von Karman Institute for Fluid Dynamics

Lecture Series 2025-01

MEASUREMENT, MODELLING AND SIMULATIONS TECHNIQUES FOR NOVEL AIRCRAFT ARCHITECTURES

November 4-6, 2024

STATE-OF-THE-ART TECHNIQUES FOR EXPERIMENTAL AEROACOUSTICS

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1 Introduction

These lecture notes are meant to provide an introductory overview of key concepts and techniques related to aeroacoustic measurements. By no means do they present a complete and comprehensive review of all state-of-the-art measurement techniques in this extensive and still rapidly evolving field. Instead, these notes are meant to serve as a starting guide and a source of inspiration on how to approach aeroacoustic measurements, especially in the context of new aircraft technologies and propulsion systems.

These lecture notes are organized as follows. First, an introduction to aeroacoustics is provided along with a discussion on the experimental approach required for planning and conducting credible aeroacoustics experiments. Second, key aspects of aeroacoustic wind tunnel test sections are reviewed. Third, sound measurement techniques for acoustic far-field applications in wind tunnel testing are explored, with a particular emphasis on methods suited for studying novel propulsion architectures. Finally, examples of how flow field measurements can be combined in aeroacoustic studies are presented to introduce several key concepts, helping to gain insights into generation mechanisms and potential mitigation strategies.

1.1 What is aeroacoustics?

Aeroacoustics is a research discipline that focuses on the following:

1. How sound is generated by flow.

2. How flow affects the propagation of sound.

3. How sound affects flow.

These aspects are particularly relevant in the context of aviation. As a subdiscipline, aeroacoustics is rooted in fluid mechanics, Therefore, most techniques used to study fluid flow, such as velocity and pressure measurements, can also be considered to provide insights in aeroacoustic research and measurement campaigns.

A fundamental tool in aeroacoustics is the use of acoustic analogies, which reformulate the classical five balance equations of fluid mechanics to describe the sound generated by flow into the form of a wave equation. One of the most famous frameworks for external flows is Lighthill's acoustic analogy. Other approaches, such as Curle's theorem and the Ffowcs Williams-Hawkings analogy extend Ligthill's acoustic analogy to problems where stationary or moving solid boundaries are present, like in rotating propellers or aircraft wings. Additionally, other theories or models exists, focusing on specific noise mechanisms, that model aeroacoustic sound generation. Examples of such models are Amiet's trailing-edge noise model or Howe's theory for edge noise. Essentially, these analogies, theories and models form the theoretical foundation for many aeroacoustic measurement techniques.

Techniques for experimental aeroacoustics are central to advancing our understanding of aeroacoustics providing real-world data to validate theoretical frameworks and numerical simulations and to interpret experimental results from which further insights and knowledge may be deduced and induced. In aeroacoustic experiments, the primary goal is often to answer questions such as:

- How does the flow around an aerodynamic body generate sound?
- What are the dominant noise sources in a system like a propeller-driven aircraft?
- How can this noise be reduced while maintaining aerodynamic performance?
- How can we develop and validate a low-order (or high-order) model to predict a certain noise mechanism?

Experimentation is the driving force of the scientific method used to answer the aforementioned questions. As an experimentalist, you must meticulously plan, design and execute experiments responsibly to ensure the highest possible credibility of your results. Starting with a well-thought-out experimental approach is pivotal, especially to justify the significant costs of state-of-the-art aeroacoustic measurements. This preparation should never be underestimated, as it is often overlooked, leading to results that lack credibility and the insights necessary to advance the field. Therefore, I will take time to address some of the key aspects and that must be carefully considered.

1.2 The experimental approach

The selection of a measurement technique is only one part of planning and executing credible experiments. Several aspects must be considered (Coleman and Steele, 2018), for example:

1. What research question must be answered?
2. What are the relevant underlying physics?
3. What level of certainty is required?
4. What type of experiments can be conducted?
5. Which variables should be changed, and which should remain fixed?
6. What is the necessary operational range of the variables?
7. How many and which data point are required, and at what conditions?
8. What should be the accuracy and precision in controlling the variables?
9. Which measurement techniques are available and how do they compare?
10. What are the potential sources of uncertainty and how do they affect the combined uncertainty of a particular experiment?
11. What are the financial or resource limitations?

1.2.1 Defining the research question

A successful and credible aeroacoustic measurement relies on meticulous and thoughtful planning of the experimental approach. This process must always begin with clearly defining the research question, or motivating question. This question not only guides the experimental design, but also justifies the time, effort and costs to conduct an aeroacoustic measurement. Furthermore, it is essential to recognize that different levels of the research question can and must be defined. For example, let us consider a project aimed at studying the effect of subjecting a propeller with diameter D to non-uniform inflow by immersing it in a turbulent boundary layer of thickness δ, and analyzing its impact on far-field noise. A schematic representation of the problem is shown in Figure 1. A low-level, or level

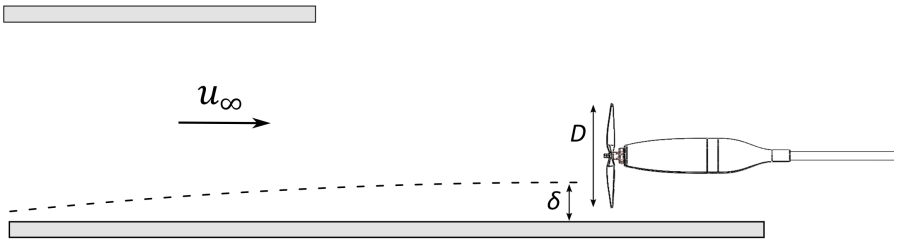


Figure 1: Schematic representation of the example project.

1, research question could be: How does the far-field overall sound pressure level (SPL) change with varying flow non-uniformity, expressed by the parameter δ/D. This question can be answered by varying (and measuring) δ/D and measuring the SPL. A second-level research question could be: How does the structure of the boundary-layer affect the SPL?. This would require measuring 'first-order' boundary-layer characteristics, such as the mean velocity profile. Subsequently, a third-level research question could be: How does the SPL change with varying momentum across different turbulent length scales within the boundary layer? Answering this would necessitate measuring 'higher-order' quantities, like the velocity (i.e., energy) spectrum within the boundary layer.

The reason for outlining these levels is twofold. First, in aeroacoustics (and fluid mechanics more generally), there is often a tendency to assume that high-order quantities will explain low-order behavior. This is rarely the case. Second, it becomes evident that the level of the motivating question directly determines the measurement techniques and level of certainty required and attainable. For the first-level research question, a single microphone in the acoustic far-field and a simple total pressure probe (or Pitot-static tube) to measure the boundary layer thickness would suffice. For the second-level question, you would still only need a total pressure probe to obtain a mean velocity profile, without the necessity of a more advanced measurement techniques like hot-wire anemometry. However, anwering the third-level question would require more advanced techniques, such as hot-wire anemometry or laser Doppler anemometry.

In general, lower-level research questions allow for greater uncertainty and therefore simpler experimental setups, while higher-level questions demand lower uncertainty and more complex setups and instrumentation. Therefore, it is always advisable to start with a first-level question, progressibly moving to higher levels as you deepen your understanding of the problem[1]. This approach is also essential to justify the increased costs and resources

needed for more state-of-the-art experiments in aeroacoustics. For further reference, the reader is referred to Moffat and Henk (2021).

1.2.2 Understanding the underlying physics and dimensional analysis

To determine the level of certainty required in an experiment, it is essential to first understand the underlying physical principles of the problem and to subsequently identify and develop appropriate mathematical frameworks that enable the quantification of some acceptable uncertainty. However, modern aeroacoustics problems are often highly complex, requiring thoughtful strategies to make them more tractable. The crucial key here is to simplify the problem to its most essential and basic components, making modeling idealizations and assumptions that remain sufficiently true to the underlying physics. These assumptions should and can then in turn be validated through experimentation[2].

One particularly useful tool in this process is dimensional analysis, which can provide valuable insights even in seemingly complex problems. The reader is referred to Bridgman (1963). The key realization here is that physics operates independently of the scales familiar to humans. Units of mass, length or momentum are human constructs, not inherent to nature itself. Consequently, physical problems are governed by non-dimensional numbers, as postulated by the Buckingham Pi theorem. By identifying these dimensionless groups, this approach allows you to define relationships between different physical quantities, e.g., inertial and viscous forces in the Reynolds number. Alternatively, exact solutions or acoustic analogies can be identified or derived for certain problems. In both cases, however, the identification of relevant scales and the application of goal-oriented order reduction are crucial for making appropriate assumptions and approximations tailored to the specific goal of the problem or experiment. Through these carefully chosen strategies you can navigate complex aeroacoustics problems, understand the underlying physics, achieve meaningful results and ultimately quantifying the level of certainty required to answer a specific research question.

1.2.3 The importance of uncertainty analysis

Lastly, I would like to reflect on the critical importance of performing uncertainty analysis not only after conducting an experiment but also during the planning phase, before an experimental setup is designed and any data is collected. To illustrate this, let us conder a simple example, adapted from Coleman and Steele (2018). Suppose you are interested in determining which of two models- Model 1 or Model 2-is better suited to describe a particular problem. You run an experiment (referred to as Experiment 1) and compare the experimental results with the prediction of both models, as shown in Fig. 2. At first

[1]In essence, this reflects Newton's experimental philosophy. While Newton did not explicitly outline this philosophy in detail, it can be inferred from the following translated statements: "We are to admit no more causes to natural things than such as are both true and sufficient to explain their appearance." (Newton, Rule 1, Rules of Reasoning in Philosophy, Principia) and "... for all difficulty of philosophy seems to consist in this – to investigate the forces of nature from the phenomena of motions, and then from these forces demonstrate the other phenomena..." (Newton, Preface, Principia).

[2]"Divide each difficulty into as many parts as possible, and begin with the simplest to gradually ascend to knowledge of the more complex, ensuring nothing is omitted." - Descartes, Discourse on the Method.

glance, you might be inclined to believe that Model 2 provides a better fit than Model 1 based on a qualitative assessment. However, without having quantified the uncertainty associated with the experimental data, no definitive conclusions can be drawn from this comparison.

Therefore, to give credibility to the experiment, it is essential to quantify the uncertainty in the data of Experiment 1, which is illustrated in Fig. 3. By addition of these error bars in Y, you can now assess, with a certain degree of probability, how well Model 1 performs relative to Model 2. Evidently, even with the uncertainty quantification, neither model can definitely be considered superior based on the Experiment 1. This highlights the necessity of designing experiments with meticulous care to ensure that the resulting uncertainty is sufficiently low, as is illustrated in Fig. 4. By carefully planning another experiment (referred to as Experiment 2), and employing regression models, you can quantify the uncertainty and establish a confidence interval. This approach will enable you to state, with a defined probability, how likely it is that Model 2 provides a better description of the problem under the conditions of the experiment. It is then up to the experimentalist to determine the required level of confidence and to identify which sources of uncertainty (e.g., random or systematic) are to be considered and evaluated. This includes deciding how these errors should be propagated in the data reduction equations and whether certain uncertainties should be classified and modeled as Type A or Type B. For further guidance, readers are referred to Coleman and Steele (2018) and the Guide to the expression of Uncertainty in Measurement (GUM) by (BIPM et al., 2008).

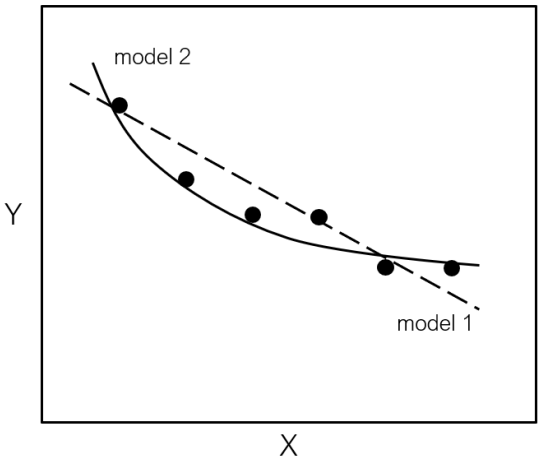


Figure 2: A comparison between experimental result and two theoretical models without uncertainty quantification of experiment 1.

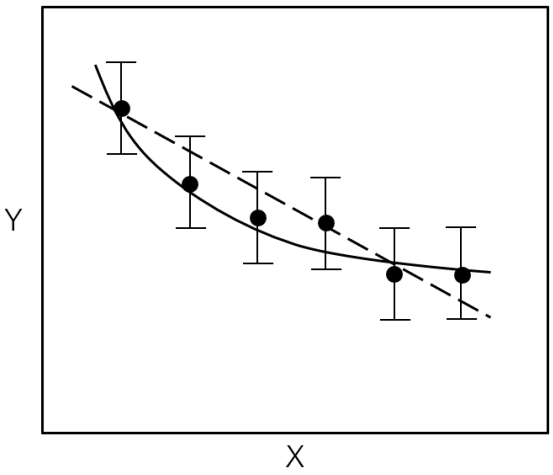


Figure 3: A comparison between experimental result and two theoretical models with uncertainty quantification of experiment 1.

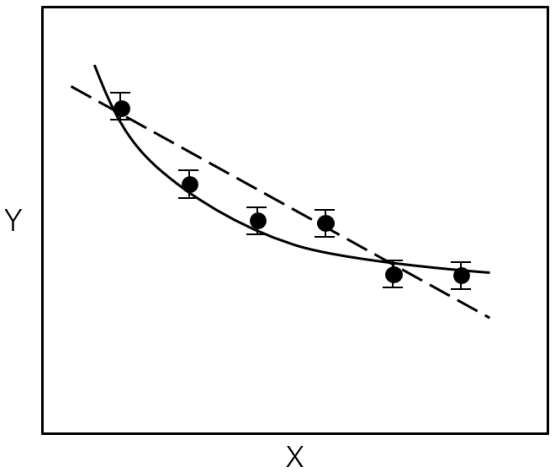


Figure 4: A comparison between experimental result and two theoretical models with uncertainty quantification of experiment 2.

2 Aeroacoustics Wind Tunnels

Aeroacoustic wind tunnels are specialized facilities designed to study the aerodynamics and acoustic characteristics of test objects under controller airflow conditions. These wind tunnels are specifically engineered to minimize background noise and provide high-quality acoustic measurements (Devenport and Glegg, 2023). This requires designing wind tunnels with low-noise characteristics, typically operating at low Mach numbers, to simulate realistic flow conditions while ensuring that the flow remains sufficiently similar to full-scale scenarios (Barlow et al., 1999). One of the primary challenges in aeroacoustic testing is the accurate installation of microphones for sound measurements. The positioning and mounting of microphones in wind tunnels directly affects measurement accuracy and are complicated by the different wind tunnel test section designs, whether hard-walled (closed), open or hybrid test sections.

The comparability of aeroacoustic measurements between different wind tunnel test section types remains a challenging topic and can vary significantly due to differences in, e.g., boundary conditions, facility background noise, configurations of microphone arrays, and a lack of standardized correction frameworks. Studies such as those by Oerlemans and Sijtsma (2004); Oerlemans et al. (2007); Bahr et al. (2021); Bahr (2021); Sanders (2022) highlight that while noise characteristics are generally comparable across setups, differences in noise levels, especially at low and high frequencies, emphasize the need for standardized correction methods, and careful calibration and uncertainty quantification to ensure accurate and consistent results.

2.1 The hard-walled test section

Hard-walled test sections are preferred for aerodynamic studies because they offer the best flow uniformity and turbulence levels, allowing for more accurate and controlled aerodynamic measurements. However, this type of test section presents significant challenges for

aeroacoustic testing due to the confined environment, which 'traps' sound waves, leading to, e.g., reverberations and reflections in sound measurements. Sound measurements require the microphones to be installed in the side walls of the wind tunnel where they are also exposed to the pressure fluctuations in the wall boundary layer, leading to pseudo-sound and decreasing the signal-to-noise ratio. These aspects make it difficult to isolate noise emitted from test objects.

To mitigate these issues, microphones can be recessed and installed in special optimized mounting configurations and coverings (Fleury et al., 2012; VanDercreek et al., 2021; Sijtsma and Holthusen, 1999; Jaeger et al., 2000; Sanders et al., 2022). By doing so, the microphones are shielded from the airflow while still capturing the sound generated by the test object. Different mounting configurations influence the acoustic response of the microphones and must be carefully calibrated to ensure accuracy. Calibration techniques, such as in-situ calibrations, are essential to correct for this. Additionally, part of the closed test section's side walls can be replaced with acoustically transparent panels, such as perforated metal or mesh of stretched Kevlar cloth. These panels can either open to an anechoic chamber (e.g., in Dekker et al. (2023); Sanders et al. (2023)), allowing sound to dissipate without reflections, or be backed by acoustically absorbing materials in an enclosed space, (e.g., in Bento et al. (2022)) Both approaches help reduce internal noise reflections and improve the quality of the sound measurements by creating a more acoustically optimal environment.

2.2 The open-jet test section

Open-jet test sections are generally preferred for aeroacoustic measurements due to their ability to provide a clear path for sound propagation, allowing for directivity measurements and higher signal-to-noise ratios compared to hard-wall test sections. The open environment (combined with an anechoic chamber) minimizes sound reflections from tunnel sections. These aspects make open-jet test sections more ideal for testing novel propulsion systems (Giraldo et al., 2023; De Paola et al., 2024; Wickersheim et al., 2024). Additionally, in the case of boundary layer ingestion propulsion systems, open-jet test sections are often preferred to enable the utilization of side-wall boundary layers to create non-uniform inflow conditions for studying the effects of boundary layer ingestion on propeller noise. However, open-jet test sections are less favorable for aerodynamic measurements for over-the-wing propeller distributed propulsion concept studies. For aeroacoustic measurements of those type of configurations, a hard-walled (de Vries et al., 2021) or hybrid test section may be preferred (Brown et al., 2021).

One of the main aspects in open-jet test sections is the free shear layer that forms between the jet flow and the quiescent air. This shear layer is much thicker than the boundary layers found on the walls of a closed test sections and the velocity fluctuations are also much larger. This can significantly affect sound propagation (Biesheuvel et al., 2021). As the sound waves pass through the shear layer, they are subject to, e.g., refraction (Amiet, 1978; Sarradj, 2017), spectral broadening of tonal noise (Sijtsma et al., 2014), and wavefront distortion (Dougherty, 2003; Biesheuvel et al., 2023). The latter which leads to coherence loss in phased microphone arrays (Biesheuvel et al., 2019). These sound propagation effects may complicate the accurate localization and quantification of noise sources, making it necessary to apply advanced signal processing techniques to correct for

the shear layer's impact on the sound measurements.

2.3 The hybrid test section

Hybrid test sections aim to combine the benefits from both hard-walled and open-jet test sections. These test sections are designed with porous or acoustically transparent materials covering part of the side-walls. Most widely used are wall panels of stretched Kevlar cloth (Smith et al., 2005; Devenport et al., 2013; Ragni et al., 2022), but other acoustic transparent materials may also be used (Szoke et al., 2022). This hybrid test section type provides better aerodynamic flow conditions than open-jet configurations, though both aerodynamic and acoustic corrections may be more complex Brown (2016). One limiting challenge in sound measurements in hybrid test sections arises from the self-noise generated by the at high frequencies. This noise can interfere with acoustic measurements, especially when dealing with high-frequency sound sources. Additionally, there is transmission loss through the acoustic transparent panels that must be considered to correct microphone signals. Another important consideration may be the absorption of sound by the turbulent boundary layer over the Kevlar panels, which is reported to attenuate acoustic signals (Ahuja et al., 1978; Devenport et al., 2013). Arguably, coherence loss in phased microphone arrays may also arise in hybrid test sections, requiring careful consideration.

3 Sound Measurements in the Acoustic Far-Field

3.1 Single Microphone Measurements

The simplest and most direct method for conducting sound measurements is through single microphone measurements. This approach is typically used when the noise level generated by the source of interest is significantly higher than the background noise of the wind tunnel, meaning the signal-to-noise ratio is sufficiently high. This is typically the case when evaluating the nosie of novel propulsion systems, such as those using distributed electric propulsion or boundary layer ingestion (Zaman et al., 2024c; Meloni et al., 2022; Ahmed et al., 2024; Castelucci et al., 2023; Roger et al., 2022). Arrays of microphones, arranged in line or arc configurations, are frequently used to capture sound directivity and assess noise shielding effects, for example in over-the wing configurations (Dekker et al., 2023). One of the advantages of using arrays of individual microphones is that uncertainty analysis remains relatively straightforward.

When planning and reporting microphone measurements, it is crucial to account for factors like source directivity, wind tunnel effects (e.g., shear layer refraction), microphone directivity, frequency response, and corrections for free-field or pressure field conditions. Properly addressing these factors and reporting how uncertainties are quantified is essential for ensuring the reproducibility of experiments and enhancing the credibility of the conclusions drawn from the data. For a comprehensive understanding of microphone measurements in aeroacoustics, refer to Mueller (2002) and consult a specialized microphone handbook, such as Brüel&Kjaer (2019).

In addition to basic single microphone measurements, advanced post-processing techniques such as wavelet analysis and phase-averaged analysis can be applied for further un-

derstanding. Wavelet analysis allows for the separation of tonal and broadband noise components, which might be useful for identifying and differentiating different noise sources. An example is in the work of Meloni et al. (2022) which showed how this method can be used to isolate tonal noise generated by the propeller from broadband noise. Additionally, phase-averaged analysis can be used to study propeller noise in novel propulsion concepts such as boundary layer ingestion systems Zaman et al. (2024c). In these systems, the noise generation may vary significantly depending on the blade's phase relative to the incoming flow. Phase-averaged sound measurements allow for a detailed analysis of noise generation at different phases of a complete rotation of the propelled. For novel propulsion concepts, phase-averaging may help pinpoint noise generation associated with unsteady loading, turbulence ingestion, and other interactions between the propeller blades and the surrounding flow.

3.2 Beyond Single Microphones

To enhance the signal-to-noise ratio of far-field sound measurements, acoustic mirrors or multiple microphones must be used. Early enhancement methods use an acoustic mirror with elliptical shape that can be used that focus sound waves from a specific source point onto a single microphone (Grosche et al., 1976, 1977, 1997; Schinkler, 1977; Verges i Plaza et al., 2022; Pott-Pollenske et al., 2003). In practical wind tunnel setups, an acoustic mirror could be combined with a microphone phased array to quantify sound sources over a range of frequencies. However, the primary limitation of acoustic mirrors is the restricted frequency range over which the mirror is effective, depending on the size of the mirror. Moreover, moving the acoustic mirror setup to conduct sound mapping in multiple points can be time-consuming and thereby cost-inefficient.

Coherence-based techniques, such as the coherent output power method (Brooks and Hodgson, 1981; Hutcheson and Brooks, 2002) can be used as another sound measurement method. Famously used in airfoil self noise studies Brooks and Hodgson (1981), this method works by calculating the coherence between multiple microphone signals, enabling the experimentalist to filter out incoherent noise, such as wind tunnel reflections or background noise. When using two microphones, uncertainty analysis is relatively straightforward (Bahr, 2010). However, incorporating more microphones increases the complexity, requiring advanced methods like Monte Carlo simulations to properly assess uncertainty.

3.3 Acoustic Beamforming using Microphone Phased Arrays

Nowadays, acoustic beamforming using microphone phased arrays has become the standard technique for sound measurements in aeroacoustics. A microphone phased array way first used by Billingsley and Kinns (1976) then named 'the acoustic telescope'.

3.3.1 Conventional Beamforming

Conventional beamforming in the frequency domain is the most widely used sound source localization method (Sijtsma, 2010). The essence of conventional beamforming lies in steering the vector towards different potential sound source locations by 'back-propagating'

the microphone signals assuming an acoustic free-field propagation model and monopole point sound sources. By steering the microphone signals into potential locations, the sound from this location is amplified, while noise from other directions is attenuated. The result is often a two-dimensional acoustic map that shows the locations of sound sources. Key advantage of conventional beamforming include its simplicity and the ability to quickly create source localization maps. These sound sources can then also be quantified using the source power integration technique Brooks and Humphreys (1999). The spatial resolution is primarily influenced by the size of the microphone phased array and the wavelength of sound. Additionally, in general it can be stated that the more microphone in the array, the closer the response of the microphone array to the limiting diffraction pattern, known as an Airy disk pattern.

One of the critical aspects of phased array measurements is the array design, which includes aspects such as the total number of microphones, their geometric arrangement, and the spacing between them. These design parameters may significantly influence the array's ability to detect and resolve sound sources, particularly those with lower signal-to-noise ratios. For guidance on optimizing microphone phased arrays, readers are referred to Malgoezar et al. (2016). When designing arrays, it is important to account for the effect of design changes on the uncertainty of the acoustic maps and the sound power integration method in particular. The uncertainty can be modeled using Monte Carlo simulations as described by Yardibi et al. (2010). Additionally, proper array calibration is essential for accurate results and best practices for this can be found in Mueller (2002). Examples of the use of microphone phased arrays in aeroacoustic measurements of novel aircraft architectures can for example be found in Gomes and Wickersheim (2024) where the results enable the assessment of propeller-wind interaction mechanisms.

3.3.2 Advanced Algorithms

To improve the spatial resolution of acoustic maps and minimize sidelobe interference, advanced beamforming algorithms, such as CLEAN-SC and DAMAS, are widely used. For a detailed review and comprehensive overview of several algorithms, see Merino-Martínez R. (2019). It is important to note here that different implementations of these algorithms can produce varying results, even when applied to the same datasets (Bahr et al., 2017; Sarradj et al., 2017). Therefore, the choice of algorithm and its specific implementation can have a significant impact on the final acoustic maps and the conclusions derived from the data. In cases where noise sources are moving, such as propeller blades or rotating turbines, specialized beamforming techniques are necessary to accurately localize and quantify noise, as outlined in Sijtsma (2006).

3.3.3 Three-dimensional beamforming

The mapping of sound sources in three dimensions has gained increasing attention in recent years, due to the need for accurate localization of sound sources that are not confined to a single plane. Traditionally, the depth spatial resolution of two-dimensional planar microphone arrays is significantly lower than the lateral resolution, which hampers accurate 3D sound source localization Biesheuvel (2022). This limitation becomes especially pronounced when dealing with complex geometries such as aircraft components, rotating

machinery, or distributed propulsion systems. Several 3D sound source localization techniques have been developed to address this, as presented by Padois et al. (2013); Padois and Berry (2017); Xu et al. (2021); Lima Pereira et al. (2021).

One particularly promising method is sound source localization through tomographic reconstruction (Tuinstra and van der Meulen, 2019). This technique enables 3D deconvolution of sound sources by using beamforming maps from microphone arrays positioned at different angles around the sound source. It is especially useful in complex wind tunnel setups where there are limited options for mounting microphone arrays. By leveraging measurements from multiple array positions, this method has been shown to reconstruct 3D sound fields with higher accuracy, reducing artifacts and enhancing spatial resolution. It has been demonstrated successfully in test cases involving landing gear configurations and full aircraft models. This reconstruction method provides a significant improvement over conventional approaches, particularly in terms of spatial resolution and its ability to adapt to the challenges of novel propulsion system testing. This makes it an attractive option for overcoming the inherent limitations of 2D planar arrays in aeroacoustic research.

3.3.4 A final note on the use and comparison of different measurement methods

In the aeroacoustics research community, there remains a noticeable gap in the regular practice of performing uncertainty analysis for sound measurements, whether using single microphones or microphone phased arrays. Proper uncertainty quantification is critical to ensure the reliability of experimental results and should be conducted systematically. Additionally, calibration procedure for both individual microphones and arrays should be well-documented and consistently reported, as this will enhance the reproducibility and credibility of the findings. Moreover, it is recommended that newly implemented acoustic beamforming algorithms should always be bechmarked. As demonstrated in studies such as those by Bahr et al. (2017) and Sarradj et al. (2017), different implementations can yield significantly different results. Therefore, comparing acoustic beamforming outcomes should not rely solely on comparing integrated spectra from sound power integration methods with methods (e.g., the BPM model) that use coherent output power techniques. According to Bahr (2010), these methods can produce divergent results. Finally, the community would benefit greatly from more open-source initiatives and collaborative efforts. With the increasing number of beamforming algorithms and post-processing techniques available- such as those for background noise removal, transient data classification, wind tunnel setup corrections, array design optimization, and Monte Carlo simulations for uncertainty quantification- there is a need for a shared development space. While initiatives like Acoular represents a step in the right direction, more collective efforts are required to standardize practices. Readers are highly encouraged to engage in and support such efforts.

4 Combining Flow Field Measurements with Aeroacoustic Applications

For novel propulsion system configurations, combining flow-field and far-field sound measurements is crucial for understanding the mechanisms that lead to noise generation or reduction. These configurations present very complex flow dynamics where, for example, boundary layers and wakes interact with propellers, generating unsteady aerodynamic loads leading to significant noise generation. To tackle the challenge of understanding the underlying flow mechanisms, various flow measurement techniques can be combined with sound measurements. For a comprehensive overview, the reader is referred to Ragni et al. (2022). Which measurement techniques should be used and combined depends on the research question one wants to answer and the theoretical foundation that one can use.

A great example of the use and combination of theoretical frameworks with measurement techniques for the prediction of turbulent boundary layer trailing-edge noise is the work of Pröbsting et al. (2015). in this work, trailing edge noise is estimated using high-speed tomographic particle image velocimetry (PIV) measurements. The PIV measurements provide time-resolved volumetric flow field data around the trailing-edge of a model. These measurements allow the estimation of unsteady surface pressure statistics used with Amiet's model, as the foundational model, to predict trailing edge noise. The PIV-based estimates are then compared to microphone phased array measurements. This approach demonstrates how flow field measurements combined with sound measurements can be used understand and even estimate noise mechanisms.

Several advanced flow measurement techniques can be used in combination with acoustic measurements to provide some insights or deeper understanding of the flow mechanisms responsible for noise generation such as hot-wire anemometry (HWA), laser Doppler anemometry (LDA), Particle Image Velocimetry (PIV), Particle Tracking Velocimetry (PTV) or unsteady wall pressure microphone measurements.

4.1 Hot-wire anemometry and laser Doppler anemometry

Hot-wire anemometry and laser Doppler Anemometry can be used to measure, e.g, 'higher-order' turbulence statistics, such as turbulence intensity, energy spectra, and integral length scales. These measurements can be valuable for understanding how different turbulent structures contribute to noise generation mechanisms or to inform noise prediction models. This is demonstrated, for example in studies examining the impact of turbulent inflow conditions on propeller noise Capobianchi et al. (2024); Brown et al. (2021) and trailing-edge noise Botero-Bolívar et al. (2024). Furthermore, in over-the-wing or boundary layer ingestion configurations, HWA cis useful for studying the development of the turbulent boundary layer along a wing or surface before it interacts with a propeller or other propulsion system (Zaman et al., 2024a).

4.2 Particle Image velocimetry and Particle Tracking Velocimetry

PIV and PTV enable the measurement of time-averaged or time-resolved 2D or 3D velocity fields enabling both low-order and high-order flow field characterization. These measurement techniques are valuable for interpreting how changes in the flow field contribute to

variations in noise production. PIV mainly allows for the measurement of time-averaged flow fields, giving insights into, e.g, velocity and turbulence intensity profiles. These results could be interpreted and linked to the noise generation. For example, increase turbulence intensity profiles in the boundary layer upstream of a boundary layer ingestion configuration may lead to stronger unsteady pressure fluctuations on the bladed, resulting in higher acoustic emissions. Performing such measurements may enable the deduction of modeling approximations or assumptions, further advancing research. Furthermore, instantaneous flow fields might be useful in identifying coherent flow structures, such as vortex shedding, which can periodically interact with surfaces. Static pressure fields can furthermore be reconstructed from PIV or PTV velocity field measurements providing additional information and insights. Additionally, unsteady surface pressure can also be reconstructed using time-resolved PIV or PTV data.

In systems with rotating components or periodic phenomena, an especially valuable technique is phased-locked PIV combined with phase-averaging (Zaman et al., 2024b). This method is highly effective in analyzing periodic flow phenomena and their effects on far-field noise. For example, in boundary-layer ingestion systems, phase-locking involves synchronizing the flow measurements with a specific phase in the propeller's rotation cycle, allowing for precise observation of flow features at different points in the cycle. Additionally, phase-locking other measurement techniques, such as sound, force and pressure measurements, can provide deeper insights into propeller-blade flow interactions that were previously not possible-particularly for 3D velocity field measurements. This combined approach offers a more comprehensive understanding of the unsteady aerodynamic processes that contribute to noise generation.

4.3 Unsteady surface pressure

Finally, unsteady surface pressure measurements are a valuable technique for gaining insights into noise mechanisms, particular in systems like boundary layer ingestion. Surface pressure measurements provide detailed information about turbulent boundary layers and can be applied on various surfaces, including walls, airfoils and propeller blades (Roger, 2017). When installed on rotating blades, these measurements can capture unsteady blade pressure fluctuations (de Vries et al., 2021; Heidelberg and Woodward, 1987) and turbulent boundary layer characteristics, which are for example essential for validating broadband noise prediction models (Rozenberg et al., 2010).

Different mounting techniques, such as flush-mounted microphones, microphones under pinholes, or remote microphone probes (dos Santos et al., 2023), allow experimentalists to gather data even in complex or challenging geometries. A particularly promising approach involves using MEMS (Micro-Electro-Mechanical Systems), which enable the deployment of a large number of low-cost sensors. MEMS microphones are ideal for capturing high-precision pressure data and are well-suited for array configurations because of their relative small size. This makes them particularly effective for determining wavenumber-frequency spectra in noise analysis (Schram and de Wyer, 2018). Additionally, MEMS microphones can also be used for far-field acoustic measurements (Humphreys et al., 2005), and there is significant potential for scaling up these measurements to arrays with thousands of sensors as demonstrated in studies involving up to 7,200 sensors (Daniel et al., 2024).

An exciting recent development is the combination of unsteady surface pressure measurements using MEMS sensors with new techniques for identifying noise sources on complex surfaces, as explored by (Delfs, 2024).

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