Integrating CFD, CAA, and Experiments towards Benchmark Datasets for Airframe Noise Problems

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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. The combination of geometric complexity, high Reynolds number turbulence, multiple regions of separation, and a strong coupling with adjacent physical components makes the problem of airframe noise highly challenging. 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 state of the art computational fluid dynamics, computational aeroacoustics, and in depth, holistic, and multi-facility measurements targeting a selected set of canonical yet realistic configurations. This paper provides a brief summary of the BANC effort, including its technical objectives, strategy, and selective outcomes thus far.

Key words: aeroacoustics, airframe noise, computational fluid dynamics, computational aeroacoustics

Introduction

With the advent of quieter, ultra-high-bypass-ratio engines, flow unsteadiness in the vicinity of various airframe components has emerged as an important contributor to the noise signature of subsonic commercial transports during their approach for landing. The major sources of airframe noise include high-lift devices (i.e., leading-edge slat and trailing-edge flaps) and the aircraft undercarriage. 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, it is critical to integrate experiments with computational fluid dynamics (CFD) related to the nearfield unsteadiness (i.e., noise sources) and computational aeroacoustics (CAA) for the propagation of nearfield information to predict the acoustic signature at the location(s) of interest. A similar integration is also essential on the purely experimental front to enable combined (and preferably simultaneous) measurements of the unsteady flow and the acoustic signature. Furthermore, such interplay across multiple levels has to begin from the outset of any fundamental investigation of 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 very important in the context of airframe noise problems.

The BANC Workshops

The paradigm shift from exact analytical solutions towards 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 and the delicate unsteady flow physics.

Even though fundamental investigations of airframe noise have become increasingly common in recent years, the efforts have typically been fragmented across the community, which has impeded both the pace and the impact of these efforts. Due to the continued need for noise reduction on flight configurations, the fundamental efforts have sometimes 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. 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 (BECAN DG) of the American Institute of Aeronautics and Astronautics [1]. The BECAN DG is jointly sponsored by the Fluid Dynamics and Aeroacoustics Technical Committees of AIAA. This effort has led to a series of international workshops on Benchmark Problems for Airframe Noise Computations (BANC). 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 have ranged 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.

In part, the BANC series of workshops has followed the modus operandi of the highly successful Drag Prediction Workshops [2] and Unsteady CFD Validation Workshop [3] in the purely aerodynamics arena but has been more ambitious in targeting additional elements related to the delicate physics of the unsteady flow and/or its coupling with the radiated acoustic field from the outset. 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 near-field 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.

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 BECAN 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 workshop configurations reflected a compromise based on several criteria [1], including:

i. Non-proprietary 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

It was recognized 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 towards that goal.

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 [4]. Most evident was the community spirit in coming together to support the BECAN DG's 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. 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:

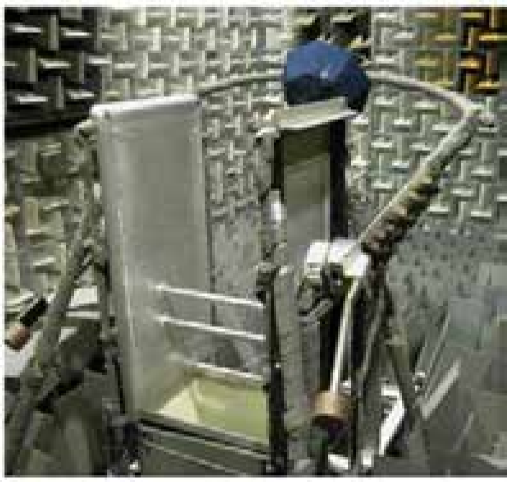
5. The LAGOON Simplified Landing Gear configuration tested by Airbus and ONERA,
6. Slat Noise (DLR/ONERA Configuration)
7. Slat Noise (NASA led effort on a modified 30P30N High Lift Configuration)
8. Acoustic Propagation Phase of Airframe Noise Prediction

Technical details of the integration between CFD, CAA, and both fluid dynamic and aeroacoustic measurements in the context of each technical category are beyond the scope of this brief overview and the reader is referred to the problem statement definitions at the BECAN DG website [5] as well as summary documents for individual categories. See, for instance, Refs. [6], [7] for summaries pertaining to categories 2 and 3.

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 a typical aircraft undercarriage. This deceptively simple configuration was computationally demanding because of a number of factors such as (i) an often bistable flow behavior within computational solutions [6], 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], 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 the open jet tunnel stream) and secondary scattering agents (e.g., nozzle lips, side plates, collector plate) that exerted a significant influence on the measured acoustic field [9, 10, 11].

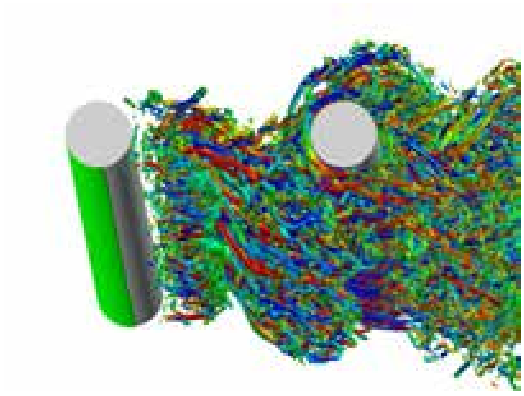
Multiple factors contributed to the successful bridging of the gap between computations and farfield acoustic measurements for the tandem cylinder configuration. The combination of factors included: careful design and planning of experiments, close coordination between experimental team and computational stakeholders throughout the experimental campaign [12, 13, 8], near-field computations performed by different groups using a variety of methodologies [14-23] and their comparison with the holistic set of multi-facility measurements as well as with each other, coupled aeroacoustic predictions, and finally, dedicated investigations to isolate the effects of secondary scattering [9, 11, 22], tunnel installation effects [11, 22], and extraneous noise sources associated with the facility [22]. An interesting finding was that, in spite of the relatively long span of the cylinder models (a span of 16 times the cylinder diameter), the decay in spanwise correlations was impacted by the presence of the side walls wherein the cylinders were mounted and, furthermore, that including the signature of unsteady flow events over the side plate surfaces accounted for a measurable correction to the far field acoustics [22]. Accounting for the model installation effects enabled a close match with the measured acoustics, including both the tonal peaks associated with vortex shedding and the broadband portion and, hence, also provided a meaningful basis to assess the computations without any installation effects, i.e., with spanwise periodic boundary conditions.

(a) Installation in a closed wall wind tunnel: Basic Aerodynamics Research Tunnel (red arrows indicate azimuthal arrays of static pressure ports) [13]

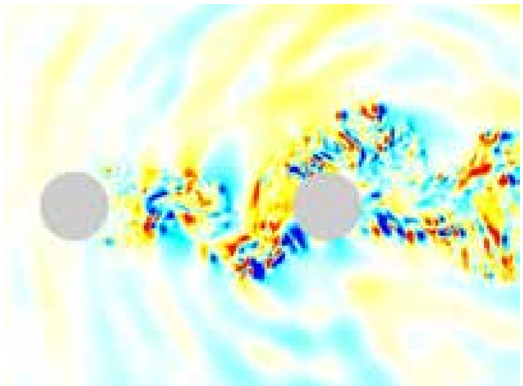


(b) Installation in an open jet facility: Quiet Flow Facility (QFF) at NASA Langley Research Center [16]

Fig. 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

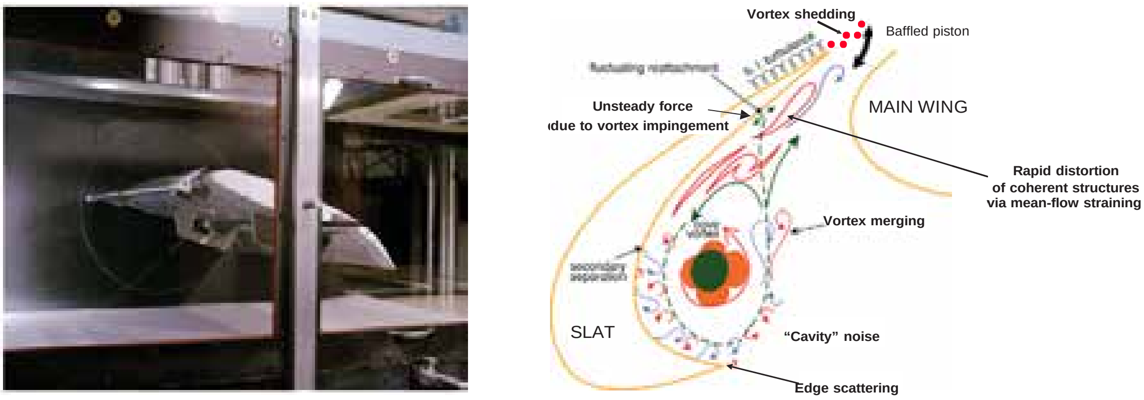


(b) Instantaneous pressure fluctuation around tandem cylinders showing noise generation and propagation

Fig. 2 A hybrid RANS/LES computation around the inline tandem cylinders [19]

Developed as an anchor for the initial BECAN-DG activities, the integration between computational and experimental activities for the tandem cylinder configuration was primarily sequential in nature. Because of the relative simplicity of the configuration and a reasonable body of prior results from the literature (albeit at low Reynolds number and purely aerodynamic in nature), with due planning, it was possible to acquire a thorough set of measurements without a great deal of *a priori* assistance from numerical computations. Of course, as discussed above, computations were essential to understand the limitations of the measurements as well as to raise the quality of the benchmark dataset.

The modus operandi for most other BANC configurations has been different from category 2, with a tighter and necessarily parallel coupling between CFD and experiments. Hence, a concomitant set of multi-phase investigations has been a necessity for these configurations as exemplified by the slat noise categories (categories 6 and 7) from the BANC-II workshop [5]. The flow configuration for category 7 (Fig. 3(a)), in particular, has already undergone multiple rounds of experimental and computational investigations (see, for instance, Refs. [24-30]) and further measurements led by NASA as well as JAXA are currently under way or planned for the near future. The detailed flow measurements using established techniques, along with the scrutiny afforded through multiple computational investigations, is also providing the opportunity to mature promising techniques such as unsteady pressure sensitive paint [31] 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 [27]. Measurements at multiple resolutions are necessary to adequately characterize the scale disparity across noise relevant unsteady flow structures (Figs. 3(b) and 4(a)).



(a) 30P30N airfoil installed in the Basic Aerodynamics Research Tunnel [25]

(b) Potential sources and physical mechanisms behind noise generation near a leading edge slat [27]

Fig. 3. Category 7 of BANC-II Workshop: 30P30N 3-Element, Simplified High-Lift Configuration

(a) Vortex structure of turbulent shear-layer inside of 30P30N slat

(b) Instantaneous pressure fluctuation around 30P30N slat showing noise generation and propagation

Fig. 4. A hybrid RANS/LES computation of 30P30N 3-Element, Simplified High-Lift Configuration [32]

The difficulties encountered in the context of the tandem cylinder configuration are amplified in category 7 (Fig. 3(a)). The factors contributing to the extra difficulties include: (i) the increased complexity of noise generation (Fig. 3(b) and 4(b)) including multiple narrow-band peaks superimposed on the primarily broadband spectrum of slat cove noise, (ii) large time averaged lift on the model which leads to large deflections of the tunnel stream in an open jet facility and, hence, leads to unacceptable variations in the 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, and (vi) Reynolds number effects that may not be fully amenable to holistic measurements. Yet, the computational results presented at the BANC-II workshop [5] suggest a good prognosis provided the installation effects can be addressed satisfactorily.

Summary

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 of 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 multi-faceted understanding of the aeroacoustic phenomena in terms of both mean-flow features and near-field 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, phased microphone arrays have enabled a thorough 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 towards 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. Yet, several opportunities still remain to improve the computational and experimental methodologies and those would be addressed during the future BANC workshops.

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