Delivering better power: the role of simulation in reducing the environmental impact of aircraft engines

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The growth in simulation capability over the past 20 years has led to remarkable changes in the design process for gas turbines. The availability of relatively cheap computational power coupled to improvements in numerical methods and physical modelling in simulation codes have enabled the development of aircraft propulsion systems that are more powerful and yet more efficient than ever before. However, the design challenges are correspondingly greater, especially to reduce environmental impact. The simulation requirements to achieve a reduced environmental impact are described along with the implications of continued growth in available computational power. It is concluded that achieving the environmental goals will demand large-scale multi-disciplinary simulations requiring significantly increased computational power, to enable optimization of the airframe and propulsion system over the entire operational envelope. However even with massive parallelization, the limits imposed by communications latency will constrain the time required to achieve a solution, and therefore the position of such large-scale calculations in the industrial design process.

1. Introduction

The computational power available to the computational fluid dynamics (CFD) user has increased by several orders of magnitude over the past 25 years. Some estimates predict a further growth of 1000-fold during the next 25 years [1]. Such increases in computational power will fundamentally change the way in which gas turbines are designed but only if that power can be harnessed to provide reliable predictions in usable time scales for the designer.
In this paper, we consider how such an increase in computational power could be employed to design better gas turbine propulsion systems that will help to reduce the environmental impact of air travel. We also consider the practical issues in realizing such a growth in computational power for routine design calculations.

2. The gas turbine

A cutaway illustration of a typical modern aeronautical gas turbine is shown in figure 1. Air is admitted through the intake to the fan, where the pressure is increased before the flow either travels along the bypass duct to mix downstream with the exhaust flow or enters the core engine. The flow into the core engine passes through several stages of compressor before entering the combustion system. Here, liquid fuel is injected and burned, accelerating the flow through the turbine which generates the power to drive the fan and compressor. From the turbine, the flow passes through the exhaust and so out to the atmosphere. Alongside this primary gas path is the secondary air system which is fed with air bled from the main gas path to provide cooling of the discs holding the rotating compressor and turbine blades while the combustor and turbine main gas path surfaces are also cooled in order to improve component life. The operation of the gas turbine is described in more detail in texts such as [2].

All of the gas turbine manufacturers are addressing the challenges of improving component life and performance while reducing the environmental impact of both manufacturing and operating the equipment. The ACARE (Advisory Council for Aviation Research in Europe) 2020 goals [3], customer demands and the needs of local communities all require continuous efforts to reduce the environmental impact from aviation, both in the form of the combustion by-products and noise levels. The latest proposed targets [4] are to achieve, by 2050, a 75% reduction in CO₂ and 90% reduction in NOx emissions per passenger kilometre with a reduction in perceived noise emissions of 65%, all relative to typical new aircraft of 2000. Meanwhile air traffic is forecast to grow at an annual rate of 4–5% worldwide⁽¹⁾ which places even more pressure on reducing the environmental impact. The gas turbine is now so efficient that achieving further improvements through incremental technology changes is increasingly difficult. Achieving such ambitious targets in a highly competitive environment will require both a holistic view of the

⁽¹⁾ Airbus Global Market Forecast 2010–2029.
aircraft and propulsion system along with a significant increase in the use of computational simulation in order to explore the design space more extensively and identify revolutionary solutions.

3. A look backwards

Twenty-five years ago, the gas turbine design process was dominated by empirical design methods and experimentation. Designs were generally based on existing configurations, modifications developed through the use of correlations and past experience and then components tested experimentally. CFD was used to a limited extent but most often to confirm a design in conjunction with test data instead of being used to guide the design. Turbomachinery use of CFD was largely confined to multiple two-dimensional calculations of individual bladerows (the S1–S2 streamsurface calculations [5]) most often using inviscid flow models with coupled boundary layer analyses. Prediction of flow and pollutant levels in realistic combustion systems was in its infancy [6], but even at this stage it was necessary to use fully three-dimensional turbulent flow models. Calculations were performed on single-block structured grids using serial codes, although some industrial use of vector computers was beginning.

4. The present day

CFD is now an established part of the design process for all parts of the gas turbine. Steady-state RANS (Reynolds-averaged Navier–Stokes) methods are now the minimum level of fidelity used for most components. Turbomachinery blading is now designed using three-dimensional multi-bladerow analyses. Calculations can also be performed for multiple passages up to the whole assembly for a bladerow, although such calculations are computationally highly expensive. Combustion systems are designed using detailed multi-phase calculations to predict turbine entry temperature distributions and overall gaseous pollutant levels. Intakes and exhausts are designed with the aid of CFD while the secondary air system uses extensive CFD analysis to predict cooling flow distribution and heat transfer. Noise from turbomachinery and exhausts can be predicted to allow the development of lower noise propulsion systems, most commonly using RANS calculations which then provide sources for acoustic analogies as described in, for example, [7]. However, these methods have been most effective for tone noise, while broadband noise has remained a more challenging problem.

Most calculations use unstructured meshes to allow more geometric fidelity and calculations are routinely run on parallel computers. The availability of relatively cheap parallel systems using commodity hardware in the form of distributed-memory PC clusters has enabled the use of computational meshes fine enough to reduce numerical errors to acceptable levels for many calculations.

The increase in computational power has also allowed optimization and design space exploration to be used to improve the performance and robustness of designs. The computational cost of performing the large number of calculations required for a typical optimization is high and so a surrogate model approach [8] is often used. As an example, the work in [9] applies a surrogate model approach to aid in the design of compressor blades that maintain their performance even with erosion of the blade profile.

These improvements all together have permitted the development of new gas turbines that are quieter and more fuel-efficient than ever before thereby reducing their environmental impact in line with legislation and customers’ expectations.

5. A look to the future: the potential

We now consider what impact a 1000-fold increase in computational power may have on the use of CFD in the design process for future gas turbines, and how this will help to contribute to the reduction in environmental impact.
Three complementary avenues of exploitation seem likely: to perform more detailed component calculations; to include additional physics; and to move from component-based to system-level calculations. In order to achieve the required improvements in environmental performance, we need to consider more radical designs and so the analyses must include automated design space search and optimization. As the computational power becomes available, these avenues will converge.

The objective must always be to deliver information relevant to developing the engine design within the required time scales and to an acceptable level of quality, which will place great demands on how rapidly these increasingly complex calculations can be completed and analysed to extract useful information. We consider each of the avenues in turn.

(a) More detailed component calculations

A significant increase in available computational power will permit the routine running of more detailed component calculations. Larger grid sizes will allow more features of the real geometry to be captured, such as clearance gaps and leakage flows and to permit more physics to be represented. A move from RANS modelling to eddy-resolving methods such as LES (large eddy simulation) or hybrid RANS/LES will have significant benefits in many areas of the engine. The prediction of mixing processes (such as within the combustion chamber or the exhaust) will be significantly enhanced by the routine use of eddy-resolving methods instead of RANS, since the large-scale momentum and scalar transport processes can be simulated and not modelled. The prediction of noise sources is also significantly enhanced by having the time-dependent Reynolds stresses available for acoustic analogies and propagation of the noise to the far-field instead of simply using time-averaged sources. The prediction of combustion chamber performance will also be improved by the ability to run more complex models of combustion chemistry and turbulence–combustion interaction as a routine part of the design process. This will aid the development of lower emissions combustion systems.

Turbomachinery predictions will see particular benefits from the ability to run larger models. This will be manifested as routinely running calculations of a complete assembly (i.e. all blades in a row) for multi-bladerow domains. This type of calculation allows the effects of interactions between bladerows to be captured without any assumptions on periodicity, including the effects of non-uniform inlet conditions as may arise from some of the airframe concepts under consideration for reduced environmental impact (see §5d). The second benefit for turbomachinery will be the ability to move to eddy-resolving calculations which is likely to be especially important for the prediction of cooled turbine blades and for calculations at off-design conditions where flow separation can occur [10]. These will guide the design of turbomachinery systems with higher efficiency in more hostile environments.

(b) Multi-physics

More computational power will allow the emerging trend for multi-physics or multi-disciplinary calculations to grow. Already the use of aeroelastic calculations for assessing turbomachinery blade mechanical response to unsteady aerodynamic loads is commonplace for fans; this will become routine for all blade types. Coupled calculations of the airflow and thermal response of the structure, as is currently performed for internal air systems [11], will also become routine for all ‘hot end’ components to enable the prediction of component temperatures and also the airflow in the presence of the real hot geometry shape.

(c) System-level calculations

Possibly the most important development that will be enabled by a 1000-fold increase in available computational power will be a move from component-based CFD analyses to whole system models. Such system-level models, up to the simulation of the whole engine, will allow the
Figure 2. Potential future civil airframe configuration. (Online version in colour.)

various component interactions to be identified at the design stage instead of during the full engine physical testing. Such ‘virtual engine’ calculations have been active research areas for a number of years (see [12] for a review of some of the efforts) but are currently too expensive to run in full as part of the gas turbine design cycle. However with sufficient computational power available, the prospect of simulating the entire gas turbine becomes feasible. In the early stages of the design, this may be a variable-fidelity model employing CFD where required and low-order models to represent the rest of the engine as appropriate. This would then move up to a full CFD analysis of the entire engine for verification of system-level behaviour and interactions before finalizing the design. Optimization would be used at the component level, with the associated ‘scenery’ of the rest of the engine, and at the entire gas turbine level to ensure that whole-engine parameters such as thrust and emissions are properly considered.

As an example, the whole engine core calculations of Schlüter et al. [13] are a demonstration of the type of analysis that at present is a flagship demonstration, impractical within an engineering design environment. However with a 1000-fold increase in computational power this type of analysis, coupling RANS and eddy-resolving methods as appropriate, will be a commonplace part of the design process.

Such a ‘virtual engine’ calculation will ultimately be the culmination of the trends described above and encompass multi-physics modelling (coupled aerodynamic, thermal, mechanical) and where necessary moving from RANS models to eddy-resolving methods. Such calculations will require billions of cells (an estimate of 10–100 billion is made in [14]) and, even with the increases in computational power postulated for the next 25 years, will probably remain at the limit of what will be possible. This capability, especially with an ability to use variable levels of fidelity as described, will give the gas turbine community the freedom to produce more innovative, revolutionary designs to meet the ever more severe product requirements that are essential to deliver a safe and environmentally sustainable growth in aviation.

(d) Integration with the airframe

The ambitious environmental targets proposed in [4] cannot be achieved simply by developments to the propulsion system. Instead, they require a holistic view whereby the airframe, propulsion system and operation are considered and optimized together to achieve low environmental impact. When considering radical new airframe concepts such as the Silent Aircraft [15,16], assessing the integration of the airframe and propulsion system computationally becomes imperative. As an example of new airframe concepts that may be required to meet these environmental targets, we show in figure 2 the SAX-40 concept from the Silent Aircraft Initiative, a development of the configuration described in [15]. This aircraft, fitted with embedded rear-mounted engines, represents the type of highly integrated design required to achieve a major reduction in environmental impact and which will need to employ highly integrated and detailed computational analyses during the design. Airframes of this type will reduce environmental impact by reducing fuel consumption through lower drag and improved aerodynamic efficiency, while noise pollution is reduced by using the airframe as shielding and by employing higher bypass ratio engines with low-speed fans and lower velocity propulsive jets. Other concepts for commercial aircraft that could be viable in the time scales being considered here have been examined as part of the NASA ‘N + 3’ study, including advanced ‘tube and wing’ aircraft and
blended wing body designs similar to the silent aircraft geometry. Some of these concepts are described, along with the required propulsion systems, in [17] where it is emphasized that high-fidelity simulation and design optimization will be required throughout the design process, but especially in the early stages, to develop systems capable of meeting the N + 3 programme goals.

A complete CFD-based coupled analysis of the virtual aircraft and virtual engine around the flight envelope will probably still be prohibitive in 25 years’ time as a design tool. However, such an approach using a CFD-based virtual aircraft and a lower-fidelity virtual engine using data from the full multi-physics virtual engine should be a feasible design tool. Such an approach would also enable the airframe designer and the propulsion system designer to jointly develop an integrated and optimized system while still respecting each partner’s intellectual property. With suitably accurate physical models for gaseous emissions and noise, it will then be possible to evaluate the environmental impact of the aircraft over the entire flight cycle.

6. Challenges

The step change in modelling capability described above and realizing the impact on the gas turbine design process will not be achieved by simply waiting for computer power to increase to a level where such calculations are feasible. Instead significant areas of research are also required in order to enable the efficient use of the computational power within the context of a gas turbine design cycle. These research areas can be broadly categorized into pre- and post-processing; physical modelling improvements; and developments that can be categorized as the underlying computational engineering.

(a) Input generation and post-processing

To perform the kind of large-scale calculations described in §5, especially the virtual engine calculations, we will require mesh generation techniques that are faster, more reliable and better able to deliver good quality meshes than anything currently available. In order to be useful for influencing the design, a virtual engine calculation comprising over a billion nodes must be capable of being defined, meshed, run and post-processed within a few days. This will require a high degree of automation in both mesh generation and post-processing. To be able to harness the computational power effectively the mesh generation must be capable of delivering good quality meshes with little or no user input for the whole primary and secondary gas paths, such that it may be embedded in an automated system-level optimization. Similarly, the post-processing of the calculation results to extract meaningful engineering information will be fully automated which will require the use of data mining and pattern recognition methods to identify features of interest or concern. If we are considering mesh sizes of 10–100 billion cells, as proposed in [14] for a fully-resolved virtual engine, then a high degree of parallelism will also be required in both pre- and post-processing in order to make the problem manageable.

In order to improve data flow and reduce user intervention, the mesh generation system will have to be closely coupled to the CAD (computer-aided design) system used to design the components. This will remove problems associated with translating the native CAD model into a format usable by the mesh generator. Similarly after running an optimization process, the revised geometry should be automatically fed back into the CAD model so that it is synchronized with the analysis results.

(b) Physical modelling

In order to realize the benefits of increased computational power in calculating more detailed component- or subsystem-level problems, we require further advances in physical modelling to extend the reach of CFD. The increased use of eddy-resolving methods, with a corresponding move away from statistical turbulence models for design verification, should aid the development of reliable prediction methods for phenomena such as transition which is important in the intake
and in turbomachinery. The need to predict pollutant emissions throughout the flight cycle will also mandate the development of improved combustion chemistry models and associated turbulence–chemistry interaction modelling, while prediction of the combustor mixing processes will again be aided by adopting eddy-resolving methods as standard.

While eddy-resolving methods will undoubtedly become the norm for design verification, there will still be a place for RANS calculations. This level of modelling will be particularly important in design space search and optimization, where large numbers of calculations will be required. The speed advantage of RANS will enable a more comprehensive exploration of the design space than would be possible with eddy-resolving methods. However, in order to guide the design in the correct direction, the RANS results must be reliable and so further development of RANS models is likely in order to ensure their effectiveness, driven by databases combining experimental results and calculations using eddy-resolving methods. This use of eddy-resolving methods to guide RANS and other lower order model development is likely to be particularly fruitful in areas such as plume mixing and noise prediction as in [18].

(c) Computational engineering

Perhaps the greatest challenges in the efficient harnessing of the growth in computational power can be categorized as computational engineering challenges.

The trends in chip design have continued to follow Moore’s law [19] in the way that component counts have grown and this currently shows no sign of abating. However, clock speeds have generally stagnated since the early 2000s and gains in performance have been achieved by increasing parallelism. The dominant paradigm in CFD for gas turbines is the use of unstructured mesh RANS codes, for which great efforts have been made to increase parallel efficiency. One such effort is described in [20] which considers an unstructured edge-based code using MPI on distributed memory parallel architectures. The improvements achieved by careful tuning are impressive with near linear speed-up for sufficiently large problems to over 1000 cores.

The current trend in parallel execution is towards many-core computing; the use of very large numbers of simpler cores to achieve rapid turn-around. This trend and its implications are explored in more detail in [21]. One leading example of this trend towards many-core computing is the use of GPUs (graphics processing units) for running CFD such as [22]. The authors present a three-dimensional unsteady RANS turbomachinery code running on GPUs with speeds high enough to enable whole assembly, multi-bladerow calculations to be realistic. However, this code uses a multi-block structured mesh arrangement that is most suited to the architecture of the GPU. Efforts to make general unstructured mesh codes work efficiently on many-core architectures have required significant investment as described in [23], for example. In this work, a semi-automatic method for conversion of a legacy Fortran code to GPUs is described along with the effort required for certain problematic areas such as the linear equation solver. Speculation that the model for high-performance parallel CFD in the near future will be a heterogeneous CPU–GPU hybrid [24] suggests that current industrial CFD codes will have to function efficiently on this type of architecture in order to see the required performance growth in the short term. In the longer term, it appears likely that the route for even higher performance will be through some form of many-core architecture. As a result, a considerable effort in conversion and validation will be required for legacy industrial codes although tools such as those described in [23] and environments such as OpenACC [25] will aid the conversion.

At first glance, it would appear that a move to many-core architectures and ever-more massive parallelism will deliver the performance improvements required to achieve the vision of the CFD or multi-physics virtual engine described above as a tool to enable gas turbines with lower environmental impact. However, the reality is significantly more complex. The speed increases that have been achieved in different components of the computer have been achieved at different rates: processor speeds have advanced faster than data transfer rates in memory, which have advanced faster than memory latency which itself has advanced faster than latency of the interconnects between processors [26]. The result is that for many-core systems
growth in compute power soon delivers no benefit for a fixed problem size. Running ever larger calculations delays the point at which the communications latency begins to dominate the compute speed but does not circumvent it. This problem was also present with traditional parallel implementations on smaller numbers of CPUs, but for many-core systems using thousands of cores the communications latency as well as memory latency and bandwidth become more critical to the ultimate performance of the code.

As well as the communications latency problem, a move to many thousands of cores as the route to our 1000-fold increase in computational capability brings the additional considerations of power consumption and reliability. A system with tens or hundreds of thousands of cores will consume significant amounts of power which will increase the cost of large-scale multiphysics calculations and must be included in a project’s budget requirements. This cost must be considered carefully in the light of the accuracy of the simulation; otherwise, there is a danger of the simulation not being worth the cost, especially when compared with an experiment. The reliability of such massively parallel systems will also need to be very high, with an ability to keep solutions running by re-routing calculations to other nodes in the event of a hardware failure on the compute host.

The eventual stagnation of the time to solution even with massively parallel systems first raises the question of whether current industrial codes are suitable for this architecture, and secondly the question of whether the current CFD paradigms are still the most appropriate. The codes in common use within the gas turbine community have been optimized for systems with at most a few thousand cores. Extending these to tens of thousands of cores and above may not be viable without extensive modification and so new codes optimized for the prevailing architecture may be more appropriate. These codes can then be constructed with the memory and communications latencies of many-core systems in mind and adopt procedures to improve execution times, as described in [26]. This will require considerable effort in both writing and qualifying these new codes. However, it is inescapable that most industrial codes are built on methods that were conceived in the serial processing era which have been adapted to the shared or distributed memory parallel models using for example MPI. In order to achieve the parallel efficiencies and compute speeds offered by the projected exascale systems [1], we should consider whether now is the time to invest in research on alternative CFD solution methods that may be better suited to delivering the goal of a multi-physics virtual engine that can be used to develop and then verify a design in advance of any hardware being manufactured.

7. Expectations for computational fluid dynamics

Finally, we consider the question: what are our expectations for CFD in the gas turbine design environment? In the early stages of the design, when major decisions are being made about the engine architecture (such as the number of compressor stages) then analyses that give a reliable trend and ranking of different options are often sufficient. At this stage, when the design space may still be large, it is more important to have a method that can be run rapidly and so a calibrated RANS approach will be the preferred tool. However, when we wish to verify a design then accurate quantitative analysis is essential which, with current CFD paradigms, suggests a large-scale eddy-resolving approach, including modelling developments of the kind outlined in §6b. The models must be capable of delivering highly accurate results with, for example, turbomachinery stage efficiencies predicted to within 0.01%, in order to demonstrate the required level of performance in advance of manufacture. This will be a significant challenge to the CFD method, physical modelling and best practices to ensure repeatable and reliable calculations.

8. Conclusion

In this paper, we have considered the ways in which a further 25 years of growth in computational power (postulating a 1000-fold increase) may change the way in which CFD is used in the design of gas turbines. In particular, this growth of computational power will enable the use of CFD to
help identify revolutionary new designs to reduce the environmental impact of aircraft engines in the form of lower gaseous emissions and lower noise.

While the vision is relatively clear, there are a number of challenges to achieving it which will form productive areas of research. In particular, the ultimate stagnation of solution speed with increasing parallelization will impose a limit on how rapidly these large-scale calculations can be performed and ultimately limit their usefulness in the design process. It may well be the case that current unstructured production codes are not suitable for such massively parallel environments which will require new codes that are designed for the many-core architectures foreseen. However, this may not be enough to harness the full power of future exascale hardware and so we must consider whether an entirely new type of CFD solution approach is in fact needed to realize the potential of rapid virtual engineering.

Acknowledgements. The author thanks Rolls-Royce plc for permission to publish this paper. The views expressed in this paper are those of the author and not necessarily those of Rolls-Royce plc.

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