Advances in aeroacoustics research: recent developments and perspectives

Sergey Karabasov, Lorna Ayton, Xuesong Wu, Mohammed Afsar

Aeroacoustics continues to be a subject of active research now nearly 70 years since its genesis in the 1950s at the dawn of the jet age. Although fundamentally a branch of fluid mechanics, aeroacoustics has grown into a discipline of its own right with well-defined scientific and technological missions, namely, modelling both the generation and outward propagation of sound, and more critically developing novel noise-reduction techniques. Given the ongoing expansion of civil aviation set against the introduction of ever more stringent regulations on aviation noise, it is imperative to reduce aircraft noise even further. Moreover, unexplored noise sources from diverse areas, such as that generated by flow over unmanned aerial vehicles, wind turbines and the forthcoming urban air mobility vehicles, present further challenges.

In line with the technology demands, the importance of continued aeroacoustics research is reflected by increased numbers of high-level technical meetings and journal special volumes including the current Theme Issue. The contributions to this Theme Issue address either of the topics of 'aerofoil noise' and 'jet noise'. Naturally, each topic is tackled by both theoretical and computational methods which complement each other and further the understanding of aerodynamic noise.

Theoretical modelling of isolated aerofoil noise focuses primarily on the far-field sound generated by turbulence scattering off its leading or trailing edges. The simplest model is that of a harmonic wave being scattered off a semi-infinite plate in a uniform flow, and the resulting mathematical problem is solved using the Wiener-Hopf technique. Recently the model and technique have been extended to aerofoils embedded in a non-uniform mean flow possessing much more realistic geometries such as finite chord, camber effects and spanwise serrated edges—a design that mimics owl wings, which have evolved to fly more-or-less silently relative to background noise levels. Considerable research effort continues to be directed towards the fundamental aspects of shear-flow/edge interaction and jet noise. The main applications of this research include installation noise abatement, supersonic jet noise reduction by fluid injections and prediction of co-axial jet noise, closely related to modern turbo-fan aero-engines. Different mathematical approaches to jet noise modelling include the generalised acoustic analogy that takes into account mean flow propagation and source anisotropy effects within a single unified description of broadband turbulence. On the other hand, phenomenological methodology such as the two-source model that emphasises discrete dynamics of coherent structures, or wavepackets, also found their merits. The formal asymptotic approach, based on detailed analysis of the near field, complements acoustic analogy by probing into the underling physical processes of sound radiation in jets and certain wall-bounded flows.

While applied mathematical techniques are vital for the development of physically insightful and fast-turn-around-time reduced-order methods, computational modelling based on high-fidelity methods plays an increasingly important role in modern aeroacoustics due to both the geometric and physical complexity of realistic engineering problems, where turbulence-surface and turbulence-sound interactions may be important. Furthermore, extraction of relevant turbulence correlations, needed for acoustic analogy approaches that assume the source structure is known, must be supplied by numerical computations. One of high-fidelity methods to overcome these challenges is the scale-resolving approach of Large Eddy Simulations (LES), which may be performed either in traditional Eulerian Navier-Stokes framework, or via the Lattice Boltzmann Method (LBM). Here, efficient numerical algorithms which enable high concurrency of simulations on modern computer architectures need to be exploited. In comparison with reduced-order modelling approaches, high-fidelity methods typically require large computer resources (thousands of processor hours) and involve manipulations with big datasets (now at terabyte level), which invariably demand expert knowledge to develop the relevant post-processing technology. The reward is that once carefully validated, the high-fidelity methods can provide an unparalleled wealth of information that can help advance mathematical models further.

The papers within this theme issue are written by leading experts who have contributed much to the developments highlighted above. Despite differences in flow details, which are as numerous as the utilised technology demands, there is a great deal of similarity in many of the aeroacoustic problems presented herein, in terms of the methods used. Hence, a distinct focus of the issue is on discussions of the methods that can be potentially employed and developed for new applications that are likely to emerge in the future. By consolidating these methods into one special volume, we showcase the breadth of current research activities on the one hand, and on the other provide an easy reference for practioners in the field.

The issue opens with the contribution of Ayton [1] which discuses recent advances in mathematical modelling of turbulence scattering from a bio-inspired wing with serrated leading and trailing edges. The paper also presents an acoustic analogy model to predict the roughness noise generated from a bio-inspired porous trailing-edge aerofoil adaptation which utilises asymptotic analysis to understand the high-frequency noise increase due to the surface roughness. In the following contribution by Jaworski [2], a semi-analytical model based on a Schwarz-Christoffel conformal mapping is presented for the fluid-structure interaction between a vortex and a flexible fibre attached to a rigid wall. The solution obtained is relevant for aerofoil surface treatments typical of the soft feather coating on the owl wing, which serves to reduce aerofoil noise by deflecting vortices from the trailing edge.

On the computational modelling front, the contribution by Grace, Gonzalez-Martino and Casalino [3] analyses the computational results for two-vane configurations. The data come from Very Large Eddy Simulations based on the Lattice Boltzmann Method. Challenges related to post-processing of large amount of data generated in the high-fidelity simulation are discussed as well as the lessons learnt from extracting the statistical quantities (such as the streamwise and transverse turbulent length scales) which can be useful for subsequent reduced-order modelling.

Next, a review of the history and recent developments of the two-source jet noise model is presented by Tam [4], who provides arguments in favour of the phenomenological approach to modelling jet noise. Motivated by jet flow physics, the two-source model proposes empirical fine-scale and large-scale spectra to account for the contributions of fine-scale turbulence and large-scale coherent structures to far-field noise, respectively. Examples of applications of the two-source model range from the noise generated by laboratory jets to rockets and volcano eruptions.

Taking a different approach to the above, the contribution by Afsar, Sescu and Leib [5] uses asymptotic analysis within the generalised acoustic analogy to model the peak noise from isothermal subsonic jets. This work uses a Reynolds Averaged Navier Stokes (RANS) calculation for the mean flow field to approximate turbulence source structure and to determine the adjoint vector Green's function of the Linearized Euler equations via a non-parallel flow asymptotic solution. Special consideration is given to the effect of mean flow spreading in the calculation of the appropriate Green's function. In the contribution of Li and Xu [6], another modification of the generalised acoustic analogy is proposed, which (inspired by Tam's two-source model) separates the acoustic integral into fine-scale and large-scale sources, which are characterised by different length scales and amplitudes. The latter are modelled through the RANS calculations with empirical constants being determined by fitting with experimental data.

A matching asymptotic expansion approach, which is complimentary to both acoustic analogy and phenomenological modelling, is discussed next in the contribution by Wu and Zhang [7]. Rather than pre-designating the source and sound, this approach identifies and characterizes the true emitter according to the far-field asymptote of the fluctuation, and it has led to first-principle descriptions of sound generation by nonlinearly modulated wavepackets of supersonic and subsonic instability modes in free shear layer, as well as by instability waves scattered by short-scale inhomogeneity in wall-bounded shear flows.

Goldstein, Leib and Afsar [8] review recent developments in Rapid Distortion Theory (RDT), namely, its application to jet-surface-interaction noise. RDT uses a formalism similar to the acoustic analogy in the sense of determining a Green's function and modelling the unsteady turbulence source structure. But in contrast to jet noise modelling the basic interaction problem is linear and can be solved in terms of a single convected scalar quantity that is an arbitrary function of its arguments. The paper summarizes how the latter can then be related, exactly, to the physically realizable unsteady flow field.

From a computational perspective, high-resolution simulations of free-shear flows such as jets have reached a state of maturity in comparison with the wall-bounded flows. An extensive survey of different contributions in the area of high-fidelity jet flow and noise modelling based on LES is given by Lele and Bres [9]. The review discusses a broad range of common issues pertinent to jet noise applications -- from boundary conditions, grid generation and high-performance computing, through turbulence modelling, to details of the far-field noise prediction schemes and the flow solution analysis based on the LES data.

As a further illustration of modern LES capabilities, the contribution by Prasad and Morris [10] discusses the computational modelling of the effect of fluid injections to abate both the jet mixing noise and the broad-band-shock-associated noise in supersonic jets. Modelling here is based on a general commercial Computational Fluid Dynamics (CFD) solver (Star CCM+), which makes results of this work accessible to a wide audience in industry and academia where this software is used. The Issue concludes with the contribution by Markesteijn and Karabasov [11], which showcases advantages of using state-of-the-art computer architecture such as Graphics Processing Units (GPU) for short-turn-around-time flow and noise calculations of co-axial jets at high fidelity. The simulations are based on Wall Modelled LES approach with a synthetic turbulence inflow condition and the CABARET (Compact Accurately Boundary-Adjusting high-REsolution Technique) space-time scheme for solving the Navier-Stokes equations on locally refined unstructured meshes with asynchronous time stepping.

References

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