NUMERICAL EXPERIMENTS OF AEROFOIL NOISE: THE ROLE OF DIRECT NUMERICAL SIMULATIONS IN UNDERSTANDING AND CONTROLLING NOISE

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Abstract

Aerofoil self-noise is the noise produced by the interaction between an aerofoil with its own boundary layers and wake and is of concern as it is an important contributor to the overall noise in many applications, e.g. wind turbines, cooling fan blades, or air frames. The continued growth of available computing power has made direct numerical simulations (DNS) of compressible flows with application to aerofoil noise possible. In this review paper, challenges associated with such simulations and numerical details of a DNS code that is able to exploit modern high-performance computing systems are presented. DNS data of flow at moderate Reynolds number are used to evaluate the accuracy of approximations commonly made in deriving trailing edge noise theories. Data from simulations of flow over NACA-0012 aerofoils with straight and serrated flat-plate trailing-edge extensions are presented to highlight the potential of DNS to study noise reduction technologies.

1. Introduction

The continued spectacular advances in available computing power over the last decades have enabled the use of high-fidelity flow simulation approaches for investigation of aerodynamically generated noise. Broadly speaking, the so-called computational aeroacoustics (CAA) approaches can be classified as direct or hybrid approaches. In the latter case, flow simulations are conducted as a first step to provide the noise source field that serves as input for various types of acoustic analogies, used to propagate sound to the acoustic far field. In hybrid approaches, either compressible or, should the flow parameters allow, incompressible simulations of the flow field can be conducted. In contrast, in direct noise computations (DNC), compressible flow solvers are used to simulate the hydrodynamic and acoustic fields simultaneously. In the late 1990s, such computational aeroacoustics simulations were described as still being in their infancy, with “the sound from a canonical flow such as a perfectly expanded supersonic jet has only just been computed …” [1].

However, over the last decade and a half, significant progress has been made applying direct numerical simulation (DNS) in the context of computational aeroacoustics, and the technique is becoming more popular as computing power increases.

The focus of the current review paper is to present compressible direct numerical simulations with application to aerofoil noise. The challenges in conducting such simulations, mainly in terms of computational effort, will be discussed. A high-fidelity multi-block structured curvilinear compressible Navier-Stokes solver purposely developed for exploiting high-performance computing systems (HPC) will be introduced and its performance presented. Results are shown for turbulent flow over trailing edges, testing acoustic theories, and for noise reduction strategies for aerofoils.

2. Challenges for Direct Numerical Simulations of Aerodynamic Noise

Directly solving the unsteady compressible Navier-Stokes equations to study aerodynamically generated noise introduces several computational challenges. Crighton [2] pointed out that the extent of the acoustic field is considerably larger than the relevant flow field due to the much greater wave length of acoustic waves when compared to lengthscales of flow structures. This implies that large domains are needed to capture the acoustic field, while a fine resolution in the source region is required to resolve all relevant scales of the flow.

Assuming simulation of a volume of isotropic turbulence, the computational effort to resolve all turbulence and acoustic scales can be estimated as a function of Reynolds and Mach numbers as follows.

For each spatial direction, the number of grid points N^{1D} required to resolve the smallest scales of turbulence motion, the Kolmogorov scale η_K, over the length of the largest scales l, that are associated with the geometry of the flow, scales as $N^{1D} = l / \eta_K \sim Re_T^{3/4}$, with Re_T denoting the turbulent Reynolds number.

As turbulence is intrinsically three-dimensional, the number of grid points N^{3D} that are required to resolve the turbulence flow field is thus proportional to $Re_T^{9/4}$. If one now factors in the timestep required to also resolve all unsteadiness of the flow and the noise, and including the acoustic wave length, the total computational effort is proportional to Re_T^3/M^4.

While the adverse Reynolds number scaling can be somewhat remedied by introducing turbulence modelling, e.g. to Re_T^2 in large-eddy simulation, the high power of the Mach number in the denominator constitutes a severe constraint when considering small Mach numbers. In such situations, direct noise computations become computationally prohibitively expensive and one typically resorts to hybrid approaches using incompressible flow solvers, in which the acoustics are uncoupled from the flow. However, in cases where the acoustic field affects the flow field, e.g. in the presence of acoustic feedback mechanisms, hybrid approaches cannot be used due to their inherent one-way fluid-to-acoustics coupling and very high computational expense is unavoidable.

Additional challenges to the direct simulation of aerodynamically generated noise, besides the computational cost, are due to the difference in amplitude between the aerodynamic and acoustic pressure fluctuations, that can be approximated as M^4 [2]. This demands very accurate numerical schemes with minimal levels of dissipation. Furthermore, suitable free-space boundary conditions are required to avoid spurious reflections that can contaminate the acoustic field. More information on the topic of computational aeroacoustics and its challenges can be found in recent review papers [3-5].

3. Compressible DNS Code

3.1 Numerical methods

To meet the numerical challenges outlined in the previous section, direct noise simulations require numerical codes that can exploit modern high-performance computing (HPC) systems. In the current paper the in-house multi-block structured curvilinear compressible Navier-Stokes solver HiPSTAR (High Performance Solver for Turbulence and Aeroacoustics Research) is presented. To minimize computation time for a given problem in order to make best use of the available resources, the numerical algorithm was designed to resolve flow features with minimal amplitude and phase errors, for efficiency of the scheme (i.e. high ratio of accuracy to computational cost) and high parallel efficiency on HPC systems.

One of the most effective ways to increase the performance of a numerical code on bandwidth-limited systems is to reduce the memory requirement of a simulation for a given problem. In HiPSTAR, this is achieved by a combination of high-order spatial methods, using finite differences and a spectral approach, and time-integration schemes.

To take full advantage of massively parallel HPC systems, the code was initially parallelized

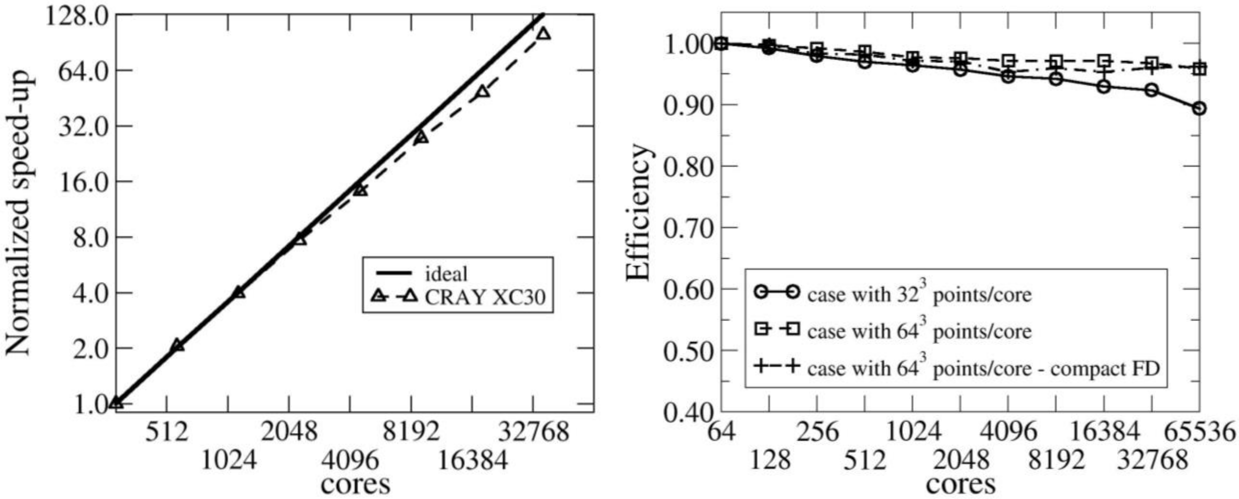

Figure 1. Strong scaling for single-block test case with 1.3 billion grid points on CRAY XC30 (left) and weak scaling on CRAY XE6 (right)

using the message passing interface (MPI), enabling computing on distributed memory machines, and then extended to hybrid OpenMP/MPI parallelization for modern multi- or many-core HPC systems.

3.2 Parallel performance

The performance of the DNS code has been evaluated on several different computing architectures, but for conciseness here only results obtained on the UK national supercomputing facilities HECToR, a CRAY XE6 architecture, and ARCHER, a CRAY XC30 system, are presented. Initial scaling tests were performed on ARCHER on a single-block test problem with 2,404 points in the streamwise and lateral directions, and 128 Fourier modes in the spanwise direction, resulting in a total number of collocation points of 1.3×10^9. First a strong scaling test, i.e. the numbers of cores are varied for a given problem size, was considered. Figure 1 shows the excellent scaling of the code between 288 and 36,864 cores, for which a real speed-up factor of 102 is achieved versus the ideal factor of 128.

Another technique to test parallel performance is the so-called weak-scaling test in which the number of operations every core has to perform and the MPI messages every core has to send/receive is kept identical for increasing overall number of cores. When using 32^3 points per core, very good scaling is obtained for all core numbers tested, with efficiency not dropping below 90%. The larger test case with 64^3 points per core shows even better scaling, with efficiency remaining as high as 96% up to 65,536 cores (resulting in a case with 17.2×10^9 grid points). An additional scaling study was performed with 64^3 grid points/core with a compact finite difference scheme which also showed high efficiency. More importantly, despite the significant increase in computational effort, for compact schemes banded matrices need to be inverted, the overall computational cost did only increase by 13%. This can be explained by the fact that codes with better ratios of algorithmic operations (FLOPs) over communication fare better on current bandwidth-limited computing systems.

4. Results

4.1 Testing trailing-edge noise theories

As a first step, DNS of turbulent flow passing an infinitely thin trailing edge (TE) were conducted. The boundary layer on the upper side was turbulent, whilst the boundary layer on the other side of the plate was laminar. This set-up was chosen as it best replicates the assumptions made deriving trailing-edge noise theories, in particular that of Amiet [6]. One of the objectives was to assess the accuracy of the assumptions made in the classical trailing-edge noise theory, using DNS data. The simulation was conducted using 106×10^6 gridpoints. Full details about the grid and numerical set up are given in [7].

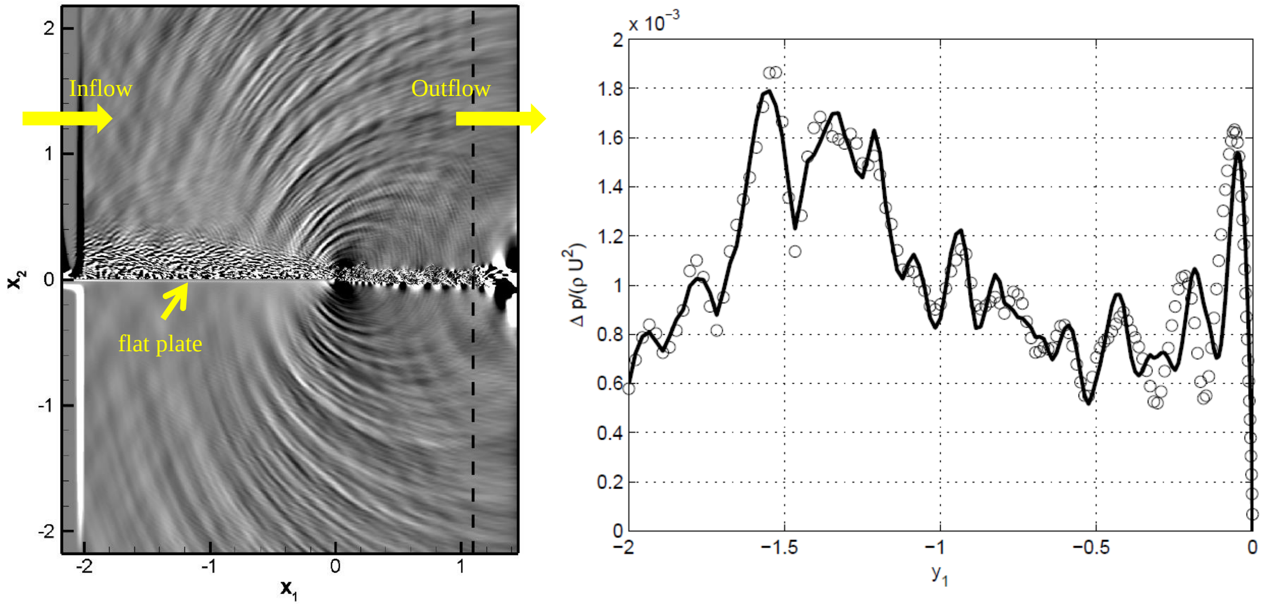

Figure 2. Instantaneous contours of dilatation, with levels [-2×10^{-3}; 2×10^{-3}] (left); total surface pressure difference, open circles obtained by using Amiet's theory, line from DNS data (right)

A qualitative view of the flow field is given in Figure 2 by instantaneous contours of dilatation. It is clear from the Figure that the noise radiated to the farfield originates from the trailing edge, located at (x_1, x_2) = (0, 0), and that the boundary conditions are able to reduce spurious reflections to a level that allows for study of trailing edge noise. Furthermore, the Figure also reveals that on the upper surface of the flat plate, the turbulent boundary layer contributes to the overall noise above the plate, while on the lower side the acoustic field is only comprised of the trailing-edge noise component.

Amiet's theory [6] assumes that the far field sound can be evaluated as a function of the total surface pressure difference and that this quantity can be obtained by adding the incident pressure field, i.e. the turbulent fluctuations convecting over the plate, to the pressure field scattered off the trailing edge. In the classical theory, the prediction of the scattered pressure relies on a surface pressure jump transfer function. The current set-up featuring turbulent and laminar boundary layers on the top and bottom surfaces of the splitter plate, respectively, allows the computation of the incident pressure field by comparing the bottom surface pressure and the top surface pressure. Using this incident pressure field, the total surface pressure difference can be evaluated using the approach of Amiet [6] and can then be compared to the total surface pressure difference directly obtained directly from the DNS data. Thus the accuracy of one of the key elements of the trailing-edge noise theory, the surface pressure jump function, can be assessed.

A comparison between the predicted and the directly computed total surface pressure difference is shown in Figure 2 over the length of the plate for a low frequency of St = 0.5, with St denoting the Strouhal number. The agreement between prediction and DNS is reasonably good and improves when investigating higher frequencies (not shown here). This good agreement with DNS data implies that obtaining the incident pressure field by adding the bottom surface pressure from the top surface pressure is a useful approach.

Other elements of Amiet's trailing edge noise theory, such as the assumption of frozen turbulence spectra and an approximation of the spanwise correlation length were also assessed using the DNS data and a detailed discussion is given in [7]. One aspect to be particularly aware of is that the use of periodic boundary conditions in the spanwise direction used for the simulations can artificially increase the amplitude of the noise measured in the simulations.

4.2 Aerofoil noise reduction

DNS of the flow around a NACA-0012 aerofoil at freestream Mach number 0.4 and chord-based Reynolds number Re_C = 50,000 were conducted. A thin flat plate geometry attached to the aerofoil was chosen so that bluntness effects could be avoided. The additional geometrical complexity introduced

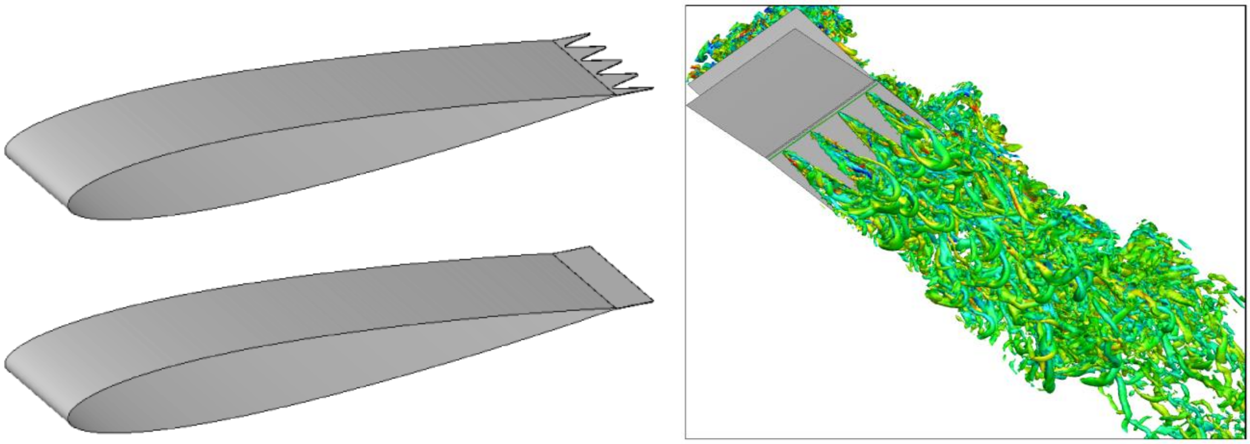

Figure 3. Geometry of cases with and without serrations (left) and Instantaneous iso-surfaces of the second invariant of the velocity-gradient tensor coloured by streamwise vorticity for a serrated trailing-edge case

by the trailing-edge serrations represents a considerable numerical challenge when using high-order accuracy spatial schemes. Therefore, an immersed boundary method was employed to represent the flat-plate trailing-edge extensions with and without serrations. The size of the trailing-edge extensions were chosen such that the lifting surface area of the aerofoils with and without serrations was the same.

The geometry of the trailing-edge extensions with and without serrations is shown in Figure 3, along with iso-surfaces of the second invariant of the velocity-gradient tensor to visualize the turbulent flow field in the vicinity of the trailing-edge modifications. A wide range of turbulent spatial scales can be observed, including both streamwise- and spanwise-orientated and horseshoe-type vortices. The serrations appear to limit the maximum spanwise extent of turbulent structures to a spanwise dimension of one serration width. When viewing a large number of snapshots in time (not shown here for conciseness), the presence of the serrations also appears to promote the development of horseshoe-type vortices in the wake with more regularity and the structures seem to originate from the serrations themselves.

Importantly, comparing the acoustic fields of the un-serrated to serrated cases, the serrations are found to reduce noise. This noise reduction can be visualized by looking at contours of modulus of pressure, as shown in Figure 4. The detailed flow field in the wake was not written to disk to reduce storage requirements; hence the wake region is cut out of the graphs.

One-third octave averaging about several target frequencies was performed to account for the broadband nature of the airfoil-noise. According to the analytical study by Howe [8], for the selected geometry of the serrations noise reduction should not be expected below a target frequency of St ≈ 5.

The left subfigure of Figure 4 shows the case with serrations at a target frequency of St = 3.37. It is clear from the image that a significant contribution of trailing-edge noise is present at this frequency. In previous studies it was found that the target frequency St = 7.75 corresponds to the most amplified frequency of instabilities in the laminar-turbulent transition region and structures observed in the laminar separated shear layer on the suction side of the airfoil are consequences of these instabilities. This frequency is above the threshold for noise reduction predicted by the analytical approach of Howe [8]. As illustrated by Figure 4 the trailing edge noise contribution below the airfoil indeed appears considerably weakened by the addition of TE serrations. Note that the noise reduction is not obvious on the upper surface due to the presence of additional noise sources associated with turbulent reattachment that cannot be expected to be affected by serrations.

From further analysis of the DNS data [9] it was found that neither the directivity or spanwise correlation levels of the acoustic radiation change significantly for frequencies at which significant noise reduction is achieved. In addition, Reynolds stress amplitudes, turbulent spectra and spanwise correlations are similar for the serrated and straight trailing-edge cases, implying that the incident pressure field to the trailing-edge scattering mechanisms is unaffected by the serrations. This suggests that changes in the sound radiation are caused mainly by changes to the scattering process itself.

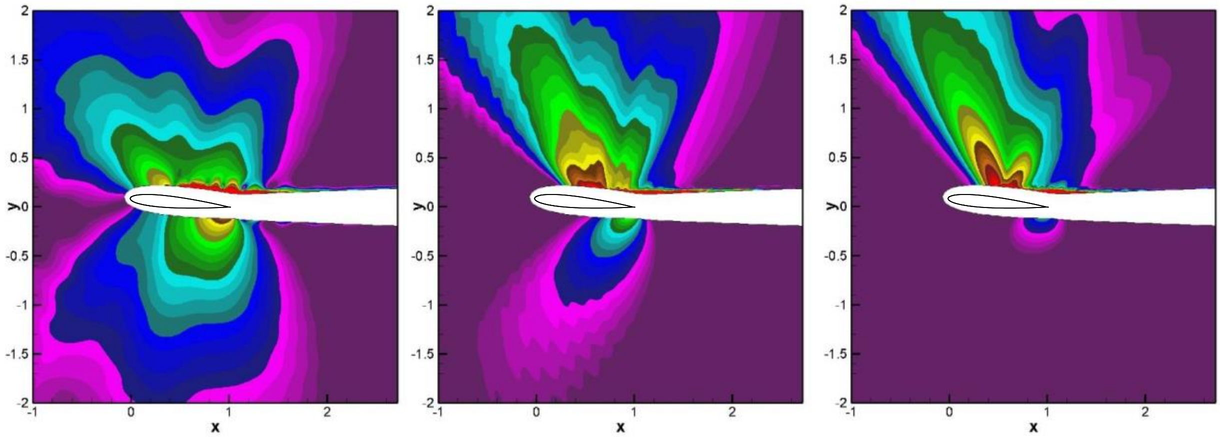

Figure 4. Logarithmically spaced contours of one-third octave averaged modulus of pressure at target frequency St = 3.37 without serrations (left) and at St = 7.75 without (middle) and with (right) serrations

5. Conclusions

The challenges associated with conducting high-fidelity aeroacoustic simulations have been outlined and a high-performance compressible Navier-Stokes solver, purposely developed to exploit modern high-performance computing systems has been introduced and its high performance demonstrated.

Large-scale compressible direct numerical simulations were performed of a number of cases, each with a different objective. Data obtained from the DNS of turbulent flow over a trailing edge was mainly used to test assumptions made in commonly used trailing-edge noise theories. DNS of aerofoils with and without flat-plate trailing-edge extensions with and without serrations were conducted to investigate the noise reduction mechanisms. It was found that serrations can indeed achieve a substantial noise reduction, which is mainly attributed to the geometrical change of the scattering mechanism.

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