placed above a silicon substrate with embedded circuitry [19].

[4]Conderser https://www.researchgate.net/publication/275046278_A_Study_of_New_Pulse_Auscultation_System
Dynamic https://www.thomann.de/nl/onlineexpert_page_dynamic_microphones_what_is_a_dynamic_microphone.html
MEMS https://www.eeherald.com/section/design-guide/mems-microphone.html [Retrieved on 11-07-2023]

Advantages

- Small size and lightweight, enabling easy integration into compact systems.
- Low power consumption, making them suitable for portable or battery-operated setups.
- Low self-noise.

Disadvantages

- Limited sensitivity compared to larger microphones, impacting the detection of low-level acoustic signals.
- Can be more prone to distortion at high sound pressure levels.
- Less rugged compared to dynamic microphones, requiring careful handling.

These are the most commonly used microphones in aeroacoustic testing. Other types, such as ribbon microphones and laser microphones, may also find specific applications depending on the testing requirements. Selecting the appropriate microphone involves considering factors like frequency response, sensitivity, durability, compatibility with data acquisition systems, and cost.

4.2.1. Analog or digital microphones

Aside from the type of microphone one can already perform a trade-off in the decision based on whether the microphones should be analogue or digital. Both have advantages and disadvantages with as most impactfull difference being that analogue microphones, when applied to arrays have a higher dynamic range and better performance at higher frequency. However, the digital microphones are significantly cheaper, especially when combined with the required DAQ. Thus, for lower frequency measurements, the cheaper, digital microphones, such as MEMS microphones, could be a sufficient option [20].

4.3. Microphone arrays

Phased microphone arrays are advanced tools used in aeroacoustic testing to capture and analyse sound fields with high spatial resolution. Comprising an array of closely spaced microphones, these arrays enable precise localisation and characterisation of sound sources. By applying time delays and phase shifts to the microphone signals, phased arrays can focus on specific regions of interest, enhancing the signal-to-noise ratio and enabling the separation of different sound sources. Phased microphone arrays are particularly valuable in studying complex aerodynamic noise phenomena, such as jet noise, turbulent boundary layers, and rotorcraft noise. Their ability to capture spatial information and provide detailed source mapping makes them essential for understanding and mitigating noise-related challenges in various industries, including aviation, automotive, and wind energy [21, 22]. A visual representation of this is displayed in Figure 4.5 where a linear array of microphones can be seen with a plane wave under an angle. In the directional sensitivity diagram on the right, it is visible that the main lobe is in the direction of the plane wave with a side lobe in the direction of the reflection.

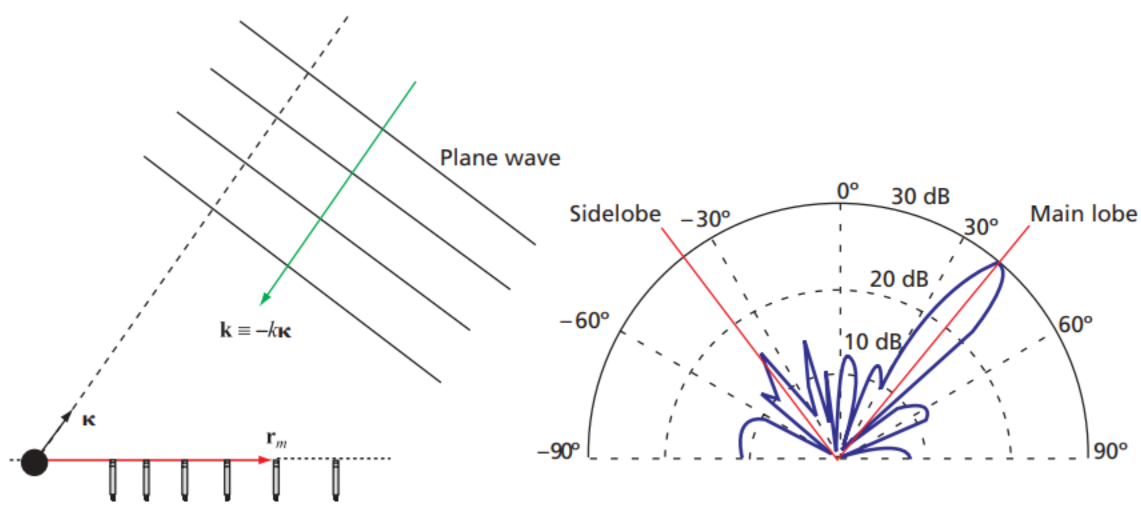


Figure 4.5: Principle of a phased microphone array [23]

Phased microphone arrays employ the concept of beamforming, which exploits the phase differences of sound waves arriving at different microphones. By adjusting the time delay and amplitude of each microphone's signal, the array can steer the sensitivity pattern, creating constructive interference in the desired direction and nulls in other directions. This allows focus on specific sound sources while minimising noise and unwanted reflections. Since beamforming is a way of data or signal processing, it will be further discussed in chapter 6.

Phased microphone arrays find extensive use in aeroacoustic testing due to their ability to localise and characterise sound sources accurately. They enable the identification and analysis of noise generation mechanisms in complex systems such as aircraft engines, rotor blades, or turbulent flows around airframes. Phased arrays are employed in various testing scenarios, including wind tunnel experiments, aircraft flyover noise measurements, and airport noise monitoring [24].

Phased microphone arrays offer several advantages in aeroacoustic testing. They enable detailed acoustic mapping of complex noise sources, providing insights into noise generation mechanisms and helping engineers devise effective noise reduction strategies. These arrays can also perform real-time source tracking, allowing for dynamic analysis and immediate feedback during testing. Furthermore, phased arrays facilitate source separation and source identification, aiding in the development of quieter and more efficient aircraft. While phased microphone arrays offer significant benefits, they also have limitations. The complexity of array design, calibration, and synchronisation requires expertise and resources. Phased arrays are most effective in capturing far-field sound sources and may have limitations in capturing near-field or low-frequency components accurately. Additionally, environmental factors such as wind and temperature variations can affect array performance. Moreover, computational resources are often required to process the data from the array and extract meaningful information.

4.3.1. Microphone array design

Designing an effective phased microphone array involves several considerations. The array geometry, spacing between microphones, and the number of elements impact the array's resolution and directivity. The choice of microphones should consider their frequency response, sensitivity, and self-noise characteristics to ensure accurate measurements. Additionally, the array must be synchronised and calibrated precisely to maintain phase coherence and avoid phase errors that can degrade the beamforming performance [25, 26, 27].

To start the design of an array, it is important to define the main parameters. In general, any planar array can be described by the following three properties [28]:

- Pattern of arrangement
- Aperture, or overall dimension of the array
- Number of microphones

These properties describe the array and its quality. Therefore, to understand the effect each of these properties has on the array, they will be discussed in the following sections.

Pattern of arrangement

There are many configurations in the market ranging between traditional configurations and spiral or random arrays. The simplest patterns are the square grid and circle array, these two configurations have a regular spacing between the microphones to make the shape of a rectangular grid or circle.

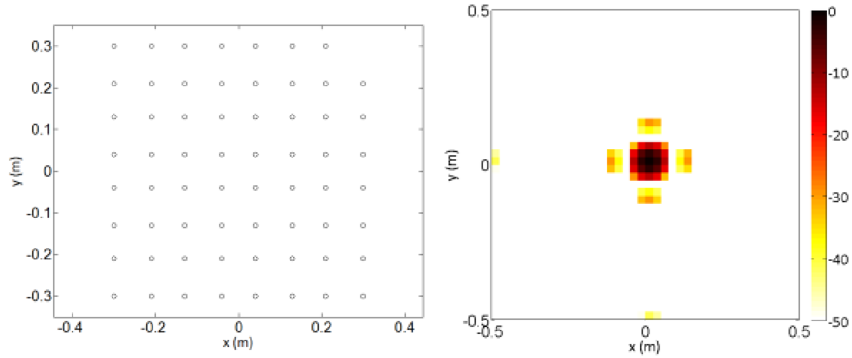


Figure 4.6: Grid array with beamforming result [29]

Due to their configuration they are prone to displaying many side lobes or ghost images. These side lobes show up on a source map as false sources when the source frequency exceeds a calculated limit, which occurs more often in traditional arrays [15]. Additionally, due to the even spacing, grating lobes appear at high frequency, which are a specific form of side lobe that appear when the microphone spacing is greater than half of the wavelength [30]. They approach the level of the main lobe and make it hard to determine the actual source location. These lobes can be decreased by diminishing spatial aliasing as a result of the even spacing of the microphones.

To do that, irregular spacing can be used, which is the case in many spiral arrays. These spiral arrays have lower side lobe levels than traditional configurations but there is still a range of options and configurations to choose from or to design. In Figure 4.7, six commonly used spiral configurations are displayed that were compared by Prime [31].

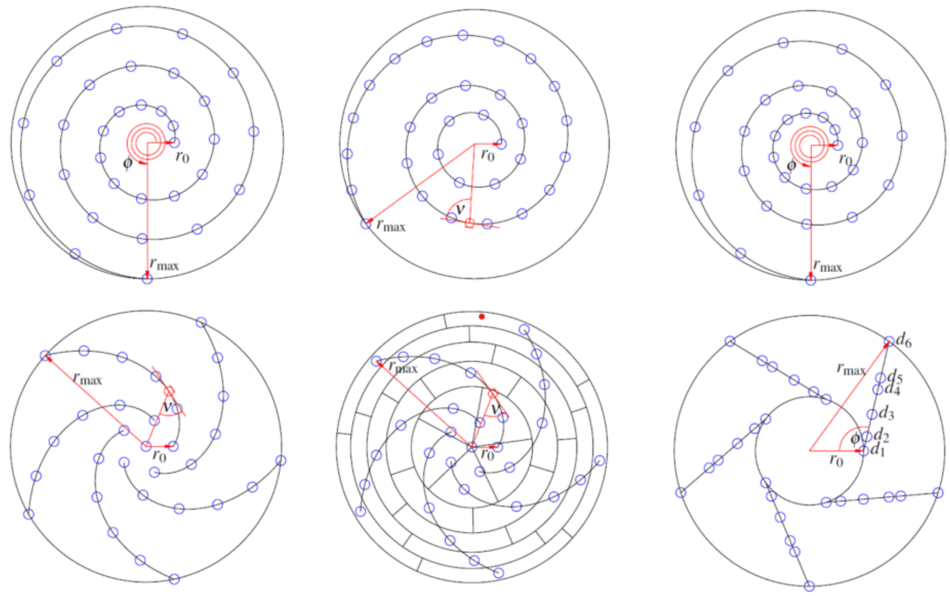


Figure 4.7: Six popular configurations from top left to bottom right: Archimedean spiral, Dougherty log spiral, Arcondoulis spiral, Multi-spiral, Underbrink array, Brüel and Kjær style array [31]

The comparison of these six designs led to the result that the Underbrink array is the best in all-round performance for both near- and far-field applications even though for specific cases, one of the others might be better. In general, an array with multiple arms, with microphones evenly distributed around the array area leads to the best resolution with admissible maximum sidelobe levels (MSL) [32]. Additionally, if the microphones are more closely-spaced towards the middle of the array, and the source is located at the center, the best values for MSL are found. This does however lead to a worse array resolution and decreases the performance over a large area [31].

In addition to these structured arrays, one can also use non-redundant random arrays. These arrays are based on a geometry where no difference vector between any two microphone positions is repeated combined with a random positioning. They are generally better than traditional arrays since their sidelobe structure does not show a sharp cut-off frequency. It is however a complex problem to find out how to best design the array. Additionally, they can be hard to manufacture given the complicated geometry. Furthermore, optimising a random array is numerically demanding due to the large number of free variables [23]. Since the optimisation of an array depends on many parameters such as the investigated noise frequencies, distance to the noise source, allowable MSL and budget, an array is optimised for a specific use case [33]. This gives the impression that for an all-round array, a specifically optimised random array might not be the best fit and a spiral array might be more suitable [34].

Aperture

The aperture of an array, or the total dimension of the array, determines the possible resolution and lowest effective frequency. The Rayleigh limit can be used to determine this resolution [35]. The spatial resolution in the scan plane is given by:

$$\theta_B z_s = R = 1.22 \frac{c z_s}{f D} \tag{4.1}$$

Here the Rayleigh resolution limit $\theta_B z_s$ or R [m] is a function of c [m], the speed of sound, z_s [m], the distance between the array and the source, f [Hz], the frequency of the noise, and D [m], the aperture of the array. For maximum resolution, this value needs to be as small as possible. Therefore, the best resolution will be obtained for the minimum value of $\frac{z_s}{L}$, or in other words the shortest distance to the source with the largest aperture [36]. It is however specific to the use case to what extent this rule is useful. For example, for a large distance to the source, a big aperture can handle sources to a low frequency with better resolution. If this distance is decreased, it comes at the cost of getting a narrow source width for a given frequency. For this case, the grid points would need to be denser to find the sources or a smaller grid should be used.

Number of microphones
The last design parameter of an array is the number of microphones it contains, which depends on a number of parameters. Generally, the more microphones, the better the beamforming will be. But with more microphones comes more cost for both the microphones and the DAQ. A DAQ has a maximum number of input channels which limits the amount of microphones that can be connected to the DAQ. Ultimately it comes down to the optimisation of the locations of the microphones and their total number since an optimised layout might lead to the same result with fewer microphones as a less optimised layout with more microphones.

4.4. Microphone protection

As mentioned at the start of this chapter, the performance of an array or any kind of measurement set-up is also dependent on the surroundings. If there are a lot of reflections, microphone self noise or other noise sources, the array can be very good but still end up giving less reliable or lower-quality results. Therefore, forms of protection of the measurement set-up have been a subject of interest for a time. Specifically in a closed section wind tunnel, there are some noise sources that have a high impact on the measurement capabilities and are generally louder than the noise source of interest. Since microphones are often wall mounted they are situated in or next to the turbulent boundary layer of the wind tunnel as can be seen in Figure 4.8. That is why they are often flush-mounted with respect to the wall.

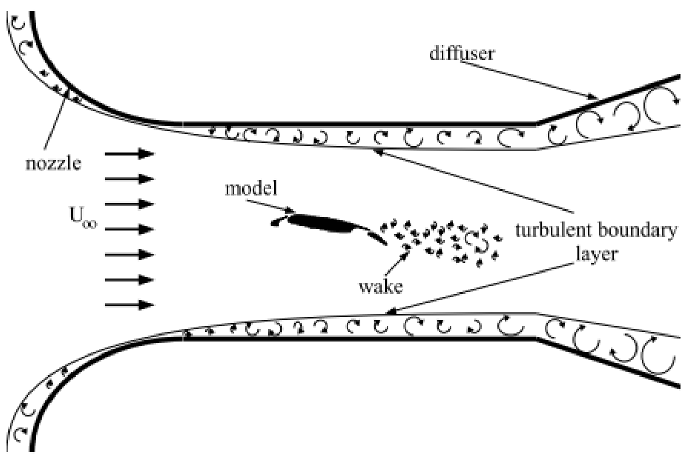


Figure 4.8: Aerodynamic testing in a closed test section wind tunnel [37]

These flush-mounted microphones perform better than microphones that are placed within the flow but there are more options for protecting the microphones. One of these methods is the application of cavities. VanderCreek [38] performed extensive research into the use of cavities and their design. Using different materials for the cavities and different shapes and sizes, the performance of the microphone as displayed in Figure 4.9 was tested. The depth, diameter, angle and padding material were changed to make three different arrays. These arrays were then covered with a stainless steel cloth.

After performing a set of measurements. It could be concluded that the arrays with cavities laced with melamine foam reduced the turbulent boundary layer (TBL) noise by up to 40 dB. The hard-walled cavity already reduced the TBL noise by up to 25 dB, with the exception of amplifying the signal for a number of frequencies due to an acoustic mode. From this, it is safe to say that cavities might play a role in improving the data acquisition by the microphones due to an enhanced SNR. Especially when well-designed, cavities can positively augment the acoustic imaging capabilities of a microphone array [38]. This application of cavities was also found to have a positive impact by Di Marco et al.[39] and Jaeger et al. [40].

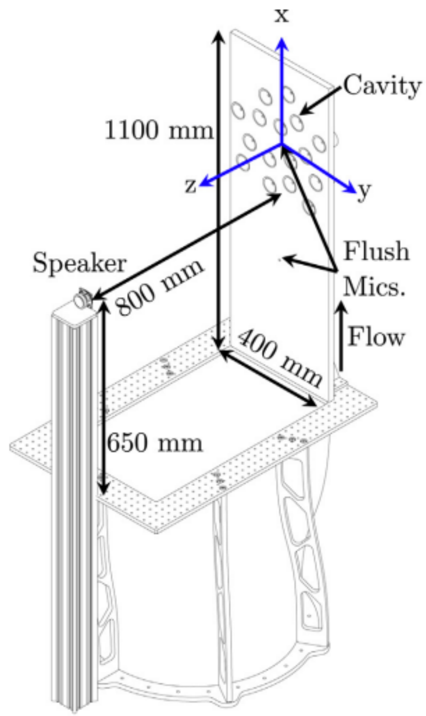


Figure 4.9: Wind tunnel set-up as used by Van der Creek et al.[38]

In addition to applying cavities, a protective layer to place between the microphone array and the TBL can be considered [41]. Specifically, a layer of protection that is acoustically open, and aerodynamically closed. In literature multiple different materials have been considered. Especially stretched Kevlar has been a material of interest. Jaeger et al.[40] tested fibreglass, stainless steel and Kevlar cloths. During those experiments, it was found that fibreglass cannot resist the shear forces and disintegrates due to the flow. The stainless steel performed better but fatigued downstream of the array due to its stiffness and the unsteady loads. Using the Kevlar cloth these problems did not occur due to its high resistance to shear forces and low acoustic impedance. Kevlar is, however, costly, requiring the need to further assess whether, at lower flow velocities, stainless steel cloths might be sufficient to improve the data acquisition of the array.

5
Wind tunnel alterations

Another possibility worth looking into is the alteration of the wind tunnel to either increase quietness and/or dampen background noise. It is, however, of paramount importance to keep the decrease in aerodynamic performance to a minimum. Therefore, different ways of wind tunnel alterations will be discussed in the following paragraphs. The challenges and possible solutions are elaborated upon after which conclusions can be drawn.

5.1. Acoustic treatment

Another option for improving the aeroacoustic testing capabilities of a wind tunnel is to decrease the noise from other sources than the one under investigation. For example, if one can decrease the noise from the fans, or the noise generated by the guiding vanes, the background noise is reduced and better base results are obtained. However, in a wind tunnel that was built for aerodynamic testing, only limited alterations can be made to still maintain the aerodynamic properties and efficiency. Therefore it is important to look at different ways in which sound can be absorbed at different stages of the wind tunnel.

5.1.1. Sound Absorbers

Sound absorbers are modules that can be used to absorb sound at different locations and frequencies. They often consist of fibrous or porous materials where the frequency of the sound that can be absorbed relies on the thickness of the absorber, with low-frequency sounds requiring thicker absorbers. Additionally, the shape of the absorber can play a role. A commonly-used example of this combination of thickness and shape are different acoustic wedges, of which some examples are shown in Figure 5.1.

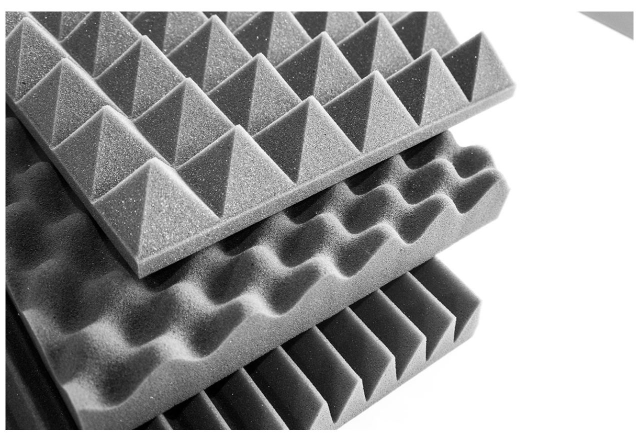


Figure 5.1: Three examples of acoustic panels with different geometries. [1]

These wedges have a low impedance at the surface and a higher internal impedance. This impedance increases with increasing wedge thickness and therefore decreases the propagation of the sound [42]. These wedges are however less applicable to wind tunnel testing due to their effect on the aerodynamic properties of the flow and the chance of deterioration of the fibres as a result of the flow. Therefore, other sorts of absorbers can be considered, with different applicability levels. In Blumrich et al.[42], a comparison was made between the following four absorbers:

- Membrane Absorbers

[1] https://business.uratex.com.ph/product/isound-acoustic-foam/

- Compound Panel Absorbers
- Broadband Compact Absorbers
- Microperforated Panel Absorbers

In this comparison, the Broadband Compact Absorber was found to be the most applicable to aeroacoustic wind tunnels. This form of absorber consists of a compound panel absorber and an additional micropore foam layer. A schematic of the structure of these absorbers can be seen in Figure 5.2. Here it can be seen that metal pates are combined with the micropore foam plates which work as a mass/spring and plate resonator assembly. This system is normally tuned to low frequencies and the application of the extra foam plate in the broadband compact absorber that has good absorption properties in higher frequencies expands the applicability of the absorber. This allows for this kind of absorber to be used in a.o. acoustic wall treatment for wind tunnels.

(a) Compound panel absorber

(b) Broadband Compact absorber

Figure 5.2: Structures of different absorbers [43]

These sound absorbers can be applied to different sections of the wind tunnel with varying effects on both the aerodynamic and acoustic performance of the wind tunnel[44]. Therefore it is important to consider where to apply absorbers if at all. Santana et al.[45] performed an analysis of the effects of acoustic treatment in different areas of the wind tunnel. For that research, areas with a high risk of boundary layer separation or other expected aerodynamically sensitive phenomena were discarded. This led to the application of acoustic treatment on several walls, the guiding vanes, and the fan area. The areas that were treated in the wind tunnel can be found in Figure 5.3.

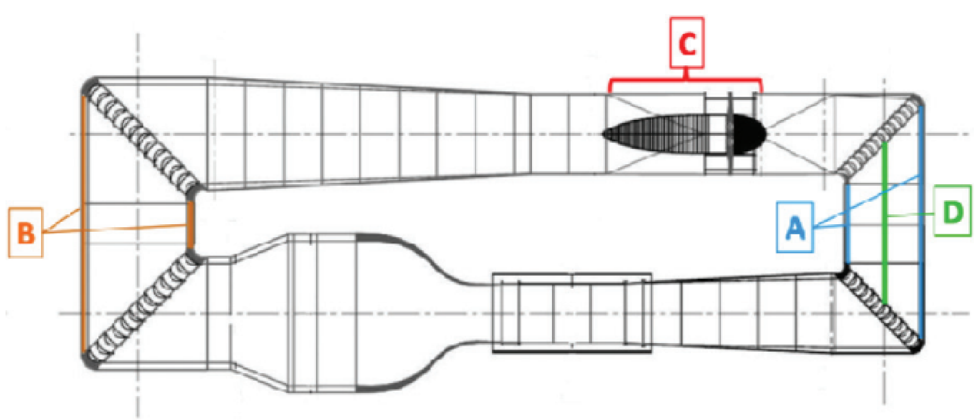


Figure 5.3: Top view of LAE-1 acoustically treated wind tunnel sections [45]

Here, sections B are downstream of the fan and sections A are upstream of the fan. These sections were chosen and the thickness of the applied acoustic panels was altered to accommodate for a maximum decrease in flow speed of 1.5 percent. The absorbers used for this alteration are melamine foam panels, of which some were later replaced with compound panel absorbers [46]. The study by Almeida et al. [46], was a continuation or further development of the same wind tunnel that was altered by Santana et al.[45] and delves more into the possibilities of changing the test section and microphone set-up which was discussed before. Another wind tunnel that has undergone elaborate acoustic treatment is the Virginia Tech Anechoic Wind Tunnel with alterations as displayed in colours in Figure 5.4. The applied treatment to the different sections is:[47]

1. 5-cm thick Melamine foam lining applied to the downstream ends of the sidewalls of the diffuser absorbing high-frequency noise coming upstream from the fan.
2. Variable thickness foam liner installed around the fan blade tips to reduce tip noise. The diffuser and fan treatments alone produced about a 5 to 6 dB reduction across the entire frequency range.
3. A 5-cm thick urethane foam liner was installed on the walls of the settling chamber, covering about 56 m2. This liner produced substantial further reductions of up to about 6 dB, particularly below 1 kHz.
4. A 5-cm thick urethane foam liner was installed on the walls of the northern leg of the flow circuit, upstream of the settling chamber, covering about 74 m2 of wall space.
5. Extensive work was undertaken to acoustically treat the 3 by 7.6-m northeast vane set that follows the fan. The final configuration, which includes 2.5 cm thick melamine foam applied to the pressure side of the vane, was chosen because it appeared to have no adverse effects on the pressure distribution while providing an acoustically absorbent flow surface that faced the fan.
6. 5-cm urethane foam was also applied to the floor of the north leg of the tunnel circuit
7. 5-cm urethane foam was also applied to the walls of the southern leg of the circuit, continuous with the diffuser treatment

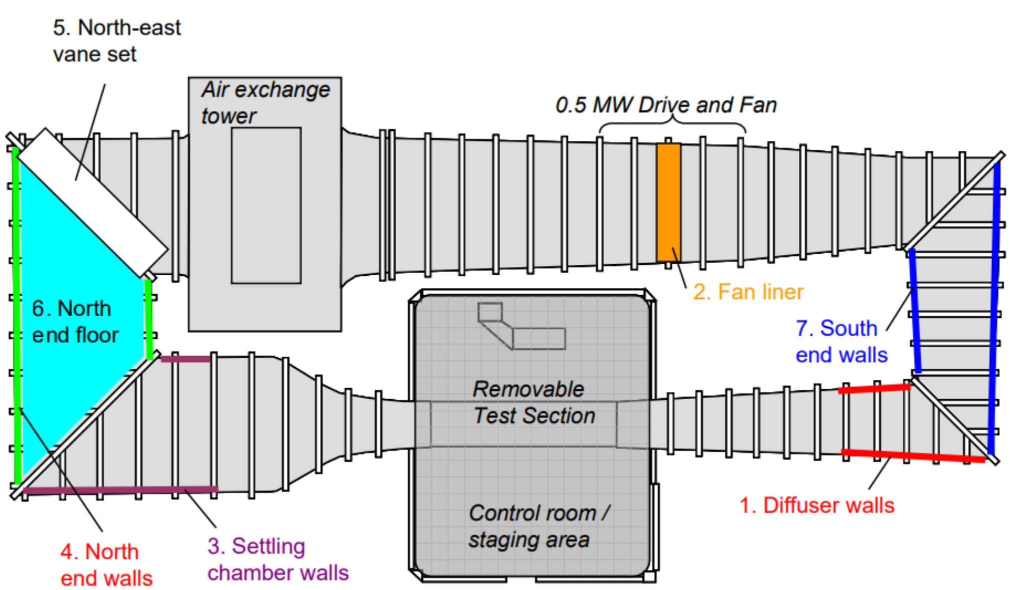


Figure 5.4: Acoustic treatment in the Virginia Tech Anechoic Wind tunnel [47]

This application of different kinds of foams and alterations led to a decrease of background noise between 10 and 15 dB depending on the frequency. These alterations do however affect the aerodynamic properties of the wind tunnel much more than the alterations in the LAE-1 tunnel. Therefore, not all of these alterations are realistic from both a cost and performance perspective if the goal is to minimise the decrease in aerodynamic performance.

In addition to the type, placement, and size of absorbers, the materials and costs need to be considered. Commonly used materials for the purpose of acoustic treatment are a.o. melamine foam, PU foam and polyester wool. These porous materials have good sound absorption characteristics due to high viscous resistivity. [48] Aside from their properties with regards to performance, they also range in price. Due to the low production cost, Polyurethane (PU) foam is, as can also be seen from the alterations in the Virginia Tech Wind Tunnel[47], a much-used option. [49] Cost-wise, a commercial cost from ≤ 100 per m^2 for 5 cm thick foam [2] can be found.

5.1.2. Wind tunnel part redesign

In addition to acoustically treating (parts of) the wind tunnel, better acoustic performance can also be reached by redesigning parts of the wind tunnel. For this, the alterations that are least impactful to the structure and therefore also least expensive are changes to the guiding vanes and fan(s). Since these systems are more easily replaceable, the redesign of them can be considered. However, due to the impact on the aerodynamic performance of the wind tunnel and the involved cost. These kinds of alterations are not considered for the research that was described in this report.

5.1.3. Test section treatment

Another way of acoustic treatment that has proven useful is the replacement of walls in the test section by kevlar panels which make the wind tunnel aerodynamically closed but acoustically open. This means that the best of both an open wind tunnel and a closed tunnel are combined. A schematic example of this can be seen in Figure 5.5. These acoustic windows are surrounded by anechoic chambers to improve the measurements. [47]

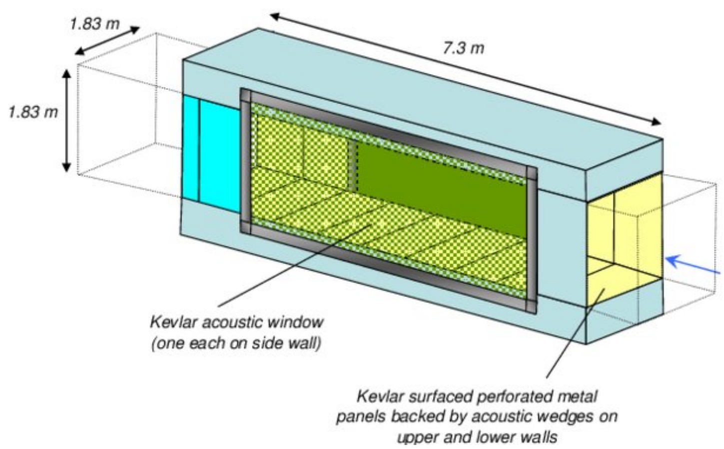


Figure 5.5: The new acoustic test section at the Virginia Tech anechoic Wind Tunnel [47]

As stated before, the complete replacement of walls or other structural parts of the Peutz B.V. wind tunnel was deemed out of scope. However, due to the current state of the wind tunnel, which includes a window on the side that can be opened and taken out, this is a relevant alteration that needs to be further researched, especially combined with the information that was described above in section 4.4. Brown et al.[50] investigated testing in an anechoic wind tunnel where the walls of the test section were also replaced by Kevlar panels. This research was performed on a test section with one hard wall and one Kevlar wall as displayed in Figure 5.6.

[2] https://www.eki.nl/schuim/polyetherschuim/eki120# [Retrieved on 27-07-2023]

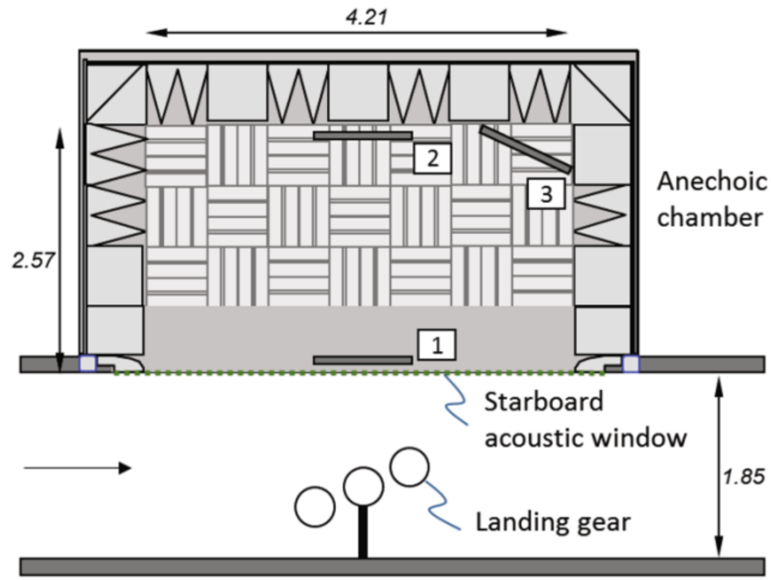


Figure 5.6: Half anechoic wind tunnel test in the Virginia Tech wind tunnel [50]

These tests resulted in the conclusion that aeroacoustically, these hybrid anechoic test sections perform better than a regular, closed-section wind tunnel. Aerodynamically, due to their close resemblance with closed-section wind tunnels, fewer corrections are required than in an open-section wind tunnel but some corrections still need to be taken into account [50].

5.2. Active and adaptive noise control

Active noise control (ANC) techniques play a crucial role in wind tunnel testing by mitigating the adverse effects of aerodynamic noise generated during experiments. ANC involves the use of sound wave cancellation methods to reduce or eliminate unwanted noise. In the context of wind tunnel testing, ANC systems employ loudspeakers strategically placed within the test section to emit anti-noise signals that destructively interfere with the aerodynamic noise generated by the model.

Another option for cancelling unwanted noise is adaptive noise control (AdNC). This is an electronic, in-wire signal cancellation technique. Hence, it does not involve the actual pressure fluctuation cancellation [51].

Research has been done into both active and adaptive noise control or cancellation and both options have their own benefits and challenges [52, 53, 54, 55].

For this thesis, adaptive noise control is deemed out of scope due to its electronic complexity. However, active noise control might offer several benefits for a potentially lower complexity. Firstly, it enables researchers to separate the acoustic contributions of the model and the background wind tunnel noise, thereby providing more accurate measurements of the model's noise characteristics. Additionally, ANC can be employed to create quieter testing conditions, allowing for better signal-to-noise ratios and enhancing the clarity of acquired data. This helps in precisely identifying and characterising noise sources, leading to improved understanding and noise reduction strategies.

However, the implementation of ANC in wind tunnel testing is not without challenges. Designing an effective ANC system requires precise measurement and modelling of the aerodynamic noise sources, as well as the dynamic characteristics of the wind tunnel[51]. The control algorithms must be carefully optimised to achieve optimal noise cancellation without adversely affecting the desired flow conditions. Moreover, ANC systems need to account for variations in noise sources and flow conditions across different test cases. To deal with these varying issues, most ANC systems use adaptive filters.

The control structure of ANC can be classified as either feedforward or feedback control. These types explain the basic workings of the system while immediately defining the hardware required. A feedforward system a reference sensor, a secondary loudspeaker and an error sensor. A feedback control system only requires an error sensor and a secondary loudspeaker [56]. While an ANC system could provide better results, there has not yet been a successful ANC application in closed-section wind tunnels. Therefore, some basic testing of such a system will be performed during the thesis but it will not be the main focus of the research.

6
Data Processing

This chapter describes the data processing of aeroacoustic test results, specifically beamforming and different conventional and advanced beamforming techniques. Additionally, there are ways to decrease the background noise in data processing which will be discussed in this chapter.

6.1. Beamforming

"Beamforming is a technique to improve the signal-to-noise ratio of received signals, eliminate undesirable interference sources, and focus transmitted signals to specific locations." [1] In other words, it is a form of signal processing that relates to the spatial filtering of a signal. Conventional beamforming methods combine the signals from a number of microphones to localise, separate and characterise noise sources. In addition to the conventional method, more specific, accurate and/or precise methods have been developed which will discussed later on.

The conventional beamforming (CBF) method is based on the phase delays between the emission of the sound signal at the source and the signal received by the microphones [57]. It is applicable for both the time domain and frequency domain. Of these, the frequency is generally more interesting since it allows for the possibility of a frequency analysis [58]. The development of beamforming methods has always depended on hardware development due to the available input channels, computational time and data reduction [59]. In the simplest version of beamforming, microphone outputs are scaled by the elements of the steering vector, and summed. This leads to the mathematical steering to a position. This steering vector, or microphone weight vector, can then be used to find the estimate of the sum over the array of microphones of the acoustic pressure caused by the source at a single point [60]. Still, the possibilities and results of the beamforming method depend highly on the array and position in the wind tunnel.

6.1.1. Beamforming in wind tunnels

Since phased arrays in closed wind tunnels usually consist of a set of microphones flush-mounted in the wall of the test section, they are subject to the wall boundary layer. This creates a signal that can be higher than the acoustic radiation from the model. To accommodate for this, it is possible to only process the sound that is correlated between pairs of array microphones. Mathematically this would mean that the diagonal of the cross spectral matrix is deleted before beamforming [60].

$$\mathbf{C} = \langle \vec{p}(t) \cdot \vec{p}^{\dagger}(t) \rangle$$

Where C is the cross-spectral matrix and p are the pressure vectors. Additionally, in closed-section wind tunnels, reflection can become an issue. This can be accounted for by considering the reflected images as additional sources. (See Figure 6.1) Then, by confining the beamforming grid to the size of the test section, these reflections could be ignored.

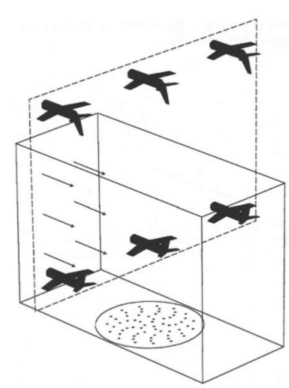


Figure 6.1: Test section with reflective images [60]

[1] https://nl.mathworks.com/discovery/beamforming.html [Retrieved on 14-07-2023]

6.1.2. Advanced beamforming methods

In recent years, several advanced beamforming methods have been developed to further enhance the capabilities of aeroacoustic testing [62]. These deconvolution methods are used for the post-processing of the source maps obtained by the conventional frequency domain beamforming (CFDBF). They offer improved source localisation accuracy, better noise suppression, and increased robustness against environmental factors. There are several extensively tested and widely applied methods but this chapter will only focus on DAMAS (Deconvolution Approach for the Mapping of Acoustic Sources) and CLEAN-SC (CLEAN based on Source Coherence)[2] due to their application in the industry [61].

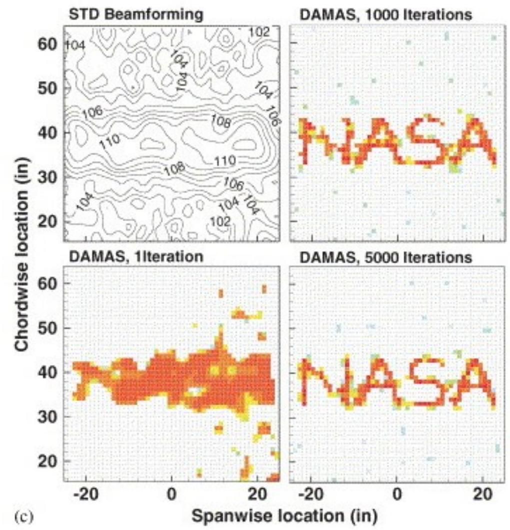


Figure 6.2: Standard beamforming and DAMAS results for f = 30kHz and a resolution of $\Delta x/B = 0.25$ where Δx is the distance between grid points and B is the beamwidth [61]

DAMAS

DAMAS is a beamforming algorithm that employs a regularised least-squares approach to enhance the localisation and separation of sound sources. As a first step, it uses traditional beamforming. Then the purpose of DAMAS is to pose the array problem in a way that the required source strength distributions are cleanly obtained from the beamforming array characteristics [61]. This is achieved mathematically by creating a system of linear equations that relate a spatial field with beamformed array-output responses to source distributions with the same location points. This system is then used as the DAMAS inverse problem. Experimental results of this method can be seen in Figure 6.2.

CLEAN-SC

CLEAN-SC is another advanced beamforming method. Like DAMAS it starts with a conventional beamformer to obtain an initial beamforming map. Then, it iteratively removes the part of the source plot which is spatially coherent with the peak source. It can also extract the absolute sound power levels from the source plots. Other features of CLEAN-SC include high processing speeds and the ability to filter low-frequency wind tunnel noise. [63] An example of the impact of this method can be seen in Figure 6.3.

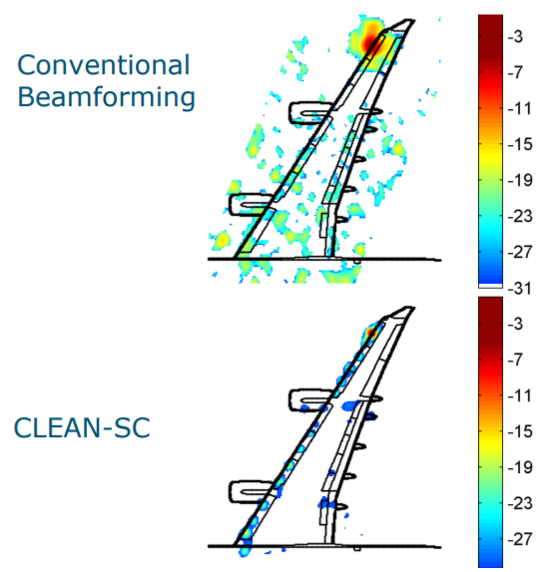


Figure 6.3: Conventional beamforming versus the Clean-SC method[63]

These advanced beamforming methods offer enhanced capabilities and improved accuracy in aeroacoustic testing. Naturally, they still depend on the quality of the data that is generated by the measurement system but these methods can be used to draw better conclusions on the data even when the data is imperfect.

[2] https://www.gfaitech.com/knowledge/faq/clean-sc [Retrieved on 16-8-2023]

7
Conclusion & Summary

Due to the rising interest in noise pollution and its mitigation, aeroacoustic testing is becoming a larger player in the industry. Especially since early detection of noise generation mechanisms can lead to changes in the design of industrial buildings, infrastructure, and other products. For that reason, it is important to qualitatively and quantitatively assess noise in the design stages of these products. Due to the broad application and validated way of measuring using wind tunnels, it is a logical step to start viewing wind tunnels as an option to perform aeroacoustic tests in the early design stages. However, for that to be reliable and applicable, some alterations might need to be made, and techniques need to be researched and assessed.

The purpose of this literature study was to generate, assess, and summarise the current best practices and state-of-the-art techniques in aeroacoustic testing. To do that, multiple subjects within aeroacoustic testing were researched and a large number of papers, articles, books, and other resources were analysed and compared. This ultimately led to the current report.

After getting familiar with the basics of aeroacoustics and wind tunnel testing, while also taking a look at different wind tunnel types and configurations, three subjects were defined as subjects of interest. The measurement set-up, wind tunnel alterations, and data processing. These subjects were researched on their state-of-the-art practices, limitations, costs, and possibilities.

The measurement set-up section discussed different kinds of microphones, configurations of microphones in arrays and ways to protect the microphones from the flow. For the application in closed-section wind tunnels, either condenser or MEMS microphones are the best contenders due to their cost and capabilities. Arrays are widely viewed as a validated way of performing aeroacoustic tests and the configuration and size of the array have a high impact on the performance of it. Therefore, in the thesis research, attention needs to be paid to these properties to ensure the best performance for a reasonable price. Furthermore, there have been very promising experiments on the protection of microphones by placing them in cavities and behind sheets or cloths of Kevlar or stainless steel as protection from the turbulent boundary layer.

Furthermore, limited alteration to the wind tunnel might prove to have a positive effect on the aeroacoustic possibilities. To achieve this, acoustic padding can be applied to some places around the wind tunnel without drastically impacting the aerodynamic properties of the wind tunnel. Due to the current layout and structure of the wind tunnel that will be used for the thesis, even a somewhat hybrid anechoic test section may be an option. In this hybrid test section, the already open side of the wind tunnel could be used to create an anechoic chamber combined with an array and protection as discussed before to significantly improve the aeroacoustic capabilities of the wind tunnel. Lastly, the use of adaptive noise control and active noise control has been researched. These two ways of decreasing the background noise, one physical, and one in-wire signal, might prove to be applicable but due to their complexity, they do not carry the highest priority going forward.

Lastly, the data processing of the results has been discussed where conventional beamforming methods might be altered or expanded with more advanced methods to improve the data in retrospect. To achieve this, two methods have been discussed that show potential and will be further considered in the future.

All in all, this report contains a thorough investigation into the current best practices with regard to aeroacoustic testing to ultimately answer the research question:

> *To what extent can the use of different measurement techniques, possibly combined with limited alterations to the wind tunnel, improve the aeroacoustic testing capabilities of a closed-section wind tunnel?*

III

Supporting work

A
Overview of Beamforming program

In addition to the physical building of the test set-up and the performance of the tests, a pre-existing program used for beamforming, created by dr. R. Merino-Martinez, was updated and altered to allow for fast and complete data processing. After changing the datatype of the recordings to allow for use by the program, it performs a full analysis leading to spectra, spectrograms, beamforming graphs, and more data on the signals. This program was altered and improved using data from a preliminary test with the system and data from the first experimental campaign. After the acquisition of the data from the second experimental campaign, only limited changes were made to the program. Furthermore, advanced beamforming methods were applied to determine if and to what extent this form of post-processing could further improve the results.

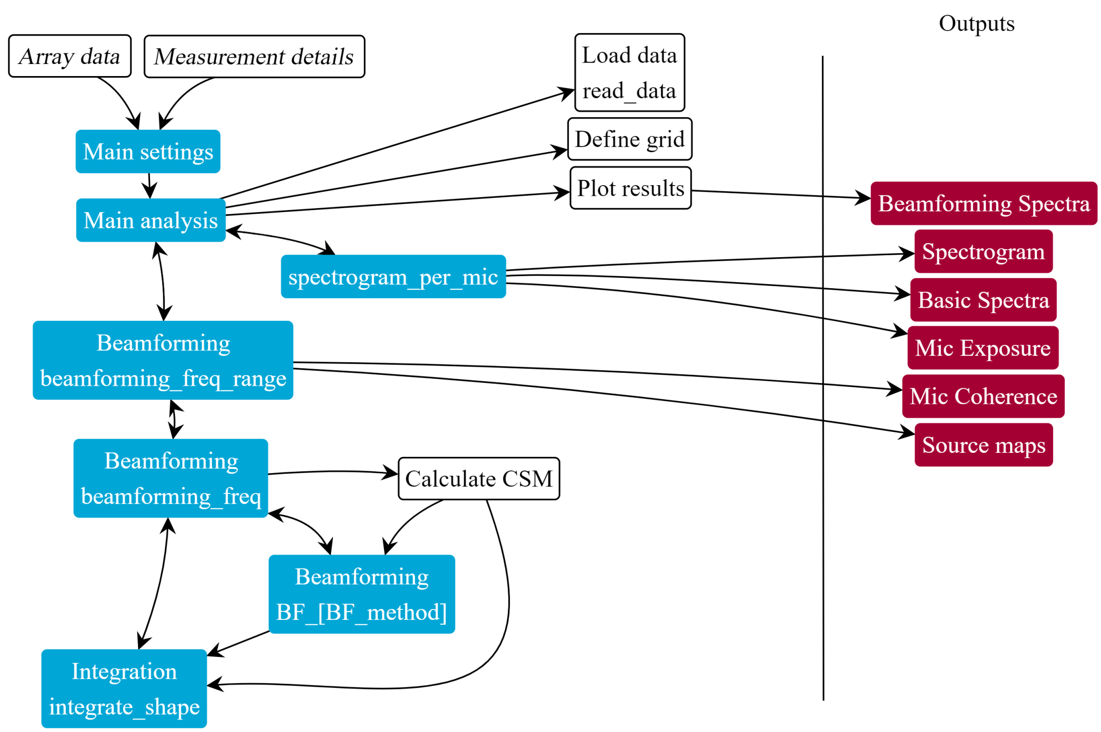


Figure A.1: Workflow of the beamforming program

These advanced beamforming methods were chosen because they are commonly used in the field and because they were mostly integrated in the program already. Their principles were explained in the last section of the literature study and further researched during the thesis.

B
Notes on Experiment

To further understand the experimental campaign, this appendix displays more pictures of the set-ups and recommendations on the set-up.

Figure B.1: Set-up with mesh inside

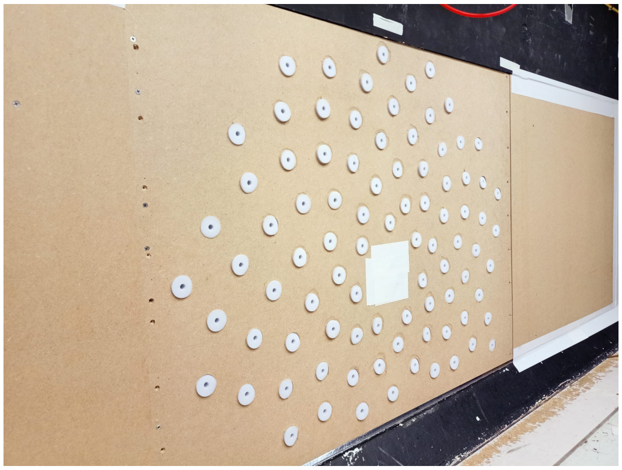


Figure B.2: Set-up 3 with melamine rings (no mesh)

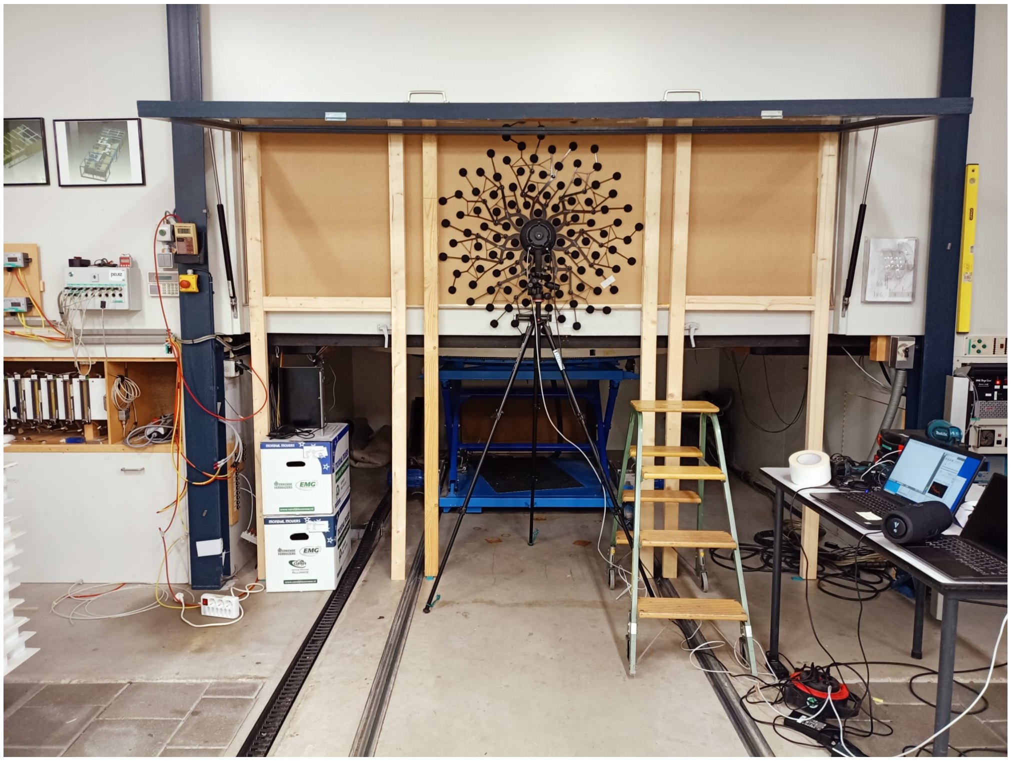


Figure B.3: Overview of wind tunnel including set-up 2

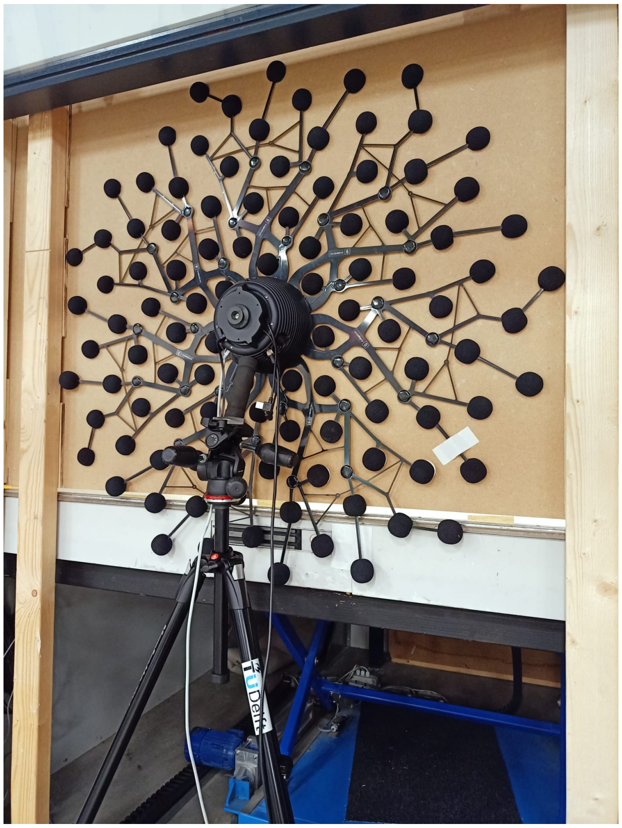


Figure B.4: Close-up Set-up 2

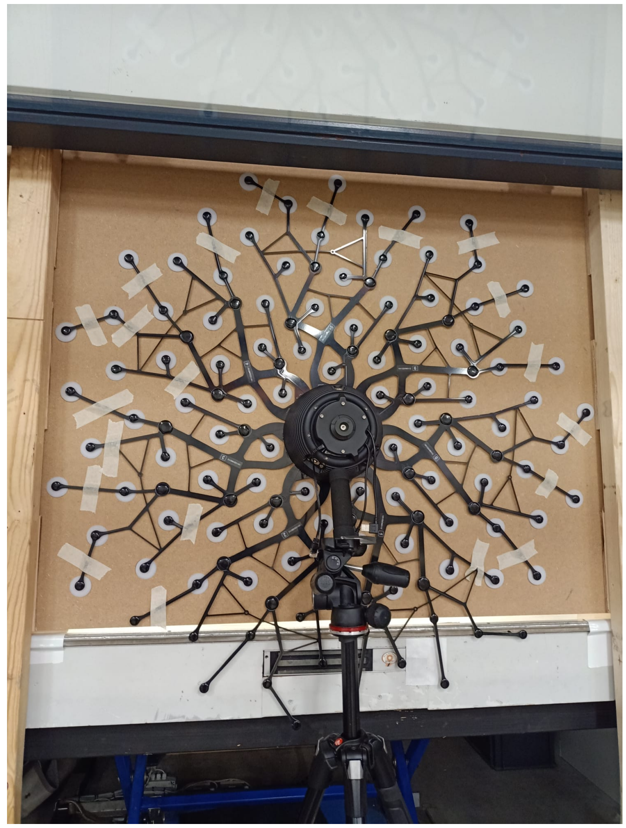


Figure B.5: Close-up Set-up 3

Figure B.6: White fence experiment

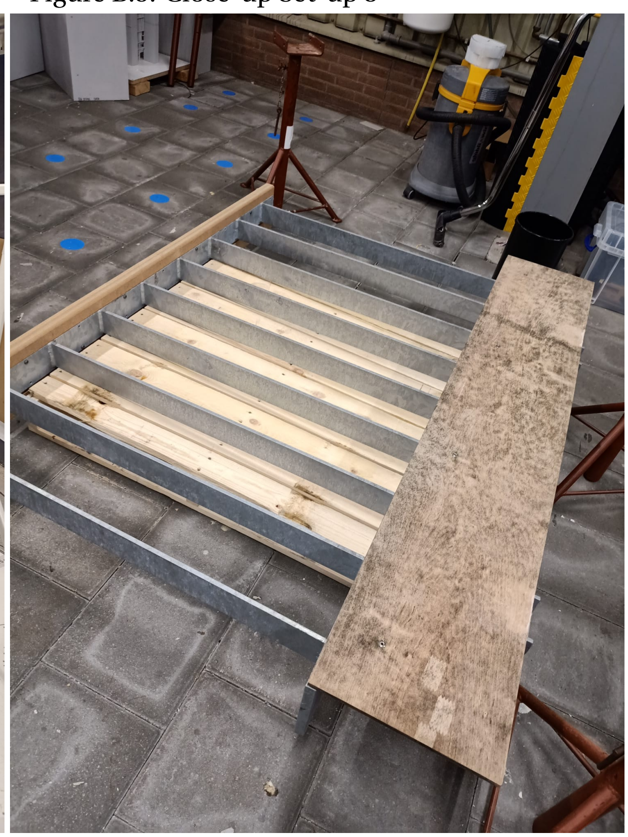


Figure B.7: Grey fence experiment

In addition to these pictures, some recommendations can be made. It is recommended that additional tests are performed to accommodate for missing, corrupted, and invalid recordings. Due to loose contacts, linking issues and the placement of the array in the wind tunnel with not all microphones in line with the wind tunnel, cleaner and more complete results could be found in these tests. Additionally, using a different sound source, with a higher signal-to-noise ratio and more tonal noise measurements at different frequencies would complement the results and provide a bigger picture of the true applicability of the used method.

Given the location of the noise source on the wind tunnel floor, the results were prone to many reflections which might be reduced by placing the noise source at a different location in the wind tunnel.

Furthermore, during the first set of measurements, the camera of the array was broken. As this was repaired between the two test days, visual analysis could only be performed on those measurements. It is also expected some of the synchronisation issues were resolved during this repair which increased the efficiency on the second and third test day.

Another note on the hardware that was used during the tests: the internal memory of the laptop can at times have a hard time performing the recording in the Noise Inspector Software leading to incomplete recordings and unreliable data. This could be prevented by using a laptop with a faster CPU and more internal memory.

Lastly, a quiet surrounding outside of the wind tunnel is of utmost importance to prevent corrupted measurements, this could be achieved in several ways and for this research, simply silencing other machines and refraining from talking during the measurements was deemed sufficient. However, further improvements to the set-up by enclosing the array on the outside could provide better and cleaner results.

C

Test Matrix Experiment 1

Data point	WT velocity	Source Frequency	Turntable angle	Z distance to mic array	Set-up	Notes
1	5	500	0	155	1	
2	5	1000	0	155	1	
3	5	1500	0	155	1	
4	5	2000	0	155	1	
5	5	2500	0	155	1	
6	5	5000	0	155	1	
7	5	500	90	260	1	
8	5	1000	90	260	1	
9	5	1500	90	260	1	
10	5	2000	90	260	1	
11	5	2500	90	260	1	
12	5	5000	90	260	1	
13	5	500	-90	50	1	
14	5	1000	-90	50	1	
15	5	1500	-90	50	1	
16	5	2000	-90	50	1	
17	5	2500	-90	50	1	
18	5	5000	-90	50	1	
19	10	500	0	155	1	
20	10	500	0	155	1	
21	10	1000	0	155	1	
22	10	1500	0	155	1	
23	10	2000	0	155	1	
24	10	2500	0	155	1	
25	10	5000	0	155	1	
26	10	500	90	260	1	
27	10	1000	90	260	1	
28	10	1500	90	260	1	
29	10	2000	90	260	1	
30	10	2500	90	260	1	
31	10	5000	90	260	1	

32	10	500	-90	50	1	
33	10	1000	-90	50	1	
34	10	1500	-90	50	1	
35	10	2000	-90	50	1	
36	10	2500	-90	50	1	
37	10	5000	-90	50	1	
38	FALSE	FALSE	FALSE	FALSE	1	
39	FALSE	FALSE	FALSE	FALSE	1	
40	FALSE	FALSE	FALSE	FALSE	1	
41	FALSE	FALSE	FALSE	FALSE	1	
42	FALSE	FALSE	FALSE	FALSE	1	
43	FALSE	FALSE	FALSE	FALSE	1	
44	15	background		155	1	
45	10	background		155	1	
46	5	background		155	1	
47	15	500	90	260	1	
48	15	1000	90	260	1	
49	15	1500	90	260	1	
50	15	2000	90	260	1	
51	15	2500	90	260	1	
52	15	5000	90	260	1	
53	15	500	-90	50	1	
54	15	1000	-90	50	1	
55	15	1500	-90	50	1	
56	15	2000	-90	50	1	
57	15	2500	-90	50	1	
58	15	5000	-90	50	1	
59	15	500	0	155	1	
60	15	1000	0	155	1	
61	5	background		155	2	
62	5	500	0	155	2	Disturbance
63	5	1000	0	155	2	
64	5	1500	0	155	2	
65	5	2000	0	155	2	
66	5	2500	0	155	2	
67	5	5000	0	155	2	
68	5	500	90	260	2	
69	5	1000	90	260	2	
70	5	1500	90	260	2	
71	5	2000	90	260	2	

72	5	2500	90	260	2
73	5	5000	90	260	2
74	5	500	-90	50	2
75	5	1000	-90	50	2
76	5	1500	-90	50	2
77	5	2000	-90	50	2
78	5	2500	-90	50	2
79	5	5000	-90	50	2
80	10	background		155	2
81	10	500	0	155	2
82	10	1000	0	155	2
83	10	1500	0	155	2
84	10	2000	0	155	2
85	10	2500	0	155	2
86	10	5000	0	155	2
87	10	500	90	260	2
88	10	1000	90	260	2
89	10	1500	90	260	2
90	10	2000	90	260	2
91	10	2500	90	260	2
92	10	5000	90	260	2
93	10	500	-90	50	2
94	10	1000	-90	50	2
95	10	1500	-90	50	2
96	10	2000	-90	50	2
97	10	2500	-90	50	2
98	10	5000	-90	50	2
99	15	background		155	2
100	15	500	0	155	2
101	15	1000	0	155	2
102	15	1500	0	155	2
103	15	2000	0	155	2
104	15	2500	0	155	2
105	15	5000	0	155	2
106	15	500	90	260	2
107	15	1000	90	260	2
108	15	1500	90	260	2
109	15	2000	90	260	2
110	15	2500	90	260	2
111	15	5000	90	260	2

112	15	500	-90	50	2
113	15	1000	-90	50	2
114	15	1500	-90	50	2
115	15	2000	-90	50	2
116	15	2500	-90	50	2
117	15	5000	-90	50	2
118	5	background		155	3
119	5	500	0	155	3
120	5	1000	0	155	3
121	5	1500	0	155	3
122	5	2000	0	155	3
123	5	2500	0	155	3
124	5	5000	0	155	3
125	5	500	90	260	3
126	5	1000	90	260	3
127	5	1500	90	260	3
128	5	2000	90	260	3
129	5	2500	90	260	3
130	5	5000	90	260	3
131	5	500	-90	50	3
132	5	1000	-90	50	3
133	5	1500	-90	50	3
134	5	2000	-90	50	3
135	5	2500	-90	50	3
136	5	5000	-90	50	3
137	10	background		155	3
138	10	500	0	155	3
139	10	1000	0	155	3
140	10	1500	0	155	3
141	10	2000	0	155	3
142	10	2500	0	155	3
143	10	5000	0	155	3
144	10	500	90	260	3
145	10	1000	90	260	3
146	10	1500	90	260	3
147	10	2000	90	260	3
148	10	2500	90	260	3
149	10	5000	90	260	3
150	10	500	-90	50	3
151	10	1000	-90	50	3

152	10	1500	-90	50	3	
153	10	2000	-90	50	3	
154	10	2500	-90	50	3	
155	10	5000	-90	50	3	
156	15	background		155	3	
157	15	500	0	155	3	
158	15	1000	0	155	3	
159	15	1500	0	155	3	
160	15	2000	0	155	3	
161	15	2500	0	155	3	
162	15	5000	0	155	3	
163	15	500	90	260	3	
164	15	1000	90	260	3	Disturbance
165	15	1500	90	260	3	
166	15	2000	90	260	3	
167	15	2500	90	260	3	
168	15	5000	90	260	3	
169	15	500	-90	50	3	
170	15	1000	-90	50	3	
171	15	1500	-90	50	3	
172	15	2000	-90	50	3	
173	15	2500	-90	50	3	
174	15	5000	-90	50	3	
175	0	500		155	3	
176	0	1000		155	3	
177	0	1500		155	3	
178	0	2000		155	3	
179	0	2500		155	3	
180	0	5000		155	3	

D
Test Matrix Experiment 2

Data point	WT velocity	Noise Source	Turntable angle	Z distance to mic array	Set-up	Notes
1	5	Fence 1	0	155	1	
2	5	Fence 1	10	155	1	
3	5	Fence 1	20	155	1	
4	5	Fence 1	30	155	1	
5	5	Fence 1	40	155	1	
6	5	Fence 1	50	155	1	
7	5	Fence 1	60	155	1	
8	8	Fence 1	60	155	1	
9	8	Fence 1	70	155	1	
10	8	Fence 1	60	155	2	
11	8	Fence 1	50	155	2	
12	8	Fence 1	30	155	2	
13	8	Fence 1	0	155	2	
14	10	Fence 1	60	155	2	foam
15	10	Fence 1	60	155	2	
16	8	Fence 1	60	155	2	foam
17	5	Fence 1	60	155	2	foam
18	5	Fence 1	60	155	3	
19	8	Fence 1	60	155	3	
20	8	Fence 1	295	155	3	
21	10	Fence 1	295	155	3	
22	10	Fence 1	295	155	3	foam
23	10	Fence 1	60	155	3	foam
24	10	Fence 1	60	155	3	
25	8	Fence 1	60	155	3	foam
26	5	Fence 1	60	155	3	foam
27	5	Fence 2	0	155	3	foam
28	8	Fence 2	0	155	3	foam
29	8	Fence 2	5	155	3	foam
30	8	Fence 2	10	155	3	foam
31	8	Fence 2	15	155	3	foam
32	8	Fence 2	20	155	3	foam

33	11	Fence 2	0	155	3	foam
34	6	Fence 2	0	155	3	foam
35	6	Fence 2	5	155	3	foam
36	6	Fence 2	10	155	3	foam
37	6	Fence 2	15	155	3	foam
38	6	Fence 2	20	155	3	foam
39	6	Fence 2	25	155	3	foam
40	6	Fence 2	30	155	3	foam
41	6	Fence 2	190	155	3	foam
42	6	Fence 2	0	155	2	
43	6	Fence 2	10	155	2	
44	6	Fence 2	20	155	2	
45	6	Fence 2	30	155	2	
46	7,8	Fence 2	20	155	2	
47	8	Fence 2	20	155	2	
48	8	Fence 2	10	155	2	
49	8	Fence 2	0	155	2	
50	11	Fence 2	0	155	2	
51	11	Fence 2	0	155	2	foam
52	0	WN	0	155	1	
53	0	WN	90	260	1	
54	0	WN	270	50	1	
55	5	BG	0	155	1	
56	5	BG	0	155	1	
57	5	WN	0	155	1	
58	5	WN	90	260	1	
59	5	WN	270	50	1	
60	10	BG	0	155	1	
61	10	WN	0	155	1	
62	10	WN	90	260	1	
63	10	WN	270	50	1	
64	15	BG	0	155	1	
65	15	WN	0	155	1	
66	15	WN	90	260	1	
67	15	WN	270	50	1	
68	0	WN	0	155	2	
69	0	WN	90	260	2	
70	0	WN	270	50	2	
71	5	BG	0	155	2	
72	5	WN	0	155	2	

73	5	WN	90	260	2	
74	5	WN	270	50	2	
75	10	BG	0	155	2	
76	10	WN	0	155	2	
77	10	WN	90	260	2	
78	10	WN	270	50	2	
79	15	BG	0	155	2	
80	15	WN	0	155	2	
81	15	WN	90	260	2	
82	15	WN	270	50	2	
83	0	WN	0	155	2	foam
84	0	WN	90	260	2	foam
85	0	WN	270	50	2	foam
86	5	BG	0	155	2	foam
87	5	WN	0	155	2	foam
88	5	WN	90	260	2	foam
89	5	WN	270	50	2	foam
90	10	BG	0	155	2	foam
91	10	WN	0	155	2	foam
92	10	WN	90	260	2	foam
93	10	WN	270	50	2	foam
94	15	BG	0	155	2	foam
95	15	WN	0	155	2	foam
96	15	WN	90	260	2	foam
97	15	WN	270	50	2	foam
98	0	WN	0	155	3	
99	0	WN	90	260	3	
100	0	WN	270	50	3	
101	5	BG	0	155	3	
102	5	WN	0	155	3	
103	5	WN	0	155	3	
104	5	WN	90	260	3	
105	5	WN	270	50	3	
106	10	BG	0	155	3	
107	10	WN	0	155	3	
108	10	WN	90	260	3	
109	10	WN	270	50	3	
110	15	BG	0	155	3	
111	15	BG	0	155	3	
112	15	WN	0	155	3	

113	15	WN	90	260	3	
114	15	WN	270	50	3	
115	0	WN	0	155	3	foam
116	0	WN	90	260	3	foam
117	0	WN	270	50	3	foam
118	5	BG	0	155	3	foam
119	5	WN	0	155	3	foam
120	5	WN	90	260	3	foam
121	5	WN	270	50	3	foam
122	10	BG	0	155	3	foam
123	10	WN	0	155	3	foam
124	10	WN	90	260	3	foam
125	10	WN	270	50	3	foam
126	15	BG	0	155	3	foam
127	15	WN	0	155	3	foam
128	15	WN	90	260	3	foam
129	15	WN	270	50	3	foam
130	11	BG	0	155	3	foam
131	8	BG	0	155	3	foam
132	6	BG	0	155	3	foam
133	5	WN	moving	50	3	foam
134	5	BG	0	155	3	foam + wall
135	5	WN	0	155	3	foam + wall
136	5	WN	90	260	3	foam + wall
137	5	WN	270	50	3	foam + wall
138	5	BG	270	50	3	foam + wall

E
Background reduction set-ups

In addition to the change in signal-to-noise ratio. It is interesting to look at the overall reduction in background noise as a result of the different set-ups. In Figure E.1, it is clear that the different set-ups reduce the background noise at higher frequencies up to a reduction of 10 dB compared to the set-up that had just the mesh panel. Another interesting note is that the second set-up, with just the panel and incorporated black windscreens, is consistently worse in reducing the background noise in the 2000 - 4000 Hz range.

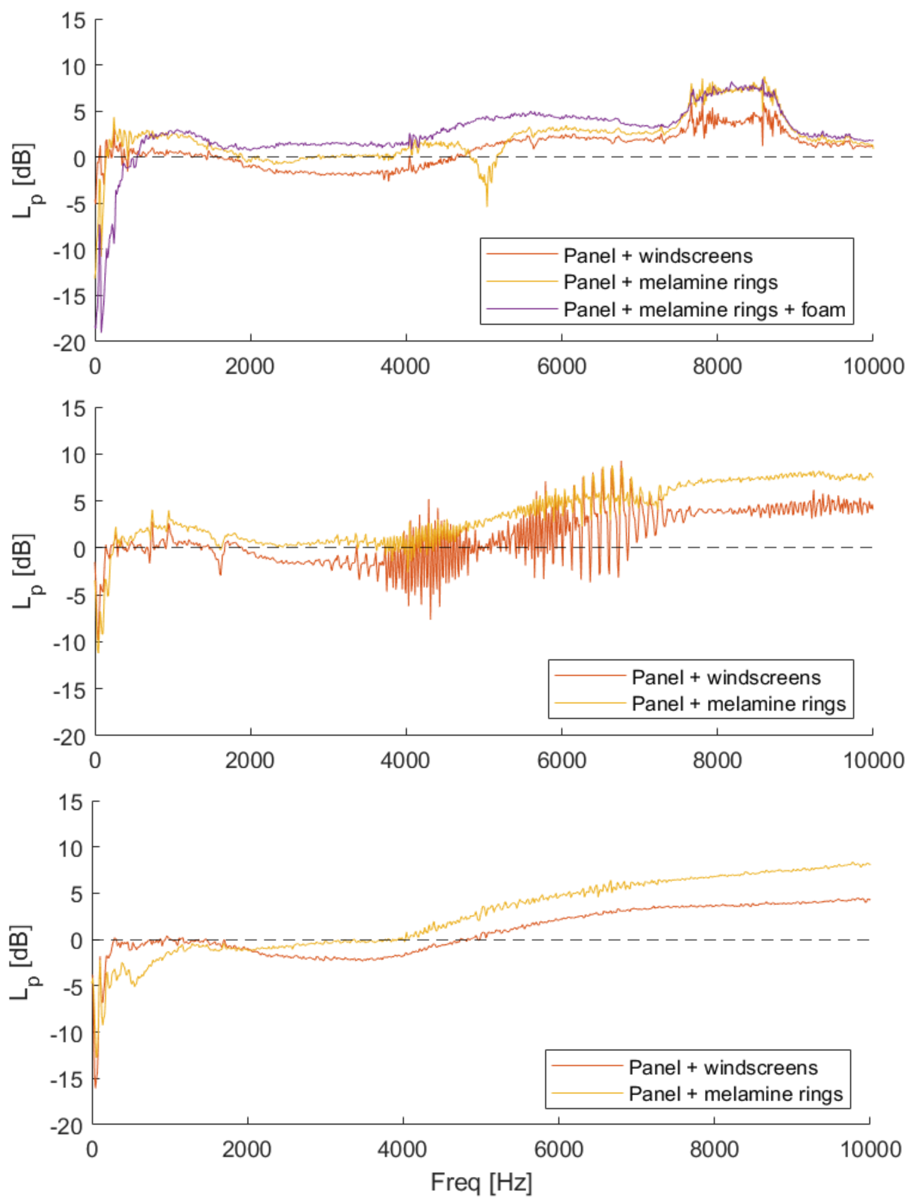


Figure E.1: Increase in background noise reduction w.r.t set-up 1 (Mesh only) at 5, 10, and 15 m/s

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