Simulations and Measurements of Airframe Noise: A BANC Workshops Perspective

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ABSTRACT

Airframe noise corresponds to the acoustic radiation due to turbulent flow in the vicinity of airframe components such as high-lift devices and landing gears. Since 2010, the American Institute of Aeronautics and Astronautics has organized an ongoing series of workshops devoted to Benchmark Problems for Airframe Noise Computations (BANC). The BANC workshops are aimed at enabling a systematic progress in the understanding and high-fidelity predictions of airframe noise via collaborative investigations that *integrate computational fluid dynamics, computational aeroacoustics, and in-depth measurements targeting a selected set of canonical yet realistic configurations that advance the current state-of-the-art in multiple respects. Unique features of the BANC Workshops include: intrinsically multidisciplinary focus involving both fluid dynamics and aeroacoustics, holistic rather than predictive emphasis, concurrent, long term evolution of experiments and simulations with a powerful interplay between the two, and strongly integrative effort involving multi-team, multi-facility, multiple-entry measurements. This paper illustrates these features in the context of the BANC problem categories and outlines some of the challenges involved and how they were addressed. A brief summary of the BANC effort, including its technical objectives, strategy, and selective outcomes thus far is also included.*

1.0 INTRODUCTION

With the advent of quieter, ultra-high-bypass-ratio engines, acoustic radiation due to turbulent flow in the vicinity of airframe components such as landing gear and high-lift devices (i.e., leading-edge slat and trailing-edge flaps) has emerged as an important contributor to the noise signature of subsonic commercial transports during their approach for landing. The combination of geometric complexity, high Reynolds number turbulent flow with multiple regions of separation and a strong coupling between adjacent physical components makes the problem of airframe noise prediction highly challenging. Therefore, to enable the development of reliable, physics based prediction tools for airframe noise applications, it is critical to integrate experiments with computational fluid dynamics (CFD) of nearfield unsteadiness (i.e., noise sources) and computational aeroacoustics (CAA) for the propagation of the nearfield information to predict the far-field acoustic signature at the location(s) of interest. A similar integration is also essential on a purely experimental front to enable combined (and preferably simultaneous) measurements of the unsteady flow and the acoustic signature. Furthermore, such interplay along each level has to begin from the outset of any fundamental investigation involving the airframe noise sources.

As a consequence of the increased maturity of CAA, the field has outgrown the range of simple problems with closed form solutions, forcing the community to rely upon measured data as a means of validation/accuracy assessment for the progressively complex configurations of interest. This, too, has made an increased coupling between unsteady CFD, CAA, and experiments rather important in the context of airframe noise problems. The paradigm shift from exact analytical solutions toward imperfect measured "solutions" as a yardstick for benchmarking aeroacoustic simulations imposes additional requirements on the quality and details of the benchmark dataset. The extra requirements pertain to both the accuracy/uncertainty and spatio-temporal resolution of the measurements involved and the need to quantify the multiple links within the causal chain from flow unsteadiness to far-field noise. Due to practical constraints, such stringent requirements cannot be easily met by a single investigator or even a single organization, especially in the context of airframe noise, because of the combined complexity of flow geometry, delicate unsteady flow physics, the typical scale and amplitude disparity between hydrodynamic and acoustic fluctuations, the increased frequencies in subscale configurations, and the potential for flow acoustic interaction.

Due to the continued need for noise reduction on flight configurations, the fundamental efforts have at times assumed a secondary role to the applied research focused on the development of low fidelity prediction tools for real world airframe systems and/or the typically empirical development of noise reduction devices. Even though fundamental investigations of airframe noise became increasingly common over the past two decades, these efforts were often fragmented across the community, which impeded both the pace and the impact of these efforts. To accelerate the understanding of airframe noise sources and to help develop validated high-fidelity computational models, a grass-roots effort was initiated in 2007 by the Discussion Group on Benchmark Experiments and Computations for Airframe Noise (BE&CAN DG) of the American Institute of Aeronautics and Astronautics [1]. The BE&CAN DG is jointly sponsored by the Aeroacoustics and Fluid Dynamics Technical Committees of AIAA. This effort has led to a series of international workshops on Benchmark Problems for Airframe Noise Computations (BANC). The objectives of the BANC workshops are to:

1. Provide a forum for a thorough assessment of simulation-based noise-prediction tools in the context of airframe configurations including both nearfield unsteady flow and the acoustic radiation generated via the interaction of this flow with solid surfaces.
2. Identify current gaps in physical understanding, experimental databases, and prediction capability for the major sources of airframe noise.
3. Help determine best practices, and accelerate the development of benchmark quality datasets.
4. Promote future coordinated studies of common configurations for maximum impact on the current state of the art in the understanding and prediction of airframe noise.

Several organizations within the airframe noise community have participated in the collective development of a hierarchy of benchmark configurations by contributing experimental data and/or computational solutions to help advance the state of the art at the fundamental level. As described later, the benchmark configurations range from trailing edge noise from a single airfoil to a variety of canonical configurations relevant to nose and main landing gears and the leading edge slat under approach conditions. The selection of these configurations reflects a compromise based on several criteria [1], including:

i. Nonproprietary geometry and of wide interest
ii. More realistic than previous CAA benchmarks, providing a balance between geometric complexity, relevant physics, computational requirements, and experimental constraints
iii. Experiments conducted in more than one facility, with measurements addressing the full causal chain from unsteady flow structures to far-field acoustics

We note that the requirements of a benchmark dataset will not be achieved in all cases and, hence, the title of this workshop series reflects the quest for the benchmark datasets and the collective journey toward that goal.

The following four problem categories were included in the BANC-I workshop, which was held in Stockholm in June 2010:

1. Airfoil trailing edge noise
2. Unsteady wake interference between a pair of inline tandem cylinders
3. Minimal 4-wheel landing gear
4. Partially-dressed, cavity-closed nose landing gear

The above categories were identified by the BE&CAN DG and subsequently vetted with the technical community during special sessions at the 2008 and 2009 AIAA Aeroacoustics Conferences in Vancouver and Miami, respectively. The BANC-I workshop was attended by over eighty-five researchers from fourteen countries. Eight government organizations from Asia, Europe and the United States, five major industry organizations, five software vendors, and a number of academic institutions participated in the workshop. A broad set of computational techniques were applied to a common set of problems, spanning structured, unstructured, overset and Cartesian grid solvers, low- and high-order algorithms, finite volume, finite difference, and lattice Boltzmann schemes, and Large Eddy Simulation (LES) or hybrid Reynolds Averaged Navier-Stokes (RANS)/LES methods [2]. Most evident was the community spirit in coming together to support the BE&CAN DG goals and, in particular, the paradigm shift in benchmark activities for computational aeroacoustics, from closed form analytical solutions and single facility, single organization experiments, to collaboratively planned, multi-facility, multi-group experiments.

The follow-on BANC-II workshop was held in Colorado Springs, Colorado, in June 2012 [3]. To broaden the portfolio of the BANC datasets and, in particular, to address additional noise sources related to high-lift devices, the BANC-II workshop included new problem categories in addition to categories 1 through 4 from the BANC-I workshop, which continue to be used by the research community since their introduction at the BANC-I Workshop. The new problem categories were as follows:

5. The LAGOON Simplified Landing Gear configuration tested by Airbus and ONERA,
6. Slat Noise (DLR/ONERA Configuration)
7. Slat Noise (NASA led effort on a modified 30P30N High Lift Configuration)
8. Acoustic Propagation Phase of Airframe Noise Prediction

A majority of category 2 objectives were met during the first two workshops, and therefore, this category was retired from the workshop activities, yet allowing for continued investigations to be reported via conference sessions and archival publications. The contributions to category 3 highlighted a few important challenges in aeroacoustic predictions for main landing gear configurations characterized by interactions between multiple rows of wheels. Consequently, category 3 has been in hiatus since the BANC-II Workshop, pending further breakthroughs that lead to a successful resolution of those issues. Accordingly, the subsequent BANC workshops (namely, the BANC-III Workshop in Atlanta, Georgia, in June 2014, and the BANC-IV Workshop in Lyon, France, in June 2016) have focused on categories 1, 4, 5, 6, 7, and 8.

The BANC series represents the first set of workshops to be cosponsored by the Aeroacoustics and Fluid Dynamics Technical Committees of AIAA. In part, it has followed the general modus operandi of the highly successful Drag Prediction Workshops [4] and the Unsteady CFD Validation Workshop [5] from the purely aerodynamic arena but has been more ambitious in targeting additional elements related to the delicate physics of the unsteady flow and its coupling with the radiated acoustic field from the outset [6]. Highlights of the BANC workshops include: intrinsically multi-disciplinary focus involving fluid dynamics as well as acoustics; holistic rather than predictive emphasis; concurrent evolution of experiments and simulations with a powerful interplay between the two; strongly integrative nature by virtue of multi-team, multi-facility, multiple-entry measurements; and a long-term, collective focus on selected canonical problems across multiple workshops until the goals set for each category have been achieved. This paper provides a partial overview of these features in the context of selected BANC problem categories and outlines a few of the challenges involved and how they were addressed. A brief summary of the selective outcomes thus far is also included. An in-depth description of the integration between CFD, CAA, and the fluid dynamic and aeroacoustic measurements for each problem category are beyond the scope of this overview; hence, this summary is more illustrative than comprehensive, and the reader is referred to the problem statement definitions at the BE&CAN DG website [1] as well as summary documents for individual categories (Refs. [7] through [14]) for further details, especially in the case of problem categories that are discussed rather briefly herein or not discussed at all.

2.0 CATEGORY 2: UNSTEADY WAKE INTERFERENCE BETWEEN A PAIR OF INLINE TANDEM CYLINDERS

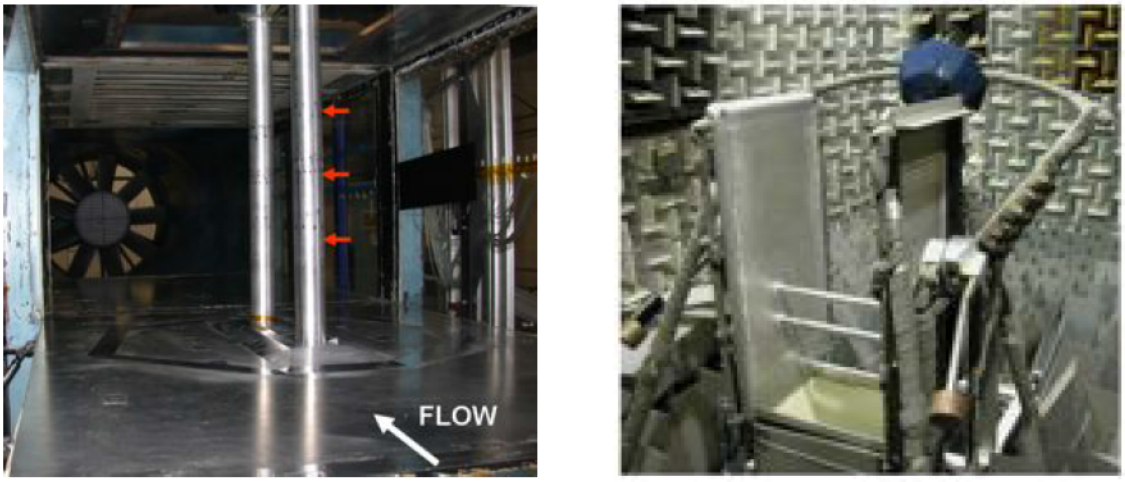
Category 2, i.e., unsteady wake interference between a pair of circular cylinders in tandem (Figs. 1 and 2), was developed as a canonical example of component interactions within the complex assembly of an aircraft undercarriage. To simulate the turbulent separation characteristics encountered in full-scale applications, tripping of the boundary layer was employed along either just the front cylinder or along both cylinders. The cylinder spacing to cylinder diameter ratio of L/D = 3.7 was chosen to represent the supercritical regime, where both cylinders shed separately and the downstream cylinder is buffeted by the unsteady structures from the wake of the upstream cylinder. At this spacing, the unsteady flow and the radiated acoustic field are predominantly tonal, with a substantially weaker broadband component. This deceptively simple configuration was computationally demanding because of a number of factors such as (i) an often bistable flow behavior within computational solutions [8], which alternated between a co-shedding state observed in the experiments at the cylinder spacing of interest and an altogether different state resembling the measured flow behavior at smaller, subcritical spacings such that only the rear cylinder shed a Karman vortex street, (ii) the intricate effects of boundary layer tripping on the rear cylinder in spite of being buffeted by the strong unsteady wake from the front cylinder [8, 15], and (iii) the effects of model installation within a wind tunnel facility and other facility details involving extraneous noise sources (e.g., mixing layers bounding an open jet tunnel stream) and secondary scattering agents (e.g., nozzle lips, side plates, collector plate) that exerted a finite influence on the measured acoustic field [16, 17, 18, 19].

The simple, tandem cylinder configuration exemplifies some of the major difficulties involved in benchmark quality measurements related to airframe noise problems. Conventional aerodynamic wind tunnels are not well-suited for such measurements because of the reverberation of radiated acoustic waves within the enclosed environment. For microphones mounted on (or close to) the tunnel walls, the issue of signal contamination due to turbulent flow along the surface must also be dealt with. At the low frequencies of the tandem cylinder configuration ($f < 200$ Hz for cylinder sizes required for adequate resolution of PIV measurements), the reflections from tunnel walls effectively ruled out the use of closed wall tunnels for acoustic measurements.

Open jet wind tunnels largely overcome the above two difficulties, yet they may not be able to fully eliminate the effects of turbulent flow due to the presence of one or both sidewalls. They also entail other sources of extraneous noise such as the free shear layer bounding the jet and its interaction with the collector unit at the downstream end. Furthermore, the open jet facilities present a couple of significant aerodynamic limitations. One of these corresponds to the deflection of the jet due to the lift forces on the model; however, this is not a problem for the tandem cylinder configuration (and isolated landing gears in general) because of the zero (or relatively modest) value of the mean lift on the model. The other aerodynamic limitation of open jet facilities arises from the fact that they must operate at atmospheric pressure, which inevitably amounts to rather low Reynolds numbers in the case of subscale models. Because of these considerations, a dual use of both closed wall (Fig. 1(a)) and open jet facilities (Fig. 1(b)) was deemed highly desirable, if not critical, to characterize the sensitivity of the relevant fluid dynamic metrics to the wind tunnel facility. While the conventional facility could not provide acoustic data, it served the additional purpose of allowing an assessment of the effects of spanwise aspect ratio of the tandem cylinder model.

Because of the impact of boundary layer transition on the separation characteristics of the cylinders, especially on bluff bodies such as the tandem cylinder configuration, artificial trips must be employed to mimic the transition behavior on full-scale airframe components. Selection of trip parameters for the tandem cylinders was rather tricky because of the strongly favorable pressure gradient along the front portions of the cylinders, which makes the incoming boundary layer very stable and the post-trip boundary layer flow (particularly along the front cylinder) susceptible to relaminarization prior to separation. A considerable effort was spent on the sizing and placement of trips to ensure an effective yet optimal tripping of the boundary layer flow during the experiments [15, 20, 21]. A direct measurement of the state of the boundary layer is often impractical during airframe noise experiments, even during the pursuit of benchmark quality data. However, detailed measurements of surface pressure distribution along with the PIV data helped ensure that the separation characteristics on the models were representative of high Reynolds number configurations. While the majority of the unsteady measurements were deemed to be free of side effects due to boundary layer tripping, certain features of the relatively subdominant, high-frequency portion of surface pressure spectra were still suspected to be influenced by the boundary layer trips [15]. Emulating the turbulent separation behavior was relatively easy for hybrid RANS-LES codes. However, modeling the effects of boundary layer trips was particularly difficult for the purely LES computations. The NASA vision for CFD in 2030 [22] has recognized the broader implications of the challenge in transition modeling during LES computations, and has highlighted integrated transition modeling as one of the two major pacing items for CFD in the analysis and design of aerospace systems by 2030.

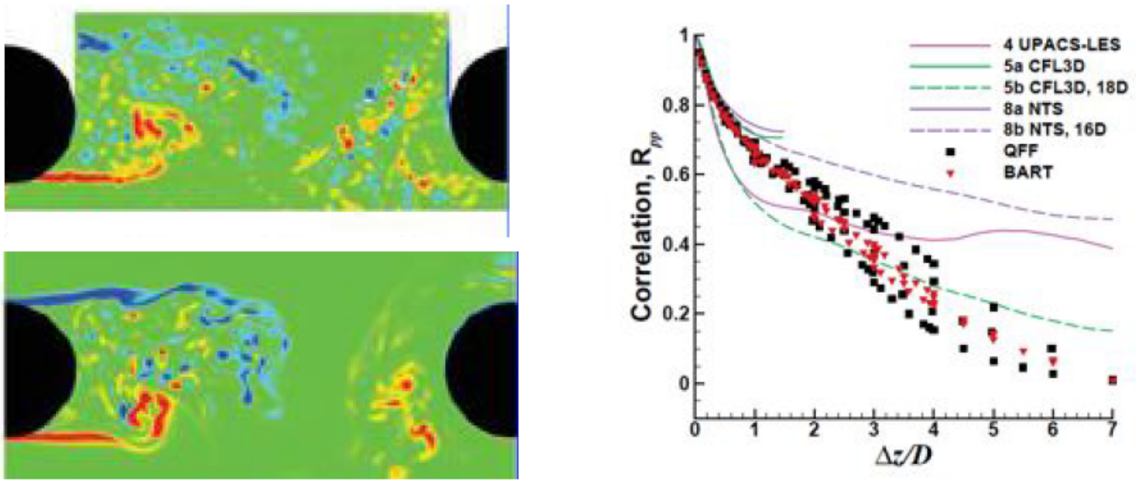
Multiple factors contributed to the successful bridging of the gap between computations and farfield acoustic measurements for the tandem cylinder configuration. The combination of factors included: careful design and planning of experiments, use of two different facilities that allowed the effects of facility environment and sensitivity to model aspect ratio to be examined, close coordination between experimental team and computational stakeholders throughout the experimental campaign [15, 16, 20, 21], nearfield computations performed by different groups using a variety of methodologies [23-32] and their comparison [Fig. 2] with the holistic set of measurements that extended across on-surface, off-body, and far-field regions, and finally, dedicated investigations to isolate the effects of secondary scattering [17, 19, 27], tunnel installation effects [19, 31], and extraneous noise sources associated with the facility [31].



(a) Installation in a closed wall wind tunnel: Basic Aerodynamics Research Tunnel (red arrows indicate azimuthal arrays of static pressure ports) [15]

(b) Installation in an open jet facility: Quiet Flow Facility (QFF) at NASA Langley Research Center [16]

Figure 1: Category 2 of BANC-I and BANC-II Workshops: Unsteady wake interference between a pair of inline tandem cylinders



(a) Vorticity structures within turbulent wake behind tandem cylinders (PIV: top, selected simulation from BANC-I Workshop: bottom)

(b) Spanwise correlation of pressure fluctuation at 45 deg location on the front face of rear cylinder (symbols: measurements in open jet and closed wall tunnels, lines: computational predictions from BANC-I Workshop)

Figure 2: A hybrid RANS/LES computation around the inline tandem cylinders [8]

Provided that the aspect ratio of the finite-span model is sufficiently large (whether in experiment or in simulations), the single point statistics of the unsteady flow over tandem cylinders at supercritical spacing was found to be relatively insensitive to spanwise end effects [8]. However, in addition to the amplitudes of the surface pressure fluctuations, their spanwise coherence also plays an equally important role in determining the strength of the radiated acoustic field. The latter consideration imposes more stringent requirements for both the instrumentation placement in the experiment and the modeling of lateral boundaries in the nearfield simulations. Thus, Category 2 participants were encouraged to pursue niche computations targeting the effects of sidewall installation. The resulting simulations helped clarify the magnitude of corrections necessary to account for the effects of tunnel sidewalls in the experiment, paving the way for more meaningful comparisons with the typical and more practical numerical simulations that did not consider end wall effects. A comprehensive, facility-scale numerical simulation [31] indicated a dual role for the end walls. Including the signature of unsteady flow events over the side plate surfaces accounted for a measurable correction to the far field acoustics, corresponding to a nearly uniform increment of between +1 to +2 dB in the overall sound pressure level (OASPL). These simulations also indicated that, in spite of the relatively long span of the cylinder models (16 times or greater with respect to the cylinder diameter), the decay in spanwise coherence was greatly impacted by the spanwise boundary conditions. Whereas including the presence of the side walls led to a substantial decay in spanwise coherence across the model span, a spanwise periodic boundary condition maintained large levels of coherence throughout the spanwise length of the cylinders. Accounting for both of the abovementioned effects of model installation led to a close match between the predicted and measured acoustics, including the tonal peaks associated with vortex shedding and the broadband component and, hence, also provided a meaningful basis to assess the computations that did not include any installation effects, i.e., used spanwise periodic boundary conditions.

3.0 CATEGORIES 6 AND 7: SLAT NOISE

Noise radiation from the leading-edge slat of a high-lift system is known to be an important component of the aircraft noise during approach [33]. Slat noise is primarily broadband, but may be accompanied by multiple narrowband, tonal peaks (NBPs) within the frequency range of highest broadband noise. The occurrence and the relative strength of the NBPs depends on several factors including the geometry of the configuration and the flow conditions. Problem Categories 6 and 7 from the BANC series of workshops target slat noise in the most rudimentary approach setting of a generic, unswept, 3-element, high-lift configuration. The LEISA-2 model used in category 6 emulates the F-15 configuration of DLR, which has been the focus of a large number of investigations related to high-lift aerodynamics [12]. In a similar vein, the category 7 is focused on the 30P30N configuration that has been used in the U.S. as a benchmark for aerodynamic predictions of 2D high-lift configurations [13]. Thus, a validated aeroacoustic prediction capability and the understanding of noise source mechanisms for these simplified configurations should provide a strong basis for addressing the complexities of slat noise associated with a realistic high-lift configuration, e.g., sweep, taper, twist, brackets, and geometric details of an operational slat. The selection of multiple synergistic configurations for a given source of airframe noise is, again, a hallmark of the BANC strategy. The benefits include: characterization of the sensitivity to both wind tunnel facility and the geometry of high-lift configuration, ability to confirm major trends/features of both noise sources and the radiated acoustic field, and overlapping yet complementary measurement techniques.

Numerical simulations of slat noise involve a number of challenges [15]; these include a high computational cost associated with large spanwise domains (which may be needed in spite of the quasi-2-D behavior of a high-lift configuration of large aspect ratio) and the physical complexity of the flow field (which makes it difficult to precisely identify the noise generation mechanisms). Therefore, a holistic and team oriented approach focused on a simple configuration has been found to be the most effective way to advance the computational state-of-the-art for this class of problems as described below.

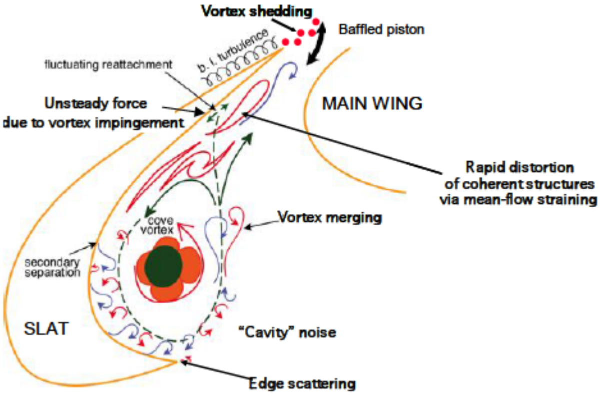


Figure 3: Potential physical mechanisms behind noise generation near a leading edge slat [34]

As a result of the two-dimensional geometry of the slat noise configurations, categories 6 and 7 share a number of validation challenges with the tandem cylinder configurations. Experience gathered during the BANC workshops suggests that, unlike the tandem cylinder configurations, the unsteady flow field near the slats does not involve a flip-flopping between multiple flow states over a long time scale. However, in all other respects, the high-lift configurations have been much more challenging in terms of developing a validation quality database. The factors contributing to the extra difficulties include [6]: (i) the increased complexity of noise generation (Fig. 3) including mixed acoustic spectra with a primarily broadband spectrum superimposed with multiple narrow-band peaks (NBPs), (ii) large time averaged lift on the model, which leads to significant deflections of the tunnel stream in an open jet facility and, hence, may cause unacceptable variations in aerodynamic characteristics of the model, (iii) aerodynamic and aeroacoustic effects of brackets connecting the slat and flap elements to the main wing, (iv) extraneous noise sources within the model such as main element cove, main and flap trailing edges, and possible separation over the flap, (v) more complex sidewall interference effects on the high-lift configuration, (vi) Reynolds number effects that may not be fully amenable to holistic measurements, and finally, (vii) the practical challenge of accommodating adequate surface mounted instrumentation (static pressure ports and dynamic pressure transducers) within a limited space. Dual use of the tubing designed for static pressure measurement along with remote microphones has been attempted to circumvent the lack of space for dynamic instrumentation; however, this method has been found to be inadequate, at least when implemented as an *a posteriori* consideration.

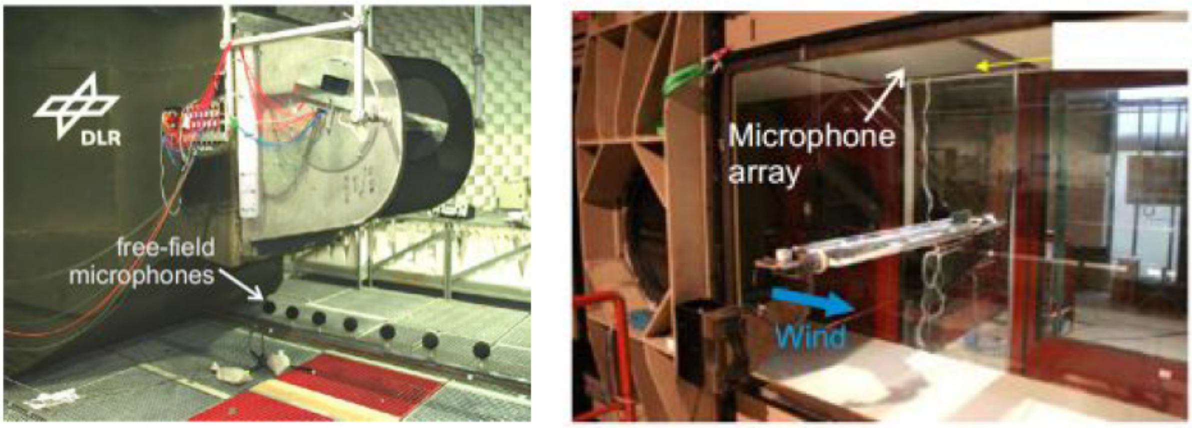
In principle, many of the acoustic measurement challenges for high lift experiments (along with other types of airframe noise tests) may be addressed using microphone phased arrays. Similar to solid-state radar, microphone phased arrays simultaneously acquire data at multiple measurement locations. The acquired data can then be "steered" in post-processing to isolate noise coming from the target direction/location from that associated with extraneous noise sources. Such processing can isolate the desired slat noise from the noise due to connecting brackets, sources along the main element and the flap, sidewall interference, and facility background noise. However, while array signal processing is fundamentally a mature field [35], there are many unique challenges in aeroacoustics that hamper its use for quantitative validation of acoustic simulations.

First, arrays have limited spatial resolution, driven by their aperture, and finite sidelobe patterns, driven by their microphone count and layout. Resolution limitations inhibit the ability to separate adjacent sources, and sidelobes may appear as false sources. Deconvolution techniques such as DAMAS [36] and CLEAN-SC [37] are implemented to mitigate some of these issues, but as with most common techniques for array processing, the deconvolution techniques also assume that the aeroacoustic noise sources act as a distribution of uncorrelated monopoles [38, 39]. When the sources possess distributed coherence characteristics, as is the case with jet noise depending on the operating condition [40], localization and levels determined from the array may be in error. The latter could also apply to the BANC workshop problems in that some noise sources such as the tandem cylinders possess significant spanwise coherence based on surface pressure measurements. The NBPs from categories 6 and 7 also exhibit larger spanwise coherence lengths than those associated with the broadband component. Additionally, multipole source characteristics may influence the computed results [41]. Beyond the source assumptions, array signal processing must assume a propagation model. This model is usually for a source located in an unbounded medium, which is never the case in an experiment. In closed-walled aerodynamic wind tunnels, reverberant sidewalls influence the acoustic propagation characteristics. In open jet wind tunnels, the free shear layer bounding the test section refracts the acoustic propagation path. Corrections can be applied for reverberance [42] and refraction [43]. However, the limitations of various corrections are still being actively investigated [44]. Additionally, the influence of turbulence in the acoustic propagation path may affect the results and analysis [45]. Finally, signal contamination from flow over the microphones or facility background noise sources may be present and require consideration in processing [46].

All of the aforementioned challenges are considered in a careful experiment, and corrections applied. However, full validation of these corrections is still an active field of research. A working group sponsored by the AIAA Aeroacoustics Technical Committee has recently initiated efforts to understand the variability of results due to various corrections and processing methods. Those activities are beginning to illustrate what can be expected from the current state of the art in airframe noise measurements [47, 48]. The continuing validation activity provides an opportunity for advancing both CAA techniques and array processing methods. While this effort synergizes with most of the BANC categories, it was discussed in the present section because of the particular set of challenges present in high-lift aeroacoustic testing.

Due to the increased challenges in both measurements and computations of slat cove noise, the modus operandi for categories 6 and 7 has been rather different from category 2, with a tighter and necessarily parallel coupling between CFD and experiments and a concomitant set of investigations over multiple rounds of experimental and computational studies (see, for instance, Refs. [49-53] for category 6 and Refs. [54-64] for category 7). Measurements with the F-16 model from category 6 have been performed in the AWB open jet facility at DLR (Fig. 3(a)) and the F2 aerodyamic wind tunnel at ONERA (Fig. 3(b)). A comparison of the measurements obtained in these two facilities has shown that the mean loading characteristics from the F2 tunnel can be matched rather well within the open jet tunnel provided that the model size is sufficiently small relative to the dimensions of the test section (i.e., the tunnel blockage is low) [52]. Thus, in this case, the acoustic measurements in the open jet facility have been shown to be suitable for comparison with simulations based on spanwise periodic boundary conditions, provided that the microphone array measurements are processed specifically to isolate the contribution from the mid-span section of the model where the flow and the beamforming data are nearly homogeneous in span. On the other hand, reverberation effects in the aerodynamic facility were found to result in differences in acoustic spectra of greater than 3 dB with respect to the open-jet measurement [53]. Hence, the aerodynamic facility could not provide validation quality acoustic data in this case, but it did yield an extensive set of measurements related to the unsteady nearfield, i.e., the acoustic sources, in the form of time accurate LDV measurements and PIV data along with unsteady surface pressures [52].

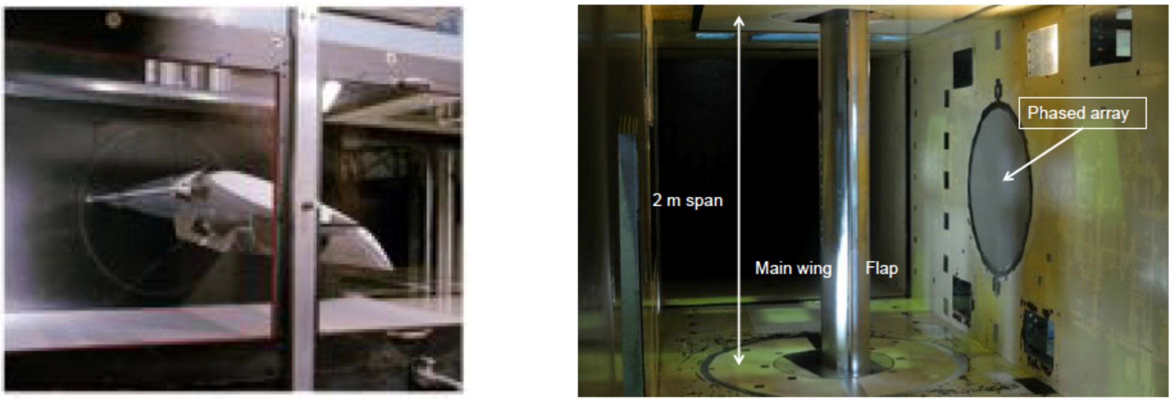
Two additional strategies are being pursued to enable quantitative comparisons between microphone array measurements and computed acoustic predictions. In category 6, facility scale simulations will be used to obtain synthetic microphone array data that will be processed similar to the experimental measurements using signals from the physical microphones [49]. In category 7, measurements in Kevlar wall test sections [63] within an anechoic chamber are being used to minimize the effects of reflections from tunnel walls without the undesirable aerodynamic effects of an open jet. The Kevlar wall [65] is not without its own complications, however, because of its elasticity (which leads to deformation of the walls facing the pressure and suction surfaces of the model) and the nonzero permeability leads to a transpiration of flow across those same walls.



(a) DLR AWB acoustic wind tunnel

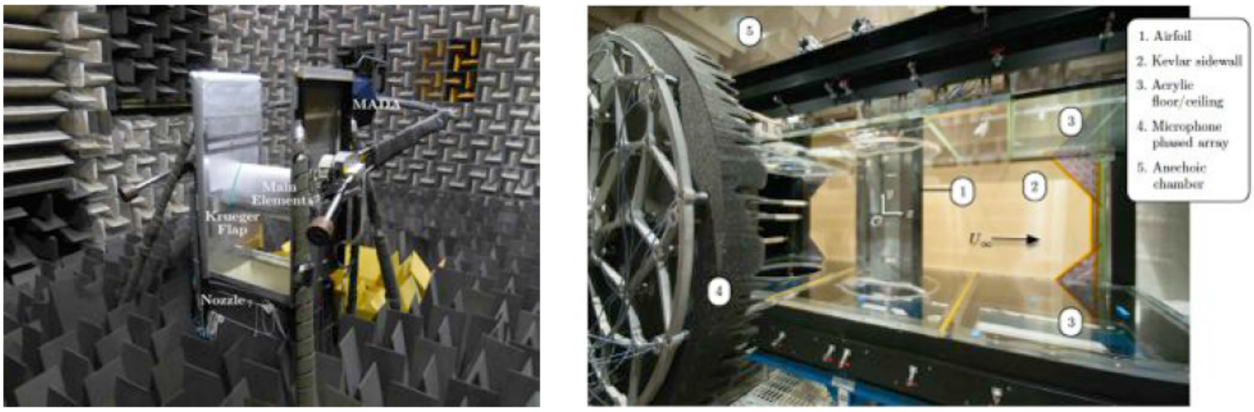
(b) ONERA F2 aerodynamic wind tunnel

Figure 3: Category 6 of BANC Workshops: F-16 3-Element, Simplified High-Lift Configuration from the LEISA2 Project [53]



(a) Basic Aerodynamics Research Tunnel (BART) at NASA Langley [55]

(b) JAXA-LWT2 Wind Tunnel [62]

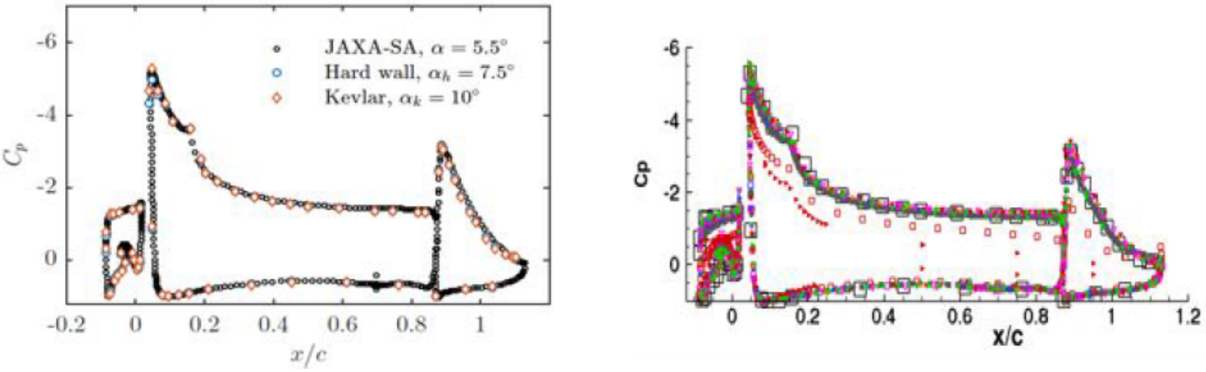


(c) Open jet Quiet Flow facility (QFF) at NASA Langley Research Center [64]

(d) Kevlar-wall test section of Florida State Acoustic Tunnel (FSAT) [61, 63]

Figure 4: Category 7 of BANC Workshops: 30P30N 3-Element, Simplified High-Lift Configuration

The 30P30N configuration of category 7 has previously undergone measurements in the Basic Aerodynamic Research Tunnel at NASA Langley Research Center (Fig. 4(a)), the 2m x 2m LWT2 wind tunnel at JAXA (Fig. 4(b)), the open jet Quiet Flow Facility at NASA Langley (Fig. 4(c)), and the Florida State Acoustic Tunnel (FSAT) (Fig. 4(d)). Measurements in FSAT have been performed with both open and closed wall test sections as well as a Kevlar-wall test section. These measurements have shown that, at the modest angles of attack of interest in airframe noise applications, the aerodynamic effects of the Kevlar wall can be entirely corrected via a modified angle of attack (Fig. 5(a)). An excellent comparison has been obtained between the C_p distributions in different facilities and a majority of computational submissions to the BANC Workshops, with the understandable exceptions of open jet measurements and simulations with rather coarse grids (Fig. 5(b)). Additional measurements for the same high-lift geometry have also been performed by Embraer and University of Sao Paulo in Brazil [66]. Indeed, even after a nearly decade long investigation, the category 7 configuration is still undergoing measurements to address the issues related to aerodynamic and acoustic challenges in slat noise measurements. Further tests of the 30P30N configuration under a collaborative effort between JAXA and NASA are planned for the near future they would allow direct comparisons between acoustic measurements obtained with Kevlar-wall and hard wall test sections in the same facility.

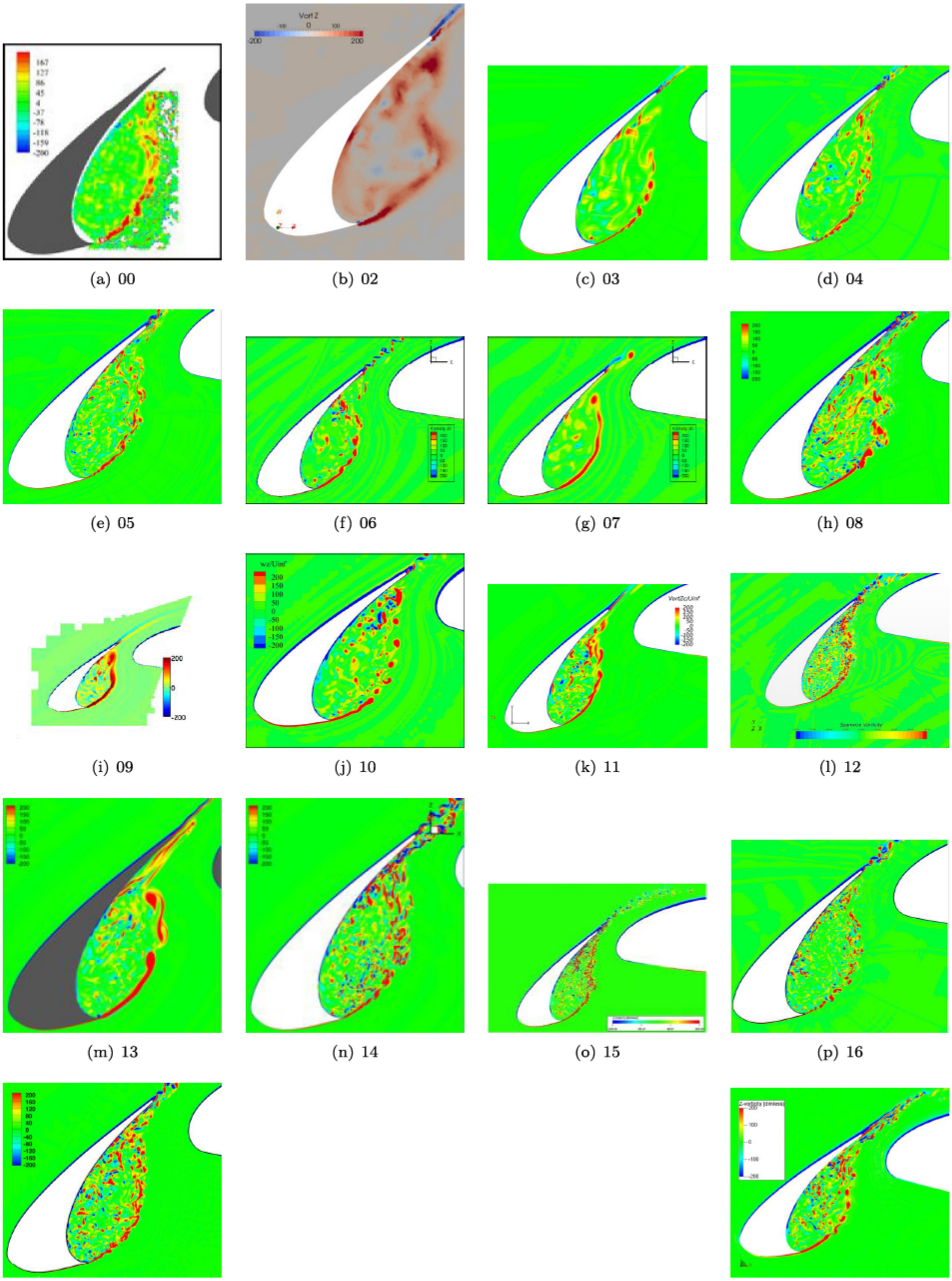


(a) Comparison of open-air CFD predictions with FSAT measurements in closed wall and Kevlar-wall test sections [63]

(b) Comparison of mean C_p distribution from three different wind tunnels and time accurate simulations from BANC-IV Workshop (The outliers corresponds to measurement in open jet facility and simulations on rather coarse grids)

Figure 5: Mean C_p distribution on category 7 configuration at a free-flight –equivalent angle of attack of 5.5 degrees

The detailed flow measurements using established techniques, along with the scrutiny afforded through multiple computational investigations of categories 6 and 7, is also providing the opportunity to mature promising techniques such as unsteady pressure sensitive paint [67] that could provide measurement detail that has not been possible in the context of airframe noise experiments thus far. The interplay between computations and measurements has also established the need to pay careful attention to the spatial resolution of global measurement techniques like particle image velocimetry, especially in high gradient regions such as the initial region of shear layer development behind the slat cusp [57]. PIV measurements at multiple resolutions have been necessary to adequately characterize the scale disparity across noise relevant unsteady flow structures (Figs. 6 and 7).



(a) 00 (b) 02 (c) 03 (d) 04

(e) 05 (f) 06 (g) 07 (h) 08

(i) 09 (j) 10 (k) 11 (l) 12

(m) 13 (n) 14 (o) 15 (p) 16

(q) 17 (r) 19

Figure 6. Visualization on instantaneous spanwise vorticity in *xy* plane [13]

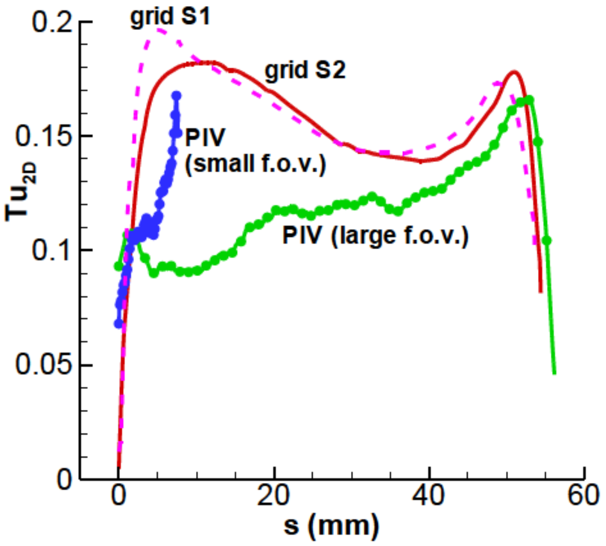


Figure 7. 2D turbulence intensity along mixing layer trajectory emanating from slat cusp (s denotes distance from the cusp): comparison of PIV data obtained with large and small fields of view indicates the need for fine-scale resolution of slat mixing layer to capture the mixing-layer transition (indicated by first peak in the evolution of 2D turbulent kinetic energy) [48]

Similar to the tandem cylinder configuration, boundary layer tripping has a strong influence on the acoustic spectra. The measurements acquired at JAXA [62] suggest that the NBP amplitudes can be highly sensitive to boundary layer trips, especially at lower angles of attack (Fig. 8). Limiting the comparison to the broadband component of noise spectra would therefore provide more robust comparisons with computational predictions, especially in the near term. Whereas sufficiently higher angles of incidence do lead to substantially weaker NBPs, and are also less suitable to acoustic validation experiments because of greater susceptibility to model vibrations as found during the FSU Kevlar wall experiments. As a compromise, the focus of category 7 investigations for future workshops has been augmented to include an intermediate angle of attack for which the NBPs are significantly lower but still visible. Consistent with the continued evolution of the slat noise category, a future wind tunnel entry will focus on obtaining acoustic measurements over a broader range of angle-of-incidence in the (larger) JAXA wind tunnel with the Kevlar wall configuration. Other outstanding issues related to benchmark quality acoustic measurements of slat noise include an accurate characterization of the acoustic transmission loss across this wall, especially for obliquely incident acoustic waves [63].

In spite of the various difficulties in validating slat noise predictions as outlined above, the results obtained under the BANC workshops thus far suggest a good prognosis provided that the model installation effects can be addressed satisfactorily. See, for instance, the comparison between different measurements as well as with numerical simulations of both nearfield unsteady pressures along the surface (Fig. 9(a)) and those at a farfield, overhead location (Fig. 9(b)).

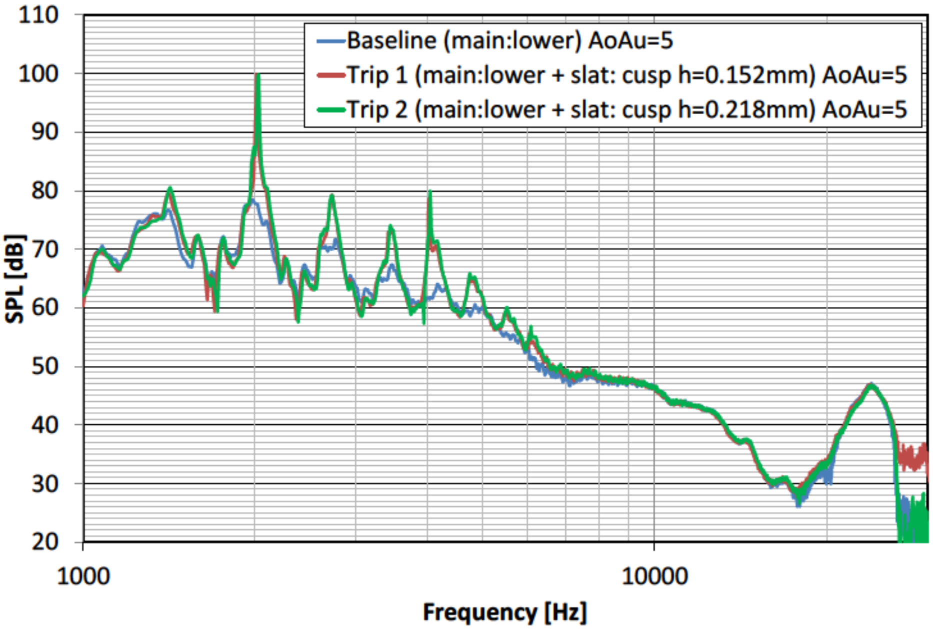
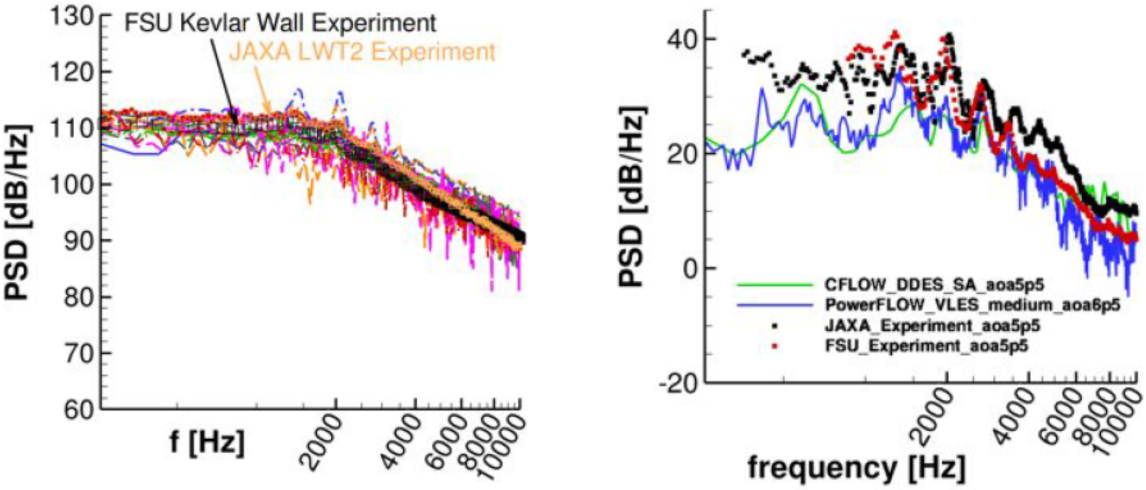


Figure 8: Effect of boundary layer trips on microphone phased-array based acoustic spectra obtained by integration of noise source maps for category 7 high-lift configuration at AoA = 5.5 deg, U_∞ = 58 m/s (spectral bin width = 10 Hz) [62]



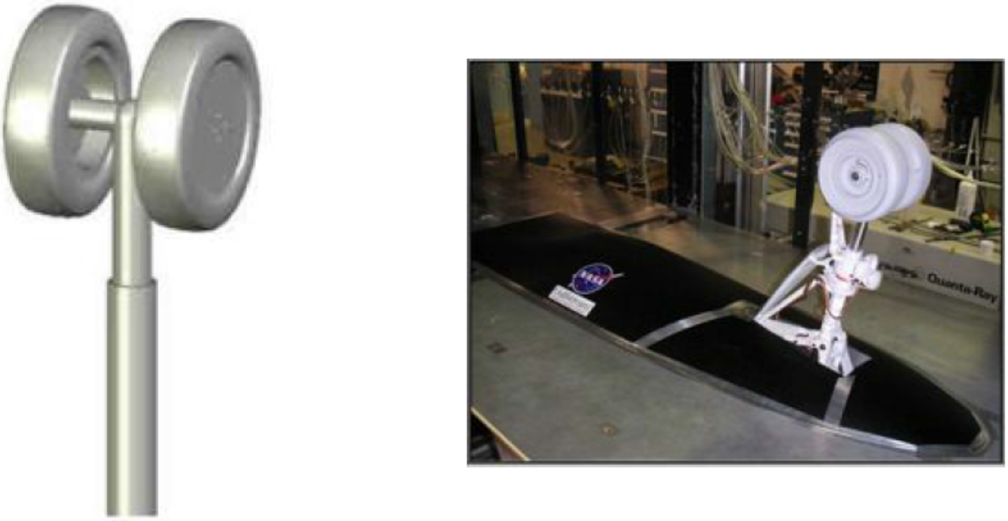
(a) Frequency spectrum near reattachment location: comparison of measurements and numerical data submitted by BANC-IV Workshop participants

(b) Far-field acoustic spectra: selective comparison of experiments and computations

Figure 9: Unsteady pressure spectra for nearfield source and radiated acoustic field from 30P30N high-lift configuration

4.0 CATEGORIES 4 AND 5: TWO-WHEEL NOSE LANDING GEARS

Categories 4 and 5 of the BANC Workshops are focused on 2 wheel landing gear configurations representative of nose landing gears. Originally designed and tested in the LAGOON project funded by Airbus-France, the category 5 configuration involves a simplified geometry (Fig. 10(a)) that is compatible with a wide range of numerical methods while retaining the physics of interaction between the larger scale components of the landing gear. On the other hand, the PDCC-NLG configuration of category 4 represents a high fidelity model of the nose landing gear on a Gulfstream regional jet (Fig. 10(b)).



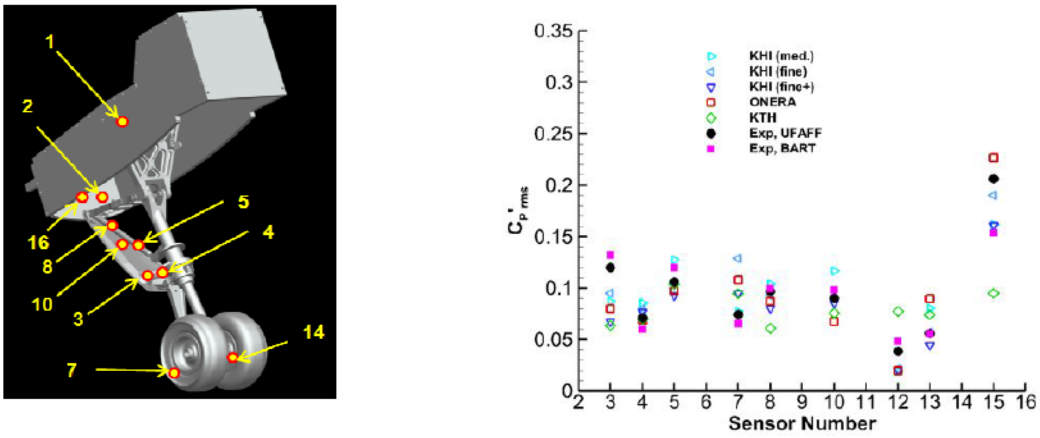
(a) Category 5: LAGOON simplified nose landing gear [11]

(b) Category 4: PDCC-NLG configuration [10]

Figure 10: Two wheel landing gear configurations of categories 4 and 5

Because of the enormous challenges in gridding the complex geometry of the Gulfstream nose landing gear, numerical simulations of this configuration using available solvers were nearly impractical when the model was designed and even when the wind tunnel experiments were performed [68]. Therefore, the interaction between experiments and simulations has been primarily one way in nature. In particular, the specification of measurement locations, especially for point measurements based on unsteady pressure transducers, could not benefit from numerical simulations. However, beamforming measurements performed at UFAFF by Zawodny et al. [69] were used in computations [70] to define the zones requiring special attention. In particular, the beamforming data had suggested that the main acoustic source may be located in the shock strut-torque arms region, with secondary source next to the trunnion. Optimizing the grid to focus on these regions led to efficient resolution of the unsteady flow field, resulting in acoustic spectra that were in close agreement with the measured data over a majority of the frequency range of interest.

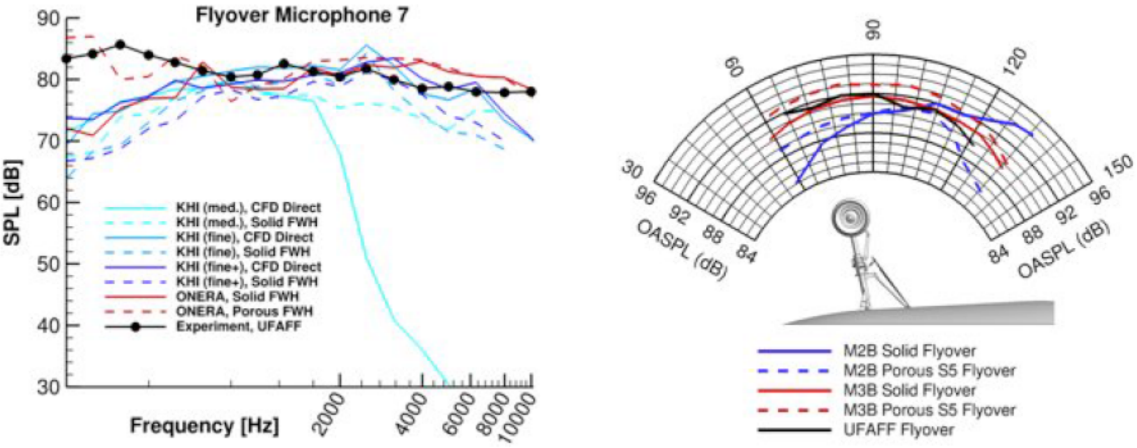
Comparison of predicted pressure fluctuation amplitudes at selected surface locations with measurements obtained using dynamic pressure transducers indicate significant differences in the case of the PDCC-NLG configuration (Fig. 11). However, a number of contributors to the BANC workshops have been able to achieve rather encouraging agreement with the measured frequency spectrum and directivity pattern of the acoustic field (Fig. 12). Admittedly, there is no definitive information as yet to determine which surface transducer locations play an important role in determining the acoustic signature along the directions of interest. However, a likely conclusion appears to be that measurements of RMS pressure amplitudes may not provide as strong a validation metric as one might have believed before the BANC Workshops. Thus, additional work remains to be done in order to clarify the role of unsteady surface pressures in validating airframe noise simulations.



(a) Schematic of transducer locations

(b) Comparison between measurements and data submitted by BANC Workshop participants

Figure 11. RMS pressure fluctuations at the locations of unsteady pressure measurement along the surface of the PDCC-NLG configuration [10]



(a) Acoustic spectra [10]

(b) Directivity pattern: measurement vs. a selected set of simulations [70]

Fig. 12. Comparisons between measured and predicted acoustic fields for the PDCC-NLG configuration of category 4

5.0 CATEGORY 8: PROPAGATION PHASE OF AIRFRAME NOISE PREDICTION

CFD-based noise prediction in practical applications typically involves the hybrid approach, which couples CFD computations of unsteady aerodynamics and acoustics in the near field with a propagation algorithm to calculate the acoustic signal at an observer position of interest. Typically, the acoustic propagation phase does not involve any noise generating mechanisms; however, it has to account for the effects of shielding/scattering bodies or flow heterogeneities that mostly occur in a mid-field region. Once outside this mid-field region, noise typically propagates through a homogeneous medium to an observer. Figure 13a shows propagation with no body interactions and an immediate transition from near- to far field. Figure 13b shows propagation with potential shielding and scattering interactions, as well as heterogeneous propagation effects in the mid-field. There are several different approaches to calculating the noise propagation, summarized in Figure 14, including Integral Methods (IM) (such as Kirchhoff extrapolations [71, 72] and Acoustic Analogies [73, 74]), Ray Methods (RM) [75], Boundary Element Methods (BEM) [76, 77], Equivalent Source Methods (ESM) [78, 79], and Computational AeroAcoustics (CAA) [80]. Each of the approaches must be provided a solution to the near field region, including unsteady aerodynamics and acoustics, in order for it to provide a prediction at an observer position in the near or far field. Once a pressure time history at the observer location(s) is determined, post-processing algorithms can be applied to determine the characteristics of farfield noise radiation, better assess the noise sources within the near field, and perform a direct comparison with wind tunnel measurements.

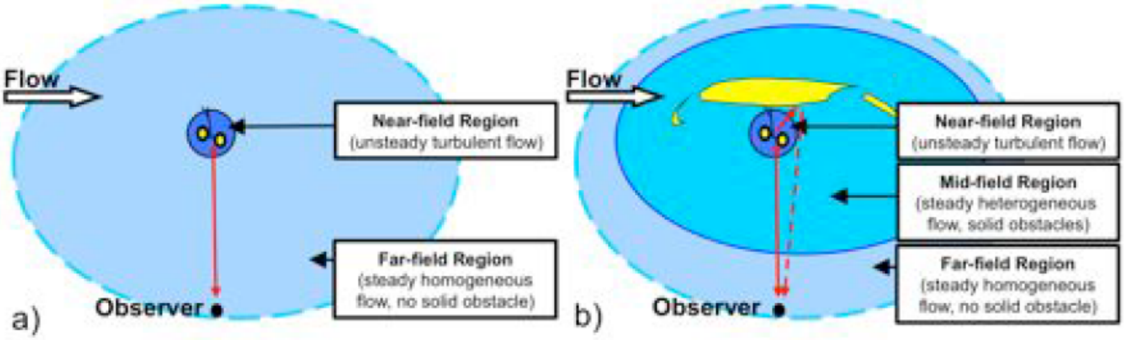


Figure 13. Summary of regions of CFD-based noise prediction: a) Noise generating region placed in isolation where no bodies influence noise propagation. b) Body exists near noise generating region influencing the noise propagation.

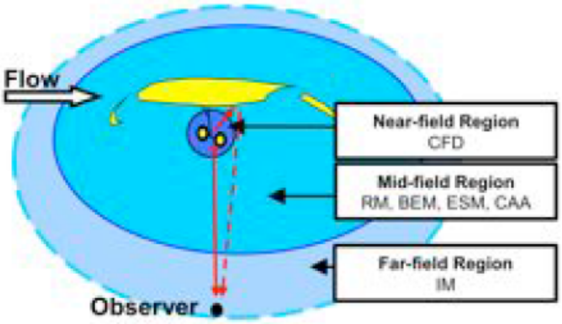


Figure 14: Summary of coupled CFD and propagation components of CFD-based airframe noise prediction.

The goal of Category 8 of the BANC workshop is to quantify the variability in the propagation phase of CFD-based noise prediction; the attributes of interest include the resources required, computation time, and accuracy of the result. Toward that end, two subcategories were created to quantify the variability. Subcategory 1, Scattering of Noise by a Sphere, was created as a simple test case to quantify the execution time, resources, and accuracy of each approach compared to an analytical solution. Subcategory 2, Nose Landing Gear, was created to assess the variability in the results when provided a common CFD solution of a complex noise-generating region. Only results and insights gained from Subcategory 2 are shown here.

For Subcategory 2, participants were provided a CFD solution of the flow around a nose landing gear geometry (the Airbus-ONERA LAGOON configuration used in BANC-II Category 5) [11,12]. The solution, provided as an internet download of dimensional flow quantities, included on-body (impermeable) and off-body (permeable) surfaces, the latter of which is designed as a nearly cubic interface encompassing the wheels and is composed of 6 panels shown in Fig. 15. Participants were asked to provide the acoustic pressure at 5 far field observer locations (designated F1 through F5), 4 nearfield observer locations (designed N1 through N4), and at an observer at the midpoint (origin) between the wheels inside the surfaces (designated as the origin). Supplied results were to include pressure time signals and power spectral densities. The observer locations, with the exception of the origin, coincided with measurement locations used in ONERA's open-jet anechoic wind tunnel CEPRA19 in Saclay, France [11].

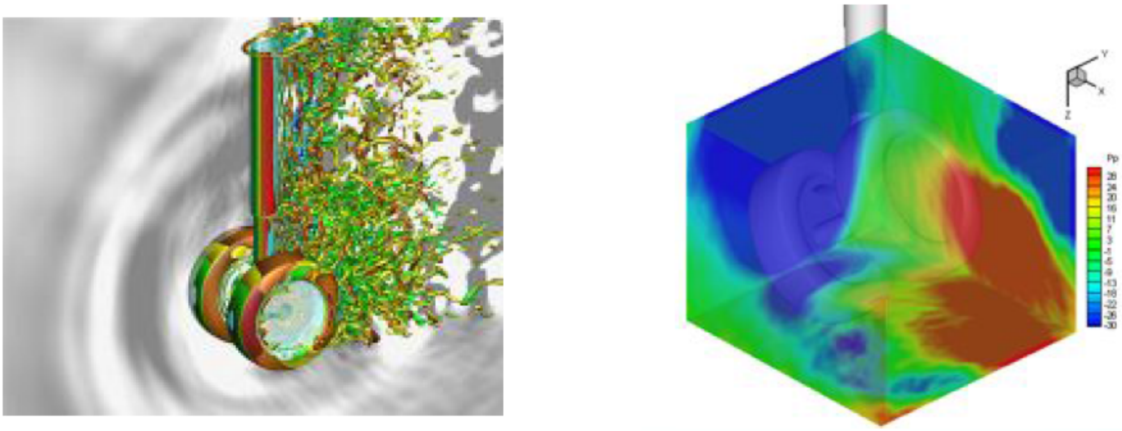


Figure 15: CFD solution of flow around LAGooN geometry (left) and subsequently extracted data over a permeable interface (right) that forms the input for the acoustic propagation phase.

Subcategory 2 at the BANC-III Workshop included three participants: two IM solvers (NASA's ANOPP2-F1A [81] and JAXA's upacsAcoustics [82]) and one CAA solver (ONERA's sAbrina [83]). ANOPP2-F1A and upacsAcoustics utilized the entire CFD solution (not downsampling in space and time); however, sAbrinA utilized a solution that was downsampled in space (1:2 ratio) and time (sufficient to resolve a maximum frequency of 3kHz). Figure 16 shows predictions at F1 through F5 from the three participants using the permeable surface solution of Fig. 15 as input. For all observer positions, all predictions agree very well with the experiment and with each other. It is interesting to note that all predictions tend to over predict around and below 1kHz and under predict in the high-frequency range. Since all methods are behaving similarly, this trend indicates a dependence on the simulation data used as input rather than some characteristic of the codes. Undoubtedly, the diffusive nature of the CFD simulation results in an artificial decay of high-frequency waves (above 2kHz). The sAbrinA results decay even faster at high frequencies, possibly because of subsampling the input data, but most likely because of its 3kHz cut-off frequency (low-pass sharp filters).

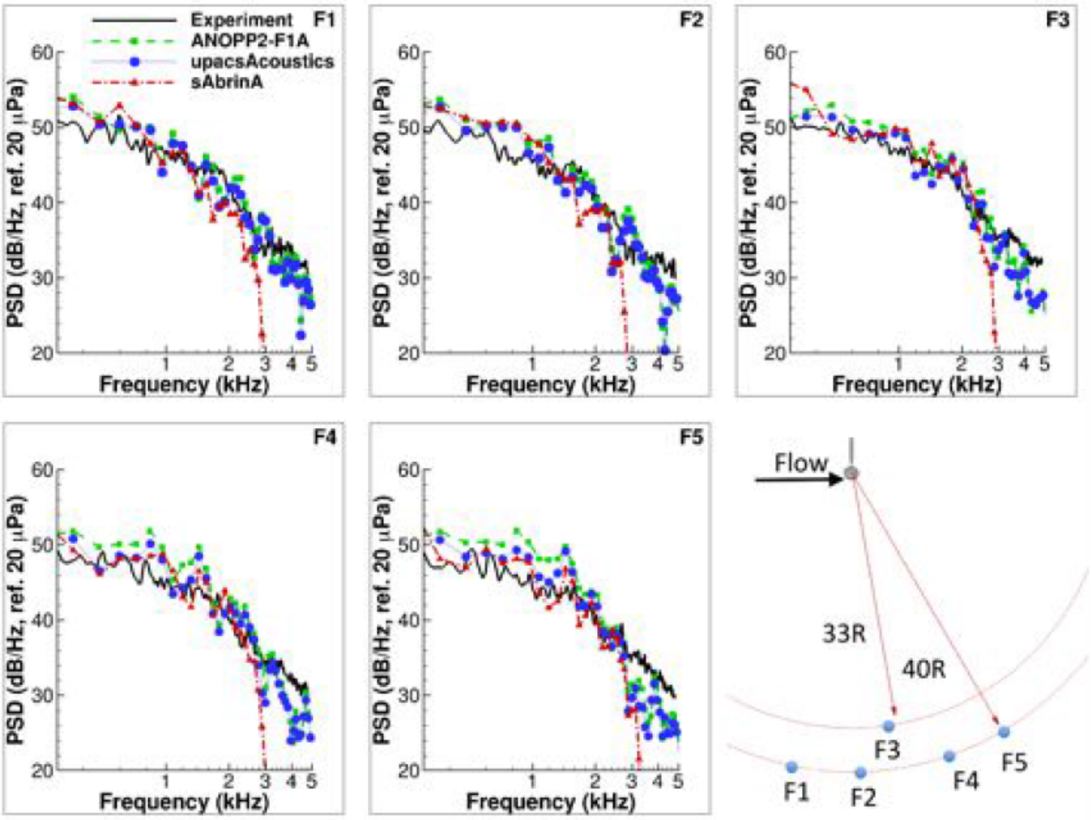


Figure 16: Power spectral densities at microphone locations F1 through F5 from ANOPP2-F1A, upacsAcoustics, and sAbrinA codes using permeable surfaces. Five FFT averages were applied, resulting in a 120 Hz bin width.

Category 8 of the BANC-III and BANC-IV workshops represents a first step in quantifying the importance of the propagation phase of CFD-based noise prediction. During the effort, there were several challenges that had to be overcome, the majority of which were due to either file formatting/non-dimensionalizing to a common dataset, transferring large datasets to participants, and differences in post-processing techniques across participants which lead to significant differences in the power spectral densities provided by the participants. Ultimately, the post-processing portion of the effort had to be excluded, and a common post-processing algorithm was applied to the time histories from all participants. In the future, additional categories will be added, in particular ones that focus on calculating the scattering/shielding of noise and accounting for the influence of flow heterogeneities in the mid-field region. In addition to new categories, future work in category 8 will involve modifying the resolution of the input data and adding more complex configurations of both Subcategory 1 and 2 that will allow a focused assessment of the variability due to influences such as computational reliability and flow characteristics. This will allow for improved understanding and assessment of the validity of predictions, including frequency ranges and observer positions.

In addition, such efforts for quantifying the variability of the propagation phase shall be extended to include other aspects of the overall problem. As an illustration, following the present Subcategory 2 exercise, some of the propagated acoustic signals were processed via two distinct array methods of source localization, namely Classical Beam Forming (CBF) and Deconvolution Approach For Maps of Acoustic Sources (DAMAS) – see Fig. 17 [84]. This effort led to the development of a benchmark test case for the so-called Array Methods workshop, which is an international initiative that seeks to improve the signal processing techniques commonly employed for identifying aircraft noise sources.

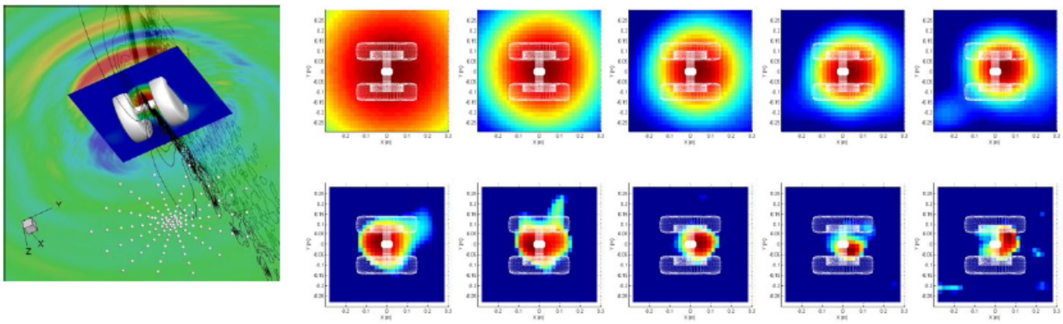


Figure 17: Localization of LAGooN noise sources through an application of phased array techniques to CFD-CAA time series acquired over a mid-field antenna (in white, on left side). Classical Beam Forming (top) and DAMAS (bottom) noise-source maps for acoustic emission at 1kHz, 1.5kHz, 2kHz, 2.5kHz and 3kHz (from left to right).

6.0 CONCLUDING REMARKS

Installation effects and facility background noise are two of the most important and daunting challenges in airframe noise investigations. From the outset of any experimental campaign, sufficient thought must be given to the model setup and whether such setup is amenable to high-fidelity simulations without an extraordinary degree of difficulty. The BANC effort has been rather unique in pursuing a simultaneous development of experimental and computational methodologies to achieve the targeted goal of benchmark quality datasets, rather than merely using the best set of previously available measurements as a source of validating the computations. Thus, both the experimental dataset and the CFD/CAA solutions have continued to grow, feeding off each other and allowing the benchmarks to evolve at a rapid pace. The datasets developed as part of the BANC workshops should continue to be of value to the technical community, not only for the validation of noise prediction approaches including high fidelity simulations and reduced order models, but also in the computation of unsteady flows using large-eddy-simulation and other hybrid RANS/LES techniques.

Integration between simulations and experiments has been a critical ingredient in facilitating the BANC goal of enabling substantial collaborative advances in physics based predictions of airframe noise. In each case, the integration began from the outset with a stronger than usual role by computational researchers in the design of the experimental campaign, continuing through the execution and analysis of the data. The holistic focus on measurements has been another core aspect of the BANC effort, mandating in-depth characterization of each significant link between flow turbulence and the final metric of interest in the form of farfield acoustics. The multifaceted understanding of the aeroacoustic phenomena in terms of both mean-flow features and nearfield unsteadiness, surface and off-body flow features relevant to the noise source of interest, and simultaneous acoustic measurements based on individual microphones and, wherever possible, microphone phased arrays have enabled a detailed comparison between computations and experiments. Such comparison has provided increased confidence into the reliability of the simulation process as well as a better understanding of the physics of noise generation. This, in turn, opens the doors to the application of the knowledge base toward the development of reduced-order prediction models for design cycle applications as well as robust yet efficient noise reduction techniques. Furthermore, the successful integration in the context of simpler benchmarks has provided valuable lessons regarding the measurement and simulation of more complex airframe noise configurations. In particular, the success of landing gear categories 4 and 5 in validating the computational simulations has been rather impressive, despite the high degree of geometric complexity involved. On the other hand, aeroacoustic validation for quasi-2D airframe noise sources that extend over a large “spanwise” extent and/or entail substantial end wall effects has proven to be more elusive so far. Overall, several opportunities still remain to improve the computational and experimental methodologies and those would be addressed during the future BANC workshops. One such issue pertains to the observation from the BANC workshops that, in many cases, the computational predictions of the far field acoustic spectra are less sensitive to mesh resolution than the nearfield pressure spectra along the model surface. Thus, the role of unsteady surface pressure measurements in validating the predictions of airframe noise still remains to be ascertained in its entirety.

Microphone array measurements have been a critical component of experimentally validating the airframe noise simulations. While experiments are used to validate the computations, computations are also necessary to validate the processing of the array measurements. Building on the effort within some of the categories under the BANC workshops, future validation experiments should include a calibration component within the test matrix, wherein a well-defined source is measured and analysed. Such a calibration experiment must be sufficiently robust to address all of the major array processing challenges that are expected to play a role in a given airframe noise measurement, while maintaining known source characteristics for reference. This requirement will move array calibration beyond the simple methods used in previous work, subject to careful planning and possible collaboration with the CAA community. Such collaboration further emphasizes the benefit of the working relationships established in the BANC workshop series, as (again) both the computational and experimental communities benefit from each other's efforts. Indeed, these benefits may extend beyond the scope of airframe noise investigations. Advances in experimental methods could, for instance, be readily applied to aeroacoustic tests of isolated and installed propulsors.

ACKNOWLEDGMENT

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