A second golden age of aeroacoustics?

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In 1992, Sir James Lighthill foresaw the dawn of a second golden age in aeroacoustics enabled by computer simulations (Hardin JC, Hussaini MY (eds) 1993 Computational aeroacoustics, New York, NY: Springer (doi:10.1007/978-1-4613-8342-0)). This review traces the progress in large-scale computations to resolve the noise-source processes and the methods devised to predict the far-field radiated sound using this information. Keeping focus on aviation-related noise sources a brief account of the progress in simulations of jet noise, fan noise and airframe noise is given highlighting the key technical issues and challenges. The complex geometry of nozzle elements and airframe components as well as the high Reynolds number of target applications require careful assessment of the discretization algorithms on unstructured grids and modelling compromises. High-fidelity simulations with 200–500 million points are not uncommon today and are used to improve scientific understanding of the noise generation process in specific situations. We attempt to discern where the future might take us, especially if exascale computing becomes a reality in 10 years. A pressing question in this context concerns the role of modelling in the coming era. While the sheer scale of the data generated by large-scale simulations will require new methods for data analysis and data visualization, it is our view that suitable theoretical formulations and reduced models will be even more important in future.

1. Introduction

Aeroacoustics encompasses the science and technology related to sound generated by aerodynamic flows. The topic of aerodynamically generated sound became
an important issue as jet-powered aircraft came into service. The terrifying loud noise of early turbojet-powered civilian aeroplanes, such as the B707, prompted major research in jet noise and techniques for its mitigation. The design of the supersonic civilian aircraft Concorde required reduction of supersonic jet noise while managing the loss in thrust performance. This period of intense research can be regarded as a golden age of aeroacoustics. Through the 1970s and continuing to date, the introduction of turbofan engines with ever larger bypass ratio has brought gains in propulsive efficiency and reduced engine noise while allowing the engine power to increase. As the importance of jet mixing noise to the overall take off noise of civilian aircraft has reduced, other components of engine noise were emphasized, most notably the fan noise that radiates both in the forward arc of the aircraft as well as out of the exhaust nozzle and radiates to aft angles. Since the 1990s, the contribution of the airframe components to the aircraft noise in a landing configuration has become a topic of significant importance alongside the noise associated with the propulsive jet and the fan. As aviation technology has developed, the aeroacoustic noise issues have become increasingly more complex; as the dominant noise sources of a specific configuration are reduced other sources, often multiple in origin, have gained importance. This trend is expected to continue into the foreseeable future. As aviation continues to grow, its unwelcome noise threatens to impact a larger community and drives ever more stringent noise regulations. Meeting the aviation noise goals of the future, envisioned by many as a practically silent aircraft whose noise outside the airport perimeter is no louder than other ambient noise such as traffic, requires new concepts and design and optimization methodologies far more sophisticated than in use today. As underscored by design studies, such as the silent aircraft initiative [1,2], the drive towards a green, environmentally responsible aircraft requires unconventional concepts for significant aerodynamic and engine efficiency gains, aircraft weight reduction, and for noise reduction and greater noise shielding.

Design and launch of environmentally responsible aircraft can provide the impetus for a second golden age of aeroacoustics. Just as computational fluid dynamics (CFD) plays a vital role in the detailed design and optimization of any new aircraft today, one may expect computational analysis to play an ever expansive role in multi-disciplinary analysis, optimization and design of future aircraft which must meet aggressive noise, fuel burn and emissions constraints. This paper attempts to review the critical challenges in computational aeroacoustics (CAA), including the tools required for simultaneous aerodynamic, aeroacoustic and aero-structural optimization. Discussion is limited to issues regarded as central with an attempt to illustrate recent success. Space limitations allow only an outline of many complex topics, but it is hoped that together with the other contributions in this Theme Issue, a useful projection into the future is achieved.

2. Current status

It is useful to take stock of the advances made in aeroacoustics research, with emphasis on computational methods, in the past two decades to get a sense of what may be ahead in the next 20 years. For this purpose, we consider approximately the period 1990–2010. The phrase computational aeroacoustics was not in routine use prior to 1990, and the ICASE/NASA workshop in 1992 [3] discussed the promise offered by CAA. As echoed in the concluding panel discussion (summarized by Sir James Lighthill) two major thrusts were identified: (i) comprehensive CAA where the flow process generating the sound and its near-field propagation are both computationally resolved and (ii) hybrid CAA where the nonlinear flow process of sound generation is captured by the computations, but the acoustic radiation to the far-field is computed by the use of an acoustic theory. Comprehensive CAA is also referred to as direct calculation, or direct noise computation (DNC) in later literature and many variants of the hybrid CAA have also been developed. It should be underscored that aviation applications typically involve modest to high Reynolds number (Re) flows which are typically turbulent and laminar flow region, if present, may be limited. Simulations which capture the flow processes responsible for the dominant sound radiation must resolve the energy-containing eddies. Capturing the
Figure 1. (a) Simulations of a stalled NACA0012 aerofoil [22] and (b) cylinder–aerofoil interaction [23] using a higher-order compact overset scheme. In both cases, the generated acoustic field visualized in greyscale contours of dilatation depends on the aerodynamic and acoustic interaction between the unsteady flow and the solid surfaces. In the latter case, contours of $\lambda_2$ highlight the unsteady flow. (Online version in colour.)

Dissipative scales of turbulence or DNS is possible only at low $Re$. The viscous scaling of near-wall energy-containing eddies limits standard (wall-resolved) large-eddy simulation (LES) to moderate $Re$ (see [4,5]). Some form of modelling of near-wall eddies is essential to achieve the Reynolds numbers of applications.

Different hybrid approaches for flow simulations, such as zonal LES [6], detached eddy simulation (DES) and its variants [7,8], wall-modelled LES [9,10], and hybrid Reynolds-averaged Navier–Stokes (RANS)–LES, have been developed and are being investigated for aeroacoustics. A discussion with greater technical depth is given in [11,12]. Hybrid flow simulation methods are reviewed in [7,13]. Concise highlights of the progress related to computational aeroacoustics for aircraft noise follow.$^1$

(a) Computational algorithms

Both hybrid CAA and DNC require accurate acoustic propagation in the region of focus. Control of dispersive and dissipative errors and accurate non-reflecting boundary conditions are essential for acoustics. Accurate representation of the nonlinear flow processes without significant numerical dissipation, including turbulence, coherent vortices and shock waves, each of which may be important for sound generation, and ensuring that numerical artefacts do not become dominant sources are also critical. Much progress has been made towards these objectives using optimized high-order structured-grid-based schemes (see [11,14,15]). Significant efforts continue in application of high-order schemes on structured curvilinear grids, including overset grids [16–19] and multi-step time advancement [20] and unstructured mesh schemes such as the discontinuous Galerkin scheme [21] for aeroacoustic applications. Figure 1 shows two examples from recent calculations using a high-order compact overset scheme. Figure 2 shows examples from an unstructured mesh algorithm that provides flexibility in handling complex geometry. Capturing turbulent eddies of various scales and accurate wave propagation with minimum numerical artefacts is challenging.

Computational methods to efficiently extrapolate near-field flow data to predict far-field radiated noise (power spectra, directivity and time-domain signals) have advanced considerably. Kirchhoff formulations for stationary and moving surfaces, especially as embodied in the Ffowcs Williams–Hawkings equation [28–30], are commonly solved in the frequency domain. Convective effects of uniform flow [31,32] and modification owing to potential flow at low speed [33] can be accounted for in noise predictions. Treatment for two-dimensional flow [34], fast evaluation of the aeroacoustic integrals [35] and the treatment to reduce spurious attribution of vortical outflow as a noise source [36,37] are computationally beneficial. Computations of sound propagation in a general non-uniform flow, i.e. using the full (linearized or nonlinear) Euler equations,$^1$Page constraints and our knowledge of this broad subject limit the scope of discussion.
Figure 2. Examples of unstructured LES calculations for aeroacoustic prediction. (a) A supersonic jet impinging on a jet blast deflector [24]. Near-field temperature contours and far-field pressure contours are shown. (b) A Mach 1.4 jet from a rectangular nozzle with chevrons [25] matching that of experiment [26]. Near-field temperature contours and far-field pressure contours are shown on a vertical midplane. (c) A twin jet configuration [27]. (Online version in colour.)

(b) Simulation of jet noise and noise source modelling

Major advances in computational simulations of jet noise have occurred in the past decade. Studies of vortex dynamics in mixing layers and dynamics of instability waves in jets and the resulting sound radiation have contributed to improved understanding of sound generation [43–45]. They have also provided a useful test bed for assessing computational methods and developing theoretical models of sound generation in shear flows [46–48]. Major progress in the LES of compressible turbulent jets for aeroacoustic predictions came with the work of Shur et al. [49,50]. They combined RANS calculations of the jet flow from specific nozzles with LES of the flow downstream of the nozzle exit. Besides obtaining good agreement with available data on round nozzles for various operating conditions, they also reported the ability to compute the jet noise sensitivity to nozzle geometry change using emulated boundary conditions (see [51] for in-depth assessment). LES calculations directly including the nozzle geometry, with chevrons, internal mixing, etc., using an unstructured grid, were achieved more recently using a finite volume method [25,52–55]. Although finite volume methods are nominally only second-order accurate, excellent agreement with flow and both near- and far-field acoustic measurements was achieved with approximately 40–70 M control volumes [56]. This success was due, in part, to careful control of dissipation and dispersion errors using widened numerical stencils, and, in part, to the fact that unstructured meshes allow efficient placement of resolution where required. Further developments for realistic treatment of nozzle internal flow, installation effects in experiments and applications are underway. Figure 2 illustrates the current capability.

Jet flow and noise simulations using high-order structured solvers have also progressed significantly. Initial efforts excluded the nozzle and focused on the jet plume development [57–59]. Effect of the inlet condition on the jet development and its noise as well as the effect of jet Reynolds number were studied later [60,61]. Simulations by Bogey et al. recover the subtle changes observed in the experiments by Zaman and explain the mechanisms. Internal boundary layer flow within the nozzle has also been captured more recently [62,63].

Simulations of jet aeroacoustics have reached a point where the flow-field and acoustic databases generated by the simulations can support data-driven discovery and modelling of jet noise sources. Statistical noise source covariances, which are very difficult to obtain via laboratory measurements, can be computed using simulation data. As anticipated in previous studies [43,64,65], analysis of the recent databases is providing a comprehensive characterization of the jet noise source covariances. The structural differences in different Reynolds stress covariance
components and scale-dependent convection velocity [66–68] have been noted. More importantly, the often assumed independence among the different (source) components is shown to be flawed, particularly in relation to source terms involving enthalpy fluctuations [68,69]. It can be anticipated that as databases spanning different operating conditions (varying jet Mach number, heating level and nozzle geometry) are analysed useful guidance for statistical models of jet noise sources will emerge. Jet flow databases are also enabling examination of alternative models of noise generation, such as the intermittent wave-packet model (see [70] for a recent review). Another important trend is the use of simulations to discover important unsteady flow phenomena associated with strong sound emissions. Leakage of shock waves trapped in the supersonic core flow of pressure-mismatched jets [71–74] enabled by strong vortices and the recent discovery that crackle, which is a particularly annoying noise, originates as a shocklet embedded within energetic eddy motions [75,76] are just two examples.

High-fidelity computations provide not only a tool for predicting jet noise based on first principles and thus a tool to explore the sensitivity of the noise to design variations of the nozzle, but they also support the development of lower fidelity models. The latter can be used as engineering tools with greater confidence. Simulations also uniquely enable scientific study of flow processes responsible for sound generation, because particular processes can be artificially enhanced or suppressed. In the coming decades, we envision all three types of uses to grow, both in sophistication and with greater integration with parallel laboratory experiments, rig and flight tests.

(c) Simulations of airframe noise

Significant strides have been made since the 1992 ICASE workshop [3] in understanding the noise sources associated with an aircraft in a landing configuration, collectively referred to herein as airframe noise (see [77] for a review). Acoustic measurements using elliptic mirrors and phased microphone arrays in wind tunnel tests of airframe components and their modifications and scaled models of full aircraft have provided equivalent source strength maps covering the frequency range of interest. Empirical methods have been developed using such data for estimating the noise radiation from different source regions, such as the flap (cove, gap and flap track) [78], slat (gap and side edge) [79,80], landing gear (nose gear, main landing gear and its components) [81,82], wheel cavity, etc. These methods are part of aircraft noise prediction tools, such as ANOPP, and used to assess the noise of future aircraft concepts (see [83–85]). Airframe noise predictions based more directly on unsteady aerodynamic simulations of the high-lift system, landing gears, etc., have also seen much progress, but unsteady CFD tools are yet to be incorporated in the design practice. This is expected to change in the future. We briefly highlight some key elements of progress in simulating and modelling trailing-edge noise, slat noise and landing-gear noise. These components of airframe noise are expected to be prominent for NASA’s $N + 2$ advanced configurations, such as the blended wing–body or innovative tube and wing designs (see [84,85]). Trailing-edge noise and stall noise are important for the design and operation of large wind turbines. The unusually high level of amplitude modulation noise produced by large wind turbines has become an important issue for wind energy developers.

(i) Slat noise

As discussed by [79,86,87] several phenomena contribute to the unsteady flow in the slat region. The flow separating from the lower trailing edge (slat cusp) as a shear layer is highly turbulent and reattaches on the slat underside. Flow acceleration through the gap between the slat and the main wing distorts the turbulent eddies. Unsteady shear layer reattachment and passage of anisotropic turbulent eddies over the slat trailing edge generate unsteady forces on the slat. This mechanism (referred to as an edge-dipole source [79]) is regarded as a major contributor to slat noise generation. High-fidelity simulation of the multi-element aerofoil flow, and in particular
of the slat flow, using improved versions of DES (see [6,88]), implicit DES [89,90], with wall-model LES (see [10]) and stochastic source models coupled with acoustic perturbation equation solution [91,92] has provided important insights into slat noise generation and radiation. Strong collaboration between the computations and laboratory measurements (see [93]) even when simulations were limited to two-dimensional unsteady RANS, has resulted in faster progress. This interplay has also generated many ideas for reduction of slat noise, such as an inflatable filler for the slat cove, slat cusp extension, slat trailing-edge modifications, whose promise was assessed in simulations and then with laboratory tests. A recent in-depth study by Knacke et al. [88] of slat noise sources on the 30P30N configuration using delayed DES is representative of the current state of the art. In addition, see Deck & Laraufie [94] for computations of a different high-lift configuration using zonal DES and comprehensive aeroacoustic analysis, including the scaling of slat and flap noise and self-excited resonances. Figure 3 reproduced from [88] shows a visualization of the turbulent flow in the slat cove region and its frequency spectrum at various stations along the mean flow streamline separating from the slat cusp. Broadband noise with a peak close to a slat chord-based Strouhal number of 2 is observed to preferentially radiate at observer angles perpendicular to the slat trailing edge.

(ii) Trailing-edge noise

Turbulence passing over a rigid surface is constrained by it. The wall normal velocity of turbulent eddies is kinematically blocked by the wall, an effect modelled by the image eddies in the wall of the real turbulence. As the turbulent flow passes over a trailing edge this blocking ends abruptly and provides a site for potentially efficient conversion/scattering of hydrodynamic disturbances into sound [95–97]. The turbulent flow approaching the trailing edge and the sound produced by it can be computed using both DNC and hybrid CAA. Laboratory experiments and technical applications involving trailing-edge noise are typically at moderate-to-high chord-based Reynolds numbers (see [98] for a recent review of experiments and theory including trailing-edge devices to reduce the noise). Laboratory experiments often use trips near the leading edge and details of the laminar to turbulent transition are challenging to compute owing to the high-resolution requirements and ‘numerical tripping’ can generate excessive spurious noise and requires special attention [99]. At high Reynolds number, it is also not practical to resolve the near-wall turbulence, see [5], and hybrid schemes requiring resolving only the outer-layer eddies which scale with boundary layer thickness [9,10] are attractive. Wolf et al. [100] used a
high-order compact scheme with approximately 54 M points to simulate the turbulent flow over NACA0012 aerofoil at different angles of attack and Mach number at a Reynolds number of $408 \times 10^3$, and with laminar or turbulent boundary layers on the pressure side. They showed very good comparison with the available flow and noise measurements [101] and analysed the convective effects on noise radiation. Simulations at the slightly higher Reynolds number of $600 \times 10^3$ at $M = 0.2$ for the DU96 aerofoil [102] used 130 M points. Also see [103–105] for further perspectives on trailing-edge noise, including DNC. Moreau and co-workers [106] have simulated trailing-edge noise for a fan blade aerofoil using incompressible LES using about 5 M points with acoustic theory [95,107] and have shown the importance of computationally modelling the non-idealities, such as tunnel confinement and aerodynamic non-uniformities, existing in laboratory tests. Trailing-edge noise simulations using compressible wall-model LES [108] are showing significant promise with the ability to predict the blade aerodynamics including stall at a reasonable computational cost. Comparisons conducted under the BANC-II workshop [109] provide an assessment of semi-empirical and CAA-based methods for airframe noise prediction, including trailing-edge noise. Use of simulations for passive shape modification which reduce noise while maintaining other constraints (see [110,111]) is a promising area for further research.

(iii) Landing gear noise

The geometrical complexity of landing gear components with their multiplicity of geometrical features encompassing a very broad range of scales presents unique challenges for CAA. Struts, wheels, supporting links, hydraulic lines, pin holes, cavities, etc., are all exposed to the flow and generate complex, three-dimensional wakes that may impinge on other nearby structures and generate a broadband distribution of interacting noise sources. Each wake-generating element contributes to noise with a spectral peak at a frequency proportional to $U/D$, where $U$ is the local flow speed and $D$ is the transverse scale of the body. Besides this multi-scale wake shedding and aerodynamic interaction, there is also the potential for coupling via acoustic feedback and generation of resonant tones. See Dobrzynski [77] for a careful review and discussion of semi-empirical noise prediction methods and concepts for noise reduction. Landing gear components are generally expected to contribute noise as compact dipoles in proportion to the local flow speed to the sixth power, but note Spalart’s reminder [112] that this could be an oversimplification. Various groups are actively pursuing turbulence resolving simulations of the flow over simplified landing gear (nose landing gear and main landing gear). Spalart and co-workers [113,114] have focused on simplified main gear, whereas the NASA and ONERA groups have focused on the nose landing gear (see [115–118]). Comparisons conducted under the BANC-I and BANC-II workshops provide a perspective on the current status. A wide range of numerical algorithms including the lattice Boltzmann approach with a model for near-wall turbulence [119,120] are being investigated.

(iv) Fan and turbomachinery noise

As the bypass ratio of the modern turbofan engines has increased to gain higher propulsion efficiency the contribution of fan noise has grown in importance relative to jet noise. This trend is expected to continue in future and other components of turbomachinery noise (low-pressure turbine and core noise) are also projected to become important. Fan noise radiates out of the engine inlet and through the by-pass duct and out of the nozzle as aft radiation [121]. Fan noise is both tonal and broadband with each contributing comparable radiated power. The fan tonal noise is associated with the periodic displacement in the flow (thickness noise) and periodic forces (loading noise) exerted by the rotating blades, and by the interaction of the rotor wakes with the stator vanes (OGVs). The broadband noise is generated by the turbulent boundary layer eddies on the rotor blade scattered at the trailing edge and via the three-dimensional flow near the tip, and via the interaction of the turbulent rotor wake with the stator vanes. Non-uniformities in the inflow to the rotor (steady and unsteady) also generate tonal and broadband noise. Sound generated by the rotor wake OGV interaction propagates through a swirling sheared
flow between the rotor and OGV. Fan noise propagates through the flow in the engine inlet and in the bypass duct and is attenuated by the acoustic liners on the walls of these ducts [122]. As the engine size has grown with rated power and to accommodate higher bypass ratio, the length of the inlet duct has shrunk and thus the opportunity for attenuation by liners. At high-power settings, with transonic fan tip speeds, the rotor generates upstream directed buzz-saw noise associated with weak shockwaves [123]. Sound propagation within the engine ducts is typically described in terms of the propagating and evanescent duct modes of various circumferential and radial mode order. These duct modes are transformed/scattered into the radiating waves by the engine inlet geometry and the nozzle [124]. Turbulence in the nozzle exhaust flow refracts the aft-radiated sound and also Doppler shifts the radiated tones to create hay-stacking.

Prediction of turbomachinery noise, including fan noise, presents its own unique challenges (see [125,126] and the recent review by Peake & Parry [127]). Methods based on duct mode acoustics driven by the rotating blade sources (thickness and loading) and gust response of a cascade [128–130] with a statistical representation of inflow turbulence and wakes form the basis of noise predictions. Acoustic theory based on the linearized unsteady response in a swirling sheared base flow [131] is being developed for improved modelling. Computations based on the linearized Euler equations (LEEs; see [132–135]) are seen as a way of more realistically treating the effects of three-dimensional blade shapes and complex wakes while accommodating the transonic swirling base flow. Turbulence resolving simulations of turbomachinery cascade flows have been used more for studies of bypass-transition on low-pressure turbine and compressor blading and for heat-transfer studies of high-pressure turbines including film cooling, etc. (see Tucker [136] for extensive discussion). Use of zonal LES for broadband noise prediction in turbomachinery flows is not yet developed. Such an approach would require coupling a time-domain LEE solver with the zonal LES. Stochastic source models [137,138] coupled to an LEE solver are a lower-cost alternative but with a lower fidelity source model.

(v) Propulsion–airframe interaction noise and installation effects

The noise of an installed engine differs significantly from that of the engine alone operating at nominally the same conditions. The pylon wake modifies the exhaust jet plume and its noise; in fact, pylon interaction has been exploited in designing nozzle chevrons to reduce shock-cell noise. Fan noise scatters from the wing and fuselage and its directivity is modified. Propulsion–airframe interaction effects are being exploited in advanced configurations proposed for reducing the noise footprint of environmentally responsible or green aircraft. Aft-mounted and over the wing engines exploit the wing and tail surfaces to shield the ground observer, as would a buried engine inlet and airframe integrated distributed nozzle. Installation effects are also expected to be significant for military aircraft, including unmanned aerial vehicles. The interaction between propulsion system and airframe can be both aerodynamic and acoustic. For example, the landing-gear wake may interact with the high-lift system, pylon wake interacts with rotor in a pusher configuration, engine exhaust plume may interact with flaperon and so on. Installation effects can be tailored to produce a noise reduction when they can be predicted and considered part of the design. While CFD is already used to examine aerodynamic interactions, it is only natural to envision CAA to play a significant role in assessment and exploitation of installation effects. Prediction of scattering and shielding owing to the airframe, prediction of flight effects on the installed system noise, as well as prediction of the vibroacoustic environment around the fuselage including the crew cabin are some of the areas of importance for future CAA applications.

3. Opportunities and pacing items

While significant progress has been made in simulations of jet noise, airframe noise and fan noise, many research opportunities remain. In §3a, we discuss some overarching themes which are likely to play a significant role in aeroacoustics research in the next 20 years.
(a) Trends in HPC: towards exascale computing

Although Moore’s law has successfully predicted the increase in the speed of computers over the past 40 years, the manner in which these gains continue to be realized has recently shifted significantly. Traditionally, reductions in the physical size of integrated circuitry enabled enhanced processor speeds. Today, however, integrated circuits have reached a scale where further reductions are prevented by quantum mechanics and thermodynamics. As a result, processor clock speeds have stagnated in the past 10 years [139]. Gains in processing speed are now achieved almost exclusively through enhanced parallelism. Current supercomputers link together millions of processors to achieve petascale performance. The trend towards ever increasing parallelism means that effective CAA algorithms must be both scalable and resilient.

In 2004, Colella [140] classified scientific computing applications into seven motifs or ‘dwarfs’, representing patterns of computation that he believed would remain important to engineering and science for at least a decade. Although the list was later expanded to include 13 categories, the motifs important to high-performance computing still numbered seven: dense linear algebra, sparse linear algebra, spectral methods, $N$-body methods, structured grids, unstructured grids, and MapReduce. Aeroacoustics codes span this entire range: explicit resolution of acoustic sources using DNC or hybrid CAA falls under the categories of structured and unstructured grids. These motifs rely upon spatially local information and are highly scalable: recently, a strong scaling study of an unstructured LES solver (CharLES) demonstrated 83% parallel efficiency on one million cores at a granularity of 650 grid points per core. Alternatively, spectral methods provide highly accurate representation of acoustic sources and propagation of waves. Spectral methods, however, require global (all-to-all) communication, limiting scalability.

Simulation of low Mach number flows naturally leads to either implicit or semi-implicit methods—requiring the solution of a Poisson or Helmholtz equation for example. This falls under the motif of sparse linear algebra, and also requires global communication. This communication can be structured and thus limited, however, using iterative methods such as Jacobi, conjugate gradient or multi-grid. Recently, a strong scaling study of a three-dimensional Poisson solver using a mixture of the conjugate gradient and multi-grid methods demonstrated 60% parallel efficiency for one million processes with a parallel granularity of 2000 grid points per core [141]. This was achieved by limiting global communication to collective all_reduce operations for which IBM BG/Q provides hardware support. Without this, the granularity below which strong scaling stops was found to be 10 times as great. This highlights a useful aspect of the seven dwarfs classification: if we can use this framework to identify and distil simple global communication patterns important to scientific computing, such as all_reduce, then we can guide hardware developers on where to focus their efforts. In addition, while iteration provides one way to structure communication in sparse linear solvers, an exciting class of direct solvers based on hierarchical matrices have been shown to yield $O(N \log N)$ performance on serial platforms [142], and potentially will map in a similar manner to large-scale parallel platforms.

In the hybrid CAA approach, computation of the aeroacoustic integrals used for propagating to the farfield can be accelerated by the wideband multi-level fast multipole method [33], which falls into the category of $N$-body methods. Acoustic scattering also leads to boundary integral equations where multi-pole methods or hierarchical matrices may help structure communication. If the number of far-field observers is not too many, then the MapReduce motif is also useful as a method to query and project acoustics from large-scale databases derived from LES [143].

In summary, the current trend towards extreme levels of parallelism means that the performance of aeroacoustic algorithms in the future will hinge upon how well they optimize communication, rather than necessarily the number floating point operations performed. Communication-avoiding algorithms will become a necessity, and theoretical lower bounds on communication have been derived for several of the motifs [144]. While some parallel motifs are more naturally suited to the exascale environment, evidence suggests that others
may be enabled by hardware supporting a small subset of global communication operations (if the scientific community identifies them now), indeed enabling a second golden age for aeroacoustics.

(b) Reduced-order modelling for design and optimization

Although computational capacity is continuing to grow exponentially, industry largely relies upon lower fidelity steady RANS calculations coupled with empirical databases to make noise predictions. Although noise is fundamentally an unsteady phenomenon, steady solvers are the norm because of their low computational expense. As computational capacity continues to increase, however, the more accurate and robust unsteady solvers will inevitably replace their steady-state counterparts. This transition will naturally incorporate low-fidelity LES first: while high-fidelity simulations involving 200–500 M cvs are possible today, the time-to-solution of such methods is orders of magnitude too great to be directly integrated into the design cycle. Such simulations do, however, yield a wealth of information that may be used for data-driven modelling. Before discussing data-driven modelling, we first address the role of RANS calculations in design.

For jet noise, steady RANS may provide base flows about which unsteady perturbations or instability waves are calculated. The parabolized stability equations (PSEs) provide an efficient way to compute unsteady perturbations about base flows, which organize into wavepackets for subsonic jets [145,146]. While this method has proved successful for subsonic jet noise [147], low-frequency noise from hot supersonic jets remains difficult to predict [148]. With increased computational power, it is also possible to directly compute global modes of supersonic jet noise [149] which do not rely upon the assumption of a streamwise slowly varying base flow. Compared with low-fidelity LES, the resulting set of combined PSE and global modes would represent an even further reduced model of jet noise sources.

RANS models will also likely remain important for predicting airframe noise in the next 20 years. The change in length scale that results from the constraining effect of a wall on turbulence places severe spatial and temporal resolution requirements upon wall-resolving LES. Hybrid RANS–LES techniques, based on steady RANS, unsteady RANS or partially averaged Navier–Stokes models close to the wall will therefore be essential.

Viewing a base flow as an input–output system for perturbations is useful for constructing optimal control strategies. Models of such systems must be balanced between the most prevalent outputs and the most dangerous inputs. For example, while much aerofoil noise is generated close to the sharp trailing edge, adjoint calculations show that the system is most receptive to perturbations in the centre of the pressure side of the aerofoil [150]. For this reason, reduced-order models based on proper orthogonal decomposition (POD) modes alone may require additional modes to reproduce important dynamics [151]. A reduced-order model can instead be formed by projecting the system operator onto the first few direct and adjoint-balanced truncation modes [152]. Balanced truncation modes are similar to POD modes in that they may be computed through a snapshot method. For a discussion of optimal control applied to input–output reduced-order dynamical models, see [153]. For controlled flows, it is also possible to use the linearized dynamics represented by the reduced-order model to compute second-order statistics with which to update the RANS base flow, closing the loop [154].

(c) Data-driven modelling and uncertainty quantification

For jet noise, experimental evidence suggests that supersonic turbulent mixing noise may be composed of two different components, corresponding to the large and small scales of turbulent motion [155,156]. Advanced data-decomposition methods applied to experimental far-field acoustic measurements from high-speed jets failed, however, to separate the data into two different statistically independent components for all radiation angles [157]. Wavelet analysis reveals intermittency as an important characteristic of sound sources [158], as different source
modes may continually interfere with one another. For flows containing strong tonal components, dynamic mode decomposition [159] and its sparsity-promoting variant [160] enable extraction of coherent dynamics from a sequence of snapshots with minimal spectral leakage.

A fundamental problem with modelling noise sources is to separate sources of the noise from the propagation of sound away from these sources. The simplest such separation is Lighthill’s acoustic analogy whereby the Navier–Stokes equations are rearranged, so that the wave equation appears on the one side, balanced by terms analogous to acoustic sources on the other [161,162]. While exact, Lighthill’s equation assumes propagation with respect to a quiescent base flow and neglects refraction effects caused by convection and variable density. Instead, these effects are lumped into the source terms, masking their physical relevance. Goldstein [163] generalized the acoustic analogy approach, rearranging the Navier–Stokes equations into the form of the linearized inhomogeneous Euler equations. In this form, the propagator accounts for refraction owing to both convection and variable density. For supersonic jet noise, Leib & Goldstein [164] point out that the fourth-order correlation tensor is more accurately modelled with a decaying exponential function than with a Gaussian. In addition to modelling subgrid-scale motions for accurate prediction of the resolved large-scale turbulent motions, a noise model is required to account directly for the noise produced by the missing scales [165].

While accurate models of acoustic sources and propagation are important to free shear flows such as jets, they are even more critical to wall-bounded aeroacoustic flows where near-wall eddies cannot be efficiently resolved. Although it is hoped that high-fidelity simulations and experimental databases can be mined to construct robust and accurate models, the models will inevitably represent an epistemic source of uncertainty. In addition, as previously discussed, aeroacoustic flows are also sensitive to aleatory sources of uncertainty such as small changes to geometry, upstream turbulence levels and even temperature. The method of stochastic collocation (SC) [166] is well suited to leverage exascale computational resources against the models to bound uncertainty associated with them. This technique was applied to low-speed axial fan noise for a hierarchy of low-fidelity acoustic and flow models to assess their predictive performance [167]. The models showed the largest discrepancies close to the fan blade tips—an important aspect of uncertainty quantification procedures is that they may be used as a rational guide in focusing efforts aimed at constructing better models. To demonstrate this methodology for low-fidelity LES, SC was applied to noise generated by the interaction of a cylindrical rod placed in front of an aerofoil, where it was found that the acoustic field was sensitive to the precise position of the rod [168]. As hybrid methods which combine different levels of modelling and different numerical schemes are developed and applied to more complex aeroacoustic problems, the problem of uncertainty quantification would need to be addressed in parallel with model development and evaluation.

4. An outlook for the future

This review has attempted to highlight the progress made in computational aeroacoustics in selected key areas during the past 20 years to underscore important trends which may influence future progress. The progression from simple, idealized configurations isolating specific unsteady flow processes to more complex flow problems with realistic geometry is already apparent. Greater fidelity in capturing a range of turbulent flow scales and thus the noise generation processes associated with them and hybrid approaches which mix models of different fidelity in different regions of the flow are being used. This is part of the trend towards computational simulations of entire devices or systems enabled by the availability of massively parallel computing.

While the technical challenges in high-performance computing on new architectures at ever larger scale of parallelism will surely drive much research in future, entirely different challenges in engineering higher education and professional development must also be addressed to ensure that engineers of tomorrow adopt the new simulation technologies. Development of best practices, automation of computational work flow including grid adaptation, model reduction
and model improvement, and on the fly analysis and visualization are necessary. The history of CFD may serve as useful guide as well as reminder that coherent, sustained research programmes are necessary to overcome the barriers. Chapman’s view [169] of when LES would impact aerodynamic design turned out to be too optimistic. But, his proposition that circumventing the turbulence modelling problem by resolving the important nonlinear dynamics of turbulent eddies where statistical models are known to fail remains valid and is likely to open up design and analysis methods for aviation technology in new ways. Confidence building in the new higher-fidelity and hybrid-fidelity tools is essential through systematic verification and validation. Will all this bring about a new golden age in aeroacoustics or more broadly in aeronautics? The answer will depend on whether the professional community is successful in offering creative solutions which not only meet the constraints on fuel consumption, emission and noise, but also the global economic realities.

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